An Energy-Efficient Multi-hop Hierarchical Routing Protocol for Wireless Sensor Networks

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Abstract

Clustering provides an effective method for improving the performance of wireless sensor networks (WSNs). In this paper, we study that different number of clusters leads to different network performance on the energy consumption, energy balancing and network lifetime. We propose an Energy-Efficient Multi-hop Hierarchical Routing Protocol (MHRP) for wireless sensor networks to enhance the network lifetime and avoid the formation of energy holes. MHRP is a hierarchical routing protocol which selects sensor nodes with criterion of residual energy level to act as cluster heads and establish intra-cluster multi-hop routing based on the tradeoff between the two criteria of residual energy level and distance. Simulation results show that our MHRP can largely reduce the total energy consumption and significantly prolong the network lifetime compared to other routing algorithm like LEACH.

Keywords: *Wireless sensor networks, energy efficiency, clustering, multi-hop routing, network lifetime*

1. Introduction

Wireless sensor networks (WSNs) are usually composed of a large number of low-cost and tiny sensor nodes used for gathering information and sending it in a multi-hop manner to sink nodes. These sensor nodes have some computational power, storage and communication capability. WSNs are used broadly at military surveillance and tracking, environment monitoring and forecasting, healthcare etc. WSNs are energy-limited and application-specific. The energy of sensor nodes is usually limited and commonly non-rechargeable. Thus, how to utilize the limited energy resource of each sensor node in an efficient way is the primary research challenge [1, 2].

A typical wireless sensor network consists of densely deployed static sensor nodes with static sink node [3]. In WSNs, energy consumption and energy-balancing are one of the primary research issues. The traffic generally follows a many-to-one pattern, where sensor nodes closer to the sink node will consume more energy and deplete their energy faster for the heavier traffic loads. Namely the sensors nearer to the fixed sink node not only need to transmit their own packets, but also forward packets gathering from other sensor nodes that are far away from the fixed sink node. As a result, the uneven consumption will reduce the network performance such as network lifetime, energy consumption and so on.

Network performance can be significantly improved by using proper hierarchical routing protocol. Based on the network topology, we can simply classify the routing protocols as flat routing protocols and hierarchical routing protocols. In flat routing protocols, sensor nodes are on the equal terms. Data is routed from sensor nodes to the sink node using routing protocols such as Direct diffusion [4] and Rumor [5] etc. Compared with the flat routing protocols, hierarchical routing protocols often divide the sensor nodes into cluster heads and normal nodes. The entire network is composed of clusters consisting of cluster heads and several normal nodes. Cluster heads can process, filter and aggregate data sent by ordinary cluster members among clustering algorithms. They are in charge of coordinating the work of the cluster members and forwarding the processed data. However, cluster heads rotation will generate additional energy overhead and consume major energy in aggregating and transmitting data. So an energy-efficient mechanism for cluster heads election and rotation is necessary and particularly important.

In this paper, we propose and evaluate an energy-efficient multi-hop hierarchical routing protocol (MHRP) for WSNs. We prefer to select sensor nodes with the highest energy level to act as cluster heads and establish routing path based on residual energy and distance between sensor nodes. Based on the energy model of [6, 7], we argue that different cluster number has different influence on network performance, such as the energy consumption, and the network lifetime, and get the optimal cluster number to minimize the energy consumption. On the basis, we divide the sensor network area into several regions where we choose nodes with the highest residual energy level as cluster heads and adopt multi-hop manner to transmit data. MHRP can ensure relatively uniform distribution of cluster heads in entire network and save energy which contributes to prolong the network lifetime.

The rest of the paper is organized as follows. Section 2 provides some related work about routing protocols for WSNs. Section 3 presents relevant network and energy models. Section 4 explains our algorithm in details. Section 5 provides simulation results to verify our algorithm and section 6 concludes this paper.

2. Related Work

According to the network topology, we can roughly classify the existing routing protocols into two categories, namely, flat routing protocols [4-5] and hierarchical routing protocols [6-16].

Under flat routing protocols, network flow evenly scatters in sensor networks. All sensor nodes are treated equally and they will find a route consisting of multi-hop to the sink node to transfer data. Commonly, the probability of participating in data transmission process is higher for the nodes around the sink node than those nodes far away from the sink node. So, the nodes around the sink node deplete their energy soon.

