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A Density-Aware Protocol for Multihop Clustering in Nonuniformly Deployed Wireless Sensor Networks

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Abstract

Reducing the energy consumption in the battery-operated sensor nodes of wireless sensor networks (WSNs) is very important for prolonging the network lifetime. In this paper, a density-aware multihop clustering (DAMC) protocol is proposed to reduce the energy consumption in nonuniformly deployed WSNs. Each node determines its probability of becoming a cluster head (CH), based on the node density around it and thus, the CHs are distributed evenly over the network and every cluster has almost the same coverage area. Excessively redundant nodes are switched to the sleep mode to save energy. Then, a multilevel tree is constructed in each cluster for low-energy multihop transmissions. The network lifetime in DAMC can be prolonged significantly because excessively redundant sensing and transmissions are reduced remarkably and because multihop transmissions are used instead of single-hop transmissions in the clusters. The performance study shows that the proposed DAMC protocol outperforms the conventional clustering protocols in terms of the network lifetime.

Keywords: Wireless sensor network; nonuniform deployment; multihop clustering; energy consumption; network lifetime.

INTRODUCTION

Wireless sensor networks (WSNs) are widely used for various applications such as environment monitoring, logistics, target tracking, applications in military fields, home networks, and industrial diagnosis [1]. A WSN consists of several battery-powered sensor nodes that sense their surroundings and send the sensed data to a sink node or a base station. In many WSNs, the batteries are difficult to replace and, even if replaceable, the replacement cost is very high [2]. Thus, reducing energy consumption in sensor nodes is very important for prolonging the network lifetime.

In WSNs, routing is the process of forwarding data gathered by sensor nodes to the sink or base station. A WSN consists of many sensor nodes, and it is inefficient for all sensor nodes to send their sensed data to the single sink node directly. Instead, the sensor nodes are grouped into clusters, and every sensor node sends its sensed data to its cluster head (CH). Then, the CHs send the aggregate data to the sink. Such a hierarchical routing is more energy efficient when compared to the flat routing wherein every sensor delivers the sensed data to the sink directly.

The typical hierarchical routing or clustering protocols are the low-energy adaptive clustering hierarchy (LEACH) [3], low-energy adaptive clustering hierarchy-centralized (LEACH-C) [4], hybrid energy-efficient distributed (HEED) clustering [5], base-station controlled dynamic clustering protocol (BCDCP) [6], threshold-sensitive energy-efficient sensor network protocol (TEEN) [7], hybrid protocol for efficient routing and comprehensive information retrieval in WSNs (APTEEN) [8], tree-based clustering (TBC) [9], and balanced clustering algorithm (BCA) [10]. The well-known LEACH is the pioneer clustering protocol in WSNs, and TBC is the most advanced clustering scheme for uniformly deployed WSNs. The recently developed BCA is a single-hop clustering scheme targeting nonuniformly deployed WSNs. The existing clustering algorithms will be reviewed in more detail in Section II.

In many applications such as environment monitoring, the sensor nodes may be deployed nonuniformly due to some limiting conditions. For example, when the sensor nodes are deployed over a mountainous area by a helicopter, it is possible that they will be deployed nonuniformly. In such a nonuniformly deployed WSN, the sensing area or coverage area of the cluster varies in each region; i.e., there are many small-area clusters in dense regions and a few large-area clusters in sparse regions. In BCA [10], equal-size clustering is achieved even in nonuniformly deployed WSNs and the excessively redundant nodes are switched to the sleep mode to save energy and to prolong network lifetime. In BCA, however, the single-hop transmissions from the sensor nodes to their CHs need more energy than the multihop transmissions in a cluster because the transmission power increases exponentially with distance. On the other hand, TBC [9] implements a multilevel tree within a cluster, enabling multihop transmission; however, it does not consider the nonuniform deployment, resulting in severe interference and unnecessary energy consumption in dense regions.

In this paper, a density-aware multihop clustering (DAMC) protocol is proposed for nonuniformly deployed sensor networks to reduce energy consumption and prolong network lifetime. The node density in this paper is defined as the number of nodes within the node's sensing range divided by the node's sensing area. During the initial network configuration, every node calculates the node density and determines the probability of becoming a CH based on this node density. Thus, the CHs are distributed evenly over the network and every cluster has almost the same coverage area. Excessively redundant nodes are switched to the sleep mode to save energy. Then, a multilevel tree is constructed in each cluster for low-energy multihop transmissions. In the proposed DAMC protocol, the network lifetime can be prolonged significantly because excessively redundant sensing and transmissions are reduced remarkably and because multihop transmissions are used instead of single-hop transmissions in the clusters.

