Energy Consumption Reduction of Clustering Communication Based on Number of Neighbors for Wireless Sensor Networks

Noritaka Shigei*, Hiromi Miyajima†, and Hiroki Morishita‡

Abstract— **The wireless sensor network (WSN) technology is a key component for ubiquitous computing. In order to achieve the long term operation of WSNs, communication protocols based on clustering have been extensively studied such as LEACH, ACE and HEED. In this paper, we describe clustering communication methods for WSNs. The features of the methods are: 1) the number of neighboring nodes is grasped with less communication overhead and 2) the radius of broadcast is determined based on the number of neighboring nodes. Thanks to those features, each cluster has almost even members and their energy consumption is smaller than conventional methods. We also describe to extend the method to a multi-hop communication version. Further, as a new contribution in this paper, we propose "long-term sleep", which can effectively reduce the energy consumption of the methods presented in [9]. Its basic idea is that, if sensor nodes are capable of covering an area of fixed size, it is sufficient that at least one sensor node operates for every area of fixed size. The effectiveness of the proposed methods are demonstrated by numerical simulation.**

Keywords: wireless sensor network, energy efficient, clustering, multi-hop communication

1 Introduction

The wireless sensor network (WSN) technology is a key component for ubiquitous computing. A WSN consists of a large number of sensor nodes as shown in Fig.1. Each sensor node senses environmental conditions such as temperature, pressure and light and sends the sensed data to a base station (BS), which is a long way off in general. Since the sensor nodes are powered by limited power batteries, in order to prolong the life time of the network, low energy consumption is important for sensor nodes. In general, radio communication consumes the most amount of energy, which is proportional to the data size and proportional to the square or the fourth power of the distance. In order to reduce the energy consumption, a clustering and data aggregation approach has been extensively studied[7]. In this approach, sensor nodes are divided into clusters, and for each cluster, one representative node, which called cluster head (CH), aggregates all the data within the cluster and sends the data to BS. Since only CH nodes need long distance transmission, the other nodes save the energy consumption.

In order to effectively manage clusters and CHs, distributed clustering methods have been proposed such as LEACH, HEED, ACE and ANTCLUST[2, 3, 4, 6]. LEACH, which is the most popular method, guarantees that every nodes evenly become CHs but does not take into account battery level and the interrelationship among nodes[2]. HEED, ACE and ANTCLUST achieve better performance than LEACH by taking into account battery level, communication cost, node density, etc. We have also shown that, in addition to those considered issues, communication overhead needed for determining clusters and CHs should be reduced to obtain a better performance[8].

In this paper, firstly, we describe more effective clustering communication methods[9] for WSNs than conventional ones. The features of the methods are: 1) the number of neighboring nodes is grasped with less communication overhead and 2) the radius of broadcast is determined based on the number of neighboring nodes. Thanks to those features, each cluster has almost even members and their energy consumption is smaller than conventional methods. We also describe to extend the method to a multi-hop communication version. Further, as a new contribution in this paper, we propose "long-term sleep", which can effectively reduce the energy consumption of the methods presented in [9]. Its basic idea is that, if sensor nodes are capable of covering an area of fixed size, it is sufficient that at least one sensor node operates for every area of fixed size. The effectiveness of the proposed methods are demonstrated by numerical simulation.

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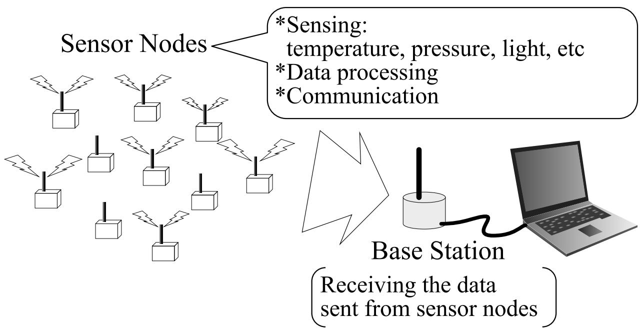

Figure 1: The concept of wireless sensor network.

2 Wireless Sensor Network

2.1 WSN model

This section describes the wireless sensor network (WSN) model considered in this paper[2, 3, 4, 6, 8]. The WSN model consists of N sensor nodes and one base station (BS) node as shown in Fig.1. All sensor nodes are identical and are assumed to have the following functions and features: 1) sensing environmental factors such as temperature, pressure and light, 2) data processing by low-power micro-controller, 3) a radio communication function in which the transmission power is controlled according to the distance to the target node, 4) powered by a limited life battery, 5) the distance to an arbitrary node can be estimated from the receiving signal level, and 6) low clock skew requirement is guaranteed by using a clock synchronization method[5].

