A Level-based Energy Efficiency Clustering Approach for Wireless Sensor Networks

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Abstract

In wireless sensor networks, energy efficiency is an important research issue. The data transmission times could be decreased effectively to achieve energy efficiency by applying a cluster-based structure. This study proposed a level-based energy efficiency clustering approach. Each cluster replaces its cluster head and re-clusters periodically according to the established energy level. A cluster head is a node that has more residual energy and lower communication cost compared to other nodes. This level-based energy efficiency clustering approach could decrease the replacement times of cluster heads, thus avoiding the excessive energy consumption caused by frequent replacement of cluster heads. The simulation results showed that this approach has less energy consumption and can effectively extend the network lifetime.

1. Introduction

In recent years, with the development of the micro-electro-mechanical system and wireless communication network technology, wireless sensor network has been widely applied in fields of defense and military, environmental monitoring, and medical technology. Sensor nodes with wireless communication, ambient sensors, data operation and storage capabilities are deployed in sensory environments. The environmental information can be detected or monitored by these nodes, so that users can collect or obtain the sensed data easily and remotely. Such sensor technology is known as the wireless sensor networks (WSNs) [1].

Wireless sensor nodes have the advantage of compact size and low cost, and can be deployed in large sensory environments. However, there are many hardware limitations, such as arithmetic capability, storage space and finite energy. The energy problem is one of the most important issues in wireless sensor networks. In recent years, many researches have focused on improving or optimizing the energy efficiency.

Cluster-based approach [2, 3] is a data aggregation technology in wireless networks and can achieve energy efficiency effectively. As shown in Figure 1, in sensory environment, several nodes are selected as cluster head and other nodes join appropriate cluster heads to form a cluster. Each cluster head collects the sensory information of nodes in the cluster, and transmits it to back-end base station or data-acquisition center (sink node). The sensory information of all nodes is collected by the cluster heads, thus the times of data transmission are decreased and the effect of energy efficiency is achieved [9, 10]. However, in a cluster-based structure, the problem of unbalanced energy load may appear. The cluster head is in charge of most operations in the cluster, and consumes more energy than general cluster nodes, causing cluster

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heads to die faster. Moreover, the cluster size can also affect the energy load balance when the number of nodes in the cluster increases, cluster head consumes more energy; in case that cluster head dies, many control packets are consumed to re-cluster. Accordingly, more energy is consumed. Although many clustering approaches aiming for energy efficiency have been proposed, and some have achieved energy efficiency and extension of network lifetime, the problems of frequent replacement of cluster heads remain. Thus, the energy consumption still increases. As a result, how to find an energy efficiency approach to decrease the energy consumption of the sensor networks is an important research topic. Many researches [4-8] have proposed various technologies to achieve this.

2. Related works

The cluster-based structure in wireless sensor networks can be classified according to the network environment, sensor nodes capacity and cluster operation modes. This research focused on the operation approach for the selection of cluster heads, which can be classified into two types: iterative and probabilistic.

In the iterative cluster-based approach, the cluster head is determined according to the events sensed by the nodes or the rules and conditions defined based on the demand. This approach includes distributed clustering algorithm (DCA) [4] and algorithm for cluster establishment (ACE) [5]. In the distributed clustering algorithm, the cluster head is determined by comparing the weights initially defined for each node. The weights are compared between each round sensor node and its neighbor nodes. If its weight is higher than that of all the neighbor nodes, it would become the cluster head and broadcast information to request other nodes to join this cluster. If its weight is lower, it waits for the join-in request of others and joins other clusters with higher weight. However, the iterative cluster-based approach may have delay problems, thus nodes with lower weight have to wait for join-in information broadcasted by all cluster heads, causing the operation time to increase due to higher time complexity in high-density network environments.

Algorithm for cluster establishment (ACE) [5] can solve the high time complexity problem of the iterative cluster-based structure. During each round, each node only needs to compare the condition values of neighbor nodes within the establishment bound to decide the cluster head, thus, the delay problems can be reduced. After the cluster head is selected, it polls all member nodes to obtain data in the cluster and calculates the overlap degree between the node in case of being selected as the cluster head and other clusters. Thus, the node with the lowest overlap degree is selected as the new cluster head to adjust the network topology. Therefore, highly uniform cluster formation can be established to achieve the effect of balanced energy load.

