An Energy-efficient Clustering Routing Algorithm for Heterogeneous Wireless Sensor Networks

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Abstract. In wireless sensor networks, clustering has the advantages of low energy consumption, simple routing scheme and good scalability, and is widely adopted. How to reduce the energy consumption while prolonging the network lifetime stays the key problem though. In this paper, a Density-based Energy-efficient Clustering Heterogeneous Algorithm (DECHA) is proposed for routing. Following the thoughts of LEACH, the election probability of nodes to become cluster heads is evaluated. With regard to the probability, we have density refer to the position information of a node, and together with its energy capacity serve as primary weighted metrics. Further evaluation is done for a better selection of cluster heads. Simulation results show that total energy consumption is reduced and lifetime of the network is prolonged compared with LEACH.

Keywords: wireless sensor networks, heterogeneous, clustering, density

1 Introduction

Routing in Wireless Sensor Networks (WSNs) [1] has been the subject of intense research efforts for years. As the battery, capability of computing, storage and data processing of a sensor are limited, how to reduce the energy consumption while prolonging the network lifetime stays the key problem.

Clustering is widely adopted in WSNs, where the entire network is divided into multiple clusters. Clusters have cluster heads (CHs) be responsible for data aggregation. It has the advantages of low energy consumption, simple routing scheme and good scalability, and it reduce the energy hole problem to some extent. Most traditional clustering routing protocols for WSN are based on homogeneous networks where all sensor nodes are identical in terms of battery energy and hardware configuration. However, due to the variation of nodes’ resources and possible topology change of the network, heterogeneous senor networks [2] are more practical in reality. The presence of heterogeneous nodes with enhanced capacity is known to increase network reliability and lifetime. [3]

In this paper, we have some senor nodes equipped with additional energy resources than other normal nodes. We have assumed that all sensor nodes are
uniformly distributed. We propose a Density-based Energy-efficient Clustering Heterogeneous Algorithm (DECHA). Following the thoughts of LEACH [4], it is based on weighted election probabilities of each node to become cluster heads. In DECHA, we consider the position information of nodes, define the density of each node as the number of its neighbor nodes, and together with the energy capacity, regard it as an important evaluation metric for electing candidate CHs. DECHA also sets further adjustments to seek more proper CHs, thus promote both lifetime and energy-efficiency.

2 Related Work

Various popular algorithms are examples of cluster based protocols that are designed for homogeneous WSNs. LEACH [4] is a typical clustering algorithm. In a periodical way, it randomly chooses the cluster heads. Ref. [5] is an improvement over LEACH. It's a chain-based protocol. Each node communicates only with a close neighbor and takes turns to transmit data to the sink. In Ref. [6], cluster heads are decided based on the average minimum reachability power. Unequal clustering algorithms like Ref. [7] aim to reduce the energy hole problem. For the clusters, the closer they are to the sink, the smaller size they are formed.

Election of cluster heads plays a significant role. In many researches, nodes’ position and connectivity have been focused. Ref. [8] uses fuzzy logic technique considering two factors: neighbor nodes and remaining energy. Cluster heads elected in Ref. [9] are determined to have minimum composite distance of sensors to cluster head and cluster head to base station. In Ref. [10], the cluster-head selection depends on remaining energy level of sensor nodes for transmission. Ref. [11] provides the first trajectory based clustering technique for selecting CHs and meanwhile extenuate the energy hole problem. Ref. [12] improves LEACH based on a metric of nodes’ relative density.

Heterogeneous algorithms are also introduced. Ref. [13] is a heterogeneous-aware protocol that sets two types of nodes according to the initial energy. In Ref. [14], the cluster-heads are elected by a probability based on the ratio between the residual energy of each node and the average energy of the network. Ref. [15] has cluster heads respectively perform data fusion and data communication. Nodes with higher residual energy, lower communication cost and more strong data processing capacity will be prior to become the cluster-head. In Ref. [16], weighted election probabilities of each node to become a cluster head are set according to the residual energy in each node. Ref. [17] introduces a weighted factor which can be adjusted to optimize the election probability of an advanced node or a normal one to be a cluster head. Relationship of heterogeneous parameters is discussed. Ref. [18] studies on a three-level heterogeneous network. Considers the occasion that all normal, advance and super nodes have same probability for CH selection and define the absolute residual energy level to avoid unnecessary punishment. Ref. [19] is dynamic and depends on local (inter-cluster) information of about energy remaining in sensor nodes without requirement of global knowledge of residual energy of the network.
3 Our Proposed DECHA

3.1 Relevant Models

We consider the scenario that the network is composed of $N$ sensor nodes, denoted as: $\{s_1,s_2,...,s_N\}$ respectively. They are randomly deployed in a $M \times M$ square region. The nodes always have data to transmit to a base station, denoted as $BS$, which is assumed to be at the center of the area. They continuously monitor the surrounding environment. We make the following assumptions:

1) Sensor nodes are heterogeneous as some are equipped with relative larger energy than others.

