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Energy-balanced clustering protocol for data gathering in wireless sensor networks with unbalanced traffic load

KUI Xiao-yan(奎晓燕), WANG Jian-xin(王建新), ZHANG Shi-geng(张士庚)

School of Information Science and Engineering, Central South University, Changsha 410083, China

Abstract: Energy-efficient data gathering in multi-hop wireless sensor networks was studied, considering that different node produces different amounts of data in realistic environments. A novel dominating set based clustering protocol (DSCP) was proposed to solve the data gathering problem in this scenario. In DSCP, a node evaluates the potential lifetime of the network (from its local point of view) assuming that it acts as the cluster head, and claims to be a tentative cluster head if it maximizes the potential lifetime. When evaluating the potential lifetime of the network, a node considers not only its remaining energy, but also other factors including its traffic load, the number of its neighbors, and the traffic loads of its neighbors. A tentative cluster head becomes a final cluster head with a probability inversely proportional to the number of tentative cluster heads that cover its neighbors. The protocol can terminate in $O(n/\lg n)$ steps, and its total message complexity is $O(n^2/\lg n)$. Simulation results show that DSCP can effectively prolong the lifetime of the network in multi-hop networks with unbalanced traffic load. Compared with EECT, the network lifetime is prolonged by 56.6% in average.

Key words: energy-balance; clustering; data gathering; wireless sensor networks; unbalanced traffic load

1 Introduction

Data gathering is one of the most important operations in wireless sensor networks (WSNs) [1−2]. How to conserve the limited energy of sensor nodes in order to extend the network lifetime is an important issue in data gathering. The network lifetime is usually defined as the duration of the network until the first node depletes its energy [3].

In order to effectively extend the lifetime of a WSN, many clustering protocols have been proposed. In clustering protocols, sensor nodes are grouped into different clusters. In each cluster, a cluster head (CH) is selected to take charge of collecting, processing, and transmitting data of the members in the cluster. In clustered WSNs, cluster heads (CHs) play an important role because they drain energy more rapidly than other member nodes. A CH is responsible for managing its member nodes, maintaining the cluster structure, as well as providing inter-cluster connectivity. Thus, a CH performs much more work than the ordinary cluster member nodes do, thus drains more energy per unit time, resulting in quicker energy depletion and earlier death.

The formation of clusters and selection of cluster heads are critical to achieve maximized lifetime of the network. Many existing clustering mechanisms are based on the dominating set (DS) of the network [4−7]. A DS of a network is a subset of its nodes, which makes that any node not in the DS is adjacent to a node in the DS. DS-based clustering mechanisms are preferred because they can be executed in a constant number of rounds [4−5]. Within a cluster, single-hop communication is usually used because most cluster members are close to the cluster head and their links to the cluster head have good quality [8].

Existing mechanisms usually assume that the traffic load contributed by each node is the same. In other words, they assume that same amounts of data are sent to the CH from cluster members. However, in realistic environments, traffic loads produced by different sensor nodes may differ from each other. The unbalanced traffic load makes those nodes with higher traffic load drain energy more rapidly than those with lower traffic load. Some cluster heads may have much higher traffic load than the others, which makes them drain energy more rapidly than the other CHs. Existing mechanisms do not take into account the unbalanced traffic load distribution in the formation of clusters and the selection of cluster heads, and are not applicable to WSNs deployed in

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Corresponding author: WANG Jian-xin, Professor, PhD; Tel: +86−731−88830212; E-mail: jxwang@csu.edu.cn

realistic environments.

A novel dominating set based clustering protocol (DSCP) was proposed to construct energy-balanced clusters and select cluster heads in multi-hop WSNs with unbalanced traffic load. It can well balance energy consumption among nodes and consequently prolong the lifetime of the network. In DSCP, each node takes its energy, its traffic load, the number of its neighbors, and the traffic loads of its neighbors into consideration. Then, each node calculates the number of potential rounds of data gathering it can afford if it acts as cluster head and claims to be a tentative cluster head if it can afford the most rounds of date gathering among its neighbors. Each tentative cluster head will become a final cluster head according to a probability that is inversely proportional to the median of numbers of tentative cluster heads that its neighboring nodes are covered. In this work, we theoretically analyze the complexity of DSCP and conduct extensive simulations to evaluate its performance.

