

# A Novel Self-organizing Hybrid Network Protocol for Wireless Sensor Networks

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## Abstract

*Recent development of Wireless Sensor Networks (WSN) has led to the appearance of many application specific communication protocols which must be energy-efficient. Among those protocols developed for WSN, LEACH (Low Energy Adaptive Clustering Hierarchy) protocol is one of the most promising protocols. In this paper, a novel self-organizing energy efficient hybrid protocol based on LEACH is presented, combining cluster based architecture and multiple-hop routing. Multi-hop routing is utilized for inter-cluster communication between cluster heads and the base station, instead of direct transmission in order to minimize transmission energy. Besides, this protocol adds some mechanisms to CSMA/CD (Carrier Sense Multiple Access with Collision Detection) so as to avoid collisions, instead of using other more complicated MAC protocols during the period of cluster formation. The performance of the novel protocol is evaluated and compared with LEACH. Simulation results demonstrate that our novel protocol can achieve better performance on energy efficiency and the lifetime of WSN.*

## 1. Introduction

Distributed sensing and computing have been made possible and practical by the advance of wireless communication technology and the availability of integrated miniature sensors and many lightweight, compact, portable computing devices. Wireless Sensor Networks (WSN) can achieve data collection, aggregation and communication from a remote environment through many distributed individual sensor nodes, called microsensors, which can be connected by radio link. WSN can be used to monitor a variety of environments for applications such as surveillance, machine failure diagnosis, and chemical/biological detection [1][2][3].

There are many rigid constraints in the design of WSN such as small size, light weight, ultra-low energy consumption and low cost [4]. Among them energy efficiency should be considered one of the most critical issues since it is impractical to replace batteries on thousands of microsensors. Furthermore, in some cases the microsensors may not be accessible for battery replacement. Therefore designing power-efficient protocols is crucial for prolonging the lifetime of WSN.

This paper builds on the work described in [5] by giving a detailed description and analysis of our novel application specific network protocol for WSN. The remainder of this paper is organized as follows: Section 2 gives related work in the field of network protocols for WSN. A brief introduction of LEACH protocol and its potential problems are presented in Section 3. Section 4 describes the design of our novel protocol in detail. Simulation and results are discussed in Section 5. Finally, conclusions are made in Section 6.

## 2. Related work

The recent interest in WSN has led to a number of network protocols. Because of high correlation of the data from the neighboring nodes, some protocols adopted cluster based network architectures. The researchers in [6] propose a new chain-based protocol called PEGASIS that minimizes the energy consumption at each sensor node. In [7], the authors present a new minimum spanning tree-based protocol, called PEDAP and its power-aware version PEDAP-PA. In [8], a protocol called APTEEN is introduced that uses an enhanced TDMA schedule to efficiently incorporate query handling.

Besides the protocols above, the LEACH protocol presented in [9] is an elegant solution to the data aggregation problem where clusters are formed in a self-organized manner to fuse data before transmitting

to the end user. In LEACH, a designated node in every cluster, called the cluster head is responsible for collecting and aggregating the data from sensors in its cluster and eventually transmitting the result to the end user.

Our novel protocol is based on the LEACH protocol described in [9] by integrating a multiple-hop routing scheme for inter-cluster communication between cluster heads and the base station far away, instead of direct transmission, for prolonging the lifetime of WSN. Furthermore, CSMA incorporating some collision avoidance mechanisms is utilized for MAC protocol during the period of cluster formation.

### 3. LEACH protocol architecture

In LEACH, the operation of the whole network is divided into many rounds. Every round includes set-up phase and steady-state phase. The latter is divided into many frames as shown in Fig.1.