2) Nodes can adjust their transmission power according to the relative distance to receiver

3) Links are symmetric.

For energy calculation, we use the same energy model in Ref. [20]. Each sensor node will consume the following $E_{Tx}$ amount of energy to transmit a $l$-bits packet over distance $d$, where the $E_{elec}$ is the energy dissipated per bit to run the transmitter or receiver circuit, $\epsilon_p$ and $\epsilon_{mp}$ represent the transmitter amplifier’s efficiency and channel conditions:

$$E_{Tx}(l,d) = \begin{cases} 
E_{elec} + l \epsilon_p d^2, & d < d_a \\
E_{elec} + l \epsilon_{mp} d^2, & d \geq d_a
\end{cases}$$

(1)

To receive a packet, radio consumes energy:

$$E_{Rx}(l) = lE_{elec}$$

(2)

Cluster heads aggregate $n$ $l$-bits packets received from its members into a single $l$-bits fixed packet. The energy consumption is calculated as, where $E_{DA}$ is the data aggregation cost of a bit per signal:

$$E_{aggregation}(n,l) = nE_{DA}$$

(3)
3.2 Selection of Cluster Heads

In DECHA, the density of a node $Den_i$ is set to represent the number of neighbor nodes located within its transmission range. We set parameter $\alpha$ to represent the relative $Den_i$ of nodes:

$$\alpha = \frac{\text{Den}(s_i)}{\text{Den}_{\text{avg}}} = \frac{\text{Den}(s_i)}{\sum_{i \in N} \text{Den}(s_i) / N}$$

(4)

where $\alpha$ is the average density of all nodes. The larger $\alpha$ is, the more neighbors the node has. Namely, it can cover more nodes as a cluster head.

As nodes are heterogeneous in energy capacity, DECHA also selects cluster heads according to their energy condition. Not only is the initial energy capacity valued, but also its residual energy after previous rounds of operation.

Here, we have the initial energy of a node noted as $E_{\text{init}}$. The relative initial energy of a node can be represented by parameter $\beta$ as follows:

$$\beta = \frac{\sum_{i \in \text{CHs}} E_{\text{init}}(s_i)}{N}$$

(5)

It indicates that nodes with different initial energy can be evaluated respectively, which is more suitable for the multi-level heterogeneous WSNs.

A parameter $\gamma$ stands for its relative residual energy among all nodes.

$$\gamma = \frac{E_{\text{res}}}{E_{\text{avg}}}$$

(6)

In our DECHA, besides the density of a node, both its original energy and current residual energy are evaluated as important metrics for CH selection. We determine the cluster heads according to the election probability of each node following the thoughts of LEACH. With both energy capacity and distribution of CHs into consideration, the probability is weighted as follows:

$$p(s_i) = p_{opt} \cdot \alpha \cdot \beta \cdot \gamma = p_{opt} \cdot \frac{N \cdot \text{Den}(s_i)}{\sum_{i \in N} \text{Den}(s_i)} \cdot \frac{N \cdot E_{\text{res}}}{E_{\text{init}}} \cdot \frac{E_{\text{res}}}{E_{\text{avg}}}$$

(7)

A node with much energy and good location turns to have a relative larger $p(s_i)$, therefore it has more chance to be a CH. However, as cluster heads are still elected with randomization, the probability cannot fully decide. We regard them as candidate CHs. In the next step, a metric $\eta$ is evaluated. It aims to judge whether
the chosen candidate CH is reasonable.

$$\eta = \frac{E_{res}}{E_{ini}}$$

(8)

From the above formula, we can see $\eta$ represents the proportion of the residual energy and initial energy of a node. In this paper, we pre-determine a threshold number $\eta_{threshold}$ such as 10%. Once $\eta \leq \eta_{threshold}$, the cluster head lacks capacity and its CH role can be given to one of its neighbor randomly.

A metric denoted as $Level$ is defined and evaluated among the neighbors of a candidate CH. It represents the energy level set for data transmission and can adjust the candidate to a more proper CH in practice.

$$Level(s_i) = \frac{E_{res}(s_j)}{\sum_{0 \leq s_i \leq N \& D(s_i, CH) \leq R} Cost(s_j) / Den(s_j)}$$

(9)

where $Cost(s_j)$ denotes the energy consumption for the CH to communicate with its neighbor within the transmission range; $\sum_{0 \leq s_i \leq N \& D(s_i, CH) \leq R} Cost(s_j) / Den(s_j)$ represents the average energy consumption among its neighbors, namely a standard of average cost of energy in its cluster. The metric aims to find nodes with relative more residual energy and less transmission cost in neighborhood. Nodes with larger $Level$ is set as actual CHs in current round. It is energy-efficient with regard to data transmission.

