An Energy-Balanced Relaying Communication Protocol Based on Power and Distance Cooperation

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Abstract

Wireless sensor networks (WSNs) composed of a large number of cheap microsensor nodes with limited battery power and highly correlated collected data is intelligent and autonomous system for measure and management. To reduce the redundant data among the nodes and consequently prolong networks’ lifetime, clustering protocols which perform application-specific local data aggregation have been put forward. To balance energy consumption in the whole network, in this paper, we propose and analyze energy-balanced adaptive clustering hierarchy (EBACH) protocol, a novel approach adding a new kind node called relay-node besides cluster-head and cluster member node. Simulation results demonstrate that our energy balancing mechanism can obviously improve the system performance compared with general clustering protocols.

Keywords: Wireless Sensor Networks, Data Aggregation, clustering, relay node, EBACH.

1. Introduction

Wireless sensor networks are composed of hundreds or thousands of small size, inexpensive and power-limited sensor nodes, each with the sensing, computing, data processing and wireless communication capability. Recently, rapid advances in sensor technology have enabled the deployment of large scale sensor networks in civil and military applications, such as environmental monitoring, infrastructure monitoring, target tracking, disaster relief and battlefield surveillance [1].

Distinguished from traditional wireless networks, WSNs are restricted by severe power, computation, and memory constraint. Hereinto, unbalanced energy consumption is an inherent problem, and it is largely orthogonal to the general energy efficient problem. Considering the strict energy constraint, energy resource of sensor networks should be managed wisely to extend the networks lifetime.

Signal processing and communication activities are the main consumers of node’s energy. Usually, the cost of transmitting a bit is much higher than the computation, and hence sensor nodes can be organized into clusters for achieving high energy efficiency and increasing the network scalability. In the cluster environment, the cluster heads can perform the data gathering and aggregation “in place” in order to eliminate data redundancy caused by multiple adjacent sensors in the high density network [2].

Typical hierarchical routing protocols based on clustering method are LEACH (Low-Energy Adaptive Clustering Hierarchy) and LEACH-C (LEACH-Centralized) [3]. LEACH that makes self cluster among sensor nodes has motivated the design of many other protocols as the first clustering protocol for WSNs. In LEACH, the member node transmits data to its cluster head and cluster heads transmits the aggregated data to sink node. LEACH uses randomization to rotate the cluster heads and achieves the equivalent energy consumption of all nodes.

However, there is no guarantee of the number and location of heads due to lacking of nodes’ location information, which leads to the uneven distribution of clusters. LEACH-C, using a central control algorithm to form cluster, has been developed out of LEACH. In this way, base station receives residual energy and current location information from nodes and decides cluster heads for this round using the annealing algorithm. Upon that, some areas for improvement to make the two protocols more efficiency can be modified, such as algorithm about cluster heads selection [5] and LEACH-CE in [6].

In this paper, we propose and evaluate a cluster-based three-layer optimal forwarding algorithm, a modification of LEACH, considering a collection of metrics mainly distance, power and link usage, in order
to balance energy dissipation over the network and prolong the life.

The remainder of this paper is organized as follows: Section 2 describes some relate works in this area. In section 3, we present the EBACH in detail. Section 4 discusses our simulation efforts and the analysis of the results obtained, and finally section 5 concludes this paper with directions for future work.

2. Related work

The literature of sensor networks contains several mechanisms for energy-efficient and energy-balanced communication.

LEACH [3][4] is the first cluster-based routing protocol that minimizes a global energy usage by randomized rotation of local cluster heads to evenly distribute the energy load among the sensors in the network. The operation of LEACH is divided into rounds. During each round, the clusters are organized in a set-up phase, followed by a steady-state phase. In set-up phase, each node has a certain probability of becoming a cluster head. The larger the probability is, the more likely the node is to be a cluster head for the current round. Once the cluster heads are determined, the non-cluster heads send join requests to join in the nearest cluster requiring the minimum communication distance. Based on the number of nodes in the cluster, the cluster head creates a TDMA schedule and announces the slot for each cluster member when it can transmit. In the data transmission phase, cluster head collects and aggregations data from member nodes and transmits to BS directly.

