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Energy-Efficient Routing Algorithm Based on Unequal Clustering and Connected Graph in Wireless Sensor Networks

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Abstract Clustering and multi-hop routing algorithms substantially prolong the lifetime of wireless sensor networks (WSNs). However, they also result in the energy hole and network partition problems. In order to balance the load between multiple cluster heads, save the energy consumption of the inter-cluster routing, in this paper, we propose an energy-efficient routing algorithm based on Unequal Clustering Theory and Connected Graph Theory for WSN. The new algorithm optimizes and innovates in two aspects: cluster head election and clusters routing. In cluster head election, we take into consideration the vote-based measure and the transmission power of sensor nodes when to sectionalize these nodes into different unequal clusters. Then we introduce the connected graph theory for inter-cluster data communication in clusters routing. Eventually, a connected graph is constituted by the based station and all cluster heads. Simulation results show that, this new algorithm balances the energy consumption among sensor nodes, relieves the influence of energy-hole problem, improve the link quality, achieves a substantial improvement on reliability and efficiency of data transmission, and significantly prolongs the network lifetime.

Keywords Wireless sensor networks · Energy-efficient routing algorithm · Unequal clustering · Connected graph · Network lifetime

1 Introduction

As the rapid development of microelectronics technology, low-power embedded technology, wireless communication technology and distributed information processing technology, wireless sensor networks (WSNs) have become a hotspot of modern science and technology, known as the third technological revolution. These networks are widely used in many applications, such as smart earth, environmental monitoring, target tracking, and military surveillance. Sensor nodes in such network can be equipped with different components for different applications. However, WSNs are characterized by limited power, computation ability and memory constraint. Due to the energy in any sensor node is non-rechargeable, the energy source should be managed wisely, thus how to prolong sensor network lifetime becomes a big challenge when designing a new protocol for WSNs. In order to address these issues, a good solution is that the sensor nodes can be organized hierarchically via utilizing some clustering algorithms.

Previous research has shown that direct transmission is usually less energy efficient than multi-hop communication between a source node and the sink owing to the characteristics of wireless channel. However, it will cause the

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'energy-hole' problem when using the multi-hop forwarding model in inter-cluster communication. It is the inherent phenomenon in data gathering network, where data traffic follows many-to-one communication pattern. In WSNs, nodes nearer to the sink deplete their energy faster and trend to die early for the reason that they relay heavier traffic load, and this leaves areas of the network uncovered and results in network partition. Subsequent data cannot reach the sink because the transmission distance is limited. Consequently, the network dies even with energy left in the isolated network partitions. Experimental results show that if the nodes are uniformly distributed in the network, up to 90 % of the total initial energy of the nodes is left unused when the network lifetime is over [1, 2]. It has an important application foreground and practical value to do a deep research on how to make better use of the energy and prolong the network lifetime with higher energy efficiency. Many methodologies have been proposed in solving the above questions, such as node's deployment, power control, data aggregation, sink mobility, appropriate data storage and algorithms for balancing energy consumption. In [3] and [4], sensor nodes closer to the sink are deployed with higher density. Li and Mohapatra [5] firstly find that combination of hierarchical network topology and data aggregation is effective in prolonging the network lifetime with alleviating the energy-hole problem. To improve the energy efficiency, the method of deploying the sensor nodes that have larger initial energy in the region around the sink was employed in [6]. Sensor nodes use different transmission power levels to transmit data. As their energy consumption is related to the transmission distance, the effects caused by energy hole may be relieved if the sensor nodes in different regions employ some different transmission distances [7].

Energy consumption can be obviously reduced by clustering and multi-hop forwarding. Therefore, many energy-aware clustering routing protocols have been proposed [8, 9]. Although some measures contained in the literatures came up with reducing energy consumption on forwarding paths to improve energy efficiency, the main disadvantage is that, due to the many-to-one traffic pattern, these measures do not necessarily prolong the network lifetime. Thus in this paper, we propose a novel energy-efficient routing algorithm (UCCGRA) to improve energy efficiency and prolong the network lifetime. Simulation results show that, this new algorithm balances the energy consumption among sensor nodes, relieves the influence of energy-hole problem, improve the link quality, achieves a substantial improvement on reliability and efficiency of data transmission, and significantly prolongs the network lifetime.

