Energy Efficient Broadcasting for Situation Awareness in Ad hoc Networks

Stephanie Lindsey and Cauligi S. Raghavendra

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

Abstract

Ad hoc wireless networks and sensor networks have nodes with limited battery power, and broadcasting is an important operation in such networks. In this paper, we consider energy efficient one-to-all and all-to-all broadcast communications in such power constrained networks. It is assumed that nodes have power control and can adjust the range of their transmissions. Given a network of N nodes in a playing field of size D x D, we establish a lower bound and present a simple scheme for a source-to-all broadcast operation. Using simulations we show that the average energy cost of broadcasting from any source is within 25% of this lower bound in a network of 100 nodes in a 500m x 500m and a 1000m x 1000m area. In the situation awareness application, each node periodically transmits a small packet of 60 bytes to all other nodes in the network. For this all-to-all broadcast communication, we present a cluster scheme when nodes are allowed to transmit long distances, and a chain based scheme when nodes are limited to short distances. Our schemes for situation awareness significantly improve the life of the network compared to schemes with direct transmissions.

1. Introduction

In wireless ad hoc networks and sensor networks, all nodes cooperate to maintain connectivity. These networks are power constrained as nodes operate with limited battery power. We consider networks where each node has transmit power control and an omni-directional antenna and therefore can adjust the area of coverage with its transmission [6,7,13]. It is necessary to perform energy management for communications to maximize nodes' lifetimes, reduce bandwidth consumption by using local collaboration among the nodes, and tolerate node failures [12,15]. Since wireless communications consume significant amounts of battery power, energy efficiency is critical in performing multi-point communications in these networks [3].

With the availability of inexpensive wireless and sensor nodes [1,12], there has been a lot of interest in power aware and energy conserving communications protocols. Power aware channel access, routing, and broadcasting in ad hoc networks are presented in [2,9,10,11]. Scalable coordination and data gathering in sensor networks are considered in [4] and [5] respectively. More recently, the problem of broadcasting from a source to all nodes in a network, with power control, is presented in [14]. The approach taken in [14] is to build a source rooted spanning tree by adjusting transmit powers of nodes, followed by a sweep operation to remove redundant transmissions. Since finding the optimal broadcast tree is difficult, as it requires all possible spanning trees to be evaluated, the authors presented several heuristics.

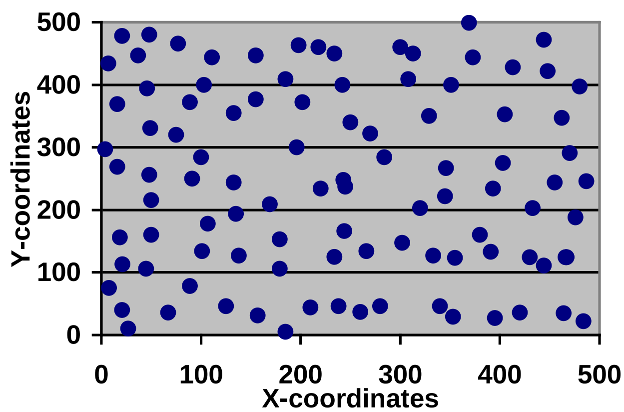

Figure 1. A 100-node network in a 500m x 500m field.

In this paper, we consider one-to-all and all-to-all broadcast problems in power constrained networks. In one-to-all broadcasting, we are interested in reducing the energy cost for single source broadcast operation as well as average cost for broadcasting from any source. For developing our algorithms and evaluations, we use a network of *N* nodes in a 2-dimensional area *D x D*. Figure 1 shows a 100-node network in a playing field of size 500m x 500m. The wireless nodes are homogeneous and have power control to reach nodes at any distance in the playing field. We assume that every node has location information of every other node in the network. However, if this was not the case, nodes could experiment with the power needed to reach the appropriate destination(s). This would be an increase in energy consumption, but only in the initial stages. We show that a shortest energy cost path from the source node to the central node, followed by a direct broadcast from the central node to reach all nodes performs well on the average. Our simulation of 100-node networks show that the results are within 25% of a lower bound established based on the area of coverage.