According to the simulation results, the proposed DAMC protocol outperforms the conventional clustering protocols by up to 85% in terms of the network lifetime for a given simulation setting. The network lifetime in our performance study is defined as the duration until half the sensor nodes die due to the energy depletion in the battery.

The rest of this paper is organized as follows: In the following section, the existing clustering protocols are reviewed in detail. In Section III, the operating principles and characteristics of the proposed DAMC protocol are discussed. In Section IV, the performance of DAMC protocol is evaluated via extensive computer simulations and is compared to that of the conventional schemes. Finally, the paper is concluded in Section V.

RELATED WORKS

For more than a decade, many clustering algorithms based on randomness have been studied. Ever since the pioneer clustering protocol LEACH was introduced [3], more advanced clustering algorithms have been proposed [4]–[10]. In this section, they are reviewed with respect to their major characteristics and improvements.

A. LEACH

In the LEACH protocol [3], each round consists of a set-up phase and a steady-state phase. Clusters are formed during the set-up phase, and the sensed data are periodically delivered to the sink through the CHs during the steady-state phase.

In LEACH, CHs are elected probabilistically in every round. Every sensor node generates a random number between zero and one and it becomes a CH if the generated number is less than the calculated threshold value. For a node *n*, the threshold value $T(n)$ in the *r*-th round is calculated by

$$T(n) = \begin{cases} \dfrac{p}{1 - p(r \bmod \frac{1}{p})}, & \text{if } n \in G \\ 0, & \text{otherwise} \end{cases} \tag{1}$$

where the parameter *p* is the probability that a sensor node becomes a CH and *G* is the set of sensor nodes that have not been chosen as a CH for the past $1/p$ rounds. If a node *n* has not been chosen as a CH in the last $1/p$ rounds, $T(n)$ is calculated using (1); if the generated random number is less than $T(n)$, the node becomes a CH in the current round; otherwise, $T(n)$ is set to zero and the node *n* is not elected as a CH in the current round.

Once CHs are chosen according to the above procedure, every CH broadcasts the fact that it has become a CH. Then, sensor nodes send a join message to the nearest CH based on the received signal strengths of the broadcast messages.

In the steady-state phase after cluster formation, sensor nodes send their sensed data to their CHs periodically as per the time division multiple access (TDMA) schedule assigned by the CHs. CHs aggregate the received data and send the aggregate data to the sink node.

This series of procedural steps are repeated every round. That is, the CHs are rotated per round because they consume more energy than normal sensor nodes. This makes the energy consumption of all the nodes as even as possible, resulting in increased network lifetime. However, when sensor nodes are nonuniformly deployed over the network area, balanced energy consumption is not possible because of the unbalanced clustering.

B. TBC

In the TBC protocol, a multilevel tree is constructed in a cluster, in which the CH is the root node [9]. The CH is elected in the same manner as in the LEACH protocol. The broadcast and join messages, which are sent by the CH and the normal sensor nodes, respectively, are also similar to those in LEACH. Unlike LEACH, however, the location information of the sensor node is included in the join message.

After receiving the join messages from the sensor nodes, the CH finds the farthest sensor node; the distance between the CH and the farthest sensor node is denoted as d_{max}. Then, the maximum distance d_{max} is divided by the tree depth α, where α is also called the tree height or the maximum level of the tree. Therefore, the average transmission distance d_{avg} between a node and its parent node in a tree can be represented by

$$d_{avg} = \frac{d_{\max}}{\alpha}. \tag{2}$$

The CH is at level 0 in the tree and the member nodes are at various specific levels according to their distances from the CH. Fig. 1 shows an example of the construction of a tree in TBC when α is 3. Once the cluster is divided into α concentric circles as shown in Fig. 1, each sensor node selects an upper-level node that is at a minimum distance from itself as its parent node. Finally, a single tree is generated.

In a cluster, the multihop transmission from the sensor nodes to the CH through the multilevel tree reduces the energy consumption when compared to the single-hop transmission, because the transmission power increases exponentially with distance. Moreover, the energy consumption is distributed over the network. As in LEACH, however, the unbalanced clustering causes unbalanced energy consumption in the network if the sensor nodes are deployed nonuniformly. In addition, if there is an error or failure at the parent node, the messages from its child nodes cannot be delivered.

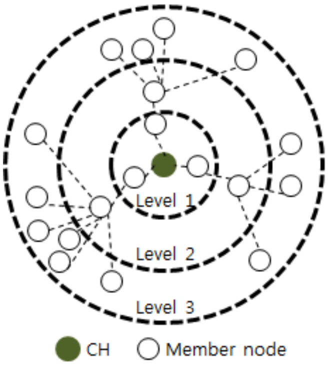


Figure 1. Example tree in TBC when α = 3.

