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Small-World-Network Model Based Routing Method for Wireless Sensor Networks

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SUMMARY This paper proposes a Watts and Strogatz-model based routing method for wireless sensor network along with link-exchange operation. The proposed routing achieves low data-collection delay because of hub-node existence. By applying the link exchanges, node with low remaining battery level can escape from a hub node. Therefore, the proposed routing method achieves the fair battery-power consumptions among sensor nodes. It is possible for the proposed method to prolong the network lifetime with keeping the small-world properties. Simulation results show the effectiveness of the proposed method.

key words: *sensor network, hub node, data collection, small world, Watts and Strogatz model, delay, network lifetime*

1. Introduction

Wireless sensor networks have gained attention in recent years. Sensor nodes can sense, measure, and gather information from various environment, which transmit the sensed data to a sink node. Because sensor nodes are battery-driven, saving power consumption is one of the most important problems for wireless sensor network operations. Low data-collection delay and high connectivity are also required in wireless sensor networks, which can be modified by routing method improvement. Recently, the routing method for sensor network have been discussed actively [1]–[19].

In the cluster-topology based routing method [1]–[7], cluster head nodes collect data from sensor nodes in own cluster and transmit data to the sink node. Because the transmission load is concentrated to the cluster-head nodes, the power consumptions of the cluster-head nodes are much more than the other nodes. Therefore, the unfairness in the usage of the battery power among nodes appears, which degrades the network lifetime. On the other hand, chain-topology-based routing methods has an advantage of long network lifetime [8]–[14]. This is because a sensor node is connected with neighbor nodes with short geographic distance. Because the transmission power is usually proportional to the square of the transmission distance, the chain topology obtains a large impact to the power-consumption reduction. In the chain-topology-based routing methods, however, the data collection delay is much higher than the cluster-topology based routing because of large hop number.

A small-world network has the small-world properties, which are high clustering coefficient and short average path length. Small-world-network construction procedures have been discussed actively [20], [21]. For example, the Newman-Watts (NW) and Watts-Strogatz (WS) models construct a small world network from the regular ring lattice by randomly adding or exchanging the links [20], [21]. The small-world properties are expected to solve the problems in wireless sensor networks because it is possible to shorten the average path length with maintaining connectivity. In [15], an energy efficient small world network construction method was proposed. The method in [15] adds shortcut links to the wireless network with a certain probability, which resembles to NW model. Because the power consumptions of nodes depend on the transmission distance, the method in [15] determines the link addition probability, taking into account geographical distance between nodes and node degree. Because the average path length is short, the method in [15] can reduce the data-collection delay compared with chain topology only by adding some shortcut links. There are, however, hub nodes in the small-world-network based topology. Therefore, the network lifetime is limited, which is a problem of the small-world-network based routing.

This paper proposes a WS model based routing method for wireless sensor network along with link-exchange operation. The link-cut operation is applied to network construction in the proposed method, which is different from the method in [15]. By link-exchange operation, namely link cut-and-rewiring operations, a node with low remaining battery level can escape from a hub node and a node with high remaining battery level becomes a hub node. Therefore, the proposed routing method achieves the fair battery-power consumptions among sensor nodes. Because the link-exchange operation resembles to the WS model, it is possible to keep the small-world properties even though the link exchanges are carried out, taking into account remaining battery level and geographical distance between nodes. As a result, it is possible for the proposed method to prolong the network lifetime with keeping the small-world properties, namely low data-collection delay with high connectivity.

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Simulation results show the effectiveness of the proposed method.

2. Related Works

Figure 1 shows examples of the network topologies of the sensor networks discussed in this paper.

2.1 Cluster-Topology Based Routing

Figure 1(a) shows an example of cluster topologies. In the cluster-topology based routing methods [1]–[6], N_c nodes are selected as cluster heads, which connect to a sink node as shown in Fig. 1(a). Other nodes belong to a certain cluster. A cluster-head node collects data from child sensor nodes in own cluster. Therefore, the cluster-head nodes work as hub nodes. Cluster-topology based routing method can relay data from sensor nodes with small hop number, which achieves data collections with low delay. The cluster-head nodes, however, should receive and transmit all sensor data in the same cluster to the sink node. Therefore, the remaining battery levels of cluster-head nodes are much lower than other sensor nodes [3]–[5], which generates unfair power consumptions among network nodes. Therefore, it is difficult to realize long network lifetime.