The main contributions of this paper are presented as follows:

1. We propose an improved unequal clustering algorithm for WSNs (i.e., the vote-based unequal clustering algorithm), which takes into consideration the voting result and the average transmission power to its cluster members of a potential sensor node. It is a distributed competitive algorithm. A node's competition range decreases as its distance to the sink decreasing. As a result, clusters closer to the sink are expected to have smaller cluster sizes. They will consume less energy during the intra-cluster data processing, and preserve more energy for the inter-cluster relay traffic.
2. We design a connected graph-based multi-hop routing algorithm for inter-cluster communication. This algorithm exploits the geographical location information of sensor nodes to construct a connected graph, and use it to guide routing procedure to find an optimal path. Our algorithm adopts a localized and decentralized routing decision mechanism and has good scalability and stability. It is suitable for WSNs with special characteristics such as distributed control, vulnerability to failure, and large network dimension.
3. We have performed comprehensive simulation to evaluate our proposed method. The experimental results show that our new method (UCCGRA) successfully balances the energy consumption over the network, and achieves a remarkable network lifetime improvement.

The rest of this paper is organized as follows. In Sect. 2, we discuss the related work on clustering routing protocols. We describe the concept of unequal clustering routing in Sect. 3. Sections 4 and 5 introduce our vote-based unequal clustering algorithm and connected graph-based multi-hop routing algorithm in detail. Section 6 describes the data transmission strategy, which divides into intra-cluster data transmission and inter-cluster data transmission. Section 7 gives our experimental results with discussions. Finally, we conclude this paper, and make directions for future work in Sect. 8.

2 Related Work

LEACH [10] is a typical clustering protocol for periodical data gathering applications in WSNs. The nodes elect themselves as cluster heads with some probability. This choice of probability for becoming a cluster head is based on the assumption that all nodes start with an equal amount of energy, and that all nodes have data to send during each frame. If nodes have different amounts of energy (or an event-driven model is used, whereby nodes only send data when some event occurs in the environment), the nodes with more energy should be cluster heads more often than the nodes with less energy, to ensure that all nodes die at approximately the same time. LEACH enables data fusion in each cluster by aggregating the data in order to reduce the total amount of data before sends them to the sink. The sensors within a cluster transmit their sensed data over short distances, whereas cluster heads communicate directly with the sink.

In HEED [11], each sensor's primal probability to become a cluster-head is depended on its remnant energy. Sensors that are not covered by any cluster heads have twice fold probability to become a cluster-head. A sensor selects the cluster-head which has the *average minimum reach-ability power (AMRP)* when it is within the cluster radius of multiple cluster heads. As in LEACH, each sensor can communicate with its cluster head firsthand in intra-cluster communication in which cluster heads can communicate with each other to collect their information via multi-hop hops.

Under the circumstances, an ad hoc routing protocol, such as Flooding [12], can be applied to data forwarding between cluster heads. It is significant for maintaining network connectivity to select the intra-cluster transmission range and the inter-cluster transmission range carefully.

The authors propose a generic weight-based clustering algorithm that associates each sensor with some *weight* In WCA [13]. *Weight* is calculated from a sensor's local properties, such as the ideal node-degree, transmission power, mobility and the battery power of the nodes. Cluster heads are selected from those nodes that have the minimum *weights* among their neighbors. WCA uses single-hop routing where each node can transmit directly to the cluster-head, and single-hop routing where the cluster-head to another cluster-head.

An unequal clustering model is first investigated to balance the energy consumption of cluster heads in UCS [14]. The sink is located in the center of the observed area, and it collects data from the network. The positions of the cluster-heads are determined a priori, with all cluster heads arranged symmetrically in concentric circles around the sink. Every cluster is composed of nodes in the Voronoi region around the cluster head. The data from all sensors in the cluster are collected at the cluster-head, which aggregates and forwards the data toward the sink. The forwarding of aggregated packets is done through multiple hops, where every cluster head chooses to forward its data to the closest cluster head in the direction of the sink.

In EEUC [15], the authors propose an Energy-Efficient Unequal-Clustering mechanism for periodical data gathering applications in WSNs. By using unequal-clustering and multi-hop routing, it organizes the network sensibly. EEUC is a distributed competitive algorithm, where cluster heads are selected by partial competition. Cluster head selects a relay node with more remnant energy to forwarding its data from its candidate set in inter-cluster data transmission.

