Data Gathering in Sensor Networks using the *Energy*Delay* Metric

Stephanie Lindsey
Cauligi Raghavendra
Krishna Sivalingam

Corresponding Author: Cauligi Raghavendra
Computer Systems Research Department
The Aerospace Corporation
P.O. Box 92957
Los Angeles, CA 90009-2957

E-mail: raghu@aero.org
Tel: 310-336-1686
Fax: 310-336-4402

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Stephanie Lindsey*+, Cauligi Raghavendra*, and Krishna Sivalingam+

***Computer Systems Research Department**
The Aerospace Corporation
P. O. Box 92957
Los Angeles, CA 90009-2957

+School of Electrical Engineering and Computer Science
Washington State University
Pullman, WA 99164-2752

Abstract

In this paper we consider the problem of data collection from a sensor web consisting of N nodes, where nodes have packets of data in each round of communication that need to be gathered and fused with other nodes' packets into one packet and transmitted to a distant base station. Nodes have power control in their wireless communications and can transmit directly to any node in the network or to the base station. With unit delay cost for each packet transmission, if all nodes transmit data directly to the base station, then both high energy and high delay per round will occur. In our prior work [6], we developed an algorithm to minimize the energy cost per round, where a linear chain of all the nodes are formed to gather data, and nodes took turns to transmit to the base station. If the goal is to minimize 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. The goal is to find data gathering schemes that balance the energy and delay cost, as measured by *energy*delay*. We conducted extensive simulation experiments with a number of schemes for this problem with 100 nodes in playing fields of 50m x 50m and 100m x 100m and the base station located at least 100 meters and 200 meters, respectively, from any node. With CDMA capable sensor nodes, a chain-based binary scheme performs best in terms of *energy*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. These schemes perform 60 to 100 times better than direct scheme and also outperform a cluster based scheme, called LEACH [3].

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1. Introduction

Inexpensive sensors are deployed for data collection from the field in a variety of scenarios including military surveillance, building security, in harsh physical environments, for scientific investigations on other planets, etc. [2,4,13]. A sensor node will have limited computing capability and memory, and it will operate with limited battery power. These sensor nodes can self organize to form a network and can communicate with each other in a wireless manner. 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 [5,10,12]. Figure 1 shows a 100-node fixed sensor network in a playing field of size 50m x 50m with the base station (BS) fixed and far away from all the sensor nodes.

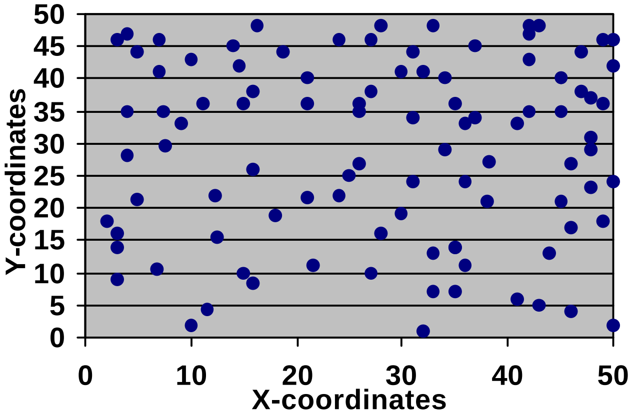

Figure 1. Random 100-node topology for a 50m x 50m network. BS is located at (25, 150), which is at least 100m from the nearest node.

In this paper we consider sensor nodes that have power control so that they can transmit their data directly to the base station or to any other nodes in the network [5,7]. Further, the sensor nodes are assumed to be homogeneous and energy constrained with uniform energy. An important operation in a sensor network is systematic gathering of data from the field, where each node has a packet of information in each round of communication [3]. In this operation, data sensed by the nodes need to be combined into a single message and sent to a distant base station. This data fusion among the sensor nodes requires wireless communications. The amount of energy spent in transmitting a packet has a fixed cost in electronics and a variable cost that depends on the distance of transmission. Receiving a data packet also has a similar fixed energy cost in electronics. Therefore, to conserve energy short distance transmissions are preferred. In order to balance the energy spent in the sensor nodes, nodes should take turns transmitting to the BS, as this is an expensive transmission.