2.2 Chain-Topology Based Routing

In the chain-topology-based routing method [8]–[14], network nodes are connected with close neighbor nodes with short geographical distance one another. For the chain-topology constructions, all the links formulate a ring topology as the first step as shown in Fig. 1(b). One node with the maximum remaining battery power is selected as a leader node, which transmits data to the sink node. The chain topology is constructed by cutting the opposite side link from the leader node as shown in Fig. 1(c). Neighbor sensor-node data is combined with own data, which is relayed to the leader node. The total hop number in the chain-topology network is much more than the cluster-topology-based routing as shown in Figs. 1(a) and (c), which generates high delay for data collections. However, all sensor nodes consume the battery power fairly and low power consumptions can be achieved because of the short geographical distance between linked nodes. Therefore, long network lifetime can be obtained compared with the cluster-based routing.

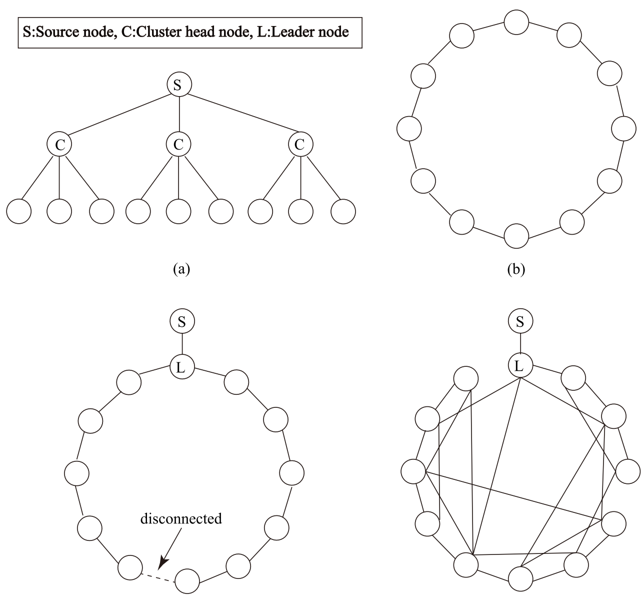

Fig. 1 Examples of the network topologies of the sensor networks discussed in this paper. (a) Cluster topology. (b) Ring topology. (c) Chain topology. (d) Small-world network.

2.3 Small-World-Network Based Routing

Small-world networks lie somewhere between regular ring lattice and random networks as shown in Fig. 2. A small-world network has the small-world properties, which are high clustering coefficient and short average path length. The clustering coefficient of a node is the ratio of the triangle connection establishments among arbitral three nodes. The average path length is the expected minimum link number between arbitral two nodes, which is regarded as the expected hop number between two nodes in sensor networks. The introduction of the small-world properties is expected to solve the problems in wireless sensor network routings because it is possible to shorten the average hop number with maintaining connectivity.

There are some small-world-network construction procedures [20], [21]. The NW model [21] can construct small world networks by adding the links from the regular ring lattice with the link adding probability γ_{NW}. The WS model [20] is also one of the major small-world-network construction methods. The WS model constructs small world networks by rewiring the links from the regular ring lattice with the link rewiring probability γ_{WS}. In [15], an energy-efficient small-world-network model based on the NW model was proposed for sensor-network routing. Figure 3 shows an example of the network topology constructed by [15]. The model in [15] makes a routing topology by adding shortcuts from a ring lattice with a certain probability $\gamma_{a_{ij}}$, which has a similar meaning of γ_{NW}. The most important difference between the complex network theory and the actual sensor network is the existence of geographical distances between

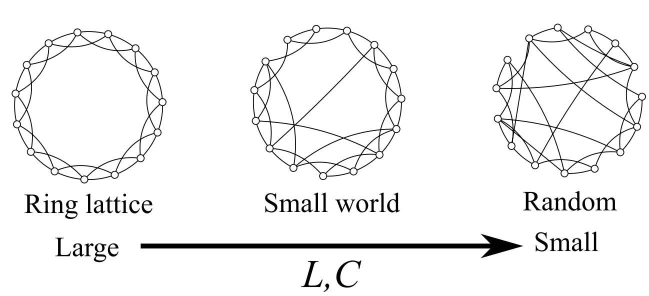

Fig. 2 Example of small world network.

