Power-Aware Broadcasting in Mobile Ad Hoc Networks*

Suresh Singh
Department of ECE
Oregon State University
Corvallis, OR 97331
e-mail: singh@ece.orst.edu

C. S. Raghavendra and James Stepanek
The Aerospace Corporation
P.O. Box 92957
El Segundo, CA 90245
email: raghu,stepanek@aero.org

Abstract

In this paper we present five different *power-aware metrics* based on battery power consumption at nodes for determining broadcast routes in wireless ad hoc networks. We show that using these metrics in 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. An interesting property of using power-aware broadcasting is that the average packet delays do not increase.

Technical Subject Area: Adaptive Traffic and Access Control Protocol, Radio Resource Management

Index Terms: Wireless Networks, Broadcasting, Battery Power, Radio Links

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

1 Introduction

Ad hoc wireless networks are multi-hop wireless networks where all nodes cooperatively maintain network connectivity. Ad hoc networks are useful in any situation where temporary network connectivity is needed without a backbone wired infrastructure. For instance, consider the problem of establishing a temporary wireless network in a region hit by some natural disaster. An ad hoc network here would enable medics in the field to retrieve patient history from hospital databases (assuming that one or more of the nodes of the ad hoc network are connected to the Internet) or allow insurance companies to file claims from the field. Building such ad hoc networks poses a significant technical challenge because of the many constraints imposed by the environment. Thus, the devices used in the field must be lightweight. Furthermore, since they are battery operated, they need to be energy conserving so that battery life is maximized. Several technologies are being developed to achieve these goals by targeting specific components of the computer and optimizing their energy consumption. For instance, low-power displays (see [12]), algorithms to reduce power consumption of disk drives (see [7, 17, 32]), low-power I/O devices such as cameras (see [5]), etc. all contribute to overall energy savings. Other related work includes the development of low-power CPUs (such as those used in laptops) and high-capacity batteries.

There is significant energy consumption 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. Thus, [18] observes that the average life of batteries in an *idle* cellular phone is one day. [30] studies power consumption of several commercial radios (WaveLAN, Metricom and IR) and observes that even in Sleep mode the power consumption ranged between 150-170 mW while in Idle state the power consumption went up by one order of magnitude. In transmit mode the power consumption typically doubled. 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. Since there is significant energy consumption when a node transmits or receives data, the radio channels have to be allocated to nodes carefully to achieve a power efficient broadcast protocol. 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. With this approach to turning radios off when not involved in a communication the remaining battery power in different nodes will vary with time. 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 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.

Our research has focussed on designing protocols that increase the life of nodes and the network. In order to produce a *complete solution*, we have attacked each layer (MAC, network and transport) individually. In our bottom-up approach, we optimize the energy consumption of the MAC layer first followed by the network layer and finally the transport layer. In [21] we present a MAC layer protocol for ad hoc networks that reduces energy consumption by 40% to 70% for different load and network conditions. An overview of this work is provided in section 3. In a recent paper [22], we explored the issue of increasing node and network life by using power-aware metrics for routing data. Intuitively, it is best to route packets through nodes that have sufficient remaining power (rather than through a node whose battery is on its last legs). Similarly, routing packets through lightly-loaded nodes is also energy-conserving because the energy expended in contention is minimized. We showed that power-aware routing (built on top of a power-aware MAC protocol) can save overall energy consumption in the network and, simultaneously, increase battery life at all nodes. **In this paper we study broadcasting by using power aware metrics and we assume in this study that all nodes have only broadcast traffic**.

The remainder of this paper is organized as follows. In the next section we discuss the problem of routing in multi-hop wireless networks and provide a survey of metrics used by current routing protocols. In section 2 we discuss *different metrics* that result in power-aware routing. Section 3 outlines our energy conserving MAC layer protocol for multi-hop wireless networks. Section 4 presents the results of our simulations where we demonstrate the use of new power-aware metrics. Finally, section 5 summarizes the main results and outlines our future research.

2 Metrics for Power-Aware Broadcasting

Broadcast operation is an important function in networks. It can be used for sending critical control information or topology update information to all nodes. 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.

We will consider an n-node ad hoc network connected topology to investigate power-aware metrics suitable for broadcasting. For the study in this paper we assume that only broadcast packets arrive at each node with some distribution and these packets must be received by all other nodes. So, a broadcast packet will be transmitted first by the source which will be heard by all its immediate neighbors. One or more of these neighbors will retransmit and this procedure continues until all nodes receive that packet. So, a broadcast packet will flow along a tree in the network. We can construct a broadcast tree starting with the source as the root and spanning all the nodes in the network. Since our interest is in minimizing power consumed we will have different broadcast trees for different source nodes.

We present several power-aware metrics that do result in energy-efficient broadcasting.

