# Power-Aware Broadcasting in Mobile Ad Hoc Networks*

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May 28, 1999

## Abstract

In this paper we present a power-aware broadcasting algorithm reduces the cost/broadcast of routing packets to all destinations by 5-50% over a broadcast tree constructed using a greedy strategy based on network topology information only (this cost reduction is on top of a 40-70% reduction in energy consumption obtained by using PAMAS, our MAC layer protocol). We also show that the maximum node cost after many broadcasts is reduced by 20-150% with the power-aware algorithm compared to the non-power-aware algorithm, thereby increasing the life of the network significantly. For comparison purposes, we also ran simulations with the flooding algorithm for broadcasting which performs worse by a factor of 10 compared to the power-aware algorithm.

## 1 Introduction

Ad hoc wireless networks are multi-hop wireless networks where all nodes cooperatively maintain network connectivity. Ad hoc networks use nodes that communicate with radios which are battery operated, they need to be energy conserving so that battery life is maximized. Significant energy is consumed when a node transmits or receives data through its radio channel. We have been developing strategies for reducing the energy consumption of the communication protocols to enhance the life of nodes and increasing the life of an ad hoc network. Recent studies have stressed the need for designing protocols to ensure longer battery life [6, 12]. The DEC Roamabout radio [1] consumes approximately 5.76 watts during transmission, 2.88 watts during reception and 0.35 watts when idle. Thus, in most commercial radios, typically energy consumed in transmitting is roughly twice the amount of energy consumed in receiving a packet.

In an ad hoc network, since the radio channel is shared by all neighboring nodes, it becomes necessary to control access to the shared media within a hop. Recently, for channel access, we developed a power aware protocol called PAMAS which saves significant power by turning off radios that do not participate in a communication. That is, when a node transmits data to a specific neighbor, all other neighbors of the transmitting node will turn themselves off for the duration of this transmission to save power. The PAMAS protocol uses a separate control channel to explicitly request channel access and obtains grants through RTS/CTS signaling mechanism. We have shown that the PAMAS protocol operates in a power efficient manner in multi-hop wireless networks.

The problem studied in this paper is broadcasting data from a source to all nodes in an ad hoc wireless network. Each node can broadcast a packet to all its immediate neighbors with a single transmission. In broadcasting a packet, each node must receive a packet only once and designated intermediate nodes will be required to retransmit received packets. The key idea in conserving energy is to let the radios turn themselves off when a node is not transmitting or receiving a packet. There is plenty of opportunity to conserve energy during a broadcast as radios can turn themselves off if they have received a packet once already. In order to ensure long life for the network, intermediate nodes for retransmitting a packet need to be chosen carefully. This paper evaluates via simulation a *power-aware* broadcast algorithm that performs significantly better than a broadcast scheme that uses just the topology information.

The broadcast algorithms for ad hoc networks will be developed on top of the PAMAS protocol and additional power savings can be achieved at the network level. In this paper we comparatively study two different broadcast algorithms – non power-aware and power-aware. Through extensive simulations, we show improvements of 20% or better for average cost/broadcast with power-aware broadcasting in ad hoc networks with 20 or more nodes. We associate a

*This research was supported by NSF grant NCR-9706080.

cost with each node which increases as the node consumes more power. The power aware broadcasting algorithms tries to minimize the maximum node cost after operating for a while as well as improve the cost per broadcast. We show improvement of 20-150% for maximum node cost implying significant increase in life time for ad hoc networks with our power-aware scheme.

## 2 Power-Aware Broadcasting

The simplest algorithm to broadcast a packet in an ad hoc network is via flooding. This simple technique does not require gathering any global topology information and thus requires little control overhead. The flooding scheme will complete broadcast with minimum hops, however, it will have many intermediate nodes retransmitting packets leading to excessive consumption of energy. As we have shown in our recent paper on power-aware routing, it is important to optimize for the frequent case rather than the infrequent case. In this context, this translates to it is worth spending some energy in topology gathering to determine the best broadcast tree to use for data packets.

Our key intuition in this paper is that conserving power and carefully sharing the cost of routing broadcast packets will ensure that node and network life are increased. In order to conserve power, each node's transmission must reach as many new nodes as possible. We can use a scheme where a broadcast tree is constructed starting from a source and expanding with a neighbor with highest outgoing degree. This is a greedy strategy and increases the number of nodes reached via broadcast aggressively in each step. This scheme will only use the topology information and we will call this scheme *non-power-aware*. By considering the remaining battery power of the nodes, we can construct broadcast trees by expanding nodes that will increase the size of the tree with minimum node cost. This is accomplished by expanding along a node whose cost per degree is lowest. This latter scheme we call *power-aware* scheme. We would like to compare these schemes via simulations assuming that each node only has broadcast traffic.