C. BCA

In the BCA protocol [10], every cluster area is almost the same even when sensor nodes are deployed nonuniformly over the network area. Balanced clustering is achieved by electing the CH based on the relative node density. For a node n, the relative node density $D(n)$ is obtained by dividing the node density by the network density, where the node density is the ratio of the number of nodes within the node's sensing range over the node's sensing area, and the network density is the ratio of the total number of nodes in the network over the network area. Therefore, $D(n)$ can be represented by

$$D(n) = \frac{F/(\pi R^2)}{N/A} = \frac{F/N}{\pi R^2/A}, \tag{3}$$

where F is the number of nodes within the node's sensing range, N is the total number of nodes in the network, R is the sensing range, and A is the network area.

The CH is selected according to a new threshold that takes $D(n)$ into consideration. That is, for a node n, the new threshold value $\tilde{T}(n)$ in the r-th round is calculated by

$$\tilde{T}(n) = T(n) + \frac{mT(n)}{N}\left(\frac{1}{D(n)} - 1\right), \tag{4}$$

where $T(n)$ is the threshold value calculated in (1), N is the total number of nodes in the network, and m is the number of living nodes in the network.

In the region where the node density is high, is less than $T(n)$ and thus, lesser number of CHs are selected every round. This results in balanced clustering even when sensor nodes are deployed nonuniformly. After cluster formation, if the number of nodes in a cluster exceeds the average number of nodes per cluster in the network, randomly chosen excessive nodes in the cluster are maintained in the sleep mode every round. That is, the nodes not included in clusters in dense regions remain in the sleep mode in every round. However, when sensor nodes are deployed regularly in the network area, the BCA incurs extra overhead for calculating the node density unnecessarily.

D. Other Clustering Protocols

In addition to the above-mentioned clustering protocols, some more interesting protocols have been studied. LEACH-C [4] is a centralized version of LEACH. All nodes in the network send a message including their position and residual-energy information to the sink. Then, the sink elects CHs and broadcasts the information about the clusters to all nodes. HEED [5] uses a few values that take into account the node's residual energy, for cluster formation. A node with higher residual energy can be elected as a CH. In BCDCP [6], complex calculations are assigned to the sink that elects a candidate set of CHs to determine the CH. CHs send aggregate messages to the sink on a multihop basis without direct transmission. In TEEN [7], sensor nodes manage the threshold data reactively. The cluster formation process in TEEN is the same as that in LEACH. After cluster formation, the CHs transmit the system parameters to their member nodes. As a hybrid protocol, APTEEN [8] combines the advantages of LEACH and TEEN. It unites the data transmission according to a threshold value (as in TEEN) with the periodic data transmission (as in LEACH). After cluster formation, the CHs transmit the threshold value and parameters to their member nodes.

Recently, some works on clustering have been reported in the literature [11]–[13] even though they do not achieve a major quantum jump. They mainly focus on the improvement of energy efficiency because the energy efficiency is one of the most important design criteria for prolonging network lifetime in battery-operated WSNs. However, they do not take the nonuniform deployment of sensor nodes into consideration.

DENSITY-AWARE MULTIHOP CLUSTERING

In this section, the operating principles and characteristics of the proposed DAMC protocol are discussed in detail. CH selection, sleep-node selection, tree construction, sensing, and data transmission are presented. As in TBC [9], it is assumed that each node has its own location information and that it can adjust its transmission power depending on the distance to its receiver.

A. Selection of Cluster Heads

For density-aware clustering in a nonuniformly deployed WSN, DAMC considers the node density for cluster formation, similar to the BCA [10]. As mentioned in Section I, the node density in this paper is defined as the number of nodes within the node's sensing range divided by the node's sensing area. During the initial network configuration, just after network deployment, every sensor node calculates the node density and determines its probability of becoming a CH, based on the node density. As a result, CHs are distributed evenly over the network area. This means that every cluster has almost the same coverage area.

The number of CHs is decided in accordance with the probability that a sensor node becomes a CH. Usually, this probability is usually initialized when the sensor nodes are deployed. Just after the CHs are chosen probabilistically, every CH broadcasts that it has become a CH. Each sensor node can receive multiple broadcast messages from multiple CHs and calculate their received signal strengths. Then, each sensor node sends a join message to the nearest CH, based on the received signal strengths of the broadcast messages. By doing so, the cluster membership is determined and every sensor node belongs to a cluster. However, the number of nodes in each cluster varies because of the node density.