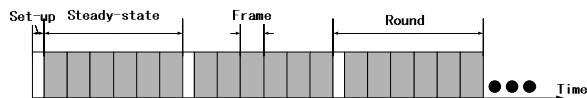


Fig.1. Time line showing operation of LEACH

During the period of set-up phase all nodes are organized into some clusters through communicating with short messages and one node becomes cluster head. Every cluster head sets up a TDMA schedule for all member nodes of its cluster. All nodes broadcast short messages using carrier-sense multiple access (CSMA) MAC protocol [10]. Following the set-up phase, the data is transferred from member nodes to cluster heads according to the TDMA schedule during a frame, aggregated to reduce redundant data and then passed on to the base station (BS) at the end of each frame. Fig.2. shows the time line of one stretched round.

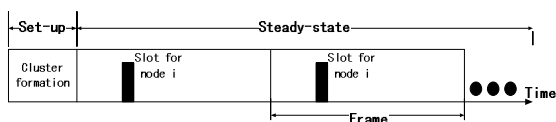


Fig.2. Time line in one round

A potential problem with LEACH is that all cluster heads send the compressed data to the BS directly. If all sensor nodes are pervasive in a large area, some clusters are far from the BS and others are close to the BS. This can lead to great difference between the transmission energy dissipations that the nodes use to transmit data to the BS. The radio transmission energy dissipation includes two parts of radio electronics energy and power amplifier energy. Generally the

amplifier energy required for a successful transmission is much larger than the radio electronics energy and dominates the transmission energy dissipation. According to the free space channel model, the minimum required amplifier energy is proportional to the square of the distance from the transmitter to the destined receiver ( $E_{Tx-amp} \propto d^2$ ) [11]. So the transmission energy consumption will increase greatly as the transmission distance rises. It means that the cluster heads far from the BS must use much more energy to send the data to the BS than those close to the BS. Therefore after the network operates for some rounds there will be considerable difference between the energy consumption of the nodes near the BS and that of the nodes far from the BS. We assume that all nodes begin at the same energy storage. The nodes far from the BS will use up their energy before those near the BS. As a result the network will be partitioned into regions with live nodes and dead nodes and the performance of the network will decline.

Besides there can be high probability of collisions among the short messages at the set-up phase in LEACH because all nodes are within communication range of each other and utilize the same frequency band. This may lead to the result that some important short messages fail to be received by their expected destination nodes because of collisions. As a result some nodes cannot be organized into clusters and lose connectivity with the network during a round. Thus the network loses its function partly.

### 4. Our novel protocol

To solve the preceding problems, we propose a novel self-organizing hybrid protocol for WSN. This protocol combines cluster architecture of LEACH with multi-hop routing to reduce transmission energy.

In many WSN and Ad hoc wireless networks multi-hop routing is adopted. This approach makes a node that wants to transmit data to a destination node find one or multiple intermediate nodes. The data packets from the source node are relayed among the intermediate nodes until it reaches the destination [12]. In other words the data packets take several hops among the nodes. The main advantage of this approach is that transmission energy consumption can be reduced. But at the same time latency of the network and delay of data packets will increase. However, as for some cases that have no rigid requirements on latency the multi-hop routing can lead to high energy efficiency.

In our protocol after clusters are organized, the cluster heads could form a multi-hop routing backbone. For the communication within a cluster every member node sends data to the cluster head directly. While for

the communication between the cluster head and the BS, a multi-hop routing is adopted to reduce the transmission energy and minimize the difference of energy consumption among all nodes. Our protocol uses “minimum transmission energy” (MTE) routing [13][14] as the routing algorithm.

In order to reduce the probability of collisions at set-up phase, we add some collision avoidance mechanism to CSMA MAC protocol. In contrast to many developed MAC protocols capable of avoiding collisions effectively, such as 802.11 [15] which is applied to most Ad hoc wireless networks, the approach is much simpler and more energy efficient. Thus it is more suitable to WSN.

For the development of our protocol, we make the same assumptions as LEACH about the network model as follows. Firstly, every node in the network has the same infrastructure and is homogenous. Besides, every node has limited energy. Secondly, all nodes in the network have enough power to directly communicate with any node in the network including BS. This means that all nodes can use power control to vary their transmission power and range. At the same time, each node has enough processing power to support different protocols and signal processing tasks. These assumptions have been made possible because of the availability of many advanced radio frequency devices and low power computing devices. Finally, we assume that those nodes nearby have highly correlated data that is redundant for BS. The following section describes our protocol in more detail.

