Design of a distributed energy-efficient clustering algorithm for heterogeneous wireless sensor networks

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Abstract

The clustering Algorithm is a kind of key technique used to reduce energy consumption. It can increase the scalability and lifetime of the network. Energy-efficient clustering protocols should be designed for the characteristic of heterogeneous wireless sensor networks. We propose and evaluate a new distributed energy-efficient clustering scheme for heterogeneous wireless sensor networks, which is called DEEC. In DEEC, the cluster-heads are elected by a probability based on the ratio between residual energy of each node and the average energy of the network. The epochs of being cluster-heads for nodes are different according to their initial and residual energy. The nodes with high initial and residual energy will have more chances to be the cluster-heads than the nodes with low energy. Finally, the simulation results show that DEEC achieves longer lifetime and more effective messages than current important clustering protocols in heterogeneous environments.
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1. Introduction

Recent technological advances in hardware have enabled the deployment of tiny, low-power sensors with limited on-board signal processing and wireless communication capacities. Wireless sensor networks (WSN) become increasingly useful in variety critical applications, such as environmental monitoring, smart offices, battlefield surveillance, and transportation traffic monitoring. In order to achieve high quality and fault-tolerant capability, a sensor network can be composed of hundreds or thousands of unattended sensor nodes, which are often randomly deployed inside the interested area or very close to it [1].

Since WSN is usually exposed to atrocious and dynamic environments, it is possible for the loss of connectivity of individual nodes. Conventional centralized algorithms need to operate with global knowledge of the whole net-

work, and an error in transmission or a failure of a critical node will potentially cause a serious protocol failure [2]. On the contrary, distributed algorithms are only executed locally within partial nodes, thus can prevent the failure caused by a single node. It is realized that localized algorithms are more scalable and robust than centralized algorithms. As each sensor node is tightly power-constrained and one-off, the lifetime of WSN is limited. In order to prolong the network lifetime, energy-efficient protocols should be designed for the characteristic of WSN. Efficiently organizing sensor nodes into clusters is useful in reducing energy consumption. Many energy-efficient routing protocols are designed based on the clustering structure [3,4]. The clustering technique can also used to perform data aggregation [5,6], which combines the data from source nodes into a small set of meaningful information. Under the condition of achieving sufficient data rate specified by applications, the fewer messages are transmitted, the more energy is saved. Localized algorithms can efficiently operate within clusters and need not to wait for control messages propagating across the whole network. Therefore localized

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algorithms bring better scalability to large networks than centralized algorithms, which are executed in global structure. Clustering technique can be extremely effective in broadcast and data query [7,8]. Cluster-heads will help to broadcast messages and collect interested data within their own clusters.

In this paper, we study the performance of the clustering algorithms in saving energy for heterogeneous wireless sensor networks. In the sensor network considered here, each node transmits sensing data to the base station through a cluster-head. The cluster-heads, which are elected periodically by certain clustering algorithms, aggregate the data of their cluster members and send it to the base station, from where the end-users can access the data. We assume that all the nodes of the sensor network are equipped with different amount of energy, which is a source of heterogeneity. It could be the result of reenergizing the sensor networks in order to extend the network lifetime [9]. The new nodes added to the networks will own more energy than the old ones. Even though the nodes are equipped with the same energy at the beginning, the networks cannot evolve equably for each node in expending energy, due to the radio communication characteristics, random events such as short-term link failures or morphological characteristics of the field [9]. Therefore, WSN are more possibly heterogeneous networks than homogeneous ones. The protocols should be fit for the characteristic of heterogeneous wireless sensor networks. Currently, most of the clustering algorithms, such as LEACH [10], PEGASIS [11], and HEED [12], all assume the sensor networks are homogeneous networks. These algorithms perform poorly in heterogeneous environments. The low-energy nodes will die more quickly than the high-energy ones, because these clustering algorithms are unable to treat each node discriminatorily in term of the energy discrepancy. In [9], SEP scheme is proposed for the two-level heterogeneous wireless sensor networks, which is composed of two types of nodes according to the initial energy. The advance nodes are equipped with more energy than the normal nodes at the beginning. SEP prolongs the stability period, which is defined as the time interval before the death of the first node. However, it is not fit for the widely used multi-level heterogeneous wireless sensor networks, which include more than two types of nodes.