A probabilistic cluster-based structure is an operation approach frequently discussed in recent years, in which, the cluster head is determined by the nodes according to random number or approach rules. Each node is operated step-by-step and individually and does not need base station or the controllers to transmit the control packet. The distribution operation has the advantage of energy efficiency and fast
deployment. The low-energy adaptive clustering hierarchy (LEACH) [6, 7] selects the cluster head probabilistically. It defines an initial probability value, and each node in each round determines the cluster head randomly according to this probability value. Other nodes then join the nearest cluster head and their probabilities of being selected as cluster head is increased in the next round. The purpose of this approach is to arrange the cluster-based structure quickly, and select each node to be cluster head in a certain round, thus the energy load is dispersed. However, this approach causes an unbalanced load between cluster heads, since cluster head selected probabilistically in denser area would have larger energy load due to the non-uniform arrangement density of the cluster.

A hybrid, energy efficiency distributed clustering approach for ad hoc sensor networks (HEED) [8] is also a probabilistic cluster-based approach. It regards the residual energy and communication cost as the selection probabilities of cluster heads. The selection probabilities of the node and other nodes within the communication range are compared first. If their selection probabilities are the same, then their communication costs are compared to determine the cluster head. The selection probabilities of the nodes and cluster head are compared periodically in each round. If the selection probability of a certain node is higher than that of cluster head, then it is replaced as cluster head. In this approach, the nodes with the most energy could be selected as the cluster head. However, in case of equal or similar node energy, the frequent replacement of cluster head would increase the transmission of the control packet, thus increasing the energy consumption.

Based on the above-mentioned researches, probabilistic cluster-based approach has good well energy load balance and extensibility, and could achieve energy efficiency and extend the network lifetime, thus has greater advantage in the wireless sensor networks, where the nodes have finite energy. Compared to iterative cluster-based structures, it is more applicable to the operation in special application environments. Therefore, this research proposed a level-based probabilistic energy efficiency clustering approach.

3. Level-based energy efficiency clustering approach

This section will introduce the operation process and algorithm for the level-based energy efficiency clustering approach, and explain the deployed network environment.

3.1 Network environment

The operational network environment of the level-based energy efficiency clustering approach proposed in this paper is as follows: sensor nodes are randomly deployed within the sensory range while base station is outside the sensory range. Moreover, the assumptions for the environmental conditions of the wireless sensor networks mentioned in this paper are as follows:

I. Nodes are in fixed positions.
II. The initial energy and operational capacities of the nodes are uniform.
III. The battery of the nodes cannot be replaced.
IV. The energy consumption of the nodes varies according to transmission distance.
V. The nodes have the capability to directly communicate with the base station.

The energy module [7] used in this research and the energy consumption of a sensor node transferring k bits information to the destination node at d distance are both as follows:

\[ T_x(k, d) = \begin{cases} k \times E_{elec} \times k \times \varepsilon_{fs} \times d^2, & d < d_0 \\ k \times E_{elec} \times k \times \varepsilon_{mp} \times d^4, & d \geq d_0 \end{cases} \]  

(1)

The energy consumption of a sensor node receiving k bits information is as follows:

\[ R_x(k) = k \times E_{elec} \]  

(2)

This energy module is established based on the two transmission models, free space model and multi-path fading model. If the transmission distance is within the threshold value \(d_0\), free space model is applied \(d^2\) energy consumption. If the transmission distance exceeds the threshold value \(d_0\), a multi-path fading model is applied \(d^4\) energy consumption. \(E_{elec}\) is the energy needed by electronic building bricks of the communication module; \(\varepsilon_{fs}\) and \(\varepsilon_{mp}\) are the energy needed by the amplifiers of these two models to transfer the information.

3.2 Operation process

In the cluster-based wireless sensor networks, it can solve the problem of high energy load and frequent replacement of cluster heads that was discussed in section 2. Therefore, a level-based energy efficiency clustering approach was applied to select the cluster head. The election probability of cluster head \(P_{CH}\) for sensor node i is defined according to residual energy and communication cost:
\[ S_{i,P_{CH}} = \frac{E_i}{E_{\max}} \times \left(1 - \frac{C_{i,B_{BS}}}{B_{S_{\max}}} \right) \times \left(1 - \frac{C_{i,s_{nbar}}}{C_{\max}} \right) \]

where, \( E_i \) is the residual energy of the nodes; \( E_{\max} \) is the maximal energy of the nodes; \( C_{i,B_{BS}} \) is the communication cost between the nodes and base station; \( B_{S_{\max}} \) is the maximal communication cost between the nodes and base station; \( C_{\max} \) is the maximal communication cost of nodes in the cluster; \( C_{i,s_{nbar}} \) is the average communication cost of nodes in the cluster, calculated as the following equation:

\[ C_{i,s_{nbar}} = \frac{\sum_{j=1}^{N} C_j}{N} \]

where \( N \) is the number of neighbor nodes in the cluster, \( C_j \) is the communication cost of the node to the neighbor nodes in the cluster.