An important application where all-to-all broadcast communication is used is in the situation awareness problem. A scenario is illustrated in Figure 2, where each node represents a soldier and the presence and position information is broadcast to all others. We will develop energy efficient solutions to the situation awareness problem, where each node in the network is required to transmit a short packet, about 60 bytes, to all other nodes periodically. The period is relatively large, and therefore, the time to perform this all-to-all broadcast operation is not critical. However, it is important to minimize the energy to keep the network operating as long as possible. Each message consists of 40 bytes header and 20 bytes of information, and there is opportunity to conserve energy by combining messages with a single header.

We use the radio model discussed in [5] which is the first order radio model to calculate the energy costs. 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. Thus, the receiving energy spent in the electronics depends only on the message length, where as transmitting a message has a fixed cost and a variable cost that depends on the distance of transmission. In general, this variable part for transmitting to a distance r is proportional to r^n, where the exponent n is in the range of 2 to 4 [8]. 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). 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

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

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

We will consider two different energy dissipation models, d^2 and d^4 energy cost for transmitting to a range of distance d, where the former represents free space environment and the latter a noisy urban environment. For both these models, we give energy efficient solutions for a situation awareness problem to maximize the life of the network. We start with an uniform initial amount of energy in each node, and our goal is to maximize the time before the first node dies. We evaluate the performance of our algorithms and direct schemes by calculating the number of rounds completed, where each round corresponds to finishing an all-to-all broadcast.

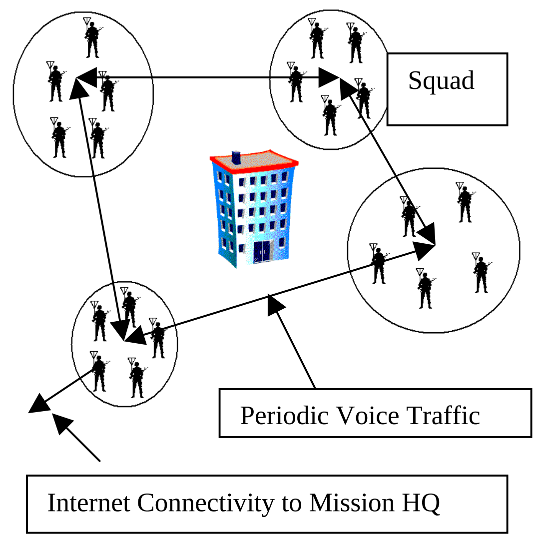

Figure 2. Situation Awareness- Crisis Management: Squads surround building to handle a terrorist activity

A simple approach to accomplish this all-to-all broadcast communication is for each node to transmit its data directly to all nodes in the network using appropriate range for transmission. With this approach, nodes that are far from other nodes spend more energy per round of an all-to-all broadcast and die off quickly. We will show that a significantly improved performance can be achieved with a scheme similar to the one in [5] by forming clusters of nodes, combining messages in each cluster, and broadcasting from a cluster head to all other nodes. However, we form clusters only once keeping the energy spent in this overhead to a minimum. Nodes take turns to becoming cluster heads, thereby dissipating energy more uniformly. For the d^2 energy cost model case, we show that this clustering approach achieves about 100% more rounds compared to the direct approach. With a given network size and the same initial energy in each node, we present results for the number of rounds before 1%, 10%, 25%, and 50% of the nodes die.

For the noisy environment, where d^4 energy cost is used, a node will not be able to successfully transmit to larger distances. For this case, the clustering approach described above will not be applicable as the cluster heads transmit to all nodes in the network. We develop another scheme where we build a chain with each node communicating only with a close neighbor. Data moves from node to node along the chain in both directions to accomplish the all-to-all broadcast operation. With this scheme, each node collects data from its neighbor, concatenates its data, and transmits to the next node. With a single header of 40 bytes, successive nodes transmit only slightly longer messages. With a given network and the same initial energy in each node, our chain based scheme achieves between 200% and 300% more rounds before a node dies compared to the direct approach.

This paper is organized as follows. In Section 2, we present a simple algorithm to perform a broadcast operation from a source to all nodes in the network. We show that the average energy cost for broadcasting is within a reasonable percentage from the lower bound. In Section 3, we describe the details of our clustering approach for all-to-all broadcast communication. In Section 4, we present the details of our chain based algorithm for all-to-all broadcasting suitable for noisy environments. Finally, we give some concluding remarks in Section 5.