In this paper, we propose and evaluate a new distributed energy-efficient clustering scheme for heterogeneous wireless sensor networks, which is called DEEC. Following the thoughts of LEACH, DEEC lets each node expend energy uniformly by rotating the cluster-head role among all nodes. In DEEC, the cluster-heads are elected by a probability based on the ratio between the residual energy of each node and the average energy of the network. The round number of the rotating epoch for each node is different according to its initial and residual energy, i.e., DEEC adapt the rotating epoch of each node to its energy. The nodes with high initial and residual energy will have more chances to be the cluster-heads than the low-energy nodes.

Thus DEEC can prolong the network lifetime, especially the stability period, by heterogeneous-aware clustering algorithm. Simulations show that DEEC achieves longer network lifetime and more effective messages than other classical clustering algorithms in two-level heterogeneous environments. Moreover, DEEC is also fit for the multi-level heterogeneous networks and performs well, while SEP only operates under the two-level heterogeneous networks.

The remainder of the paper is organized as follows. In Section 2, we briefly review related work. Section 3 describes the heterogeneous network model. Section 4 presents the detail of DEEC algorithm and argues the choice of its parameters. Section 5 shows the performance of DEEC by simulations and compares it with LEACH and SEP. Finally, Section 6 gives concluding remarks.

2. Related work

There are two kinds of clustering schemes. The clustering algorithms applied in homogeneous networks are called homogeneous schemes, and the clustering algorithms applied in heterogeneous networks are referred to as heterogeneous clustering schemes. It is difficult to devise an energy-efficient heterogeneous clustering scheme due to the complicated energy configure and network operation. Thus most of the current clustering algorithms are homogeneous schemes, such as LEACH [10], PEGASIS [11], and HEED [12].

The cluster-heads have to spend extra energy for aggregating data and performing long-range transmission to the distant base station. The LEACH protocol selects cluster-heads periodically and drains energy uniformly by role rotation. Each node decides itself whether or not a cluster-head distributed by a probability. Under the homogeneous network, LEACH performs well, but its performance become badly in the heterogeneous network as shown by [9]. In PEGASIS, nodes will be organized to form a chain, which can be computed by each node or by the base station. The requirement of global knowledge of the network topology makes this method difficult to implement. HEED is a distributed clustering algorithm, which selects the cluster-heads stochastically. The election probability of each node is correlative to the residual energy. But in heterogeneous environments, the low-energy nodes could own larger election probability than the high-energy nodes in HEED. The heterogeneity of nodes in terms of their energy is considered in our DEEC, which is designed for heterogeneous networks. At the same time, DEEC keeps the merits of the distributed clustering algorithms.

Estrin et al. [8] discuss a hierarchical clustering method with emphasis on localized behavior and the need for asymmetric communication and energy conservation in sensor networks. They suggest using the remaining energy level of a node for cluster-head selection. In [10], it is proposed to elect the cluster-heads according to the energy left in each node. We call this clustering protocol LEACH-E.

The drawback of LEACH-E is that it requires the assistance of routing protocol, which should allow each node to know the total energy of network. SEP [9] is developed for the two-level heterogeneous networks, which include two types of nodes according to the initial energy, i.e., the advance nodes and normal nodes. The rotating epoch and election probability is directly correlated with the initial energy of nodes. SEP performs poorly in multi-level heterogeneous networks and when heterogeneity is a result of operation of the sensor network. Our DEEC protocol assigns different epoch of being a cluster-head to each node according to the initial and residual energy. In DEEC, a particular algorithm is used to estimate the network lifetime, thus avoiding the need of assistance by routing protocol.

Many LEACH-like algorithms are proposed to improve the performance of LEACH recently. In [13], the authors have studied multi-hop clustered networks, and use a randomized clustering scheme to organize the sensors. They provide methods to compute the optimal values of the algorithm parameters. Mhatre and Rosenberg [14] study the case of multi-hop routing within each cluster, which is called M-LEACH. In M-LEACH, only powerful nodes can become the cluster-heads. EECS [15] elects the cluster-heads with more residual energy through local radio communication. In cluster formation phase, EECS considers the tradeoff of energy expenditure between nodes to the cluster-heads and the cluster-heads to the base station. But on the other hand, it increases the requirement of global knowledge about the distances between the cluster-heads and the base station. In LEACH-B [16], a new adaptive strategy is proposed to choose cluster-heads and to vary their election frequency according to the dissipated energy. The simulation results show that the improvement obtained by LEACH-B is limited.