### 3.3 Routing Procedure

After determining all cluster heads, sensor nodes send data to one cluster head directly within one hop. The corresponding cluster head should be determined with the least energy consumption for the transmission cost along the path. According to formula (1) in the energy model, distance plays a significant role. The inter-cluster algorithm can be formulated as to find the node with smallest distance to the cluster head.

In LEACH, cluster heads send data to the base station directly within one hop. There is high chance that it consumes large energy due to the remote location of some cluster head. In our DEGRA, we perform inter-cluster routing in a multi-hop way. Suppose cluster head $CH_i$ chooses another $CH_j$ as its relay node and let $CH_j$ communicate directly with the sink node $BS$. In order to deliver a $l$-length packet to $BS$ via $CH_j$, the energy consumed of $CH_j$ is calculated as formula (10) where $E$
and \( \alpha \) vary in different situations according to the energy model:

\[
E_{CH} = E_{\text{Tx}}(l, d(CH_i, CH_j)) + E_{\text{Rx}}(l) + E_{\text{Rx}}(l, d(CH_j, BS))
\]

\[
= 3E_{\text{elec}} + \epsilon d(CH_i, CH_j) + \epsilon d(CH_j, BS)
\]

(10)

For each cluster head \( CH_i \), we choose an optimal relay cluster head which maintains the least energy consumption \( E_{CH_i} \). We compare it with the direct communication cost to \( BS \), and determine the optimal inter-routing according to the smaller energy dissipation.

4. Performance Evaluation

4.1 Simulation Environment

We evaluate the performance of the DECHA via simulations in Matlab. The simulation environment is set up with the parameters listed in Table.1.

<table>
<thead>
<tr>
<th>Parameter Name</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length of the packet (( \mathcal{L} ))</td>
<td>4000bits</td>
</tr>
<tr>
<td>Initial energy of the sensor nodes (( E_{\text{initial}} ))</td>
<td>0.5<del>1J/1.5</del>2J</td>
</tr>
<tr>
<td>Energy consumption on circuit (( E_{\text{elec}} ))</td>
<td>50nJ/bit</td>
</tr>
<tr>
<td>Channel parameter in free-space model (( \epsilon_{fs} ))</td>
<td>10pJ / bit / m²</td>
</tr>
<tr>
<td>Channel parameter in multi-path model (( \epsilon_{mp} ))</td>
<td>0.0013pJ / bit / m²</td>
</tr>
<tr>
<td>Channel parameter for data aggregation (( \epsilon_{DA} ))</td>
<td>5pJ/bit/signal</td>
</tr>
</tbody>
</table>

4.2 Simulation Results

Fig. 1 shows the scenario of a uniform dispersion of 100 sensor nodes in a \( 500 \times 500m^2 \) square region. Without loss of generality, here we assume that the base station is located at the coordination of \( (250,250) \). Here we have “\( \bullet \)” represent the normal nodes while “\( + \)” stands for advance nodes with relative larger energy capacity.
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We compare the network lifetime of LEACH and our DECHA, as is shown in Fig. 2 where the network is set as $500 \times 500$ m$^2$. For LEACH, all nodes become invalid in 1195$^{th}$ round. For DECHA, nodes die out in 4924$^{th}$ round and shows better performance as the first node is found in 249$^{th}$ round, which is obviously much later than LEACH. It proves a longer stability period of the network. It is mainly due to the dynamic changes of cluster head roles considering nodes’ energy and distribution.

We compare the total energy consumption of LEACH and our DECHA, as is shown in Fig. 3 where the network is set as $500 \times 500$ m$^2$. DECHA shows better performance with much less total energy consumption than LEACH. This is because the clusters are evenly divided and it reduces possibility of wasting resources. In addition, the multi-hop inter-cluster routing method saves much energy as well.
5. Conclusions

As most existed clustering algorithms are not suitable for heterogeneous environment. In this paper, we propose a Density-based Energy-efficient Clustering Heterogeneous Algorithm (DECHA) to deal with the possible heterogeneity of WSNs. Aimed at saving energy and prolonging network lifetime, we define the density of a node and together with its energy condition to adjust the probability for the candidate cluster head selection dynamically. Further adjustments are made to improve the CH selection. An intra-cluster and multi-hop inter-cluster routing algorithm is also introduced. Simulations show that the stability period and network lifetime are both prolonged. And total energy consumption is reduced compared with LEACH.

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References

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