Data Gathering Algorithms in Sensor Networks Using Energy Metrics

Stephanie Lindsey, Cauligi Raghavendra, *Fellow Member*, *IEEE*, and Krishna M. Sivalingam, *Senior Member*, *IEEE*

Abstract—Sensor webs consisting of nodes with limited battery power and wireless communications are deployed to collect useful information from the field. Gathering sensed information in an energy efficient manner is critical to operating the sensor network for a long period of time. In [12], a data collection problem is defined where, in a round of communication, each sensor node has a packet to be sent to the distant base station. There is some fixed amount of energy cost in the electronics when transmitting or receiving a packet and a variable cost when transmitting a packet which depends on the distance of transmission. If each node transmits its sensed data directly to the base station, then it will deplete its power quickly. The LEACH protocol presented in [12] is an elegant solution where clusters are formed to fuse data before transmitting to the base station. By randomizing the cluster-heads chosen to transmit to the base station, LEACH achieves a factor of 8 improvement compared to direct transmissions, as measured in terms of when nodes die. An improved version of LEACH, called LEACH-C, is presented in [14], where the central base station performs the clustering to improve energy efficiency. In this paper, we present an improved scheme, called PEGASIS (Power-Efficient GAthering in Sensor Information Systems), which is a near-optimal chain-based protocol that minimizes energy. In PEGASIS, each node communicates only with a close neighbor and takes turns transmitting to the base station, thus reducing the amount of energy spent per round. Simulation results show that PEGASIS performs better than LEACH by about 100 to 200 percent when 1 percent, 25 percent, 50 percent, and 100 percent of nodes die for different network sizes and topologies. For many applications, in addition to minimizing energy, it is also important to consider the delay incurred in gathering sensed data. We capture this with the $energy \times delay$ metric and present schemes that attempt to balance the energy and delay cost for data gathering from sensor networks. Since most of the delay factor is in the transmission time, we measure delay in terms of number of transmissions to accomplish a round of data gathering. Therefore, delay can be reduced by allowing simultaneous transmissions when possible in the network. With CDMA capable sensor nodes [11], simultaneous data transmissions are possible with little interference. In this paper, we present two new schemes to minimize $energy \times delay$ using CDMA and non-CDMA sensor nodes. If the goal is to minimize only the delay cost, then a binary combining scheme can be used to accomplish this task in about $\log N$ units of delay with parallel communications and incurring a slight increase in energy cost. With CDMA capable sensor nodes, a chain-based binary scheme performs best in terms of $energy \times delay$. If the sensor nodes are not CDMA capable, then parallel communications are possible only among spatially separated nodes and a chain-based 3-level hierarchy scheme performs well. We compared the performance of direct, LEACH, and our schemes with respect to $energy \times delay$ using extensive simulations for different network sizes. Results show that our schemes perform 80 or more times better than the direct scheme and also outperform the LEACH protocol.

Index Terms—Wireless sensor networks, data gathering protocols, energy-efficient operation, greedy algorithms, performance evaluation.

1 Introduction

Inexpensive sensors capable of significant computation and wireless communications are becoming available [4], [6], [8], [10], [16], [23]. A web of sensor nodes can be deployed to collect useful information from the field in a variety of scenarios including military surveillance, landmine detection, in harsh physical environments, for scientific investigations on other planets, etc. [1], [10], [16], [29]. These sensor nodes can self-organize to form a network and can communicate with each other using their wireless interfaces. Energy efficient self-organization and initialization protocols are developed in [18], [19]. Each node has transmit power control and an omni-directional antenna, and therefore can adjust the area of coverage with its wireless transmission. Typically, sensor nodes collect audio, seismic, and other types of data and collaborate to perform a high-level task in a sensor web. For example, a sensor network can be used for detecting the presence of potential threats in a military conflict. Since wireless communications consume significant amounts of battery power, sensor nodes should be energy efficient in transmitting data [3], [17], [25], [27]. Energy efficient communication in wireless networks is attracting increasing attention in the literature [5], [22], [24], [28], [30].

A typical application in a sensor web is gathering of sensed data at a distant base station (BS) [12]. Fig. 1 shows a 100-node sensor network in a playing field of size $50m \times 50m$. There is an energy cost for transmitting or receiving a packet in the radio electronics and there is a variable energy cost depending on the distance in transmissions. Due to the r^2 or larger radio signal attenuation for a

- *S. Lindsey is with Microsoft Corporation, Redmond, WA 98052.*
- *C. Raghavendra is with the Department of Electrical Engineering Systems, University of Southern California, Los Angeles, CA 90089-2562, and with the Computer Systems Research Department, The Aerospace Corporation, PO Box 92957, Los Angeles, CA 90009-2957, E-mail: raghu@usc.edu*
- *K.M. Sivalingam is with the School of Electrical Engineering and Computer Science, Washington State University, Pullman, WA 99164-2752.*

Manuscript recieved 5 June 2001; accepted 4 Aug. 2002.
For information on obtaining reprints of this article, please send e-mail to: tpds@computer.org, and reference IEEECS Log Number 116282.

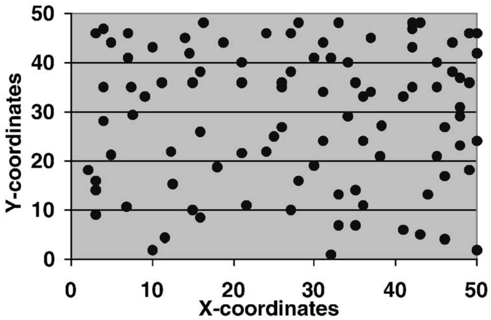


Fig. 1. Random 100-node topology for a $50m \times 50m$ network. The base station (BS) is assumed to be located at (25, 150), which is at least 100m from the nearest node.

range r, it is important to limit transmission distances to conserve energy.

In this paper, we assume the following:

- Each sensor node has power control and the ability to transmit data to any other sensor node or directly to the BS [20], [22].
- Our model sensor network contains homogeneous and energy constrained sensor nodes with initial uniform energy.
- Every node has location information.
- There is no mobility.

1.1 Energy Reduction for Data Gathering in Sensor Networks

In each round of this data-gathering application, all data from all nodes need to be collected and transmitted to the BS, where the end-user can access the data. In some sensor network applications, data collection may be needed only from a region and, therefore, a subset of nodes will be used. A simple approach to accomplishing this data gathering task is for each node to transmit its data directly to the BS. Since the BS is typically located far away, the cost to transmit to the BS from any node is high so nodes will die very quickly. Therefore, an improved approach is to use as few transmissions as possible to the BS and reduce the amount of data that must be transmitted to the BS in order to reduce energy. Further, if all nodes in the network deplete their energy levels uniformly, then the network can operate without losing any nodes for a long time.

In sensor networks, data fusion helps to reduce the amount of data transmitted between sensor nodes and the BS [9], [15], [31]. Data fusion combines one or more data packets from different sensor measurements to produce a single packet, as described in [12]. For example, sensors may collect temperature, pressure, humidity, and signal data from the field. We would be interested in finding the maximum or minimum values of such parameters. Data fusion can be used here to combine one or more packets to produce a same-size resultant packet. The LEACH protocol presented in [12] is an elegant solution to this data collection problem where a small number of clusters are formed in a self-organized manner. The nice property of the LEACH protocol is that it is completely distributed and sensor nodes organize in a cluster hierarchy to fuse their data to eventually transfer to the BS. In LEACH, a designated node in each cluster collects and fuses data from nodes in its cluster and transmits the result to the BS. LEACH uses randomization to rotate the cluster heads and achieves a factor of eight improvement compared to the direct approach, before the first node dies.

In LEACH, clusters are formed in a self-organized manner in each round of data collection. About 5 percent of the nodes in the network selected randomly become cluster heads. These cluster heads send a strong beacon signal to all nodes and sensor nodes decide which cluster to join based on received signal strength. The distributed cluster formation in each round in LEACH may not produce good clusters to be efficient. In an improved version of this scheme, called LEACH-C [14], this cluster formation is done at the beginning of each round using a centralized algorithm by the BS. Although the energy cost for cluster formation is higher in LEACH-C, the overall performance is better than LEACH due to improved cluster formation by the BS. The steady state part of the LEACH-C protocol, i.e., data collection in rounds, is identical to the LEACH protocol (p. 94 in [14]). LEACH-C improves the performance by 20 percent to 40 percent (p. 97 in [14]), depending on the network parameters, compared to LEACH in terms of the total number of rounds of data collection that can be achieved before sensor nodes start to die.