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. A simple approach to accomplish this task is for each node to transmit its data directly to the BS. Since the BS is located far away, the cost to transmit to the BS from any node is high, and therefore, the total energy cost per round will be high. In sensor networks, data fusion helps to reduce the amount of data transmitted between sensor nodes and the BS. Data fusion combines one or more data packets from different sensor measurements to produce a single packet as described in [3]. The LEACH protocol presented in [3] is an elegant solution to this data collection problem, where a small number of clusters are formed in a self-organized manner. A designated node, the cluster head, 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 improves the energy cost per round by a factor of 4 compared to the direct approach for the 100 node network of Figure 1.

Recently, we developed an improved protocol called PEGASIS (Power-Efficient GAthering in Sensor Information Systems), which requires less energy per round compared to LEACH [6]. 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 moves from node to node, get fused, and eventually a designated node transmits to the BS. Nodes take turns to transmit 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. PEGASIS protocol achieves up to 100% improvement with respect to energy cost per round compared to the LEACH protocol.

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. The delay for a packet transmission (we assume that all packets are 2000 bits long) is dominated by the transmission time as there is no queueing 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 100 units (1 unit per transmission). The linear chain-based scheme, although energy efficient, will also require 100 units of delay as the transmissions are sequential. 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*Delay* is an interesting metric to optimize per round of data gathering.

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*delay* reduction for our data gathering problem separately for these two cases.

In this paper we present two protocols for *energy*delay* reduction: a chain-based binary combining protocol that uses CDMA capable nodes and a 3 level hierarchy chain-based protocol for non-CDMA nodes. A chain is formed among the sensor nodes in both of these protocols so that each node will receive from and transmit to a close neighbor at the lowest level of the hierarchy. 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. The binary scheme has a hierarchy of log N, with N equal to the number of nodes. The binary scheme would therefore have a delay of 7 +1 (for transmitting to the base station) for 100 nodes and performs better than LEACH by a factor of 8. The 3 level hierarchy chain-based protocol has a higher delay but is better than the binary scheme with non-CDMA nodes. This is because in the binary scheme there are many nearby simultaneous transmissions at the lower levels and the interference will be very high. In the 3 level scheme, fewer and distant simultaneous transmissions take place causing less interference. This 3 level chain-based protocol performs better than the direct scheme by a factor of about 60.

The paper consists of the following sections. In Section 2, the radio model for energy calculations is discussed. In Section 3, an analysis of the *energy x delay* metric for data gathering is given. Section 4 introduces the chain-based binary approach using CDMA capable sensor nodes. Section 5 introduces the chain-based 3 level scheme without CDMA capable sensor nodes. Experimental results are given in Section 5. Finally, Section 7 concludes the paper and proposes future work.

2. Radio Model for Energy Calculations

We use the same radio model as discussed in [3] which is the first order radio model. In this model, a radio dissipates E_{elec} = 50 nJ/bit to run the transmitter or receiver circuitry and $\in_{amp}$ = 100 pJ/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 [8,11]. The equations used to calculate transmission costs and receiving costs for a *k*-bit message and a distance *d* are shown below:

Transmitting

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

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

Receiving

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

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

Receiving is also a high cost operation, therefore, the number of receives and transmissions should be minimal.

In our simulations, we used a packet length *k* of 2000 bits. With these radio parameters, when d^2 is 500m^2, 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 energy required to transmit a message from node *j* to node *i* for a given signal to noise ratio (SNR), typically 10 dB. 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 are calculated as a small fraction of the energy from other unintended transmission. 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 few spatially distant pairs can communicate simultaneously.

3. *Energy*Delay* Analysis for Data Gathering

In this section we will analyze the *energy*delay* cost per round for data gathering from a sensor web to the distant BS. Recall that the data collection problem of interest is to send 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 but minimize delay at the same time. 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 data fusion. The delay cost can be calculated as units of time. On a 2Mbps link, a 2000 bit message can be transmitted in 1ms. Therefore each unit of delay will correspond to about 1 ms 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 1 unit for each 2000 bit message transmitted.

