Energy Efficient All-to-all Broadcasting for Situation Awareness in Wireless Ad hoc Networks*

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Abstract

Ad hoc wireless networks have nodes with limited battery power and energy efficient communications are critical in such networks. In this paper, we consider energy efficient one-to-all and all-to-all broadcast operations in ad hoc networks. It is assumed that nodes have power control, and therefore, can adjust the range of their transmissions. Given a network of N nodes in a playing field of size D x D, we first establish a lower bound and then present a simple scheme for one-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 small fields of size 500m x 500m and 1000m x 1000m. 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 only short distances. Our schemes for situation awareness significantly improve the life of the network compared to a scheme with direct transmissions.

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1. Introduction

With the recent growth in wireless networks and small portable computing devices, there is tremendous interest in the development of protocols and network services for ad hoc networks. Ad hoc networks are multi-hop wireless networks where all nodes cooperatively maintain network connectivity. These types of networks are useful in any situation where temporary network connectivity is needed, such as in the battlefield and in disaster relief. In such a multi-hop wireless network, every node may be required to perform routing in order to achieve end-to-end communication among nodes. 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 [8,10,16]. 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 [15,18]. There is significant amount of energy consumption when a node transmits or receives data through its radio channel [5], and therefore, energy efficiency is critical in performing multi-point communications in these networks [3].

With the availability of inexpensive wireless nodes and devices, there has been a lot of interest in the design of power aware and energy conserving protocols for ad hoc networks [1,5-7]. Power aware channel access, routing, and broadcasting in ad hoc networks are presented in [2,12-15]. Recently, the problem of broadcasting from a given source to all other nodes in a network, with power control was presented in [17]. The approach taken in [17] 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.

In this paper, we consider one-to-all and all-to-all broadcast operations in ad hoc networks where nodes have power control. In the one-to-all broadcast, we are interested in reducing the energy cost for a 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 of size $D \times D$. Figure 1 shows a 100-node network in a playing field of size

500m x 500m. The wireless nodes are homogeneous and have enough power to reach nodes at any distance in this playing field with a single transmission. If nodes are not within transmission range of each other, then alternative, possibly multi-hop transmission paths will have to be used.

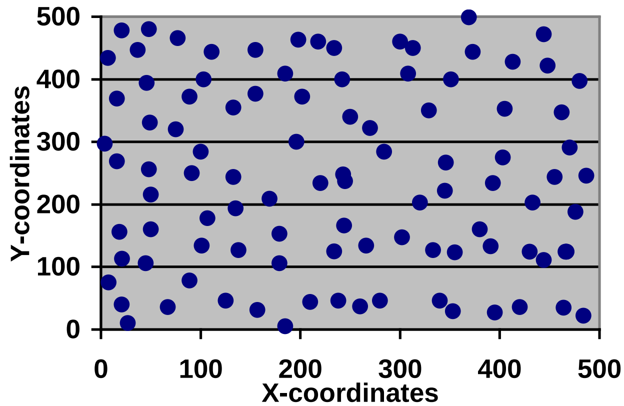

Figure 1. A 100-node network in a 500m x 500m field.

We assume that nodes are not mobile and that every node has location information of every other node in the network, e.g., using GPS. However, if locations of nodes are unknown, nodes could experiment with the power needed to reach the appropriate destination(s). Alternatively, there are techniques to determine the relative distances between nodes without GPS [9]. This would be an increase in energy consumption, but only in the initial stages. Mobility can be handled by keeping track of locations of nodes through suitable location update algorithms. In this paper, for one-to-all broadcasting we show that a shortest energy cost path from the source node to some central node, followed by a direct broadcast from that central node to reach all other in the field nodes performs quite 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 [4]. A situation awareness scenario is illustrated in Figure 2, where each node represents a soldier and the presence and position information of each soldier needs to be broadcast to all others periodically. We will develop energy efficient solutions to this situation awareness problem, where each node in the network is required to transmit a short packet, about 60 bytes, to all other nodes periodically [4]. 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.

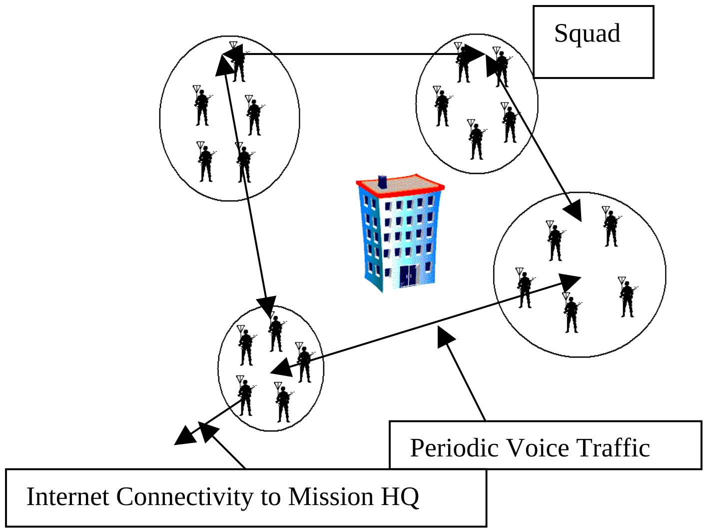

Figure 2. Situation Awareness- Crisis Management: Squads surround building to handle a terrorist activity

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 [11]. For both these models, we give energy efficient solutions for all-to-all broadcast operation needed in situation awareness problem to maximize the life of the network. We start with a uniform initial amount of energy in each node, and our goal is to maximize the time before any 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 operation.

