

Energy-efficient Broadcast and Multicast Routing in Multihop *Ad Hoc* Wireless Networks

Maggie Xiaoyan Cheng* Jianhua Sun Manki Min Yingshu Li Weili Wu

Abstract—This paper addresses the problem of broadcasting and multicasting in large scale multihop *ad hoc* wireless networks. We focus on the energy-efficient broadcast routing in stationary networks and consider the case where wireless nodes can dynamically control their transmission power for each broadcast session.

Minimum Spanning Tree(MST) has the property that the longest edge in the tree is the shortest among all the spanning trees. We introduce a new algorithm called MLE (Minimum Longest Edge) that constructs a broadcast tree based on Minimum Spanning Tree, and for networks where nodes have different energy reserves, we introduce Minimum Weight Incremental Arborescence(MWIA) algorithm to compute the broadcast tree. Multicast tree can be obtained by pruning broadcast tree. These algorithms provide a scheme to balance the energy consumption among all nodes. The simulation results show that MLE and MWIA improved the energy balance and network lifetime for a wide range of networks, and the improvement is more significant when the network size grows.

KEY WORDS: wireless, ad hoc, broadcast, multicast, power control

I. INTRODUCTION

Wireless *ad hoc* network consists of a collection of mobile hosts dynamically forming a temporary network without the use of any existing network infrastructure([1], [6], [7]). In such a network, each mobile host can serve as a router. For traffic across the network, multi hops may be needed to reach the destination. The selection of relay nodes and their transmission power is a major consideration in routing algorithm design. Unlike the wired network, in which the energy consumption is not a concern, energy-efficiency is very important in wireless *ad hoc* network, such as in military *ad hoc* networks and wide area voice and data networks. In such networks, the mobile hosts are powered by

batteries, therefore the limited battery lifetime imposes a constraint on the network performance. In military *ad hoc* networks, to recharge or replace the individual user's battery is impossible, so if a small set of batteries are drained out too early, the entire network may be partitioned and network lifetime reduced.

Most of the previous work addressed the issue of energy-efficient routing from the perspective of minimizing total energy consumption of all the mobile hosts. In this chapter, we address this problem from a different approach, i.e., to improve the energy efficiency with an objective of balanced energy consumption.

In a network that mobile hosts are deployed in a batch mode, the traffic should be routed to avoid the overuse of a small set of mobile nodes. In order to maximize the network lifetime, ideally, the traffic should be routed in such a way that the energy consumption is minimized and balanced among all the nodes. However, there is always a trade-off between achieving the minimum total energy and balanced energy distribution. We believe there is an optimal point in between. This is the motivation of this work.

In this study, we define the earliest time that a mobile host is depleted of energy as the network lifetime. In order to maximize the network lifetime, the maximum energy consumption among all nodes must be minimized. We propose a polynomial time algorithm that produces a broadcast tree with the shortest longest edge among all the spanning trees. This algorithm can be used in multicast routing by pruning the broadcast tree and eliminating transmissions that are not necessary to reach the destinations. For random multi-session traffic, our simulation result shows that compared with BIP algorithm, the best *minimum energy broadcast* algorithm known so far, the maximum energy consumption of MLE is decreased by 15% and the standard deviation of energy consumption among all the nodes is decreased by 6%. As the network size increases, the improvement in maximum energy consumption is more significant.

* Correspondence to: Maggie Cheng, Faculty of Computer Science Department, University of Missouri at Rolla. E-mail: chengm@umr.edu.

Jianhua Sun, Manki Min and Yingshu Li are with Computer Science Department, University of Minnesota. E-mail: {sun,min,yili}@cs.umn.edu.

Weili Wu is with Computer Science Department, University of Texas at Dallas, E-mail: weiliwu@utdallas.edu.

II. RELATED WORK

A. Minimum Total Energy Broadcast

The energy-efficiency problem in broadcast wireless network design has received significant attention in the past three years. One of the important features is the vertical coupling of protocol layer functionality [12], i.e., routing decision is made with the choice of transmitter power levels. The majority of these published works seek to minimize the total energy consumption in each broadcast session.

This problem was also studied in [9] and [4]. The authors stated that this problem is NP-hard, and it is also hard to approximate. Wieselthier, Nguyen and Ephremides addressed the problem in [11] and [10], and provided a few heuristics to find the near-optimal solution. We list a few of the heuristics below.

(1)*Exhaustive Search of Minimum Energy Broadcast Tree* The total energy is defined as the sum of the transmission power of all the transmitting nodes. In order to find the optimal broadcast tree, an exhaustive search is used, the tree that consumes the least total energy is chosen. This algorithm is not scalable and is only good for small networks[11].

(2)*Broadcast Least-Unicast-cost algorithm(BLU)* A minimum-cost path from the source to each reachable destination is established, and the broadcast tree is formed by superposition of unicast paths to all the destinations. Since the cost metric for unicast is a link-based cost, the wireless broadcast advantage is not taken into consideration. The aggregation of the individual shortest paths does not guarantee that the resultant broadcast tree will have minimum total cost [11].