The BS node is assumed to have an unlimited power source, processing power, and storage capacity. The data sensed by sensor nodes are sent to the BS node over the radio, and a user can access the data via the BS node.

The radio communication consumes more energy than the data processing on a sensor node. We assume the following energy consumption model for radio communication. The transmission of a k-bit message with transmission range d meters consumes $E_{\mathrm{T}}(k,d)$ of energy.

$$E_{\mathrm{T}}(k,d) = \begin{cases} k(E_{\mathrm{elec}} + \varepsilon_{\mathrm{fs}} d^2) & \text{for } d \le d_0 \\ k(E_{\mathrm{elec}} + \varepsilon_{\mathrm{mp}} d^4) & \text{for } d > d_0, \end{cases} \tag{1}$$

where E_{elec} is the electronics energy, and $\varepsilon_{\mathrm{fs}}$ and $\varepsilon_{\mathrm{mp}}$ are the amplifier energy factors for free space and multipath fading channel models, respectively. The reception of a k-bit message consumes $E_{\mathrm{R}}(k)$ of energy.

$$E_{\mathrm{R}}(k) = k \cdot E_{\mathrm{elec}} \tag{2}$$

2.2 Clustering Approach for WSN

In order to save the energy consumption of WSN, a clustering approach for WSN as shown in Fig.2 has been considered. In the approach, N sensor nodes are divided into clusters, and each cluster has a representative sensor node called cluster head (CH). Each non-CH sensor node sends the sensed data to the CH node in its own cluster, instead of to BS. Each CH node aggregates the received data into smaller size and sends it to BS. This approach has the following advantages: 1) non-CH sensor nodes can save the energy consumption because the nodes can avoid long-distance communication and have only to send data to its own CH being nearby and 2) the amount of data to be sent to BS can be reduced, which also saves the energy consumption.

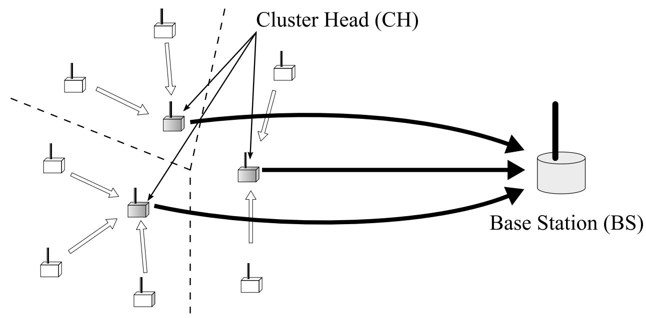

Figure 2: The concept of the clustering approach for WSN.

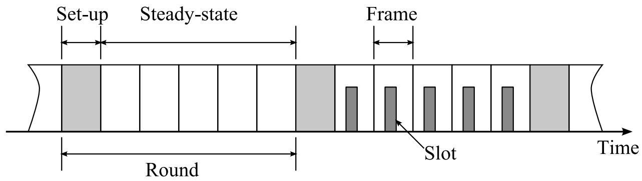

Figure 3: The operating cycle in clustering methods.

The operating cycle of clustering methods is shown in Fig.3. Each round consists of consecutive frames. The first frame is for set-up, and the others are for steady-state. In the set-up frame, CH nodes and clusters are determined based on the used clustering algorithm, and each CH assigns a non-CH node to a slot in order to create a time-division multiple-access (TDMA) schedule. In the steady-state frames, each non-CH node sends data to CH at the assigned slot in TDMA fashion, and CHs fuse (compress) the received data and send it to BS.

In order to decide CHs and clusters, clustering algorithms such as LEACH and HEED have been proposed[2, 3]. In LEACH, CHs are determined in a distributed autonomous fashion. At each round l, each node v independently decides to become a CH with probability $P_v(t)$ if the node v has not been a CH in the most recent $(l \bmod (N/k))$ rounds.

$$P_v(l) = \frac{k}{N - k(l \bmod \frac{N}{k})}, \tag{3}$$

where k is the average number of CHs for each round. This means that each node becomes CH at least once every N/k rounds.