A simple approach to accomplish this all-to-all broadcast communication is for each node to transmit its data with enough power to reach all nodes in the network using a single transmission. With this approach, nodes that are far from other nodes spend more energy per round in 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 [6] by forming clusters of nodes, combining messages in each cluster, and then broadcasting from cluster heads to 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 for larger distances. For this case, the clustering approach described above will not be applicable as the cluster heads cannot reach 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, the radio model for energy calculations is discussed. In Section 3, a simple algorithm to perform broadcast operation from a given source to all nodes in the network is presented. It is shown that the average energy cost for broadcasting is within a reasonable percentage from the lower bound. In Section 4, the details of our clustering approach for all-to-all broadcast communication is described. In Section 5, the details of our chain based algorithm for all-to-all broadcasting suitable for noisy environments are presented. Finally, some concluding remarks are given in Section 6.

2. Radio Model for Energy Calculations

Energy consumed in radio transmissions depends on several factors including the number of bits sent, the range of transmission, and the losses in the environment [11]. The ratio of signal strength to the noise level at a receiver must be above a certain threshold for reliable detection.

There are two primary components of the energy cost for communication between a pair of wireless nodes: a fixed component of energy consumed in electronic circuits when transmitting or receiving a packet, and a variable component when transmitting a packet, that depends on the distance of transmission. In general, this variable part for transmitting to a distance d is proportional to d^n, where the exponent n is in the range of 2 to 4 [11]. Therefore to conserve energy, fewer bits need to be communicated (data fusion or combining messages helps) and shorter distances should be chosen whenever advantageous.

Most commercial wireless nodes have a range of a few hundred meters and consume a few watts of power for transmitting and receiving packets. Some amount of power is lost even when a node is in idle mode. Detailed energy cost measurements of widely used WaveLAN network interface card can be found in [5] which shows that the power consumed in transmitting and receiving packets in standard WaveLAN cards range from 800 mW to 1200 mW. This paper [5] also shows that the fixed cost involved in processing overhead is significant. A recent paper [7] surveys various energy efficient network protocols for wireless networks and discusses detailed energy costs for various aspects of communication protocols. This paper also reports that the power costs in RangeLAN2 and WaveLAN cards are significant and ranges from 0.75W to 1.5W. There is considerable power consumption even in standby mode.

For energy cost calculations, we use the radio model discussed in [6] 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. With these radio parameters, when k=2000 and d^2 is 500, the energy spent in the amplifier part equals the energy spent in the electronics part, and therefore, the cost for transmission of a packet will be twice the cost for reception. These numerical constants depend on the electronics circuitry design and we can expect these to go down with increasingly low power designs becoming available. Thus the receiving energy spent in the electronics depends only on the message length, where as transmitting a message has a fixed cost that depends on the length of message, and a variable cost that depends on the distance of transmission. The radios can exercise power control to expend the minimum required energy to reach the intended recipients. The radios can also be turned off to avoid receiving unintended transmissions. 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 data is also a high cost operation, therefore, the number of receives and transmissions should be minimal to reduce the overall energy cost of an application. 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.

3. Single Source Broadcast in Ad hoc Networks

In this section, we consider the problem of a single source broadcasting a message to all other nodes in a network. We assume that the *N* nodes of ad hoc network are uniformly distributed in an area *D x D* and that all nodes have power control. The energy cost model used in [17] ignores the fixed electronics cost in the digital part and uses only the 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 with the currently available nodes, and therefore, it will be more efficient to use fewer transmissions to cover a given area. Of course, with a given radio one can determine a threshold as in [6] beyond which it is more efficient to use higher power to reach longer range. If the fixed costs are significant, as in currently available radios, an ideal solution for broadcasting is to just use one transmission to exactly cover the entire area of the network. Since nodes have power control, the source node can increase its power to directly broadcast to all nodes instead of using multiple hops. With radiation in all directions, it is usually not 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-dimensionall area. For the broadcast operation, since all nodes must receive the message and there is a cost for receiving data by the *N* nodes with any algorithm. 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 one-to-all broadcasting is a single transmission from some imaginary central point 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 then given by $N * E_{elec} * k + \in_{amp} * k * a^2$ where k is the size of broadcast message.

This lower bound is not tight as 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 this additional cost instead of the cost to the central node. 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 in dense ad hoc networks.

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

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

Slightly improved results for one-to-all broadcasting may be achieved by using few additional steps. The goal is to cover only the areas where the nodes are located and better solutions can be found only when the node distribution is known. The proposed solution performs well with uniform distribution of nodes in the field.

4. 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 1^{st}, 10^{th}, 25^{th}, and 50^{th} 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 3 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 [6]. 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.

Network Area	Protocol	1^{st} node	10^{th} node	25^{th} node	50^{th} 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

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

5. 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.

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

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

6. 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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