(3)*Broadcast Incremental Power(BIP) algorithm* This algorithm takes into account the wireless broadcast advantage in the formation of low-energy broadcast trees, and it is a node-based spanning tree algorithm, which means the transmission power of a non-leaf node is the power needed to reach all its direct children. BIP is similar to Prim's MST algorithm. In Prim's algorithm, the nodes are added into the tree one at a time on a minimum cost basis, until all nodes are included in the tree, where the cost is defined as the cost of the link connecting the new node to the tree. In BIP, the nodes are added to the tree in a similar way. The only difference is that the cost is defined as the incremental cost to add a new node to the tree.

If the link cost between node i and node j is P_{ij} , and node i currently transmits at level $P(i)$, then the incremental cost for connecting node j is

$$P'_{ij} = P_{ij} - P(i)$$

Prim's algorithm takes P_{ij} as input and this information remains unchanged throughout the execution of the algorithm; whereas the BIP algorithm takes P'_{ij} as input and

this information must be updated at each step. Unlike Prim's algorithm, BIP does not guarantee to provide a minimum-cost tree, even though the objective in [10] is minimum total energy.

B. Energy-Efficient Unicast Routing

One of the objectives in unicast routing is to minimize the total cost along the route. A conventional approach is to use the shortest path between the source and the destination. However, this may lead to the overuse of some heavy-loaded paths and may in turn lead to reduced network lifetime. Another category of energy-efficient algorithms are energy-aware routing, which achieves balanced energy consumption among the nodes[2]. These algorithms can significantly improve the system lifetime by balancing the energy consumption rates in proportion to their energy reserves. Although this algorithm works well for unicast case, it can not be used in broadcast case. The superposition of unicast paths does not give an optimal broadcast tree in terms of maximum system lifetime. But the idea of balanced energy consumption is very important for broadcast routing algorithm design.

III. ENERGY EFFICIENCY METRICS

Total energy consumption has been used as an important metric to evaluate *ad hoc* routing algorithms. However, having minimum total energy consumption may have a negative effect in the long term, because this may result in the overuse of energy resources of a small set of nodes. The early energy depletion of some critical nodes may lead to the network partition.

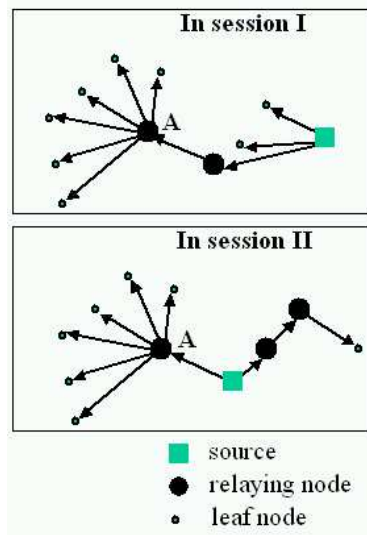


Fig. 1. Minimum energy broadcast leads to the overuse of node A

Consider the wireless network in Figure 1. We assume that total energy is the cost metric, and that BIP

algorithm is used to compute the broadcast tree. In any broadcast session with the source node in the right half area, node A will be selected as a single relay node to reach all the nodes in the left half area. So the energy reserve of node A will be drained out faster than others. If node A's energy is fully depleted, the network lifetime is ended, even though some other nodes may still have plenty of energy left.

Besides the total energy expenditure, the maximum energy consumption of each node is another important metric we need to consider. For many wireless *ad hoc* networks, the wireless nodes are deployed in a batch mode where battery replacement or recharge is not possible. If some node at a critical position has depleted its energy, the whole network may be partitioned and network lifetime ended. In section VI, we propose algorithms that aim to provide maximum network lifetime. We will describe the wireless communication model in section IV.

IV. WIRELESS COMMUNICATION MODEL

In this study, we address only stationary wireless *ad hoc* networks. We assume the node position is static or changes slowly. So the node mobility is not considered in this paper. We also assume there exists an underlying protocol to provide the network connectivity information. We ignore the energy consumption in the information exchange and focus only on the energy-efficient broadcast routing for data traffic.

The wireless *ad hoc* network is modeled as a complete graph, in which each vertex represents a wireless node, and the edge is weighted by the cost or energy needed to communicate between the two vertices. The energy consumed by a wireless node have two components: the receiving/processing energy and transmission energy. We assume that the transmission energy is dominant, and the receiving/processing power is negligible. Therefore only the transmission power contributes to the total energy consumption.

We also assume that the received signal power is proportional to $r^{-\alpha}$, where α is a parameter between 2 and 4, depending on the communication medium; r is the distance between the two nodes [8]. We set the signal detection threshold constant equal to be C , and this can be further normalized to 1. So the power needed for the communication between node i and node j is

$$p_{ij} = r_{ij}^\alpha$$

where r_{ij} is the distance between node i and node j .