More effective clustering methods than LEACH have been proposed such as HEED, ACE and ANTCLUST[3, 4, 6]. These methods achieve better performance than LEACH by taking into account battery level and node distribution. However, they need additional inter-node communications for clustering.

3 The Proposed Methods

All the methods described in this section are performed in a distributed autonomous fashion. In the methods, the role of BS is just to receive sensed data from CHs. In the past work, we have proposed more effective method than the conventional ones such as HEED, ACE and ANTCLUST[8]. The distinguished features of the proposed method were as follows: 1) aware of remaining battery power level, 2) aware of node density, and 3) a small communication overhead in the clustering process. LEACH has a small communication overhead but is not aware of remaining battery level and node density. HEED and ANTCLUST are aware of remaining battery level and node density but their communication overheads are large. Section 3.1 describes Clustering Communication based on Number of neighbors (CCN)[9], which is an improved method of one in [8]. Section 3.2 describes the extension of CNN to a multi-hop communication version[9]. Further, in section 3.3, as a new contribution in this paper, we propose "long-term sleep", which can effectively reduce the energy consumption of the methods described in sections 3.1 and 3.2.

3.1 Clustering Communication Based on Number of Neighbors

This subsection describes an improved method of our previous proposal[8]. The distinguished features of the method are 1) the number of broadcastings required to calculate the number of neighbor nodes is reduced and 2) the energy consumption involved in clustering is reduced.

The proposed algorithm consists of four phases performed in a setup frame[1]. Let $l \geq 1$ be the current round number. In Phase 1, each node calculates the number of neighbor nodes. In the calculation, the number of broadcastings is reduced compared with the previous method. In Phase 2, CH nodes are determined. In the process, a node decided to become CH broadcasts a candidacy message. The broadcasting range varies according to the number of neighbor nodes. As a result, the consumption energy is reduced. Phases 3 and 4 are the determination of cluster members and the creation of TDMA schedule, respectively. The proposed algorithm CCN (Clustering Communication based on the number of Neighbors) is presented as follows:

Algorithm CCN

Phase 1:
(i) For $l = 1$.
All active nodes broadcast their node IDs within R_{inf} meters radius. All nodes count how many IDs are received. Let $m_v(l)$ be the counted number for node v at l-th round.

(ii) For $l \neq 1$.
Let e_v be the remaining battery level of node v. For each node v, if $e_v < \theta_v$, then node v decides to go down. θ_v is the threshold of remaining battery level for shutdown as follows:

$$\theta_v = \alpha \cdot E_{\text{T}}(S_{\text{data}}, d(v, bs)), \tag{4}$$

where $\alpha > 1$ is an appropriate constant for margin, S_{data} is the data packet size transmitted in a frame and $d(v, bs)$ is the distance between node v and the base station. The node decided to go down broadcasts a message within R_{inf} meters and then goes down. The message informs its neighbors the fact that the node will go down soon. The other node v decrements the counter m_v by the number of received messages.

Phase 2: Each node v performs the procedure **(a)** in descending order of the following evaluation function

$$f(m_v, e_v) = m_v e_v^4. \tag{5}$$

When each node v receives a candidacy for CH from a node v', perform the procedure **(b)**.
(a) If a node v has not received a candidacy for CH from other nodes, broadcast its candidacy for CH within R_v meters radius. The broadcast radius R_v is defined as follows:

$$R_v = R_{\text{inf}} \sqrt{\frac{N_{\text{cm}}}{m_v}}, \tag{6}$$

where N_{cm} is the expected number of nodes in a cluster.
(b) If a node v has not been received any candidacy, $c_v \leftarrow v'$ and $d_v^{\min} \leftarrow d(v, v')$. Otherwise, if $d_v^{\min} > d(v, v')$, then $c_v \leftarrow v'$ and $d_v^{\min} \leftarrow d(v, v')$.

Phase 3: The nodes that broadcast the candidacy in Phase 2 become CHs. The other nodes become non-CHs. The non-CH node v sends *intentions of participating* to the nearest CH candidate c_v.
Phase 4: Each CH node creates a TDMA schedule and sends it to the non-CH nodes as the registration approval.
□

In the first round $l = 1$, Phase 1 involves the same number of broadcastings as for the conventional method. However, after the first round $l > 1$, this phase needs no broadcasting before the battery level of a node v is going to be less than the threshold θ_v. The success of this approach relies on choosing an appropriate value of θ_v, which is adjusted by a parameter α. The parameter α

[1] In l-th round, each node begins each phase $q \in \{1, 2, 3, 4\}$ at a specific time $(l-1)T_{\text{rnd}} + \sum_{j=1}^{q-1} T_j$, where $T_{\text{rnd}} = \sum_{j=1}^{4} T_j + T_{\text{ss}}$ and T_{ss} is the period of the stead state.