1. *Minimize Energy consumed/broadcast:* This is one of the most obvious metrics that reflects our intuition about conserving energy. Assume that some broadcast packet j traverses nodes $n_1, \ldots, n_k$ where n_1 is the source and $n_2, \ldots, n_k$ are the intermediate nodes that retransmit this packet. Let $T(a)$ denote the energy consumed by a node a in transmitting one packet. Since all nodes must receive this packet, as this is a broadcast, we will not consider the energy to receive packet in this metric. Then the energy consumed by all the transmitters for packet j is,

$$e_j = \sum_{i=1}^{k} T(n_i)$$

Thus, the goal of this metric is to,

$$\text{Minimize } e_j, \forall \text{ broadcast packets } j \tag{1}$$

Discussion: This metric requires that we choose intermediate transmitters such that the energy consumed for that packet is minimized. It is easy to see that this metric will minimize the average energy consumed per broadcast packet. However, it is not easy to achieve this metric as it is difficult to select the appropriate broadcast trees to achieve this goal. One serious drawback of this metric is that nodes will tend to have widely differing energy consumption profiles which could result in early death for some nodes.

2. *Maximize Time to Network Partition:* In our context of broadcast, as soon as the first node dies the network is said to be partitioned. This metric is very important in mission critical applications such as battlesite networks. Unfortunately, optimizing this metric is very difficult if we need to simultaneously maintain low delay and high throughput.

   Discussion: For this metric, we need to select the various broadcast trees in such a way that the energy of nodes are depleted uniformly. Given a network, we can determine one or more nodes that are critical meaning that they will be used in more number of broadcast trees than other nodes. These critical nodes will be prime candidate nodes that can cause partition. A broadcast procedure therefore must divide the work going through these critical nodes to to maximize the life of the network. This problem is similar to the "load balancing" problem where tasks need to be sent to one of the many servers available so that the response time is minimized – this is known to be an NP-complete problem.

3. *Minimize Variance in node power levels:* The intuition behind this metric is that all nodes in the network are equally important and no one node must be penalized more than any of the others. This metric ensures that all the nodes in the network remain up and running together for as long as possible. Therefore, the goal will be to minimize the maximum node cost (optimize the worst case power depletion).

   Discussion: For this metric we will have to choose the broadcast trees to achieve a global balance of work done by the nodes. This problem is similar to "load sharing" in distributed systems where the objective is to minimize response time while keeping the amount of unfinished work in all nodes the same. Achieving this optimally is known to be intractable due to unknown execution times of future arrivals. A scheme that can be used to achieve the stated goal reasonably well is a policy called Join the Shortest Queue (JSQ). We can adopt such an idea by using a broadcast procedure where each node sends traffic through a neighbor with the least amount of data waiting to be transmitted. We can improve this further by doing some lookups of waiting traffic few hops away to decide the next best hop. A broadcast tree construction algorithm could be developed that looks at the queue lengths of various nodes in finding the appropriate tree.

4. *Minimize Cost/Packet:* If our goal is to maximize the life of all nodes in the network, then metrics other than energy consumed/packet need to be used. The paths selected when using these metrics should be such that nodes with depleted energy reserves do not become intermediate nodes on many broadcast trees. Let $f_i(x_i)$ be a function that denotes the *node cost or weight* of node i. x_i represents the total energy expended by node i thus far. We define the total cost of sending a packet along a broadcast tree as the sum of the node weights of all nodes that are transmitters on that tree. The cost of sending a packet j from source n_1 to all nodes via intermediate nodes $n_2, \ldots, n_k$ is,

$$c_j = \sum_{i=1}^{k} f_i(x_i)$$

   The goal of this metric is to,

$$\text{Minimize } c_j, \forall \text{ packets } j \tag{2}$$

Discussion: Intuitively, f_i denotes a *node's reluctance to forward packets* and we can see that with an appropriately chosen f_i, we can achieve different goals. Thus, if f_i is a monotone increasing function, then nodes that can lie on many trees will not be over used thus increasing their life. However, it is likely that the delay and the energy consumed/packet may be greater for some packets. f_i can also be tailored to accurately reflect a battery's remaining lifetime. Many batteries display a discharge curve which decrease faster than linearly with increased use. So, we can consider two reasonable f_i's, linear and quadratic, in determining the cost to forward a packet through a node.

We can summarize some of the benefits of this metric as:

- It is possible to incorporate the battery characteristics directly into the broadcast protocol,
- As a side-effect, we increase time to network partition and reduce variation in node costs (though we do not optimize these metrics), and
- Effects of network congestion are incorporated into this metric (as an increase in node cost due to contention). This can improve the average delay/broadcast.

5. *Minimize Maximum Node Cost:* Let $C_i(t)$ denote the cost of transmitting a packet through node i at time t. Define $\hat{C}(t)$ denote the maximum of the $C_i(t)$s. Then,

$$\text{Minimize } \hat{C}(t), \forall t > 0 \tag{3}$$

metric minimizes maximum node cost. An alternative definition is to minimize the maximum node cost *after completing N broadcast packets in the network or after T seconds.* All of these variations ensure that node failure is delayed and a side effect is that the variance in node power levels is also reduced. Unfortunately, we see no way of implementing this metric directly in a broadcast protocol but minimizing cost/node does significantly reduce the maximum node cost (and hence time to first node failure).