The authors use WCA clustering algorithm which uses vote mechanism to choose cluster head In UCRA [16]. In clustering phase, nodes exchange information to calculate vote, then choose the node with the max vote as cluster head. Cluster heads broadcast control messages to inform other nodes. Left nodes choose the best cluster head to join according to fitness or other mechanisms. This procedure iterates until all nodes are covered by at least one cluster-head. Therefore, WCA needs many times of iteration and can't make sure the connectivity between cluster heads. For inter-clustering algorithm, EEUCR uses the MEC routing algorithm which makes the energy more efficient. But MEC uses probe and answer method to find the next hop to sink, so MEC can not guarantee each probe message gets a reply. In that case, MEC starts another probe with bigger broadcast radius which needs the energy consumption.

3 Unequal Clustering Routing Mechanism

Maximizing the network lifetime under given energy constraints is a primary problem in WSNs. It requires us to balance energy consumption among all nodes. Cluster head plays the role of periodically rotating among nodes to balance the energy consumption in homogeneous networks. Nevertheless, the energy-hole problem can not be absolutely averted. The primary target of rotation is to balance the energy consumption among cluster heads and member nodes, but not among cluster heads in the inter-cluster multi-hop routing. Nodes closer to the sink cannot make good use of all nodes' energy because it tends to die faster. The main goal of this paper is trying to prolong the network lifetime by designing a novel unequal clustering routing mechanism.

Figure 1 is an overview of the unequal clustering routing mechanism, in which the circles of unequal size illustrate the clusters of unequal size and the multi-hop forwarding method is represented by the traffic among cluster heads. The followings are the parameters in Fig. 1. R_{max} is the maximum competition radius which is predefined, d_0 represent the radiation radius of each sensor node, d_{max} and d_{min} denote the maximum and minimum distance between sensor nodes and the sink.

4 The New Vote-Based Unequal Clustering Mechanism

The following two subsections are the particular representations of the new unequal clustering mechanism: unequal clustering radius, vote method.

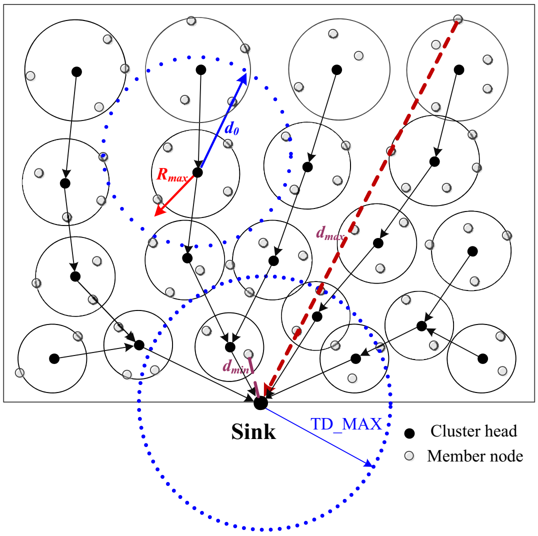

Fig. 1 An overview of the unequal clustering routing mechanism

4.1 Unequal Clustering Radius

Segmenting the nodes into clusters is clustering. Each cluster consists of a cluster head and some general nodes as its members. We put forward a *new vote-based unequal clustering algorithm* for WSNs, with view of the vote method and transmission power of a sensor node. In the distributed cluster head competitive algorithm, cluster-head is selected principally on the basis of the weight of each node.

The cluster heads closer to the sink should support smaller cluster sizes due to higher energy consumption among the inter-cluster multi-hop forwarding communication. As a result, we should produce more clusters closer to the sink. In other words, the competition radius of the node should decrease while its distance to the sink is monished. The competition radius range of the network should be controlled. Suppose R_{max} is the maximum competition radius that is predefined. We set R_i of node v_i as a function of its distance to the sink [13, 16]:

$$R_i = \left(1 - c \times \frac{d_{\max} - d(v_i, \mathrm{sink})}{d_{\max} - d_{\min}}\right) R_{\max} \tag{1}$$

where, $d(v_i$, sink) means the distance between v_i and the sink, c is a constant coefficient between 0 and 1. The competition radius varies from $(1-c)$ R_{max} to R_{max} according to Eq. (1). Other parameters' indication can be found in Fig. 1.

4.2 Vote Method

During the clustering phase, sensors compete with each other based on the *vote method*. Topology, residual energy and transmission power become the three primary factors in selecting cluster heads. We define a *vote* function to represent the topology and residual energy of sensor nodes, and a distance function P to represent the transmission power.

