Chapter 19
An Energy-Balanced Clustering Routing Algorithm for Wireless Sensor Networks

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Abstract Aimed at the problem of nodes energy imbalance, which is caused by the heavy burden of cluster heads in clustering wireless sensor networks, an uneven clustering routing algorithm based on multihop communication has been proposed for wireless sensor networks. An election algorithm is used for reasonable selection of cluster heads based on candidate threshold and time driven, the independent nodes are introduced to reduce burden of the cluster heads, and the multihop routing based on angle is applied to optimize the intercluster routing algorithm. Simulation results show that the algorithm can save the network energy effectively and balance the energy consumption.

19.1 Introduction

Wireless sensor network (WSN) is a self-organizing and distributed network which is comprised of a large number of microsensor nodes and some base stations (BS) owning wireless communication and computing capacity. WSN has been widely used in many fields, such as environmental monitoring, traffic management, health care, and national defense [1]. Sensor nodes generally come with a disposable battery powered, and their energy is very limited; therefore, the design of routing protocol is the key. In recent years, many researchers have proposed a variety of WSN routing algorithms. Among them, the clustering protocols are concerned by the researchers. LEACH is a clustering routing algorithm [2], in which each node has a certain probability of becoming a cluster head per round, and data deliver directly to BS by single-hop. Previous research has proved that

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W.E. Wong and T. Zhu (eds.), *Computer Engineering and Networking*, Lecture Notes in Electrical Engineering 277, DOI 10.1007/978-3-319-01766-2_19,

multihop routing communication can save more energy [3], but it easily leads to dissipation of energy and the hot spots problem [4]. An energy-efficient unequal clustering (EEUC) algorithm was proposed [5], but it still has the following problems (1) the candidate cluster heads are selected by a preset probability, sensors with low residual energy can still become candidate cluster heads, and their energy is consumed in the election of final cluster heads. The energy of nodes is more imbalanced in the network. (2) The ordinary nodes join the cluster whose signal is the strongest, but it does not consider that some nodes near BS which send directly to BS will consume smaller energy than indirectly. (3) The method of multihop routing is unreasonable, resulting in waste of energy.

In view of the above problems, this chapter presents an energy-balanced uneven clustering routing algorithm for wireless sensor networks (EBUC). It owns the following advantages (1) differentiated from randomly producing candidate cluster heads, the EBUC selects candidate cluster head whose residual energy is not less than the cluster average energy, and the residual energy of nodes is quantified as the time for driving the cluster heads election. The selected cluster heads own high energy, and the message complexity of the cluster formation algorithm is reduced. (2) By defining the independent nodes, the loads of some cluster heads are reduced nearby BS. (3) The routing algorithm based on angle is proposed, reducing the intercluster energy consumption.

19.2 Network Model

The network consists of N sensor nodes, which are randomly deployed over a vast field. Each node has a unique ID in the network, and we assume it has the following characteristics.

1. All sensor nodes are energy heterogeneous, whose positions are fixed, and have the capability of sensing signal emission angle.
2. BS has endless energy, a strong computing and storage capacity.
3. If transmission power is known, the distance between the sender and the receiver can be calculated [6].
4. Sensors can use power control to vary the amount of transmission power which depends on the receiver.

We use a simplified model in which the radio hardware energy dissipation consists of the sending circuit loss and the power amplifier loss [7]. As shown in Eq. (19.1), both the free space (d^2 power loss) and the multipath fading (d^4 power loss) channel models are used in the model, depending on the distance between the transmitter and receiver. The energy spent for transmission of an l-bit packet over distance d is

$$E_{Tx}(l,d) = \begin{cases} lE_{elec} + l\varepsilon_{fs}d^2, d < d_o \\ lE_{elec} + l\varepsilon_{mp}d^4, d \geq d_o \end{cases} \tag{19.1}$$

Equation (19.2) shows energy consumption, when the node receives this packet.

$$E_{Rx}(l) = lE_{elec} \tag{19.2}$$

A cluster head consumes E_{DA} amount of energy for data aggregation. We also assume that the sensed information is highly correlated, so the cluster heads can always aggregate the data received from its members into a single length-fixed packet.