The five metrics discussed above do, in different ways, express our intuition about conserving energy in the network by selecting broadcast trees carefully. However, what *protocols* best implement these metrics? It is easy to see that any algorithm that finds broadcast trees based on the first and fourth metrics discussed above will perform well. To implement the first metric, we simply associate a node weight with each node in the network based on the degree of this node in the network topology. The idea is that if a node has more neighbors, it can retransmit a packet to a larger group of nodes, thus reducing the energy. We will find the broadcast trees using node weights based on node degree to reduce the cost of finding the intermediate nodes. Therefore, with this approach, the broadcast tree for each source need only be computed once. This is our non-power-aware broadcast tree algorithm which we will comparatively evaluate with the power-aware broadcast algorithm.

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 f_i, that is either linear or quadratic, with each node and compute the broadcast trees. We have not yet implemented the other three metrics but we have determined that they are optimized somewhat by the metric (cost/packet) if we select f_i's carefully.

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

In this section we provide an overview of our MAC layer protocol for ad hoc networks. 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.

A fundamental problem that arises when nodes power themselves off is, *for how long can a node remain powered off*? In the optimal case, a node powers itself off exactly when one of the conditions above holds true. However, in actual implementation, a node needs to estimate this length of time (keep in mind that a node cannot sense carrier when it is powered off so it has no way of knowing when a transmission in its neighborhood has completed). In our 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 any 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. Collisions during this enquiry (which are likely in high-degree networks since several nodes may power off as a consequence of a transmission and may waken simultaneously) are handled with a modified binary backoff algorithm. This algorithm can be tuned so that overhead of the algorithm is traded off against accuracy in the estimate of the length of the remaining transmission.

Figure 1 illustrates the power savings obtained (as a percentage) when using PAMAS. The network used is a 20-node random network. The x-axis denotes the edge probability. Different curves indicate power savings for different network loads. Note that at high loads the power savings are smaller because a large amount of power is consumed in contention. The savings, however, increase with increasing node connectivity since a node has more opportunities to power-off. The PAMAS protocol is non-trivial and we cannot explain its operation in any detail here. However we would like to point out that in PAMAS the *delay* and *throughput* are not changed even when nodes power off. This is because the conditions under which nodes power off are such that the node powering off cannot transmit or receive packets anyway. A detailed discussion of PAMAS is provided in [20]. We have derived bounds on the maximum achievable power savings in [21].

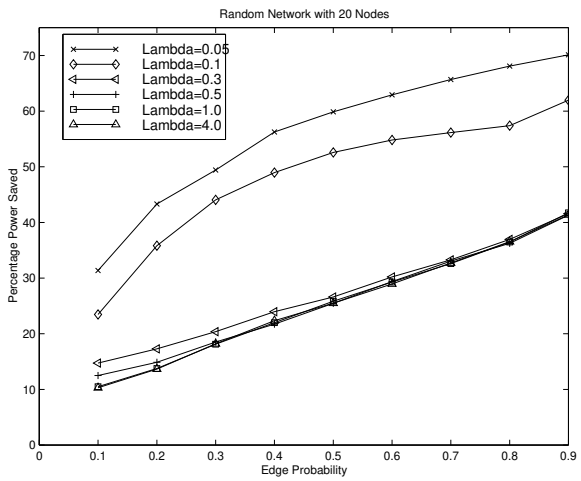

Figure 1: Power saved in random networks with 20 nodes.

[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.

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.

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 λ 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 2 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 λ. Figure 3 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 4 and 5 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.

