Summary of Energy-Efficient Communication Protocol for Wireless Microsensor Networks

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Abstract

Conventional routing protocols may not be optimal for sensor networks. LEACH (Low-Energy Adaptive Clustering Hierarchy) is a clustering-based protocol that utilizes randomized rotation of local cluster base stations to evenly distribute the energy load among the sensors in the network. Simulations show that LEACH can achive as much as a factor of 8 reduction in energy dissipation compared with conventional routing protocols. LEACH also distributes energy dissipation evenly throughout the sensors, increasing the lifetime of the system.

1 Introduction

Microsensor network consist of many spatially distributed sensors , which are used to monitor phenomena at different locations. A sensor is equipped with a radio transceiver, a small microcontroller, and an energy source, usually a battery. Usually sensors are physically small and inexpensive. Small sensors are not as reliable as more expensive macrosensors,but small size and small cost of an individual sensor, allow production and deployment in large numbers. Microsensor networks can contain hundreds or thousands of sensor nodes and such netwoks rely on large numbers to obtain high quality results. Sensor networks are used in a variety of commercial and military applications, for example as an intrusion detection network.

Sensors should be energy-efficient as possible, because of when a sensor node runs out of energy it is useless. Network protocols should be fault tolerant because of eventually sensors, without external powersource, will run out of energy and die. Since the limited wireless channel bandwidth must be shared among all the sensors in the network, routing protocols for these networks should be able to perform local collaboration to reduce bandwidth requirements.

Eventually, the data being sensed by the nodes in the network must be transmitted to a control center or base station, where the end-user can access the data. There are many possible models for these microsensor networks. We only consider following two cases

- The base station is fixed and located far from the sensors.
- All nodes in the network are homogeneous and energy constrained.

Thus, communication between the sensor nodes and the base station is expensive, and there are no "high-energy" nodes through which communication can proceed.

Sensor networks contain too much data for an end-user to process. Therefore, automated methods of combining or aggregating the data into a small set of meaningful information is required. Data aggregation, also known as data fusion. It is possible to combine several unreliable data measurements to produce a more accurate signal by enhancing the common signal and reducing the uncorrelated noise.The classification performed on the aggregated data might be performed by a human operator or automatically. Both the method of performing data aggregation and the classification algorithm are application-specific. Large energy gains can be achieved by performing the data fusion or classification algorithm locally, thereby requiring much less data to be transmitted to the base station.

2 First Order Radio Model

Different assumptions about the radio characteristics, including energy dissipation in the transmit and receive modes, will change the advantages of different protocols.

Heinzelman et al. assumed a simple model where the radio dissipates $E_{elec} = 50$ nJ/bit to run the transmitter or receiver circuitry and $\epsilon_{amp} = 100$ pJ/bit/m^2 for the transmit amplifier to achieve an acceptable $\frac{E_b}{N_o}$. In addition Heinzelman et al. assumed r^2 energy loss due to channel transmission. These parameters are slighty better than the current state-of-the-art in radio design. Transmiting a k-bit message a distance d using above model radio expends:

$$\begin{aligned} E_{Tx}(k,d) &= E_{Tx-elec}(k) + E_{Tx-amp}(k,d) \\ E_{Tx}(k,d) &= E_{elec} * k + \epsilon * k * d^2 \end{aligned} \tag{1}$$

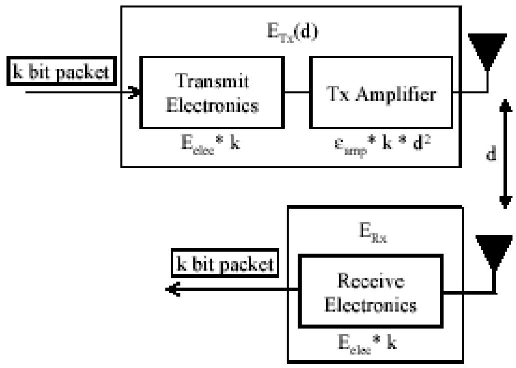

Figure 1: First order radio model

Receiving this message, radio expends:

$$E_{Rx}(k) = E_{Rx-elec}(k)$$
$$E_{Rx}(k) = E_{elec} * k \quad (2)$$

For these parameter values, receiving a message is not a low cost operation; the protocols should thus try to minimize not only the transmit distances but also the number of transmit and receive operations for each message. It is reasonable to assume that the radio channel is symmetric such that the energy required to transmit a message from node A to node B is the same as the energy required to transmit a message from node B to node A for a given SNR. in these experiments it is also assumed, that all sensors are sensing the environment at a fixed rate and thus always have data to send to the end-user.