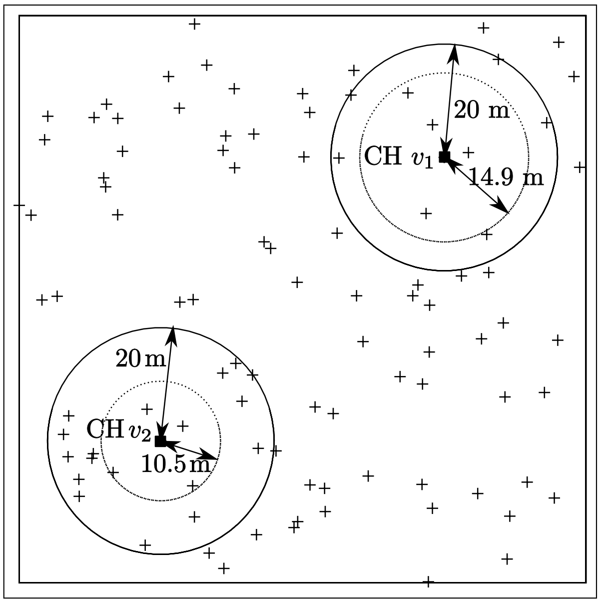

Figure 4: An example of Phases 2 ($R_{\text{inf}} = 20$m, $N_{\text{cm}} = 5$).

should be at least greater than 1.0, because if the node becomes CH then its battery is going to run out in the middle of the round. Therefore, we will adopt a sufficient-large value $\alpha = 3.0$ in our simulation.

In Phase 2, each node v announces its candidacy for CH in descending order of Eq.(5)[2]. The key idea in Phase 2 of the proposed algorithm is to vary the range of broadcasting for candidacy according to the number of neighbors. The range R_v for node v is given by Eq.(6). Empirically, it is known that there exists an optimal number N_{opt} of member nodes per a cluster. Therefore, it is sufficient to broadcast a message within the range that covers N_{opt} nodes. Assuming that the nodes are uniformly distributed, the circular area with radius R_v contains N_{cm} nodes on average. Fig.4 shows an example of Phase 2 for $R_{\text{inf}} = 20.0$ m and $N_{\text{cm}} = 5$. In this figure, two CH nodes v_1 and v_2 are shown[3]. For node v_1, the number of neighbors, which are in the circular area with radius 20.0 m, is 9. For node v_2, the number of neighbors is 18. Therefore, $R_{v_1} = 20.0\sqrt{\frac{5}{9}} = 14.9$ m and $R_{v_2} = 20.0\sqrt{\frac{5}{18}} = 10.5$ m. As a result, for both v_1 and v_2, the broadcast range covers 4 nodes.

3.2 Multi-Hop Communication

In this subsection, the algorithm CCN is extended to a multi-hop communication version, called CCNM (CCN with Multi-hop communication). In the CCNM algorithm, a multi-hop communication scheme is incorporated into the communication between CH and BS. A relay node is determined in the similar manner as in Phase 2 of CCN, and the multi-hop communication is adaptively performed. In addition to Phases 1 to 4, the following Phase 5 is added to the CCNM algorithm.

[2]The detail of its execution is described in [8]

[3]Note that CH nodes other than two indicated ones should exist in this case.

Phase 5: Let A be the set of non-CH nodes. Let $g(v, e_v)$ be an evaluation function as follows:

$$g(v, e_v) = \frac{d_{\max}}{d(v, bs)} e_v^4, \tag{7}$$

where $d_{\max}$ is the diameter of the field where the sensor nodes are distributed. If $g(v', e'_v) = \min_{v \in A} g(v, e_v)$, node v' broadcasts its candidacy for relay node and the cost $C(v', bs)$ within $d_{\max}$ meter radius, where

$$C(v_1, v_2) = \frac{1}{e_{v_1}} \left(E_{\text{T}}(v_1, v_2) + E_{\text{R}}(v_1, v_2) \right). \tag{8}$$

All other nodes $v \in A \setminus \{v'\}$ receiving the candidacy give up to become a relay node, and all CH nodes memorize the cost $C(v', bs)$. □

Note that there exists only one relay node in the network.