Further improvements can be obtained if each node communicates only with close neighbors and **only one** designated node sends the combined data to the BS in each round in order to reduce energy. A new protocol based on this approach, called PEGASIS (Power-Efficient GAthering in Sensor Information Systems), is presented in this paper, which significantly reduces energy cost to increase the life of the sensor network. The PEGASIS protocol is near optimal in terms of energy cost for this data gathering application in sensor networks. The key idea in PEGASIS is to form a chain among the sensor nodes so that each node will receive from and transmit to a close neighbor. Gathered data move from node to node, get fused, and, eventually, a designated node transmits to the BS. Nodes take turns transmitting to the BS so that the average energy spent by each node per round is reduced. Building a chain to minimize the total length is similar to the traveling salesman problem, which is known to be intractable. However, with the radio communication energy parameters, a simple chain built with a greedy approach performs quite well. The PEGASIS protocol achieves between 100 to 200 percent improvement when 1 percent, 25 percent, 50 percent, and 100 percent of nodes die compared to the LEACH protocol. PEGASIS performance improvement in comparison with LEACH-C will be slightly less as LEACH-C improves upon LEACH by about 20 percent to 40 percent. In the rest of this paper we present all our performance comparisons with respect to the LEACH protocol with the understanding that the improvement is less by the extent that LEACH-C improves upon LEACH [14]. When attribute-based search is to be performed, then the area and, hence, selected sensor nodes, will also change dynamically. In these situations, the BS selects the area of interest and only selected nodes in the region participate in data collection. We will still use the same chain ordering of nodes and only the selected nodes will be on to form the truncated chain. Likely, these nodes will still be nearby on the shortened chain and the data collection will still be efficient.

Our scheme can be modified appropriately if some of the stated assumptions about sensor nodes are not valid. If nodes are not within transmission range of each other, then alternative, possibly multihop transmission paths will have to be used. In fact, our chain-based schemes will not be affected that much as each node communicates only with a local neighbor and we can use a multihop path to transmit to the BS. We need to make some adjustments in the chain construction procedure to ensure that no node is left out. Other schemes, including LEACH, rely on direct reachability to function correctly. To ensure balanced energy dissipation in the network, an additional parameter could be considered to compensate for nodes that must do more work every round. If the sensor nodes have different initial energy levels, then we could consider the remaining energy level for each node in addition to the energy cost of the transmissions. The assumption of location information is not critical. The BS can determine the locations and transmit to all nodes or the nodes can determine this through received signal strengths. For example, nodes could transmit progressively reduced signal strengths to find a close neighbor to exchange data. This would require the nodes to consume some energy when trying to find local neighbors; however, this is only a fixed initial energy cost when constructing the chain. If nodes are mobile, then different methods of transmission could be examined. For instance, if nodes could approximate how often and at what speed other nodes are moving, then it could determine more intelligently how much power is needed to reach the other nodes. Perhaps, the BS can help coordinate the activities of nodes in data transmissions. Discussion of schemes with mobile sensor nodes is beyond the scope of this paper.

1.2 $Energy \times Delay$ Reduction for Data Gathering in Sensor Networks

Another important factor to consider in the data gathering application is the average delay per round. Here, we assume that data gathering rounds are far apart and the only traffic in the network is due to sensor data. Therefore, data transmissions in each round can be completely scheduled to avoid delays in channel access and collisions. The delay for a packet transmission is dominated by the transmission time as there is no queuing delay and the processing and propagation delays are negligible compared to the transmission time. With the direct transmission scheme, nodes will have to transmit to the base station one at a time, making the delay a total of N units (one unit per transmission, where N is equal to the number of nodes). To reduce delay, one needs to perform simultaneous transmissions. The well-known approach of using a binary scheme to combine data from N nodes in parallel will take about $\log N$ units of delay, although incurring an increased energy cost. $Energy \times delay$ is an interesting metric to optimize per round of data gathering in sensor networks.

Why $energy \times delay$ metric? Clearly, minimizing energy or delay in isolation has drawbacks. For battery operated sensors, longevity is a major concern and priorities can be entirely different when energy reserves become depleted. Energy efficiency often brings additional latency along with it. Minimizing delay is not always practical in sensor network applications. Maximizing the throughput is not the best strategy for energy-critical links. Generally, increased energy savings come with a penalty of increased delay. However, several practical applications set limits on acceptable latency, as specified by QoS requirements. For example, the data gathering delay per round may have a bound. Therefore, there is a tradeoff between energy spent per packet and delay; $energy \times delay$ is an appropriate measure to optimize for in wireless sensor networks. Specifically, our view is that minimizing $energy \times delay$ while meeting acceptable delays for applications can lead to significant power savings.

Simultaneous wireless communications among pairs of nodes is possible only if there is minimal interference among different transmissions. CDMA technology can be used to achieve multiple simultaneous wireless transmissions with low interference. If the sensor nodes are CDMA capable, then it is possible to use the binary scheme and perform parallel communications to reduce the overall delay. However, the energy cost may have to go up slightly as there will still be a small amount of interference from other unintended transmissions. Alternatively, with a single radio channel and non-CDMA nodes, simultaneous transmissions are possible only among spatially separated nodes. Since the energy costs and delay per transmission for these two types of nodes are quite different, we will consider $energy \times delay$ reduction for our data gathering problem separately for these two cases.

In this paper, we present the following new protocols for data gathering using the $energy \times delay$ metric:

- a binary chain-based scheme with CDMA sensor nodes,
- a three level chain-based scheme which performs better than direct and PEGASIS with this metric for non-CDMA sensor nodes.

Both of these protocols use hierarchical organization of sensor nodes with possible simultaneous data transmissions in each level of the hierarchy. A greedy chain is formed among the sensor nodes in both of these protocols which will form the lowest level in the hierarchy. The binary scheme has a hierarchy of $\lceil \log N \rceil$, where N is the number of nodes in the sensor network. The second protocol uses a 3-level hierarchy by forming groups in each level and promoting one node from each group to the next level. Simulation results show that both schemes perform 80 or more times better than direct scheme and the binary scheme performs eight times better than LEACH with respect to the $energy \times delay$ metric.

This paper is organized as follows: In Section 2, the radio model for energy calculations used throughout this paper is discussed. In Section 3, an analysis of the energy cost is given for the data gathering problem. The PEGASIS scheme is presented in Section 4, which is shown to be a near-optimal solution for minimizing energy. In Section 5, an analysis of the $energy \times delay$ metric for data gathering is given. Two new protocols for reducing $energy \times delay$ for data gathering with and without CDMA capable nodes are presented in Sections 6 and 7, respectively. Extensive simulation results with different size networks and simulation parameters are presented in Section 8. In all our simulation experiments, we considered only the original LEACH protocol and our proposed new protocols. The performance improvements with respect to LEACH-C will be slightly less corresponding to the extent LEACH-C improves upon LEACH. Finally, some concluding remarks are given in Section 9.

2 Radio Model for Energy Calculations

We use the same radio model as discussed in [12], which is the first order radio model. In this model, a radio dissipates $E_{elec} = 50nJ/bit$ to run the transmitter or receiver circuitry and $\epsilon_{amp} = 100pJ/bit/m^2$ for the transmitter amplifier. The radios have power control and can expend the minimum required energy to reach the intended recipients. The radios can be turned off to avoid receiving unintended transmissions. An r^2 energy loss is used due to channel transmission [21], [26]. The equations used to calculate transmission costs and receiving costs for a k-bit message and a distance d are shown below:

.0.a **Transmitting**

$$E_{Tx}(k,d) = E_{Tx-elec}(k) + E_{Tx-amp}(k,d)$$

$$E_{Tx}(k,d) = E_{elec} \times k + \epsilon_{amp} \times k \times d^2$$

.0.b **Receiving**

$$E_{Rx}(k) = E_{Rx-elec}(k)$$

$$E_{Rx}(k) = E_{elec} \times k$$

Receiving data is also a high cost operation, therefore, the number of receptions and transmissions should be minimal to reduce the energy cost of an application. With these radio parameters, when $k = 2,000$ and d^2 is 500, the energy spent in the amplifier part equals the energy spent in the electronics part and, therefore, the cost to transmit a packet will be twice the cost to receive. It is assumed that the radio channel is symmetric so that the energy required to transmit a message from node i to node j is the same as the energy required to transmit a message from node j to node i for a given signal-to-noise ratio (SNR), typically 10 dB. For the comparative evaluation purposes of this paper, we assume that there are no packet losses in the network. It is not difficult to model errors and losses in terms of increased energy cost per transmissions. With known channel error characteristics and error coding, this cost can be modeled by suitably adjusting the constants in the above equations.