Directed diffusion (DD) [4] is a query-based routing protocol in which all communication is for named data. Routes are dynamically formed as data is sensed. By using data aggregation, caching and reinforcement techniques, the appropriate link is dynamically selected from the candidates. Links are created only when data of interest is sensed. Thus, less energy will be used by this protocol. However, flooding broadcast of interest in diffusion make the energy consumption relatively large. To reduce the cost of route setup, Rumor routing protocol [5] was proposed which combined query flooding and event flooding protocols in a random way. However, due to the path generated randomly, the data transmission path is not the optimal path and there may be routing loops.

Compared to flat routing protocols, hierarchical routing protocols can effectively manage and organize the sensor nodes. It provides an energy efficient way to find an available route and guarantee the good scalability of networks.

Low-energy adaptive clustering hierarchy (LEACH) [6] is one of the most famous hierarchical routing protocols for WSNs, which utilizes randomized rotation of local cluster heads to evenly distribute the energy load across the entire network. Compared with other ordinary routing protocols, LEACH can guarantee network scalability and prolong network lifetime up to 8 times. However, the 5% of cluster heads are randomly chosen and cluster heads transmit data directly to the sink node. To address this deficiency, LEACH-C algorithm [7] centralize to choose cluster heads through the sink nodes.Power efficient gathering in sensor information systems (PEGASIS) [8] uses chain structure to connect and select the nearest neighbor to communicate. Each chain selects only one node as the head communicating with the sink node. The main shortcoming is that PEGASIS requires global knowledge of the whole network. A hybrid, energy-efficient, distributed (HEED) [9] clustering protocol considered the residual energy of sensor nodes and the cost of communication within the cluster during cluster heads selection. It can not only minimize the control overhead, but also prolong network lifetime since cluster heads are well distributed.

In recent years, a few new research achievements of hierarchical routing have been reported in the literatures [10-16]. The author in [10] introduced an energy efficient heterogeneous clustered scheme for WSNs based on weighted election probabilities of each node to become cluster heads according to the residual energy. In [11], the author introduced an adaptive decentralized re-clustering protocol (ADRP) for WSNs. In ADRP, cluster heads and next heads are elected on residual energy of each node and the average energy of each cluster. In [12], the author proposed a novel distributed clustering algorithm where cluster heads are elected following a three-way message exchange between each sensor and its neighbors. Sensor's eligibility to be elected cluster head is based on its residual energy and its degree. To enhance lifetime, in [13], the author proposed an energy efficient clustering protocol (EECPL) which organizes sensors into clusters and uses ring topology to send data packets. In [14], the author proposed a hop-based energy aware routing algorithm to save and balance energy consumption for WSNs. In [15], the author proposed an Energy conserving multicast (ECMA) protocol to reduce the number of data transmissions within the WSNs for decreasing the energy consumption of the sensor nodes. In [16], considering the parameters that include number of packets sent in the network, energy consumed by the network, remaining energy level of nodes at specific time and network lifetime, the author proposed an energy efficient routing technique Energy Aware Intra Cluster Routing (EAICR).

3. System Model

3.1. Network Model

In our paper, we assume that all the sensor nodes are deployed in a circular area with a radius of R, and there is no big obstacle between source node and sink node. All the sensor nodes are homogeneous and stationary. The sensor node is location-aware and each sensor node has the capability of transmitting data to the sink node directly. The entire network only has one sink node and it is located at the center of the area. Source nodes can adjust their transmission power according to the relative distance to target nodes. We assume the optimal cluster number k is 5, and then divide the circle network with radius R into 5 equal sectors. N sensors are approximating evenly distributed in each sector and continuously monitor their surrounding environment.

3.2. Energy Model

We use the similar energy model as that of [11, 14]. Based on the distance between the source and target nodes, a free space or multi-path fading channel models are used. Each node will consume the following E_{Tx} amount of energy to transmit a l-bits message over distance d and the following E_{Rx} amount of energy to receive the message.

$$E_{Tx}(l,d) = \begin{cases} lE_{elec} + l\varepsilon_{fs}d^2, d < d_0 \\ lE_{elec} + l\varepsilon_{mp}d^4, d \geq d_0 \end{cases} \quad (1)$$

$$E_{Rx}(l) = lE_{elec} \quad (2)$$

Here, N nodes in sensing field are evenly divided into k equal regions. According to the formula (1) and formula (2), each cluster will consume the following $E_{cluster}$ amount of energy to communicate, and the total energy consumption of entire network is represented as E_{total}.