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#### 4.1. Period of cluster formation

At this period, all nodes are organized into clusters through short messages like LEACH. All nodes when taking any actions are autonomous. Thus the whole network is highly self-organizing.

At the beginning of this phase every node in the network must decide whether it will become a cluster head or not. Each node makes decision to become a head with probability  $P_i$ .  $P_i$  is calculated according to a cluster head selection algorithm given in LEACH. This algorithm ensures that each node can take its turn to act as cluster head, the expected number of cluster head nodes for every round is  $k$  and every node can be a cluster head only once in  $N/k$  rounds on average (We assume that there are  $N$  nodes in the whole network and the network is divided into  $k$  clusters). Because cluster heads act as intermediates between members and BS, a cluster head node consumes energy much more rapidly than a member node. In order to prevent some nodes being overused so as to run out of energy

before others due to being cluster heads much more times than others, we must try to distribute the energy burden among all nodes in the network. This cluster head selection algorithm solves the problem above efficiently. The detailed algorithm can be found in [9].

After some nodes have become cluster heads, they should make all other nodes know they have been cluster heads for this round. To complete this, every head broadcasts an announcement (ANNOU) message through CSMA MAC protocol. This message is a short message including the node's ID and message content indicating that the message is ANNOU. ANNOU contains the unique spreading code of the node and coordinate of the node's location. The former is for the intending direct-sequence spread spectrum (DSSS) within a cluster and the latter is for multi-hop routing among cluster heads at steady-phase.

At this stage all cluster heads load a random delay time  $t_i$  after they decide to become heads. After  $t_i$  they broadcast ANNOU messages. The random delay time  $t_i$  is uniformly distributed between zero and  $T_i$ . The value of  $T_i$  should be set appropriately according to the number of cluster heads and end-to-end delay of the network to make sure that there can be enough interval time between sending messages of two random heads. This approach ensures that all heads broadcast ANNOU messages at different time and the messages can reach a member node at different times. Thus the probability of collisions is minimized and nearly all messages can be received successfully by member nodes.

A cluster head can receive some ANNOU messages from other heads after it finishes sending its ANNOU. This can make a cluster head acquire spreading codes and the coordinates of other heads. The information will be stored for the subsequent routing algorithm.

After every member node receives several ANNOU messages from different heads it will choose the closest cluster head to join the cluster. The member nodes estimate the distances from every cluster head to them using the received signal strength of the messages based on a channel propagation model and then pick the cluster head with the smallest distance. This is because the closest cluster head to a member node is the one that requires the minimum transmission energy for the member node to communicate with.