3. Heterogeneous network model

In this section, we describe the network model. Assume that there are N sensor nodes, which are uniformly dispersed within a $M \times M$ square region (Fig. 1). The nodes always have data to transmit to a base station, which is often far from the sensing area. This kind of sensor network can be used to track the military object or monitor remote environment. Without loss of generality, we assume that the base station is located at the center of the square region. The network is organized into a clustering hierarchy, and the cluster-heads execute fusion function to reduce correlated data produced by the sensor nodes within the clusters. The cluster-heads transmit the aggregated data to the base station directly. To avoid the frequent change of the topology, we assume that the nodes are micro mobile or stationary as supposed in [10].

In the two-level heterogeneous networks, there are two types of sensor nodes, i.e., the advanced nodes and normal nodes. Note E_0 the initial energy of the normal nodes, and m the fraction of the advanced nodes, which own a times more energy than the normal ones. Thus there are mN advanced nodes equipped with initial energy of $E_0(1 + a)$, and $(1 - m)N$ normal nodes equipped with initial energy of E_0. The total initial energy of the two-level heterogeneous networks is given by:

$$E_{\text{total}} = N(1 - m)E_0 + NmE_0(1 + a) = NE_0(1 + am). \quad (1)$$

Therefore, the two-level heterogeneous networks have am times more energy and virtually am more nodes.

We also consider the multi-level heterogeneous networks. For multi-level heterogeneous networks, initial energy of sensor nodes is randomly distributed over the close set $[E_0, E_0(1 + a_{\max})]$, where E_0 is the lower bound and $a_{\max}$ determine the value of the maximal energy. Initially, the node s_i is equipped with initial energy of $E_0(1 + a_i)$, which is a_i times more energy than the lower bound E_0. The total initial energy of the multi-level heterogeneous networks is given by:

$$E_{\text{total}} = \sum_{i=1}^{N} E_0(1 + a_i) = E_0 \left(N + \sum_{i=1}^{N} a_i \right). \quad (2)$$

As in two-level heterogeneous networks, the clustering algorithm should consider the discrepancy of initial energy in multi-level heterogeneous networks.
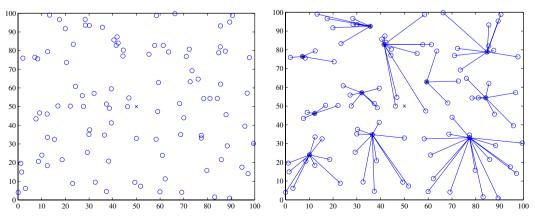

Fig. 1. (Left) 100-node random network; (right) dynamic cluster structure by DEEC algorithm.

4. The DEEC protocol

In this section, we present the detail of our DEEC protocol. DEEC uses the initial and residual energy level of the nodes to select the cluster-heads. To avoid that each node needs to know the global knowledge of the networks, DEEC estimates the ideal value of network life-time, which is use to compute the reference energy that each node should expend during a round.

4.1. Cluster-head selection algorithm based on residual energy

Let n_i denote the number of rounds to be a cluster-head for the node s_i, and we refer to it as the rotating epoch. In homogenous networks, to guarantee that there are average $p_{\text{opt}}N$ cluster-heads every round, LEACH let each node s_i $(i = 1, 2, \ldots, N)$ becomes a cluster-head once every $n_i = 1/p_{\text{opt}}$ rounds. Note that all the nodes cannot own the same residual energy when the network evolves. If the rotating epoch n_i is the same for all the nodes as proposed in LEACH, the energy will be not well distributed and the low-energy nodes will die more quickly than the high-energy nodes. In our DEEC protocol, we choose different n_i based on the residual energy $E_i(r)$ of node s_i at round r.