For each source we will construct a broadcast tree with the source as the root node. Among its immediate neighbor, one node is selected as an intermediate transmitter if it has the highest number of unseen neighbors. When constructing a tree, at each step, among all the leaf nodes we select that node as intermediate node which has the highest number of unseen nodes of the network. Ties are broken arbitrarily. Thus, we can see that this is a step-wise greedy strategy aiming to increase the number of nodes visited in each step as much as possible. We can expect this to result in a tree with small number of intermediate transmitters. However, this algorithm uses only network topology information and ignores the remaining battery power in the nodes.

Alternatively, we can develop a similar algorithm that takes into account cost of visited nodes in constructing the tree. Here also we will start building a broadcast tree from the source. A node's cost increases as it transmits or receives packets, implying that it is more expensive to retransmit broadcast packets through nodes with higher accumulated cost. As before, at each step of building the broadcast tree, we look at each of the leaf nodes and determine how many unseen neighbors each node has. We will use the current value of node cost divided by its unseen neighbors as the cost of growing the tree and select a node with the minimum value as the intermediate node to expand the tree. This is identical to the non-power-aware algorithm if all the node costs remain the same. Since node costs continuously change, for the power-aware algorithm, we will have to compute broadcast tree for each packet. Broadcast packets belonging to the same source may traverse different trees as they are determined based on current costs of nodes. In this algorithm that uses the metric to minimize cost/packet, we associate node costs with a function $f_i$, that is either linear or quadratic, with each node and compute the broadcast trees.

## 3 Overview of PAMAS (*Power-Aware Multiple Access protocol with Signalling*)

In this section we briefly describe our MAC layer protocol for ad hoc networks [7, 8]. We use this protocol as the MAC protocol in our simulator as well. **Thus, the energy savings reported in section 4 are savings that are obtained *on top of* the considerable savings due to PAMAS**. The PAMAS protocol saves 40-70% of battery power by intelligently turning off radios when they cannot transmit or cannot receive packets. The specific conditions under with nodes power off in PAMAS are:

- A node powers off if it is overhearing a transmission and does not have a packet to transmit,
- If at least one neighbor is transmitting and at least one neighbor is receiving a transmission, a node may power off. This is because, even if the node has a packet to transmit, it cannot do so for fear of interfering with its neighbor's reception,
- If all of a node's neighbors neighbors are transmitting (and the node is not a receiver), it powers itself off.

In our PAMAS protocol, as in all other MAC layer protocols for ad hoc networks, nodes attempt to grab the channel by exchanging RTS/CTS (ready to send and clear to send) messages. Thus, the sender transmits a RTS message. The receiver responds with a CTS message if it received the RTS message uncorrupted. The sender begins transmission upon receiving the CTS. In PAMAS, this exchange of RTS/CTS messages takes place over a separate signalling channel[1]. Thus, this exchange does not affect a ny ongoing data transmissions. The RTS/CTS messages contain the length of the packet the sender will send. Thus, any other node in the neighborhood can determine the length of the transmission and power off if one of the above conditions is met. A problem arises in the case when a node that has powered itself off wakens to hear a new ongoing transmission. In this case, it needs to be able to estimate the length of the remaining transmission and power itself off (if one of the conditions above is met) again. We have a protocol that runs over the signalling channel that allows nodes to query transmitters about the length of the remaining transmission.

### 3.1 Support for Broadcasting

Broadcasting is often necessary in networks and, even though broadcasting is typically a network layer function, it is often necessary to provide MAC layer support. In PAMAS and other ad hoc network MAC layer protocols, a sequence of message exchanges (RTS-CTS) precedes transmission of a packet. This message exchange ensures that the receiver is ready to receive the transmission. However, if a node needs to broadcast a message to all its neighbors, using the RTS-CTS sequence is meaningless because all the neighbors are potential receivers of the broadcast. If they all respond with a CTS (or if some respond with a CTS and others with a Busy Tone), the transmitter will hear noise and will be unable to decide what to do.