If a sensor has more neighbors, each neighbor receives a smaller *vote* since there are many candidate nodes for this node. Each neighbor gives some votes to a sensor, and sensors with more neighbors tend to receive more votes. Therefore, for a sensor v_i, the *vote* it casts on another sensor v_j is:

$$v(v_i, v_j) = \begin{cases} \dfrac{e_j}{\sum\limits_{d_{ik} \le R_i} e_k} & d_{ij} \le R_i \\ 0 & d_{ij} > R_i \end{cases} \tag{2}$$

where, d_{ik} is the distance from sensor v_i to sensor v_k, and e_j is the residual energy of sensor v_j. The total vote of sensor v_i is the sum of the votes from all voters,

$$vote(v_i) = \sum_{d_{ij} \le R_i} v(v_j, v_i) \tag{3}$$

We calculate an *announcement* A_i for each node v_i,

$$A_i = \frac{vote(v_i)}{\sum\limits_{k=1}^{n} (d_{ik})^2 \Big/ n} \tag{4}$$

where, d_{ik} is the distance between v_i and any of its n-th neighbors. If a node has no neighbors, its *announcement* value is 1. A node receiving a broadcast from another node can know the location of its neighbor. We choose the node with a maximum announcement to be the cluster-head.

To calculate the *announcement* value, a sensor needs to know the residual energy and distance of all its neighbors. They need to broadcast its *id*, location and residual energy information within one hop (within the scope of competition radius range). Thus, every node is made aware of its neighboring nodes and their corresponding distances. After receiving these messages, each sensor needs to update and broadcast its *announcement* to all neighbors.

The energy consumption of a cluster-head depends on the number of neighbors. To balance the energy distribution, more sensors should subscribe to a high-energy cluster-head. We define a *fitness* function to represent such properties of a cluster-head. The fitness of a sensor v_i is defined as:

$$fitness_i = \alpha \frac{e_i}{\mathrm{degree}_i} + (1 - \alpha) \frac{d_0}{10 d_{ij}} \tag{5}$$

where, d_{ij} is the distance between node j and cluster head i, $degree_i$ is the degree of sensor v_i (i.e., the number of its neighbors). When a sensor is within the cluster radius of multiple cluster heads, it chooses the cluster-head with the highest fitness value. If the residual energy is the same, cluster-head with many neighbors has a smaller fitness than those with few neighbors.

5 Cluster Multi-hop Routing Algorithm

Detailed descriptions of the inter-cluster multi-hop routing algorithm are in the following three subsections.

5.1 Theory Basis-Improved Scheme Based on Tree Structure

As some deficiencies of the classical LEACH protocol, researchers present some improved protocol based on LEACH [10]. While in the inter-cluster routing phase, these improved protocols are to form tree structure with the base station as the root, and with all cluster-heads as the branch or leaf node. Data transmission is routed by way of tree routing: the cluster heads to collect data, transmit them layer-by-layer upward along with established branches, and eventually reach the base station [17].

However, these improved schemes raise some new problems due to the defects of tree structure itself, as follows: (1) Once tree structure is formed completely, data transmission paths are confirmed between all cluster heads and the base station, and hardly changes in this round; (2) As undertaking more data transmission tasks from sub-tree, cluster heads near to the base station will consume more energy than others far from the base station; (3) In the tree structure, a branch cluster head failure will lead to all of its following sub-tree cannot work well, and form chain scission; (4) When a cluster head has too many sub-trees and send data frequently, this will increase the burden of the cluster head and result in excessive energy consumption of this branch; (5) If it needs to transmit data between the different cluster heads, but needed by the base station, leading to additional energy waste.

5.2 Forming Connected Graph

All final cluster head nodes do not form the tree structure, but the connected graph. Each cluster head including the base station possesses an upper neighbor list and a lower neighbor list. Each element of the upper neighbor list is a five-tuple $U(ID, E_{node}, E_{BS}, Delay_{BS}, Load_{node})$, while it is a two-tuple $U(ID, E_{node})$ for the lower neighbor list. Where, the upper cluster head (ID), residual energy of this upper cluster head (E_{node}), minimum energy consumption through its upper cluster head to the base station (E_{BS}), minimum time delay through its upper cluster head to the base station ($Delay_{BS}$), link load of its upper cluster head ($Load_{node}$), etc.

Edge relations of the connected graph are represented and maintained through the upper and lower neighbor list, and ultimately to form a connected graph $G(V, E)$ that the base station and all the cluster heads are as the node set V, and the edge relations between the upper and lower neighbor lists are as the edge set E.

