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Research Article

An Energy-Aware Distributed Unequal Clustering Protocol for Wireless Sensor Networks

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Due to the imbalance of energy consumption of nodes in wireless sensor networks (WSNs), some local nodes die prematurely, which causes the network partitions and then shortens the lifetime of the network. The phenomenon is called "hot spot" or "energy hole" problem. For this problem, an energy-aware distributed unequal clustering protocol (EADUC) in multihop heterogeneous WSNs is proposed. Compared with the previous protocols, the cluster heads obtained by EADUC can achieve balanced energy, good distribution, and seamless coverage for all the nodes. Moreover, the complexity of time and control message is low. Simulation experiments show that EADUC can prolong the lifetime of the network significantly.

1. Introduction

A wireless sensor network (WSN) consists of thousands of low-cost, low-power, and tiny sensor nodes which can be widely used in military, national security, environmental science, traffic management, disaster prediction, medical, manufacturing industry, and city information construction. As sensor networks have limited and nonrechargeable energy resources, energy efficiency is a very important issue in designing the topology, which affects the lifetime of sensor networks greatly.

Clustering is proved to be an effective scheme in increasing the scalability and lifetime of WSNs. In clustering schemes, sensor nodes are grouped into clusters and a main node is selected as the cluster head (CH) of a cluster and the other nodes are called cluster members (CMs) [1]. Each CM collects local data from the environment periodically and then sends it to the CH. When the data from all the CMs arrives, the CHs aggregate the data and send it to the BS.

As CHs are responsible for receiving and aggregating the data from their CMs, and transmitting the aggregated data to a long distance, The energy consumption of CHs is much larger than that of CMs. In order to balance the energy among nodes, most clustering algorithms divide the operation into rounds and periodically rotate the roles of CHs in the network. However, there is one more question. Energy consumption among cluster heads is imbalanced due to the distance to the BS. In single-hop networks, CHs farther away from the BS need to transmit data to a long distance. Therefore, the energy of CHs farther away from the BS is larger than that of the CHs closer to the BS. In multihop networks, CHs closer to the BS undertake data forwarding, which means that the energy consumption of CHs closer to the BS is larger. The imbalanced energy consumption of nodes leads to a certain number of nodes dying prematurely, causing network partitions. This phenomenon is called "hot spot" problem or "energy hole" problem [2]. Researchers proved that unequal clustering algorithms can effectively mitigate the "energy hole" problem.

In this paper, an energy-aware distributed unequal clustering protocol in multihop heterogeneous wireless sensor networks is proposed. It elects cluster heads based on the ratio between the average residual energy of neighbor nodes and the residual energy of the node itself, and uses uneven competition ranges to construct clusters of uneven sizes. The cluster heads closer to the BS have smaller cluster sizes to preserve some energy for the intercluster data forwarding, which can balance the energy consumption among cluster heads and prolong the network lifetime.

The rest of the paper is organized as follows. Section 2 covers the related works in this area. Section 3 exhibits the network model and problem description. Section 4 presents the energy-aware distributed unequal clustering protocol in detail. Section 5 analyzes several properties of the algorithm. In Section 6 we describe our simulation efforts and the analysis of results. Finally, Section 7 concludes the paper.

2. Related Work

LEACH [3] is a typical clustering protocol proposed for periodical data gathering applications in wireless sensor networks. In LEACH, each node independently elects itself as a cluster head with a probability. Cluster heads receive and aggregate data from cluster members and send the aggregated data to the BS by single-hop communication. In order to balance the energy consumption, the role of cluster head is periodically rotated among the nodes. LEACH protocol is simple and does not require a large communication overhead. However, the performance of LEACH in heterogeneous networks is not very well, because it elects cluster heads without considering the residual energy of nodes. To solve this problem, researchers improved LEACH and proposed some new algorithms such as centralized algorithm LEACH-C [4], multi-level clustering algorithm EEMLC [5], algorithm based on heterogeneous networks EEHC [6], and algorithm based on multihop communication LEACH-M [7].