In each frame shown in Fig.3, a CH collects the data from own member nodes, compresses the received data, and sends it to BS. The data transmission to BS is performed in adaptively multi-hop or single-hop fashion. That is, if the multi-hop manner requires less communication cost than the single-hop one, then the multi-hop one is employed. Otherwise, the single-hop one is employed. Assuming that v_{CH} and v_{relay} are a CH node and the relay node, respectively. Then the costs for single-hop and multi-hop manners are $C(v_{\text{CH}}, bs)$ and $C(v_{\text{CH}}, v_{\text{relay}}) + C(v_{\text{relay}}, bs)$, respectively.

Further, some applications allow that the data received for relaying is compressed on the relay node. Our simulation presented in the next section will consider two cases, i.e., with or without compression on relay node.

3.3 Energy Consumption Reduction by Long-Term Sleep

When the density of sensor nodes is dense, the operation of all the nodes would not be necessary. Because, if a node is capable of covering an area of fixed size, it is sufficient that at least one sensor node operates for every area of fixed size. From this point of view, in order to further reduce energy consumption of sensor nodes, we introduce long-term sleep, which halts some sensor nodes for each round. That is, a node assigned long-term sleep does not send data to CH throughout the round. Data collection based on TDMA as described in section 2.2 also provides non-CH nodes a sleep whose term is about the frame length. The term of this sleep is shorter than that of long-term sleep, when the number of slots for one round is more than one.

The key issue of this approach is how to determine long-term sleeping nodes. We propose an algorithm executed in a distributed fashion. The algorithm is obtained to modify Phase 3 of CCN presented in section 3.1. Assuming that each sensor node is capable of covering a circular area of radius R_{sense} meters. The algorithm of Phase 3 is as follows.

Phase 3:
(3-1) The nodes that broadcast the candidacy in Phase 2 become CHs. The other nodes become non-CHs. The non-CH node v sends the nearest CH candidate c_v the following four items: 1) *intentions of participating*, 2) its own ID, 3) its own remaining battery level and 4) ID of its *very-close* node (if it exists), where *very-close* node of node v, which is the nearest non-CH node within R_{vc} meters, can be calculated in Phases 1 and 2. Note that R_{vc} is much smaller than R_{inf}.

(3-2) Assuming that CH node v receives *intentions of participating* from non-CH nodes $v_1, v_2, \cdots, v_n$, where i is assumed to be ID of the node v_i. Further, assuming that CH node v receives n pairs of messages (e_1, vc_1), (e_2, vc_2), $\cdots$, (e_n, vc_n), where e_i and vc_i are remaining battery level and ID of *very-close* node of the node v_i, respectively. Note that, if there does not exist *very-close* node of v_i, vc_i is *null*.

The CH node v classifies $v_1, v_2, \cdots, v_n$ into m groups $G_1, G_2, \cdots, G_m$ such that:

- if $|G_k| = 1$ and $G_k = \{i\}$, $vc_i = null$,
- if $|G_k| \geq 2$, $vc_i = j$ or $vc_j = i$ for any $i, j \in G_k$ s.t. $i \neq j$,
- $\bigcup_{k=1}^{m} G_k = \{1, 2, \cdots, n\}$, and
- $G_k \cap G_l = \emptyset$ $(\forall j \neq k)$.

An example of the classification is shown in Fig.5.

(3-3) Each CH node determines long-term sleeping nodes as follows: for each group k s.t. $|G_k| \geq 2$, a node with minimum residual battery level $e_{i_{\min}}$ in G_k is designated as long-term sleeping node, where $e_{i_{\min}} = \min_{i \in G_k} e_i$. □

Note that, if $|G_k| = 1$, node $i \in G_k$, which is only one node in G_k, is not designated as long-term sleeping node.

4 Numerical Simulation

This section shows two types of simulation in order to demonstrate the effectiveness of our proposed methods. In section 4.1, our methods proposed in [9] are evaluated. In section 4.2, our methods proposed in this paper are evaluated.

