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A Clustering Protocol for Periodic Data Acquisition in Wireless Sensor Networks

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Abstract

Periodic data acquisition is a typical application in wireless sensor networks (WSNs) which needs to acquire the data periodically from the network. The transmission cycle of nodes can be controlled by the user for different conditions of the application. LEACH (Low-Energy Adaptive Clustering Hierarchy) is a well-known clustering protocol for data acquisition in WSNs. For the randomness of cluster formation algorithm in LEACH, the transmission cycle of nodes is variable among clusters, so it is not suitable for periodic data acquisition. In this paper, we propose a clustering protocol for periodic data acquisition (CP-PDA) in WSNs. CP-PDA employs a TDMA scheme with the adjustable length of frame for data transmission and a cluster formation algorithm to control the number of nodes in clusters. Simulation results show that every node in CP-PDA has the same transmission cycle, and CP-PDA is more energy efficient than LEACH.

***Keywords**: Clustering, Periodic Data Acquisition, Wireless Sensor Networks*

1. Introduction

Wireless sensor networks (WSNs) consist of a large number of sensors with sensing, computation and wireless communication capabilities. It has numerous applications for its particular advantages such as easy deployment and low cost. The requirements of the sensor network change with the application, so it is application-specific [1].

Based on the mode of functioning and the type of target application, Manjeshwar *et al.* [2] have classified the sensor networks into proactive networks and reactive networks. In proactive networks, the nodes periodically switch on their radios and transmit the sensor data, while in reactive networks, the nodes react immediately to sudden changes in the value of sensed attributes. Periodic data acquisition is a typical application of the proactive networks. The user needs to acquire the data periodically from the network, and the period can be controlled by the user for different conditions of the application.

LEACH (Low-Energy Adaptive Clustering Hierarchy) is a proactive network protocol developed in [3]. It uses an adaptive clustering algorithm to form the clusters. The cluster heads (CHs) are rotating periodically among all nodes to evenly distribute energy loads in the network. Once the clusters are formed, the cluster heads broadcast TDMA schedule giving the order for data transmission. The adaptive clustering algorithm of LEACH well suits the characteristic of wireless sensor network, and is widely adopted in related research works. However, for the randomness of cluster formation algorithm, the transmission cycle is variable among clusters and cannot be controlled by the users. Hence LEACH is not suitable for periodic data acquisition.

In this paper, we propose a clustering protocol for periodic data acquisition (CP-PDA). CP-PDA employs a TDMA scheme with the adjustable length of frame to ensure that the nodes in sensor network will transmit their data in a constant cycle which depends on the

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requirement of applications. And a new cluster formation algorithm is adopted to control the number of nodes in clusters. Simulation results show that CP-PDA is able to fulfill the requirement of periodic data acquisition.

2. Related Works

Manjeshwar *et al.* [2] have proposed a classification of sensor network as proactive and reactive networks. They also introduce a new energy efficient protocol, TEEN (Threshold sensitive Energy Efficient sensor Network protocol) for reactive networks which respond immediately to the changes in the relevant parameters of interest.

LEACH is a well-known hierarchical clustering algorithm proposed by Heinzelman *et al.* in [3]. We will discuss LEACH in details in Section 3.

Handy *et al.* [4] extend LEACH's cluster head selection algorithm by a deterministic component. Furthermore, they present a new approach to define lifetime of sensor networks using three new metrics FND (First Node Dies), HNA (Half of the Nodes Alive), and LND (Last Node Dies).

Wang et.al [5] have noticed that the number of cluster heads is not guaranteed to be equal to the expected optimal value for the randomness of cluster head selection algorithm in LEACH. They have proposed a clustering scheme called SWATCH (StepWise Adaptive Clustering Hierarchy), which inserts an add-on selection stage to the cluster head selection phase. As a result, the number of cluster heads in each round tends to congregate in a narrow range around the optimal value. Besides, the DARC protocol [6] uses adaptive routing strategy to effectively balance the energy consumption in the routing phase.

On the other hand, HCR protocol [7] combines the gradient routing with dynamic clustering to generate connected and efficient topology with limited transmission range. Based on HCR, the improved protocol HCR-1 [8] effectively balances the energy consumption of nodes by using adaptive relay selection and tunable cost functions. Moreover, the JCR protocol [9] theoretically analyzes the probability of a node to be a cluster head and improves the cluster head selection algorithm. The cluster head selection of JCR takes the impacts of neighbor nodes into account, and has a better performances.