When there are multiple simultaneous transmissions, the transmitted energy should be increased to ensure that the same SNR as with a single transmission is maintained. With CDMA nodes using 64 or 128 chips per bit (which is typical), the interference from other transmissions is calculated as a small fraction of the energy from other unintended transmissions. This effectively increases the energy cost to maintain the same SNR. With non-CDMA nodes, the interference will equal the amount of energy seen at the receiver from all other unintended transmitters. Therefore, only a few spatially distant pairs can communicate simultaneously in the network.

3 Energy Cost Analysis for Data Gathering

In this section, we will analyze the energy cost of data gathering from a sensor web to the distant BS. Recall that the data collection problem of interest is to gather a k-bit packet from each sensor node in each round. Of course, the goal is to keep the sensor web operating as long as possible. A fixed amount of energy is spent in receiving and transmitting a packet in the electronics and an additional amount proportional to d^2 is spent while transmitting a packet. There is also a cost of 5 nJ/bit/message for 2,000 bit messages in data fusion. With the direct approach, all nodes transmit directly to the BS, which is usually located at some distance from the sensor network. Therefore, every node will consume a significant amount of power to transmit to the BS in each round. Since the nodes have a limited amount of energy, nodes will die quickly, causing the reduction of the system lifetime.

As observed in [12], the direct approach would work best if the BS is located close to the sensor nodes or the cost of receiving is very high compared to the cost of transmitting data. For the rest of the analysis, we use 50, 100, and 200-node sensor networks. In a scenario where the BS is located far away, energy costs can be reduced if the data is gathered locally among the sensor nodes and only a few nodes transmit the fused data to the BS. This is the approach taken in LEACH and its variants, where clusters are formed dynamically in each round and cluster-heads (leaders for each cluster) gather data locally and then transmit to the BS. Cluster-heads are chosen randomly, but all nodes have a chance to become a cluster-head in LEACH to balance the energy spent per round by each sensor node. For a 100-node network in a $50m \times 50m$ field with the BS located at (25, 150), which is at least 100 meters from the closest node, LEACH achieves a factor of 8 improvement compared to the direct approach in terms of number of rounds before the first node dies.

Although this approach is significantly better than the direct transmissions to the BS, there is still some room to save even more energy. The cost of the overhead to form the clusters in LEACH is expensive. In LEACH, in every round, five percent of nodes are cluster-heads and these nodes must broadcast a signal to reach all nodes to determine the members in their clusters.This overhead has been eliminated in the improved version, LEACH-C [14]; otherwise, LEACH-C is identical to LEACH in collection of data in each round. However, several cluster-heads, typically five in a network of 100 nodes, transmit the fused data from the cluster to the distant BS. Further improvement in energy cost for data gathering can be achieved if only one node transmits to the BS per round and if each node transmits only to local neighbors in the data fusion phase. This is exactly what is done in the PEGASIS protocol (defined in Section 4) to obtain an additional factor of two or more improvement compared to LEACH and LEACH-C.

For the 100-node network shown in Fig. 1, we can determine a bound on the maximum number of rounds possible before the first node dies. In each round, every node must transmit their packet and some node or the BS must receive it. So, each node spends two times the energy cost for electronics and some additional cost, depending on how far a node transmits its data. Since at least one node must transmit the fused message to the BS in each round, on the average each node must incur this cost at least once every 100 rounds. With the energy cost parameters and the dimensions of the playing field in Fig. 1 with 100 nodes and 2,000 bit messages, we can calculate the maximum rounds possible. The energy spent in each node for 100 rounds is about 100*0.0002 joules for the electronics and at least 0.002 joules for one message transmission to the BS. With an initial energy in each node of .25 joules, the maximum number of rounds possible before a node dies is given by: $(100 \times 0.25)/0.022 \approx 1,100$.

The actual number of rounds achievable before a node dies will be less since we did not account for the energy spent in the variable part of transmissions, which depends on the distance of transmission and the cost for data fusion. Since each node needs to transmit its data at least to its closest neighbor, there can be about five to 10 percent more energy cost per round. The exact value clearly depends on the distribution of nodes in the network. Therefore, the upper bound will likely be less than 1,000 rounds. The PEGASIS protocol achieves about 800 rounds, which will likely be within 15-20 percent of this upper bounds, and therefore can be claimed to be near optimal. The following section presents the details of the PEGASIS protocol.

4 PEGASIS: Power-Efficient Gathering in Sensor Information Systems

The main idea in PEGASIS is for each node to receive from and transmit to close neighbors and take turns being the leader for transmission to the BS. This approach will distribute the energy load evenly among the sensor nodes in the network. We initially place the nodes randomly in the playing field and, therefore, the ith node is at a random location. The nodes will be organized to form a chain, which can either be computed in a centralized manner by the BS and broadcast to all nodes or accomplished by the sensor nodes themselves using a greedy algorithm. If the chain is computed by the sensor nodes, they can first get all sensor nodes location data and locally compute the chain using the same greedy algorithm. Since all nodes have the same location data and run the same algorithm, they will all produce the same result. We used random 50, 100, and 200-node networks for our simulations with similar parameters used in [12]. Since this chain computation is done once, followed by many rounds of data communication (typically, several hundred rounds, as shown later), the energy cost in this overhead is small compared to the energy spent in the data collection phase. Therefore, in comparing various schemes, we only consider the energy cost for data collection, fusion, and transmission to the BS and evaluate when the first node dies. With our assumption of no mobility, there will be no change in the chain in the case of PEGASIS and no change in clusters in LEACH-C until the first node dies.

For constructing the chain, we assumed that all nodes have global knowledge of the network and employed the greedy algorithm. We could have constructed a loop. However, to ensure that all nodes have close neighbors is difficult as this problem is similar to the traveling salesman problem. The greedy approach to constructing the chain works well and this is done before the first round of communication. To construct the chain, we start with the furthest node from the BS (select a node randomly if there is a tie). The closest neighbor to this node will be the next node on the chain. Successive neighbors are selected in this manner among unvisited nodes (with ties broken arbitrarily) to form the greedy chain. We begin with the farthest node in order to make sure that nodes farther from the BS have close neighbors as, in the greedy algorithm, the neighbor distances will increase gradually since nodes already on the chain cannot be revisited. Fig. 2 shows node $c0$ connecting to node $c1$, node $c1$ connecting to node $c2$, and node $c2$ connecting to node $c3$, in that order. When a node dies, the chain is reconstructed in the same manner to bypass the dead node.

For gathering data from sensor nodes in each round, each node receives data from one neighbor, fuses the data with its own, and transmits to the other neighbor on the chain. Note that node i will be in some random position j on the chain. Nodes take turns transmitting to the BS and we will use node number $i \bmod N$ (N represents the number of nodes) to transmit to the BS in round i. Thus, the leader in each round of communication will be at a random position on the chain, which is important for nodes to die at random locations. The idea of nodes dying at random places is to make the sensor network robust to failures.

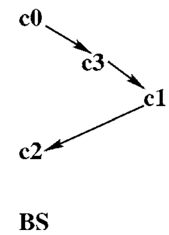


Fig. 2. Chain construction using the greedy algorithm.

Each round of data collection can be initiated by the BS with a beacon signal which will synchronize all sensor nodes. Since all nodes know their positions on the chain, we can employ a time slot approach for transmitting data. In the ith round of data collection, node $c(i-1)$ will be the leader. The end node $c0$ will transmit its data to node $c1$ in slot one, $c1$ fuses and transmits data in slot two, and so on until the leader node is reached. In subsequent slots, data transmissions happen from the node $c(N-1)$ and move toward the leader node from the right end of the chain. Finally, in the Nth slot, the leader transmits data to the BS.

