Density-Aware Multihop Clustering for Irregularly Deployed Wireless Sensor Networks

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Abstract—**In wireless sensor networks (WSNs), reducing energy consumption in battery-operated sensor nodes is very important for prolonging network lifetime. In this paper, a density-aware multihop clustering (DAMC) protocol is proposed for irregularly deployed WSNs to reduce energy consumption. Every node determines the probability that it becomes a cluster head (CH) based on the node density around itself and, thus, CHs are distributed evenly over the network and every cluster has almost the same coverage area. And excessively redundant nodes are turned into sleep mode to save energy. Then, a multi-level tree in each cluster is constructed for low-energy multihop transmissions. In DAMC, the network lifetime can be significantly prolonged because the unnecessary redundant sensing and transmissions are reduced remarkably and the multihop transmissions are used rather than single-hop transmissions in clusters. The performance study shows that the proposed DAMC outperforms the conventional clustering protocols in terms of network lifetime.**

Keywords-Wireless sensor network; irregular deployment; multihop clustering; energy consumption; network lifetime.

I. INTRODUCTION

Wireless sensor networks (WSNs) are widely used for various applications such as environment monitoring, logistics, target tracking, military fields, home networks, and industrial diagnosis [1]. A WSN consists of many battery-powered sensor nodes that sense their surroundings and send the sensed data to a sink node or 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 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 a lot of sensor nodes, and it is inefficient for all the sensor nodes to send their sensed data to the single sink node or base station directly. Instead, the sensor nodes are grouped as clusters, and every sensor node sends its sensed data to its cluster head (CH). Then, the CHs send the aggregated data to the sink. Such a hierarchical routing is energy-efficient compared to the flat routing that each sensor delivers data sensed by itself to the sink directly.

The typical hierarchical routing or clustering protocols are low energy adaptive clustering hierarchy (LEACH) [3], low-energy adaptive cluster hierarchy centralized (LEACH-C) [4], hybrid, energy-efficient distributed (HEED) [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 wireless sensor networks (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 targeted for irregularly deployed WSNs. The existing clustering algorithms will be reviewed in more detail in Section II.

In many applications such as environment monitoring, sensor nodes can be irregularly deployed due to some limited condition. For example, when the sensors nodes are deployed over a mountain area by a helicopter, there is the possibility that they may be irregularly deployed. Such an irregularly deployed WSN, the sensing area or coverage area of each cluster varies region by 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 irregularly deployed WSNs and the excessively redundant nodes are turned into sleep mode to save energy and to prolong network lifetime. In BCA, however, the single-hop transmission from sensor nodes to their CH needs more energy consumption compared to multihop transmission in a cluster because transmission power is exponentially increased with distance. On the other hand, TBC [9] implements a multi-level tree within a cluster enabling multihop transmission, but it does not take the irregular deployment into consideration resulting in severely conflicted transmissions and unnecessary energy consumption in dense regions.

In this paper, a density-aware multihop clustering (DAMC) protocol is proposed for irregularly 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 that it becomes a CH based on the node density so that CHs are distributed evenly over the network area and every cluster has almost the same coverage area. Excessively redundant nodes are turned into sleep mode to save energy. Then, a multi-level tree in each cluster is constructed for low-energy multihop transmissions. In the proposed DAMC, the network lifetime can be significantly prolonged because the unnecessary redundant sensing and transmissions are reduced remarkably and the multihop transmissions are used rather than single-hop transmissions in clusters.

According to the simulation results, the proposed DAMC outperforms the conventional clustering protocols by up to 70 percent in terms of network lifetime in the given simulation setting. The network lifetime in our performance study is defined as the time duration until half of the sensor nodes die due to the energy depletion of 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 step by step. In Section IV, the performance of DAMC is evaluated via extensive computer simulation and compared to the conventional schemes. Finally, the paper is concluded in Section V.

II. RELATED WORKS

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

A. LEACH

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

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

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

where the given 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 $1/p$ rounds. If a node n has not been chosen as a CH for the last $1/p$ rounds, $T(n)$ is calculated by (1) and, if the generated random number is less than $T(n)$, the node becomes a CH at the current round; otherwise, $T(n)$ is zero and the node n is not elected as a CH at the current round.