3. Review of LEACH

3.1. Operation of LEACH

The operation of LEACH is divided into rounds which are composed by setup phase and steady state phase. In the setup phase, nodes assign themselves as cluster heads with some probability. The cluster heads broadcast their advertisement (ADV) messages across the network, and the non-cluster head nodes join the clusters judging by the signal strength of ADV messages received. In steady-state phase, cluster heads are responsible for collecting sensor data within each cluster and then transmit the aggregated data to the base station (BS). A TDMA scheme is used for intra-cluster transmissions.

The steady-state phase is broken into frames, where nodes send their data to the cluster head at most once per frame during their allocated transmission slot. The duration of each slot in which a node transmit data is constant, hence the transmission cycle of nodes is equal to the duration of a frame which depends on the number of nodes in the cluster. The cluster head must be awake to receive all the data from the nodes in the cluster. It performs data aggregation and transmits the resultant data to the BS using CSMA scheme. At the end of a round, all nodes will reset to uncluster status and then start the set-up phase of a new round. The cluster heads are rotating periodically among all nodes to evenly distribute energy loads in the network.

3.2. Cluster Head Selection Algorithm

LEACH selects the cluster heads with a distributed algorithm, where nodes make autonomous decisions without any centralized control. In the sensor network with N nodes, each node i elects itself to be a cluster head at the beginning of round r + 1(which starts at time t) with probability $P_i(t)$,

$$P_i(t) = \begin{cases} \dfrac{k}{N - k \times (r \bmod \frac{N}{k})} & C_i(t) = 1 \\ 0 & C_i(t) = 0 \end{cases} \tag{1}$$

where k is the expected number of cluster heads. $C_i(t)$ is the indicator function determining if node i has been a cluster head in the most recent (r mod (N / k)) rounds (*i.e.*, $C_i(t)$ = 0 if node i has been a cluster head and one otherwise). This algorithm ensures that each node will be a cluster head once in every (N / k) rounds and hence distributes the energy loads among all nodes in the network.

3.3. Radio Model

LEACH uses both the free space (d^2 power loss) and the multipath fading (d^4 power loss) channel models. If the distance is less than a threshold d_0, the free space (*fs*) model is used; otherwise, the multipath (*mp*) model is used. Thus, to transmit an *l*-bit message a distance *d*, the radio expends and to receive this message, the radio expends

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

$$E_{Rx}(l) = lE_{elec} \tag{3}$$

The electronics energy, E_{elec}, depends on factors such as the digital coding, modulation, filtering and spreading of the signal, whereas the amplifier energy, $\varepsilon_{fs}d^2$ or, $\varepsilon_{mp}d^4$ depends on the distance to the receiver and the acceptable bit-error rate.

4. Problem Outline

4.1. The Effect of the Number of Nodes in Clusters

As described in Section 3.1, the transmission cycle of nodes depends on the number of nodes n in its cluster in LEACH, so the transmission cycle T_f is

$$T_f = n \times T_s \tag{4}$$

where T_s is the duration of a TDMA slot. The cluster with more nodes has longer transmission cycle than others.

Each cluster head dissipates energy for receiving signals from the nodes, aggregating the signals, and transmitting the aggregate signal to the BS. Since the BS is far from the nodes, presumably the energy dissipation follows the multipath model. Based on the formula (2) and (3), the energy dissipated in the cluster head during a single frame is

$$\begin{aligned} E_{CH} &= lE_{elec}(n-1) + lE_{DA}n + lE_{elec} + l\varepsilon_{mp}d_{toBS}^4 \\ &= lE_{elec}n + lE_{DA}n + l\varepsilon_{mp}d_{toBS}^4 \end{aligned} \tag{5}$$

where l is the number of bits in each data message, E_{DA} is the energy for data aggregation, d_{toBS} is the distance from the cluster head to the BS.

Each non-cluster head node only needs to transmit its data to the cluster head once during a frame. Presumably the distance to the cluster head is small, so the energy dissipation follows the free space model. Thus, the energy used in each non-cluster head node is

$$E_{non-CH} = lE_{elec} + l\varepsilon_{fs}d_{toCH}^2 \tag{6}$$

where d_{toCH} is the distance between the node and the cluster head. For the duration of a round is a constant Tr , the energy dissipated in the cluster head in a round is

$$\begin{aligned} E_{CHr} &= \frac{T_r}{T_f}E_{CH} = \frac{T_r}{nT_s}E_{CH} \\ &= \frac{T_r}{T_s}l(E_{elec} + E_{DA} + \frac{1}{n}\varepsilon_{mp}d_{toBS}^4) \end{aligned} \tag{7}$$

and the energy dissipated in non-cluster head node during a round is

$$E_{non-CHr} = \frac{T_r}{nT_s}(lE_{elec} + l\varepsilon_{fs}d_{toCH}^2) \tag{8}$$

According to the formula (7) and (8), the energy dissipation is mostly depended on the position of CHs and the number of nodes n. The nodes in a small cluster spend more energy because the cluster head and non-cluster head nodes transmit their data more frequent than those in larger clusters. The result is opposite to the conventional idea which believes that a great number of nodes in cluster is a heavy burden for its cluster head.