3 Energy Analysis of Routing Protocols

There have been several network routing protocols proposed for wireless networks that can be examined in the context of wireless sensor networks. The most energy-efficient protocol to use depends on the network topology and radio parameters of the system.

Using a direct communication protocol, each sensor sends its data directly to the base station. If the base station is far away from the nodes, direct communication will require a large amount of transmit power from each node (since d in Equation 1 is large). This will quickly drain the battery of the nodes and reduce the system lifetime. However, the only receptions in this protocol occur at the base station, so if either the base station is close to the nodes, or the energy required to receive data is large, this may be an acceptable (and possibly optimal) method of communication.

The second conventional approach to consider is a ”minimum-energy” routing protocol. There are several power-aware routing protocols discussed in the literature. In these protocols, nodes route data destined ultimately for the base station through intermediate nodes. Thus nodes act as routers for other nodes data in addition to sensing the environment. These protocols differ in the way the routes are chosen. Some of these protocols, only consider the energy of the transmitter and neglect the energy dissipation of the receivers in determining the routes. In this case, the intermediate nodes are chosen such that the transmit amplifier energy is minimized.

However, for this minimum-transmission-energy (MTE) routing protocol, rather than just one (high-energy) transmit of the data, each data message must go through n (low-energy) transmits and n receives. Depending on the relative costs of the transmit amplifier and the radio electronics, the total energy expended in the system might actually be greater using MTE routing than direct transmission to the base station.

It is clear that in MTE routing, the nodes closest to the base station will be used to route a large number of data messages to the base station. Thus these nodes will die out quickly, causing the energy required to get the remaining data to the base station to increase and more nodes to die. This will create a cascading effect that will shorten system lifetime. In addition, as nodes close to the base station die, that area of the environment is no longer being monitored.

Heinzelman et al. run MATLAB simulations using random 100-node (0.5J/node) network, which showed that with the above radio parameters and network topology, initially the nodes die out quicker using MTE routing than direct transmission. MTE routing is however more energy efficent in the long run. Last node dies much sooner in direct transmission than in MTE routing.

A final conventional protocol for wireless networks is clustering, where nodes are organized into clusters that communicate with a local base station, and these local base stations transmit the data to the global base station, where it is accessed by the end-user. This greatly reduces the distance nodes need to transmit their data, as typically the local base station is close to all the nodes in the cluster. However, the local base station is assumed to be a high-energy node; if the base station is an energy-constrained node, it would die quickly, as it is being heavily utilized.

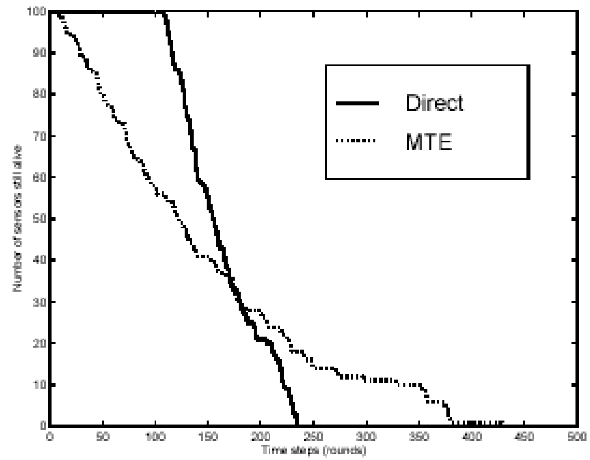

Figure 2: System lifetime using direct transmission and MTE routing with 0.5J/node.