When the final cluster head broadcasts the message elected the cluster head, the other cluster head receives this message and uses the following rules to determine whether forming a link to the cluster head. Constructing a connected graph and including the following three aspects:

1. The base station and cluster heads. Link path is formed between the base station and cluster heads away from the base station within distance $q \times d_o$ (TD_MAX). And the base station is added to the upper neighbor list of these cluster heads, these cluster heads are added to the lower neighbor list of the base station. If none of cluster head is less than $q \times d_o$ (this case only happens when many nodes die in network), the base station is connected with the nearest cluster head away from the base station.

The value of q ensures that cluster heads closer to the base station form the dense link paths. Because these cluster heads need to take on more forward tasks than others, the more intense link paths are the more selection for transferring data, and be better to balance and offset more energy consumption for these cluster heads closer to the base station.

2. Between the cluster head. Whether cluster head i and cluster head j form a link path or not depends on two factors: the distance between them and their distances to the base station. Once the cluster head i and j form a link path, they are added to their corresponding upper and lower neighbor list. If the distance between the cluster head i and j is equal and greater than d_o, do not form a link path; otherwise, according to the following formulas (9) to determine whether to form a link path.

$$\begin{cases} d_i \le d_j - (R_i + R_j)/2 & i\ is\ at\ a\ higher\ level \\ d_i > d_j - (R_i + R_j)/2 & j\ is\ at\ a\ higher\ level \\ \left|d_i - d_j\right| < (R_i + R_j)/2 & they\ are\ unconnected \end{cases} \tag{6}$$

where, R_i is the cluster radius, the value of d_o and $(R_i + R_j)/2$ directly impact on density level of the connected graph. The above formula guarantees that a link path is only formed when the distance between the cluster head is greater than $(R_i + R_j)/2$. That assures effectiveness and efficiency of the link path and prevents data from being transmitted and forwarded with less efficient in the network.

3. Isolated cluster head or isolated sub-graph. After finished the process of (1) and (2), for the cluster head with its upper neighbor list being empty, it indicates that it can not reach the base station, then it will be connected with the cluster head as upper that is

the closest to the base station and also the shortest to the isolated cluster head; if not, it directly connects the base station. The closest to the base station ensures the data is forwarded to the cluster head closer to the base station, and the shortest to the isolated cluster head ensures that the energy consumption of forwarding to the cluster head is as small as possible.

The connected graph is constructed by the above three steps, all the cluster heads and the base station are connected through link paths.

5.3 Routing Strategy

After all the cluster heads and the base station constitute a connected graph, each cluster head has multiple paths to reach to the base station. In this section we describe a method of constructing minimum energy consumption paths, so that it is the minimum and optimal path for energy consumption among all the paths reaching to the base station, and known as the 'optimal tree' of the connected graph.

For the connected graph formed by all cluster heads and the base station, we consider the base station as the source point, perform the breadth first search (*BFS*) of graph theory, and calculate E_{BS} and $Delay_{BS}$ of the element in the upper neighbor list for all cluster heads layer by layer. Here we take E_{BS} as the measure (For time-sensitive network we can take $Delay_{BS}$ as the measure). During performing the *BFS* algorithm process, since each cluster head (including the base station) has a lower neighbor list to identify its all direct lower cluster heads, so you can traverse all cluster heads. In the implementation of *BFS*, if the lower neighbor list of a cluster head is empty, this path has finished and the cluster head is a leaf node for the constructed optimal tree. In the process of executing *BFS* algorithm, when calculating the cluster head i, we choose the element having smallest E_{BS} in its all upper neighbor lists as its optimal upper cluster head, that is, energy consumption is the smallest through the optimal upper cluster head to transmit data to the base station.

6 Data Transmission

6.1 Intra-cluster Data Transmission

After clusters have been formed, the intra-cluster data transmissions start. Each cluster-head takes over the data from its cluster members and gathers them. The use of coordinated TDMA scheduling in the MAC layer has been proposed by many clustering. Even locality TDMA scheduling (as opposed to globally coordinated scheduling) should not cause much communication overhead in the shape of collisions and necessary retransmission owing to the low data rates expected in many sensor network applications. A locality TDMA schedule is generated by a cluster head in order to reduce conflicts. According to the TDMA schedule, data generated at each sensor are sent to its cluster head in time of the network operation phase. Moreover, TDMA scheduling can avoid most overhead generated by idle listening and overhearing.