2 Related work

The existing clustering mechanisms can be classified into two categories based on how to select the CH: probability-based algorithms [6−12] and DS-based algorithms [13−15].

2.1 Probability-based algorithms

In probability-based algorithms, the CH can be selected with a probability in a randomized manner, such as in LEACH [9] or HEED [8]. Such a randomized selection of the cluster head, combined with rotating the cluster head position, can effectively avoid the early drain of the energy of a particular node. However, it cannot guarantee the optimality of the selection. LEACH does not consider the residual energy of nodes when selecting cluster heads. HEED considers residual energy and node degree in cluster head selection, and achieves higher efficiency than LEACH. But, the communication overhead of HEED in clustering is very high. EADEEG [6] prolongs the lifetime of the network by minimizing energy consumption of communications and balancing the energy load among nodes. BPEC [7] is an improvement of EADEEG, in which cluster heads are elected according to two probabilities. DDC [10] is a directed clustering algorithm based on load balance. In DDC, the pre-evaluation factors that are used for pre-evaluating the energy level and load ability for each node are presented. CDAT [11] uses data prediction transmission strategy to achieve good performance. EECT [12] is an energy-efficient clustering algorithm that considers both the residual node energy and the traffic load contribution of each node. In EECT, nodes with more residual energy and less traffic load have more chances to become cluster heads. However, EECT cannot be well applied in multi-hop network, and the algorithm does not consider the energy balance among nodes.

2.2 DS-based algorithms

The dominating set problem models the optimization problem of finding a small number of cluster heads. DS-based algorithms lead to better clustering because every node in the network is either a dominating node or only one hop from a dominating node [6]. Single-hop communications within clusters are appropriate because most nodes will be close to their cluster head and the energy consumption for transmission is low. ECDS [13] proposes an energy-constrained minimum dominating set to model the problem of cluster heads selection. However, the optimization goal of ECDS is to find the smallest number of cluster heads. ECDS requires nodes to exchange information with their two-hop neighbors frequently, and thus incurs high energy consumption. Moreover, ECDS does not consider different energy levels among nodes, thus cannot balance the energy consumption effectively. FT-CDS-CA [14] constructs quality fault-tolerant connected dominating sets in homogeneous wireless networks. However, the energy balancing among nodes are not considered by the algorithm. MOC-CDS [15] aims to find a minimum CDS while assuring that any routing path through this CDS is the shortest in the network. Routing by MOC-CDS can guarantee that each routing path between any pair of nodes is also the shortest path in the network. Thus, energy consumption and delivery delay can be reduced greatly. Compared with traditional CDS, MOC-CDS can reduce routing cost significantly when it is used as a virtual backbone in wireless networks. However, the algorithm also does not consider the energy balancing among nodes. When the nodes in the shortest path have low energy, these nodes consume the energy quickly and die early.

3 System model

A scenario that is similar to the scene used in Ref. [16] is considered in this work. An aircraft (possibly unmanned) or a LEO satellite passes over these areas (battle field or virgin forest) periodically and collects data from the deployed sensor nodes. Thus, in the above scenario, the aircraft acts as the (mobile) base station. A surveillance aircraft flying at an altitude of H sweeps the area periodically and triggers a new round to sense data. Because H is usually larger than 150 m, if all sensor nodes send their data to the aircraft directly, the energy consumption will be very high, and the nodes will die quickly. We use a clustering method to save the limited energy of the nodes. The nodes are organized as clusters. During the data gathering process, all member nodes in a cluster send their data to the CH by using single-hop communication, and then the CH sends the received data with its own data to the aircraft through direct transmission. Obviously, this method can improve the energy efficiency of the network by reducing the number of nodes that need to transmit to the aircraft directly through a long distance.

Similar to LEACH, EADEEG and ECDS, the data gathering runs in rounds. There are two phases in each round: a set-up phase and a steady phase. In the set-up phase, one of the nodes in a cluster is selected as the cluster head, and the remaining nodes join the nearest cluster as cluster members. In the steady phase, the cluster members simply send their data to the cluster head through single-hop transmission. Then, the cluster head sends the received data with its own data to the aircraft (the mobile sink).