4 LEACH: Low-Energy Adaptive Clustering Hierarchy

LEACH is a self-organizing, adaptive clustering protocol that uses randomization to distribute the energy load evenly among the sensors in the network. In LEACH, the nodes organize themselves into local clusters, with one node acting as the local base station or cluster-head. LEACH includes randomized rotation of the high-energy cluster-head position such that it rotates among the various sensors in order to not drain the battery of a single sensor. In addition, LEACH performs local data fusion to ”compress” the amount of data being sent from the clusters to the base station, further reducing energy dissipation and enhancing system lifetime.
Sensors elect themselves to be local cluster-heads at any given time with a certain probability.Each node makes its decision about whether to be a cluster-head independently of the other nodes in the network and thus no extra negotiation is required to determine the cluster-heads. These cluster-head nodes broadcast their status to the other sensors in the network. Each sensor node determines to which cluster it wants to belong by choosing the cluster-head that requires the minimum communication energy. Once all the nodes are organized into clusters, each cluster-head creates a schedule for the nodes in its cluster. This allows the radio components of each non-cluster-head node to be turned off at all times except during its transmit time, thus minimizing the energy dissipated in the individual sensors. Once the cluster-

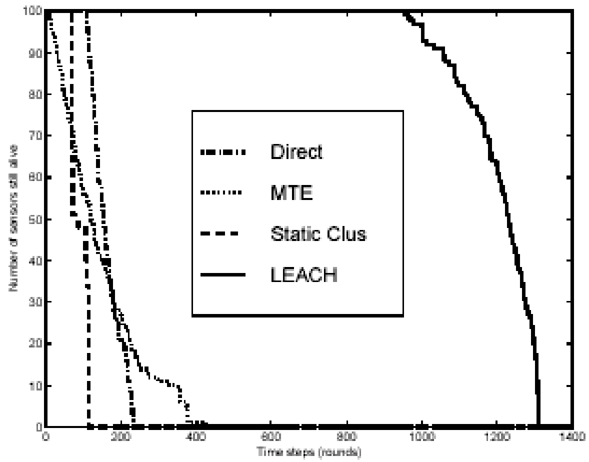

Figure 3: System lifetime direct transmission, MTE routing, static clustering and LEACH with 0.5J/node

head has all the data from the nodes in its cluster, the cluster-head node aggregates the data and then transmits the compressed data to the base station.

The system can determine, a priori, the optimal number of clusters to have in the system. This will depend on several parameters, such as the network topology and the relative costs of computation versus communication. If there are fewer than optimal number of clusterheads, some nodes in the network have to transmit their data very far to reach the cluster-head, causing the global energy in the system to be large. If there are more than optimal number of clusterheads, the distance nodes have to transmit to reach the nearest cluster-head does not reduce substantially, yet there are more cluster-heads that have to transmit data the long-haul distances to the base station, and there is less compression being performed locally. In addition to reducing energy dissipation, LEACH successfully distributes energy-usage among the nodes in the network such that the nodes die randomly and the same rate.

In the above MATLAB simulations LEACH reduced communication energy by as much as 8x compared with direct transmission and minimum-transmission-energy rounting. The first node death in LEACH occurs over 8 times later than the first node death in direct transmission. Compared to minimum-transmission-energy rounting and static clustering the last node death in LEACH occurs over 3 times later.

Energy (J/node)	Protocol	Round first node dies	Round last node dies
0.25	Direct	55	117
	MTE	5	221
	Static Clustering	41	67
	LEACH	394	665
0.5	Direct	109	234
	MTE	8	429
	Static Clustering	80	110
	LEACH	932	1312
1	Direct	217	468
	MTE	15	843
	Static Clustering	106	240
	LEACH	1848	2608

Figure 4: Lifetimes using different amounts of initial energy for the sensors.

5 LEACH Algorithm Details

The operation of LEACH is broken up into rounds, where each round begins with a set-up phase, when the clusters are organized, followed by a steady-state phase, when data transfers to the base station occur. In order to minimize overhead, the steady-state phase is long compared to the set-up phase.