Since there is only one-hop distance between the cluster member node and cluster head, the member node only needs to send the sensing data to the cluster head (a k-bit packet), its energy consumption is:

$$E_{member}(i) = k \times E_{elec} + k \times \varepsilon_{fs} \times d(i)^2 \qquad (7)$$

The cluster head needs to aggregate all intra-cluster data and forward the inter-cluster data from the other cluster heads.

6.2 Inter-cluster Data Transmision

Since the UCCGRA protocol constitutes a connected graph between the cluster head and the base station, inter-cluster data transmission is different from other clustering routing protocols, and has its own unique way. There are multiple paths from each cluster head to the base station for the connected graph, so several paths can be selected. Based on the actual application, each cluster head send data to the base station according to the above corresponding five-tuples $U(ID, E_{node}, E_{BS}, Delay_{BS}, Load_{node})$ of its upper neighbor lists, and choosing the right combination depends on last four data filed of the five-tuples.

We introduce a simple inter-cluster data transmission scheme 'The Optimal Tree'. All cluster heads transmit data to the base station through their optimal upper cluster head, so that all inter-cluster data is transmitted to the base station along with the optimal tree, then inter-cluster energy consumption of data transmission is minimum.

Given the above discussion, we found that the main advantage of connected graph-based method is more choice and more multiple paths reaching the base station when transmitting data in inter-cluster data transmission process. Thereby that improves reliability, flexibility and application-related of inter-cluster data transmission. Based on E_{node}, we can balance the residual energy of cluster heads, and to prevent the rapid death of the local cluster head. Based on E_{BS}, we can minimize energy consumption of inter-cluster data transmission, and to save energy. Based on $Delay_{BS}$, we can improve the timeliness of data transmission, and to reduce data time delay. Based on $Load_{node}$, we can balance the load on the link path, and to prevent data transmission from blocking.

7 Experimental Results

In this section, we have an estimation of the property of our UCCGRA mechanism via simulations. We carry out simulation experiments in the network simulator OMNET++ [18]. First of all, we study the clustering characteristics of the UCCGRA. Second, we check into the way the UCCGRA improves the network lifetime. In order to compare with our algorithm, we have implemented the clustering protocols and multi-hop routing algorithms of HEED [11], EEUC [15] and UCRA [16].

Table 1 gives the simulation parameters and the parameters of the radio model are identical as in [15, 16]. We randomly dispersed 200 sensors into a square of 500 × 500 m^2 in each experiment. 20 different node location sets are generated and saved. By calculating the average of 100 independent experiment rounds on each location set, we get the experiment result. We take the first node's dying time as the main indicator for the network lifetime without considering about the packet loss.

7.1 Clustering Characteristics

First of all, we study the cluster head characteristics of the unequal clustering algorithm. The UCCGRA is run in different schemes. If c is set to 0, the clustering radius of each node is the same (equal clustering), according to Eq. (4). Otherwise, each node has a disparate clustering radius (unequal clustering). Considering different values of c, we can see the relationship between the number of cluster heads and R_{max} in Fig. 5.

Figure 2 shows that the curve of the equal clustering ($c = 0$) is always lower than the unequal clustering. A larger number of clusters come from a higher value of c. Our analysis indicates that the smaller the competition radius, the larger the required number of cluster to cover the network. The competition radius R_i decreases if R_{max} is fixed and c increases according to Eq. (1). As a result, unequal clustering algorithm generates more clusters. That is to say, R_{max} and c determine the number of generated cluster heads.

Table 1 Simulation parameters

Parameter	Value
Network coverage	(0, 0)–(500, 500) m
Sink location	(250, 500) m
N	200
Transmitter circuitry	50 nJ/bit
Receiver circuitry	50 nJ/bit
ε_{fs}	10 pJ/bit/m^2
ε_{mp}	0.0013 pJ/bit/m^4
aggregation energy per bit	5 nJ/bit
Initial energy	1 J
Data packet size	128 × 8 bit
Control packet size	10 × 8 bit
d_0	87 m