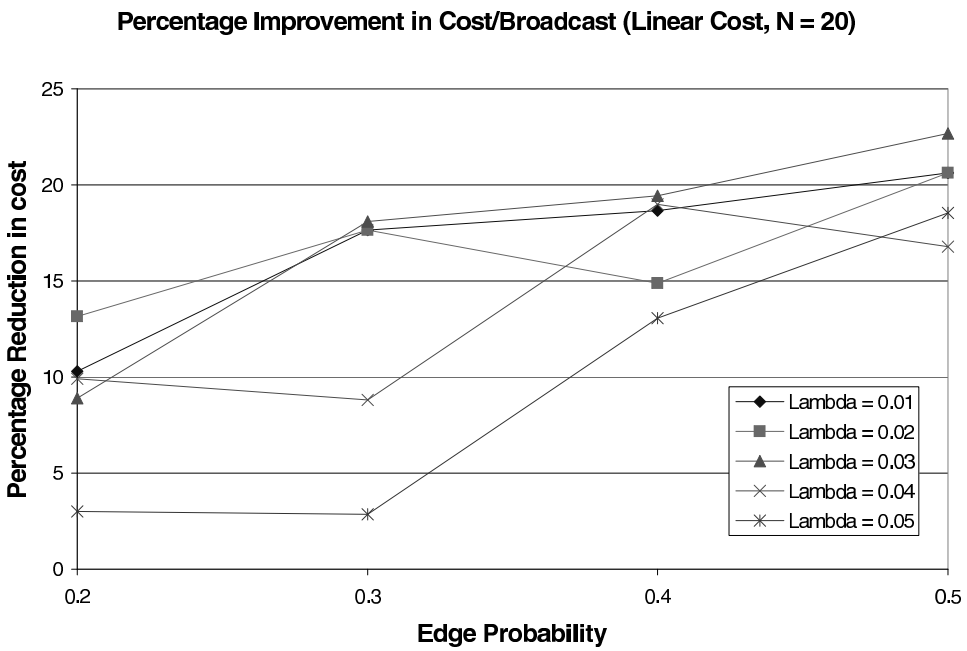

Figure 2: Percentage reduction in average cost/broadcast in 20-node networks with linear cost.

We plot the reduction in maximum node costs for 20-node random networks in Figures 6 and 7 and for 30-node random networks in Figures 8 and 9. In 20-node networks, there is a 5-50% reduction in maximum node cost for the linear cost case and a dramatic 10-140% for the quadratic cost case. These numbers become 20-50% for the linear case and 50-150% for the quadratic case when we have 30-node networks. The reasons for this dramatic increase in savings in larger networks is because of the availability of more routes. Likewise, the savings increase in denser networks and they increase with λ. All for the same reasons as discussed previously.

4.1 Summary of Results

Based on the simulations, we can conclude that using power-aware metrics to find broadcast trees is very beneficial because the difference in battery consumption between various nodes is reduced. This typically means longer network life and longer time to node failure. The specific conclusions from the experiments are:

1. Larger networks have higher cost savings,

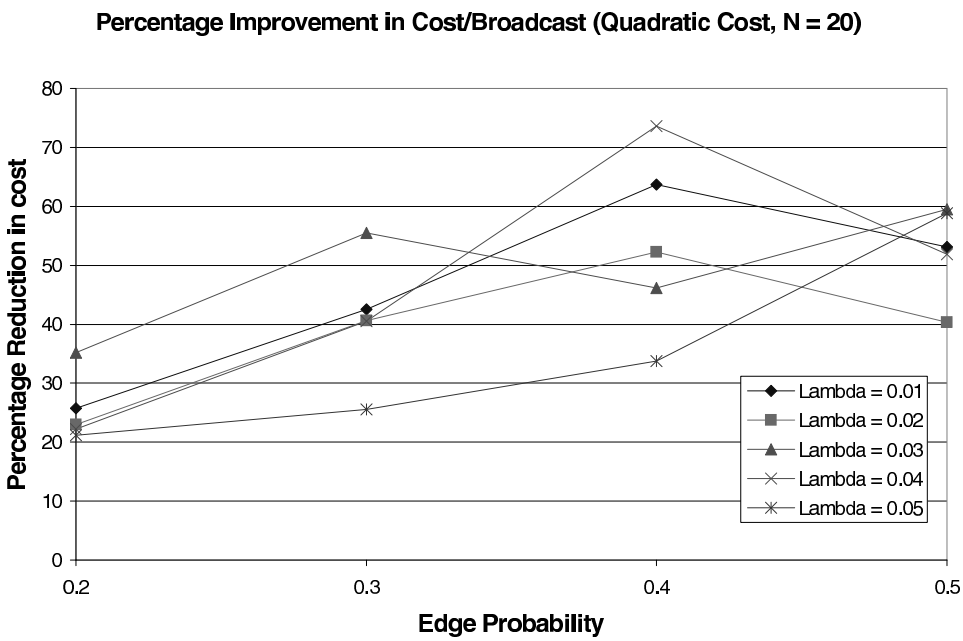

Figure 3: Percentage reduction in average cost/broadcast in 20-node networks with quadratic cost.

2. Cost savings are best at moderate network loads and negligible at very low or at very high loads,

3. Denser networks exhibit more cost savings in general, and

4. The cost function used dramatically affects the amount of cost savings.

It is worth pointing out that our results will hold true in networks where nodes are mobile. This is because nodes in real networks do not move randomly independently. Rather, clusters of nodes move in correlated ways (image a platoon of soldiers). If, however, nodes do move randomly independently, then we believe that there will be small, if any, cost savings obtainable by using power-aware metrics (note, however, that PAMAS will still deliver huge savings).

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 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.