EADEEG [8] is a novel distributed clustering algorithm. It elects cluster heads based on the ratio between the average residual energy of neighbor nodes and the residual energy of the node itself, which can achieve a good cluster heads distribution and prolong the network lifetime. There are still two points needed to be improved in EADEEG. (1) In some cases, there are "isolate points" in EADEEG. (2) It chooses $2r_c$ as intercluster communication radius, which cannot ensure the connectivity among cluster heads. For these problems, a distributed energy saving clustering algorithm called BPEC is proposed in [1]. BPEC elects cluster heads by the ratio between the average residual energy of neighbor nodes and the residual energy of the node itself as its primary probability and the node's degree as its subsidiary probability. It is proved that BPEC can avoid the "isolate points" problem in EADEEG and can keep all the cluster heads connected.

In [9, 10], energy-efficient distributed clustering algorithms HEED and EEDC are proposed. They choose sensor nodes to be cluster heads iteratively.

However, none of these algorithms mentioned above takes the solution of "energy hole" problem into account. To solve this problem, Soro and Heinzelman proposed an unequal clustering algorithm in [11]. The network field is divided into cirques. Clusters in the same cirque have the same size while clusters in the different cirques have different sizes. Deploying some high-energy nodes to take on the cluster head role to control network operation ensures that energy dissipation of these cluster heads is balanced. The algorithm can effectively prolong network lifetime. However, some high-energy nodes are needed to play as cluster heads, so the positions of cluster heads must be calculated previously.

EEUC [12] is a distributed unequal clustering algorithm which elects cluster heads based on the residual energy of nodes. Each node becomes a tentative cluster head with a probability T. Tentative cluster heads use uneven competition ranges to construct clusters of uneven sizes. The clusters closer to the BS have smaller sizes than those farther away from it, thus the cluster heads closer to the BS can preserve some energy for the intercluster data forwarding. In this way, the energy consumption among cluster heads is balanced. As the quality of the generated cluster heads is affected by T, there are "isolate points" in EEUC in some case of T.

3. Network Model and Problem Description

3.1. Network Model. To simplify the network model, we adopt a few reasonable assumptions as follows.

(1) There are N sensor nodes that are distributed randomly in an $M \times M$ square field.

(2) All the nodes and the BS are stationary after deployment.

(3) All the sensor nodes can be heterogeneous.

(4) All the sensor nodes are location-unaware.

(5) All the nodes can use power control to vary the amount of transmit power. The generated cluster heads can communicate with the BS directly.

(6) The BS is out of the sensor field. It has a sufficient energy resource and the location of the BS is known by each node.

(7) Each node has an identity (id).

The energy model is adopted from [3].

To transmit an l-bit data to a distance d, the radio expends energy:

$$E_{T_x}(l,d) = \begin{cases} l \times E_{\text{elec}} + l \times \epsilon_{\text{fs}} \times d^2, & d < d_0, \\ l \times E_{\text{elec}} + l \times \epsilon_{\text{mp}} \times d^4, & d \geq d_0, \end{cases} \tag{1}$$

where d is the transmission distance. E_{elec}, ϵ_{fs} and ϵ_{mp} are parameters of the transmission/reception circuitry. Depending on the distance between the transmitter and receiver, free space (ϵ_{fs}) or multipath fading (ϵ_{mp}) channel models is used.

While receiving an l-bit data, the radio expends energy:

$$E_{R_x}(l) = l \times E_{\text{elec}}. \tag{2}$$

Additionally, we assume that the energy for data sensing is E_{sen}, and the energy for data aggregation is E_{com}.

3.2. Problem Description. The properties of an effective clustering algorithm are usually summarized as follows.

(1) It is a distributed algorithm.

(2) It can evenly generate cluster heads to balance the energy consumption among nodes.

(3) It has acceptable algorithm overhead.

(4) It has the ability to handle heterogeneous node issues [8].

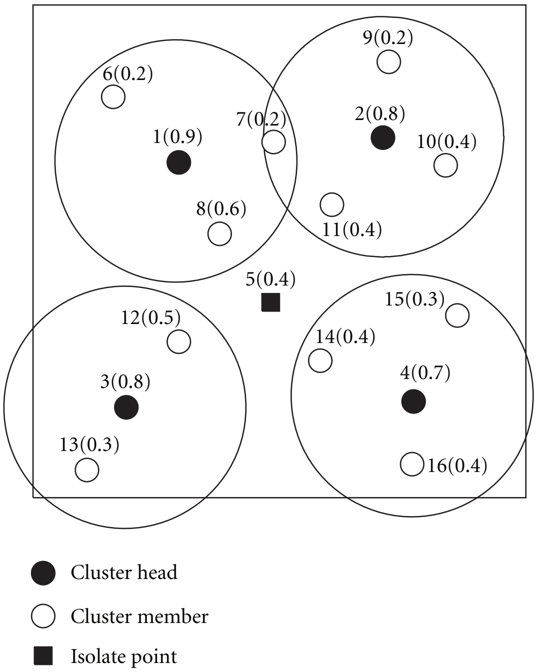

Figure 1: The "isolate point" of EADEEG algorithm.

