Lifetime Extension of Wireless Sensor Networks with Energy Harvesting

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Abstract Wireless sensor networks (WSN) consist of a large number of sensor nodes to collect various data such as temperature, humidity, speed, acceleration, and so on. In these networks, sensor nodes are usually driven by battery energy and distributed over extensive and large areas. Thus, running out of battery energy is a serious problem. For this reason, it is important to extend the lifetime of WSN. To extend the lifetime, the method of low-energy adaptive clustering hierarchy (LEACH) has been proposed. In LEACH, a cluster head (CH) is chosen without considering the residual energy of each node. Energy-harvesting technology in WSN has also been proposed. However, energy harvesting has some problems. Equipping energy-harvesting devices increases the system cost. Also, the amount of generated energy is unstable in real situations. To solve these problems, this paper proposes LEACH with partial energy harvesting (LPEH), extended LEACH with energy harvesting (ELEH), and ELEH with a sleep operation. In LPEH, the number of energy-harvesting nodes is limited to avoid increasing cost. In ELEH, a CH is chosen from the energy-harvesting nodes to extend the lifetime effectively. In ELEH with the sleep operation, each node becomes an active mode or sleep mode after consideration of the amount of remaining battery energy. In these methods, the coverage area is not considered. Thus, this paper proposes ELEH with the sleep operation considering node positions (ESNP) and ELEH with the sleep operation considering surrounding area condition (ESSA). In ESNP and ESSA, each node enters the sleep mode depending on the distance from adjacent nodes and the surrounding sensing condition, respectively, to reduce the overlapped sensing area. Thus, the unrequested data collected by other nodes becomes low and the energy consumption is reduced. As a result, the coverage area remains large in the long term.

Keywords: wireless sensor networks, LEACH, energy harvesting

1. Introduction

Recent advances in battery technologies and micro-electro-mechanical systems (MEMS) have facilitated the development of low-cost and low-power sensors with the functions of sensing, wireless transmission, computation, and data processing [1]. Wireless sensor networks (WSN) is expected to be applied to various fields such as the agriculture and military fields and disaster prevention. In WSN, sensor nodes are usually driven by battery energy. In addition, many nodes are distributed over a large and extensive area. Thus, it is difficult to change the batteries of all nodes. For this reason, it is important to extend the lifetime of WSN as much as possible.

The main of consumption energy in WSN is for data transmission to collect environmental data. To reduce the energy consumption, numerous data collection methods have been proposed such as direct transmission, relay methods, and clustering. In direct transmission, every node transmits the collected data to a base station (BS) directly [2]. Thus, each node consumes a large amount of energy. Some relay methods have been proposed, for example, the minimum transmission energy (MTE) method and cooperative relaying [3]-[5]. Clustering algorithms such as low-energy adaptive clustering hierarchy (LEACH) [6], power-efficient gathering in sensor information systems (PEGASIS) [7], and the hybrid, energy-efficient, distributed clustering approach for ad hoc sensor networks (HEED) [8] have been proposed to extend the lifetime. In LEACH, the energy consumption of the CH is small because the CH is changed on a regular basis. However, LEACH does not take into account the residual energy of each node in the CH selection procedure. Although HEED takes into account the...
residual energy in CH selection, the energy consumed in cluster forming is larger than that in LEACH. In PEGASIS, the energy consumed in cluster forming is small. However, each node must know its own position. Thus, it is necessary to equip the system with global positioning system (GPS) terminals. This increases the cost.

For lifetime extension, the application of energy-harvesting technology to WSN has been proposed [9]. Energy-harvesting wireless sensor networks (EHWSN) are much more useful and economical than simple WSN in long-term running. Energy, such as light power, wind power, vibration power, and so on, is always available. Thus, it is expected that the operation term of EHWSN can be extended without maintenance. The use of natural energy is related to green information communication technology (green ICT) [10], in which reducing the energy consumption and greenhouse gas emissions are major objectives. Thus, it is important to develop EHWSN to have achieve a more environmental friendly, safe, and secure society. However, even the best WSN routing protocols are not sufficiently efficient to be used directly in EHWSN because the amount energy generated by energy harvesting is small and unstable. In addition, the application of energy-harvesting technology increases the cost. To extend the lifetime of EHWSN, several methods have been proposed [11]-[13].