The performance of LEACH counts on evenly deploying cluster head and the number of cluster head at each round. However, it can not be guaranteed by selecting cluster head itself, so LEACH-C is proposed that decides cluster head and cluster concerning location information of sensor node and energy from base station. Results in [3] have proven that LEACH-C can achieve the better performance than LEACH protocol. Nevertheless, due to that all the nodes must communicate directly with base station which locates far away, the long distance transmission cost much energy consumption.

Considering the characteristic of two protocols, we put forward a novel scheme EBACH, which is introduced to balance the load of cluster heads. In the set-up phase, once the cluster is formed, cluster head selects a new node as the relay in each cluster, named relay node accordingly, by synthetically calculating the metrics of distance, energy dissipation and location.

In EBACH algorithm, the model sensor network has the following properties:

- The base station is fixed at a far distance from the square sensing field.
- The sensor nodes are homogeneous and have the same capabilities with equal energy.
- Each node is assigned a unique identifier.
- Nodes can use power control to vary the amount of transmission power which depends on the distance to the receiver.
- No mobility of sensor nodes.
- Node is aware of its location.

3. The protocol architecture

3.1 Energy model

In order to demonstrate the performance of our algorithm, we adopt the same radio energy dissipation model shown in Fig. 1 in the LEACH protocol [1]. To transmit a k-bit packet over the distance d, the energy consumed by the transmitter is

$$E_{tx}(k,d) = E_{tx-elec}(k) + E_{tx-amp}(k,d)$$

(1)

$$E_{tx-elec}(k) = k \cdot E_{elec}$$

$$E_{tx-amp}(k,d) = \begin{cases} k \cdot E_{elec} + k \cdot E_{fs} \cdot d^2 & d < d_0 \\ k \cdot E_{elec} + k \cdot E_{mp} \cdot d^4 & d \geq d_0 \end{cases}$$

Here, $d_0$ is a threshold. When the distance between the transmitter and the receiver $d < d_0$, we use the free space channel model, or the multipath fading model is considered.

To receive this message, the radio expends

$$E_{rx}(k) = E_{rx-elec}(k)$$

(2)

In this model, a radio dissipates $E_{elec} = 50 \text{nJ/bit/m}^2$ in the transmitter or receiver circuitry. For the transmitter amplifying, $E_{fs} = 0.1 \text{pJ/bit/m}^2$, and $E_{mp} = 0.0013 \text{pJ/bit/m}^4$. The radios can control the power to adjust the minimum energy required to reach the intended receiver based on the distance between them. The radios can be turned off to receive unintended transmissions and reduce the unnecessary energy dissipation.
3.2 procedure of proposed algorithm

EBACH is designed for data aggregation support and forwarding in cluster-based hierarchical sensor networks. The proposed protocol operates in two main processing phases, which are subdivided into set-up phase and steady-state phase. The former includes cluster forming and routing path building, while data transmitting process for the latter. The following subsections describe the two stages.

A. Formation of cluster

A flowchart of the distributed cluster formation algorithm is shown in Fig. 2. Sensor nodes elect themselves to be cluster heads using a certain probability, which is based on the assumption that all node are homogeneous with the same capabilities and have data to send during each frame. Once the cluster heads is determined, each of them broadcasts an advertisement message to adjacent nodes within its transmitting range to let the nodes know the ID of cluster heads for the current round. Based upon the received signal strength of the advertisement from each cluster head, the non-cluster head node determines its cluster head and sends the join-request message together with the energy and location of the node.

After finishing choosing its cluster members, the cluster head selects its relay node among its cluster members synthetically considering the residual energy and location factors. The relay node selecting mechanism will be detailed analyzed later in section 3.2.

Subsequently, the cluster head creates a TDMA schedule to assign and transmit the time slots to the nodes in the particular cluster. The slots are assigned according to the distance of the node. The member nodes are allowed to turn off their radio transmitting components all time except during the assigned transmit time slot in order to reduce the energy consumption. The relay node will turn its receiver on at the corresponding time when the cluster head has already gathered and aggregated packets from cluster members for the current round.