B. *Selection of Sleep Nodes*

Immediately after the CHs are selected, some nodes in densely populated clusters should be switched to the sleep mode to reduce unnecessary energy consumption and severely conflicting transmissions in densely deployed regions. That is, if the number of nodes in a cluster exceeds the average number of nodes per cluster in the network, the randomly chosen excessive nodes in the cluster remain in the sleep mode. The sleep nodes are randomly chosen every round.

The number of sleep nodes in a cluster is recalculated depending on the number of living nodes, as the number of dead nodes increases over time. That is, the number of sleep nodes in a cluster, $\tilde{S}(u,m)$, is calculated by

$$S(u,m) = u - \frac{m}{c} \tag{5}$$

and

$$\tilde{S}(u,m) = \begin{cases} \left\lceil \dfrac{S(u,m) \times m}{N} \right\rceil, & \text{if } S(u.m) > L \\ 0, & \text{otherwise} \end{cases} \tag{6}$$

where u is the number of nodes in a cluster, m is the number of living nodes in the network, c is the expected number of clusters, N is the total number of nodes in the network, and L is the minimum number of living nodes in a cluster for network operation.

After the CH selects the sleep nodes randomly, it broadcasts the identifiers of the sleep nodes to all member nodes. Then, the sleep nodes go into the sleep mode for that round.

C. *Tree Construction*

For multihop clustering of the selected member nodes without sleep nodes in a cluster, a multilevel tree is constructed in a cluster as in [9], in which the CH is the root node. When each sensor node sends a join message to the nearest CH during CH selection, the location information of the sensor node is also included in the join message. Once the cluster is divided into α concentric circles by the CH, where α is the tree height, the CH updates its active members with the information necessary for parent-node selection. Then, each sensor node selects an upper-level node at a minimum distance from itself as its parent node. After tree construction, the CH broadcasts the TDMA schedule to all active member nodes. Fig. 2 shows an example of a tree composed of 16 active nodes in a 20-node cluster when the tree height (α) is set to 3.

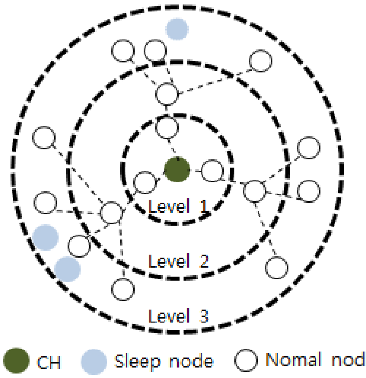


Figure 2. Example tree of 16 active nodes ($\alpha = 3$).

The multilevel tree can reduce the energy consumption significantly because a series of multihop short-distance transmissions consume much less energy than a single-hop long-distance transmission. Note here that the transmitted signal is usually attenuated in inverse proportion to the fourth power of the transmission distance. Fig. 3 shows examples of cluster formation in a nonuniformly deployed WSN, in which the four clustering schemes—LEACH, TBC, BCA, and the proposed DAMC—are compared schematically. In the figure, the shaded nodes are sleep nodes in the densely populated clusters. The sleep nodes are randomly chosen every round.

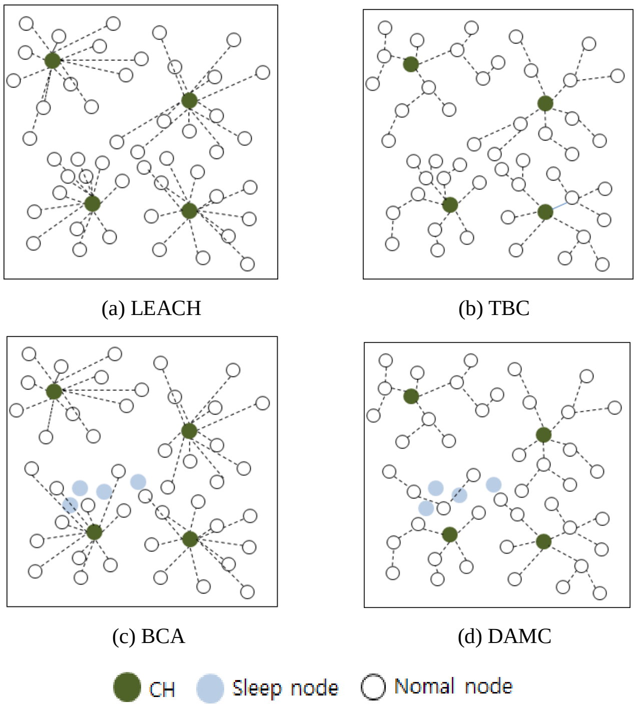


Figure 3. Examples of cluster formation in a nonuniformly deployed WSN.