nodes. Usually, the battery power consumption for data transmission is in proportion to the square of the geographical distance between the linked nodes, which is an important problem for prolonging the network lifetime. Additionally, hub nodes in the network contribute to reduce transmission delay. Therefore, $\gamma_{a_{ij}}$ is determined with the geographical distance between nodes and node degree, which is the connected node number at a node. The detailed route construction procedures proposed in [15] are as follows.

i. A ring-topology network among N nodes is formed by applying the algorithm in [9]. In addition, each node adds the link with less than K-hop linked nodes, which is regarded as the ring lattice.
ii. A shortcut links between Nodes i and j are added with the probability $\gamma_{a_{ij}}$.
iii. One node is selected as a leader node, which is connected with a sink node.
iv. A route with the shortest-hop number and total transmission distance is selected by following the links between the sink node and each sensor node. As a result, the tree-topology routing with hub nodes can be constructed.

In [15], the link-addition probability is expressed as

$$\gamma_{a_{ij}} = \begin{cases} \min\left(1, \dfrac{\gamma_0}{N} \sum_i \sqrt{\dfrac{\deg(i)}{\deg(j)}} \dfrac{d_h^{(i,j)}}{d_{ij}}\right), & \\ \hfill if\ d_{ij} < d_{th_{NW}} & \\ 0, \hfill otherwise & \end{cases} \quad (1)$$

where γ_0 is a basic link-addition probability, $\deg(i)$ is the node degree of Node i, d_{ij} is the geographical distance between Nodes i and j, $d_h^{(i,j)}$ is the total transmission distance from node i to j via intermediate nodes, and $d_{th_{NW}}$ is the boundary of long and short geographical distance for adding the shortcut link. The link-additional probability becomes high when the short-cut link realizes total transmission distance reduction as shown in Fig. 3(b). Additionally, the probability is also high when the ratio of connection node number of Node i to the Node j becomes large, which enhances to make Node i be a hub node. The difference between the small-world-network based routing and the cluster-topology based one is that the hub nodes are not connect a sink node directly as shown in Fig. 1(d), which mitigates unfairness of the power consumptions among sensor nodes. Some hub nodes in the small-world-network based topology, however, are the bottleneck of network lifetime.

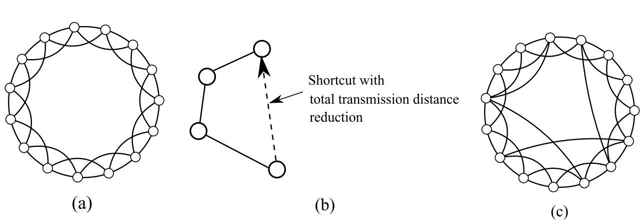

Fig. 3 Example network constructed by [15]. (a) Ring lattice. (b) Shortcut link generation taking into account transmission distance. (c) NW-model based small world network.

3. Proposed Routing Method

This paper proposes WS-model based route construction method for wireless sensor network along with link-exchange operations for prolonging network lifetime. For prolonging the network lifetime, it is effective to switch hub nodes. Intuitively, it is possible to prolong the network lifetime by cutting the links to hub nodes and rewired to another node. Namely, the link-cut processes are needed and effective to network lifetime extension. Therefore, we pay attention to WS model in this paper. The proposed routing has two steps. One is the construction of initial route with small-world properties based on the WS model. The other is the link exchange procedure for prolonging network lifetime, which switches hub node with keeping the small-world properties.

3.1 Network Construction and Route Decision

The WS-model based small world network for sensor network routing is constructed as follows. The procedures 1, 4, and 5 are the same as those in NW-model based routing.

