Uneven clustering routing protocol based on ant colony algorithm for wireless sensor networks

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Abstract. For the energy of the wireless sensor network node is limited, an uneven clustering routing protocol is proposed for wireless sensor networks. In the protocol, cluster head election uses a competitive manner, and all nodes in the first round participate in the election. The cluster head election considers the remaining energy, the number of neighboring nodes, and the distance between node and sink. The path search from the cluster head to the base station runs the ant colony algorithm to find the optimal multi-hop route. Each round no longer clusters, and re-clustering and routing will update only when the remaining energy of the cluster head is less than the predicted energy. The protocol enables its routing establishment and maintenance more self-adaptive and dynamic. The simulation shows that the routing protocol can efficiently reduce and balance the energy consumption, and prolong the wireless sensor network survival period.

1. Introduction
The wireless sensor network usually consists of a large number of sensor nodes and a base station for collecting and transmitting data. The sensor nodes are arranged in the monitoring area, the network is by self-organization, and the collection data is transmitted to the control center. The wireless sensor networks have been widely used in environmental monitoring, agricultural maintenance, and military fields due to its random deployment and self-organization.

A large number of wireless sensor nodes in a wireless sensor network are powered by limited and irreplaceable power supply. When the node is exhausted, the network will have energy hole and will not work. Therefore, energy is an important resource of wireless sensor nodes. So, how to extend the service life of networks becomes the focus of wireless sensor networks. Research on energy-saving routing protocols for wireless sensor networks is essential.

To effectively balance energy consumption of wireless sensor networks, some typical clustering routing protocols have been proposed by researchers. The LEACH protocol[1] proposed by Heinzelman is a typical uniform clustering routing protocol in wireless sensor networks. In the protocol the entire network is divided into multiple clusters of the same size, each cluster consists of one cluster head and multiple cluster members. In the protocol the cluster head sends data in a single hop, which easily causes the cluster head far away from the sink node to consume large energy and die prematurely.
The existing research[2] shows that multi-hop mode is more conducive to energy saving between the cluster head and the base station. In uniformly clustered wireless sensor networks, whether the cluster head communicates with the base station in a single hop or multi-hop mode, there will be a "hot zone" problem. For this problem, Soro et al. first proposed a non-uniform clustering algorithm (UCS)[3], which is based on a two-layer concentric ring network surrounding a base station. The cluster head located in the inner ring is closer to the base station, has less cluster members, so can save energy to forward data. The EEUC algorithm[4] uses an uneven competitive radius for clustering, with fewer cluster members close to the base station to save energy for data forwarding; multi-hop routing between clusters, and considering the remaining energy of the next node. The experimental results of EEUC algorithm show that the algorithm can effectively balance energy consumption and prolong the network life cycle. The DEBUC[5] protocol also adopts the method of uneven clustering and multi-hop routing between clusters. The cluster head competition is based on time. The time depends on the remaining energy of the candidate cluster head and neighbor nodes. The cluster head closer to the base station has a smaller competition radius, can save energy for forwarding data. The experimental results of DEBUC algorithm show that the algorithm can effectively save energy of a single node, balance energy consumption, and prolong the network life cycle.

However, in the EEUC and DEBUC protocols, according to the probability and threshold to select the cluster head, many nodes with less energy will participate in cluster head campaign and can’t guarantee the optimal node to win, and the protocols do not take into account the link quality. The research in literature [6], on the basis of uneven clustering, path search in cluster head communication is optimized by ant colony algorithm and link reliability and real-time parameters are introduced, but the link quality is not considered. The research in literature [7] has proposed uneven clustering routing algorithm based on minimum spanning tree (CSMST). In the algorithm, only the transmission energy consumption and the remaining energy of the cluster head are used as the network structure parameters, and the link quality is not considered.