Alternatively, in a given round, we can use a simple control token passing approach initiated by the leader to start the data transmission from the ends of the chain. The cost is very small since the token size is very small. In Fig. 3, node $c2$ is the leader and it will pass the token along the chain first to node $c0$. Node $c0$ will pass its data toward node $c2$. After node $c2$ receives data from node $c1$, it will pass the token to node $c4$, and node $c4$ will pass its data towards node $c2$ with data fusion taking place along the chain.

PEGASIS performs data fusion at every node except the end nodes in the chain. Each node will fuse its neighbor's data with its own to generate a single packet of the same length and then transmit that to its other neighbor (if it has two neighbors). In the above example, node $c0$ will transmit its data to node $c1$. Node $c1$ fuses node $c0$'s data with its own and then transmits to the leader. After node $c2$ passes the token to node $c4$, node $c4$ transmits its data to node $c3$. Node $c3$ fuses node $c4$'s data with its own and then transmits to the leader. Node $c2$ waits to receive data from both neighbors and then fuses its data with its neighbors' data. Finally, node $c2$ transmits one message to the BS. Thus, in PEGASIS, each node, except the two end nodes and the leader node, will receive and transmit one data packet in each round and be the leader once every N rounds. In addition, nodes receive and transmit very small control token packets.

With our simulation experiments, we found that the greedy chain construction performs well with different size networks and random node placements. In constructing the chain, it is possible that some nodes may have relatively distant neighbors along the chain. Such nodes will dissipate more energy in each round compared to other sensors. We improved the performance of PEGASIS by not allowing such nodes to become leaders. We accomplished this by setting a threshold on neighbor distance to be leaders. We may be able to slightly improve the performance of PEGASIS further by applying a threshold adaptive to the

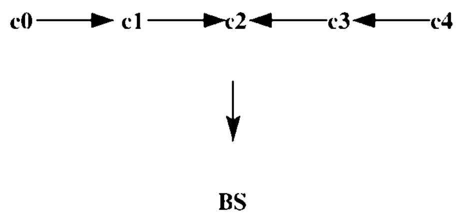


Fig. 3. Token passing approach.

remaining energy levels in nodes. Whenever a node dies, the chain will be reconstructed and the threshold can be changed to determine which nodes can be leaders.

PEGASIS protocol improves on LEACH by saving energy in several stages. First, in the local gathering, the distances that most of the nodes transmit are much less compared to transmitting to a cluster-head in LEACH. Second, the amount of data for the leader to receive is at most two messages instead of 20 (20 nodes per cluster in LEACH for a 100-node network). Finally, only one node transmits to the BS in each round of communication.

5 $Energy \times Delay$ Analysis for Data Gathering

In this section, we will analyze the $energy \times delay$ cost per round for data gathering from a sensor web to the distant BS. The delay cost can be calculated as units of time. On a 2Mbps link, a 2,000 bit message can be transmitted in $1ms$. Therefore, each unit of delay will correspond to about $1ms$ time for the case of a single channel and non-CDMA sensor nodes. The actual delay value will be different with CDMA nodes, depending on the effective data rate. For each of the systems, we assume that the delay is one unit for each 2,000 bit message transmitted.

The $energy \times delay$ cost for data gathering in a network of N nodes will be different for the schemes considered in this paper and will depend on the node distribution in the playing field. Consider an example network where the N nodes are along a straight line with equal distance of d between each pair of nodes and the BS is a far distance from all nodes. The direct transmission to the BS scheme will require high energy cost and the delay will be N as nodes transmit to the BS sequentially. The PEGASIS scheme forms a chain among the sensor nodes so that each node will receive from and transmit to a close neighbor. For this linear network with equally spaced nodes, the energy cost in PEGASIS is minimized and the variable cost is proportional to $N \times d^2$ and the delay will be N units. Therefore, the $energy \times delay$ cost will be $N^2 \times d^2$.

In the binary scheme with perfect parallel transmission of data, there will be $N/2$ nodes transmitting data to their neighbors at distance d in the lowest level. The nodes that receive data will fuse the data with their own data and will be active in the next level of the tree. Next, $N/4$ nodes will transmit data to their neighbors at a distance $2d$ and this procedure continues until a single node finally transmits the combined message to the BS. Thus, for the binary scheme, the energy cost will be:

$$N/2 \times d^2 + N/4 \times (2d)^2 + N/8 \times (4d)^2 + \ldots + 1 \times (N/2 * d)^2$$

since the distance doubles as we go up the hierarchy. In addition, there will be a single transmission to the BS and the energy cost depends on the distance to the BS. Without including this additional cost by simplifying the above expression we get for the energy cost for the binary scheme as:

$$N/2 \times d^2 \times (1 + 2 + 4 + \ldots + N/2),$$

which equals

$$N(N-1)/2 \times d^2.$$

With the additional transmission to the BS, N we can approximate the total energy cost for the binary scheme to be:

$$N^2/2 \times d^2.$$

With the delay cost of about $\log N$ units, the $energy \times delay$ cost for the binary scheme is $N^2/2 \times d^2 \times \log N$. Therefore, for this linear network, the binary scheme will be more expensive than PEGASIS in terms of $energy \times delay$. For random distribution of nodes in a rectangular playing field, the distances do not double as we go up the hierarchy in the binary scheme and the reduced delay will help reduce the $energy \times delay$ cost. It is difficult to analyze this cost for randomly distributed nodes and we will use simulations to evaluate this cost.

For the rest of the analysis, we assume 50, 100, and 200-node sensor networks in a square field with the BS located far away. In this scenario, energy costs can be reduced if the data is gathered locally among the sensor nodes and only a few nodes transmit the fused data to the BS. This is the approach taken in LEACH [12], where clusters are formed dynamically in each round and cluster-heads (leaders for each cluster) gather data locally and then transmit to the BS. Cluster-heads are chosen randomly, but all nodes have a chance to become a cluster-head in LEACH to balance the energy spent per round by each sensor node. Nodes are able to transmit simultaneously to their cluster-heads using CDMA. For a 100-node network in a $50m \times 50m$ field with the BS located at (25, 150), which is at least 100 meters from the closest node, LEACH reduces the $energy \times delay$ cost compared to the direct scheme. For the linear network of N nodes that are equally spaced, LEACH will have slightly higher energy compared to PEGASIS due to the cluster-heads transmissions to the BS and a delay of roughly N/c, where c is the number of clusters. With five clusters suggested in [12], the $energy \times delay$ for LEACH will be lower than for PEGASIS for a $50m \times 50m$ network. However, for a $100m \times 100m$ network, the $energy \times delay$ for LEACH will be higher than for PEGASIS since PEGASIS achieves increased energy savings with more sparse networks.

The next two sections present protocols that are designed to minimize the $energy \times delay$ metric.

6 A Chain-Based Binary Approach Using CDMA Capable Sensor Nodes

First, we consider a sensor network with nodes capable of CDMA communication. With this CDMA system, it is possible for node pairs that communicate to use distinct codes to minimize radio interference. Thus, parallel communication is possible among 50 pairs for a 100-node network. In order to minimize the delay, we will combine data using as many pairs as possible in each level, which results in a hierarchy of $\lceil \log N \rceil$ levels. At the lowest level, we will construct a linear chain among all the nodes, as was

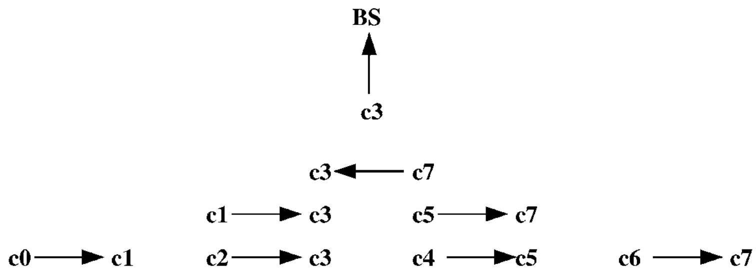


Fig. 4. Data gathering in a chain-based binary scheme.

done in PEGASIS, so that adjacent nodes on the chain are nearby. For constructing the chain, we assume that all nodes have global knowledge of the network and employ the greedy algorithm described in Section 4.