1. A ring-topology network among N nodes is formed by applying the algorithm in [9]. The connections for ring-topology network are called initial links. In addition, each node adds the link with less than K-hop linked nodes, which is regarded as the ring lattice.
2. A non-initial link between Nodes i and j is cut with probability γ_c.
3. The cut link must be reconnected with another node. The reconnected node is selected with probability

$$\gamma_{r_{ik}} = \frac{\gamma_{ik}}{\sum_{k' \in B} \gamma_{ik'}}, \quad (2)$$

where $B = \{k | 0 < k \leq N, k \neq i \text{ and } j\}$ is the set of reconnected node candidates. Additionally,

$$\gamma_{ik} = \frac{1}{1 + \exp\left(\alpha \dfrac{d_{th_{WS}} - d_{ik}}{d_{max}}\right)}, \quad (3)$$

where d_{ik} is the geographical distance between Nodes i and k, $d_{th_{WS}}$ is the boundary between long and shot geographical distances, α is a coefficient of sigmoid function, and d_{max} is the maximum geographical distance between two nodes in the network for parameter normalization.
4. One node is selected as a leader node, which is connected with a sink node.
5. A route with the shortest-hop number and total transmission distance is selected by following the links between the sink node and each sensor node. As a result, the tree-topology routing with hub nodes can be constructed.

3.2 Link Exchange and Route Decision

Some links are exchanged every round for prolonging the network lifetime. The link exchange operation has two steps, which are link cuts and link reconnections. Ideally, the links should be cut from the nodes with low battery power level and be reconnected with nodes with high battery power. However, the small-world properties need to be kept. For achieving the above purposes, the following link exchange method is proposed.

0'. The initial links never cut through the link exchanges. This rule avoids to make an isolation node in the network.

1'. Non-initial links between Nodes i and j are considered to be cut with probability

$$\gamma_{c_{ij}} = \frac{1}{1 + \exp\left\{\beta \dfrac{(p_{b_{th}} - p_{b_j})}{p_{b_{max}}}\right\}}, \tag{4}$$

where p_{b_j} is the remaining battery power of node j, $p_{b_{th}}$ is the boundary between high and low battery power levels, β is a coefficient of sigmoid function, and $p_{b_{max}}$ is fully charged battery power.

2'. The cut link of Node i should be reconnected another node with probability of $\gamma_{r_{ik}}$ in (3). In the link-reconnection step, B in (3) satisfies $B = \{k|0 < k \le N, k \ne i \text{ and } j, p_{b_k} > p_{b_j})\}$. It is expected that nodes with high power becomes new hub nodes keeping small-world properties.

3'. A leader node is newly selected and the routes from sensor nodes to a sink node are fixed as the same procedures as 4 and 5 in the previous subsection.

3.3 Routing Parameters

In the proposed method, there are five adjustable parameters: γ_c, α, and $d_{th_{WS}}$ in (3), and β and $p_{b_{th}}$ in (4). These parameters are adjusted for keeping small-world properties and achieving long network lifetime. Both the link-cut and link-reconnection probabilities are expressed as sigmoid functions as shown in (3) and (4), respectively. Figure 4 shows the relationship of the sigmoid function of $y = 1/(1 + \exp a(x_{th} - x))$. It is seen that the slope of y around the boundary x_{th} increases as a increases. The step-like response can be obtained from the sigmoid function with large a.

3.4 Features of Proposed Method

By paying attention to the WS model, the operation of link cut is newly added compared with NW-model based routing. The major contribution of this paper is that the WS model is applied to not only the small-world-network based routing but also the network lifetime extension. By link-cut

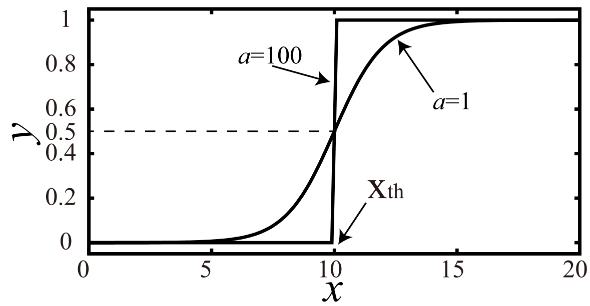

Fig. 4 Sigmoid function properties for fixed a.

operation, it is possible to reduce the connected node number from hub nodes, which realizes the fair battery-power consumptions among sensor nodes. Because the rewiring method follows that of WS model, it is possible to keep the small-world properties. Therefore, it can be stated the nodes, which work as hub nodes, are switched by the link exchange. As a result, it is possible to prolong the network lifetime with keeping the property of low data-collection delay.