3.1 Network model

Assume that there are n sensor nodes in the network that are labeled as v_1, v_2, ⋯, v_n, respectively. All the nodes are randomly deployed in a $M\times M$ field to continuously monitor the environment. The network has the following characteristics:

1) The network is static, i.e., all the nodes are stationary after deployment.

2) Nodes may have different initial energy.

3) Nodes are not aware of their geographic positions.

4) Traffic loads produced by different sensor nodes may differ from each other.

3.2 Energy model

We assume that in every round each node v_i generates a data of c_i bits, and the node can acquire the energy information of its neighbors through message exchange. The data cannot be aggregated in the gathering process. We assume that the nodes have two adjustable power levels, and we use the same energy model that is widely adopted in previous works [9, 12, 17]:

1) When v_i acts as a cluster member, the energy dissipated to deliver a packet of c_i bits from the source to the destination is defined as

$$E_\text{t}(c_i,\ r_\text{n})=c_iE_\text{elec}+c_i\,\varepsilon_\text{fs}r_\text{n}^2 \tag{1}$$

where E_elec is the energy dissipated in operating the transmitter radio, r_n is the transmission radius of v_i, and $\varepsilon_\text{fs}r_\text{n}^2$ represents the energy dissipated by transmitter amplifier that varies with the distance r_n between the two nodes.

2) When v_i acts as a CH, it will send its data to the aircraft with a transmission radius of r_c (r_c=H). The energy dissipated to deliver a packet of k_i bits from v_i to the aircraft is defined as

$$E_\text{t}(k_i,\ r_\text{c})=\ k_iE_\text{elec}+\ k_i\,\varepsilon_\text{amp}r_\text{c}^4=\ k_i(E_\text{elec}+\ \varepsilon_\text{amp}r_\text{c}^4\,) \tag{2}$$

where k_i represents the data amount of CH and is defied as $k_i=\sum_{v_j\in A}c_j+c_i$, A represents the cluster member set of v_i, E_elec is the energy dissipated in operating the transmitter radio, and $\varepsilon_\text{amp}r_\text{c}^4$ represents the energy dissipated by the transmitter amplifier that varies with the distance r_c between the CH and the aircraft.

The energy dissipated in operating the receiver radio is expressed as

$$E_\text{r}(c)=cE_\text{elec} \tag{3}$$

3.3 Definitions and notations

For the sake of brevity in describing our protocol, some definitions and notations are given here.

Definition 1: Let $N(v_i)$ be the neighbor set of a node i. $|N(v_i)|$ represents the neighbor number of a node i.

Definition 2: Let $U(v_i)$ be the set of neighboring nodes of node i that do not join any clusters. $|U(v_i)|$ represents the number of uncovered neighbors of node i.

Definition 3: The head capacity $H(v_i)$ is proportional to the minimum numbers of rounds that the cluster head can afford. A larger value of $H(v_i)$ means that v_i can afford more rounds in data gathering. The CH will receive all the data from its cluster members, and send the received data with its own data to the mobile sink in a round. Assume that v_i acts as CH and all the uncovered neighbors of v_i join the cluster of v_i, then the total energy dissipated by the CH can be denoted as

$$\sum_{v_l\in U(v_i)}c_lE_\text{elec}+\left(\sum_{v_l\in U(v_i)}c_l+c_i\right)(E_\text{elec}+\varepsilon_\text{amp}r_\text{c}^4)$$

Assuming $E(v_i)$ is the residual energy of v_i, then $H(v_i)$ can be determined by

$$H(v_i)=\left\lceil\frac{E(v_i)}{\sum_{v_l\in U(v_i)}c_lE_\text{elec}+\left(\sum_{v_l\in U(v_i)}c_l+c_i\right)\left(E_\text{elec}+\varepsilon_\text{amp}r_\text{c}^4\right)}\right\rceil \tag{4}$$

Definition 4: The degree of a node v_i, denoted by D_i, represents the number of neighbors in the transmission range of v_i, is described as D_i=| $N(v_i)$|. The average node degree, denoted by D_a, is defined as the average value of D_i. Over all the nodes in the network, there is

$$D_a = \left(\sum_{i=1}^{n} D_i\right)/n$$

where D_i appoximately represents the network density.