These methods do not consider the overlapped coverage area of all nodes and the non-coverage area. Here, the coverage area means the sensing area of the sensor nodes. The coverage area is assumed to be a circle and its radius is decided by the type of collected data. In WSN, it is necessary to cover all the observation area as long as possible. Collected data from multiple sensor nodes in nearby locations are often highly correlated. Thus, the amount of effective data may be lower than the total amount of collected data. In this regard, the literature [14] shows that the number of data transmissions can be reduced by considering the data correlation.

To solve the above-mentioned problems such as increased cost, effective routing for WSN, unstable generated energy, and maintaining a large coverage area, we propose LEACH with partial energy harvesting (LPEH) and extended LEACH with energy harvesting (ELEH). In addition, we propose ELEH with a sleep operation to avoid battery depletion when the generated energy is small. After that, we propose ELEH with a sleep operation considering node positions (ESNP) and ELEH with sleep operation considering the surrounding area condition (ESSA) to maintain a large coverage area.

The rest of this paper is organized as follows. Section 2 reviews the conventional method. In Sec. 3, our proposed method to extend the lifetime of WSN effectively will be given.

In Sec. 4, performance evaluation results obtained by computer simulation are provided. Finally, Sec. 5 summarizes this paper.

2. Conventional Method

Clustering uses a hierarchical approach and organizes by the network into a set of clusters. LEACH is a general method of clustering and is a distributed, one-hop clustering algorithm. The operation of LEACH is divided into rounds. Each round consists of a setup phase and a steady-state phase.

In the setup phase, the nodes organize themselves into clusters with a node acting as a CH. The nth node becomes a CH for the current round based on a preassigned probability threshold, \( T_n \). Here, \( T_n \) is defined by

\[
T_n = \begin{cases} 
  \frac{k}{N - k \times \left( r \mod \frac{N}{k} \right)} & (n \in G) \\
  0 & \text{(otherwise)} 
\end{cases}
\]

where \( N \) and \( k \) are the number of nodes and the number of CHs, respectively. \( r \) is the number of the current round and \( G \) is set of nodes which do not become a CH during \( k \) rounds. Once the node becomes a CH, the CH must notify the other nodes in the network that it has been chosen as the CH for the current round. Then, each CH broadcasts an advertisement message. Each non-CH node determines its cluster for this round by choosing the CH that requires the minimum communication energy based on the received signal strength indicator (RSSI) of the advertisement from each CH. After this operation, each non-CH node transmits a join request message back to the chosen CH. In a steady-state phase, on the other hand, cluster members transmit their collected data to the CH during their allocated transmission slot and enter the sleep mode. To reduce energy dissipation, each non-CH node uses power control based on the RSSI of the CH advertisement. Each CH compresses the collected data in the cluster and transmits them to the BS.

To extend the lifetime of WSN, it is necessary to set an appropriate number of cycles to reduce the energy consumed in cluster forming. Here, the number of cycles means the number of steady-state phases in one round. The nominal number of cycles is 100 [6] in this paper.

The energy-harvesting method is adopted to improve the lifetime of WSN. Energy harvesting uses natural energy such as solar power, wind power, vibrations, and radio frequency power [15]. The merit of this approach is that it is not necessary to exchange batteries. Table 1 shows the power generation density of each energy source. In real situations, it is expected that the amount of generated energy with energy harvesting is not stable. Thus, when the generated energy
is small, many nodes may run out of battery energy. To solve this problem, a sleep operation has been proposed [16]. In [16], when the battery energy of a node is low, the node enters the sleep mode. When the battery is recharged, the node returns to the active mode. In [11], there are some energy-harvesting nodes in the WSN. All the energy-harvesting nodes become CHs in every round. Thus, energy consumption of the CHs is large in comparison with normal LEACH. In addition, the generated energy is unstable in real situations. In the case of small energy generation, energy-harvesting nodes may exhaust their battery energy. To avoid this problem, it is preferable to change the CH on a regular basis. Furthermore, the relationship between the number of energy-harvesting nodes and lifetime was not discussed sufficiently in [11]. Thus, the effectiveness of the scheme is unclear and there is room for further study. In [12], the BS runs a genetic-based clustering algorithm to select the CH. Although this method can extend the lifetime, the BS needs a large memory and the calculation is cumbersome. In [13], the dutycycle and transmission power are optimized to extend the lifetime of each node. However, the lifetime of WSN was not discussed sufficiently.