In this paper, based on EEUC and CSMST protocol, an improved uneven clustering routing protocol is designed. The protocol adopts uneven clustering and multi-hop routing. The cluster head is selected by the remaining energy and the number of the neighboring nodes. The competition radius of the candidate cluster head which is close to the base station is smaller and the number of the neighboring node is less in the cluster. The cluster head close to the base station consumes less energy in intra-cluster communication to save energy for data forwarding, so that energy consumption can be balanced. The multi-hop routing between the clusters uses the ant colony algorithm to optimize path. The ant colony algorithm combines the hop count, the link quality, and the remaining energy of the next hop cluster head. Experiments show that the protocol can solve the "hot zone" problem in multi-hop communication mode, and the energy is balanced, which can effectively extend the life cycle of wireless sensor networks.

2. Related model

2.1. Network model

This routing protocol inherits the uneven clustering structure of EEUC and CSMST. Similar to EEUC and CSMST, we assume the following network model.

(1) Nodes are randomly distributed in a specific area, all nodes are fixed and energy is limited, and the base station is fixed in position and energy is not limited;
(2) Each node has a unique identification number;
(3) Each node has the same communication and data processing capabilities;
(4) The node can freely adjust the transmission power according to the distance;
(5) Nodes can form two-way symmetric links to communicate with each other. If the transmission power is known, the node can calculate the approximate distance of the sender to itself based on the received signal strength.
2.2. Communication Model
This paper adopts the same wireless communication energy consumption model as the literature [1]. The energy consumption of the sensor node mainly includes the energy consumption of the transmitted data $E_{Tx}(l, d)$ and the energy consumption of the received data $E_{Rx}(l)$. The energy consumption formula is as follows:

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

$$E_{Rx}(l) = l \times E_{elec}$$ \tag{2}

In this formula, $E_{Tx}(l, d)$ refers to energy consumption for transmitting $l$-bit data, $E_{Rx}(l)$ refers to the energy consumption for receiving $l$-bit data, $d$ refers to the distance of transmitting data, $E_{elec}$ refers to circuit energy consumption of node sending unit data, $d_0$ refers to the threshold value. When the distance of sending data is less than $d_0$, the energy consumption uses the free space mode. When the transmission distance is greater than or equal to $d_0$, the energy consumption adopts the multipath attenuation model. $\epsilon_{fs}$ refers to the energy required for power amplification in the free space mode, $\epsilon_{mp}$ refers to the energy required for power amplification in the multipath attenuation model.

3. The protocol
This protocol includes cluster head selection and multi-hop routing between the cluster head.

3.1. Communication Model
The cluster head election of the protocol preserves the unequal distributed competition mode of EEUC. The protocol uses the distance, the residual energy of the neighbor nodes, and the node number in the cluster as the main parameters. Each node saves a neighbor node table to store information about neighbor nodes. The content of neighbor table is as follows in Table 1.

| Node identifier | Residual energy | Distance from the node | Neighbor node number | Weight |
|-----------------|-----------------|-----------------------|----------------------|--------|
| ID              | $e$             | $d$                   | num                  | $w$    |

Node regards all other nodes within radius ($R_i$) of the node as its neighbor nodes, NC$i$ is the neighbor node set of node $i$. The value of $R_i$ is calculated by the following formula (3).

$$R_i = \left(1 - c \frac{d_{\text{max}} - d(n_i, DS)}{d_{\text{min}} - d_{\text{min}}} \right) R^c$$ \tag{3}

$R^c$ refers to the pre-defined maximum radius. $d_{\text{max}}$ refers to the maximum distance between the node and base station. $d_{\text{min}}$ refers to the minimum distance between the node and base station. $c$ is a value between 0 and 1. The parameter of $c$ is used to control the range of values. $d(n_i, DS)$ refers to the distance between the node $n_i$ and base station DS.

In the cluster head election stage, each node defines a weight function. The definition of the weight function includes the neighbor number of the node, the remaining energy and the distance from the node to the base station.

