Dynamic Minimal Spanning Tree Routing Protocol for Large Wireless Sensor Networks

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Abstract

Hundreds or thousands of wireless sensor nodes with limited energy resource are randomly scattered in the observation fields to extract the data messages for users. Because their energy resource cannot be recharged, energy efficiency becomes one of the most important problems. LEACH is an energy efficient protocol by grouping nodes into clusters and using Cluster Heads (CH) to fuse data before transmitting to the Base Station (BS). BCDCP improves LEACH by introducing a Minimal Spanning Tree (MST) to connect CHs and adopting iterative cluster splitting algorithm to choose CHs or form clusters. This paper proposes another innovative cluster-based routing protocol named Dynamic Minimal Spanning Tree Routing Protocol (DMSTRP), which improves BCDCP by introducing MSTs instead of clubs to connect nodes in clusters. Simulation results show that DMSTRP excels LEACH and BCDCP in terms of both network lifetime and delay when the network size becomes large.

1 Introduction

Recent advances in wireless communications and electronics have enabled the development of low-cost, low-power, small-sized sensor nodes. Hundreds or thousands of these nodes can be randomly scattered in the observation fields. Because their energy resource cannot be recharged, energy efficiency becomes one of the most important problems. We must gather data message from far away observation fields to user end or Base Station (BS) by using energy efficient routing schemes according to the requirement of a wide range of applications in order to gain the network lifetime as long as possible [1][2]. Different from other wireless networks, many applications of wireless sensor networks need not transmit all sensed data message to BS. Instead, they only send the user-cared knowledge back to BS. Therefore, data fusion helps to reduce the amount of data transmitted between sensor nodes and BS [3].

One of the energy efficient routing protocols combining data fusion and routing is firstly provided by Low Energy Adaptive Clustering Hierarchy (LEACH) [3] [4] [5]. LEACH adopts a simple and efficient data fusion scheme, which fuses a large number of data message into a small set of meaningful information by compressing methods such as Beamforming [6]. Also, LEACH chooses clubs as the basic topology of the networks. Managing clubs doesn’t need multi-hops and thus makes routing path simple. However, Cluster Heads (CHs) are randomly chosen and clusters are formed by affiliating non-CH nodes to the nearest CH based on received signal strength in LEACH. Therefore, average transmission distance from non-CH nodes to CHs is very large. Moreover, CHs send data message directly to BS worsen the energy dissipation of the wireless networks.

Base Station Controlled Dynamic Clustering Protocol (BCDCP) [7] improves LEACH from two aspects. Firstly, BCDCP uses Minimal Spanning Tree (MST) [8] to connect CHs and randomly chooses a leader to send data to BS. Secondly, BCDCP makes the best use of high-energy BS to choose CHs and form clusters by iterative cluster splitting algorithm. Thus BCDCP reduces far more energy dissipation of network than LEACH.

Although in small-scale network, LEACH and BCDCP work well to route data energy efficiently, their network topology constrains them applying to large-scale network. Because the club topology in clusters is a one-hop route scheme, it is not appropriated for long distance wireless communication.

This paper proposes Dynamic Minimal Spanning Tree Routing Protocol (DMSTRP) for large network area. The main idea is to use MSTs to replace clubs in two layers of the network: intra-cluster and inter-cluster. Because clubs are not more effective than spanning tree to connect the nodes if the network area is large, DMSTRP is an elegant solution for larger network area. Simulation results show the network lifetime of LEACH and BCDCP become worse by and by when the network area varies larger and larger. However, the network lifetime of DMSTRP is not changed greatly with the increasing network area, and thus outperforms LEACH and BCDCP when network size becomes large. Also,
trees produce less delay than clubs in wireless communication network.

2 Radio Power Model

In this paper, we use a radio power model in [3], in which the energy dissipation \( E_T(k, d) \) of transmitting \( k \)-bit data between two nodes separated by a distance of \( d \) meters is given as follows:

\[
E_T(k, d) = k(E_{elec} + \varepsilon_{FS}d^2)
\]

(1)

where \( E_{elec} \) denotes electronic energy and \( \varepsilon_{FS} \) denotes transmit amplifier parameters corresponding to the free-space model. And the energy cost incurred in the receiver of the destination sensor node \( E_R(k) \) is given as follows:

\[
E_R(k) = kE_{elec}.
\]

(2)

All of network models are similar to BCDCP in [7].