By analyzing these properties above, two points which are also necessary for an effective clustering algorithm are missed. As we mentioned above, energy hole problem leads to a certain number of nodes dying prematurely, reducing the network lifetime. Therefore, an effective clustering algorithm should have a fifth property:

(5) it has the ability to solve "energy hole" problem.

Moreover, as mentioned above, in some case there are "isolate points" in EADEEG and EEUC protocol. For example, as shown in Figure 1: since the residual energy of node 5 is lower than the average energy of its neighbor nodes 8, 11, 12, and 14, its waiting time t for broadcasting the *Head_Msg* is longer than T, in other word, it can not compete for cluster head before T, and it also can not receive any *Head_Msg*s from the neighbor cluster heads 8, 11, 12, and 14, thus node 5 does not belong to any cluster, it becomes the "isolate point" and the area around it can not be monitored. For this problem, another property is absolutely necessary to be added:

(6) there exist no "isolate points" in the network.

In this paper, a clustering algorithm EADUC satisfying the six properties is proposed. The details of EADUC are described in the next section.

4. EADUC Details

The whole operation is divided into rounds, where each round contents a setup phase and a data transmission phase just like LEACH. To form a clustering topology, the setup phase is divided into three subphases: neighbor node information collection phase, cluster head competition phase, and cluster formation phase; in the data transmission phase, cluster members collect local data from the environment, and send the collected data to the cluster heads, cluster heads receive and aggregate the data from their cluster members, and then send the aggregated data to the next hop nodes based on the routing tree we have constructed. Data transmission phase should be longer than setup phase to save the overhead of the algorithm and prolong the lifetime of the network. The state message of each node is listed in Table 1. Several control messages are needed and the description of these messages are shown in Table 2.

Table 1: Description of node state messages.

State	Description
Candidate	Candidate node
Head	Head node
Plain	Plain node

Table 2: Description of control messages.

Message	Description
Node_Msg	Tuple (selfid, selfenergy)
Head_Msg	Tuple (selfid)
Join_Msg	Tuple (selfid, headid)
Schedule_Msg	Tuple (schedule, order)
Route_Msg	Tuple (selfid, selfenergy)

4.1. Cluster Setup Phase

In the Network Deployment Phase. The BS broadcasts a signal at a certain power level. Each node can compute its approximate distance to the BS based on the received signal strength. There are three subphase in cluster setup phases: neighbor node information collection phase, whose duration is T_1; cluster head competition phase, whose duration is T_2; cluster formation phase, whose duration is T_3.

In Neighbor Node Information Collection Phase. Each node broadcasts a *Node_Msg* within radio r with the following two values: the node *id* and its residual energy E_r. At the same time, it receives the *Node_Msg*s from its neighbor nodes, according to which, each node calculates the average residual energy of its neighbor nodes E_a by using the following formula:

$$E_a = \frac{1}{d}\sum_{i=1}^{d} s_i \cdot E_r, \tag{3}$$

where s_i denotes one of the neighbor nodes, $s_i \cdot E_r$ denotes the residual energy of s_i, and d is the number of neighbor nodes.

For each node, we give the following formula to calculate its waiting time t for broadcasting *Head_Msg* message;

$$t = \begin{cases} \dfrac{E_a}{E_r} T_2 V_r, & E_r \geq E_a, \\ T_2 V_r, & E_r < E_a, \end{cases} \tag{4}$$

where E_r is the residual energy of the node, V_r is a real value randomly distributed in $[0.9, 1]$ which is introduced to reduce the probability that two nodes send *Head_Msg*s at the same time.

After T_1 expires, it starts *cluster head competition phase.* For any node s_i, in this phase, if it receives no *Head_Msg* when time t_i expires, it broadcasts the *Head_Msg* within radio range R_{C_i} to advertise that it will be a cluster head. Otherwise, it gives up the competition.