The weight function is expressed as follows.

$$w(i) = \alpha \cdot \text{num} + \beta \cdot e_i$$ \tag{4}

$\alpha$ and $\beta$ are weighted parameters and $\alpha + \beta = 1$. num refers to the neighbor node number, $e_i$ refers to residual energy of node $i$. The weighted parameters can be adjusted according to different application scenarios. The node with the largest weight in the election radius is considered to be the node that can become the candidate cluster head.
Algorithm 1. Cluster head election algorithm.

For base station DS
1: Broadcast START message to all node
For every node in the network
2: Compute \(d(n_i, DS)\) according to START
3: Compute \(R_i\) according to Eq.(3)
4: Broadcast HELLO \((ID,R_i,e_i)\) message
5: On receiving HELLO message
6: Compute neighbor node number num
7: Compute \(w(i)\) according to Eq.(4)
8: Broadcast WEI \((w_i)\) message
9: For every node in the NC_i
10: If \(\forall n_j \in NC_i\) and \(w(i) > w(j)\) then
11: Broadcast ADV \((ID)\) message
12: End if
13: On receiving ADV from \(n_i\)
14: If \(n_j \in NC_i\) then
15: Broadcast QUIT \((ID)\) message
16: \(n_j\) become an ordinary node
17: End if
18: On receiving QUIT from \(n_j\)
19: If \(n_j \in NC_i\) then
20: Remove \(n_j\) from NC_i
21: End if
22: For every head node \(n_i\)
23: Broadcast CH \((ID)\) message
24: On receiving CH from \(n_i\)
25: Add \(n_j\) to NC_i accord to RSSI
26: Send JOIN \((ID, d(n_i, DS), e_j)\) message to \(n_i\)
27: Clustering completed
28: Each cluster head broadcasts the message of the successful election to the whole network.

In the algorithm, first, the base station sends START message to all nodes, and the node computes the distance \(d(n_i, DS)\) between the node and base station accord to the START message, then computes \(R_i\) according to the formula (3). Each node sends HELLO message which includes node identifier, radius, and residual energy. The node computes neighbor node number DUI on receiving HELLO message. Each node updates its neighbor node information table. After a set period of time \(t\), each node calculates the weight of the node according to the weight formula (4). The node then broadcasts WEI message to the neighbor node. When the neighbor node receives the WEI message, the node updates its neighbor node information table again. The next step is the competition cluster head stage, the node whose weight value is greater than all neighbor nodes succeeds in the election and broadcasts the ADV information to notify its neighbor nodes, and declares itself to be the cluster head. When the neighbor node \((n_i)\) receives the ADV information, it exits the election and broadcasts the QUIT message to notify its neighbor node. When the other node \((n_i)\) receives the QUIT from the node \((n_j)\), it will be removed from the NC_i collection. After cluster head selection is completed, the cluster head generated by the competition broadcasts its CH message to the whole network. The ordinary node selects the cluster head according to the highest received signal strength, and sends a JOIN message to
notify the cluster head to join the cluster. The JOIN message includes node identifier, distance to the base station, and residual energy. So far, the network clustering has been completed.

3.2. Multi-hop Routing between Clusters

In the stage that cluster heads send data to the base station, the cluster head first fuses the cluster member data and then runs the ant colony algorithm to find the optimal path from the cluster head to the base station for data transmission through multi-hop mode. The ant colony algorithm[8] is used to construct the optimal path by the guidance of pheromone traces and heuristic information. After clustering, each cluster head establishes a routing table for recording path information, as shown in Table 2.

| Table 2. Routing table of cluster node i |
|-----------------------------------------|
| Identifier of cluster head | \( s_i \) |
| Residual energy | \( e_i \) |
| Passing distance | \( d_i \) |
| Pheromone concentration | \( \tau_{ij} \) |
| Total energy consumption | \( e_{ij} \) |
| Probability | \( p_{ij} \) |
| One hop energy consumption | \( e_i' \) |

**Algorithm 2** Multi-hop routing algorithm.

1: The base station sends the ant (A0) to the cluster head. The ant (A0) carries information which includes the destination cluster head (\( s_{ij} \ID \)), the distance to the base station (\( d(s_{ij}, DS) \)), the last passing node’s \( s_{ij} \ID \) and residual energy (\( e_{ij} \)), and the total energy consumption (\( e_i' \)) and distance traveled (\( d_i' \)). The initial value of \( e_i' \) and \( d_i' \) is 0.