4 Design and analysis of DSCP

4.1 Clustering phase

The clustering phase consists of several steps. In each step, the nodes outside the cluster exchange information with their neighbors, and compute their head capacity. They then decide whether they can become a tentative cluster head depending on their head capacity. A tentative cluster head becomes final cluster head with a probability that is inversely proportional to the number of tentative cluster heads that its neighbors are covered.

1) At the start of a step, if v_i does not join any cluster, it will check whether there are neighbors who do not join any cluster. If all of its neighbors join other clusters, v_i will become a final cluster head.

2) Otherwise, v_i will enter the clustering head election process. It broadcasts its head capacity, and then receives the head capacity information from its neighbors. If the head capacity of v_i is the maximum among its neighbors, which indicates that v_i can afford more rounds for date gathering than its neighbors, then v_i becomes a tentative cluster head.

3) Then, v_i finds the median m of $\{N_{c,j}|j\in U(v_i)\}$, and becomes a final cluster head with a probability of p_1, where $p_1=1/m$. At the same time, v_i broadcasts $c(v_i)$ message to its neighbors. The reason for using the median m is to control the number of cluster heads, avoiding generating too many dominating nodes.

4) If v_i is not the final cluster head and receives the clusterhead message from its neighbors for the first time, it will wait for its neighbors sending their clusterhead information. Then, v_i sorts the final cluster heads by their head capacity, and joins a final cluster head z with a probability of p_2:

$$p_2 = H(z)/\sum_{u\in B} H(u)$$

where B is the set of all the final cluster heads that send clusterhead messages.

5) After a node joins a cluster, it will exit the process of cluster head selection, and will not join any other cluster. Meanwhile, when a node joins a cluster, it will ignore the messages sending from other nodes in order to save energy.

4.2 Analysis of DSCP

Theorem 1: The set of the cluster heads is a dominating set when DSCP terminates.

Proof: This theorem will be proved by contradiction. Assume that there are some nodes that cannot join any cluster after the clustering process of DSCP. This means that these nodes are not chosen as the cluster heads, and there are not cluster heads in their neighbors. Denote the set of these nodes by U. For any node $v_i\in U$, according to DSCP, there are two possible cases for v_i:

1) If all the neighbors of v_i have joined some clusters, i.e., there are not uncovered neighbors of v_i, then v_i becomes the final cluster head directly.

2) If there are uncovered neighbors of v_i, then v_i will compete with its uncovered neighbors. After the competition, if v_i is selected as the final cluster head, its uncovered neighbors will join v_i. Otherwise, if v_i is not selected as the final cluster head, but there are one or more neighbors of v_i becoming the final cluster head, then v_i will join one of the cluster of these neighbors.

From the above analysis, all the nodes in U will join the cluster (as a cluster head or as a cluster head member). This contradicts with the hypothesis that there are some nodes that cannot join any cluster after the clustering process of DSCP. Thus, each node in the network will either be a cluster head or be a cluster head member when DSCP ends. Consequently, the set of all the cluster heads is a dominating set when DSCP terminates.

Theorem 2: In the worst case, the clustering phase of DSCP terminates in $O(n/\lg n)$ steps.

Proof: In the worst case, DSCP generates only one cluster in a step. We show this case with an example network shown in Fig. 1. The example network is a simple linear network consisting of four nodes v_1, v_2, v_3, and v_4. All the nodes have the same transmission radius r_n, which is set to be 100 m. Each node starts with different amounts of initial energy. The energy of v_1, v_2, v_3, and v_4 are 1, 3, 5, and 7 J, respectively. They produce 100, 200, 300, and 400 bit data in every round, respectively. According to DSCP, we have

$$H(v_1)<H(v_2)<H(v_3)<H(v_4)$$

So, in the first step, only node v_4 is selected as the tentative cluster head, and it then becomes the final cluster head. Meanwhile, v_3 joins the cluster of v_4. Similarly, only node v_2 is selected as the final cluster head in the second step, and v_1 joins the cluster of v_2. So, in this situation, DSCP generates only one cluster in each step.