2. Single Source Broadcast in Ad hoc Networks

In this section, we consider the problem of a single source broadcasting a message of length 2000 bits to all other nodes in a network. The *N* nodes are uniformly distributed in an area *D x D* and all nodes have power control. The energy cost model used in [14] ignores the fixed electronics cost in the digital part and uses d^2 dissipation model for the radiation. The algorithms presented are tree based and requires multiple transmissions. However, the fixed electronics energy cost for each transmission and reception is significant in sensor networks, and it is more efficient to use fewer transmissions to cover a given area. An ideal solution will use one transmission to exactly cover the entire area of the network. All nodes have power control, so the source can increase its power to broadcast directly instead of using multiple hops. With radiation in all directions, it may not be possible for any node in the field to use just one transmission to exactly cover the entire area of interest.

We establish a simple lower bound to achieve broadcasting in a network of nodes in a 2-dimensioanl area. All nodes must receive the message and there is a cost for receiving data by the *N* nodes. Since the energy propagation is proportional to the area of coverage with the d^2 model, any scheme must use enough energy to cover the given area of the field. When multiple transmissions are used, there will be additional fixed costs in electronics for reception and retransmission. Therefore, the minimum energy required to perform broadcasting is a single transmission that covers the entire area plus the total cost for all nodes to receive the message. For a given 2-dimensional area *a x a*, the minimum energy required for broadcasting is given by $N * E_{elec} * k + \in_{amp} * k * a^2$ where k is the size of broadcast message.

In a 2-dimensional area, a single node transmitting with enough power to reach all nodes will likely cover more than the area needed. Nodes at the edges of the playing field will obviously require lot more energy to cover the entire area than nodes in the middle. Ideally, an imaginary central point in the field can reach all nodes with a single transmission with the least amount of energy. Therefore, our approach to broadcasting is to find the central node that is closest to all other nodes. The amount of energy spent by this central node to reach all nodes in a single transmission will be the minimum required with our node distribution assumptions. A source that is not the central node needs to perform at least one transmission to reach this central node. For the purpose of calculating the lower bound, we consider each source to transmit to its nearest neighbor as the additional cost. After adding this neighbor transmission cost to the central node cost, we arrive at a lower bound for the average cost for broadcasting from any source.

In our broadcasting algorithm, a given source sends the message to the central node using a shortest energy cost path followed by a single transmission from the central node to reach all other nodes. We evaluated our algorithm for a number of different topologies with 100 nodes with two different field sizes. Table 1 presents the lower bounds for average energy cost and the average cost with our scheme for broadcasting in 8 different node distributions. The results show that our simple scheme performs well for broadcasting for dense ad hoc networks.

Table 1: Energy cost in joules for single source broadcasting in a 100-node network.

500m x 500 m Network		1 Km x 1 Km Network	
Lower Bound	Average Cost for Broadcast	Lower Bound	Average cost for Broadcast
.031775	.038065	.093371	.122304
.032356	.040316	.122039	.149361
.036393	.044276	.110955	.140033
.034949	.041814	.096166	.116801
.032216	.039401	.105239	.132063
.037728	.042586	.103744	.134718
.034954	.041490	.096913	.121043
.037424	.044087	.098260	.124449

3. Situation Awareness with Free Space Model

We now consider the all-to-all broadcast occurring in the situation awareness problem. In this section, we will use the free space model with a d^2 energy cost for transmissions. Our algorithm starts with an uniform initial energy in each node and performs all-to-all broadcasts repeatedly until nodes die. Each node has a message of length 60 bytes of which 40 bytes is the header and the other 20 bytes is the payload. We assume that any number of messages can be combined and can use a single header. Therefore, a combined message from the first 2 nodes in the chain will contain 80 bytes, and combined with the third node, the message will contain 100 bytes, etc. We also assume that the energy cost for simply concatenating is negligible compared to the communications. Our results will not be very different if we account for small energy costs for concatenation of messages. Our evaluation metric is the number of rounds completed before the 1st, 10th, 25th, and 50th node dies. In a simple algorithm, each node takes a turn broadcasting using direct transmission to reach all nodes. Alternatively, we can use the broadcast algorithm described in Section 2 for each node, however, the central node would die quickly since it is doing all the work. We now develop a cluster-based algorithm for all-to-all broadcasting and compare this to the direct approach.