After the member nodes have already known the TDMA schedule and relay nodes been assigned, the set-up phase is accomplished. Next the data forwarding operation, namely steady-state phase, can process.

B. Forwarding in EBACH

Data forwarding in the networks is carried out by three layers shown in Fig. 3. In forwarding layer one (Layer 1), the sensing nodes forward the data to the corresponding cluster head which keeps awake to receive all the data from its member nodes during their allocated transmission slot. Once all member nodes have sent data to cluster head, the cluster head then performs data aggregation to reduce the redundancy existing among the signals.

In Layer 2, each cluster head forwards the resultant data to corresponding relay node which has already been selected during the cluster formation phase in the cluster. In Layer 3, the relay node in each cluster transmits the data from its cluster head to BS without any data processing.
3.3 Selection of relay nodes (RN)

As mentioned above, LEACH protocol provides that the cluster heads performs the direct communication with BS instead of hop-by-hop after aggregating the data from its member nodes. Since the BS usually locates far away and the data messages are large, if the cluster head directly transmits the messages to BS, it will be a high-energy consumption. With the responsibility for receiving messages from member nodes, compressing them and transmitting to base station, the cluster heads usually drain their battery more quickly. This forwarding scheme not only becomes inefficient but also restricts the size of the networks.

In order to break the size limits and to reduce the overload of cluster heads, a new kind node called relay nodes are brought forward in the networks. In this way, a cluster is formed by a cluster head, a relay node and member nodes, which can be seen in Layer 1 of Fig. 3.

According to the energy model in Fig. 1, the energy dissipation in LEACH protocol while cluster head directly transmitting \( l \) bits packet to BS is:

\[
E_{CH-BS} = E_{Tx-elec}(l) + E_{Tx-amp}(l, d(CH, BS))
\]

\[
= l * E_{elec} + l * e_{mp} * d^4(CH, BS) \quad (3)
\]

In the case that cluster head sends a \( l \) bits packet to base station via a relay node, the energy expended is:

\[
E_{CH-RN-BS} = E_{CH-RN} + E_{RN}(l) + E_{RN-BS}
\]

\[
= 3 * l * E_{elec} + l * e_{fr} * d^3(CH, RN)
+ l * e_{mp} * d^4(RN, BS) \quad (4)
\]

Due to the transmitting cost is much higher than energy consumed while receiving, we only consider the energy of the transmitter and neglect the receiver’s energy dissipation. So

\[
E_{CH-RN-BS} \approx l * E_{elec} + l * e_{fr} * d^3(CH, RN)
+ l * e_{mp} * d^4(RN, BS) \quad (5)
\]

The 2-hop routing mechanism requires less energy than direct communication if and only if

\[
E_{CH-BS} > E_{CH-RN-BS} \quad (6)
\]

Substituting this inequation (6) with Equations (3) and (5), we have:

\[
e_{mp} * d^4(CH, BS) > e_{fr} * d^3(CH, RN)
+ e_{mp} * d^4(RN, BS) \quad (7)
\]

If the base station locates far enough away from the sensor network, distance \( d(CH, RN) \) tends to zero, and \( d(CH, BS) > d(RN, BS) \) can be deduced.

Non-cluster node in a cluster that meets this distance requirement can be selected as the relay node. Draw a circle with the centre BS and the radius \( d(CH, BS) \), as shown in Fig. 4. Nodes in the region overlapped by cluster and circle are eligible. Usually, several nodes exit, such as \( RN_i \) and \( RN_j \). The node with the highest residual energy among the eligible nodes, is appointed as the relay node generally. If there is more than one node with almost the same remaining energy, the one that locates nearer to BS is preference. The relay node selection is an iterative processing, which depends on the number of the eligible nodes.

On the other hand, if there is no node in the overlapped region, cluster head then communicates with BS directly, which acts the same as in LEACH protocol.

Relay node election is the last step in the set-up phase, and data forwarding will be carried on next, which is described in section 3.2B.