The energy level was established as the threshold value of cluster head replacement in the proposed cluster-based structure. When the residual energy of cluster head itself was lower than a certain threshold value, all nodes in the cluster recalculated \( P_{CH} \) to select a new cluster head. Finally, when the residual energy of all nodes was lower than the lowest energy level, cluster head was occupied by the remaining nodes in turn by the round-robin approach.

\( P_{CH} \) value reflects the sustaining capacity of the nodes operation in the cluster-based structure. Nodes with higher \( P_{CH} \) have lower energy consumption and longer lifetime in operation. If it is selected as the cluster head, it has smaller energy load. The replacement of cluster head is determined by the level-based approach, which avoids wasting the control packets caused by frequent replacement of the cluster head and enables the cluster to replace more nodes in good timing to occupy the cluster head. Therefore, the energy load of the nodes can be distributed effectively to achieve energy efficiency. The pseudo code of the level-based energy efficiency clustering approach is as follows:

**Phase I: Initialize**
1. \( S \leftarrow \{s_i|s_i \in \text{sensor field}, \forall i = 1,...,n\} \)
2. \( S_{i,nbar} \leftarrow \{s_j \text{ lie located within } s_i \text{ 's radio range}\} \)
3. \( CL_k \leftarrow \{s_j \text{ lie located within } s_i \text{ 's cluster range}\} \)
   for \( k = 1,...,c\), \( c = \text{number of clusters} \)
4. Compute \( E_i, C_{i,B_{BS}} \text{ and } C_{i,s_{nbar}} \text{ to } s_{i,nbar} \)
5. \( S_{i,P_{CH}} = \frac{E_i}{E_{\max}} \times \left(1 - \frac{C_{i,B_{BS}}}{B_{S_{\max}}} \right) \times \left(1 - \frac{C_{i,s_{nbar}}}{C_{\max}} \right) \)
6. Broadcast \( s_{i,P_{CH}} \) and control packet to \( s_{i,nbar} \)
7. \( s_{i,\text{clusterhead}} \leftarrow \emptyset \)
8. \( L \leftarrow \{\text{level}_j, \forall j = 1,...,m\} \)

**Phase II: Clustering**
9. while \( s_{i,\text{clusterhead}} = \emptyset \) do
10. Compare \( s_{i,P_{CH}} \) to \( s_{i,nbar} \)
11. if \( s_{i,P_{CH}} = \text{Max}\{s_{j,P_{CH}}, \forall s_j \in s_{i,nbar}\} \)
12. \( s_{i,\text{clusterhead}} = s_{i,ID} \)
13. Broadcast cluster head control packet to \( \in CL_k \)
14. Aggregation cluster data packet from \( \in CL_k \)
15. Transmit data packet to base station
16. else
17. \( s_{i,\text{clusterhead}} \leftarrow \{s_{i,ID} | s_{i,P_{CH}} = \text{Max}\{s_{j,P_{CH}}, \forall s_j \in s_{i,nbar}\} \}
18. \( s_i \text{ join cluster for } s_{i,\text{clusterhead}} \)
19. Transmit data packet to \( s_{i,\text{clusterhead}} \)
20. end
21. end

**Phase III: Re-clustering**
22. if \( s_{i,\text{clusterhead}} = s_{i,ID} \) & \( E_i < L \)
23. if \( s_{i,P_{CH}} = \text{Max}\{s_{j,P_{CH}}, \forall s_j \in s_{i,nbar}\} \)
24. \( s_{i,\text{clusterhead}} \leftarrow \{s_{i,ID} | s_{i,P_{CH}} = \text{Max}\{s_{j,P_{CH}}, \forall s_j \in CL_k\} \}
25. Broadcast cluster head control packet to \( \in CL_k \)
26. end
27. if \( \forall E_{i,k} \in CL_k < L \& L \neq \text{level}_j \)
28. \( L \leftarrow \text{level}_j \)
29. end
30. end

Phase I involves system initialization. Each node calculates its residual energy and communication cost and broadcast these to other nodes within the range. Phase II involves clustering. Each cluster selects the node with maximal \( P_{CH} \) probability to occupy the cluster head and establishes the cluster. The member nodes in the cluster transmit their collected information to the cluster head. Phase III is the re-clustering approach. During each network operation, each cluster checks its residual energy periodically. When the residual energy is lower than the established energy level, all nodes in the cluster recalculate their \( P_{CH} \) and
compare their probability values with each other. If the probability value of the initial cluster head is still the largest, it is not replaced, thus cluster head does not need to be replaced at each round. Finally, when the residual energy of all nodes in the cluster is less than the least energy level, the cluster head is determined by the round-robin approach, and acted on by each node in turn until all nodes died.