19.3 The EBUC Mechanism

After the deployment of sensor nodes, BS broadcasts BS_MSG to the entire network with the determined power. Each node calculates the distance to BS by the receiving signal strength. We need to control the range of competition radius in the network and set R_c of s_i as Eq. (19.3).

$$s_i.R_c = \left(1 - c \cdot \frac{d_{\max} - d_{s_i - BS}}{d_{\max} - d_{\min}}\right) \cdot R_c^0 \tag{19.3}$$

c is a constant coefficient between 0 and 1. d_{max} and d_{min} represent the maximum and minimum distance between sensor nodes to BS. d_{s_i-BS} is the distance from s_i to the BS. R_c^0 is the maximum competition radius which is predefined. According to Eq. (19.3), R_c varies from $(1 - c)R_c^0$ to R_c^0. As an example, if c is set to ⅓, R_c varies from ⅔ R_c^0 to R_c^0 according to its distance to BS.

19.3.1 *Election of Cluster Heads*

In many WSNs applications, the network node density is large, so it is not necessary for all nodes to become the candidate cluster heads. E_{ave} is the energy threshold, which is the cluster average remaining energy in the last round. If the residual energy of some node is not less than E_{ave}, it will become a candidate cluster head, and its competition time t is calculated in Eq. (19.4).

$$t = \alpha \cdot T_{CH} \cdot \frac{E_{\max} - E_i}{E_{\max} - E_{ave}}, E_i \geq E_{ave} \tag{19.4}$$

T_{CH} is a period of time for the cluster head election. E_i represents the residual energy of s_i. E_{max} means the maximum residual energy of the intercluster nodes in the last round. $\alpha \in (0.9,1)$ is a random number which is used to avoid the collisions of HEAD_MSGs which are caused by the nodes owning same residual energy.

In the election, the candidate cluster heads broadcast HEAD_MSGs (containing the node ID, the competition radius R_c, and competition time t) by radius R_c^0 at their competition time t, in order to declare that they win. The adjacent candidate cluster head set of s_i is defined as $s_i.N_c = \{s_j | d_{s_i - s_j} < \max(s_i.R_c, s_j.R_c)\}$. When the sensors receive HEAD_MSGs from N_c, they will quit their own election process. After T_{CH}, all cluster heads are selected, and then they broadcast CH_ADV_MSGs.

19.3.2 The Formation of Clusters

After all cluster heads are selected, the nodes are divided into the ordinary nodes and the cluster heads. T_r is a threshold for distinguishing the ordinary nodes. If the distance between an ordinary node and BS is less than T_r, the ordinary node is divided into the first class nodes. Otherwise, it is divided into the second class nodes. We assume that s_i is one of the first class nodes, CH is the nearest cluster head to s_i, and the distance between the two is recorded as $d_{CH\text{-}BS}$. According to Eqs. (19.1) and (19.2), when k-bit packet is transmitted to BS by single-hop, the energy consumption is shown in Eq. (19.5).

$$s_i.E_{direct} = k \cdot E_{elec} + k \cdot \varepsilon_{fs} \cdot d_{s_i - BS}^2 \tag{19.5}$$

If s_i sends k-bit packet to BS via CH, the energy consumption is shown in Eq. (19.6).

$$s_i.E_{CH} = k \cdot \left(E_{elec} + \varepsilon_{fs} \cdot d_{s_i - CH}^2\right) + k \cdot E_{elec} + k \cdot E_{DA} \tag{19.6}$$

Comparing E_{direct} with E_{CH}, we know that by which energy consumption is lower.

$$s_i.E_{CH} - s_i.E_{direct} = k \cdot \left(E_{elec} + E_{DA} + \varepsilon_{fs} \cdot d_{s_i - CH}^2 - \varepsilon_{fs} \cdot d_{s_i - BS}^2\right) \tag{19.7}$$

Order $H = (E_{elec} + E_{DA})/\varepsilon_{fs}$, then:

1. If $d_{s_i - BS}^2 - d_{s_i - CH}^2 \le H$, that is $s_i.\ E_{CH} - s_i.\ E_{direct} \ge 0$. Energy consumption that s_i sends data directly to BS is smaller than indirectly. s_i is defined as an independent node and sends a JOIN_BS_MSG to BS.
2. If $d_{s_i - BS}^2 - d_{s_i - CH}^2 > H$, that is $s_i.\ E_{CH} - s_i.\ E_{direct} < 0$. Energy consumption that s_i sends packet indirectly to BS is lower than directly, and s_i joins the nearest cluster.

For far from BS, the energy consumption is extremely high, when the second class nodes send packet directly to BS, so they send JOIN_CH_MSGs to join the nearest cluster. When all clusters are established, a Voronoi diagram [5] is formed in the network.