3. Proposed Method

3.1 LPEH: LEACH with partial energy harvesting

In WSN, it is important to distribute the energy consumption to extend the lifetime. In [9], all nodes are equipped with energy-harvesting devices. As a result, the system cost increases. To solve this problem, in our proposed method, the number of energy-harvesting nodes is limited. The CH node consumes more energy than non-CH nodes. This is because the CH collects data from all nodes in the cluster, compresses them and sends them to the BS. In LEACH, to distribute the energy consumption, each node is changed from a CH to a non-CH and vice versa on a regular basis. However, this operation is conducted without considering the remaining battery energy. Thus, when a node with little energy is chosen as a CH, the node may consume all of its battery energy. For this reason, LEACH does not extend the lifetime sufficiently. In LPEH, only a limited number of nodes (we call these nodes energy-harvesting nodes) obtain energy by energy harvesting. The CH selection operation is the same as that in LEACH. Thus, it is expected that the batteries of non-energy-harvesting nodes die earlier than those of energy-harvesting nodes.

3.2 ELEH: Extended LEACH with energy harvesting

Figure 1 shows a flowchart for the selection of the CHs and cluster members in extended LEACH.

3.3 ELEH with sleep operation

In energy harvesting, unstable generated energy is a problem in real situations. Thus, in simple ELEH,
the energy-harvesting nodes with small battery energy and nodes without energy harvesting may be selected as CHs. To solve this problem, we propose ELEH with a sleep operation. In this method, when the battery energy becomes less than the threshold value $E_{CH}$, which is the expected energy consumption of the CH, the node enters the sleep mode. In the same way, when the battery energy is increased by energy harvesting, the node enters the active mode. $E_{CH}$ is calculated by the following equation:

$$E_{CH} = l \cdot E_{elec}\left(\frac{N}{C} - 1\right) + l \cdot E_{DA} \frac{N}{C} + l \cdot E_{elec} + l \cdot E_{fs} \cdot d_{toBS}^4$$

(2)

Here, $l$ is the number of bits to be transmitted. $E_{elec}$ is the energy consumed to transmit a bit message a distance of 1 m.

$E_{fs}$ is the energy consumed by the amplifier to transmit a bit in free space, and $E_{mp}$ is the energy consumed by the amplifier to transmit a bit in a multipath environment. $E_{DA}$ is the energy consumed for data aggregation. In addition, $N$ and $C$ are the total numbers of nodes and clusters, respectively. Moreover, $d_{toBS}$ is the distance from the CH to the BS.

Even if the energy generated by energy harvesting is small, the CH is chosen from energy-harvesting nodes. In this case, it is expected that the batteries of some energy-harvesting nodes die earlier than those of non-energy-harvesting nodes.

### 3.4 ESNP: ELEH with sleep operation based on node positions

In ELEH with the sleep operation based on node positions (ESNP), the $i$th node counts the number of adjacent nodes which exist within a distance of $d_{valid}$. $d_{valid}$ is the valid distance between active nodes and is determined by the type of collection data. In this case, the distance is measured by the RSSI.

A node which has some active nodes nearby enters the sleep mode. Applying this method, the number of data transmissions is reduced. On the other hand, the system can maintain a large coverage area. Accordingly, ESNP can extend the lifetime while maintaining a high coverage area ratio, where the coverage area ratio means the proportion of the sum of the coverage areas of the nodes relative to the observation area. The correlation between the collected data from nearby locations depends on the type of data, for example, temperature, humidity, speed, acceleration, and so on. Table 2 shows the relationship between the number of nodes, the valid distance between active nodes, and the coverage area ratio. The observation area is assumed to be a square of 100 m$\times$100 m and $d_{valid}$ is assumed to be 5 m, 10 m, 20 m, and 30 m. We also assume that the coverage area ratio should be kept over 99%. When $d_{valid}$ is 5 m and 10 m, the coverage area ratios are 52.2% and 93.9%, respectively.

| Number of nodes | $d_{valid}$ | 5 m | 10 m | 20 m | 30 m |
|-----------------|-------------|-----|-----|-----|-----|
| 10              | 7.28%       | 25.3% | 65.3% | 89.2% |
| 20              | 14.1%       | 43.6% | 87.9% | 97.5% |
| 30              | 20.1%       | 58.8% | 93.7% | 99.6% |
| 40              | 26.0%       | 68.0% | 97.4% | 99.9% |
| 50              | 31.5%       | 76.2% | 99.0% | 99.9% |
| 60              | 36.0%       | 81.5% | 99.4% | 99.9% |
| 70              | 40.7%       | 86.7% | 99.9% | 99.9% |
| 80              | 44.6%       | 89.8% | 99.9% | 99.9% |
| 90              | 49.3%       | 91.7% | 99.9% | 99.9% |
| 100             | 52.2%       | 93.3% | 99.9% | 99.9% |