The channel access scheme in PAMAS needs to be extended for handling broadcast packets. For this purpose, a node that is ready to transmit a broadcast packet must ensure that all its neighbor nodes are free to receive it. We briefly explain a simple way to support channel access for broadcast, although the detailed development of the channel access protocol for broadcasting is beyond the scope of this paper. One extension to PAMAS is that a node transmits a RTS_B message when it needs to transmit a broadcast. As in the basic PAMAS protocol, however, it transmits this message if no neighbor is transmitting or is scheduled to transmit. Upon hearing the RTS_B, a node receiving another transmission responds with a Busy Tone. Nodes that are free to receive the broadcast *do not respond*. If the transmitter does not hear any response, it transmits the broadcast message. If it hears a Busy Tone or noise, it refrains from transmitting. It waits for the ongoing transmission to end (i.e., it waits for a maximum packet transmission time in case it heard noise or for the length of time specified in the Busy Tone) and retries. When a node begins receiving the broadcast packet, it transmits a Busy Tone to warn other neighbors to refrain from transmitting.

There are some additional issues to be handled to ensure that this access protocol operates efficiently. For the purposes of this paper, we assume an idealized channel access scheme for the broadcast algorithms we wish to comparatively evaluate power savings in different broadcast algorithms, and therefore do not count costs for channel access in our simulations. This is acceptable as we are comparatively evaluating the effect of power-aware selection of broadcast trees.

[1] In PAMAS the receiver transmits a busy tone once it begins hearing the packet. This is done to combat a specific hidden-terminal problem.

## 4 Evaluation by Simulation of the Power-Aware Metrics

We conducted extensive simulations to better understand the properties of the new metrics and the effect of using these metrics on broadcast packet *delay*. Specifically, we compared the performance of *non-power-aware* algorithms as explained and with *power-aware* broadcasting and quantified the difference between these two approaches using three measures given below. cost, and average packet delay.

1. End-to-end broadcast packet delays (measured as the difference between time when a broadcast packet enters the system and the time when it finally reaches all nodes),

2. Average cost/broadcast, and

3. Average maximum node cost (computed after 2000 seconds of simulation time)

For the power-aware broadcast algorithm, we used several different $f_i$ functions. In this paper, however, we only present two of these models for $f_i$. The first model was a *linear* model where $f(x) = cx$ for some constant $c < 1$ and the second model was a *quadratic* model where $f(x) = cx^2$. The linear model is based on the discharge curve of alkaline batteries while the quadratic model represents the precipitous discharge in battery life for lithium-ion batteries.

For our simulation experiments, we used 20 and 30-node random graphs. The random graphs were generated as follows. For each pair of possible edges, we toss a coin that has a probability $p$ of coming up heads. If it does come up heads, we put that edge in otherwise we leave it out. We varied the value of $p$ from 0.2 to 0.5. Intuitively, $p = 0.2$ produces a sparse graph while $p = 0.5$ produces a dense graph. We only considered connected networks in this study and we did not include node mobility. The reason we did not account for mobility is because we were not actually simulating a broadcast protocol (whose performance would depend on the mobility model) but only evaluating different power-aware metrics.

Packets arrive at each node according to a Poisson process. The packet arrival rate $\lambda$ varies between 0.01 and 0.05 packets/sec/node. This rate represents light to moderately heavy traffic as each packet generates many retransmission packets along the tree. Only broadcast packets arrive at each node as we are interested in comparative evaluation of different broadcast algorithms. We also assumed an idealized channel access scheme and so did not explicitly include costs for control packets transmission and reception. Each node maintains a FIFO buffer of packets that need to be forwarded to the next hop. Every packet is timestamped when it first enters the system and then again when it completes the broadcast allowing us to compute delays. Further, node costs are updated constantly and when a packet is transmitted over one hop, we add the current node cost to the total cost of the packet. The packet costs are averaged out at the end of the simulation as are the node costs.

We ran each simulation 20 times and computed the mean and the standard deviation for each of the three metrics mentioned earlier (delay, cost/packet and average max node cost) for non-power-aware and power-aware broadcast algorithms. In the graphs we plot the *percentage improvement* in these metrics when we use power-aware broadcasting in comparison with the non-power-aware broadcast algorithm. We have not plotted the curves for delay because there was *not much difference in the average broadcast delay* between these schemes averaged over a long period of time. This result is not surprising because the non-power aware scheme can build up queues on nodes that have high degree and in both schemes, a packet must be received by all nodes. The total number of hops used to reach all nodes (tree height) will be almost the same for both schemes and the queuing delays dominate the broadcast packet delay. What we found was that at higher loads, the power-aware scheme completed more broadcasts in a given time $T$ as it gets around congested nodes and has more uniform queue lengths.