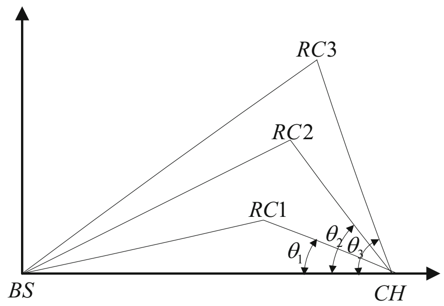

Fig. 19.1 The relay node model

19.3.3 Data Transmission

From the adjacent cluster head set of CH, the cluster heads which satisfy the condition of $0 \le \theta < \pi/2$ within the range of $n \times R_c^0$ are selected to constitute N_{RC} which is the candidate relay set of CH. n is the smallest positive integral, which makes that N_{RC} non-null. θ is an angle and measured by CH. As shown in Fig. 19.1, we assume N_{RC} of CH contains RC1, RC2, and RC3 and $\theta_1 < \theta_2 < \theta_3$.

If CH chooses RC1 as the relay node, we assume a free space propagation channel model, and RC1 communicates with BS directly. To deliver an *l*-length packet to BS, the energy consumed by RC1 and CH is

$$\begin{aligned} E_{2hop} &= E_{Tx}(l, d_{CH-RC1}) + E_{Rx} + E_{Tx}(l, d_{RC1-BS}) \\ &= 3lE_{elec} + l\varepsilon_{fs}\left(d^2_{CH-RC1} + d^2_{RC1-BS}\right) \\ &= 3lE_{elec} + l\varepsilon_{fs}\left(d^2_{CH-BS} + 2d^2_{CH-RC1} - 2d_{CH-BS}d_{CH-RC1}\cos\theta_1\right) \end{aligned} \tag{19.8}$$

According to Eqs. (19.1) and (19.2), thus we define

$$\cos t1 = d^2_{CH-RC1} - d_{CH-BS}d_{CH-RC1}\cos\theta_1 \tag{19.9}$$

Among them, d_{CH-RC1} means the distance between CH and RC1. After CH is placed in position, d_{CH-BS} is a constant, which means the distance between CH and BS. Similarly, we can calculate cost2 of RC2 and cost3 of RC3. Because of cost1 < cost2 < cost3, RC1 is selected as the relay node of CH.

19.4 Algorithm Analysis and Simulation

19.4.1 Message Complexity

Lemma 1 *The message complexity of the cluster formation algorithm is $O(N)$ in the network.*

Table 19.1 Simulation parameters

Parameter	Value	Parameter	Value
Network coverage	(0,0)~(200,200) m	E_{elec}	50 nJ/bit
BS location	(0,250)	ε_{fs}	10 pJ/(bit·m^2)
N	400	ε_{mp}	0.0013 pJ/(bit·m^4)
Initial energy	0.50 ± 0.01 J	d_o	87 m
Data packet size	4,000 bits	E_{DA}	5 nJ/(bit·signal)

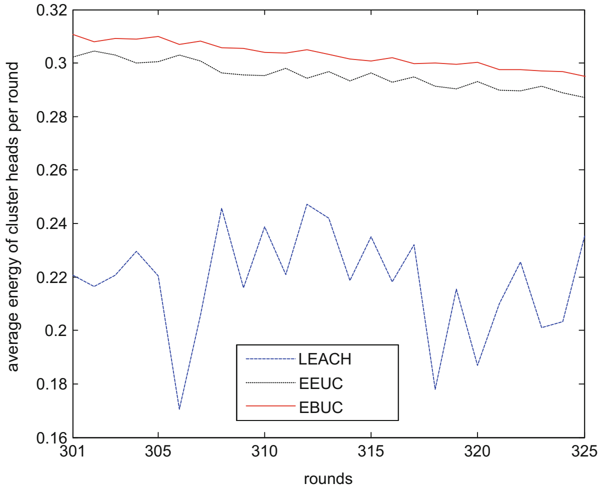

Fig. 19.2 Cluster heads average energy

Proof At the beginning of the cluster head selection phase, $N \times T$ candidate cluster heads are produced, and each of them broadcasts a HEAD_MSG. If it has x cluster heads and y independent nodes, it will send out x CH_ADV_MSGs and y JOIN_BS_MSGs, and then the ordinary nodes will send $N - x - y$ JOIN_CH_MSGs. So the messages add up to $N \times T + x + y + N - x - y = N (T + 1)$ per round. The message overhead of EBUC is $N \times T$ smaller than EEUC.