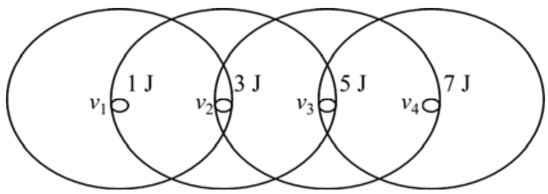

Fig. 1 One example in clustering

In order to gurantee that the network is connected, the transmission radius of r_n should satisfy the following formula [18]:

$$r_n \ge \frac{\sqrt{2}}{2} M \sqrt{\frac{1}{n} \lg\left(\frac{n}{\delta}\right)}$$

where δ represents that the probability of the network is not connected. Certainly, the number of the nodes in a cluster must satisfy

$$N_{\text{cluster}} \approx n\pi r_n^2 / M^2 \ge \frac{\pi}{2} \lg(\frac{n}{\delta}) = O(\lg n) \tag{5}$$

So, in the worst case, there are $O(\lg n)$ nodes joining a cluster in each step. We can deduce that the total step for all the nodes to join a corresponding cluster is

$$T_{\text{total}}=n/O(\lg n)=O(n/\lg n) \tag{6}$$

Thus, In the worst case, the clustering phase of DSCP terminates in $O(n/\lg n)$steps.

Theorem 3: The message complexity of the protocol is $O(n^2/\lg n)$.

Proof: We can get from algorithm description in Section 4.1, at the beginning of each step, v_i will send a capacity message; if v_i becomes the tentative cluster head, it will send a candidate message; each node will send a num-of-candidate message when acquiring the tentative cluster head number of its neighbors; if v_i becomes the final cluster head, it will send a clusterhead message; if a node decides to join a cluster, it will send a message for declaring its joining. The cluster head will send a confirming message when receiving all the messages sent from its members. Therefore, a node will send at most five messages in a step. There are n nodes in the network, thus the message complexity of the network is $O(n)$ in a step.

According to **Theorem 2**, in the worst case, clustering terminates in $O(n/\lg n)$ steps. So, we can deduce that the total message complexity of the network is $O(n^2/\lg n)$.

5 Performance evaluation

We conduct extensive simulations to evaluate the performance of DSCP. The experiments are performed in a square field of $M\times M$, in which nodes are randomly dispersed. The parameters are as follows:

Each node in the field is assigned a randomly-generated initial energy level between 1 and 10, E_{elec}=50 nJ/bit, ε_{fs}=13 pJ/(bit·m^2), ε_{amp}=0.001 3 pJ/(bit·m^4), r_c=200 m, and each node will generate only one packet of c_i bits per round, where c_i is a random integer between 200 and 300. DSCP is compared with EECT. All the experiments are performed 20 times, and their average values are taken as the final results.

5.1 Clustering effect

We simulate a network of 480 static nodes placed randomly in a 1 000 m × 1 000 m area to observe the distribution of the clusters. The transmission range of nodes is set to be 100 m, thus, D_a of this network is 15. The simulation result is shown in Fig. 2.