4. Performance Evaluations

4.1 Evaluation Environment

This section discusses characteristics of route-construction methods. This paper shows the characteristics of route-construction method based on: (1) cluster topology (CL) [1], (2) chain topology (CH) [9], (3) NW model (NW) [15], and (4) WS model (WS). Additionally, (5) NW-model with the proposed link exchange (NW-LE) and (6) WS-model with the proposed link exchange (WS-LE) are also shown.

Table 1 gives the parameter values in simulations. Sensor nodes are placed randomly in the square area of 50 m × 50 m. It is assumed that all the nodes have the same initial battery power with full charge $p_{b_{max}}$. All data generated by network sensor nodes is relayed to the sink node in one operation round. It is also assumed that all the sensor and sink nodes are located in the communication range one another and the transmission power of the sensor nodes can be controlled ideally. The leader-node selections and link exchanges are performed at the beginning of every round. The environment of the packet transmissions is ideal, namely there are no frame collisions in the Medium-Access-Control (MAC) layer and no bit errors in the Physical (PHY) layer.

4.2 Decisions of Proposed-Method Parameters

The geographical distance of shortcut link depends on α and $d_{th_{WS}}$ in (3). By considering the case of NW-model based routing in [21], it is good that the link-cut probability varies rapidly at the boundary $d_{th_{WS}}$. Therefore, $\alpha = 100$ is given in this paper.

Figure 5 shows the normalized clustering coefficient and the normalized average hop number as a function of γ_c for fixed $d_{th_{WS}}$. For obtaining small-world properties, it is

Table 1 Evaluation environments.

Number of sensor nodes N	100
Simulation area	$50 \times 50\,\mathrm{m}^2$
Coordinate of the sink node	(50, 150)
Data size	250 bytes
Initial battery power	0.25 J
MAC protocol	TDMA
Energy consumption of circuit	50 nJ/bit
Energy consumption of amplification equipment	$100\,\mathrm{pJ/bit/m^2}$
Energy consumption for combining data	5 nJ/bit/signal

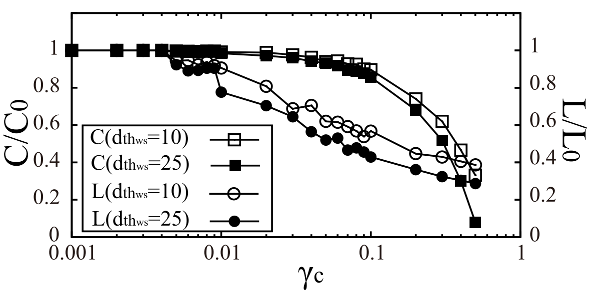

Fig. 5 Clustering coefficient and average hop number as a function of γ_c.

necessary to satisfy both the large clustering coefficient and the small hop number, which is the same meaning of short average path length simultaneously.

It is considered that parameters γ_c and $d_{th_{WS}}$ for minimizing the cost function:

$$F = \frac{L(\gamma_c, d_{th_{WS}})}{L_0} + \left(\frac{D(\gamma_c, d_{th_{WS}})}{D_0} - 1\right)^2, \quad (5)$$

provides good small-world properties, where L_0 and D_0 are the average hop number and geographical distance prior to the link exchange, respectively, which are independent of $d_{th_{WS}}$. Additionally, the average distance of nodes is

$$D(\gamma_c, d_{th_{WS}}) = \frac{1}{N}\sum_{i=1}^{N}\sum_{j\in B}\frac{2d_{ij}}{m_i(m_i-1)}, \quad (6)$$

where m_i is the connected node number of Node i posterior to link exchange. The Particle Swarm Optimization (PSO) algorithm is applied for obtaining the optimal values. Table 2 gives the parameters for PSO algorithm. The average values of optimal values for 20 patterns of random topologies are used for evaluations. We have $d_{th_{WS}} = 15$ and $\gamma_c = 0.18$ in this paper.