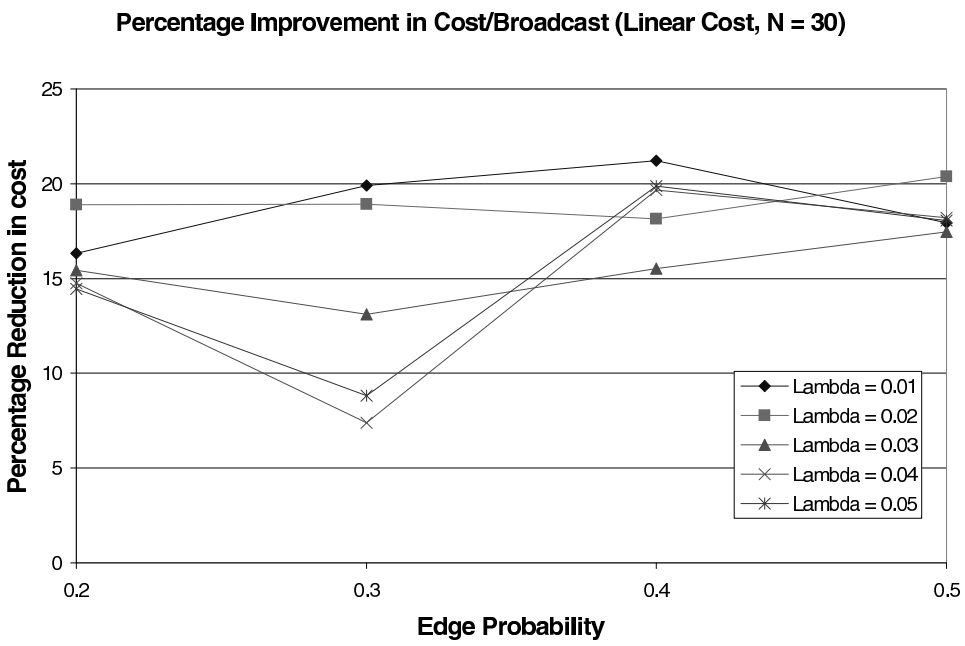

Figure 4: Percentage reduction in average cost/broadcast in 30-node networks with linear cost.

References

[1] `http://www.networks.digital.com/npb/html/products_guide/roamwir2.html` Jan 14, 1998.

[2] D. Beyer, "Accomplishments of the DARPA SURAN Program", *Proc. IEEE MILCOM'90*, Monterey, CA, Oct. 1990.

[3] V. Bharghavan, A. Demers, S. Shenkar and L. Zhang,"MACAW: A Media Access Protocol for Wireless LANs", *Proceedings ACM SIGCOMM'94*, pp. 212-225, 1994.

[4] Béla Bollobás, Random Graphs, Academic Press, 1985.

[5] A. Chandrakasan, T. Simon, J. Goodman and W. Rabiner,"Signal Processing for an ultra low power Wireless Video Camera", *3rd International Workshop on Mobile Multimedia Communications*, Princeton, NJ, September 25-27, 1996.

[6] A. Chockalingam and M. Zorzi, "Energy Consumption Performance of a class of Access Protocols for Mobile Data Networks", *Proc. IEEE VTC'98*, Ottawa, Canada, May 18-21, 1998.

[7] F. Douglis, F. Kaashoek, B. Marsh, R. Caceres, K. Lai and J. Tauber, "Storage Alternatives for Mobile Computers", *Proc. 1994 Symposium on Operating Systems Design and Implementation*, OSDI, November 1994.

[8] A. Ephremides, T. Truong, "Scheduling Broadcasts in Multihop Radio Networks," *IEEE Transactions on Communications*, Vol. 38, No. 4, pp. 456-460, April 1990.

[9] Chane L. Fullmer and J.J. Garcia-Luna-Aceves,"Solutions to Hidden Terminal Problems in Wireless Networks", *Proceedings ACM SIGCOMM'97*, Cannes, France, Sept. 14-18, 1997.