$$E_{cluster} = E_{CH} + \left(\frac{N}{k} - 1\right) E_{member} \approx lE_{elec}\left(\frac{N}{k} - 1\right) + E_{Tx} + (lE_{elec} + l\varepsilon_{fs}\frac{R^2}{2k})\frac{N}{k} \quad (3)$$

$$E_{total} = kE_{cluster} = kE_{CH} + NE_{member} = 2NlE_{elec} - lkE_{elec} + kE_{Tx} + Nl\varepsilon_{fs}\frac{R^2}{2k} \quad (4)$$

To minimize the total energy consumption E_{total}, we use the conclusion in [11] to get the optimal cluster number k_{opt} and the formula is shown as the follows.

$$k_{opt} = \frac{R}{d^2}\sqrt{\frac{N\varepsilon_{fs}}{2\varepsilon_{mp}}} \quad (5)$$

4. Our Proposed Energy-efficient Multi-hop Hierarchical Routing Protocol (MHRP)

4.1. Cluster Formation

Cluster formation is performed as a distributed algorithm at the beginning of data collection. Different from other clustering algorithms, we firstly divide the entire network into several equal sectors according to the optimal cluster number k. Here, we assume the optimal number k is equal to 5. Thus the cluster formation is achieved first, as is shown in Figure 1.

After cluster formation, we will choose cluster head based on its residual energy. Each sector has only one cluster head that manages the data collected from the normal nodes and relays the aggregated data to the sink node. To balance the energy consumption levels, we use the initial energy level to select the cluster head candidates. Comparing with the probabilistic deployment in LEACH, the distribution of cluster heads is more uniform. Data aggregation also can reduce the traffic load and then draw more accurate and reliable conclusion.

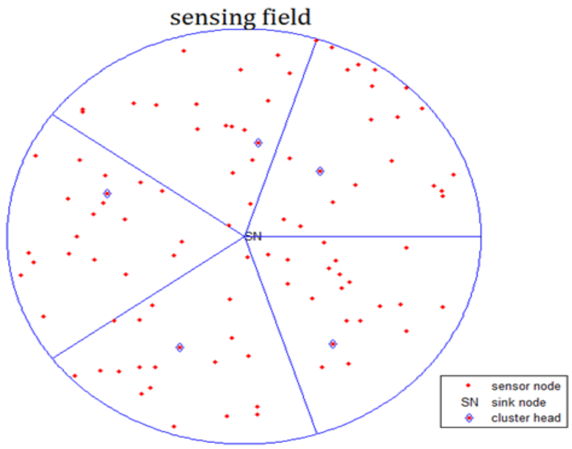

Figure 1. Cluster Formation

When the selection begins, we first motivate the sensor node S_i that will act as the cluster head candidate. Upon being selected, cluster head candidate will transmit a packet to advertise its ID, residual energy level and its distance to the sink within a neighborhood of radius r. r is the transmission radius of the sensor node and it can be adjusted based on the distance between nodes. The packets aim to motivate other nodes which are in the transmission range participating in the competition of cluster head. If any a node S_j has higher residual energy level than S_i, it becomes the new cluster head candidate and broadcasts new packet with its own information to others. If the node S_j as equal residual energy level with S_i, the node with a closer distance to the sink becomes the new cluster head candidate. If the node S_j has equal residual energy level and equal distance with S_i , the node with a smaller ID becomes the new cluster head candidate. Relatively, if the node S_j has smaller residual energy level than S_i, it still broadcasts the packet of S_i. All nodes in the region are compared only once and the un-chosen normal nodes become idle again as soon as the comparison is done. Finally, candidate with the highest residual energy level will become cluster head to responsible for data aggregation and forwarding.

4.2. Intra-cluster Multi-hop Routing

Due to the inflection of data volume and node location, some sensor nodes may consume large amount of energy through long-distance transmission. For that reason, we set a multi-hop routing protocol for intra-cluster routing. For any cluster member node S_i, the energy consumption it will cost to send data directly to its cluster head CH_{S_i} is represented as follows.

$$E_1(S_i, CH_{S_i}) = \begin{cases} lE_{elec} + l\varepsilon_{fs} d(S_i, CH_{S_i})^2, d(S_i, CH_{S_i}) < d_0 \\ lE_{elec} + l\varepsilon_{mp} d(S_i, CH_{S_i})^4, d(S_i, CH_{S_i}) \geq d_0 \end{cases} \quad (6)$$

In the same environment, suppose a node S_i chooses another node S_j which can communicate with the cluster head CH_{S_i} directly as its relay node. We adopt a free space propagation channel model to deliver an l-bits packet to cluster heads. The energy consumed by S_i and S_j is calculated as $E_2(S_i, S_j)$.