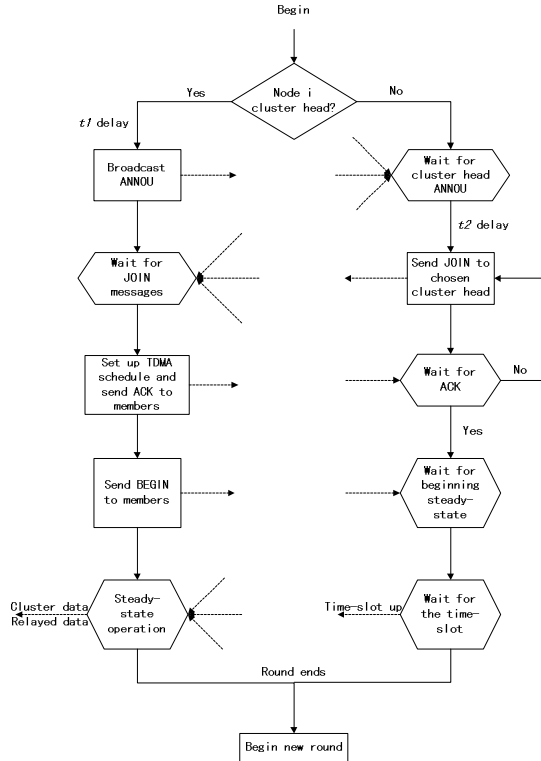


Fig.3. Flowchart of the protocol in one round

Once a member node has decided which cluster to join, it would load a random delay time  $t_2$  like in the case of cluster head nodes. After  $t_2$  it sends a join request (JOIN) message to the chosen cluster head using CSMA. After the cluster node receives the JOIN message it will send an acknowledgement (ACK) message to the member from which the JOIN comes so as to set up a time division multiple access (TDMA) schedule and allocate a time-slot number to the member. Although we use the same approach as for ANNOU to make every JOIN message sending time different from others in order to reduce probable collisions, there might still be some JOIN messages fail to be received by expected heads. Once this happens, the member node that the colliding JOIN comes from would lose connectivity with the network for this round. Thus we adopt a retransmission mechanism. After a member sends a JOIN, it would wait a fixed period of time  $t_3$  for the ACK message. If it does not receive the message after  $t_3$ , it would retransmit the JOIN message. This process will be executed iteratively during some time till it receives the ACK message. This mechanism can prevent any node from not being organized into a cluster. If a member node receives the ACK message it would wait for the beginning of the steady-state phase. When every head gets some members after some time, it would broadcast a begin-steady (BEGIN) message.

This message can keep member nodes and cluster head within a cluster synchronous and ensure that they can begin steady-state phase at the same time. Besides, it can also let other cluster heads know TDMA schedule of the cluster. The information is also useful for subsequent inter-cluster communication. After a while all nodes in the network would enter the steady-state phase simultaneously. A flowchart of the protocol operation during a round is shown in Fig.3.

## 4.2. Steady-state phase

The steady-state is made up of many frames. Each frame includes many time-slots during which every member node can send its data to the cluster head only once at its unique time-slot. This TDMA schedule avoids collisions among data messages in a cluster and allows the radio devices of each member to be turned off when it is not its time-slot. Thus the energy consumption is reduced. After the cluster head finishes receiving all data from its all member nodes at the end of each frame it will aggregate the data, reduce redundant data and then send the compressed data to the BS.

With our protocol every cluster head that has a data packet ready to be transmitted would select a route to relay the packet to the BS indirectly instead of transmitting the packet directly to the BS as in LEACH. The route is chosen according to MTE routing algorithm. Therefore, the algorithm chooses one or some intermediate nodes so that the sum of squared distances is minimized. As described in the preceding section, the dominant part of the transmission energy is proportional to the square of the distance. Thus the total transmission energy is minimized.

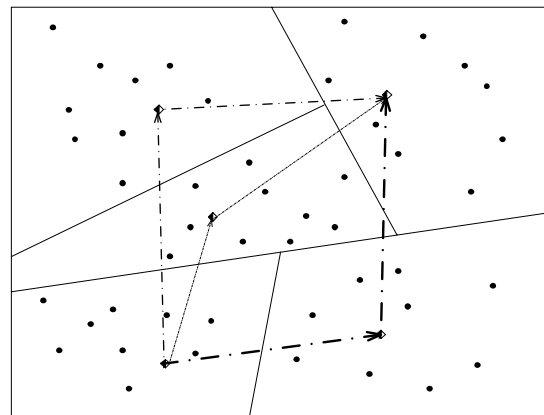


Fig.4. Five clusters in one round with logical routes between two cluster heads

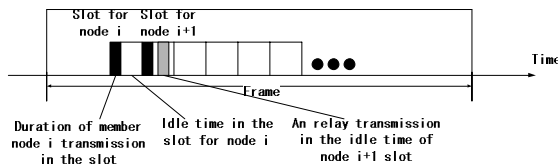
In our protocol, if there is a head node  $A$  that wants to send a packet, it would calculate the sum of squared distances function  $D(X)$  of all other heads which is defined as below:

$$D(X) = d_{A-X}^2 + d_{X-BS}^2 \quad X \in \{All \ other \ heads\} \quad (1)$$

Then the minimum of these is picked and compared to the square of the distance from head node  $A$  to the BS. Only if