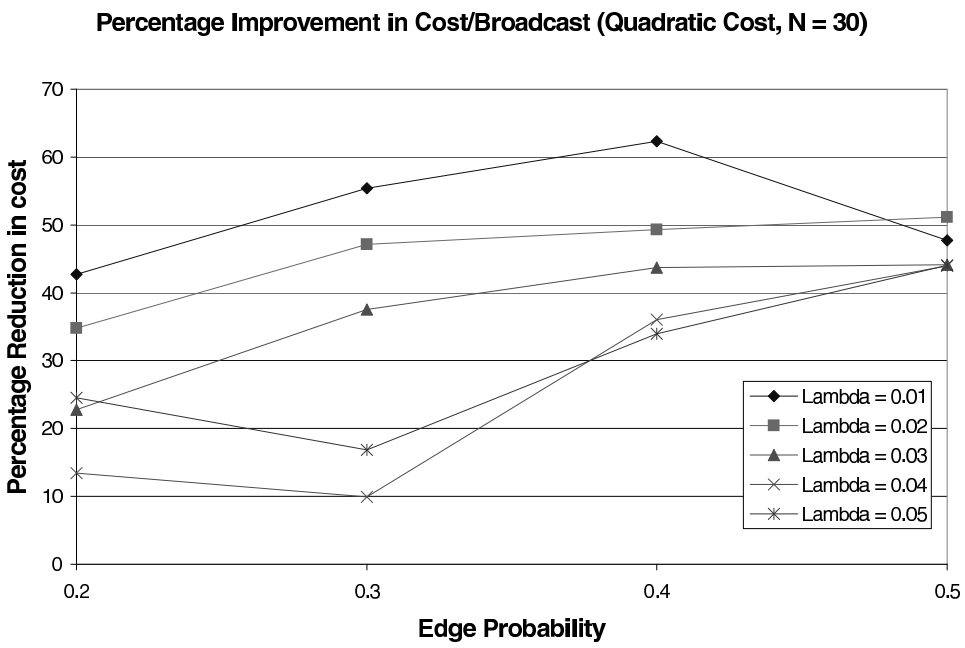

Figure 5: Percentage reduction in average cost/broadcast in 30-node networks with quadratic cost.

[10] Mario Gerla and J.T.-C. Tsai,"Multicluster, Mobile, Multimedia Radio Network", *ACM-Baltzer Journal of Wireless Networks*, Vol. 1, No. 3, pp. 255-265, 1995.

[11] S. Gold,"A PSPICE Macromodel for Lithium-Ion Batteries", *The 12th Annual Battery Conference on Applications and Advances*, California State Univ., Long Beach, CA, Jan 14-17, 1997. (see Fig. 4)

[12] E.P. Harris and K.W. Warren,"Low Power Technologies: A System Perspective", *3rd International Workshop on Mobile Multimedia Communications*, Princeton, NJ, September 25-27, 1996.

[13] David B. Johnson and David A. Maltz. "Dynamic source routing in ad hoc wireless networks", In Tomasz Imielinski and Henry F. Korth, editors, Mobile Computing, pages 153–181. Kluwer Academic Publishing, 1996.

[14] John Jubin and Janet D. Tornow, "The DARPA packet radio network protocols", *Proceedings of the IEEE*, 75(1):21–32, January 1987.

[15] P. Karn,"MACA – a New Channel Access Method for Packet Radio", in *ARRL/CRRL Amateur Radio 9th Computer Networking Conference*, pp. 134-140, 1990.

[16] Gregory S. Lauer. "Packet-radio routing", In Martha Steenstrup, editor, Routing in Communications Networks, Chapter 11, pages 351–396. Prentice-Hall, 1995.

[17] K. Li, R. Kumpf, P. Horton and T. Anderson,"A Quantitative Analysis of Disk Drive Power Management in Portable Computers", *Proceedings 1994 USENIX*, San Francisco, CA, pp. 279-291, 1994.

[18] W. Mangione-Smith and P.S. Ghang, "A low power medium access control protocol for portable multimedia systems", *3rd International Workshop on Mobile Multimedia Communications*, September 25-27 1996.

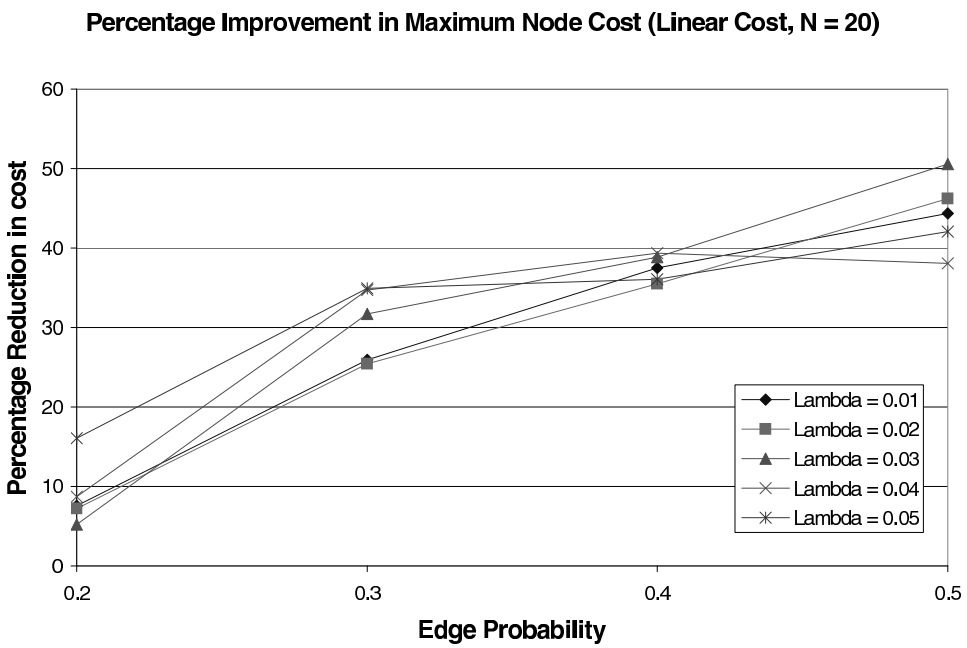

Figure 6: Percentage reduction in maximum node cost in 20-node networks with linear cost.