The *energy*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 the example network where the N nodes are along a straight line with equal distance of *d* between each pair of nodes and the BS at a faraway distance from all nodes. The direct approach will require high energy cost and the delay will be N as nodes transmit to the BS sequentially. The PEGASIS scheme [6], which is near optimal in terms of energy cost for this data gathering application in sensor networks, 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 $N*d^2$ and the delay will be N units. Therefore, the *energy*delay* cost will be N^2*d^2. The binary scheme will take $N/2* d^2 *(1+2+4+\ldots N/2)$, since the distance doubles as we go up the hierarchy. With the delay cost of about log N units, the *energy*delay* for the binary scheme is $N^2/2*d^2*\log N$. Therefore, for this linear network, the binary scheme will be more expensive than PEGASIS in terms of *energy*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*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 a 100-node sensor network 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 [3], 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 x 50m field with the BS located at (25,150), which is at least 100m from the closest node, LEACH reduces the *energy*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/k where k is the number of clusters. With 5 clusters suggested in [3], the *energy*delay* for LEACH will be lower than for PEGASIS for a 50m x 50m network. However, for a 100m x 100m network, the *energy*delay* for LEACH will be higher than for PEGASIS.

4. A Chain-based Binary Approach using CDMA

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 with 50 pairs for the 100-node network of interest. 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 log N levels. At the lowest level, we will construct a linear chain among all the nodes, as was 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. 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. We begin with this 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.

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 rise to the next level. Finally, at the top level the only node remaining will be the leader, and the leader will transmit the 2000 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* mod N (N represents the number of nodes) to transmit to the BS in round *i*. In Figure 3, for round 3, 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 its 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 equal number of sends and receives after N rounds of communication, and each node transmitting 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.

BS
↑
c3
c3 ←c7
c1→ c3 c5→ c7
c0→c1 c2→c3 c4→c5 c6→c7

Figure 3. Data gathering in a chain-based binary scheme.

The chain-based binary scheme improves on LEACH 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 3. While in LEACH, only 5 groups can transmit simultaneously, here at each level, we have multiple nodes transmit simultaneously. At each level of the binary scheme, transmissions are simultaneous making the total delay log N +1 for transmitting to the BS. In LEACH, 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 5 clusters. If all the clusters are of the same size, then the delay would be 19. Then all 5 cluster-heads must take turns to transmit to the BS, making that a total of 24. For overhead calculations, we have 1 unit of delay for cluster formation, 1 unit of delay for all nodes to broadcast to the cluster-head its presence in that cluster, and finally 1 unit of delay for the cluster-head to broadcast a TDMA schedule to the nodes so that nodes will know when to broadcast to the cluster-head.

5. A Chain-based 3 Level Scheme without CDMA

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*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*delay* cost. Therefore, in order to improve *energy*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. In the 3 level scheme also, we start with the linear chain among all the nodes and divide them into 10 groups. In the 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. Figure 4 shows an example of this scheme with 100 nodes. Here we would have 10 groups of 10. We will have a different leader each round transmit to the BS to evenly distribute the work load among the sensor nodes. We find the index *i* which will represent the leader position modulo 10. In Figure 4, 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 9 units. Then the second level will contain nodes c8, c18, c28…c98. These 10 nodes will be divided into two groups. 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 10 greater than its own. In group 2, nodes know in which direction to send the data using the leader position + 50. So here, the nodes in group 2 would send in the direction of node c68 in the same manner as in group 1. This gives us a delay of 4 units for the second level. In the third level, node c68 transmits to node c18, and then finally node c18 transmits to the base station, 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.

BS

↑

c18

c18←c68

c8 →c18←c28←c38←c48 c58→ c68← c78 ←c88← c98

c0→c1→c2→c3→c4→c5→c6→c7→c8←c9 c10→c11…c18←c19 …c90→c91…c98← c99

Figure 4. Chain-based 3 level scheme for a sensor network with non-CDMA nodes.

6. Experimental Results

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 100-node networks with CDMA nodes and non-CDMA nodes. The BS is located at (25, 150) in a 50m x 50m field, and the BS is located at (50,300) in a 100m x 100m field. We ran the simulations to determine the energy cost for all the schemes after all 100 nodes had a chance to become leader, with each node having the same initial energy level. We then used these costs to determine the average energy cost per round of data gathering. 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. Our simulations show:

- The chain-based binary scheme is approximately 8x better than LEACH and 130x better than direct for a 50m x 50m network in terms of *energy* * *delay* for sensor networks with CDMA nodes.
- The chain-based binary scheme is approximately 12x better than LEACH and 280x better than direct for a 100m x 100m network in terms of *energy* * *delay* for sensor networks with CDMA nodes.
- The chain-based 3 level scheme is approximately 4x better than PEGASIS and 60x better than direct for a 50m x 50m network in terms of *energy* * *delay* for sensor networks with non-CDMA nodes.