For gathering data in each round, each node transmits to a close neighbor in a given level of the hierarchy. This occurs at every level in the hierarchy, but the only difference is that the nodes that are receiving at each level are the only nodes that will be active in the next level. Finally, at the top level, the only node remaining will be the leader and the leader will transmit the k bit message to the BS. Note that node i will be in some random position j on the chain. Nodes take turns transmitting to the BS and we will use node number $i \bmod N$ (N represents the number of nodes) to transmit to the BS in round i. In Fig. 4, for round three (first round is round zero), node $c3$ is the leader. Since, node $c3$ is in position 3 (counting from 0) on the chain, all nodes in an even position will send to their right neighbor. Now, at the next level, node $c3$ is still in an odd position, so, again, all nodes in an even position will fuse their data with its received data and send to their right. At the third level, node $c3$ is not in an odd position, so node $c7$ will fuse its data and transmit to $c3$. Finally, node $c3$ will combine its current data with that received from $c7$ and transmit the message to BS.

The chain-based binary scheme performs data fusion at every node that is transmitting except the end nodes in each level. Each node will fuse its neighbor's data with its own to generate a single packet of the same length and then transmit that to the next node. In the above example, node $c0$ will pass its data to node $c1$. Node $c1$ fuses node $c0$'s data with its own and then transmits to node $c3$ in the next level. In our simulations, we ensure that each node performs an equal number of sends and receives after N rounds of communication and each node transmits to the BS in one of N rounds. We then calculate the average energy cost per round, while the delay cost is the same for each round. We compute the average $energy \times delay$ cost over a number of different node distributions. Experimental results are presented in detail in Section 8.

The chain-based binary scheme improves on LEACH and LEACH-C by saving energy and delay in several stages. At the lower levels, nodes are transmitting at shorter distances compared to nodes transmitting to a cluster-head in the LEACH protocol and only one node transmits to the BS in each round of communication. By allowing nodes to transmit simultaneously, the delay cost for the binary scheme decreases from that of LEACH by a factor of about three. While, in LEACH and LEACH-C, only five groups can transmit simultaneously for a 100-node network, here, at each level, we have more nodes transmitting simultaneously. At each level of the binary scheme, transmissions are simultaneous, making the total delay $\lceil \log N \rceil + 1$, including the transmission to the BS. In LEACH and LEACH-C, the delay for 100-node networks will be 27 units. The delay for all nodes to transmit to the cluster-head is the max number of nodes in any of the five clusters. If all the clusters are of the same size, then the delay would be 19. Then, all five cluster-heads must take turns to transmit to the BS, making that a total of 24. For overhead calculations, we have one unit of delay for cluster formation, one unit of delay for all nodes to broadcast to the cluster-head its presence in that cluster, and, finally, one unit of delay for the cluster-head to broadcast a schedule sequence to the nodes so that all nodes within a cluster know when to transmit their data to the cluster-head.

7 A Chain-Based Three Level Scheme without CDMA Capable Sensor Nodes

CDMA may not be applicable for all sensor networks as these nodes can be expensive. Therefore, we need a protocol that will achieve a minimal $energy \times delay$ with non-CDMA nodes. It will not be possible to use the binary scheme in this case as the interference will be too much at lower levels. We either have to increase the energy cost significantly or take more time steps at lower levels of the hierarchy, both of which will lead to much higher $energy \times delay$ cost. Therefore, in order to improve $energy \times delay$, we need a protocol that allows simultaneous transmissions that are far apart to minimize interference while achieving reasonable delay cost. Based on our experiments, we suggest the chain-based 3-level scheme for data gathering in sensor networks with non-CDMA nodes.

Also, in the 3-level scheme, we start with the linear chain among all the nodes and divide them into G groups, with each group having N/G successive nodes of the chain. Therefore, we will have G groups of N/G nodes. One node from each group will be active in the second level and, thus, there will be G nodes. These G nodes in the second level are divided into two groups of successive nodes in order to maintain only three levels in the hierarchy. G is calculated based on the number of nodes and the size of the network. For a $100m \times 100m$ network, we found that, when G is equal to 10, we get the best balance for energy and delay. In a 100-node network, therefore, only 10 simultaneous transmissions take place at the same time and data fusion takes place at each node (except the end nodes in each level). The transmissions are also far enough apart that there is minimal interference and we can still maintain low energy costs at each level in the hierarchy while maintaining a low delay. Fig. 5 shows an example of this scheme with 100 nodes. We will have a different leader in each round transmit to the BS to evenly distribute the workload

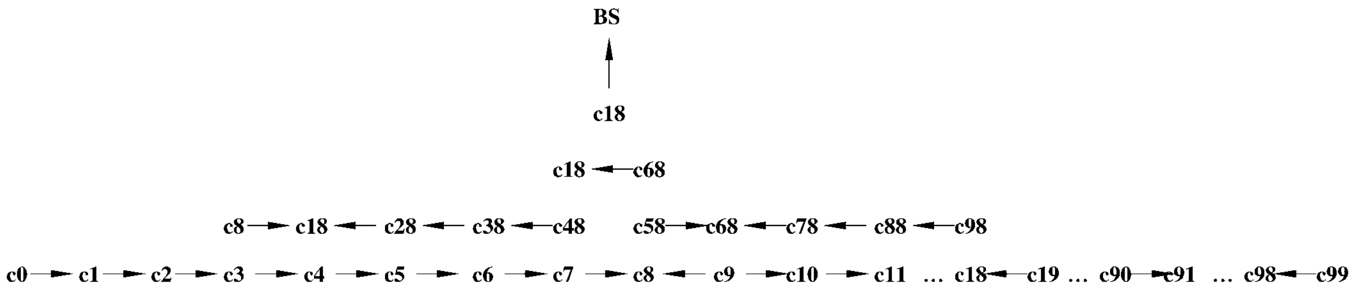


Fig. 5. Chain-based 3-level scheme for a sensor network with non-CDMA nodes.

among the sensor nodes. As before, we will use node i along the chain to be the leader in the ith round of communication. We find the index i within a group which will represent the leader position modulo N/G.

In Fig. 5, node $c18$ is our leader. Then all nodes will send their data in the direction of index 8 within their group since 18 modulo 10 is 8. The delay at the first level is nine units. Then the second level will contain nodes $c8, c18, c28 \ldots c98$. These 10 nodes will be divided into two groups. If we have more levels in the hierarchy, then distances between nodes become further apart, causing higher energy costs. By experimentation, for the networks under consideration, having three levels gives us the best balance of energy and delay. Since the leader position is 18, all nodes that are in the first group will send down the chain 10 positions from its own position on the chain. So, node $c48$ will send to node $c38$, and node $c38$ will send to node $c28$ and so on. Since node $c8$'s position is less than node $c18$'s, node $c8$ will transmit to a position that is N/G greater than its own. In group two, nodes know in which direction to send the data using the leader position $N/2$. So, here, the nodes in group two would send in the direction of node $c68$ in the same manner as in group one. This gives us a delay of four units for the second level. In the third level, node $c68$ transmits to node $c18$, who is our leader, and then, finally, node $c18$ transmits the combined packet to the BS, giving us a total delay of 15 units. The transmission schedule can be programmed once at the beginning so that all nodes know where to send data in each round of communication.

8 Experimental Results

This section presents the performance analysis of the different protocols using simulation programs written in C programming language. We used several simulation parameter variations to test our schemes. The network dimensions studied were $50m \times 50m$ and $100m \times 100m$. The BS locations were varied at (50, 150), (50, 200), and (50, 300). The packet sizes considered were 2,000, 10,000, and 20,000 bits. The number of nodes were varied as 50, 100, and 200 to test for dense and sparse networks. Extensive simulations were run to determine the optimal number of clusters to use when the number of nodes varied for the LEACH protocol. The LEACH protocol uses five clusters for a 100-node network. We found that, for a 200-node network, five clusters were optimal, and, for a 50-node network, two clusters were optimal.

8.1 Comparison of LEACH and PEGASIS Using the Energy Metric

For this experiment, the metric studied was the number of rounds of communication achieved when 1 percent, 25 percent, 50 percent, and 100 percent of the nodes die using direct transmission, LEACH, and PEGASIS. Each node is assumed to have the same initial energy level of 0.25J. Once a node dies due to battery power depletion, it is not recharged for the rest of the simulation. LEACH-C improves upon LEACH by about 40 percent due to the centralized computation by the BS to find better clusters [14]. Therefore, as stated before, in the rest of this section, we present our comparison results only with LEACH. The performance improvements will be correspondingly lesser compared to LEACH-C to the extent LEACH-C improves upon LEACH, which is about 20 percent to 40 percent, depending on network parameters [14].

