A Novel Application Specific Network Protocol for Wireless Sensor Networks

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Abstract—**The recent interest in Wireless Sensor Networks (WSN) has led to emergence 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 popular protocols. In this paper, a novel application specific energy efficient 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. Simulation results, compared with LEACH, demonstrate that our novel protocol can reduce energy consumption and hence prolong the lifetime of WSN.**

I. 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].

There are many strict constraints in the design of WSN such as small size, light weight, ultra-low energy consumption and low cost [2]. Among these 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.

The recent interest in WSN has led to a number of network protocols. Because of high correlation of data from the neighboring nodes, some protocols adopted cluster based network architectures. The researchers in [3] proposed a new chain-based protocol called PEGASIS that minimizes the energy consumption of each sensor node. In [4], the authors presented a new minimum spanning tree-based protocol, called PEDAP and its power-aware version PEDAP-PA. In [5], a protocol called APTEEN is introduced that uses an enhanced TDMA schedule for efficiently incorporating query handling.

Besides the protocols above, the LEACH protocol presented in [6] provides 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.

This paper builds on the LEACH protocol described in [6] by integrating a multiple-hop routing scheme for inter-cluster communication between cluster heads and the base station, instead of direct transmission, for prolonging the lifetime of WSN. Furthermore, CSMA incorporating some collision avoidance mechanisms is utilized as media access scheme during the period of cluster formation.

II. 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. During the period of set-up phase all nodes are organized into some clusters through communicating with short

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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 [7]. Following the set-up phase, the data are 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.1. shows the time line of one stretched round.

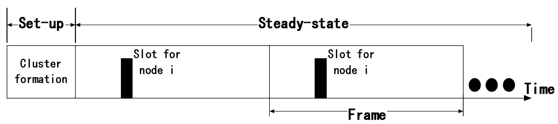

Figure 1. Time line in one round

A potential problem with LEACH protocol 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 on the transmission energy dissipations that the nodes use to transmit data to the BS. According to the free space channel model, the minimum required amplifier energy which dominates the transmission energy is proportional to the square of the distance from the transmitter to the destined receiver ($E_{Tx\text{-}amp} \propto d^2$) [8]. Therefore after the network operates for some rounds there will be considerable difference on energy consumption between the nodes near the BS and those far from the BS. If 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 hence 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. 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.

III. OUR NOVEL PROTOCOL

To solve the preceding problems, we propose a novel hybrid protocol. This protocol combines cluster architecture 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 find one or multiple intermediate nodes. The data packets from the source node are relayed among the intermediate nodes until it reaches the destination [9]. The main advantage of this approach is that the transmission energy consumption can be reduced.

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 heads 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 [10] as the routing algorithm.

In order to reduce the probability of collisions at set-up phase, we add some collision avoidance mechanism to CSMA/CD. In contrast to many developed MAC protocols capable of avoiding collisions effectively, such as 802.11 [11] which is applied to most Ad hoc wireless networks, our approach is much simpler and more energy efficient. Thus it is more suitable for 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.

A. Period of Cluster Formation

At the beginning of this phase the whole network sets a timer to control when this phase would end and steady phase would begin and keep every node synchronously. Every node in the network must decide whether it will become a cluster head or not. Each node decides to become a head with probability P_i. P_i is calculated according to a cluster head selection algorithm given in [6]. This algorithm ensures that each node can take its turn to act as cluster head. After some nodes have become cluster heads, every head broadcasts an announcement (ANNOU) message through CSMA/CD. This message is a short message including the node’s ID and message content indicating that the message is ANNOU. ANNOU also contains the unique spreading code of the node for the intending direct-sequence spread spectrum (DSSS) within a cluster and coordinate of the node’s location for multi-hop routing among cluster heads at steady phase.

At this stage all cluster heads load a random delay time t_1 after they decide to become heads. After t_1 they broadcast ANNOU messages. The random delay time t_1 is uniformly distributed between zero and T_1. The value of T_1 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 transmissions of two random heads. This approach ensures that the ANNOU 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 constant period of time later when every member node receives several ANNOU messages from different heads it will choose the closest cluster head to join the cluster according to the received signal strength of the messages. Then each member node would load a random delay time t_2. After t_2 each member node sends a join request (JOIN) message to the chosen cluster head and adds the unique spreading code of the head to the message. From then on all signals in the network would be transmitted and received with appropriate spreading codes. Therefore, in our protocol spreading codes are used from the set-up phase, and not from steady-state as in LEACH. After the cluster head 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. In order to ensure that every node can be organized into a cluster, 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 before the steady-state phase comes 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. Then all nodes in the network would enter the steady-state phase synchronously.