On the other hand, $\gamma_{c_{ij}}$ strongly affect the network lifetime. Therefore, β and $p_{b_{th}}$ are fixed for minimizing the network lifetime, which are also derived by applying the PSO algorithm. The average optimal values in 20 random topologies are $\beta = 8.66$ and $p_{b_{th}} = 0.183$, which are also used for evaluations. Figure 6 shows an example network constructed by the proposed method. Table 3 gives network-construction parameters in this section.

Table 2 Parameters for PSO.

Number of particles	10
Number of iterations	200
Maximum velocity	25
Particle's velocity	0.7
Particle's best known position	2
Best known position of whole swarm	2

Table 3 Network-construction parameters.

N_c	10
K	2
γ_0	0.03
$d_{th_{NW}}$	15
K	2
γ_c	0.18
α	100
$d_{th_{WS}}$	15
β	8.66
$p_{b_{th}}$	0.183

4.3 Evaluations of Proposed Method

Figure 7 shows the accumulated operation time as a function of the number of operational rounds. The accumulated operation time is defined as the accumulated time for data collections from all sensor nodes to the sink node. It is seen from Fig. 7 that the accumulated times of CL, NW and WS are shorter than that of CH. This result means that the hub network has a role to reduce the data collection delay. The small-world-network based topology achieves low delay because of small average path length characteristics of the small world network. It is also seen from Fig. 7 that the accumulated time of NW is almost the same as that of WS because both NW and WS have the same network characteristics from the average path length view point. Figure 8 shows the cluster coefficient and the average path length as functions of round number at a certain topology. It is confirmed from Fig. 8 that the small-world properties can be kept in spite of link exchanges. It is also seen from Fig. 7 that the accumulated time of NW-LE is the same as that of WS-LE. This result denotes that the small-world-network characteristics can be kept regardless of the link exchanges.

Figure 9 shows the individual network lifetimes of the route-construction methods. The network lifetime is evaluated as the number of operational rounds until the battery-power levels of at least one node become zero. The NW and WS obtain the shorter network lifetimes than CH because the average geographical distance between connected nodes are longer than CH due to hop-number reductions. The small-world-network based routing achieves longer network lifetime than CL. This is because that both the NW and WS make a small-world network topology from the chain lattice. Therefore, the basic geographical distance is shorter than the cluster topology. It is seen from Fig. 9 that the network lifetime of the NW-LE and WS-LE is longer than that of NW and WS. This is because the proposed link-exchange method distributes the opportunity for the sensor nodes to

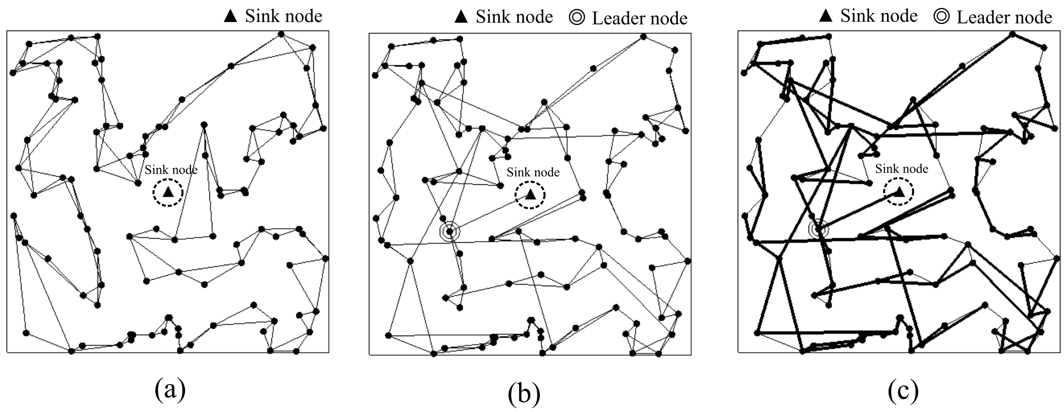

Fig. 6 Example network constructed by the proposed method (a) Ring lattice. (b) WS-model construction. (c) Route from sensor node to sink node.