4. Simulation results

The effectiveness of the energy balanced relaying routing approach is validated through simulation, which is implemented by NS-2 network simulator. This section describes the simulation environment, performance metrics and experimental results. We assume that every node is aware of its location which can be obtained from GPS devices or location-tracking approach [7]. We also assume that all nodes have the same transmission range.

In our experiment, we suppose a 100 node network in 100m \( \times \) 100m square area where nodes are randomly distributed, shown in Fig. 5.

As a radio model, we use the first order radio model largely in the area of routing protocol assessment for sensor networks [3]. The simulation parameters are given in Table 1.

<table>
<thead>
<tr>
<th>parameter</th>
<th>value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Network Area</td>
<td>100m ( \times ) 100m</td>
</tr>
<tr>
<td>Location of BS</td>
<td>(50,175)</td>
</tr>
</tbody>
</table>
In this section, we carry out a comparison between our protocol and LEACH. To do so, the simulator measures the following three statistical performance metrics:

A. **Network lifetime**

Network life will be over when the last sensor node dies. Lifetime is the criterion for evaluating the performance of sensor networks. These networks should operate as long as possible because once the nodes are deployed it may be impossible to be supplied with energy except its battery.

![Fig. 5. Network topology using 100 nodes](image)

![Fig. 6. Number of alive sensor nodes over time](image)

In this part, we compare the number of nodes that are alive along with the time. Some nodes are starting to die at 390 second and all nodes are died at about 620 second in LEACH, while in our proposed technique the time for the first node to die is 470 second and all nodes die at about 680 second, which can be seen in Fig. 6. Therefore, our protocol prolongs the network lifetime over against LEACH.

B. **Standard deviation of system lifetime**

This gives a good measure of the network lifetime. The standard deviation will be used to assess the reliability degree of the network topology. In a generally way, the smaller the standard deviation is, the more reliable the protocol will be. A routing algorithm, which minimizes the standard deviation of network lifetime for each time, is predictable and thus desirable.

![Fig. 7. Lifetime of 10 random operation times](image)

Fig. 7 shows that the network lifetime for ten random operation times. In proposed protocol, the standard deviation of network lifetime is 9.169, which is much smaller than that in LEACH. This result demonstrates that the network has more stability with EBACH than LEACH protocol.

C. **Energy efficiency.**

All nodes in the network are energy constrained. It may be inconvenient or impossible to recharge sensors batteries. Therefore, not only the hardware but also the protocols must be designed to be extremely energy efficient. Moreover, the energy efficiency and the lifetime are usually related with each other. On the other hand, the more data the base station receives, the more accurate its view of the remote environment will be. Fig. 8 has shown total data of base station received. Once the total energy is fixed, energy efficiency can be evaluated by data packet received at BS. The protocol with high energy efficiency is preference.

We can investigate the results from Fig. 8. Because the cluster heads send their packets to the base station via single hop in LEACH, the energy consumption is much high. Whereas, in EBACH protocol, due to cluster heads transmitting the data via their respective relay node, a considerable amount of energy is saved.
Fig. 8 shows EBACH has successfully balanced the energy consumption over the whole network and consequently achieved the better performance.

![Graph showing data comparison between EBACH and LEACH]

Fig. 8. Total amount of data received at the BS over time

5. Conclusion and future work

In this paper, we have described a novel energy-balanced adaptive clustering hierarchical (EBACH) protocol based on the LEACH/LEACH-C protocol for wireless sensor networks. EBACH is a cluster based routing algorithm, which puts forward a three-layer data transmitting architecture by electing the relay node to distribute the overload of cluster head in each cluster.

As a result, simulation experiments demonstrate that our algorithm evidently improves the performance of sensor networks with respect to evenly energy distribution, system stability and network lifetime, in spite of the random deployment of nodes with non-uniform distribution.

There is still much space to develop in terms of data transmission. In the large scale sensor networks, multi-hop communication is a mainstream technique for energy saving. We will drop the assumption of single-hop and design an energy efficient protocol for inter-cluster data transmission in the future work.

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