3 DMSTRP Architecture

3.1 Routing Path Forming

Clusters are formed similar to [7]. In BCDCP, the CHs are connected by a tree instead of a club. DMSTRP improves BCDCP further by connecting nodes in clusters by MSTs. In each cluster, all nodes including the CH are connected by a MST and then the CH as the leader to collect data from the whole tree. All the CHs connected by another MST goes on to route toward BS. Data fusion process is handled along the tree route.

![Fig. 1. Changing of Basic Topology.](image)

(a) A Club in LEACH and BCDCP

(b) A MST in DMSTRP

The average transmission distance of each node can be reduced by using MSTs instead of clubs as Fig. 1 shows, and thus the energy dissipation of transmitting data is reduced. However, trees increase the energy dissipation of receiving and fusing data. Therefore, only when the average transmission distance is greatly reduced by the MSTs, DMSTRP is more energy efficient than its counterparts. When the network area is larger, the reduced transmission distance is greater. Thus, DMSTRP is more energy efficient.

In the clubs, information of routing path is simple, and each node only need to know of and send data to its CH. But in trees, each node must know the next node that it would send data to. So we form the MSTs by the BS.

3.2 Routing Schedule of Dynamic Minimal Spanning Tree

We must manage the complex tree routing scheme in DMSTRP by effectively distributing time to avoid collisions and make the MST-routing time efficient. The detailed MST routing scheduling is given in this section. Firstly, the data structure of a MST is defined as follows:

\[
\text{int TreeEdge[MaxNodes][3]};
\]

Table 1. Tree Routing Schedule Algorithm

| Initially, For each i | \{the value of TreeEdge[i][0] is placed into set SI;} |
| For each j | \{if TreeEdge[j][1] \( \notin \) SI then TreeEdge[j][2] = 2 ;} |
| p =1 ; | For the number \( p \) round, where \( p \leq nEdge \) |
| For each j | \{if (TreeEdge[j][2] == 2) \&\& (TreeEdge[j][1] \( \notin \) SI ) \&\& (the value of TreeEdge[j][0] does not appear before in this round)) then TreeEdge[j][2] = 1 ;} |
| For each j | \{if (TreeEdge[j][2] == 1) |
| | \{ p = p - 1 ; |
| | \{ TreeEdge[j][0] is deleted from set SI; |
| | \{TreeEdge[j][2] = -1 ; |
| | \{Add this Edge to transmitting queue for this round; |
| | \{For each i |
| | \{if (TreeEdge[i][2] == 0) \&\& (TreeEdge[i][0] == TreeEdge[i][1]) then TreeEdge[i][2] = 2 ;} |
| | \} |
| | \} |
| | \} |

For each \( i \) from 1 to the number of sensor nodes in a cluster, the pair nodes of TreeEdge[i][0] and TreeEdge[i][1] denote the node to receive data and the node to transmit data respectively. And the value field set of TreeEdge[i][2] is \{-1,0,1,2\}, where -1,0,1 and 2 denote routed state, initial state, candidate state, and
prepare state, respectively. At the beginning, all edges are in the initial state. The prepare state is only changed from the initial state, the candidate state is only changed from the prepare state, and the routed state is only changed from the candidate state. Given the total number of edges as $n_{Edge}$, the detailed algorithm of tree routing schedule is given in Table 2.

An example is shown in Fig. 1 (b). The node-IDs are marked beside the nodes. Table 1 gives the edge information of the MST in Fig. 1(b).

Table 2. Edge Information of An Example MST

<table>
<thead>
<tr>
<th>node-ID</th>
<th>father-ID</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>2</td>
<td>-</td>
</tr>
<tr>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td>4</td>
<td>2</td>
</tr>
<tr>
<td>5</td>
<td>4</td>
</tr>
<tr>
<td>6</td>
<td>4</td>
</tr>
</tbody>
</table>

In Table 2, node-ID is ID of transmitting node and father-ID is ID of receiving node. Using algorithm in Table 1, $S_1 = \{1,2,4\}$, and thus node 3, node 5, and node 6 are leaf nodes. Because node 5 and node 6 have the same father, only node 5 can transmit in the first round. Thus the first round transmitting queue is $\{3, 5\}$, this means node 3 and node 5 can transmit their data at the same time. We can get the transmitting queue in the following round as: $\{1, 6\}$, and $\{4\}$. Thus, we can plot the time order in Fig. 2. It shows some parallel communications and reduces the delay metric of the network.

![Fig. 2. Time Order.](image)

The BS generates the schedule information and sends it to CHs. The CH notifies its members of their routing information as abovementioned. Then each sensor nodes route their data message to their CH by the given routing information.