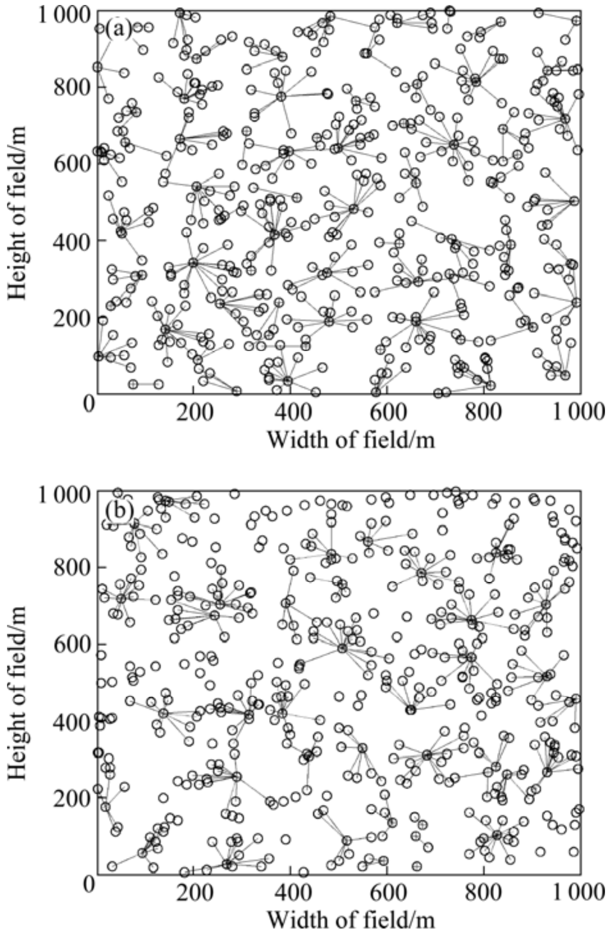

Fig. 2 Clustering effect of DSCP (a) and EECT (b)

In Fig. 2, the distribution of the clusters in DSCP is even. Cluster heads are not crowded in a small area, and all the nodes join the clusters, which effectively guarantees the network coverage. EECT generates the cluster heads based on a probability, thus it generates too small number of cluster heads, and the distribution of the clusters in EECT is not even, which causes that too many nodes cannot join a cluster.

5.2 Energy consumption in clustering

In order to compare the energy efficiency of DSCP and EECT, two metrics are used to evaluate the performance of the protocol. The first metric is the average energy consumption per node in clustering phase. The second metric is the ratio of the energy consumption in clustering to the energy consumption in data gathering, which is defined as

$$P_c = \left(\sum_{i=1}^{n} (S_i / H_i) \right) / n$$

where S_i represents the energy consumption of v_i in clustering, and H_i represents the energy consumption of v_i in data gathering.

The transmission range of nodes is 100 m, and the size of message packets is 32 bits. Two experimental scenes are considered:

1) Scene 1: The area is fixed of 1 000 m × 1 000 m, and 320, 480, 640, 800 and 960 nodes randomly distribute in the field, respectively. The average node degree is 10, 15, 20, 25 and 30 under this scene, respectively.

2) Scene 2: The average node degree D_a is fixed at 15. The area is 800 m × 800 m, 1 000 m × 1 000 m, 1 200 m × 1 200 m and 1 500 m × 1 500 m, respectively. There are 306, 480, 688 and 1 075 nodes, respectively.

The experimental results of the first metric are shown in Figs. 3(a) and (b), and the experimental results of the second metric are shown in Figs. 3(c) and (d).

We can see from Fig. 3(a), in the process of clustering, the energy consumption of nodes in DSCP increases when the average node degree grows. The reason is that DSCP is based on dominating set; nodes need to exchange messages with their neighbors to select the cluster heads. As the average node degree increases, the node needs to exchange more messages with neighbors, which exhausts more energy. However, EECT selects cluster heads based on probability, and it does not need to exchange messages in clustering, so the energy consumption of EECT is unchanged. Meanwhile, it consumes less energy than DSCP.

In Fig. 3(b), when average node degree is fixed, the energy consumption for DSCP and EECT will be unchanged. Because the numbers of average neighbors of nodes will remain unchanged when average node degree is fixed, the energy consumption will be unchanged for DSCP. Meanwhile, EECT is based on probability, and the scales of network cannot influence the performance of EECT in clustering, so the energy consumption of EECT is also unchanged.

We can see from Figs. 3(c) and (d) that, the ratio of the energy consumption in clustering to the energy consumption in data gathering of DSCP is very low (P_c<0.03%). Compared with the energy consumed in data gathering, the energy consumption in clustering can be ignored. Although EECT consumes less energy than DSCP in different scenes of network, DSCP guarantees that all the nodes in the network can join a cluster.