Our algorithm uses a clustering method similar to the LEACH protocol described in [5]. To form *k* clusters, a randomization algorithm is used so that *k* nodes elect themselves as leaders. Each leader then transmits with a fixed high energy to reach all nodes. All nodes listen to these *k* broadcasts and determine which of these *k* leaders is closest to them, and join that cluster. Here the clusters are formed once before rounds of communication begin, and we will choose an optimal value for *k* as described later. We perform all-to-all broadcasting with the following steps in each round of communication:

1. Each node in a cluster transmits its data directly to a designated cluster head. The cluster head concatenates all data from the nodes in its cluster to form a single message.
2. Cluster heads broadcast this combined data with enough power to reach all nodes in the network.
3. After each round of all-to-all broadcasting, cluster heads rotate to a different node in each cluster and this process repeats.

Here, the time to perform an all-to-all broadcast is not critical, and so the transmissions in different clusters can be performed sequentially. Nodes go off when they are not transmitting or receiving to conserve energy. In this algorithm, significant energy savings are possible through concatenation of messages, thereby reducing the number of bits transmitted by the cluster heads.

To determine the optimal number of clusters in an *N* node network, let *k* be the number of clusters, and we assume for simplicity that all clusters have equal number of nodes. Each cluster has N/k nodes. Each of the *k* cluster heads gathers data in its cluster and concatenates the messages with a single header. All nodes transmit 60 bytes of data directly to their cluster heads. Cluster heads take turns gathering data in their clusters and broadcasting this gathered data to all other nodes in the network, including its own cluster. So, each node as a cluster head collects a total of (N/k*20+40) bytes and broadcasts in every N/k rounds. So the total bytes transmitted directly to all nodes in *N* rounds is $k(N/k*20+40)$, which is equal to $20N+40k$ bytes. When a node is not a cluster head, it performs local transmissions within its cluster. Each node transmits a total of $60*(N-k)$ bytes in *N* rounds locally. Therefore, for our 100 node network, the total energy cost is to transmit $2000+40k$ bytes to cover the entire area plus $60*(N-k)$ bytes to cover the local cluster area. Local cluster area is D^2/k where D^2 is the total area of the playing field. The total energy is proportional to $(2000+40k)*D^2 + 60*D^2 /k*N - 60*D^2 /k *k$. Minimizing this energy cost with respect to k, we get $k^2 = 60N/40$ which gives $k = (6N)^{1/2}/2$. With our parameters and for N=100, the optimal number of clusters is 12.

We conducted extensive simulations to compare our results with the direct approach where nodes directly broadcast with enough power to reach all nodes in the network. We measure the number of rounds before 1%, 10%, 25%, and 50% of the nodes die for a 500mx 500m network and a 1000m x 1000m network. One round of communication is defined as every cluster head collecting data from the nodes in their clusters, the cluster heads taking turns broadcasting this gathered data to all other nodes in the network, and every node receiving all other nodes' data.

Table 2 shows that our scheme achieves approximately 100% more rounds than the direct approach for a 500m x 500m network (the shaded portion), and it also shows approximately between a 100% and 300% improvement for the 1000m x 1000m network. The initial energy level for all nodes is 2.0J. We have taken 8 100-node random networks (as shown in Figure 1) and averaged the results for both direct and the clustering approach.

Table 2. Situation awareness using all-to-all broadcast for free space model with 2.0J initial energy in each node.

Network Area	Protocol	1st node	10th node	25th node	50th node
500m x 500m Network	Direct	85	101	116	134
	Clusters	153	230	293	367
1Km x 1Km Network	Direct	24	28	33	38
	Clusters	37	58	82	110

4. Situation Awareness with Urban Model

In this section we will develop a scheme for all-to-all broadcasting in an urban scenario with a d^4 energy cost for transmissions. This model is justified in that in a noisy environment, it may take a lot more energy to successfully transmit to all nodes. We present a scheme where each node transmits only to a neighbor at short range. To perform all-to-all broadcasting, we construct a chain among all nodes in the network with each node communicating only with a neighboring node at a short distance. With our uniform distribution of nodes in the playing field, such a chain can be constructed.

We construct this chain starting from some node, say the least numbered node, and picking the next node on the chain as one of its neighbors. To ensure all nodes find a close neighbor, we use a threshold T and one step look ahead while selecting the successive nodes on the chain. If necessary, we perform backtracking to ensure that all nodes find a neighbor within this threshold value T. In our experiments, we choose a value of 200m for T, thus ensuring that all nodes transmit at a relatively short distance. This threshold value needs to be set depending on the number of nodes and the size of the field. This chain is constructed only once before rounds of communication begin. We perform all-to-all broadcasting using this chain, which is explained below.