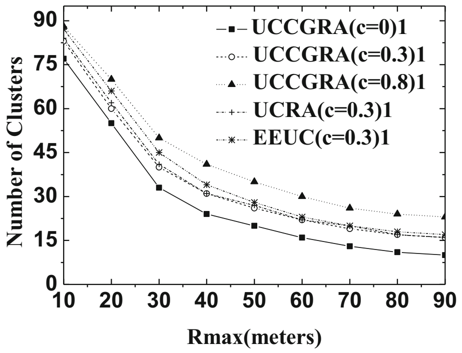

Fig. 2 The number of clusters generated by unequal clustering

In Fig. 3, we compare our UCCGRA clustering routing algorithm with the EEUC and UCRA. We set $c = 0.3$ and $R_{max} = 0$–60 m for these algorithms. As shown in Fig. 3, the average number of cluster heads selected by UCCGRA, UCRA and EEUC is very similar, because these three algorithms toward to choose cluster heads which are not neighbors within a cluster radius. For UCRA, the cluster head within its cluster range often is the node with the highest *weight which* depends on its remnant energy and cost. A sensor selects one with the largest *fitness* when it is within the cluster radius of multiple cluster heads. The UCCGRA is an enhanced vision of UCRA. In addition, in EEUC, we randomly selected tentative cluster heads on the basis of a constant T (we set $T = 0.3$ which is the same as in [16]) and the optimal head based on their remnant energy. Consequently, a little more clusters come into being by EEUC than by UCRA and UCCGRA.

We also examine the stability of our clustering algorithm. Figure 4 shows the distribution of the number of clusters in UCCGRA and EEUC, which is calculated from

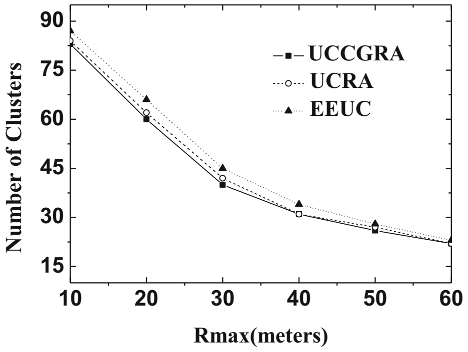

Fig. 3 Average number of clusters

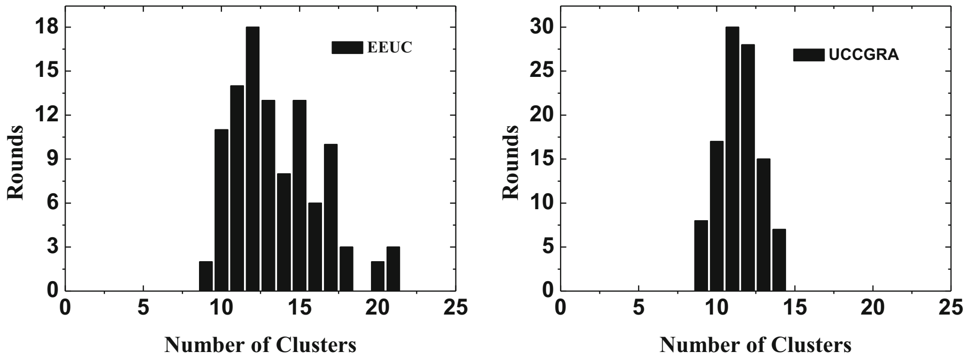

Fig. 4 Distribution of the number of clusters in 100 round

randomly selected 100 rounds of the simulation. It is apparent that the number of clusters in UCCGRA is steadier than that in EEUC. Although the expected number of cluster heads per round is deterministic, but EEUC uses a fully random approach to produce tentative cluster heads, thus it results in a variable number of clusters. In UCCGRA, sensors compete with each other based on the total received votes. Topology and residual energy become the two primary factors in selecting cluster heads. Thus UCCGRA achieves a steady number of clusters.

7.2 Network Lifetime

Figures 5, 6 and 7 show the results how our UCCGRA improves the network lifetime which has the definition of the number of rounds until the first node dies.

Firstly, we verify that the unequal clustering mechanism extends the network time. As we explained earlier, c determines the number of clusters and cluster sizes. Thus we observe the relation between c and the network lifetime via varying c from 0.1 to 0.9, and the $R_{max} = 60$ m.

The result is shown in Fig. 5, which justifies our unequal clustering mechanism. When c increases from 0, the effect of the unequal clustering method becomes distinct. Start the lifetime increases with the increase of c, and it decreases with c increases. The reason is that too many clusters will be produced closer to the sink, and each of them will deliver a data packet to the sink, thus it causes a waste of energy. Therefore, there exists an optimal value of c if other parameters are given. As shown in Fig. 5, the optimal value is about 0.2–0.4 of c given our experimental setting.