Let $p_i = 1/n_i$, which can be also regarded as average probability to be a cluster-head during n_i rounds. When nodes have the same amount of energy at each epoch, choosing the average probability p_i to be p_{opt} can ensure that there are $p_{\text{opt}}N$ cluster-heads every round and all nodes die approximately at the same time. If nodes have different amounts of energy, p_i of the nodes with more energy should be larger than p_{opt}. Let $\overline{E}(r)$ denote the average energy at round r of the network, which can be obtained by

$$\overline{E}(r) = \frac{1}{N} \sum_{i=1}^{N} E_i(r). \tag{3}$$

To compute $\overline{E}(r)$ by Eq. (3), each node should have the knowledge of the total energy of all nodes in the network. We will give an estimate of $\overline{E}(r)$ in the latter subsection of this section. Using $\overline{E}(r)$ to be the reference energy, we have

$$p_i = p_{\text{opt}} \left[1 - \frac{\overline{E}(r) - E_i(r)}{\overline{E}(r)} \right] = p_{\text{opt}} \frac{E_i(r)}{\overline{E}(r)}. \tag{4}$$

This guarantees that the average total number of cluster-heads per round per epoch is equal to:

$$\sum_{i=1}^{N} p_i = \sum_{i=1}^{N} p_{\text{opt}} \frac{E_i(r)}{\overline{E}(r)} = p_{\text{opt}} \sum_{i=1}^{N} \frac{E_i(r)}{\overline{E}(r)} = N p_{\text{opt}}. \tag{5}$$

It is the optimal cluster-head number we want to achieve. We get the probability threshold, that each node s_i use to determine whether itself to become a cluster-head in each round, as follow

$$T(s_i) = \begin{cases} \dfrac{p_i}{1 - p_i(r \bmod \frac{1}{p_i})} & \text{if } s_i \in G \\ 0 & \text{otherwise} \end{cases}, \tag{6}$$

where G is the set of nodes that are eligible to be cluster-heads at round r. If node s_i has not been a cluster-head during the most recent n_i rounds, we have $s_i \in G$. In each round r, when node s_i finds it is eligible to be a cluster-head, it will choose a random number between 0 and 1. If the number is less than threshold $T(s_i)$, the node s_i becomes a cluster-head during the current round.

Note the epoch n_i is the inverse of p_i. From Eq. (4), n_i is chosen based on the residual energy $E_i(r)$ at round r of node s_i as follow

$$n_i = \frac{1}{p_i} = \frac{\overline{E}(r)}{p_{\text{opt}} E_i(r)} = n_{\text{opt}} \frac{\overline{E}(r)}{E_i(r)}, \tag{7}$$

where $n_{\text{opt}} = 1/p_{\text{opt}}$ denote the reference epoch to be a cluster-head. Eq. (7) shows that the rotating epoch n_i of each node fluctuates around the reference epoch. The nodes with high residual energy take more turns to be the cluster-heads than lower ones.

4.2. Coping with heterogeneous nodes

From Eq. (4), we can see that p_{opt} is the reference value of the average probability p_i, which determine the rotating epoch n_i and threshold $T(s_i)$ of node s_i. In homogenous networks, all the nodes are equipped with the same initial energy, thus nodes use the same value p_{opt} to be the reference point of p_i. When the networks are heterogeneous, the reference value of each node should be different according to the initial energy. In the two-level heterogeneous networks, we replace the reference value p_{opt} with the weighted probabilities given in Eq. (8) for normal and advanced nodes [9].

$$p_{\text{adv}} = \frac{p_{\text{opt}}}{1 + am}, \quad p_{\text{nrm}} = \frac{p_{\text{opt}}(1 + a)}{(1 + am)}. \tag{8}$$

Therefore, p_i is changed into

$$p_i = \begin{cases} \dfrac{p_{\text{opt}} E_i(r)}{(1 + am)\overline{E}(r)} & \text{if } s_i \text{ is the normal node} \\ \dfrac{p_{\text{opt}}(1 + a)E_i(r)}{(1 + am)\overline{E}(r)} & \text{if } s_i \text{ is the advanced node} \end{cases}. \tag{9}$$

Substituting Eq. (9) for p_i on (6), we can get the probability threshold used to elect the cluster-heads. Thus the threshold is correlated with the initial energy and residual energy of each node directly.