2: while \( s_{ij} \ID \neq s_i \ID \)

3: if the ant of A0 arrives at the cluster head (\( s_i \))

4: if \( d(s_{ij}, s_o) < d(s_{ij}, s_o) \) and \( d(s_{ij}, DS) > d(s_{ij}, DS) \)

5: if \( d(s_{ij}, DS) < d(s_{ij}, DS) \) and \( s_i \) has not received ant of A0 from \( s_j \)

6: Add record to routing table of \( s_i \)

7: Update the information of A0 carried by the ants

8: Forward the information of A0

9: end if

10: end if

11: end if

12: end while

13: After the ants are all released, each cluster head of \( s_i \) calculates the initial pheromone concentration to the neighbor cluster head of \( s_j \) according to the routing table. The formula for calculating the pheromone concentration is as follows.

\[
\tau_{ij} = 1 - (e'_{ij}) / \sum_{k \in C_j} (e'_{jk})
\]
14: Calculate the probability($p_{ij}$) that $S_i$ will use $S_j$ as the next hop according to formula (6).

$$p_{ij} = \frac{[\eta_{ij}]^\lambda}{\sum_{k \in C_i} [\eta_{ik}]^{1-\lambda}}$$  \hspace{1cm} (6)

$$\eta_{i,j} = e_{ij} + e_{ij}^c - e_{ij}^c$$  \hspace{1cm} (7)

In the lines from 2 to 12, the ant searches for the path from the base station to the cluster head. When the ant($A_o$) of $S_j$ reaches the cluster head($S_i$), if $d_{us} < d_{us}$, $d(s_j,DS) > d(s_j,DS)$, $d(s_j,DS) < d$ and $S_i$ have not received the ant($A_o$) from $S_j$ are met, the record is added to the routing table of $S_i$ and the information carried by the ant($A_o$) is updated. The record information in the routing table of $S_i$ includes total energy consumption($e^t$ ($e^t = e^t + e_j^c$)), passing distance( $d^t$ ($d^t = d^t + d(s_j,s_j)$)), identifier of cluster head, residual energy($e_j$), one hop energy consumption($e_j^c$) and one hop distance($d(s_j,s_j)$). The updated information of the ant($A_o$) includes: replacing the node of $S_j$ with $S_i$, replacing the remaining energy ($e_j$) of the node($S_j$) with the remaining energy ($e_i$) of the node($S_i$), updating the total distance($d^t$) and total energy consumption($e^t$) in the ant($A_o$). Finally the cluster head of $S_i$ forwards the ant($A_o$) until the ant reaches the cluster head of $S_o$. In line 13, the initial pheromone concentration is calculated from the cluster head($S_i$) to the neighbor cluster head. In line 14, the probability of the cluster head($S_i$) with the neighbor cluster head as the next hop is calculated.

In formula (6) and formula (7), the factor of $\lambda$ is the regulatory factor. The factor of $\eta$ is the local heuristic value that the cluster head of $S_i$ uses the cluster head of $S_j$ as the next hop. The more residual energy ($e_i + e_j - e_j^c$) of the two cluster heads after forwarding the data, the more energy is saved, the greater the probability of being selected as the next hop.

3.3. Data Transmission

Data transmission is divided into intra-cluster transmission and inter-cluster transmission. The cluster head transmits data to the base station through inter-cluster multi-hop routing.