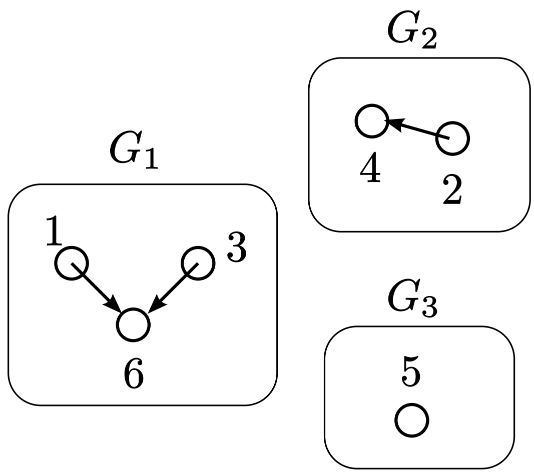

Figure 5: An example of the classification in (3-2): a circle with number i corresponds to a non-CH node with ID i and an arrowed line from i to j means $vc_i = j$.

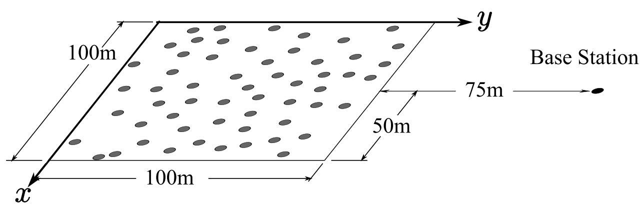

Figure 6: The node arrangement in the simulation.

4.1 Simulation 1

In this section, our methods CCN, CCNM without compression and CCNM with compression proposed in [9] are compared with the conventional methods LEACH and ANTCLUST. ANTCLUST achieves better performance than HEED.

In the simulation, N sensor nodes are randomly distributed in the square region of size 100 m $\times$ 100 m and the base station is 75 meters away from the center of a side, whose coordinates are $(0, 100)$, as shown in Fig.6. The parameters used in the simulation are summarized in Table 1. The simulation is performed for $N = 100$, 300 and 500.

The number of alive nodes versus round for $N = 100$, 300 and 500 are shown in Figures 7, 8 and 9, respectively. For $N = 300$ and 500, our proposed methods are clearly better than the conventional methods. As N becomes larger, the advantage of our methods over the conventional methods becomes larger.

Let us look closely the result for $N = 100$. For any round, CCN shows better performance than ANTCLUST. CCNM without compression sustains the node operating rate of 100% for about 700 rounds longer than

Table 1: Parameters used in the simulation.

For energy model	
d_0	75 m
$E_{\rm elec}$	50 nJ/bit
$E_{\rm fusion}$	5 nJ/bit
$\varepsilon_{\rm fs}$	10 pJ/bit/m^2
$\varepsilon_{\rm mp}$	1.3 fJ/bit/m^4
Initial battery level	0.5 Joule
Energy for data aggregation	5 nJ/bit/signal
For packet model	
Data packet size: $S_{\rm data}$	800 bit
Broadcast packet size	200 bit
Packet header size	200 bit
For proposed methods	
$R_{\rm inf}$	20 meters
$N_{\rm cm}$	30
α	3.0

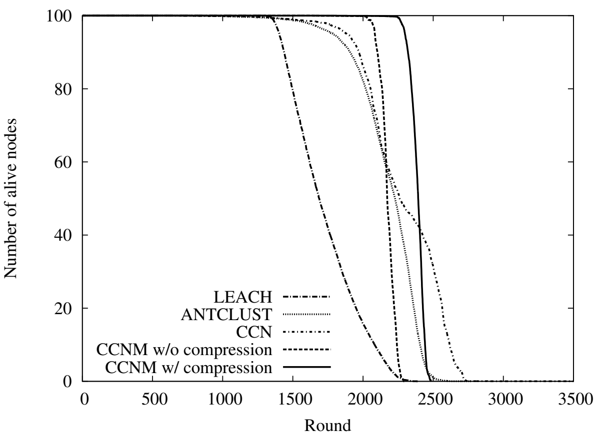

Figure 7: The number of alive nodes versus round for $N = 100$.

ANTCLUST. Further, CCNM with compression sustains it for about 1000 rounds longer.