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

In the steady-state phase after cluster formation, sensor nodes send the sensed data to their CHs periodically in accordance with the TDMA (Time Division Multiple Access) schedule assigned by their CHs. CHs aggregate the received data and send the aggregated data to the sink node.

Such a 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 all the nodes consume energy as evenly as possible, resulting in increased network lifetime. However, when sensor nodes are irregularly deployed over the network area, the balanced energy consumption is not possible due to unbalanced clustering.

B. TBC

In the TBC protocol, a multi-level 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 are also similar to those in LEACH, which are sent by CHs and normal sensor nodes, respectively. Unlike LEACH, however, the location information of the sensor node is included in the join message.

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

$$d_{avg} = \frac{d_{\max}}{\alpha}. \quad (2)$$

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

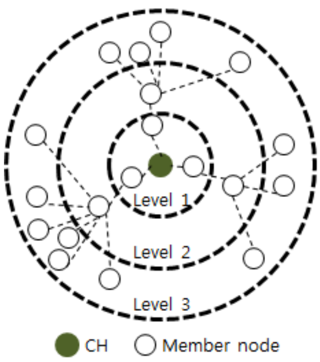


Figure 1. An example tree in TBC when $\alpha = 3$.

In a cluster, the multihop transmission through the multi-level tree from sensor nodes to the CH reduces energy consumption in comparison to single-hop transmission because transmission power is exponentially increased with distance. Also, the energy consumption is distributed over the network. As in LEACH, however, the unbalanced clustering causes unbalanced energy consumption over the network if sensor nodes are irregularly deployed. In addition, if there is an error or failure at the parent node, the messages from its children nodes cannot be delivered.

C. BCA

In the BCA protocol [10], every cluster area is almost the same even when sensor nodes are deployed irregularly over the network area. The balanced clustering is achieved by electing the CH on the basis of relative node density. For a node *n*, the relative node density *D(n)* is given by dividing node density by 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 taking the *D(n)* into consideration. That is, for a node *n*, the new threshold value $\widetilde{T}(n)$ at the r-th round is calculated by

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

where *T(n)* is the same 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, $\widetilde{T}(n)$ is decreased compared to *T(n)* and, thus, a less number of CHs are selected every round. This results in balanced clustering even when sensor nodes are irregularly deployed. After cluster formation, 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 are remained sleep every round. That is, the nodes not included in clusters in dense regions are remained sleep every round. However, when sensor nodes are regularly deployed in the network area, BCA incurs extra overhead for calculating the node density unnecessarily.

D. Other Clustering Protocols

LEACH-C [4] is a centralized version of LEACH. That is, the base station elects cluster heads and forms clusters. All nodes in the network send a message including position and residual energy information to the base station. Based on the information, the base station selects cluster heads and divides all nodes to the clusters. Then, the base station broadcasts the information of clusters to all the nodes which are deployed in the network area.

HEED [5] uses some values which take into account the nodes residual energy for cluster formation. A node with more residual energy can be elected as a cluster head for prolonging network lifetime. If candidates for the cluster head have the same residual energy, then their transmission costs are compared.

In BCDCP [6], the complex calculations are assigned to the base station as in LEACHC. In cluster formation, base station elects a candidate set of cluster heads to determine cluster heads. In this scheme, cluster heads send aggregated messages to the base station on a multi-hop basis without direct transmission.

In TEEN [7], sensor nodes manage the threshold data reactively. The process which excludes the threshold value is equal to LEACH. The cluster formation process in TEEN is the same as that in LEACH. After cluster formation, cluster heads transmit the parameters of the data, the hard threshold (HT) value, and the soft threshold (ST) value to their member nodes. All nodes collect and transmit data when the value exceeds the HT value first. After exceeding HT, nodes collect and transmit data only when the measured data exceeds ST.

APTEEN [8] combines the advantages of LEACH and TEEN. As a hybrid protocol, APTEEN unites the data transmission according to the threshold value of TEEN and the periodic data transmission of LEACH. After cluster formation, the cluster heads transmit the threshold value and parameters that include the TDMA schedule time to the member nodes.