In inter-cluster transmission, the cluster head of $S_i$ selects the cluster head of $S_j$ as the next hop according the highest probability ($P_{ij}$). In the data transmission process, the information of the number of packets and forwarding delay is counted. After the transmission is successful, the pheromone is updated according to formula (8). In order to save energy, the pheromone is updated only after the link successfully sends a certain number of packets.

$$\tau_{ij} = (1 - \rho) \cdot \tau_{ij} + \rho \cdot \Delta \tau_{ij}$$  \hspace{1cm} (8)

$$\Delta \tau_{ij} = \omega \frac{m_{ij}}{n_i} + (1 - \omega) \frac{t_{ij}}{t_{\text{max}}}$$  \hspace{1cm} (9)

In the formula (8) and (9), $\rho$ refers to the pheromone volatilization parameter, $\omega$ refers to an adjustment factor, the value of $\rho$ and $\omega$ are between 0 and 1. $n_i$ refers to the number of packets
which are sent by the node of \( s_i \) during the time of \( t \cdot m_j \) refers to the number of packets which are received by the node of \( s_j \) during the time of \( t \cdot m_j / n_i \) refers to link quality. \( t_{ij} \) refers to time delay in transmitting data from the node of \( s_i \) to the node of \( s_j \). \( t_{\text{max}} \) refers to the maximum delay for single hop. It can be seen from the formula (8) and (9) that the higher the link quality between adjacent cluster heads and the shorter the delay, the greater the pheromone concentration on the path and the greater the probability of being selected as the next hop.

4. Results and analysis

In this paper, we choose OPNET to carry out the simulation experiment, and compare with EEUC protocol and CSMST protocol. The experimental simulation parameters are shown in Table 3.

| Parameter          | Value       | Parameter          | Value       |
|--------------------|-------------|--------------------|-------------|
| Area               | 100m×100m   | Packet size        | 500bit      |
| Number of nodes    | 100         | Packet size carried by an ant | 30bit      |
| Base station coordinates | (10, -50) | Initial energy of the node | 0.2J      |
| \( \epsilon_{np} \) | 0.013 pJ/(bit·m²) | \( R_c \) | 22m        |
| \( \epsilon_{js} \) | 100pJ/(bit·m²) | \( c \) | 0.5        |
| \( E_{\text{elec}} \) | 50nJ/bit   | \( \alpha, \beta \) | 0.5,0.5    |
| \( d_o \)          | 80m         | \( \rho \)         | 0.5        |

After the clustering is completed, the time interval of sending ants by cluster heads is set to 5 seconds, and all cluster heads send a packet every 2 seconds. Figure 1 shows the change of network energy consumption with the rounds. Figure 2 shows the number change of the total survival nodes with the rounds.

![Figure 1. Network energy consumption](image1)

![Figure 2. Number of alive nodes](image2)

It can be seen from Figure 1 that the algorithm in this paper uses the ant colony algorithm, which has the lowest network energy consumption than EEUC protocol and CSMST protocol. The algorithm in this paper can better balance the energy consumption between nodes, and thus the network lifetime is extended.
It can be seen from Figure 2 that the node death time of the algorithm in this paper is the latest. This is because the degree of cluster head, residual energy and distance to base station are taken into account in the algorithm, and the cluster is no longer clustered in every round. The multi-hop communication between clusters using ant colony algorithm is more conducive to balancing energy consumption. Whether it is the first node death time or the last node death time, the algorithm in this paper is better.

5. Conclusion
This algorithm of the paper refers to the idea of uneven clustering. In view of the shortcomings of existing protocols, the neighborhood node number and residual energy are fully taken into account in the selection of cluster head, and the cluster head is no longer clustered in every round. In inter-cluster routing, ant colony optimization is adopted to effectively reduce and balance network energy consumption. It can also adaptively search for routes with better performance and lower cost.

The simulation results show that compared with EEUC protocol and CSMST protocol, the network survival time of this algorithm of the paper is much higher, and the network energy consumption is also greatly improved, which prolongs the life cycle of the network. The next step will be to study the optimal solution of various parameters for different network sizes.

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