5.1 Advertisement Phase

Initially, when clusters are being created, each node decides whether or not to become a cluster-head for the current round. This decision is based on the suggested percentage of cluster heads for the network (determined a priori) and the number of times the node has been a cluster-head so far. This decision is made by the node n choosing a random number between 0 and 1. If the number is less than a threshold T(n), the node becomes a cluster-head for the current round. The threshold is set as:

$$T(n) = \begin{cases} \frac{P}{1-P*(r*mod\frac{1}{P})} & \text{if } n \in G \\ 0 & \text{otherwise} \end{cases}$$

where P = the desired percentage of cluster heads, r = the current round, and G is the set of nodes that have not been cluster-heads in the last $\frac{1}{P}$ rounds. Using this threshold, each node will be a cluster-head at some point within $\frac{1}{P}$ rounds. The nodes that are cluster-heads in round 0 cannot be cluster heads for the next $\frac{1}{P}$ rounds. Thus the probability that the remaining nodes are cluster-heads must be increased, since there are fewer nodes that are eligible to become cluster-heads. Each node that has elected itself a cluster-head for the current round broadcasts an advertisement message to the rest of the nodes. For this "cluster-head-advertisement" phase, the cluster-heads use a CSMA MAC protocol, and all cluster-heads transmit their advertisement using the same transmit energy. The non-cluster-head nodes must keep receivers on during this phase of set-up to hear the advertisements of all the cluster-head nodes. After this phase is complete, each non-cluster-head node decides the cluster which it will belong for this round. This decision is based the received signal strength of the advertisement. In the case of ties, a random cluster-head is chosen.

5.2 Cluster SetUp Phase

After each node has decided to which cluster it belongs, it must inform the cluster-head node that it will be a member of the cluster. Each node transmits this information back to the cluster-head again using a CSMA MAC protocol. During this phase, all cluster-head nodes must keep their receivers on.

5.3 Schedule Creation

The cluster-head node receives all the messages for nodes that would like to be included in the cluster. Based on the number of nodes in the cluster, the cluster-head node creates a TDMA schedule telling each node when it can transmit. This schedule is broadcast back to the nodes in the cluster.

5.4 Data Transmission

Once the clusters are created and the TDMA schedule is fixed, data transmission can begin. Assuming nodes always have data to send, they send it during their allocated transmission time to the cluster head. This transmission uses a minimal amount of energy (chosen based on the received strength of the cluster-head advertisement). The radio of each non-cluster-head node can be turned off until the node's allocated transmission time, thus minimizing energy dissipation in these nodes. The cluster-head node must keep its receiver on to receive all the data from the nodes in the cluster. When all the data has been received, the cluster head node performs signal processing functions to compress the data into a single signal. This composite signal is sent to the base station. After a certain time, which is determined a priori, the next round begins with each node determining if it should be a cluster-head for this round and advertising this information, as described in Section 5.1.

5.5 Multiple Clusters

Transmission in one cluster will affect (and hence degrade) communication in a nearby cluster. To reduce this type of interference, each cluster communicates using different CDMA codes. Efficient channel assignment is a difficult problem, even when there is a central control center that can perform the necessary algorithms. Using CDMA codes, while not necessarily the most bandwidth efficient solution, does solves the problem of multiple-access in a distributed manner.

5.6 Hierarchical Clustering

The version of LEACH described in this paper can be extended to form hierarchical clusters. In this scenario, the cluster-head nodes would communicate with "super-clusterhead" nodes and so on until the top layer of the hierarchy, at which point the data would be sent to the base station. For larger networks, this hierarchy could save a tremendous amount of energy.

6 Conclusion

LEACH is promising routing protocol for the sensor networks, however there were not enough experimental data on diffrent network topologies and different radio parameters to make any final conclusions. Further study is required to estimate the full potential of the LEACH routing protocol.
Other interesting ideas(not mentioned in the text) would be trying to ensure that the cluster head nodes are uniformly distributed by dividing advertisement phase into smaller sub-phases and decreasing the propability of cluster heads near other cluster heads.
The use of combined LEACH and MTE routing with the cluster heads acting as routers.