More 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 wireless sensor networks. In addition, they do not take the irregular deployment of sensor nodes into consideration yet.

III. 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, and sensing and data transmission are presented step by step. As in TBC [9], it is assumed that each node has the location information of itself and it can adjust its transmission power depending on the distance to its receiver.

A. Cluster Head Selection

For density-aware clustering in an irregularly deployed WSN, DAMC considers the node density for cluster formation as in 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 the probability that it becomes 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, the probability is initially set up when sensor nodes are deployed. Just after CHs are probabilistically chosen, 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 strength. Then, each sensor node sends a join message to the nearest CH based on the received signal strength of the broadcast messages. By doing so, cluster membership is determined and every sensor node belongs to a cluster. However, the number of nodes in a cluster varies cluster by cluster because the node density differs region by region in the irregularly deployed WSN.

B. Sleep Node Selection

Immediately after CHs are selected, some nodes in densely populated clusters should be turned into sleep mode to reduce unnecessary energy consumption and severely conflicted 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 sleep mode. The sleep nodes are randomly chosen every round.

As a matter of fact, the number of sleep nodes in a cluster is recalculated depending on the number of living nodes as the number of dead nodes is increased over time. That is, the number of sleep node in a cluster, $\widetilde{S}(u,m)$, is calculated by

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

and

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

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 sleep nodes to all member nodes. Then, the sleep nodes go into sleep mode during the round.

C. Tree Construction

For multihop clustering of the selected member nodes without sleep nodes in a cluster, a multi-level 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 tree height, the CH informs its active members of the necessary information for parent node selection. Then, each sensor node selects an upper-level node with the minimum distance from the node itself as its parent node. After tree construction, the CH broadcasts the TDMA schedule to all the active member nodes. Figure 2 shows an example tree composed of 16 active nodes in a 20-node cluster when tree height (α) is set to 3.

The multi-level tree can reduce 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 inversely proportional to the fourth power of the distance. Figure 3 shows examples of cluster formation in an irregularly deployed WSN, in which four clustering schemes of LEACH, TBC, BCA and the proposed DAMC are compared schematically. In the figure, the nodes labeled S are sleep nodes in the densely populated clusters. The sleep nodes are randomly chosen every round.

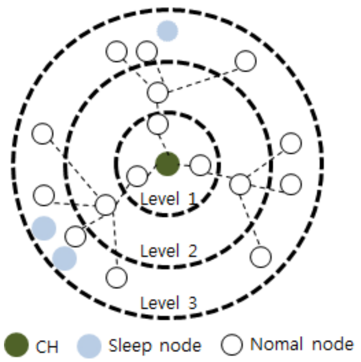
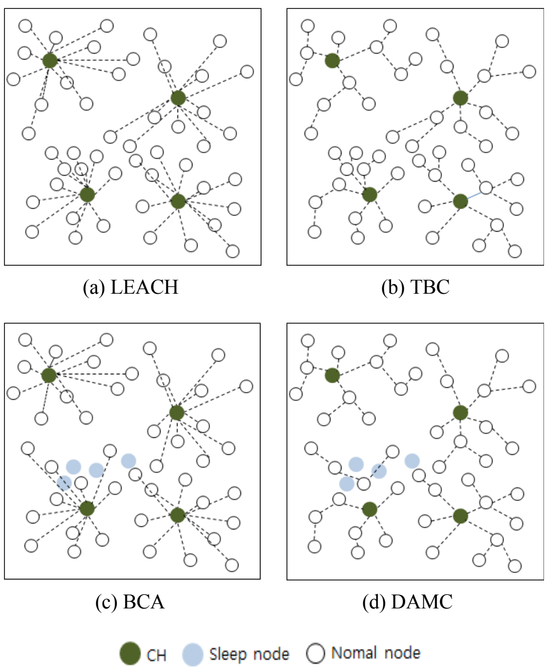


Figure 2. An example tree of 16 active nodes (α = 3).



(a) LEACH (b) TBC

(c) BCA (d) DAMC

Figure 3. Examples of cluster formation in an irregularly deployed WSN.