$$Min(D(X)) < d_{A-BS}^2 \quad (2)$$

the node that makes the function minimal (we name the node  $B$ ) is selected as intermediate node through which node  $A$  would transmit to the BS. Otherwise the node  $A$  would still transmit to the BS directly. When the packet arrives at the node  $B$ , the above algorithm will be repeated to decide whether node  $B$  should select an intermediate node or not. This process would be iterated till the packet reaches the BS. Fig.4. shows five clusters formed during one round and three possible routes for inter-cluster transmission from the cluster head in the bottom left corner to the one in the top right corner.



**Fig.5. Time line in one frame in our protocol**

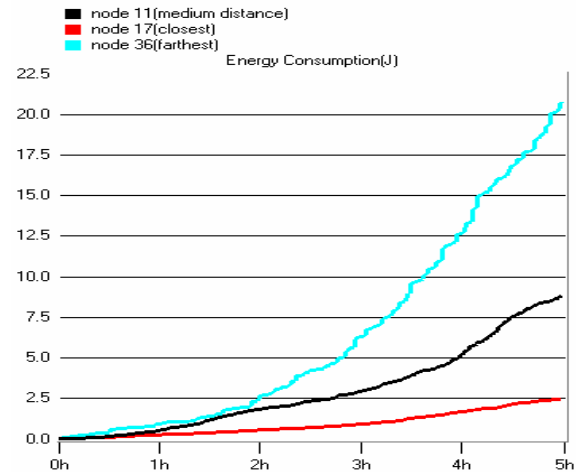
In order to avoid collisions probably occurring at a cluster head between the inter-cluster transmission and intra-cluster transmission our protocol utilizes the interval time between two time slots for member nodes to send data. Once a cluster head has aggregated data to send to the BS and select another one as intermediate node, it would estimate whether the intermediate node is at the idle time between two time slots according to the TDMA schedule of the intermediate node's cluster that is broadcasted at set-up phased. If the intermediate node is busy on receiving the data from its member nodes at that time the transmission would be deferred until it is idle. Otherwise the transmission would be performed. Fig.5. shows the time line of a frame in steady-state phase. When the packet reaches the intermediate node, the mentioned routing algorithm will be used to decide whether to select a relay cluster head or not. If a relay head is selected again, the above approach will be performed again until the packet reaches the BS. Obviously, we must make every time slot long enough to finish inter-cluster communication for using this approach. Of course, this would increase latency of the

network. But in our protocol we trade off latency for energy saving.

At this phase every cluster is assigned a unique spreading code. All nodes within the cluster transmit data using the spreading code. It can reduce inter-cluster interference efficiently. When a cluster head wants to communicate with another head, it would switch to use the spreading code for the head and then switch back to receive the data messages from its members after that. All cluster heads communicate with the BS using another fixed spreading code. Besides CSMA/CA (Collision Avoidance) [16] is used as MAC protocol at the inter-cluster level to avoid probable collisions of transmission between cluster heads and the BS.

## 5. Simulation and results

We used the network simulator OPNET to model our protocol. OPNET [17] provides a fairly realistic simulation environment for WSN among the available network simulators. Especially it takes the effect of noise into account on the performance of networks. In order to compare with original LEACH we also built a model for LEACH using OPNET and used the same power model as in [9] for both models to evaluate and compare their energy efficiency. Our simulation is based on a network with 40 nodes distributed in a 1km\*1km area.