In order to generate unequal clusters, each node needs to calculate their own competition radius R_C. The formula of R_C in [12] is

$$R_C = \left[1 - c\frac{d_{\max} - d(s_i, \mathrm{DS})}{d_{\max} - d_{\min}}\right] R_C^0, \tag{5}$$

where $d_{\max}$ and $d_{\min}$ are the maximum and minimum distance from the nodes in the network to the BS, $d(s_i, \mathrm{DS})$ is the distance from node s_i to the BS, c is a weighted factor whose value is in $[0, 1]$, and R_C^0 is the maximum value of competition radius.

In heterogeneous networks, nodes have heterogeneous initial energy. In the case that each node has the same energy consumption, the nodes with low initial energy will die prematurely, reducing the network lifetime. In order to take full advantage of the high-energy nodes, the high-energy nodes should take more task. Therefore, considering the distance between nodes and the BS and the residual energy of nodes, we give the formula of R_C:

$$R_C = \left[1 - \alpha\frac{d_{\max} - d(s_i, \mathrm{BS})}{d_{\max} - d_{\min}} - \beta\left(1 - \frac{E_r}{E_{\max}}\right)\right] R_{\max}, \tag{6}$$

where $d(s_i, \mathrm{BS})$ is the distance from node s_i to the BS, α and β is the weighted factors in $[0, 1]$, E_r is the residual energy of node s_i, and $R_{\max}$ is the maximum value of competition radius. From the above formula we can see that the competition radius of the node is determined by $d(s_i, \mathrm{BS})$ and E_r. Large $d(s_i, \mathrm{BS})$ and E_r generates a large R_C, which means that cluster heads with higher residual energy and farther away from the BS will control larger cluster areas. On one hand, cluster heads closer to the BS could save energy for data forwarding. On the other hand, cluster heads with lower residual energy control smaller clusters in order to avoid their premature death and prolong the network lifetime.

Cluster Formation Phase. It is the last subphase of cluster setup phase. Each noncluster-head node chooses the nearest cluster head and sends the *Join_Msg* which contains the *id* and residual energy of this node. Each cluster head creates a node schedule list according to the received *Join_Msg*s, and sends the schedule list to the cluster members by broadcasting *Schedule_Msg*. Each cluster is composed of the nodes in the *Voronoi* cell around the cluster head. The following pseudocode gives the details of the whole cluster setup phase.

4.2. Data Transmission Phase

4.2.1. Intra-Cluster Communication. Cluster members sense and collect local data from the environment, and send the collected data to the cluster heads. This process is called intra-cluster communication. For simplification, cluster members communicate with cluster heads directly, just like LEACH.

4.2.2. Inter-Cluster Communication. Cluster heads receive and aggregate the data from their cluster members, and then send the aggregated data to the next hop nodes. Here, we introduce a threshold distance *DIST_TH*. If the distance from cluster head s_i to the BS $d(s_i, \mathrm{BS})$ is less than *DIST_TH*, s_i communicates with the BS directly. Otherwise, s_i selects some nodes from its neighbor nodes to construct the candidate forwarding nodes set, and then it select one node from the set as the finally forwarding node according to a parameter "E_{relay}". Here we give the formula to compute the energy consumption E_{relay} when cluster head s_i chooses s_j as its next hops;

$$E_{\mathrm{relay}} = d^2\left(s_i, s_j\right) + d^2\left(s_j, \mathrm{BS}\right). \tag{7}$$

So s_i will select the node with the highest residual energy from the two nodes with the smallest "E_{relay}" in the candidate forwarding nodes set. We will set a proper *DIST_TH* to guarantee any cluster heads can find its next hop. After this phase, all the cluster heads construct a tree with the BS being the root. The data is forwarded on the edges of the tree to the BS.

5. Protocol Analysis

Theorem 1. *There is at most one cluster head in the range of any CH with covered radius R_C.*

Proof. As we state previously, V_r in formula (4) ensures that different nodes have different waiting time. We assume that node s_i has a shorter waiting time and broadcasts the *Head_Msg* within radio range R_{Ci}. Thus, all the nodes within this range give up the competition and become CMs. Therefore, there is no more than one CH in the range of any CH with covered radius R_C. □

Theorem 2. *The cluster head set generated by EADUC can cover all the network nodes.*

Proof. (1) When $E_r \geq E_a$, we have $t = (E_a/E_r)T_2V_r$ according to formula (4). Thus, we can obtain $t \leq T_2$ since $V_r \leq 1$.