This model can be easily extended to multi-level heterogeneous networks. We use the weighted probability shown in Eq. (10)

$$p(s_i) = \frac{p_{\text{opt}} N (1 + a_i)}{\left(N + \sum_{i=1}^{N} a_i\right)} \tag{10}$$

to replace p_{opt} of Eq. (4) and obtain the p_i for heterogeneous nodes as

$$p_i = \frac{p_{\text{opt}}N(1+a)E_i(r)}{\left(N + \sum_{i=1}^{N} a_i\right)\overline{E}(r)}. \qquad (11)$$

From Eqs. (10) and (11), $I_i = (N + \sum_{i=1}^{N} a_i)/p_{\text{opt}}N(1+a_i)$ expresses the basic rotating epoch of node s_i, and we call it reference epoch. It is different for each node with different initial energy. Note $n_i = 1/p_i$, thus the rotating epoch n_i of each node fluctuates around its reference epoch I_i based on the residual energy $E_i(r)$. If $E_i(r) > \overline{E}(r)$, we have $n_i < I_i$, and vice versa. This means that the nodes with more energy will have more chances to be the cluster-heads than the nodes with less energy. Thus the energy of network is well distributed in the evolving process.

4.3. Estimating average energy of networks

From Eqs. (9) and (11), the average energy $\overline{E}(r)$ is needed to compute the average probability p_i. It is difficulty to realize such scheme, which presumes that each node knows the average energy of the network. We will estimate $\overline{E}(r)$ in this paragraph.

As shown in Eqs. (4) and (7), the average energy $\overline{E}(r)$ is just used to be the reference energy for each node. It is the ideal energy that each node should own in current round to keep the network alive to the greatest extent. In such ideal situation, the energy of the network and nodes are uniformly distributed, and all the nodes die at the same time. Thus we can estimate the average energy $\overline{E}(r)$ of rth round as follow

$$\overline{E}(r) = \frac{1}{N} E_{\text{total}}\left(1 - \frac{r}{R}\right), \qquad (12)$$

where R denote the total rounds of the network lifetime. It means that every node consumes the same amount of energy in each round, which is also the target that energy-efficient algorithms should try to achieve. From Eq. (7), considering $\overline{E}(r)$ as the standard energy, DEEC controls the rotating epoch n_i of each node according to its current energy, thus controls the energy expenditure of each round. As a result, the actual energy of each node will fluctuate around the reference energy $\overline{E}(r)$. Therefore, DEEC guarantees that all the nodes die at almost the same time. This can be shown by the simulation results of Section 5. In fact, it is the main idea of DEEC to control the energy expenditure of nodes by means of adaptive approach.

To compute $\overline{E}(r)$ by Eq. (12), the network lifetime R is needed, which is also the value in an ideal state. Assuming that all the nodes die at the same time, R is the total of rounds from the network begins to all the nodes die. Let E_{round} denote the energy consumed by the network in each round. R can be approximated as follow

$$R = \frac{E_{\text{total}}}{E_{\text{round}}}. \qquad (13)$$

In the analysis, we use the same energy model as proposed in [13]. In the process of transmitting an l-bit message over a distance d, the energy expended by the radio is given by:

$$E_{Tx}(l,d) = \begin{cases} lE_{\text{elec}} + l\varepsilon_{fs}d^2, & d < d_0, \\ lE_{\text{elec}} + l\varepsilon_{mp}d^4, & d \geqslant d_0, \end{cases} \qquad (14)$$

where E_{elec} is the energy dissipated per bit to run the transmitter or the receiver circuit, and $\varepsilon_{fs}d^2$ or $\varepsilon_{mp}d^4$ is the amplifier energy that depend on the transmitter amplifier model.

We assume that the N nodes are distributed uniformly in an $M \times M$ region, and the base station is located in the center of the field for simplicity. Each non-cluster-head send L bits data to the cluster-head a round. Thus the total energy dissipated in the network during a round is equal to:

$$E_{\text{round}} = L(2NE_{\text{elec}} + NE_{\text{DA}} + k\varepsilon_{mp}d_{\text{toBS}}^4 + N\varepsilon_{fs}d_{\text{toCH}}^2), \qquad (15)$$

where k is the number of clusters, E_{DA} is the data aggregation cost expended in the cluster-heads, d_{toBS} is the average distance between the cluster-head and the base station, and d_{toCH} is the average distance between the cluster members and the cluster-head. Assuming that the nodes are uniformly distributed, we can get [13,10]:

$$d_{\text{toCH}} = \frac{M}{\sqrt{2\pi k}}, \quad d_{\text{toBS}} = 0.765\frac{M}{2}. \qquad (16)$$