[19] S. Murthy and J.J. Garcia-Luna-Aceves,"An Efficient Routing Protocol for Wireless Networks", *ACM Mobile Networks and Applications Journal*, Special Issue on Routing in Mobile Communications Networks, 1996.

[20] S. Singh and C. S. Raghavendra,"Power efficient MAC protocol for multihop radio networks", *Proc. IEEE PIMRC'98*, Sept, 1998.

[21] S. Singh and C. S. Raghavendra,"PAMAS – Power Aware Multi-Access protocol with Signalling for Ad Hoc Networks", *ACM Computer Communication Review*, July 1998.

[22] S. Singh, M. Woo, and C. S. Raghavendra,"Power-Aware Routing in Mobile Ad hoc Networks", *Proc. MOBICOM'98*, October, 1998.

[23] V. D. Park and M. S. Corson,"A Highly Adaptive Distributed Routing Algorithm for Mobile Wireless Networks", *Proc. IEEE INFOCOM'97*, Kobe, Japan, (1997).

[24] Charles E. Perkins and Pravin Bhagwat, "Routing over multi-hop wireless network of mobile computers", In Tomasz Imielinski and Henry F. Korth, editors, Mobile Computing, pages 183–205. Kluwer Academic Publishing, 1996.

[25] D. Petras and A. Krämling, "MAC protocol with polling and fast collision resolution for an ATM air interface", *Proc. IEEE ATM'96 workshop*, San Francisco, CA, Aug. 1996.

[26] Chunhung Richard Lin and Mario Gerla,"Asynchronous Multimedia Multihop Wireless Networks", *Proceedings IEEE INFOCOM'97*, (1997).

[27] Christian Röhl, H. Woesner and A. Wolisz, "A Short Look on Power Saving Mechanisms in the Wireless LAN Standard Draft IEEE 802.11", *Proc. of the 6th WINLAB Workshop on Third Generation Wireless Systems*, March 1997.

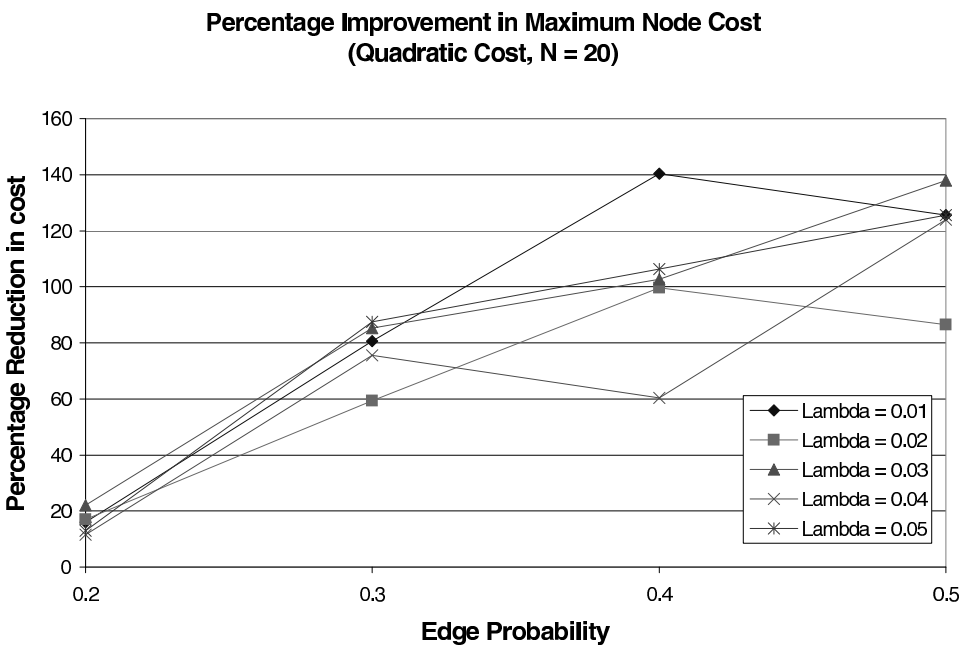

Figure 7: Percentage reduction in maximum node cost in 20-node networks with quadratic cost.

[28] Krishna M. Sivalingam, M. B. Srivastava and P. Agrawal,"Low Power Link and Access Protocols for Wireless Multimedia Networks", *Proc. IEEE Vehicular Technology Conference VTC'97*, Phoenix, AZ, May 4–7, 1997.

[29] Krishna M. Sivalingam, M. B. Srivastava, P. Agrawal and J-C. Chen, "Low-Power Access Protocols Based on Scheduling for Wireless and Mobile ATM Networks", *Manuscript*, http://www.eecs.wsu.edu/∼krishna.

[30] M. Stemm and P. Gauthier and D. Harada,"Reducing power consumption of network interfaces in hand-held devices",*3rd International Workshop on Mobile Multimedia Communications*,September 25-27, 1996.