In our computer simulations, when $d_{valid}$ is 5 m and 10 m, 700 nodes and 180 nodes are needed to cover 99% of the observation area, respectively. When $d_{valid}$ is 20 m and 30 m, 50 and 30 nodes are needed to cover 99% of the observation area, respectively. For this reason, it is necessary to appropriately set the parameter $N_{need}$. When the number of active nodes is less than $N_{need}$, some sleep nodes enter the active mode until the number of active nodes is over $N_{need}$. In this case, the nodes enter the active mode in order of ascending number of adjacent nodes.

### 3.5 ESSA: ELEH with sleep operation considering surrounding area

In ESSA, each node enters the sleep mode or active mode depending on the sensed area around the node. In this method, each node evaluates the distance of the adjacent nodes and the sensing condition. Then, the node enters the sleep mode when the non-sensed area is less than a preassigned value $CA$. On the other hand, when the non-sensed area is larger than $CA$, the node enters the active mode. In this method, when $CA$ is small, it is easy for each node to enter the active mode. Thus, the coverage area ratio becomes high and the energy consumption becomes large. On the other hand, when $CA$ is large, it is difficult for each node to enter the active mode. Thus, the coverage area ratio becomes high and the energy consumption becomes small.
Table 3  Simulation parameters

| Parameter | Value |
|-----------|-------|
| Bit rate  | 1 Mbit/s |
| Initial energy | 2 J |
| $E_{elec}$ | 50 nJ/bit |
| $E_{fs}$ | 10 pJ/bit/m^2 |
| $E_{mp}$ | 0.013 pJ/bit/m^4 |
| $E_{DA}$ | 50 nJ/bit/signal |

4. Performance Evaluation

4.1 Simulation model

In our computer simulation, we assumed a 100-node network where nodes were randomly distributed within a square area ($x = 0 - 100$ m, $y = 0 - 100$ m) with a BS at the point ($x = 50$ m, $y = 175$ m). The data of each message were assumed to be 2000 bits. The number of CHs was set as 5. Both free-space ($d^2$ power loss) and multipath fading ($d^4$ power loss) channel models were used depending on the distance between the transmitter and receiver [17]. Power control was used to compensate for the path loss by appropriately setting a power amplifier. If the distance is less than the threshold $d_0$, the free-space model is used, otherwise the multipath model is used. Thus, to transmit an $l$-bit message by a distance of $d$, the radio expends an energy of

$$E_{Tx}(l,d) = \begin{cases} 
  lE_{elec} + lE_{fs}d^2, & d < d_0 \\
  lE_{elec} + lE_{mp}d^4, & d \geq d_0
\end{cases}$$

(3)

and to receive this message, the radio expends an energy of

$$E_{Rx}(l) = lE_{elec}$$

(4)

Table 3 shows the computer simulation parameters. Each energy-harvesting node obtains the energy from a solar power cell and we assume that it obtains an energy of 0.085 J/round [18]. It is assumed that energy-harvesting devices are equipped at random. In addition, we consider the situation that the amount of generated energy changes over time. We assume that energy-harvesting nodes obtain an energy of 0.085 J/round in the daytime and no energy at night. It is also assumed that the day and night both last for 12 h. The maximum distance between the CH and BS, $d_{oBS}$, is calculated as 182 m. Substituting this value into Eq. (2), $E_{CH}$ is calculated as 0.0069 J. As we mentioned previously, when the battery energy of the $n$th node is less than 0.0069 J, the $n$th node enters the sleep mode. When the battery energy of the $n$th node is more than 0.0069 J, it enters the active mode. In this case, it is assumed that each node can monitor its battery energy. We assume that sleeping nodes do not consume energy. In ELEH with the sleep operation, each CH communicates with the BS every 10 s. In our computer simulation, the number of cycles is set as 1 instead of 100 when the generated energy is unstable. This is because we investigate the lifetime considering changes in the generated energy.

4.2 Simulation results

Figure 2 shows the relationship between the number of alive nodes and the number of rounds. When the number of energy-harvesting nodes is over 30, ELEH improves the number of alive nodes because of the small energy consumption of the CH. However, when the number of energy-harvesting nodes is 20 or less, the number of alive nodes rapidly decreases. In this case, the energy-harvesting nodes become CHs after a short period. Thus, the energy-harvesting nodes exhaust their battery energy earlier than the...
non-energy-harvesting nodes because the energy consumption is larger than the generated energy. ELEH needs a certain number of energy-harvesting nodes to extend the lifetime effectively.