Data transmission starts at one end of the chain and moves toward the other end of the chain. In each step, data received by a node is concatenated with its own data and forwarded to the next node. When the end of the chain is reached, transmission starts from that end back to the beginning node. In a given round, to accomplish the bi-directional data movements, we can use a simple control token passing approach, where a node with the token transmits data as shown in Figure 3. In pass 1, node 0 initiates the token, and in pass 2, node 4 initiates the token. The additional energy cost for transmitting the token is negligible since the token size is very small.

c0→c1→c2→ c3→c4
a. Pass 1.

c0←c1←c2←c3←c4
b. Pass 2.

Figure 3. Token passing approach and data transmission.

In our algorithm, node c0 passes its 60 bytes of data to node c1. Then node c1 concatenates its data with node c0's message, and sends this 80 bytes message to node c2. Since the header size is 40 bytes, we only have 20 bytes of new data. When node c2 receives data from node c1, it will forward 100 bytes of data to node c3, and so on until the data reaches the other end of the chain, which is node c4 in Figure 3. Once node c4 receives data, it has data from all other nodes. Now, node c4 starts over with its own 60 bytes of data and sends it to node c3. Then node c3 concatenates its data, and transmits 80 bytes to node c2.

This process repeats until node 0 receives the data from node 1. Now every node has received data from all nodes in the network. All nodes transmit the same number of bits except for the end nodes, since the end nodes only transmit their own data. This helps spread the work load among the nodes to ensure a longer network lifetime, and nodes die at random places, which make the ad hoc network robust to failures. If a node's neighbor dies, then that node simply skips over the dead node and transmits to the next alive neighbor in the chain. Some slight improvements can be achieved if we can construct a loop among all the nodes so that data can be forwarded in only one direction. However, constructing a loop in an arbitrary network is hard problem as it is related to the traveling salesman problem.

With our scheme, the number of rounds before the 1st, 10th, 25th and 50th node dies is significantly improved as all nodes consume much less energy in each round. We conducted simulations with different network topologies and compared the performance of all-to-all broadcasting with the direct approach. Table 3 summarizes the results from our experiments for a 500m x 500m and a 1000m x 1000m network. The results show that multiple retransmits over shorter distances are much more energy efficient than using more power to reach all nodes directly. We use an initial energy level of 500,000J in each node so that the overhead cost is a small percentage of the data transmissions. Typical laptops can use this much energy and operate for one hour. Our scheme shows between a 200% and 300% improvement over the direct approach. Our scheme shows an even bigger improvement when the 10th, 25th, and 50th node dies. This is because as nodes die, there is less data that nodes need to transmit to their neighbors, whereas in the direct scheme every node is still transmitting the same packet length. Also, distances between neighbors are still small compared to that of the direct approach.

Table 3. Situation awareness using all-to-all broadcasting for an urban model with 500,000J initial energy in each node.

Network Area	Protocol	1st node	10th node	25th node	50th node
500m x 500m Network	Direct	64	81	110	165
	Chain-based	149	304	730	1769
1Km x 1Km Network	Direct	4	5	7	13
	Chain-based	12	31	71	162

5. Conclusions and Future Work

In this paper, we presented energy efficient algorithms for one-to-all and all-to-all broadcasting in ad hoc and sensor networks. We established a lower bound and showed that a simple source-to-all broadcast performs well with the average cost within 25% from this lower bound. The all-to-all broadcast is useful in the situation awareness application. For the all-to-all broadcast communication, we developed a cluster-based scheme for the free space energy cost model and a chain based algorithm for the noisy urban model. For all-to-all broadcasting, the clustering solution achieves approximately 100% more rounds than the direct approach when 1%, 10%, 25%, and 50% nodes die for a 500m x 500m network, and it achieves approximately a 300% improvement for a 1000m x 1000m network. With the free space model, it is more energy efficient to have only a few nodes broadcast directly to all other nodes. This is achieved when an optimal number of clusters are used. For the urban model, the chain-based algorithm achieves between 200% and 300% more rounds than the direct approach before the first node dies for a 500m x 500m and a 1000m x 1000m network. In our future work, we will develop near optimal algorithms for these and other collective communication problems in wireless ad hoc networks.

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