(2) When $E_r < E_a$, we have $t = T_2V_r$ according to formula (4). Thus $t \leq T_2$ since $V_r \leq 1$.

Therefore, we conclude that the waiting time of any node is smaller than T_2. Thus, any expected cluster head will broadcast a *Head_Msg* and become a cluster head before T_2 expired, which can avoid the generation of isolate points. □

Theorem 3. *The overhead complexity of control messages in the network is $O(N)$.*

Proof. At the beginning of each round, each node broadcasts a *Node_Msg*. Thus, there are N *Node_Msg*s in the whole network. In each round, each cluster member broadcasts a *Join_Msg* while each cluster head broadcasts a *head_Msg*,

```
begin (cluster setup algorithm)
    state ← Candidate
    Broadcast Node_Msg
    while ($T_1$ has not expired) do
        Receive Node_Msg
        Update neighborhood table NT[ ]
    end
    $t$ ← broadcast delay time for competing a cluster head
    while ($T_2$ has not expired) do
        if CurrentTime < $t$ do
            if receive a Head_Msg from a neighbor NT[$i$] do
                state ← Plain
                NT[$i$].state ← Head
            else
                Continue
            end
        else if state = Candidate do
            state ← Head
            $R_c$ ← competing radius
            Broadcast Head_Msg
        end
    end
    while ($T_3$ has not expired) do
        if state = Plain&& has not sent Join_Msg do
            Send Join_Msg to the nearest cluster head
        else if state = Head do
            Receive Join_Msg from its neighbor Plain nodes
        end
    end
    if state = Head do
        Broadcast Schedule_Msg
    end
end
```

Algorithm 1

a *Schedule_Msg*, and a *Route_Msg*. Suppose the number of generated cluster head is k. The total number of *Join_Msg* is $N - k$, and the numbers of *head_Msg*, *Schedule_Msg*, and *Route_Msg* message are all k. Thus, the total number of control messages in the whole network is $N+(N-k)+k+k+k = 2N+2k$. Therefore, the overhead complexity of control messages in the network is $O(N)$. ☐

Theorem 4. *EADUC has a processing time complexity of* $O(1)$.

Proof. EADUC adopts a distributed clustering strategy. Thus, the time complexity of the entire network is equal to that of a single node $O(1)$. In other words, the time complexity is a constant and has nothing to do with the network size. ☐

From the above analysis, we can summarize the properties of EADUC as follows.

(1) It elects cluster heads based on the ratio between the average residual energy of neighbor nodes and the residual energy of the node itself. Nodes have relatively higher energy are elected, which is helpful in prolonging the network lifetime [8].

(2) There are no "isolate points" in EADUC, which is proved in Theorem 2.

(3) The competition radius R_C takes into account both the distance to the BS and the residual energy of nodes. Unequal clusters generated by using R_C will be more effective in prolonging the network lifetime.

(4) From Theorems 1 and 2, there is one and only one cluster head in the range of any cluster head with covered radius R_C. Here, we can draw the conclusion that, EADUC satisfies the six properties mentioned earlier.

There are three parameters in EADUC: α, β, and $R_{\max}$. α and β determine the influence of the residual energy and the distances to the BS of nodes on cluster sizes. $R_{\max}$ is the maximum value of competition radius, which determines the number of generated cluster heads binding with α and β. We will discuss this issue further in the next section.

6. Simulations

The simulations were performed in NS-2, and two scenarios are chosen.

Table 3: Parameters of the simulation.

Parameter	Value
Sensor field	200 m × 200 m
BS location	(250, 100)
Number of nodes	100
Initial energy of nodes	2 J, 1–3 J
Data packet size	500 bytes
E_{elec}	50 nJ/bit
ϵ_{fs}	10 pJ/(bit · m^2)
ϵ_{mp}	0.0013 pJ/(bit · m^4)
E_{sen}	0 J/bit
E_{com}	5 nJ/(bit · signal)
$R_{\max}$	10–200 m

Homogeneous Scenario. The initial energy of each node in the network is 2 J.