4.2. Motivation

Due to the randomness of cluster head selection algorithm in LEACH, the transmission cycle of nodes cannot be controlled by users. Figure 1 shows the number of nodes in five clusters in a round of LEACH. The number of nodes is variable among clusters in the same round. It makes the nodes in different clusters have different transmission cycle and thus the different energy dissipation.

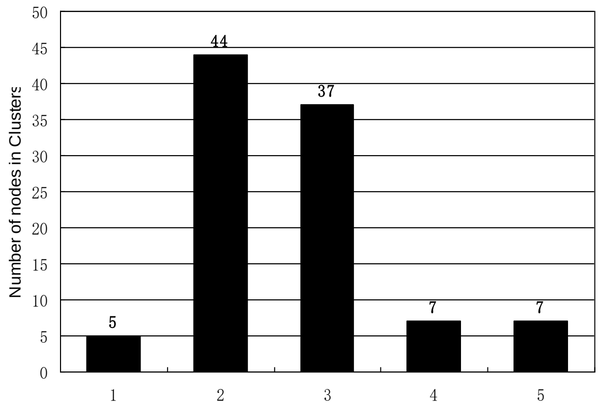

Figure 1. Number of Nodes in Five Clusters in a Round

In most applications such as remote monitoring, the users usually want to acquire the data from the sensor network periodically. For example, the user wants to collect the data every 400 ms, and we assumed that a TDMA slot lasts 10 ms. In LEACH, a cluster with 20 nodes transmits the data every 200ms in which half of the data are useless, while a cluster with 50 nodes transmits the data every 500ms which can not fulfill the requirement of application.

Our goal is to design a protocol for periodic data acquisition. The user can control the transmission cycle of nodes in network for different conditions required in applications. In addition, the nodes do not transmit unnecessary data to reduce the energy dissipation.

5. Details of CP-PDA

In this section, we present the details of a new network protocol call CP-PDA (Clustering Protocol for Periodic Data Acquisition). CP-PDA is developed based on LEACH, and has some improvements for the requirement of periodic data acquisition.

In CP-PDA, the transmission cycle of nodes T_f should not be longer than the data acquisition period T_d required in the application. According to the formula (4), the number of nodes *n* in cluster should be,

$$n \leq \frac{T_d}{T_s} \tag{9}$$

Hence the maximum number of nodes in cluster $n_{\max}$ is,

$$n_{\max} = \left\lfloor \frac{T_d}{T_s} \right\rfloor \tag{10}$$

In the steady-state phase, every node transmits its data in a constant cycle T_f which is determined by,

$$T_f = n_{\max} \times T_s \tag{12}$$

and a new cluster formation algorithm is adopted to ensure that the number of nodes in clusters will not exceed $n_{\max}$.

5.1. Cluster Head Selection Algorithm

At the beginning of round *r*, nodes assign themselves as cluster head candidates with probability,

$$P_i(t) = \begin{cases} \dfrac{k}{N - \sum_{j=m}^{r-1} H_j} & C_i(t) = 1 \\ 0 & C_i(t) = 0 \end{cases} \tag{13}$$

H_j is the number of clusters in round *j*. H_j could be obtained from the number of advertisement (ADV) messages broadcast by cluster heads. The power of ADV messages should be set high enough to reach all nodes in the network [7], hence all nodes could have the same H_j. $C_i(t)$ is the indicator function works like that in LEACH. When $N - \sum_{j=m}^{r-1} H_j < H_{\min}$, which means that almost every node has been a cluster head in the past *j*-*m* rounds, $C_i(t)$ should be reset to one and the variable *m* should be set to *j* for the beginning of new sequence of rounds.

The CH candidates broadcast their advertisement (ADV) messages across the network. All nodes keep the number of ADV messages received. If it is less than $H_{\min}$, all nodes will reset their status and repeat the steps given above until the number of ADV messages is not less than $H_{\min}$.