D. *Data Gathering and Transmission*

After the cluster formation, including tree construction, the sensor nodes send the sensed data to their CHs periodically in accordance with the TDMA schedule. Each CH aggregates the received data and sends the aggregate data to the sink node using the carrier sense multiple access (CSMA) protocol. Once a multihop cluster is formed, the data gathering and transmission are repeated in rounds as shown in Fig. 4. In the figure, the back-slashed boxes and the subsequent gray boxes indicate the communication from the cluster members to their CHs and the communication from the CHs to the sink node, respectively. It should also be noted that the node-density detection is carried out only once at the beginning, but the cluster formation is performed in every round.

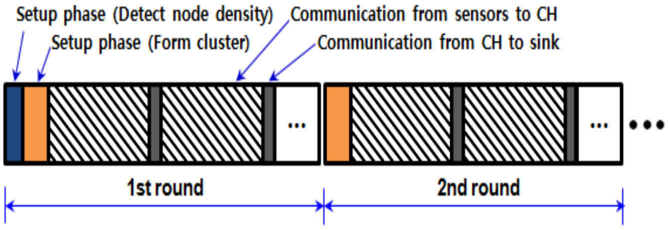


Figure 4. Rounds in the proposed DAMC.

In summary, the energy consumption in DAMC can be reduced significantly, resulting in prolonged network lifetime. This is achieved because excessively redundant sensing and transmissions are reduced remarkably and low-energy multihop transmissions are used instead of single-hop transmissions from the sensor nodes to the CHs in a cluster.

E. Comparison of Clustering Protocols

In this subsection, the four clustering protocols—LEACH, TBC, BCA, and the proposed DAMC—are compared qualitatively in terms of various technical aspects. Table I comparatively summarizes the major features and characteristics of the four protocols.

Table I. Comparison of clustering protocols.

Protocol	**LEACH**	**TBC**	**BCA**	**DAMC**
CH selection criteria	Probability	Probability	Node density & probability	Node density & probability
Performance in nonuniform deployment	Low	Low	Medium	High
Data delivery latency	Short	Medium	Short	Medium
Topology within a cluster	Star	Tree	Star	Tree
Impact of node failure	Low	Medium	Low	Medium
Energy consumption at CHs	High	Medium	Medium	Low

For nonuniformly deployed WSNs, BCA and DAMC are better than LEACH and TBC because the node density is also considered while selecting the CHs. On the other hand, the multilevel tree structure in TBC and DAMC results in not only an increased end-to-end latency in data delivery but also increased data loss when an upper-level node fails. Even so, the DAMC achieves higher performance and lower energy consumption than the other three protocols. This will be clearly shown in the next section through comparative simulations.

PERFORMANCE EVALUATION

In this section, the performance of DAMC is evaluated via computer simulation using Matlab and is compared with those of the conventional clustering schemes—LEACH [3], TBC [9], and BCA [10]. As described earlier, the popular LEACH is a pioneer protocol for clustering in WSNs. TBC is the most advanced clustering scheme for uniformly deployed WSNs, and the recently developed BCA is a single-hop clustering scheme targeting nonuniformly deployed WSNs.

A. Simulation Environment

In our simulation, 200 sensor nodes are deployed over a network area of 100 × 100 m^2. The sink node (or base station) is fixed at the location (125, 75), and the initial energy of each senor node is set to 2 J. In our simulation, six nonuniform deployments are experimented as shown in Fig. 5: (1) 100 nodes are deployed in an area of 50 × 50 m^2 and the other 100 nodes are deployed in the other regions, (2) 100 nodes are deployed in an area of 25 × 25 m^2 and the other 100 nodes are deployed in other regions, (3) 200 nodes are deployed according to the normal distribution with a mean of (50, 50) and variance of (±10, ±10), (4) 200 nodes are deployed according to the normal distribution with a mean of (50, 50) and variance of (±20, ±20), (5) 200 nodes are deployed according to the exponential distribution with a mean of (50 ± 10, 50 ± 10), and (6) 200 nodes are deployed according to the exponential distribution with a mean of (50 ± 20, 50 ± 20).