Heterogeneous Scenario. The initial energy of nodes in the network is uniformly distributed over the interval 1–3 J.

The parameters of simulations are listed in Table 3.

6.1. Cluster Head Distribution. We run EADUC in these scenarios, respectively. Figure 2 shows the relationship between the number of cluster heads and $R_{\max}$ when α and β choose different values. As shown in Figure 2, the curve of $\alpha = 1$, $\beta = 1$ is higher than that of $\alpha = 0.5$, $\beta = 0.5$. Moreover, the curve of $\alpha = 0$, $\beta = 0$ is the lowest. The reason is that, when $R_{\max}$ is fixed, the increase of α and β leads to the decrease of cluster radius. Furthermore, the number of cluster heads decreases with the increase of the radius, which means the number of generated cluster heads is determined by $R_{\max}$, α, and β.

We set $\alpha = 0.5$, $\beta = 0.5$, and $R_{\max} = 50$ and run EADUC. Figure 3 exhibits the distribution of the number of cluster heads in a certain number of randomly selected experiments. As shown in the figure, the number of cluster heads in EADUC is concentrated in a small range, which means that EADUC has a high stability and reliability.

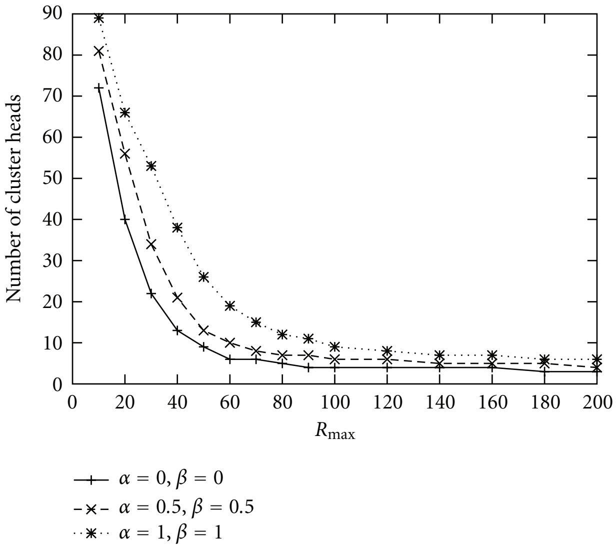

Figure 2: Number of cluster heads generated in the network.

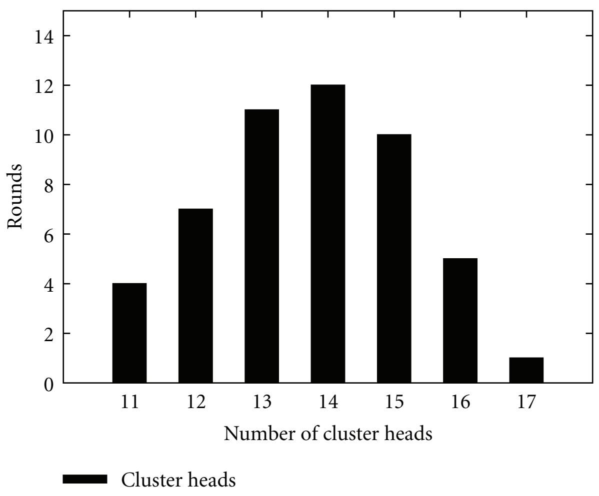

Figure 3: Distribution of the number of cluster heads.

6.2. Network Lifetime. On network lifetime, there is no clear definition. According to the definitions given in [13], the lifetime of a WSN can be quantified using the following three kinds of metrics.

(1) The time from the deployment of the network to the death of the first node (first node dies, FND).

(2) The time when a certain percent of nodes alive (percentage nodes alive, PNA).

(3) The time when all the nodes are dead in the network (last node dies, LND).

Here, we define the network lifetime as percentage node alive (PNA). That is, the network lifetime is defined as the time when 90 percent of nodes are alive. We set $\alpha = 0.5$, $\beta = 0.5$, and run EADUC. Figure 4 shows the the network lifetime of EADUC when $R_{\max}$ is 10–200. From Figure 4, we can see that EADUC gets the maximal network lifetime when $R_{\max}$ is 120–160.