Figures 6 and 7 show the different network lifetime (the number of rounds until the first node dies) for those four different algorithms (with constant $R_{max} = 60$ m and $c = 0.3$, respectively) in the network. All of UCCGRA, UCRA and EEUC produce a vast longer lifetime than HEED. The reason is that HEED is on the basis of the equal clustering which not takes into consideration the problem of unbalanced energy consumption between cluster heads. In HEED, data transmission between cluster heads the sink is by multi-hop. However, cluster head's next-hop neighbor cluster-head are randomly elected on the basis of its distance. Therefore, relay node may still be cluster heads with low remnant energy and this leads to that some nodes die too earlier in HEED. EEUC generates a longer lifetime than HEED because it employs an unequal clustering mechanism and next-hop relay cluster-head based on its remnant energy. The two figures also show that our UCCGRA improves the network life when to compare with UCRA and EEUC. EEUC's deviation increase because its instability of the clustering mechanism and the

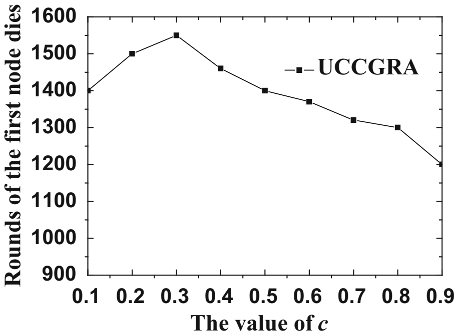

Fig. 5 The impact of c on the network lifetime

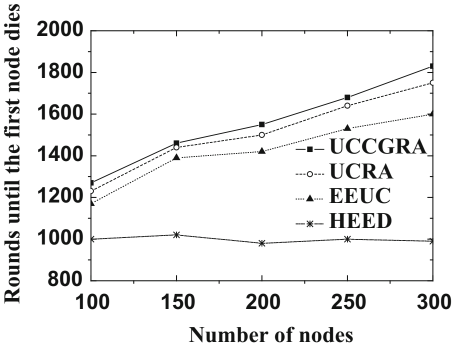

Fig. 6 Network lifetime with different number of nodes

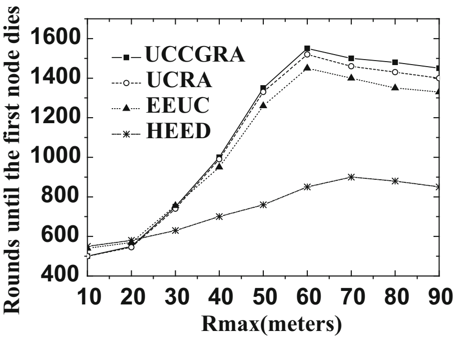

Fig. 7 Network lifetime with different Rmax

energy-aware multi-hop route although it adopts unequal clustering method. Therefore, EEUC's ability of generating longer lifetime is weaker than UCCGRA. In short, UCCGRA can better balance energy and distribute load fair.

From the above experiments, we can obtain that, according to our experimental setting, the optimal value of c is about 0.2–0.4, and the optimal value of R_{max} is about $1/2d_0$–$2/3d_0$. Moreover, using the similar approach, we can also obtain the optimal value of q is about 1.2–1.4. The simulation results analyze the effectiveness of the new routing algorithm UCCGRA. Experimental results demonstrate that, the vote-based unequal clustering method and connected graph-based multi-hop routing protocol successfully balance the energy consumption between cluster heads.

8 Conclusion

In this paper, we firstly introduce a vote-based unequal clustering method to balance the energy consumption among cluster heads. Cluster-heads closer to the sink can maintain some energy for inter-cluster data forwarding because they have smaller sizes than those farther. Secondly, we devise the connected graph-based multi-hop routing protocol for the inter-cluster data communication via studying on the Leach protocol and the enhanced protocols. The based station and all the cluster head forms a connected graph structure rather than the tree structure, so as to have multiple paths reaching the base station for each cluster head in the inter-cluster data transmission. Simulation results show that, the UCCGRA has a more even distribution of cluster head, and better balances the scale and load of all cluster heads, improves reliability and flexibility of data transmission, and significantly prolongs the network life cycle. Parameters of our mechanism, such as R_{max} and c in Eq. (1) can be tuned to optimize energy preservation. We will try to find a solution that could determine the optimal value of these parameters according to network scale in our future work. Moreover, according to this new approach, we will do a deeper research on the real-world implementations in the future.

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