By setting the derivative of E_{round} with respect to k to zero, we have the optimal number of clusters as

$$k_{\text{opt}} = \frac{\sqrt{N}}{\sqrt{2\pi}} \sqrt{\frac{\varepsilon_{fs}}{\varepsilon_{mp}}} \frac{M}{d_{\text{toBS}}^2}. \qquad (17)$$

Substituting Eqs. (16) and (17) into Eq. (15), we obtain the energy E_{round} dissipated during a round. Thus we can compute the lifetime R by (13).

In Fig. 2, using the parameters described in Table 1, we show the value of analytical lifetime when a and m are changed. Because of the affection of the energy heterogeneity, the nodes can't die exactly at the same time. If let R of Eq. (12) be the estimating value by Eq. (13), the reference energy $\overline{E}(r)$ will be too large in the end, as we can see from Eq. (12). That is to say that the network will not have a single cluster-head and a few nodes will not die finally. The simulation results have testified our inference (not shown due to room). Thus in the simulations of next section, we will let R be 1.5 times of the estimate value to avoid such situation. This also means that the premise of the energy of the network and nodes being uniformly distributed is
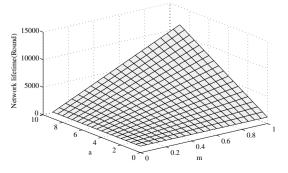

Fig. 2. Estimate of network lifetime.

Table 1
Parameters used in simulations

Parameter	Value
E_{elec}	5 nJ/bit
ε_{f_s}	10 pJ/ bit/m^2
ε_{mp}	0.0013 pJ/bit/m^4
E_0	0.5 J
E_{DA}	5 nJ/bit/message
d_0	70 m
Message size	4000 bits
p_{opt}	0.1

not prerequisite in practical operation of DEEC. The approximation of R is enough to get the reference energy $\overline{E}(r)$, thus DEEC can adapt well to heterogeneous environments.

Initially, all the nodes need to know the total energy and lifetime of the network, which can be determined a priori. In our DEEC protocol, the base station could broadcast the total energy E_{total} and estimate value R of lifetime to all nodes. When a new epoch begins, each node s_i will use this information to compute its average probability p_i by Eqs. (12) and (11). Node s_i will substitute p_i into Eq. (6), and get the election threshold $T(s_i)$, which is used to decide if node s_i should be a cluster-head in the current round.

5. Simulation results

In this section, we evaluate the performance of DEEC protocol using MATLAB. We consider a wireless sensor network with $N = 100$ nodes randomly distributed in a $100m \times 100m$ field. Without losing generalization, we assume the base station is in the center of the sensing region. To compare the performance of DEEC with other protocols, we ignore the effect caused by signal collision and interference in the wireless channel. The radio parameters used in our simulations are shown in Table 1. The protocols compared with DEEC include LEACH, SEP, and LEACH-E. In multi-level heterogeneous networks, the extended protocols of LEACH and SEP will be used. We will consider following scenarios and examine several performance measures.

5.1. Results under two-level heterogeneous networks

We first observe the performance of LEACH, SEP, LEACH-E, and DEEC under two kinds of two-level heterogeneous networks. Fig. 3 (left) shows the results of the case with $m = 0.2$ and $a = 3$, and Fig. 3 (right) shows the results of the case with $m = 0.1$ and $a = 5$. It is obvious that the stable time of DEEC is prolonged compared to that of SEP and LEACH-E. SEP performs better than LEACH, but we can see that the unstable region of SEP is also larger than our DEEC protocol. It is because the advanced nodes die more slowly than normal nodes in SEP.

We increase the fraction m of the advanced nodes from 0.1 to 0.9 and a from 0.5 to 5. Fig. 4 shows the number of round when the first node dies. We observe that LEACH takes few advantages from the increase of total energy caused by increasing of m and a. The stability period of LEACH keeps almost the same in the process.