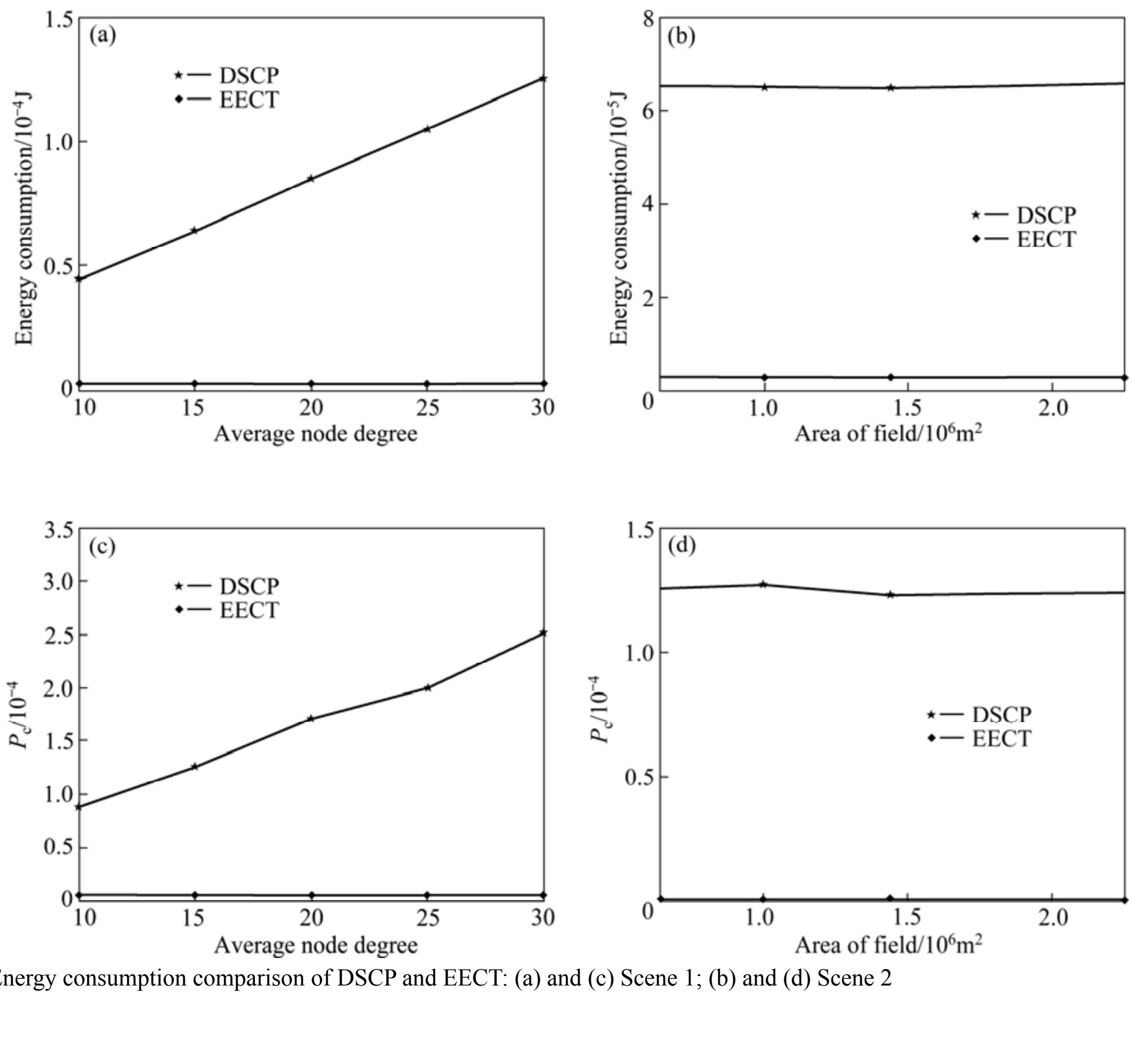

Fig. 3 Energy consumption comparison of DSCP and EECT: (a) and (c) Scene 1; (b) and (d) Scene 2

Meanwhile, the cluster heads of DSCP have the high capacity among nodes, which can take more rounds of date gathering and better satisfy the requirement of energy balance among nodes.

5.3 Network lifetime

We set the same scenes of Section 5.2 to evaluate the network lifetime. The energy of node will be reduced in data gathering and the energy is changed after every round. Node broadcasts its energy information at the beginning of each round. It incurs some communication overhead to broadcast the energy information, but the energy consumption of this part can be neglected in the network. Network lifetime achieved by these two algorithms is shown in Fig. 4.