Let us compare the proposed methods CCN, CCNM without compression and CCNM with compression. CCN achieves the longest duration of the last survival node. CCNM with compression achieves the longest duration of the node operating rate of 100%. CCNM without compression is intermediate between other proposed methods. Figure 10 shows the number of operating rounds versus the coordinate y of a node for $N = 100$. For CCN, the operating duration for a node depends on the distance from BS, that is, the farther node from BS has a shorter operating duration. For both CCNM methods, the operating duration for a node is independent of the distance from BS, which is an advantageous effect of our multi-hop communication scheme. Further, CCNM with compression is better than one without compression.

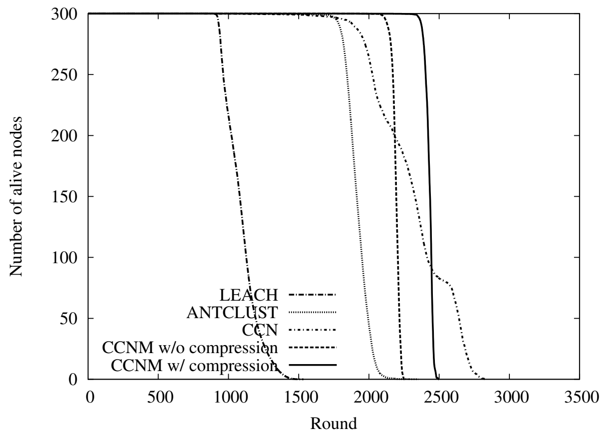

Figure 8: The number of alive nodes versus round for $N = 300$.

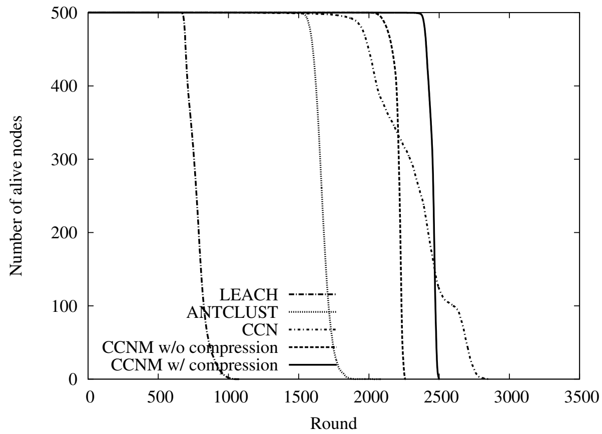

Figure 9: The number of alive nodes versus round for $N = 500$.

4.2 Simulation 2

In this simulation, the impact of "long-term sleep" proposed in section 3.3 is evaluated. For each method of CCN, CCNM without compression and CCNM with compression, we evaluate the following two factors:

- how much "long-term sleep" improves the length of operating rounds, and
- the methods with "long-term sleep" can cover the whole area to be observed.

In addition to Table 1, the parameters used in this simulation are as follows: $N = 100$, $R_{\rm sense} = 20$ meters and $R_{\rm vc} = 5$ meters. In the simulation, each method is evaluated in terms of *cover rate* defined as follows:

- 100% of *cover rate* means that there exists at least one operating sensor node for any circular area of $R_{\rm sense}$ radius, and

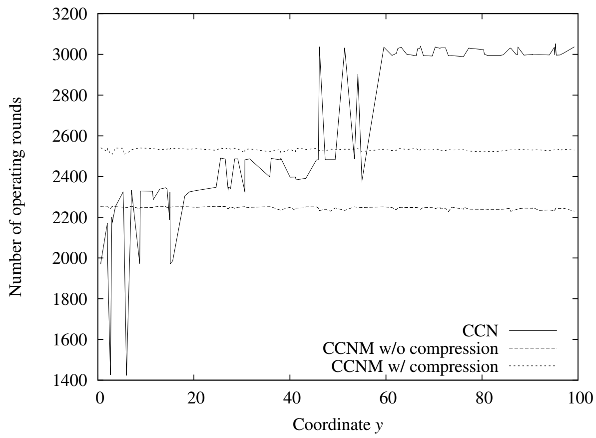

Figure 10: The number of operating rounds versus coordinate y for $N = 100$.