5.2. Cluster Formation Algorithm

When the number of ADV messages is not less than $H_{\min}$, the cluster head candidate becomes cluster head, and the non-cluster head node sends JOIN message to its cluster head judging by the signal strength of ADV messages received.

The cluster head keeps all the JOIN messages received. If the number of JOIN messages is larger than $n_{\max}$, the cluster head will choose the closest $n_{\max}$ nodes and reply acknowledgment (ACK) messages to them. Otherwise, the cluster head will reply ACK messages to all nodes that have send JOIN messages to it, and then broadcast the ADV message across the network again. If the non-cluster head node does not receive ACK messages, it will record those ADV messages and choose another cluster head.

When every node has been a part of a cluster, each cluster head broadcasts the TDMA schedule in its clusters. After that, all nodes go to the steady-state phase for data transmission.

5.3. Steady-State Phase

The steady-state phase is broken into frames, where nodes send their data to the cluster head at most once per frame during their allocated transmission slot. The length of a frame is determined by formula (12). Since the length of frame is constant, there will be some empty slots in a frame if the number of nodes in cluster is less than $n_{\max}$.

To reduce the energy dissipation, each non-cluster head node uses power control to set the amount of transmits power based on the received strength of the cluster head advertisement. Furthermore, the radio of each non-cluster head node is turned off until its allocated transmission time.

The cluster head must be awake to receive all the data from the nodes in the cluster. Once receives all the data in a frame, the cluster head performs data aggregation and sends the resultant data to the BS. The cluster head also turns off its radio in the empty slots to save the energy.

6. Performance Evaluation

We used the OMNeT++ simulator [10] to evaluate the performance of CP-PDA and compared it to LEACH. LEACH was implemented based on Solar-LEACH source code released by [11].

6.1. Experiment Setup

The simulation has been conducted on a network with 100 nodes randomly dispersed between (x=0, y=0) and (x=100, y=100) with the BS at location (x=50, y=175). Each data message is 4000 bits long, and the packet header for each type of packet is 200 bits long. Each round lasts for 20s, and the length of a TDMA slot is 10ms. The optimal number of cluster heads k is set to 5. The radio model is the same as LEACH which is given in Section 3.3.

In order to evaluate the effect of data acquisition period T_d on CP-PDA. We run CP-PDA with two different T_d : 500ms (scene 1) and 300ms (scene 2). Based on the formula (10), (11) and (12), the value of related parameters is given in Table 1.

Table 1. Parameters of Two Scenes

	Scene 1	Scene 2
T_d	500ms	300ms
n_{max}	50	30
H_{min}	2	3
T_f	500ms	300ms

6.2. Results

Figure 2 shows the transmission cycle of nodes in the first 15 rounds in one sample of the simulation. The transmission cycle of nodes varies among clusters in LEACH, so we give the maximum and minimum transmission cycle in the graph. In LEACH, the transmission cycle of nodes changes in different rounds because of the randomness of cluster formation algorithm. The maximum transmission cycle of nodes is over 500ms in one round and over 300ms in ten rounds, hence LEACH cannot fulfill the application of acquiring the data every 300ms or 500ms from the network. On the other hand, the minimum transmission cycle of nodes is lower than 100ms in seven rounds. The nodes in those small clusters consume great amount of energy for sending more data than others, but most of the data transmission is useless for periodic data acquisition.

In both scene of CP-PDA, every node transmits its data in the same transmission cycle which is equal to T_d. There is no unnecessary data transmission in CP-PDA that reduces the energy dissipation.

Next, we evaluate the lifetime of network with different protocol. We choose the metric FND (First Node Dies) proposed in [DCHS] to define the lifetime of network. It is because that the data from all nodes are necessary for periodic data acquisition. The quality of the sensor data decreases considerably as soon as one node dies. Moreover, the death of node has an impact on the cluster head selection algorithm of both CP-PDA and LEACH that will not function as expected.