- The chain-based 3 level scheme is approximately 4x better than PEGASIS and 140x better than direct for a 100m x 100m network in terms of *energy* delay* for sensor networks with non-CDMA nodes.
- A more balanced energy dissipation among the sensor nodes to have full use of the complete sensor network.

These results are summarized in Table 1 and Table 2.

Table 1. *Energy* delay* cost for Direct, PEGASIS, LEACH, chain-based binary scheme and the chain-based 3 level scheme. These results are for a 50m x 50m network.

Protocol	Energy	Delay	*Energy* Delay*
Direct (both systems)	0.32993	100	32.9938
PEGASIS (both systems)	0.024008	100	2.4008
LEACH (CDMA nodes)	0.079696	27	2.1518
Chain-based binary (CDMA nodes)	0.031847	8	0.2547
Chain-based 3 level (non-CDMA nodes)	0.035772	15	0.5365

Table 2. *Energy* delay* cost for Direct, PEGASIS, LEACH, chain-based binary scheme and the chain-based 3 level scheme. These results are for a 100m x 100m network.

Protocol	Energy	Delay	*Energy *Delay*
Direct (both systems)	1.280459	100	128.0459
PEGASIS (both systems)	0.036107	100	3.6107
LEACH (CDMA nodes)	0.204786	27	5.5292
Binary (CDMA nodes)	0.055898	8	0.4516
3 Level (non-CDMA nodes)	0.058287	15	0.8743

7. Conclusions and Future Work

In this paper, we describe two new protocols for *energy*delay* reduction for data gathering in sensor networks -- 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 binary scheme performs better than direct, PEGASIS, and LEACH. It performs better than LEACH by a factor of about 8, about 10 times better than PEGASIS, and more than 100 times better when compared to the direct scheme. In these experiments, the interfering transmissions contribute 1/128 the value of their transmission energy. The chain-based 3 level scheme with non-CDMA outperforms PEGASIS by a factor of 4 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*delay* 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*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 multi-level scheme may out perform 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*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 this paper, we restricted our discussions to the d^2 model for energy dissipation for wireless communications. In our future work, we will consider higher order energy dissipation models and develop schemes to minimize *energy*delay* cost for data gathering application.

References

[1] "Bluetooth Initiative," http://www.bluetooth.com, 1999.

[2] D. Estrin, R. Govindan, J. Heidemann, and Satish Kumar, "Next Century Challenges: Scalable Coordination in Sensor Networks," In *Proceedings of Mobicom' 99*, 1999.

[3] W. Heinzelman, A. Chandrakasan, and H. Balakrishnan, "Energy-Efficient Communication Protocol for Wireless Microsensor Networks," In *Proceedings of the Hawaii Conference on System Sciences*, Jan. 2000.

[4] J. Kulik, W. Rabiner, and H. Balakrishnan, "Adaptive Protocols for Information Dissemination in Wireless Sensor Networks," In *Proceedings of Mobicom' 99*, 1999.

[5] N. Bambos, "Toward Power-Sensitive Network Architectures in Wireless Communications: Concepts, Issues, and Design Aspects,'' IEEE Personal Communications, June 1998, pp. 50-59.

[6] S. Lindsey, C. S. Raghavendra, "PEGASIS: Power Efficient GAthering in Sensor Information Systems," Submitted to ICC 2001.

[7] R. Ramanathan and R. Hain, "Topology Control of Multihop Wireless Networks Using Transmit Power Adjustment," In *Proceedings Infocom 2000*, 2000.

[8] T. S. Rappaport, *Wireless Communications*, Prentice-Hall, 1996.

[9] S. Singh, M. Woo and C.S. Raghavendra, “Power-Aware Routing in Mobile Ad Hoc Networks,” *In Proceedings ACM/IEEE Mobicom'98*, 1998.

[10] K. M. 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.

[11] R. Steele, *Mobile Radio Communications*, Pentech Press, London, 1992.

[12] M. Stemm, P. Gauthier, D. Harada and R. Katz, “Reducing Power Consumption of Network Interfaces in Hand-Held Devices,” In *Proceedings 3rd Intl. Workshop on Mobile Multimedia Communications*, Sept. 25-27, 1996, Princeton, NJ.

[13] The WINS Project, http://www.janet.ucla.edu/WINS.

[14] M. Zorzi and R. R. Rao, “Energy Management in Wireless Communications,” In *Proceedings 6th WINLAB Workshop on Third Generation Wireless Information Networks*, March 1997.