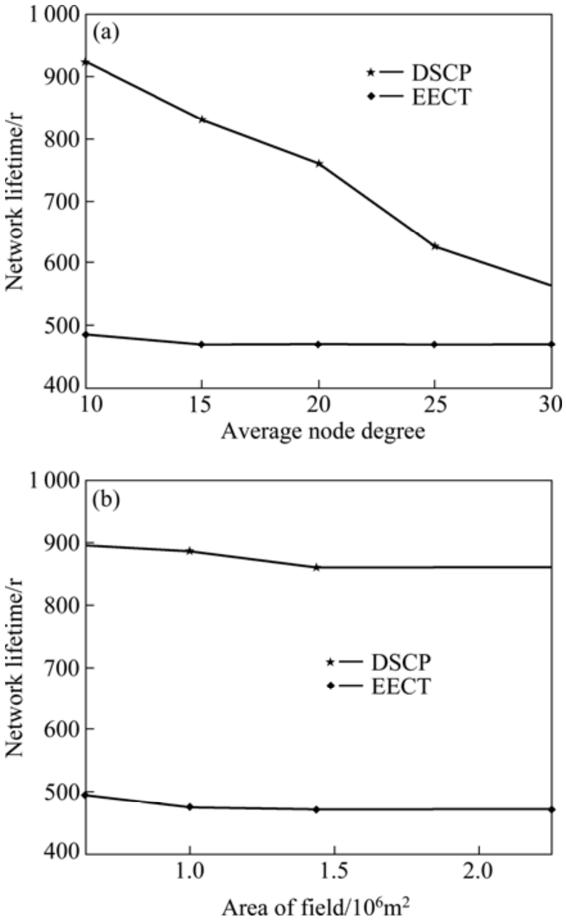

Fig. 4 Network lifetime comparison of DSCP and EECT: (a) Scene 1; (b) Scene 2

We can see from Fig. 4 that, DSCP achieves longer network lifetime than EECT in different scenes. Compared with EECT, the network lifetime of DSCP is prolonged by 56.6% in average. The reason is that DSCP can well balance the energy consumption among nodes. Recall that DSCP selects the nodes that have the highest capacity to be the cluster heads and the cluster heads transmit their data to mobile sink through a long distance communication. On the other hand, cluster members transmit their data to the cluster head through a short distance communication. Thus, DSCP can effectively balance the energy consumption among nodes, and then can enlarge the lifetime of the network.

As shown in Fig. 4(a) that, the network lifetime of DSCP decreases as the average node degree increases. The reason is that, when the average node degree increases, the number of cluster members in the cluster heads will increase, leading to heavier burden for cluster heads. However, the network lifetime of EECT is almost the same as the average node degree increases. EECT selects the cluster heads based on probability, which generates small number of cluster heads, and many nodes in EECT cannot join a cluster head under multi-hop circumstance. These nodes have no choice but to send their data to sink directly through a long distance communication, so they will consume more energy and die earlier. DSCP achieves longer network lifetime than EECT no matter how the average node degree of node changes.

In Fig. 4(b), when the average node degree is fixed, the network lifetime for DSCP and EECT will be almost unchanged in different scales of network. DSCP achieves longer network lifetime than EECT in different conditions. EECT cannot guarantee that all the nodes in the network join a cluster. The nodes that join no cluster have to send their data to the sink directly, leading to the earlier death of nodes with little energy, which greatly shortens the network lifetime of EECT. Based on the observation, we can draw the conclusion that DSCP gains better performance than EECT.

6 Conclusions

1) A new distributed scheme, DSCP, is proposed to gather data effectively in multi-hops wireless sensor networks.

2) DSCP prolongs the network lifetime by balancing energy consumption among nodes, and DSCP can be well applied in WSN with unbalanced traffic load.

3) Theoretical analyses prove that DSCP terminates in $O(n/\lg n)$ steps and the total message complexity is $O(n^2/\lg n)$.

4) Simulation results show that DSCP can not only guarantee that all nodes in the network join a cluster, but also enhance the performance of the network.

5) In the future, we consider how to extend our work into scenarios in which the cluster heads perform data aggregation on the data received from its cluster members.

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