D. *Data Gathering and Transmission*

After the cluster formation including tree construction, 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 aggregated data to the sink node by using the CSMA (Carrier Sense Multiple Access) protocol. Once a multihop cluster is formed, the data gathering and transmission are repeated in rounds as shown in Figure 4. In the figure, the back-slashed boxes and the subsequent gray boxes indicate the communications from cluster members to their CHs and the communications from CHs to the sink node, respectively. It should be also noted that the node density detection is carried out only once at the beginning, but the cluster formation is done in every round.

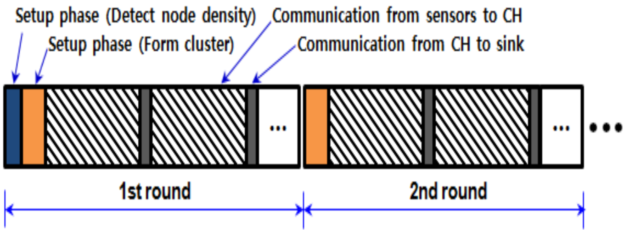


Figure 4. Rounds of the proposed DAMC.

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

IV. PERFORMANCE EVALUATION

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

A. *Simulation Environment*

In our simulation, 200 sensor nodes are deployed over the 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, two irregular deployments are experimented: (i) 100 nodes are deployed in the region of 50 × 50 m^2 and the other 100 nodes are deployed in the other regions and (ii) 100 nodes are deployed in the region of 25 × 25 m^2 and the other 100 nodes are deployed in the other regions. Figure 5 shows the two irregular deployments of 200 nodes for simulation.

In our experiment, the energy consumption model [14] 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 along with distance *d*, the energy consumption can be calculated by

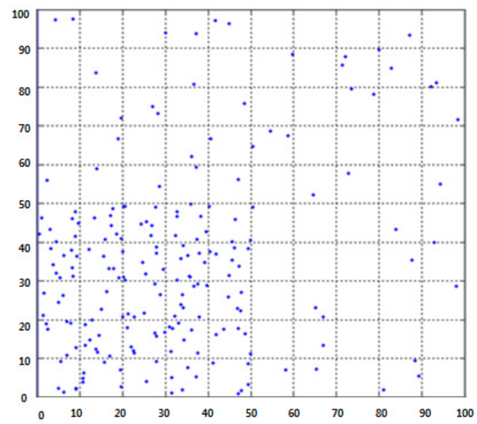
$$E_{Tx}(k,d) = E_{Tx-elec}(k) + E_{Tx-amp}(k,d) = \begin{cases} kE_{elec} + k\varepsilon_{fs}d^2, & \text{if } d < d_0 \\ kE_{elec} + k\varepsilon_{mp}d^4, & \text{otherwise} \end{cases} \quad (7)$$

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

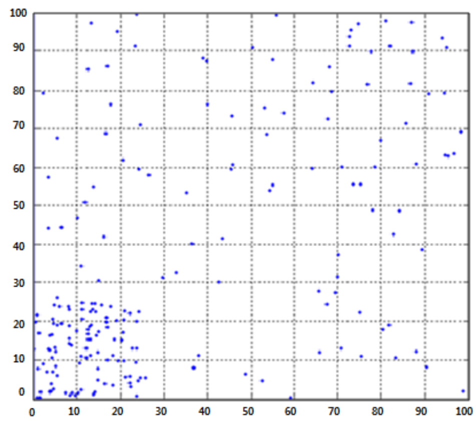
$$E_{Rx}(k,d) = E_{Rx-elec}(k) = kE_{elec}. \quad (8)$$

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

The parameters used in our simulation are summarized in Table 1. 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 results was used as the simulation results.



(a) 100 nodes are deployed in the region of 50 × 50 m2.



(b) 100 nodes are deployed in the region of 25 × 25 m^2.

Figure 5. Two irregular deployments of 200 nodes for simulation..

TABLE I. SIMULATION PARAMETER.