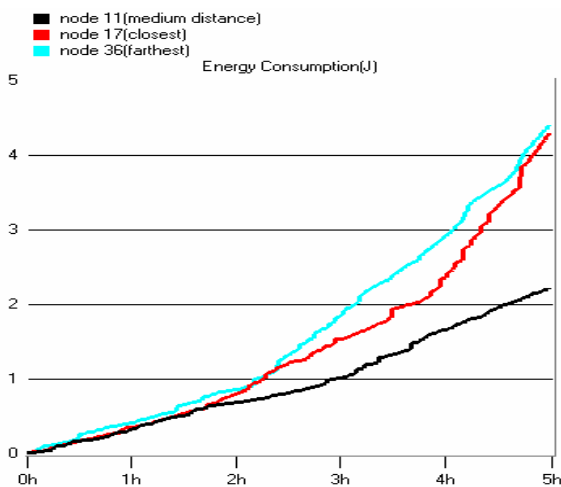


**Fig.6. Energy consumption over time of 3 nodes with LEACH**

Fig.6. shows the energy consumptions over time of three nodes with different distances to the BS using the original LEACH protocol. Clearly, there is great difference between the energy consumption of the node far from the BS and that of the closest one as expected. The farthest node consumes almost eight times more

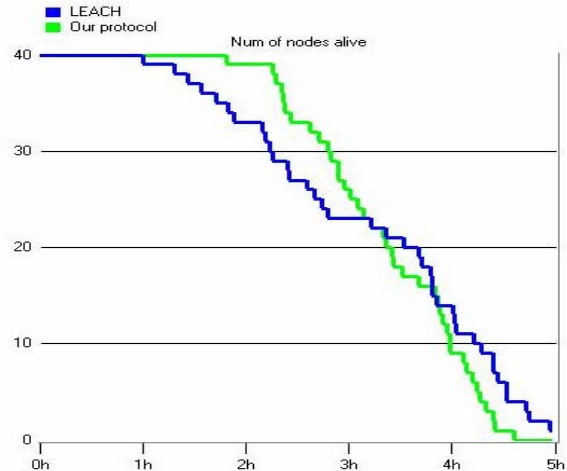
energy than the closest node, after 300 minutes of simulation time.

Fig.7. shows the same profile with our protocol as in Fig.6. However, as evident from the graph, the energy consumptions of the same two nodes (node 36 and 11) are reduced significantly for the same duration of time compared to using LEACH. With our protocol, the maximum energy consumption is 4.4J and the minimum is a little more than 2J, compared to 20.7J and 2.5J respectively for LEACH protocol. Clearly the difference of energy consumption is also reduced significantly. However, the energy consumption of the closest node (node 17) rises up a little (from 2.5J to 4.3J). This is because the nodes near the BS take the responsibility of intermediate nodes in multi-hop routing and hence consume a little more energy.



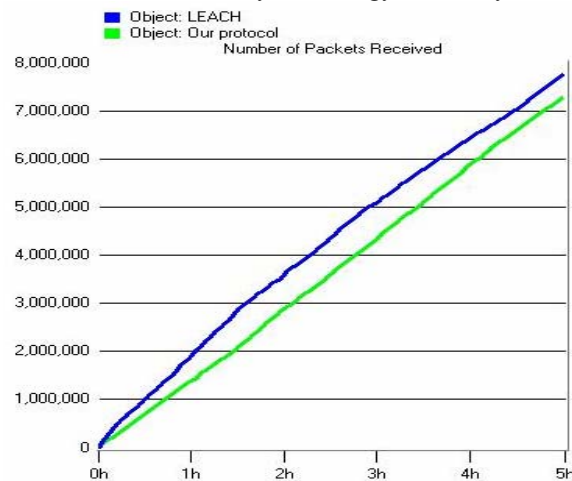
**Fig.7. Energy consumption over time of 3 nodes with our protocol**

If we limit the storage energy of every node to 2J in the simulation, we can get the number of live nodes over time for LEACH and our protocol after enough simulation time as shown in Fig.8. The number of live nodes in the network using LEACH begins to fall after 1 hour but that in the network using our protocol begins to fall after nearly 2 hours. Thus the lifetime of the network is prolonged greatly. However, the number of live nodes in the network using our protocol falls more sharply than that of using LEACH. Therefore, the network using our protocol stays alive as a whole longer, and declines a little faster.