Fig. 6 shows the number or rounds until 1 percent, 25 percent, 50 percent, and 100 percent nodes die for a $50m \times 50m$ network. PEGASIS is approximately two times better than LEACH in all cases for a $50m \times 50m$ network. The overhead energy cost in forming clusters in LEACH or chain in PEGASIS are similar. It may be more useful to compute this centrally in the BS, which doesn't have an energy limitation. The improvements in PEGASIS come due to fewer nodes transmitting data to BS in each round compared to LEACH and its variants.

The next set of experiments were conducted for a $100m \times 100m$ network. Fig. 7 shows the number of rounds completed for the same percentages of node deaths with different locations of the BS. The BS locations are at (50, 150), (50, 200), and (50, 300).

The simulation results show that PEGASIS achieves:

- approximately two times the number of rounds compared to LEACH when 1 percent, 25 percent, 50 percent, and 100 percent of nodes die for a $50m \times 50m$ network,
- approximately three times the number of rounds compared to LEACH when 1 percent, 25 percent, 50 percent, and 100 percent nodes die for a $100m \times 100m$ network,
- balanced energy dissipation among the sensor nodes to have full use of the complete sensor network,
- near-optimal performance.

However, there are some rare cases when the first node death occurs with PEGASIS slightly earlier in comparison to LEACH, as shown in Fig. 7a. This is due to the greedy chain construction procedure used, where a node may have a local neighbor very far away and thus will deplete energy more quickly and die first. This happens only for some distribution of nodes and an approach to ensure that PEGASIS always performs best before the first node death occurs is to construct a chain so that all nodes have relatively close neighbors. To construct such a chain

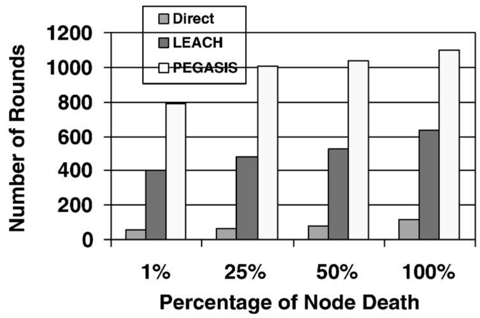


Fig. 6. Performance results for a $50m \times 50m$ network, BS location at (25, 150), and 100 nodes.

requires the use of the global knowledge of all node positions to pick suitable neighbors and minimize the maximum neighbor distance. This problem is related to the traveling salesman problem of minimizing the total length of the loop (chain), which is known to be intractable. Heuristic algorithms to solve this problem can be expensive compared to the simple scheme used in PEGASIS and the advantages are minimal as PEGASIS is nearly optimal in terms of rounds achievable when a larger percentage of nodes die.

8.2 Comparison of All Schemes Using the $Energy \times Delay$ Metric

To evaluate the performance of the chain-based binary scheme and the chain-based 3-level scheme, we simulated direct transmission, PEGASIS, LEACH, and the two new schemes using several random 50, 100, and 200-node networks with CDMA nodes and non-CDMA nodes. We used the same simulation parameters as described above for evaluating PEGASIS. However, instead of running the simulations for percentage of node deaths, we ran the simulations for enough rounds in all the schemes so that all N nodes had a chance to become leader only once. Since different schemes have to run for a different number of rounds before every node has a chance to become leader only once, it does not make sense to compare the number of rounds before nodes die. By doing this, we can compare the average energy costs per round for all the schemes fairly. We then used these costs to determine the average energy cost per round of data gathering for several different topologies. To calculate the $energy \times delay$ for these schemes, we multiply the average energy cost per round to the unit delay for the scheme. In both CDMA and non-CDMA systems, we included the interference costs when there are simultaneous transmissions to ensure that the same SNR of 10 dB is maintained as with single transmission. For the 3-level scheme, we evaluated the number of

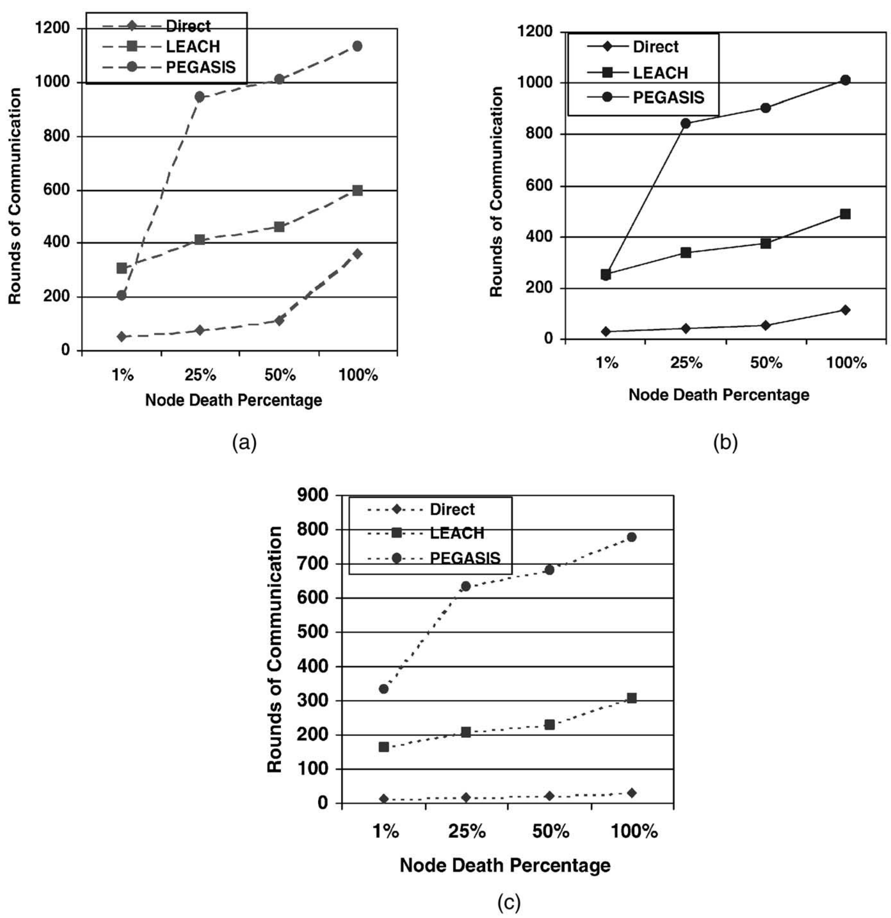


Fig. 7. Performance results for a $100m \times 100m$ network with the BS location at (a) pos = (50, 150), (b) pos = (50, 200), and (c) pos = (50, 300). The packet size is 2,000 bits and the number of nodes is 100.

TABLE 1
$Energy \times delay$ Cost for Direct, PEGASIS, LEACH, Chain-Based Binary Scheme and the Chain-Based Three Level Scheme

Protocol	Energy		Delay	Energy × Delay	
	D = 50	D = 100	D = 50 & D = 100	D = 50	D = 100
Direct (both systems)	0.3299	1.2805	100	32.9938	128.0459
PEGASIS (both systems)	0.0240	0.0361	100	2.4008	3.6107
LEACH (CDMA nodes)	0.0797	0.2048	27	2.1518	5.5292
Chain-based binary (CDMA nodes)	0.0318	0.0559	8	0.2547	0.4516
Chain-based 3 level (non-CDMA nodes)	0.0358	0.0583	15	0.5365	0.8743

These results are for a $50m \times 50m$ and $100m \times 100m$ network where D equals the dimension of a $D \times D$ network.

groups for the first level when the number of nodes change in the network to guarantee the optimal $energy \times delay$. We found that, for 50-node, 100-node, and 200-node networks, dividing the nodes into 10 groups gave us the optimal $energy \times delay$.

Table 1 gives the results for energy cost, delay cost, and $energy \times delay$ cost for direct, PEGASIS, LEACH, the chain-based binary scheme, and the chain-based 3-level scheme.

Fig. 8 shows the results for the five schemes based on different BS locations. $Energy \times delay$ is higher for all schemes as the BS moves farther away from the nodes. Fig. 9 shows the results for the five schemes based on different packet sizes. As expected, $energy \times delay$ increases with the packet size. Fig. 10 shows that, as the number of nodes increase, $energy \times delay$ becomes greater for all schemes. For all these figures, the binary scheme performs the best however if sensors are not CDMA capable, then the 3-level scheme is the best.