Parameter	Value
Network area	100 × 100 m2
Location of sink	(125, 75)
Number of nodes	200
Number of clusters	10
Initial energy	2 J
Esense	5 nJ/bit
Eda	5 nJ/bit
Eelec	50 nJ/bit
Efs	10 pJ/bit/m2
Emp	0.00013 pJ/bit/m4
Sensing range	10 m
Maximum transmission range	136 m

B. Simulation Results and Discussion

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

Figures 6 and 7 show the number of living nodes per round for the two scenarios of irregular deployment described in Section IV-A. From the two figures, it is clearly shown that the proposed DAMC outperforms the three conventional schemes of LEACH, TBC and BCA. In the first deployment that 100 nodes are deployed in the region of 50 × 50 m^2 and the other 100 nodes are deployed in the other regions, the network lifetime is 26 to 57 percent longer than the others. In the second deployment that 100 nodes are deployed in the region of 25 × 25 m^2 and the other 100 nodes are deployed in the other regions, the network lifetime is 26 to 70 percent longer than the others. That is, it can be easily inferred that the improvement is better and better as the irregularity increases.

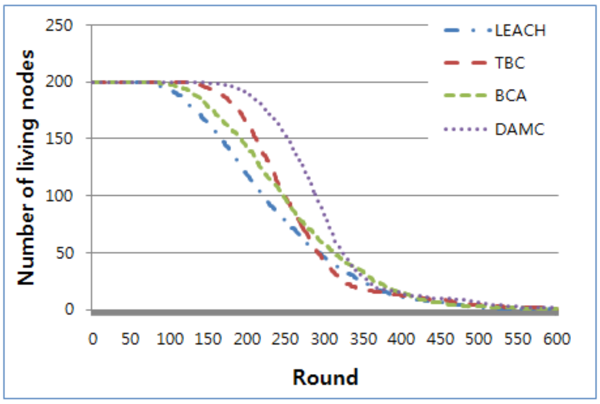


Figure 6. Network lifetime when 100 nodes are deployed in the region of 50 × 50 m^2 and the other 100 nodes are deployed in the other regions.

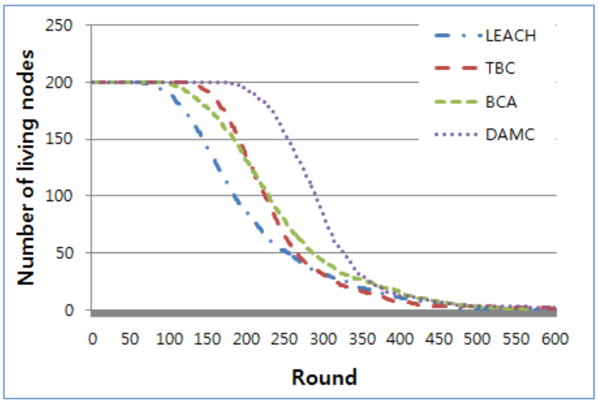


Figure 7. Network lifetime when 100 nodes are deployed in the region of 25 × 25 m^2 and the other 100 nodes are deployed in the other regions.

Among the four clustering schemes, LEACH shows the worst performance in our simulation. The comparative performance of TBC and BCA depends on the irregularity. When the irregularity is relatively low, the performance difference of them is not significant. With high irregularity, however, BCA obviously outperforms TBC as shown in the two 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 turned into sleep mode to save energy. That is, the unnecessary redundant sensing and transmissions are significantly reduced. In addition, a multi-level tree in each cluster reduces energy further thanks to low-energy multihop transmissions.

V. CONCLUSIONS

In this paper, an energy-efficient clustering protocol called DAMC for irregularly deployed WSNs has been proposed, in which the local node density and the multi-level tree structure are exploited in every cluster. During cluster formation, excessively redundant nodes are turned into sleep mode to avoid unnecessary redundant sensing and transmissions. And the multi-level tree in each cluster enables low-energy multihop transmissions rather than long single-hop transmissions. Such effects result in significantly low energy consumption and prolonged network lifetime in DAMC. The performance study has shown that the proposed DAMC outperforms the conventional clustering protocols in terms of network lifetime. As possible future works, we are going to devise a more efficient tree in a cluster and evaluate various scenarios of irregular deployment with specific probability distributions.

ACKNOWLEDGMENT

This research was supported in part by Basic Science Research Program through the National Research Foundation of Korea (NRF) funded by the Ministry of Education (NRF-2013R1A1A2011744). Correspondence should be addressed to Dr. Sangman Moh (smmoh@chosun.ac.kr).

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