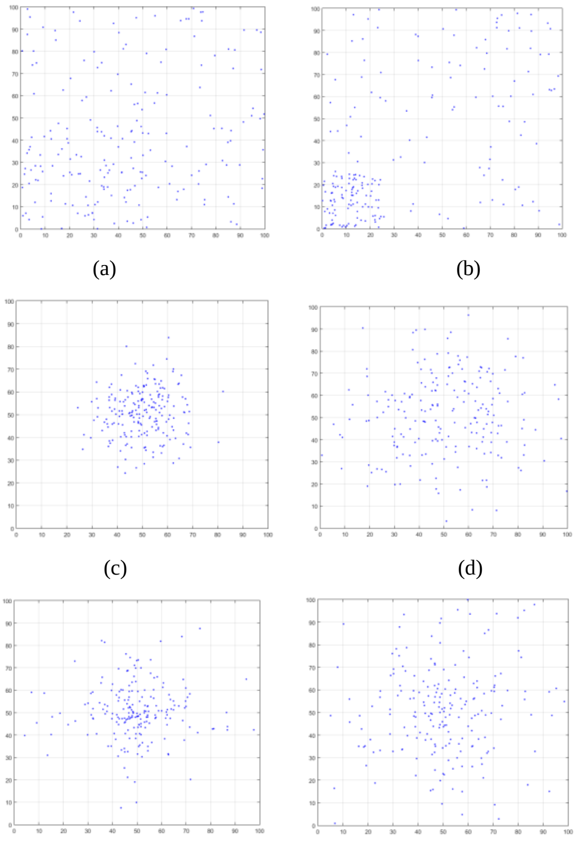
The energy consumption model [14] used in our experiment is as follows: The free-space (fs) model is used if the distance is less than a threshold d_0; otherwise, the multipath (mp) model is used. Hence, when transmitting k bits of a message over distance d, the energy consumption can be calculated by

$$E_{Tx}(k,d) = E_{Tx-elec}(k) + E_{Tx-amp}(k,d) = \begin{cases} kE_{elec} + k\varepsilon_{fs} d^2, & \text{if } d < d_0 \\ kE_{elec} + k\varepsilon_{mp} d^4, & \text{otherwise} \end{cases} \tag{7}$$

where d_0 is set to 87 m as in [9]. The energy consumption for receiving k bits of data is calculated by

$$E_{Rx}(k,d) = E_{Rx-elec}(k) = kE_{elec}\,. \tag{8}$$

In (7) and (8), E_{elec} is the radio-electronic energy that depends on the digital coding, modulation, filtering, and spreading of the signal. ε_{fs} and ε_{mp} are constants for the amplifier energy that depend on the distance to the receiver and the acceptable bit-error rate.


(a) (b)

(c) (d)

(e) (f)

Figure 5. Six nonuniform deployments of 200 nodes for simulation: (a) 100 nodes are deployed in an area of 50 × 50 m^2, (b) 100 nodes are deployed in an area of 25 × 25 m^2, (c) Normal distribution with mean (50, 50) and variance (±10, ±10) (d) Normal distribution with mean (50, 50) and variance (±20, ±20), (e) Exponential distribution with mean (50±10, 50±10), and (f) Exponential distribution with mean (50±20, 50±20).

Table II. Simulation parameters.

Parameter	**Value**
Network area	100 × 100 m^2
Location of sink	(125, 75)
Number of nodes	200
Number of clusters	10
Initial energy	2 J
Impact of node failure	5 nJ/bit
Initial energy	5 nJ/bit
E_{sense}	50 nJ/bit
E_{da}	10 pJ/bit/m^2
E_{elec}	0.00013 pJ/bit/m^4
E_{fs}	10 pJ/bit/m^2
E_{mp}	0.00013 pJ/bit/m^4
Sensing range	10 m
Maximum transmission range	136 m

The parameters used in our simulation are summarized in Table II. In the table, E_{sense} is the energy consumption required for sensing and E_{da} is the energy consumption for data aggregation. The simulations were performed 100 times for each experiment and the mean value of the results was used as the simulation result.

B. *Simulation Results and Discussion*

In our performance study, the network lifetime is extensively evaluated because it is the most important metric in WSNs. The network lifetime in our performance study is defined as the duration until half the sensor nodes die due to the energy depletion in the battery. Therefore, the number of living nodes is observed with respect to the round progress.

Figs. 6 to 11 show the number of living nodes along with the round for the six scenarios of nonuniform deployment described in Section IV-A. From the six figures, it can be observed clearly that the proposed DAMC outperforms the three conventional schemes—LEACH, TBC, and BCA.