[31] C-K Toh,"The Cambridge Ad Hoc Mobile Routing Protocol", in Wireless ATM and Ad Hoc Networks, Kluwer Academic Publishers, Boston, Chapter 9, (1997).

[32] S. Zdonik, M. Franklin, R. Alonso and S. Acharya,"Are "disks in the air" just pie in the sky?", *IEEE Workshop on Mobile Computing Systems and Applications*, Santa Cruz, CA, pp. 12-19, December 1994.

[33] Michele Zorzi and R. R. Rao, "Energy Management in wireless Communications", *Proc. 6th WINLAB Workshop on Third Generation Wireless Information Networks*, March 1997.

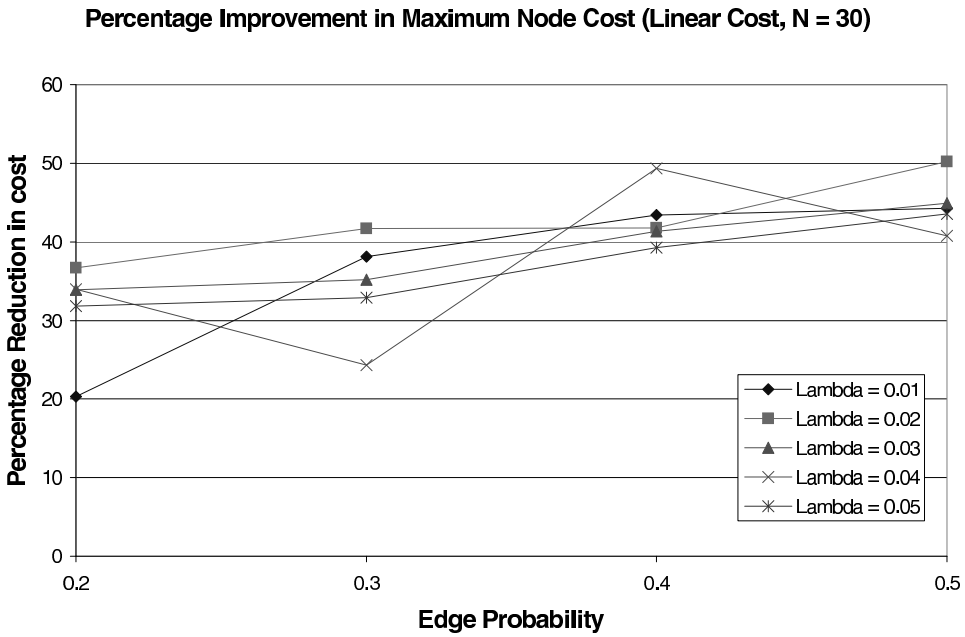

Figure 8: Percentage reduction in maximum node cost in 30-node networks with linear cost.

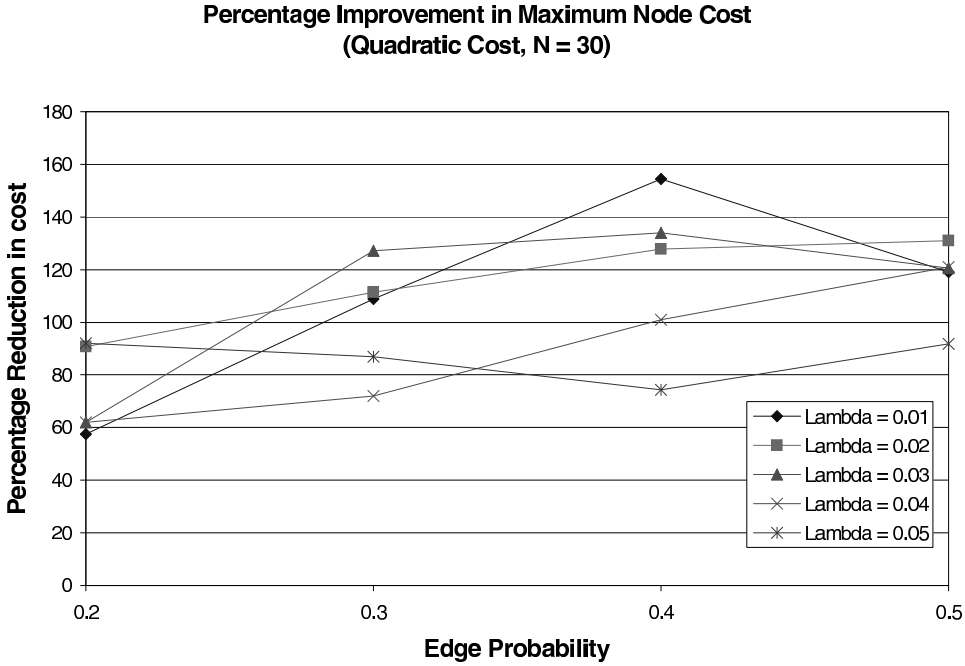

Figure 9: Percentage reduction in maximum node cost in 30-node networks with quadratic cost.