Let us now consider the relative improvement in the *cost/packet* and *max node cost* metrics when using these broadcast algorithms. We need to mention that both these broadcast protocols simulations were run on top of PAMAS in terms of turning the nodes off. That is, in both algorithms a broadcast packet is received by each node only once. Thus, the improvement we see is in addition to the improvement gained by PAMAS (which is significant). Let us first look at a 20-node random network. Figure 1 illustrates the percentage improvement in the cost/broadcast for different values of $p$ with linearly increasing function for node cost. Each curve represents a different value of $\lambda$. Figure 2 shows the same plot when we use a quadratic cost. We can see that the improvement is in the range 5-20% for the linear case and in the range 20-70% for the quadratic case. Figures 3 and 4 illustrate the same set of plots for 30-node random networks showing improvements in the range of 5-20% for the linear case and 10-60% for the quadratic case.

It is interesting to observe that the *savings are greater in larger networks*. This is not surprising because larger networks have more routes to choose from. A second observation we can make is that *savings increase with load*. This is because at very low loads, the cost differential between nodes is too small to matter. However as load increases, this cost differential increases and is reflected in cost savings per packet. Also, at higher loads, or with higher probability of edges, more number of broadcasts are completed in a given time. As the graphs show, savings are greater for the quadratic cost function than for the linear. This is because the cost differential between nodes increases sharply with a quadratic function.

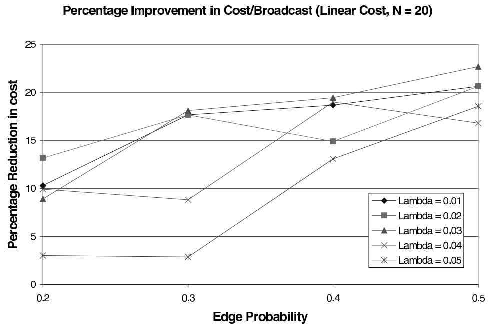


Figure 1: Percentage reduction in average cost/broadcast in 20-node networks with linear cost.

## 5 Conclusions

In this paper we discussed the need to make broadcast protocols power-aware. Thus, rather than building broadcast trees using traditional metrics such as tree height or only delay, we believe that it is more important to use cost/packet and maximum node cost (which are functions of remaining battery power) as metrics. Our simulations demonstrated that significant reductions in cost can be obtained by using power-aware broadcast algorithm as opposed to non-power-aware algorithm that uses only the node degree information. A

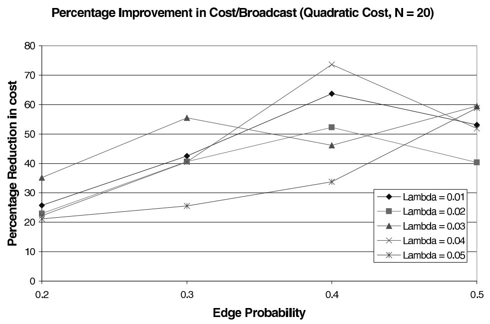


Figure 2: Percentage reduction in average cost/broadcast in 20-node networks with quadratic cost.

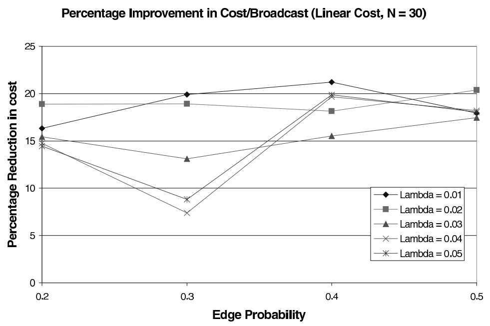


Figure 3: Percentage reduction in average cost/broadcast in 30-node networks with linear cost.

feature of our metrics is that they can be easily incorporated for use in existing broadcast protocols for ad hoc networks. In our future work, we will develop an efficient channel access protocol to support broadcast and multicast and evaluate power-aware metrics for multicasting in ad hoc networks.

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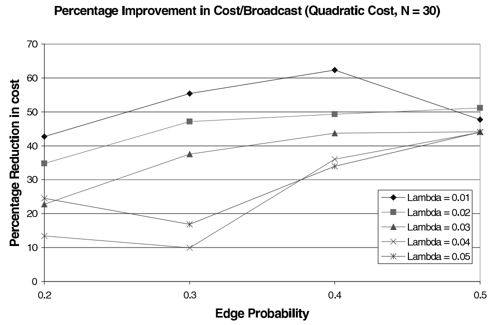


Figure 4: Percentage reduction in average cost/broadcast in 30-node networks with quadratic cost.


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