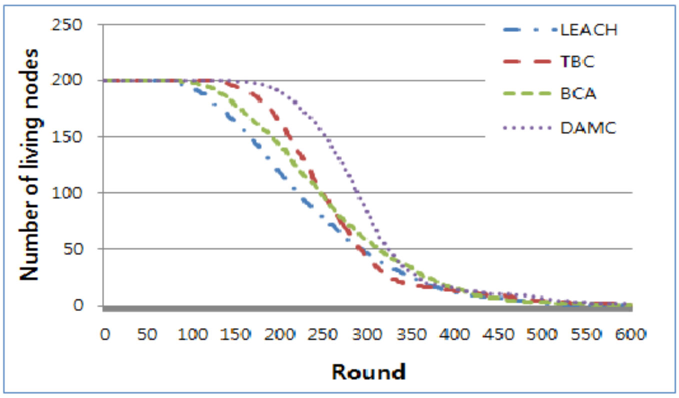


Figure 6. Network lifetime when 100 nodes are deployed in an area of 50 × 50 m^2 and the other 100 nodes are deployed in the other regions.

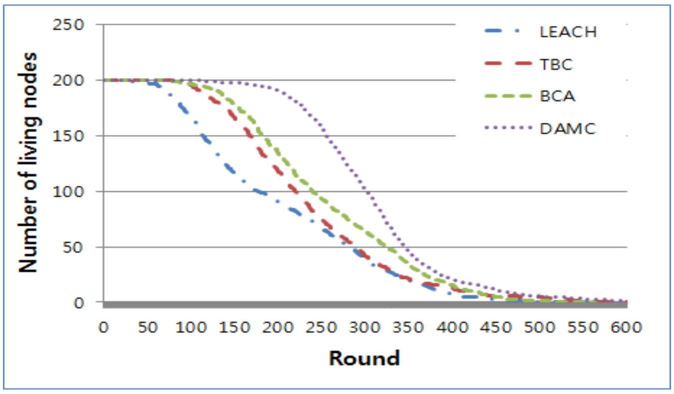


Figure 7. Network lifetime when 100 nodes are deployed in an area of 25 × 25 m^2 and the other 100 nodes are deployed in the other regions.

Figs. 6 and 7 show the number of living nodes along with the round for the two exceptional scenarios of nonuniform deployment. In the first deployment where 100 nodes are deployed in an area of 50 × 50 m^2 and the other 100 nodes are deployed in the other regions, the network lifetime is 16 to 32% longer than that in the other cases. In the second deployment where 100 nodes are deployed in an area of 25 × 25 m^2 and the other 100 nodes are deployed in the other regions, the network lifetime is 26 to 57% longer than that in the other cases. That is, it can be easily inferred that the performance is better as the nonuniformity increases.

Figs. 8 and 9 show the number of living nodes along with the round for the two normal distribution scenarios of nonuniform deployment. In the third deployment where 200 nodes are deployed according to the normal distribution with a mean of (50, 50) and variance of (±10, ±10), the network lifetime is 6 to 85% longer than that in the other cases. In the fourth deployment where 200 nodes are deployed according to the normal distribution with a mean of (50, 50) and variance of (±20, ±20), the network lifetime is 3 to 31% longer than that in the other cases. Thus, it can be easily inferred that the improvement is better as the variance decreases.

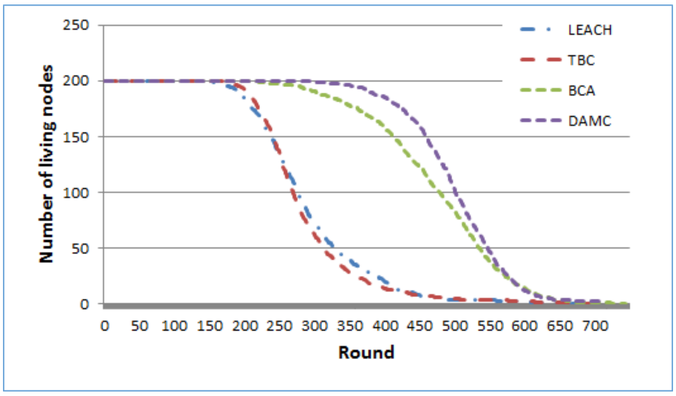


Figure 8. Network lifetime when 200 nodes are deployed according to the normal distribution with a mean of (50, 50) and variance of (±10, ±10).

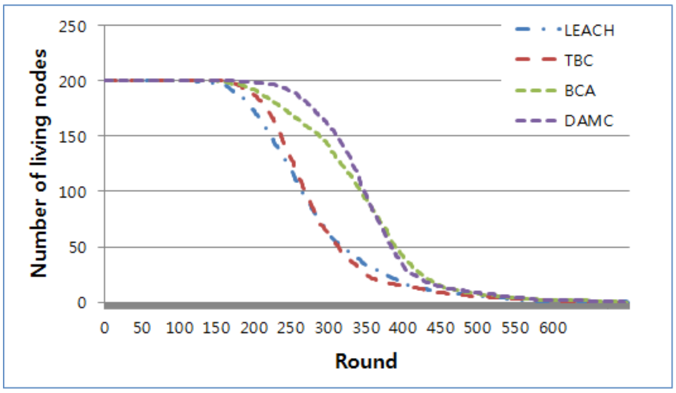


Figure 9. Network lifetime when 200 nodes are deployed according to the normal distribution with a mean of (50, 50) and variance of (±20, ±20).