Figure 3 shows the relationship between the number of alive nodes and the number of rounds in the case of 50 energy-harvesting nodes. In LEACH, LPEH, and ELEH, the lifetimes are 57, 77, and 124 rounds, respectively. The lifetime is defined as the number of rounds until the number of alive nodes is 50 in this computer simulation. ELEH improves the lifetime by 117% in comparison with that of LEACH and by 61.0% in comparison with that of LPEH. In ELEH and LPEH, the generated energy is larger than the amount of energy consumed for wireless communication. Thus, the energy-harvesting node does not exhaust its battery energy. In [11], some parameters such as the initial energy, the amount of generated energy, and so on, are not given. Thus, we cannot accurately compare the performances with each other. If the lifetime characteristic of LEACH in [11] and our result are the same, the proposed method in [11] improves the lifetime by 128%, whereas in the case of 70 energy-harvesting nodes, our ELEH method improves the lifetime by 169% in comparison with that of LEACH. Table 4 shows the improvement of the lifetime and the increase in cost in comparison with LEACH. In the calculation, the prices of sensor nodes and energy-harvesting devices were refer from [19] and [20], respectively. The lifetime improvement in ELEH is about twice that in LPEH for the same increase in cost.

Figures 4 and 5 show number of active and alive nodes as a function of time when the number of energy-harvesting nodes is 50 and 100, respectively. In ELEH with the sleep operation, all nodes are in the active mode in the daytime of the first day. At night of the first day, most nodes enter the sleep mode. At this time, some nodes become dead. In the daytime of the second day, the alive energy-harvesting nodes recharge their own batteries and enter the active mode. At night of the second day, most nodes enter the sleep mode. In the daytime of the third day, the alive energy-harvesting nodes enter the active mode, similarly to in the second daytime. We expect similar behavior to subsequently occur.

Figure 6 shows the relationship between the number of rounds and the coverage area ratio for different numbers of energy-harvesting nodes in ESNP. Here, $d_{\text{valid}}$ is assumed to be 20 m. When the number of energy-harvesting nodes is 30 or more, the coverage area ratio is maintained at almost 100% during the first 1000 rounds. On the other hand, when the number of energy-harvesting nodes is 20 or less, the coverage area ratio becomes less than 90%. ELEH has better lifetime characteristics than LEACH after 100 rounds.

Figures 7 and 8 show examples of the relationship between the number of rounds and the coverage area ratio. When the number of energy-harvesting nodes

Table 4 Relationship between lifetime improvement and increase in cost

| Number of EH nodes | Lifetime improvement | Increase in cost |
|--------------------|----------------------|-----------------|
| 30                 | 54.2%                | 9.24%           |
| 40                 | 51.8                 | 12.3            |
| 50                 | 51.8                 | 15.4            |
| 60                 | 59.2                 | 18.5            |
| 70                 | 84.8                 | 21.6            |
| 80                 | 93.0                 | 24.6            |
| 90                 | 115                  | 27.7            |
is 30 or more, ELEH can extend the lifetime as shown in Fig. 2. The coverage area of LEACH becomes 0% after 200 rounds. On the other hand, ELEH and ESNP can maintain a coverage area ratio of over 86%. When the number of rounds is 250, ESNP increases the number of alive nodes and the coverage area ratio by 165% and 12.7%, respectively, in comparison with those of ELEH. The reason for this is that in ESNP, nodes enter the sleep mode depending on the distance between nodes. The number of cluster members becomes large in areas with high active node density, where the active node density is the number of active nodes in 1 m². Then, the energy consumption of the CH becomes large. In ELEH, all alive nodes are in the active mode. Thus, the number of cluster members is large. Thus, the energy consumption of the CH is large and the variation of the active node density is large. As a result, running out of battery energy occurs locally. In ESNP, the number of active cluster members is smaller than that in ELEH because each node enters the sleep or active mode depending on the distance between nodes.

When the number of cluster members is small, the energy consumed by the CH to receive data from cluster members is small. Thus, the energy-harvesting node can be active in the long term. ESNP prevents the energy-harvesting nodes from running out of battery energy locally. Thus, ESNP improves the coverage area ratio.