DMSTRP has two advantages. (1) More energy efficiency than LEACH and BCDCP, especially in larger network area. (2) Less delay. We would analyse them in details in the next section.

4 Performance of DMSTRP

4.1 Network Lifetime of DMSTRP

All the experiments in this paper use the values of parameters shown as follows:

- Use 100 nodes randomly deployed in network area of $100m \times 100m$, $200m \times 200m$, $300m \times 300m$.
- Initial energy resource on each node is 2J.
- The number of transmission data message for each node in each round (or packet size) is 20kbits.
- $E_{elec} = 50nJ$, and $E_{FS} = 0.01nJ / bit / m^2$.
- Energy dissipation of fusing 1-bit data message is 5nJ.
- Position of BS is (25m, 150m).

We implement of an energy simulator of wireless sensor network programmed in C/C++. For ensuring the simulation results of this paper correct, we use our energy simulator to do the same experiments of LEACH that use ns2 and C++ in [3], and of BCDCP that uses Matlab in [7], and get the approximately same results.

In this paper, we use three metrics of the Time before the First Node Dies (TFND), the Time before All Nodes Die (TAND), and the Ratio of TFND and TAND (RTT) to define the system lifetime of the wireless sensor networks. They are all the greater, the better.

Also, optimal number of clusters is determined by network topology. Optimal number of clusters in LEACH is adopted according to [4], and optimal number of clusters in both BCDCP and DMSTRP is based on simulated annealing algorithm.

In Fig. 3, the number of rounds denotes the time and it shows the network lifetime of DMSTRP comparing with LEACH and BCDCP. It clearly pots that DMSTRP keeps the same performance in the network area varying from $100m \times 100m$ to $300m \times 300m$. However, LEACH performs worse by and by with the increasing network area, because of club-club two-hop topology.

In Fig. 3 (a) shows, in $100m \times 100m$ network, although TAND in DMSTRP is longer than in LEACH and BCDCP, TFND in DMSTRP is shorter than in LEACH and BCDCP. However, in $200m \times 200m$ network, Fig. 3 (b) shows DMSTRP outperforms LEACH because both TFND and TAND are longer. After 27% nodes dies, remain nodes die slower in DMSTRP than in BCDCP.

At last, when the network area is as large as $300m \times 300m$, Fig. 3(c) shows the network lifetime in DMSTRP completely excels both LEACH and BCDCP. TFND in DMSTRP is 20 times and 1.3 times longer than in LEACH and BCDCP respectively. TAND in DMSTRP is increased 11.7% and 7% of LEACH and BCDCP respectively. RTT of 80.3% in DMSTRP also outperform that of 38.7% in BCDCP and that of 4% in LEACH.
The three plots in Fig. 3 also show that tree topology makes protocol performs better than club in larger network area. DMSTRP uses tree-tree two-level topology. BCDCP has trade-offs on tree inter-cluster and club intra-cluster. The simulation results prove DMSTRP is an elegant solution in large network area.

Suppose all nodes use CDMA [9] to avoid collisions. Thus some nodes in a cluster can transmit data at the same time. Tree routing let parallel communication possible among nodes in a cluster, and thus reduces the delay time. Suppose that the delay is one unit for each packet transmitted [10]. A CH in a cluster with six nodes would use 5-delay time to collect all the sensed data by using club topology. However, after using tree topology, just as Fig. 2 shows, it only spends 3-delay time on collecting all the data from non-CH nodes. Therefore, tree would greatly increase the transmitting speed.

Fig. 3. Network lifetimes in different network areas of 100m × 100m, 200 m × 200m and 300m × 300m.

4.2 Delay Analysis of DMSTRP

Fig. 4. Delay varies with number of dead nodes in different network areas of 100m × 100m, 200 m × 200m and 300m × 300m.
Simulation results in Fig. 4 show delay metric in DMSTRP is smaller than in LEACH and BCDCP in all the network area of 100m × 100m, 200m × 200m and 300m × 300m. BCDCP performs better than LEACH in terms of delay. These results also prove that tree topologies have less delay than clubs.

5 Conclusions

DMSTRP is a multi-hop routing protocol, and thus is an elegant solution for large network area. On the one hand, it expands the network area with the limited wireless transmitting ability of sensor nodes. On the other hand, in the large network area, even if the wireless sensor nodes in the large network have capability of transmitting long distance and thus make LEACH and BCDCP possible to use for routing data, DMSTRP is more energy efficient than LEACH and BCDCP. Also, DMSTRP has less delay than its counterparts.

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References