Figs. 10 and 11 show the number of living nodes along with the round for the two exponential distribution scenarios of nonuniform deployment. In the fifth deployment where 200 nodes are deployed according to the exponential distribution with a mean of (50 ± 10, 50 ± 10), the network lifetime is 10 to 76% longer than that in the other cases. In the sixth deployment where 200 nodes are deployed according to the exponential distribution with a mean of (50 ± 20, 50 ± 20), the network lifetime is 6 to 43% longer than that in the other cases. Therefore, it can be easily inferred that the improvement is better as the mean decreases.

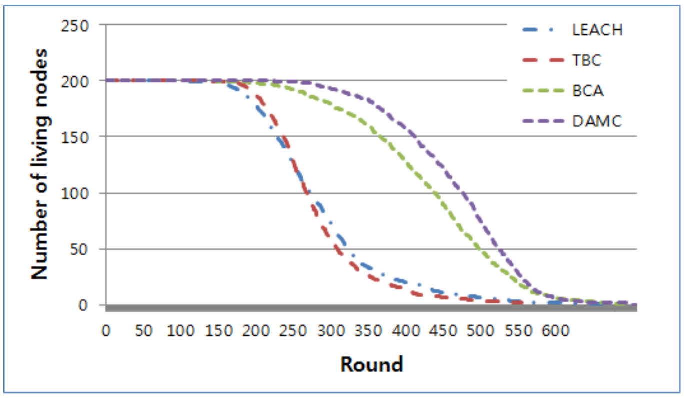


Figure 10. Network lifetime when 200 nodes are deployed according to the exponential distribution with a mean of (50 ± 10, 50 ± 10).

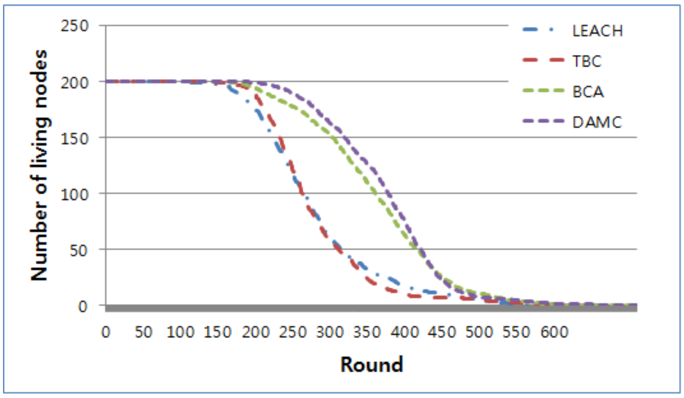


Figure 11. Network lifetime when 200 nodes are deployed according to the exponential distribution with a mean of (50 ± 20, 50 ± 20).

Among the four clustering schemes, LEACH shows the worst performance in our simulations. The comparative performances of TBC and BCA depend on the distribution patterns of the nodes. With the first and second nonprobabilistic deployments, their performance differences are not significant. With the third to sixth probabilistic deployments, however, the BCA obviously outperforms the TBC as shown in the four graphs. The proposed DAMC always outperforms the other three protocols.

In the proposed DAMC, the network lifetime is remarkably prolonged. CHs are distributed evenly over the network area and every cluster has almost the same coverage area. Excessively redundant nodes are switched to the sleep mode to save energy. That is, excessively redundant sensing and transmissions are significantly reduced. In addition, a multilevel tree in each cluster reduces the energy consumption further, because of the low-energy multihop transmissions.

CONCLUSIONS

In this paper, an energy-efficient clustering protocol called DAMC for nonuniformly deployed WSNs was proposed, in which the local node density and a multilevel tree structure were exploited in every cluster. During cluster formation, excessively redundant nodes were switched to the sleep mode to avoid excessively redundant sensing and transmissions. The multi-level tree in each cluster enabled low-energy multihop transmissions instead of long single-hop transmissions. Such effects resulted in significantly lower energy consumption and prolonged network lifetime in the DAMC. The performance study showed that the proposed DAMC outperformed the conventional clustering protocols in terms of network lifetime.

As a possible future work, we plan to investigate a more efficient tree structure in a cluster by considering the residual node energy in addition to the node density in nonuniformly deployed WSNs.

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