$$\begin{aligned} E_2(S_i,S_j) &= E_{Tx}\left(l,d(S_i,S_j)\right)+E_{Rx}(l)+E_{Tx}\left(l,d(S_j,CH_{S_i})\right) \\ &= 3lE_{elec}+l\varepsilon_{fs}\left(d(S_i,S_j)^2+d(S_j,CH_{S_i})^2\right) \end{aligned} \quad (7)$$

Due to the channel model [10] we adopted here, the variation of formula (7) mainly depends on the value of $d(S_i,S_j)^2+d(S_j,CH_{S_i})^2$. Thus the node with the smallest value of $E_2(S_i,S_j)$ will act as the relay node if necessary. Then we will compare formula (6) and formula (7), and choose the smaller one to set up route. Besides, to avoid the nodes near cluster heads depleting their energy quickly, we also consider the residual energy of the relay node. If the residual energy of the relay node S_j is smaller than that of the sensor node S_i, we still choose S_j as the intermediary, leading to aggravate the load of S_j and may format the energy hole. To prolong the network lifetime, a tradeoff should be made between the two criteria of the distance and the residual energy. The cost is defined as follows，and after each node has chosen the minimum cost node as its relay node, an intra-cluster route is constructed

$$cost(j)=\omega*\frac{d(S_i,S_j)^2+d(S_j,CH_{S_i})^2}{\max\left(d(S_i,S_j)^2+d(S_j,CH_{S_i})^2\right)}+(1-\omega)*\frac{E(S_i,CH_{S_i})}{\max\left(E(S_i,CH_{S_i})\right)} \quad (8)$$

$$,\omega\in[0,1]$$

5. Performance Evaluation

5.1. Simulation Environment

We use Matlab simulator to evaluate the performance of our algorithm. There are [200,500] nodes evenly deployed in a [150,200,300] circular area. The initial energy level of each node is 2J. The sink node is placed in the centre of the circle area. The transmission radius can be adjusted from 80 to 100 meters based on the distance between nodes. Simulation parameters are all listed in Table 1.

Table 1. Simulation Parameters

Parameter	Definition	Unit
E_{elec}	Energy dissipation to run the radio device	50 nJ/bit
ε_{fs}	Free space model of transmitter amplifier	10 pJ/bit/m^2
ε_{mp}	Multi-path model of transmitter amplifier	0.0013 pJ/bit/m^4
l	Packet length	2000 bits
d_0	Distance threshold	$\sqrt{\varepsilon_{fs}/\varepsilon_{mp}}$ m
E_0	Initial energy	2J
N	The number of the sensor nodes	[200,500]
R	Radius of the circle network	[150,200,300]m
r	Transmission radius	[80,100]m

5.2. Energy Consumption

The number of clusters has an important influence on the performance of the sensor network, as shown in Figure 2. Here, d is the average distance between the cluster head and the sink and it varies from 80, 90,100 to 120 meters.

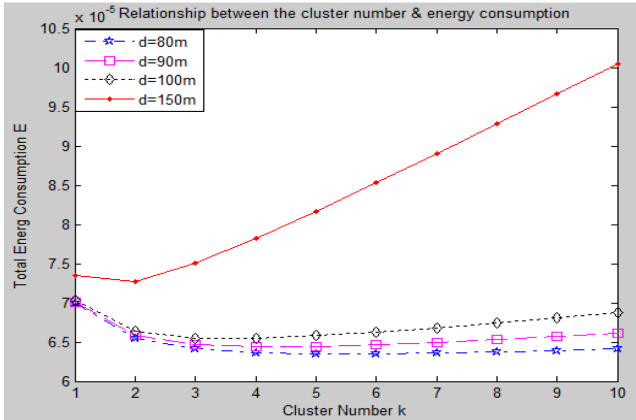

Figure 2. Cluster Number and Energy Consumption Relationship

From Figure 2, we can see that different cluster number has different influence on the energy consumption for the same value of average distance d. And for the same cluster number k, the total energy consumption will increase when the average distance d increases. According to formula (5), when the radius of the circle network is 150 meters and the number of the sensor nodes is 200, the optimal number of the cluster is equal to 16. Under this circumstance, the total energy consumption can be largely reduced. Figure 3 illustrates this point.