The simulation results show that:

- The chain-based binary scheme is approximately eight times better than LEACH and 130 times better than direct for a $50m \times 50m$ network in terms of $energy \times delay$ for sensor networks with CDMA nodes.
- The chain-based binary scheme is approximately five to 13 times better than LEACH and 80 or more times better than the direct scheme for a $100m \times 100m$ network in terms of $energy \times delay$ for sensor networks with CDMA nodes.
- The chain-based three level scheme is approximately four times better than PEGASIS and 60 times better than direct for a $50m \times 50m$ network in terms of $energy \times delay$ for sensor networks with non-CDMA nodes.
- The chain-based 3-level scheme is approximately three to five times better than PEGASIS and up to 140 times better than direct for a $100m \times 100m$ network in terms of $energy \times delay$ for sensor networks with non-CDMA nodes.
- The chain-based schemes show a more balanced energy dissipation among the sensor nodes to have full use of the complete sensor network.

9 Conclusions and Future Work

In this paper, we describe three new protocols for wireless sensor networks. One of these protocols, PEGASIS, is a greedy chain protocol that is near optimal for a data-gathering problem in sensor networks. PEGASIS outperforms LEACH by eliminating the overhead of dynamic cluster formation, minimizing the distance nonleader nodes must transmit, limiting the number of transmissions and receptions among all nodes, and using only one transmission to the BS per round. Nodes take turns to transmit the fused data to the BS to balance the energy depletion in the network and preserve the robustness of the sensor web as nodes die at random locations. Distributing the energy load among the nodes increases the lifetime and quality of the network. Our simulations show that PEGASIS performs better than LEACH by about 100 to 200 percent when 1 percent, 25 percent, 50 percent, and 100 percent of nodes die for different network sizes and topologies. The improvements will be slightly lesser compared to LEACH-C, which doesn't have the cluster formation overhead in each round. PEGASIS shows an even further improvement as the size of the network increases.

The other two protocols described in this paper that reduce the energy as well as delay for data gathering in sensor networks are a chain-based binary scheme for sensor networks with CDMA nodes and a chain-based 3-level scheme for sensor networks with non-CDMA nodes. The

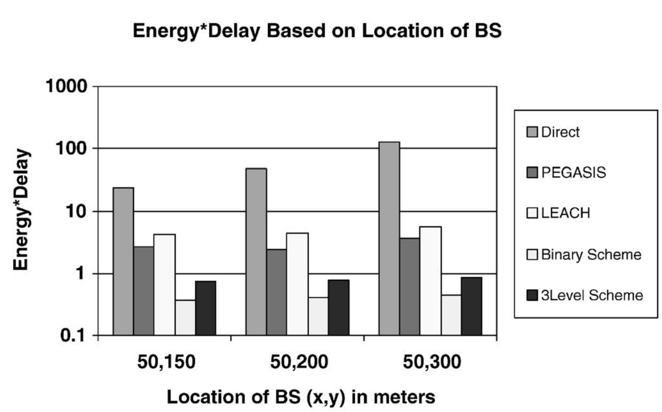


Fig. 8. Performance results for a $100m \times 100m$ network with BS locations at (50, 150), (50, 200), and (50, 300). The packet size is 2,000 bits and the number of nodes in the network is 100.

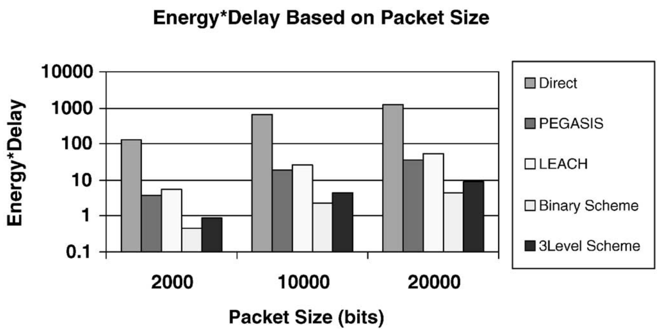


Fig. 9. Performance results for a $100m \times 100m$ network with BS location at (50, 300). The packets sizes vary at 2,000, 10,000, and 20,000 bits and the number of nodes in the network is 100.

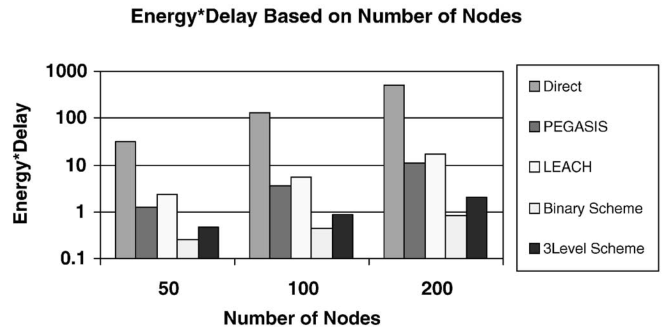


Fig. 10. Performance results for a $100m \times 100m$ network with the BS location at (50, 300). The packet size is 2,000 bits and the number of nodes vary at 50, 100, and 200.

binary scheme performs better than direct, PEGASIS, and LEACH. It performs better than LEACH by a factor of about eight, about 10 times better than PEGASIS, and more than 100 times better when compared to the direct scheme. In these experiments, the interfering transmissions contributions are assumed to be 1/128 the value of their transmission energy. With non-CDMA nodes, the interfering energy is the amount received from unintended transmissions. The chain-based 3-level scheme with non-CDMA outperforms PEGASIS by a factor of four and is better than direct by a factor of 60. The scheme outperforms PEGASIS by dividing the chain in "groups" and allowing simultaneous transmissions among pairs in different groups. While energy is still minimal, the delay is decreased from 100 units to 15 units.

It is not clear as to what is the optimal scheme for optimizing $energy \times delay$ is in a sensor network. Since the energy costs of transmissions depend on the spatial distribution of nodes, there may not be a single scheme that is optimal for all sizes of the network. Our preliminary experimental results indicate that, for all small networks, the binary scheme performs best as minimizing delay achieves best result for $energy \times delay$. With larger networks, we expect that nodes in the higher levels of the hierarchy will be far apart and it is possible that a different multilevel scheme may outperform the binary scheme. When using non-CDMA nodes, interference effects can be reduced by carefully scheduling simultaneous transmissions. Since there is an exponential number of possible schedules, it is intractable to determine the optimal scheduling to minimize $energy \times delay$ cost. A practical scheme to employ will depend on the size of the playing field and the distribution of nodes in the field.

In order to validate our assumptions, more detailed models and a network simulator, such as ns-2, need to be used for detailed evaluations. Based on our C simulations, we expect that PEGASIS will outperform LEACH and its variants and direct protocols in terms of system lifetime and the quality of the network for minimizing energy. We also expect that the binary chain-based scheme and the 3-level chain-based scheme will outperform direct, LEACH and its variants, and PEGASIS in terms of $energy \times delay$. We also restricted our discussions to the d^2 model for energy dissipation for wireless communications in this paper. In our future work, we will consider higher order energy dissipation models and develop schemes to minimize energy and $energy \times delay$ costs for this type of data gathering and other applications in sensor networks.

ACKNOWLEDGMENTS

Part of this research was conducted while the first author was a student intern at the Aerospace Corporation and a graduate student at Washington State University. Part of the research was supported by Air Force Office of Scientific Research grants F-49620-97-1-0471 and F-49620-99-1-0125; abd Laboratory for Telecommunications Sciences, Adelphi, Maryland.