Networks are not always homogeneous. Therefore, clustering algorithms should have the ability to handle heterogeneous nodes issues. We run EADUC in homogeneous and heterogeneous scenarios. When $\alpha = 0.5$, $\beta = 0.5$, and $R_{\max} = 150$, the network lifetime of EADUC in these scenarios are shown in Figure 5.

From Figure 5, we can see that the network lifetime in heterogeneous scenario is slightly longer than that in homogeneous scenario. The reason is that EADUC elects cluster heads considering the residual energy of nodes, which can take advantage of the high-energy nodes in heterogeneous scenario and prolong the network lifetime. As a comparison experiment, we set $k = 5$ and run LEACH in the same scenarios. Figure 6 shows the comparison of network lifetime of LEACH in different scenarios.

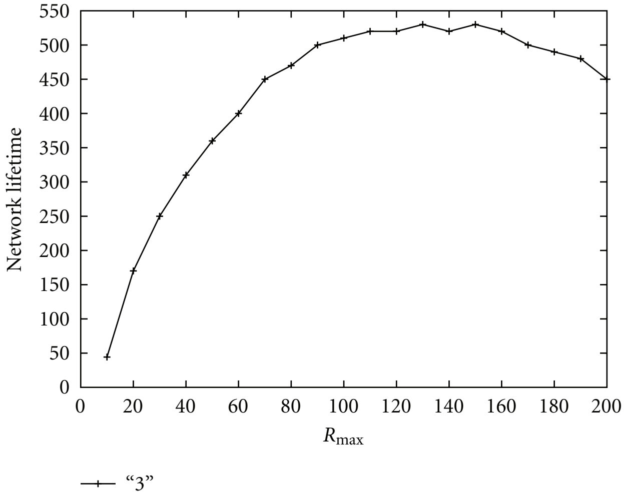

Figure 4: Network lifetime with different $R_{\max}$.

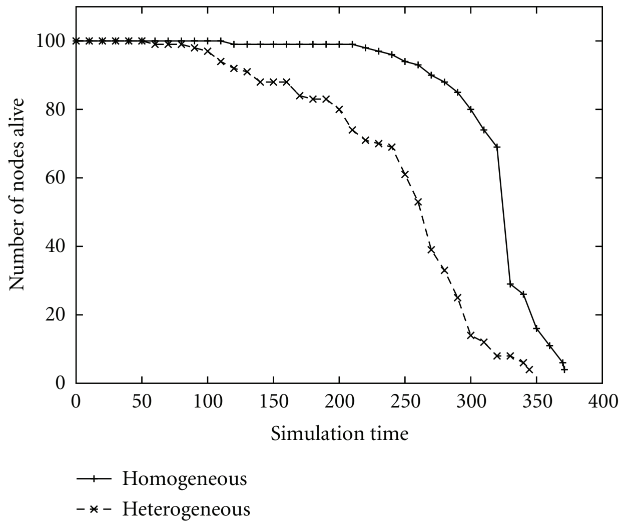

Figure 6: Network lifetime of LEACH.

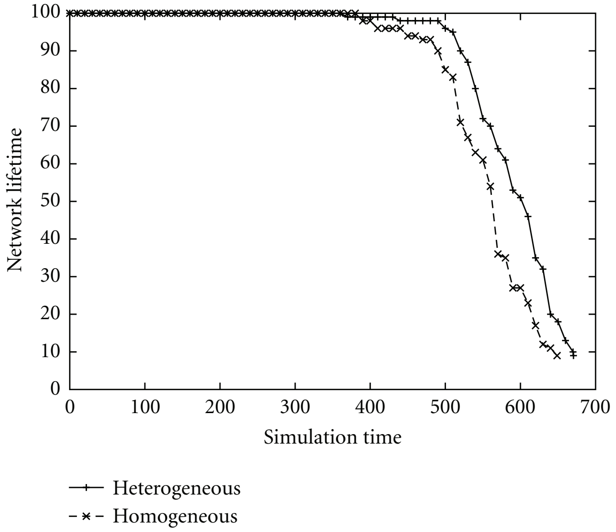

Figure 5: Network lifetime in different scenarios.