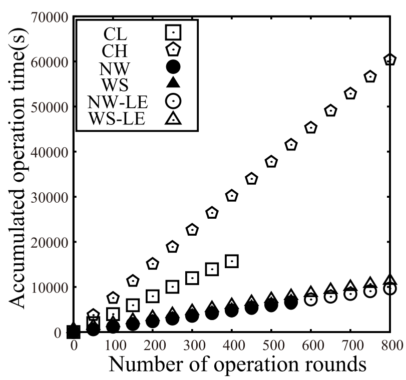

Fig. 7 Accumulated operation time as a function of the operational-round number for fixed protocol.

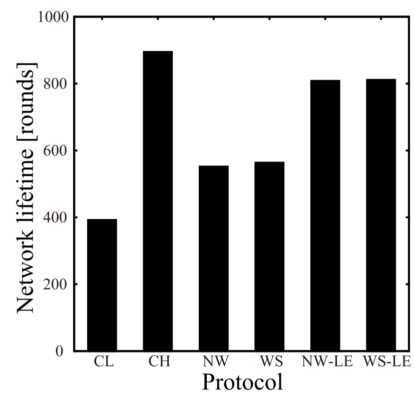

Fig. 9 Network lifetimes for fixed protocol.

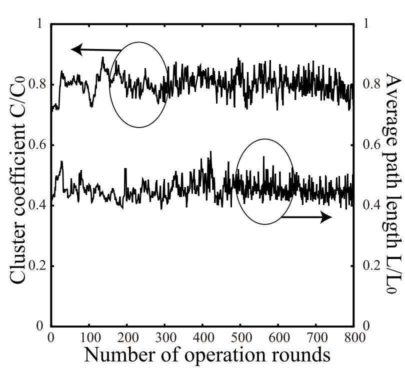

Fig. 8 Cluster coefficient and Average path length as functions of round number.

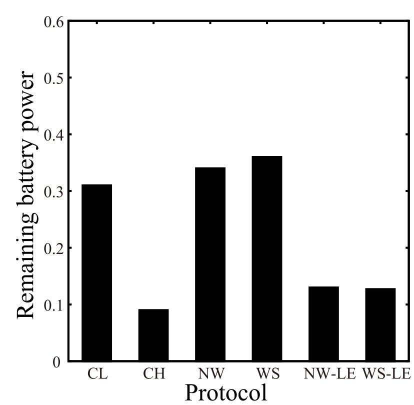

Fig. 10 Total remaining battery energy of all sensor nodes for fixed protocol.

be a hub node. It can be stated from this result that the proposed link-exchange method increases the network lifetime. It is seen from Figs. 7 and 9 that the network lifetimes of NW-LE and WS-LE reach the same level of those of CH in spite of quite small data-collection delays. Additionally, it is possible for NW-LE to obtain the similar performance to WS-LE. This result suggests that the effectiveness of the proposed link-exchange method is independent of the initial small-world-network model.

Figure 10 shows the total remaining battery levels of the network nodes at the end of network lifetime. High total remaining battery level denotes that the traffic load is concentrated at certain nodes, which may be hub nodes. It is seen from Fig. 10 that CL, NW, and WS have high remaining battery levels. These network topologies have hub nodes, which consume much power than other nodes. Therefore, many nodes have much battery powers when the power of a certain hub node becomes zero. On the other hand, that of CH is low. This is because the dispersion of connected node geographical distances are small and there is no hub node in CH. It is seen from Fig. 10 that the total remaining battery level of NW-LE and WS-LE reaches the same level of those of CH. By applying the proposed link exchange, all the sensor nodes use battery powers fairly.

5. Conclusion

This paper has proposed the WS-model based routing method for wireless sensor network along with link-exchange operation. By applying the proposed link exchanges, a node with high remaining battery level becomes a hub node. Therefore, the proposed routing method achieves the fair battery-power consumptions among sensor nodes. It is confirmed from simulation results that the proposed protocol can prolong the network lifetime with keeping the small-world properties, namely low data-collection delay.

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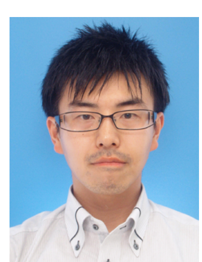

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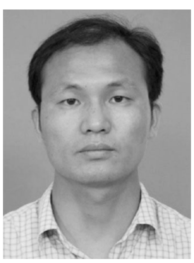

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