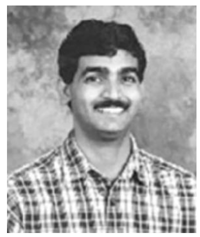
REFERENCES

[1] "The Ultimate Sting: Bees the Buzz in Landmine Detection,"http://www.pnl.gov/news/1999/99-13.htm. Apr. 2001.
[2] "Bluetooth Initiative,"http://www.bluetooth.com, 1999.
[3] N. Bambos, "Toward Power-Sensitive Network Architectures in Wireless Communications: Concepts, Issues, and Design Aspects," *IEEE Personal Comm.*, pp. 50-59, June 1998.
[4] A. Chandrakasan, R. Amirtharajah, S.-H. Cho, J. Goodman, G. Konduri, J. Kulik, W. Rabiner, and A. Wang, "Design Considerations for Distributed Microsensor Networks," *Proc. IEEE Custom Integrated Circuits Conference (CICC)*, pp. 279-286, 1999.
[5] B. Chen, K. Jamieson, H. Balakrishnan, and R. Morris, "Span: An Energy-Efficient Coordination Algorithm for Topology Maintenance in Ad Hoc Wireless Networks," *Proc. SIGMOBILE*, July 2001.
[6] L. Clare, G. Pottie, and J. Agre, "Self-Organizing Distributed Sensor Networks," *Proc. SPIE Conf. Unattended Ground Sensor Technologies and Applications*, pp. 229-237, 1999.
[7] "COTS Dust,"http://www-bsac.eecs.berkeley.edu/~shollar/macro_motes/macromotes.html. Jan. 2001.
[8] M. Dong, K. Yung, and W. Kaiser, "Low Power Signal Processing Architectures for Network Microsensors," *Proc. Int'l Symp. Low Power Electronics and Design*, pp. 173-177, 1997.
[9] D. Dudgeon and R. Mersereau, *Multidimensional Signal Processing.* Prentice Hall, 1984.
[10] D. Estrin, R. Govindan, J. Heidemann, and S. Kumar, "Next Century Challenges: Scalable Coordination in Sensor Networks," *Proc. ACM/IEEE Mobicom*, Aug. 1999.
[11] M. Ettus, "System Capacity, Latency, and Power Consumption in Multihop-Routed SS-CDMA Wireless Networks," *Proc. Radio and Wireless Conference (RAWCON)*, 1998.
[12] W. Heinzelman, A. Chandrakasan, and H. Balakrishnan, "Energy-Efficient Communication Protocol for Wireless Microsensor Networks," *Proc. Hawaii Conf. System Sciences*, Jan. 2000.
[13] W. Heinzelman, A. Sinha, A. Wang, and A. Chandrakasan, "Energy-Scalable Algorithms and Protocols for Wireless Microsensor Networks," *Proc. Int'l Conf. Acoustics, Speech, and Signal Processing (ICASSP)*, June 2000.
[14] W. Heinzelman, "Application-Specific Protocol Architectures for Wireless Networks," PhD thesis, Massachusetts Inst. of Technology, June 2000.
[15] L. Klein, *Sensor and Data Fusion Concepts and Applications.* SPIE Optical Eng. Press, 1993.

[16] J. Kulik, W. Rabiner, and H. Balakrishnan, "Adaptive Protocols for Information Dissemination in Wireless Sensor Networks," *Proc. ACM/IEEE Mobicom,* Aug. 1999.
[17] S. Lindsey, K.M. Sivalingam, and C.S. Raghavendra, "Power-Aware Routing and MAC Protocols for Wireless and Mobile Networks," *Wiley Handbook on Wireless Networks and Mobile Computing,* pp. 407-423, John Wiley & Sons, 2002.
[18] K. Nakano and S. Olariu, "Energy-Efficient Initialization Protocols for Single-Hop Radio Networks with No Collision Detection," *IEEE Trans. Parallel and Distributed Systems* vol. 11, no. 8, Aug. 2000.
[19] K. Nakano and S. Olariu, "Randomized Initialization Protocols for Ad Hoc Networks," *IEEE Trans. Parallel and Distributed Systems,* vol. 11, no. 7, July 2000.
[20] R. Pichna and Q. Wang, "Power Control," *The Mobile Comm. Handbook,* pp. 370-380, CRC Press, 1996.
[21] T.S. Rappaport, *Wireless Communications,* Prentice-Hall, 1996.
[22] R. Ramanathan and R. Hain, "Topology Control of Multihop Wireless Networks Using Transmit Power Adjustment," *Proc. IEEE Infocom,* Mar. 2000.
[23] E. Shih, S.-H. Cho, N. Ickes, R. Min, A. Sinha, A. Wang, and A. Chandrakasan, "Physical Layer Driven Algorithm and Protocol Design for Energy-Efficient Wireless Sensor Networks," *Proc. SIGMOBILE,* July 2001.
[24] S. Singh and C. S. Raghavendra, "PAMAS: Power Aware Multi-Access Protocol with Signalling for Ad Hoc Networks" *ACM Computer Comm. Rev.,* July 1998.
[25] K. Sivalingam, J. Chen, P. Agrawal, and M. Srivastava, "Design and Analysis of Low-power Access Protocols for Wireless and Mobile ATM Networks," *ACM/Baltzer Wireless Networks,* vol. 6, pp. 73-87, Feb. 2000.
[26] R. Steele, *Mobile Radio Communications,* London Pentech Press, 1992.
[27] M. Stemm, P. Gauthier, D. Harada, and R. Katz, "Reducing Power Consumption of Network Interfaces in Hand-Held Devices," *Proc. Thirdrd Int'l Workshop Mobile Multimedia Comm.,* pp. 25-27, Sept. 1996.
[28] J. Wieselthier, G. Nguyen, and A. Ephremides, "On the Construction of Energy-Efficient Broadcast and Multicast Trees in Wireless Networks," *Proc. IEEE Infocom,* Mar. 2000.
[29] *The WINS Project,* http://www.janet.ucla.edu/WINS. Feb. 1999.
[30] Y. Xu, J. Heidemann, and D. Estrin, "Geography-Informed Energy Conservation for Ad Hoc Routing," *Proc. SIGMOBILE,* July 2001.
[31] K. Yao, R. Hudson, C. Reed, D. Chen, and F. Lorenzelli, "Blind Beamforming on a Randomly Distributed Sensor Array System," *Proc. Signal Processing Systems,* 1998.

Stephanie Lindsey received the MS degree in computer science from Washington State University, Pullman, in 2000 and the BSc degree in computer science from the University of North Texas, Denton, in 1999. She is currently employed at Microsoft Corporation, Redmond, Washington. Her research interests include wireless ad hoc and sensor networks.

C.S. Raghavendra received the PhD degree in computer science from the University of California at Los Angeles in 1982. He is a professor of electrical engineering and computer science and director of Computer Engineering Division in the Electrical Engineering Department at the University of Southern California (USC), Los Angeles. Previously, he was a faculty member in the Department of Electrical Engineering-Systems at USC from 1982 to 1992, was the Boeing Chair Professor of Computer Engineering in the School of Electrical Engineering and Computer Science at the Washington State University in Pullman, from 1992 to 1997, and was with The Aerospace Corporation from 1997 to 2001. He is a recipient of the Presidential Young Investigator Award for 1985 and is a fellow of the IEEE.



K.M. Sivalingam received the PhD and MS degrees in computer science from the State University of New York (SUNY), at Buffalo in 1994 and 1990, respectively. He received the BE degree in computer science and engineering in 1988 from Anna University, Madras, India.- While at SUNY Buffalo, he was a presidential fellow from 1988 to 1991. He is currently an associate professor in the School of Electrical Engineering and Computer Science, at Washington State University, Pullman, where he was an assistant professor from 1997 to 2000. Earlier, he was an assistant professor at the University of North Carolina, Greensboro, from 1994 to 1997. He has conducted research at Lucent Technologies' Bell Labs in Murray Hill, New Jersey, and at AT&T Labs in Whippany, New Jersey. His research interests include wireless networks, optical wavelength division multiplexed networks, and performance evaluation. He has served as a guest coeditor for a special issue of the *IEEE Journal on Selected Areas in Communications* on optical WDM networks. He is a corecipient of the Best Paper Award at the IEEE International Conference on Networks 2000 held in Singapore. He has published an edited book on optical WDM networks in 2000. His work has been supported by the US Air Force Office of Scientific Research, Laboratory for Telecommunication Sciences, US National Science Foundation, Cisco, Bellcore, Alcatel, Intel, and Washington Technology Center. He holds three patents in wireless networks and has published several research articles, including more than 20 journal publications. He has served as the technical program co-chair of SPIE/IEEE/ACM OptiComm Conference in Boston, in July 2002 and as the workshop co-chair for the Workshop on Wireless Sensor Networks and Applications (WSNA) to be held in conjunction with ACM MobiCom 2002 in Atlanta, in September 2002. He has also served on several international conference committees in various capacities, including ACM Mobicom 2001, Opticomm 2001, Opticomm 2000, ACM Mobicom 1999, MASCOTS 1999, and IEEE INFOCOM 1997. He is a senior member of the IEEE and a member of ACM.