For SEP, we get the same results as in [9]. The stability period of SEP is much longer than that of LEACH. Though LEACH-E is not realizable because each node should know the residual energy of other nodes, it performs well and achieves the stability period longer by about 10% than SEP (see Fig. 5). This is because LEACH-E is an energy-aware protocol, which elects cluster-head according to the residual energy of node. Being also an energy-aware protocol, DEEC outperforms other clustering protocols. Especially when a is varying, DEEC obtains 20% more number of round than LEACH-E.

5.2. Results under multi-level heterogeneous networks

For multi-level heterogeneous networks, the initial energy of nodes are randomly distributed in $[E_0, 4E_0]$. To prevent the affection of random factors, the network is equipped with the same amount of initial energy. SEP is extended to multi-level heterogeneous environment by choosing weight probability $p(s_i)$ in Eq. (10) for each node.

In Fig. 6 (left), detail views of the behavior of LEACH, SEP, LEACH-E, and DEEC are illustrated. We observe that LEACH fails to take full advantage of the extra energy provided by the heterogeneous nodes. The stability period
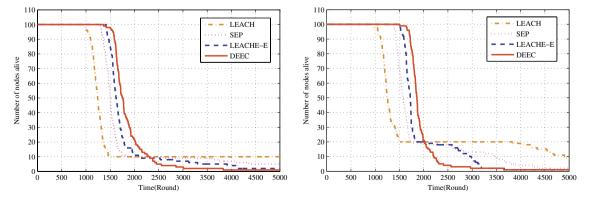

Fig. 3. Number of nodes alive over time of LEACH, SEP, LEACH-E, and DEEC under two-level heterogeneous networks. (Left) When $m = 0.2$ and $a = 3$. (Right) When $m = 0.1$ and $a = 5$.
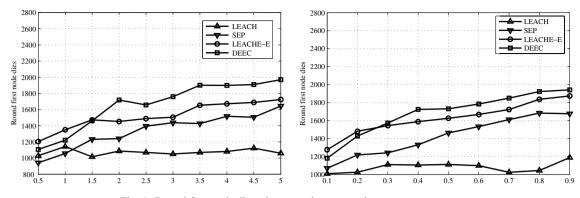
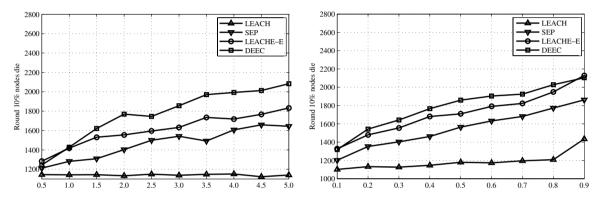Fig. 4. Round first node dies when *m* and *a* are varying.

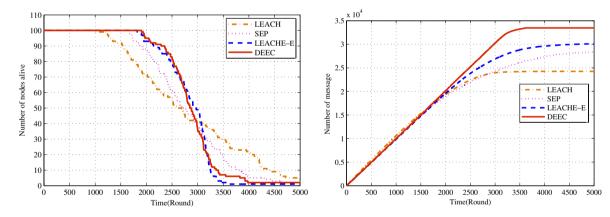Fig. 5. Round 10% nodes die when *m* and *a* are varying.

Fig. 6. Performance of LEACH, SEP, LEACH-E, and DEEC under multi-level heterogeneous networks. (Left) Number of nodes alive over time. (Right) Number of message received in base station over time.

of LEACH is very short and nodes die at a steady rate. This is because LEACH treats all the nodes without discrimination. SEP has longer stability period than LEACH just because of discriminating nodes according to their initial energy. LEACH-E and DEEC take initial energy and residual energy into account at the same time. The results show that LEACH-E and DEEC increase 15% more rounds of stability period than SEP. Interestingly, though the number of nodes alive of DEEC seems same as LEACH-E, the messages delivered by DEEC are more than that of LEACH-E. This means that DEEC is more efficient than LEACH-E.
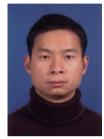
6. Conclusions

We describe DEEC, an energy-aware adaptive clustering protocol used in heterogeneous wireless sensor networks. In DEEC, every sensor node independently elects itself as a cluster-head based on its initial energy and residual energy. To control the energy expenditure of nodes by means of adaptive approach, DEEC use the average energy of the network as the reference energy. Thus, DEEC does not require any global knowledge of energy at every election round. Unlike SEP and LEACH, DEEC can perform well in multi-level heterogeneous wireless sensor networks.

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