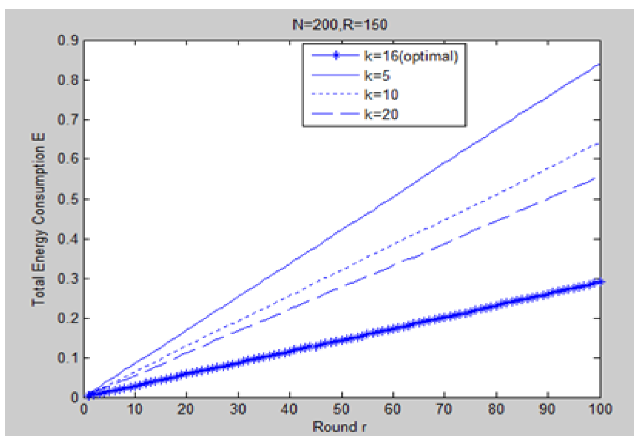

Figure 3. Comparison of Energy Consumption

From Figure 3, we can observe that for the same round r, the energy consumption is the least when $k_{opt} = 16$. On this basis, we divide the sensor field into 16 equal sectors and select nodes with the highest residual energy level to act as cluster heads. The neighborhood of the sink node will communicate directly with the sink node to relieve the load of cluster heads.

We compare the total energy consumption between our MHRP and LEACH algorithm, as is shown in Figure 4. Since the highest energy assigned to cluster heads and the more evenly distribution of cluster heads, MHRP consumes much less energy than LEACH algorithm. Besides, multi-hop routing also can save energy inside each cluster. The resulting energy savings have a significant impact on the network lifetime.

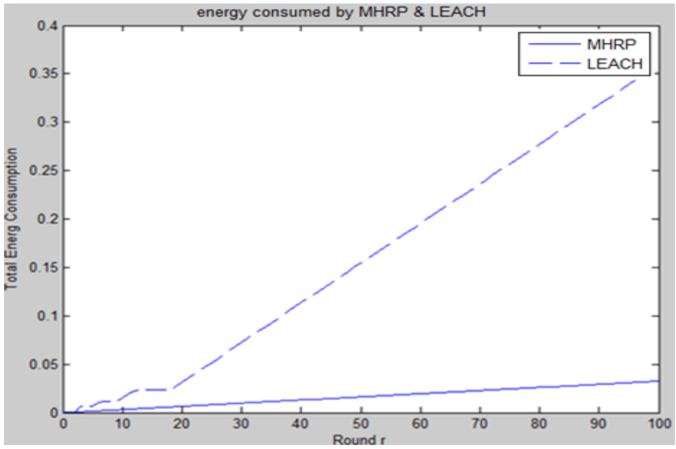

Figure 4. Energy Consumption

5.3. Network Lifetime

We evaluate the network lifetime using MHRP and LEACH respectively under the same network environment. The number of "Alive node" in one region over simulation time is illustrated in Figure 5. Here, we define the network lifetime as the period of time until the first node in the network depletes its energy. Figure 5 shows that the lifetime of MRHP in one region is around 2087 rounds, whereas the lifetime of LEACH is around 1478 rounds. Thus MHRP has a better performance in extending network lifetime.

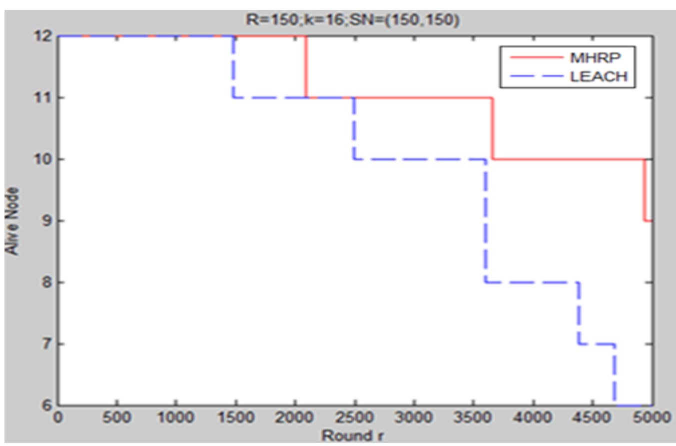

Figure 5. Network Lifetime

6. Conclusions

In this paper, an energy-efficient multi-hop hierarchical routing protocol (MHRP) is proposed to improve the performance of wireless sensor networks, such as energy balancing and reduction, lifetime elongation. MHRP selects those nodes with the highest residual energy level to act as cluster heads. In each sector, we adopt a multi-hop communication protocol between normal nodes and cluster head to reduce the cost of long distance transmission. MHRP can make a tradeoff between the two criteria of the distance and the residual energy during the period of the establishment of multi-hop route. Simulation results demonstrate that MHRP can effectively reduce the energy consumption of the entire network and avoid the formation of energy hole. To a large extent, MHRP can significantly prolong the network lifetime.

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