**Fig.8. Number of live nodes over time with both protocols**

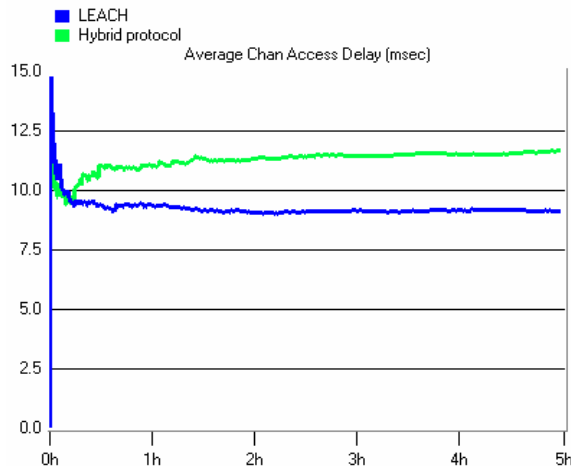
Fig.9. shows the number of received packets by the BS over time in LEACH and our protocol. In our protocol delay of the packets to the BS increases compared to LEACH because they take several hops to reach the BS. This leads to a little decrease in the number of packets received. But this could be tolerated since our protocol prolongs the lifetime of the network significantly. Therefore, we have got a good tradeoff between network latency and energy efficiency.



**Fig.9. Number of received packets over time by the BS in both protocols**

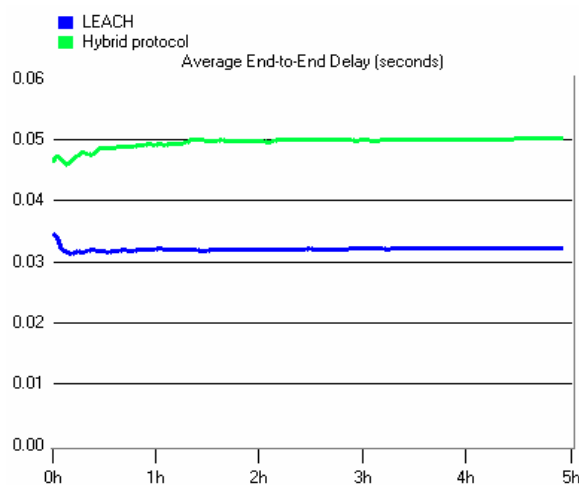
Channel access delay is defined as the time latency between the time when a data packet is given to the network layer at a source and the time when it is sent out by getting access of the channel. This metric represents the level of channel busyness in the network. Fig.10. show the average channel access delay of the network using two protocols with different speeds during the simulations. The average channel access

delay of our hybrid protocol is a little higher than that of LEACH due to increased traffic load by applying multihop routing for inter-cluster communication.



**Fig.10. Average channel access delay using two protocols**

End-to-end delay, which is the main metric about network latency, is defined as the time latency between the time when a data packet is given to the network layer at a source and the time when it reaches the destination including channel access delay and all other possible delays of transmission. Figure.11. shows the average end-to-end delay over time using two protocols. This graph is similar to the channel access delay. Because aggregated data packets from cluster heads might take hops to the BS in our hybrid protocol, the end-to-end delay is higher than that in LEACH as expected.



**Fig.11. Average end-to-end delay using two protocols**

The simulation results demonstrate that our hybrid protocol improve energy efficiency and prolong the

network lifetime. Besides, compared with LEACH, the performance of our hybrid protocol is quite robust even though the network has high rate of mobility. At the same time the latency of network increases a little in our hybrid protocol. But this could be tolerated since our protocol prolongs the lifetime of the network significantly. Therefore, we have got a good tradeoff between network latency and energy efficiency.

## 6. Conclusions and discussions

In this paper, we have presented a novel self-organizing hybrid network protocol for WSN and compared it to the LEACH protocol. Results from our simulations show that our protocol provides better performance for energy efficiency and network lifetime.

Our protocol can still be improved further. For example, multi-hop routing algorithm can be implemented for all nodes in the network. It means that when a cluster head has a packet to send to the BS, it would route the packet using all nodes including both heads and members to find the optimal route. This approach can utilize the sleeping time of member nodes and distribute the intermediate load among all nodes.

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