Figure 9 shows coverage area ratio as a function of time when the generated energy is unstable. Here, we set the number of cycles of LEACH as one to compare it with our proposed methods. d_valid is assumed to be 20 m. In this case, when the number of energy-harvesting nodes is more than 50, the coverage area ratio is maintained at 95% for 60 h during both day and night. The coverage area ratio of LEACH becomes 0% after 20 h.

Figure 10 shows the coverage area ratio as a function of time for ELEH with the sleep operation and ESNP when the number of energy-harvesting nodes is 50. In this figure, the first 12 h corresponds to daytime and the subsequent 12 h corresponds to night. In ELEH with the sleep operation, all alive nodes are in
the active mode in the daytime and almost all nodes are in the sleep mode at night. Thus, in the daytime, this method can maintain a high coverage area ratio. On the other hand, at night, the coverage area ratio becomes low. In ESNP, each node enters the active mode or sleep mode depending on the distance between nodes. Thus, some nodes enter the sleep mode and do not consume battery energy in the daytime. At night, some active nodes almost exhaust their battery energies and enter the sleep mode. Then, some sleep nodes with battery energy of more than 0.0069 J enter the active mode. For this reason, ESNP can maintain a coverage area ratio of more than 95% during both day and night. ESNP improves the coverage area ratio by 80% at night in comparison with ELEH with the sleep operation.

Figure 11 shows the relationship between the coverage area ratio and the number of rounds for ESSA. When $CA$ is 200 or less, the coverage area ratio is improved in comparison with that of ESNP when the number of rounds is 1000. On the other hand, ESSA does not improve the coverage area ratio when $CA \geq 400$. This is because the nodes enter the active mode when the non-sensed area around the node is larger than $CA$. Thus, it is difficult for nodes to enter the active mode and the coverage area ratio becomes low.

Figure 12 shows the relationship between the number of alive nodes and the number of rounds. As $CA$ increases, the number of alive nodes increases. In ESSA, the coverage area ratio and lifetime are improved in comparison with those in ESNP by 2.13% and 51.9%, respectively, when the number of rounds is 1000 and $CA = 200$. The coverage area ratio and the number of alive nodes in LEACH are 0 after 200 rounds. Thus, ESSA can maintain a higher coverage area ratio than LEACH.

Table 5 shows the density of active nodes. As $CA$ becomes large, the density of active nodes becomes small. In ESNP, the active node density is 6.88, which was obtained from another computer simulation. ESSA can reduce the number of active nodes to fewer than that in ESNP for $CA \geq 200$. For $CA = 1$, on the other hand, the number of active nodes is larger than that in ESNP. Thus, the energy consumption becomes large and many nodes run out of battery energy. As a result, ESSA does not maintain a high coverage

| $CA$ | Active node density ($1/m^2$) |
|------|-----------------------------|
| 1    | 8.26                        |
| 200  | 4.05                        |
| 400  | 3.32                        |
| 600  | 2.98                        |
| 800  | 2.47                        |
| 1000 | 2.38                        |
| 1200 | 1.99                        |
area ratio for $CA = 1$.

5. Conclusion

This paper proposed LPEH and ELEH with a sleep operation to extend the lifetime of WSN without increasing the cost. In addition, we proposed ESNP and ESSA to extend the lifetime for which a high coverage area is maintained. In ESNP and ESSA, each node enters the sleep mode depending on the distance between the active nodes and the surrounding sensed area, respectively. After describing the principle of the proposed method, computer simulations were conducted to show the effectiveness of the proposed method. The simulation results show the improvement of lifetime in ELEH in comparison with that in LEACH. In addition, when the number of energy-harvesting nodes is half of the total number of nodes, ELEH improves the lifetime by 117% and 31.9% in comparison with those of LEACH and LPEH, respectively. The lifetime is extended by applying ELEH with the sleep operation for both day and night. ESNP improves the coverage area ratio by 10% in comparison with that of ELEH when the amount of generated energy is constant. When the generated energy differs by day and night, in the daytime ELEH with the sleep operation and ESNP can maintain a high coverage area ratio. At night, ESNP improves the coverage area ratio by 80% in comparison with that of ELEH with the sleep operation. ESSA can reduce the number of active nodes without reducing the coverage area ratio.

In this paper, we considered a two-hop network for simplicity. For the long-distance transmission of a large amount of data, multihop communication is needed. Thus, we have to consider a method of reducing the memory size and the energy consumption of the whole network. We also have to consider an effective routing method for EHWSN.

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