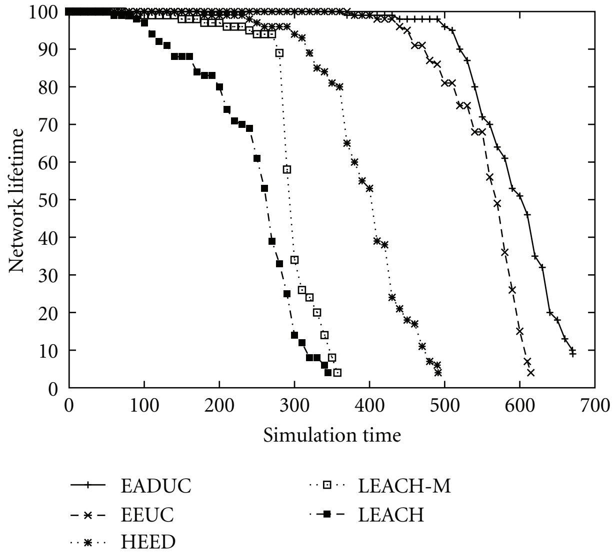

Figure 7: Network lifetime.

In Figure 6, the network lifetime in heterogeneous scenario is shorter. Since nodes in LEACH elect themselves by a probability without considering the residual energy, low-energy nodes may die prematurely and the network lifetime is reduced.

In heterogeneous scenario, we run LEACH, LEACH-M, HEED, EEUC, and EADUC to compare their performance in network lifetime. As shown in Figure 7, EADUC and EEUC perform far better than LEACH, LEACH-M, and HEED in prolonging network lifetime attributed to the consideration of energy.

7. Conclusions

In this paper, we propose an energy-aware distributed unequal clustering protocol EADUC, which elects cluster heads based on the ratio between the average residual energy of neighbor nodes and the residual energy of the node itself. The unequal competition radius of nodes which is used to construct unequal clusters is determined by the distance to the BS and the residual energy. There are no isolate points in EADUC. Besides, the cluster heads closer to the BS have smaller cluster sizes to preserve some energy for the intercluster data forwarding, which can balance the energy consumption among cluster heads and prolong the network lifetime. Furthermore, EADUC satisfies the properties of an effective clustering algorithm and can prolong the lifetime of the network significantly.

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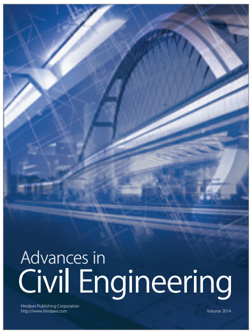
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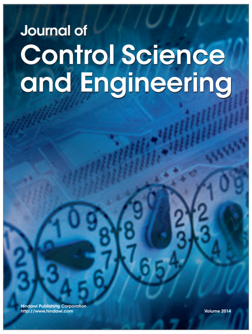
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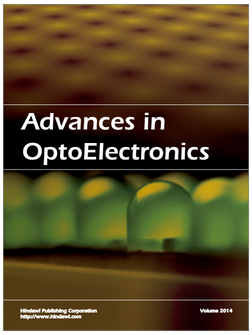
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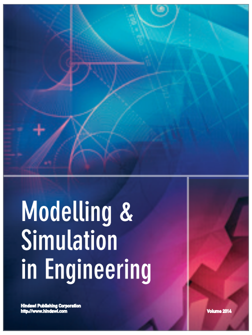
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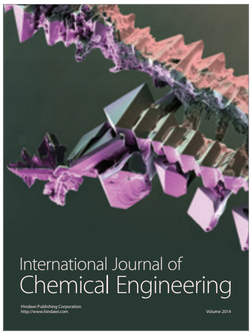
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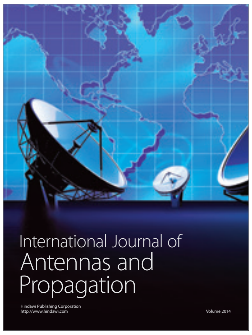
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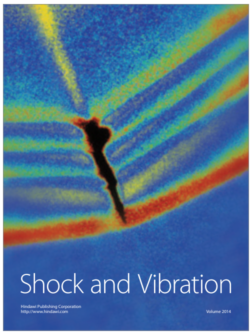
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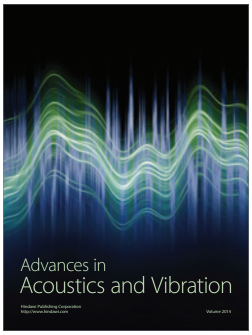
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