B. 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 during 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. At the end of each frame the cluster head aggregates the data from its all member nodes, reduce redundant data and then send the data packet 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.

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

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

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

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

the node that makes the function minimal (we name the node B) would be selected as intermediate node. Otherwise the node A would still transmit to the BS directly. When the packet arrives at node B, the above algorithm will be repeated to decide whether node B should select an intermediate node or transmit to the BS directly. This process would be iterated till the packet reaches the BS.

All nodes within a cluster transmit data using a unique spreading code that was assigned in set-up phase as mentioned. When a cluster head wants to communicate with another head or the BS, it would use the appropriate spreading code of the destination. At the inter-cluster level CSMA/CA (Collision Avoidance) [12] is used as MAC protocol.

IV. SIMULATION AND RESULTS

We use the network simulator OPNET to model our protocol. OPNET [13] provides a fairly realistic simulation environment for WSN among the available network simulators. Especially it takes into account the effect of noise on the performance of networks. In order to compare with original LEACH we have also built a model for LEACH using OPNET and used the same power model as in [6] 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.2. 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 on the energy consumption between 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.

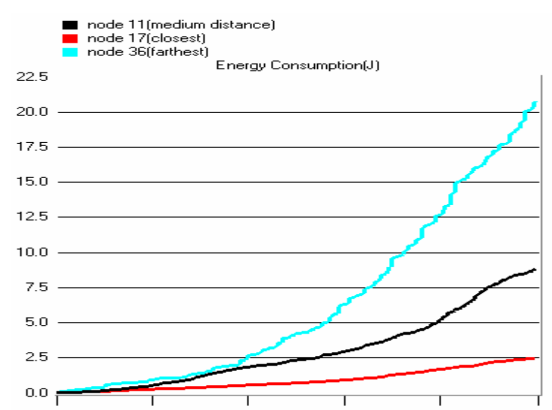

Figure 2. Energy consumption over time of three nodes with LEACH

Fig.3. shows the same profile with our novel protocol as in Fig.2. 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.

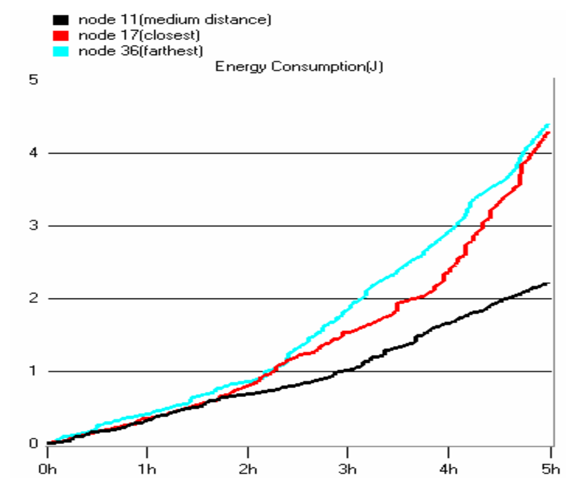

Figure 3. Energy consumption over time of three nodes with our protocol

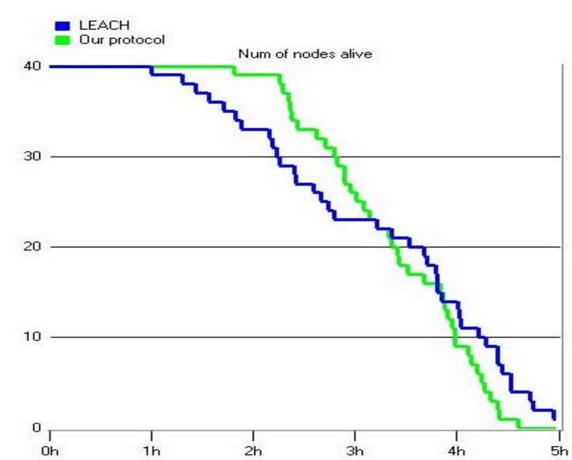

Figure 4. Number of live nodes with both protocol

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 novel protocol as shown in Fig.4. 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.

V. CONCLUSIONS AND DISCUSSIONS

In this paper, we have presented a novel 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. This means that when a cluster head has a packet to send to the BS, it would route the packet using all nodes including both cluster heads and members to find the optimal route.

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