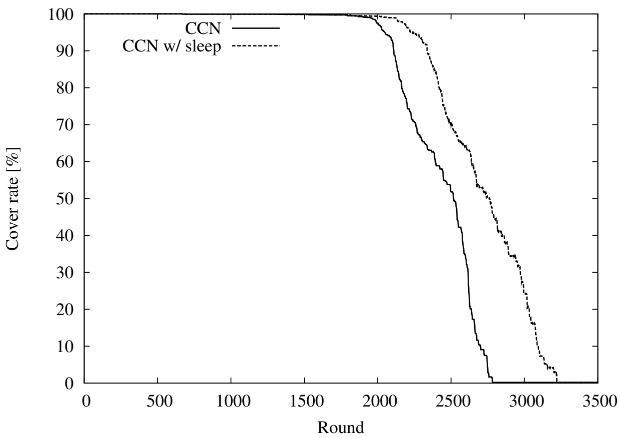

Figure 11: The cover rate versus round for CCN.

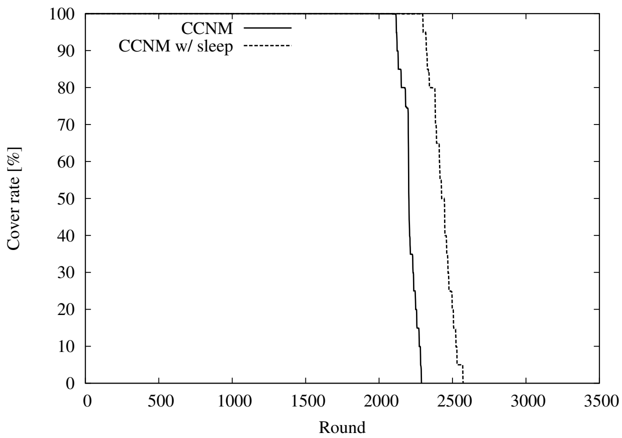

Figure 12: The cover rate versus round for CCNM.

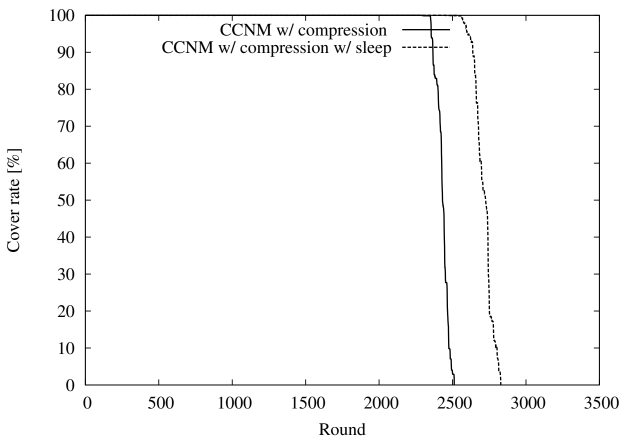

Figure 13: The cover rate versus round for CCNM with compression.

- the spots having no sensor node within R_{sense} radius increase as *cover rate* decreases.

The simulation results for CCN, CCNM and CCNM without compression are shown in Figures 11, 12 and 13, respectively. In the figures, "w/ sleep" means "with long-term sleep". From the results, we can observe the following tendencies.

- For any method, "long-term sleep" improves the length of operating rounds. The improvements more than 10% are achieved.

- Throughout most of the operating rounds the methods with long-term sleep achieve almost 100 % of cover rate.

The simulation results show that our "long-term sleep" can reduce energy consumption without reducing the coverage of observed area.

5 Conclusions and Future Work

In this paper, firstly, we described clustering communication methods CCN and CCNM for WSNs, which we have proposed in [9]. The features of CCN are 1) the number of broadcastings for calculating the number of neighbors is reduced and 2) the energy consumption involved in clustering is reduced by adaptively varying the range of broadcasting. Secondly, we described CCNM, which is the extension of CCN to the multi-hop version and have been also proposed in [9].

Further, as new contribution in this paper, we proposed "long-term sleep" in order to achieve further improvement of energy efficiency. The long-term sleep scheme can be used in CCN, CCNM and CCNM with compression.

Two types of simulation were presented in order to show the effectiveness of the proposed methods. The first simulation showed that our methods proposed in [9] prolong the network lifetime longer than the conventional methods LEACH and ANTCLUST. Further, the simulation results showed that CCNM can equalizes the lifetime of nodes regardless of the node location, which is an important property for WSNs. The second simulation showed that our new contribution "long-term sleep" can achieve further improvement of energy consumption without reducing the coverage of observed area.

Our future works are theoretical analysis of the proposed methods, further improvement of prolonging performance, consideration on other models such as WSN models with solar cell, and evaluation on a WSN testbed.

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