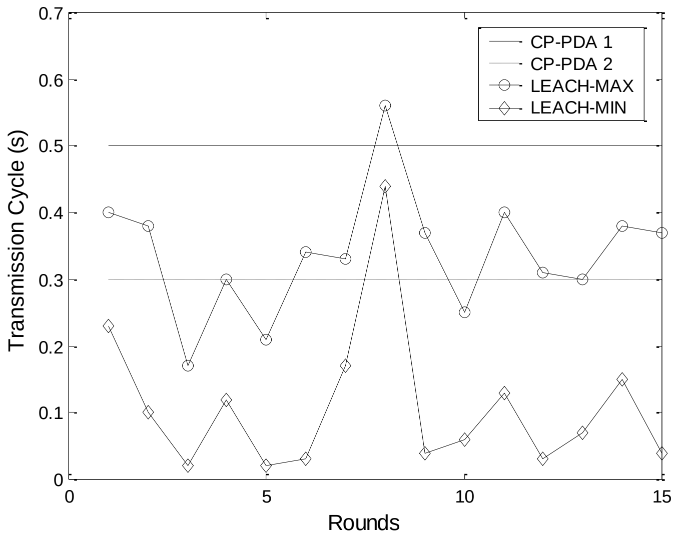

Figure 2. Transmission Cycle of Nodes

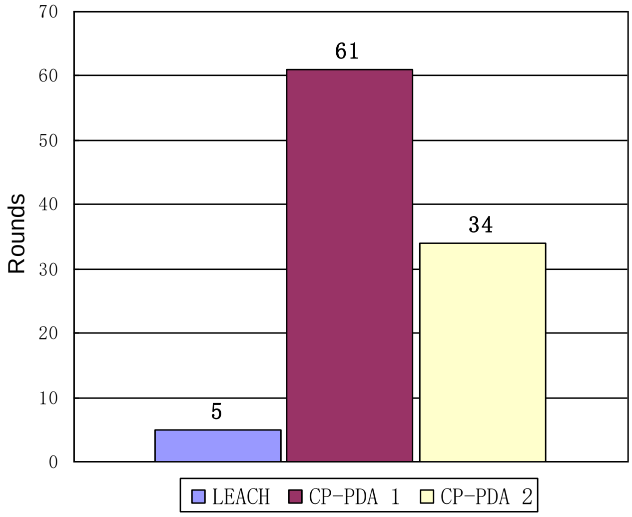

Figure 3. Lifetime of Networks (FND)

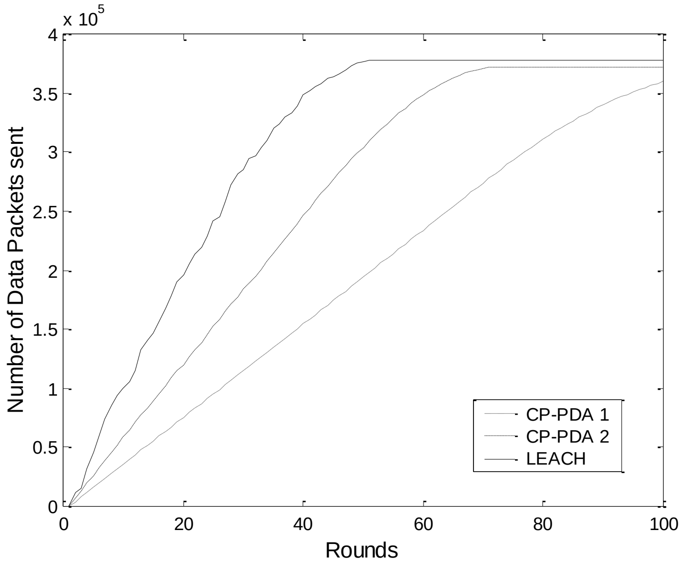

Figure 4. Number of Data Sent from the Network

According to Figure 3, the first dead node appears quickly in LEACH, because the cluster with small number of nodes is a heavy burden for its cluster head which has to transmit data with BS frequently. The lifetime of CP-PDA has a great improvement over that LEACH by reducing the unnecessary data transmission. Every cluster head transmits the resultant data in the same cycle no matter how many nodes in its cluster. The lifetime of network decreases in scene B for the nodes have to send more data than nodes in scene A.

Finally, we compare the number of data sent from the network. Figure 4 shows the number of data sent in 100 rounds in one sample of the simulation. LEACH transmits more data than CP-PDA in the first several rounds. However, the growth of sent data in LEACH decreases for the death of nodes, so CP-PDA and LEACH have sent almost the same number of data in total.

The number of sent data grows steadily in CP-PDA because all nodes transmit their data in the same transmission cycle. The number of data in scene 2 grows faster for the nodes transmit their data more frequent than that in scene 1.

7. Conclusion

In this paper, we propose a new clustering protocol CP-PDA for periodic data acquisition in wireless sensor networks. It allows the user to control the transmission cycle of nodes for different conditions of application. Simulation results show that every node in CP-PDA has the same transmission cycle, and CP-PDA is more energy efficient than LEACH.

However, the cluster formation algorithm of CP-PDA may not be efficient when the data acquisition period T_d is small. It may spend more time on adjusting the clusters that has a great impact on the performance of the protocol. We will focus on this problem in the future work.

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