The proposed cluster-based approach can establish different energy levels according to applied sensory environment. For example, given three energy levels of 75, 50 and 25, when the energy of cluster head is lower than the three energy levels by 75%, 50% and 25%, the above-mentioned re-clustering approach is performed. When the residual energy of all nodes in the cluster is lower than 10%, the cluster head is replaced by other nodes in a round-robin manner. Replacement of cluster head is determined by this approach, which avoids wasting control packets caused by frequent replacement of cluster heads and enables the cluster to replace more nodes in good timing to become the cluster head. Therefore, the energy load of the nodes can be distributed effectively to achieve energy efficiency.

4. Simulation results

This section discusses the experimental simulation based on the cluster-based approach. To validate the efficiency of the approach, efficiency analysis was performed on the following items: (1) network lifetime; (2) average residual energy of cluster heads; (3) efficiency analysis of the energy level. Network lifetime is the rounds of operations from the beginning until all nodes are died. The average residual energy is to calculate the average residual energy of all cluster heads in each round. Then, the efficiency of different energy level approaches is analyzed. The simulation network environment was as follows: 100 sensor nodes were deployed randomly within a 100m × 100m range, the base station was placed outside the (50m, 175m) range, the initial energy of each node was 0.5 Joule and the nodes communication range was 50m. The energy consumption module was as mentioned above, its parameters were: $E_{elec} = 50 \text{ nJ/bit}$, $E_{fs} = 10 \text{ pJ/bit/m}^2$, $E_{mp} = 0.0013 \text{ pJ/bit/m}^4$, $E_{da} = 5 \text{ nJ/bit}$, threshold distance=75m, data packet size=2000 bits, control packet size=100 bits. We evaluated the proposed method by using MATLAB that is a high-level technical computing language.

Based on the cluster-based approach, the lifetimes of 3-level clustering and LEACH were compared, the result of which are shown in Figure 2. The network lifetime is the rounds of network operation that span from deployment to the instant when all network nodes run out of energy. When the residual energy of the cluster head is lower than a certain level, re-clustering is performed to determine whether to replace the cluster head or not. The results showed that, some nodes began dying after 1900 rounds. Compared to LEACH, in which, cluster head is reselected in each round by the probabilistic approach, more control information is consumed, nodes begin dying after about 1000 rounds, in this method, the time intervals of nodes death are remote and most nodes die after about 1500 rounds. As seen, this approach could achieve lower energy consumption and distribute the energy load effectively to extend the network lifetime.

![Figure 2 Network lifetime](image)

The average residual energy of cluster heads showed the energy load size of the cluster-based approach. Since the cluster head consumes more energy than the general sensor nodes, thus how to reduce cluster head load is also an important research topic. Figure 3 shows the average residual energy through these two approaches. As seen, the average residual energy of cluster heads in each round by this approach could be maintained at a certain degree and not consumed continuously. Moreover, only when the residual energy of cluster heads is lower than the threshold value, the replacement of cluster head is carried out. Therefore, the replacement times of cluster heads is reduced to achieve energy efficiency. Compared to LEACH, which replaces cluster heads at every round and consumes more energy, the average residual energy of cluster heads by this approach is reduced linearly in each round.

Finally, the network lifetime of different energy levels were compared on the proposed level-based clustering approach. In the experiment, four energy level approaches were compared. Each approach
defined an energy level with different numbers, as shown in Figure 4. More energy levels were established, since the replacement times of cluster heads increased, thus the energy consumption was increased and the survival rounds decreased. Compared to the lower energy level, the replacement times of cluster heads decreased, thus the survival rounds became longer. However, in the three-level approach and one-level approach, lower energy level would decrease the replacement times of cluster heads but increase the time of nodes acting as the cluster head, thus causing load imbalance and nodes to die early. The experiment showed that, both higher and lower energy levels could not achieve energy efficiency. Therefore, the ideal energy level must be chosen according to the applied network environment and to achieve energy efficiency.

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5. Conclusions

In wireless sensor networks, there are energy limitations. The cluster-based structure is a technology which can save energy effectively. Since the cluster head in cluster-based structure is in charge of many operations, it also consumes more energy. Therefore, this research proposed a level-based energy efficiency clustering approach. Cluster heads are replaced by the level-based approach to reduce the replacement times of cluster heads for re-clustering and avoid the excessive energy consumption caused by the frequent replacement of cluster heads in the traditional cluster-based structure. Moreover, it has the capacity of homogeneously distributing the nodes load. The experiment results indicated that this cluster-based approach is able to achieve energy efficiency and load balancing.

6. References