19.4.2 Simulation Analysis

To illustrate the energy efficiency of EBUC, we use MATLAB to simulate LEACH, EEUC, and EBUC under an ideal condition, and packet loss and delays are ignored. The energy consumption of data aggregation and transmission is measured in the experiment. Firstly, survival time of the network is measured, and the energy efficiency of EBUC is analyzed. Secondly, the residual energy and energy consumption characteristic of cluster heads are analyzed. The simulation parameters are shown in Table 19.1.

Figure 19.2 is the cluster heads average energy curve of three protocols in 25 randomly selected rounds, and it shows that the cluster heads average energy

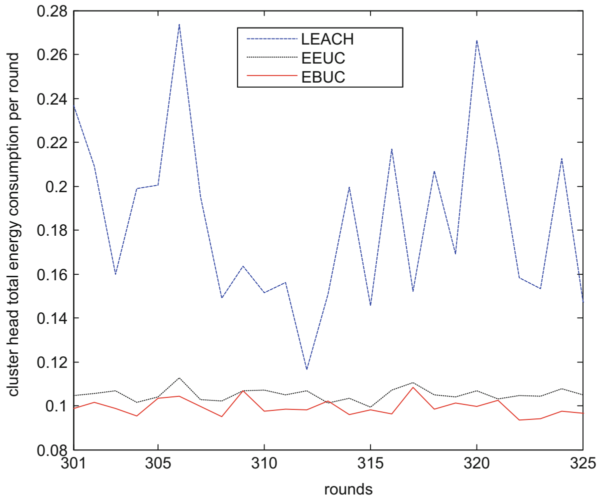

Fig. 19.3 Cluster heads energy consumption

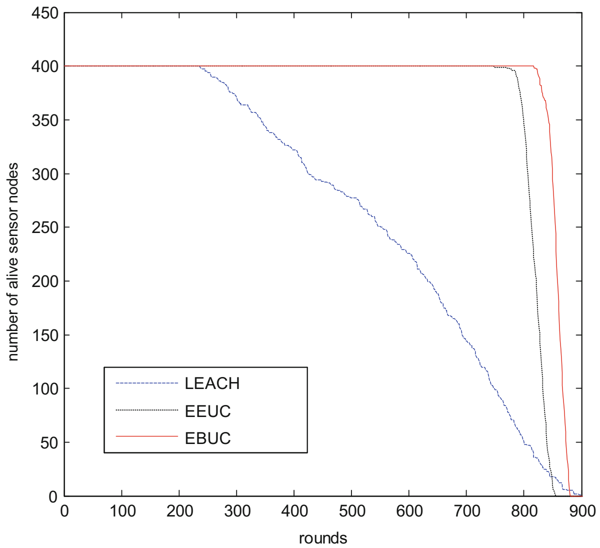

Fig. 19.4 Number of survival nodes curve

of EBUC is the highest of the three algorithms. Figure 19.3 is the comparison of cluster heads total energy consumption of three protocols in 25 randomly selected rounds. It shows that the total energy consumption of EBUC is the lowest of the three algorithms.

Finally, we examine the network lifetime of three algorithms. Figure 19.4 shows that EBUC clearly improves the network lifetime over LEACH and EEUC. In EEUC, candidate cluster heads are randomly selected. Therefore, sensors with low residual energy can still become candidate cluster heads, and their energy is consumed in the election of final cluster heads. Such is avoided in EBUC. Multihop routing based on angle is used in EBUC, so its energy consumption of EBUC is lower than EEUC as illustrated in Fig. 19.3. Comparing to EEUC, stable period of EBUC is increased by 10.6 %. Simulation results show (1) EBUC is able to effectively balance the energy consumption of nodes in the network and extend the network survival time. (2) The cluster heads of EBUC own the highest average energy and capacity of data transmission of the three algorithms. (3) The energy consumption of EBUC cluster heads is the smallest of the three algorithms.

19.5 Conclusion

The article proposes an energy-balanced uneven clustering WSN routing algorithm EBUC. The main idea is that the candidate cluster heads are produced by the candidate threshold and their own competition time, so it avoids that the candidate cluster heads are produced randomly and at the same time the message complexity is reduced. Then, it introduces the concept of the independent nodes to reduce some cluster head loads, and the intercluster route is optimized by the factor of multihop energy consumption for saving energy of cluster heads. Simulation results show that the cluster heads energy of EBUC is the highest of the three algorithms, and its energy consumption is the lowest, and it can efficiently prolong the network lifetime.

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