Another important assumption is that omni-directional antennas are used. So if a node i transmits at power level $P(i) = r^\alpha$, all the nodes within the range r of node i can receive the signal. For example, consider the situation described in Figure 2, $r_{ij} > r_{ik}$. node i is the source,

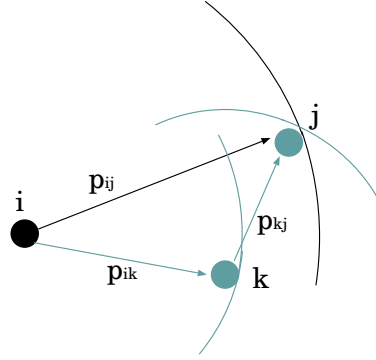


Fig. 2. A comparison of two routes: $i \rightarrow j$ and $i \rightarrow k \rightarrow j$

node j and k are destinations. One solution is that node i transmits at power level p_{ij} , so both node j and node k can be reached. Another choice is that node i transmits at power level p_{ik} and node k transmits at power level p_{kj} . This may or may not result in less total energy consumption, but the maximum transmission power in the broadcast tree is reduced, which is very important to balance the energy consumption among all the nodes and to maximize the network lifetime.

V. MINIMUM SPANNING TREE PROPERTY

Theorem 1: Minimum Spanning Tree has the minimum longest edge among all the spanning trees.

Proof:

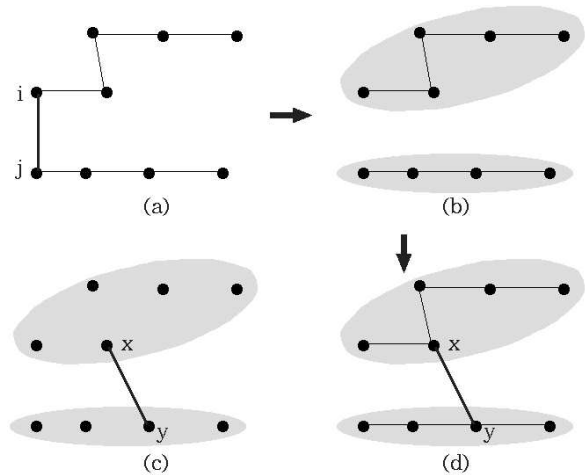


Fig. 3. MST has the Minimum Longest Edge

The proof is based on the invariant of Minimum Spanning Tree(MST) that every edge in MST is a light edge across the two connected components it straddles [3].

In Figure 3.(a), the MST T has the longest edge $e(i, j)$, which connects the two connected compo-

nents(Figure 3.(b), the shaded area). For any other spanning tree T' , assume its longest edge is $e(u, v)$. Assume $|e(i, j)| > |e(u, v)|$. We can prove that this leads to a contradiction that T is not a Minimum Spanning Tree.

First we find an edge in T' that straddles the two set of vertices. Let's call it $e(x, y)$ as shown in Figure 3.(c).

Case 1: Edge $e(x, y)$ is different from edge $e(i, j)$. Since $|e(u, v)| \geq |e(x, y)|$, so if $|e(i, j)| > |e(u, v)|$, then $|e(i, j)| > |e(x, y)|$. In original MST T , by replacing $e(i, j)$ with $e(x, y)$ as is shown in 3.(d), we can get a spanning tree T'' , which has less cost than T does.

Case 2: Edge $e(x, y)$ happens to be the same edge as $e(i, j)$. This leads to another contradiction: $|e(i, j)| > |e(u, v)| \geq |e(i, j)|$.

Now we can conclude that the Minimum Spanning Tree T has the minimum longest edge among all the spanning trees. An example of energy consumption for single session broadcast is shown in Figure 4. As is expected, the MLE algorithm makes the energy consumption more balanced and the maximum energy decreased. In this particular example, the maximum energy consumption in MLE is only 58% of that in BIP. In multi-session random traffic simulation, the maximum transmitting power of MLE is decreased by 15% in average.

VI. CENTRALIZED ALGORITHMS

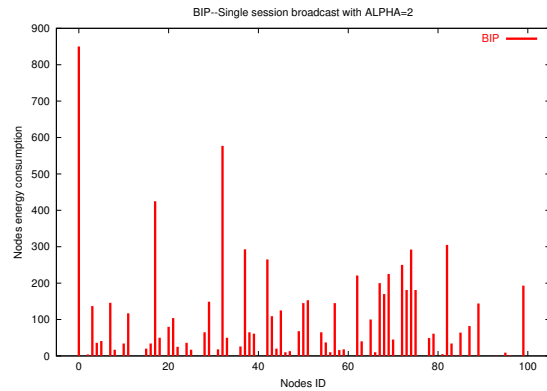
A. MLE Broadcast Tree Construction Algorithm

In this section, we introduce a broadcast tree construction algorithm for networks where wireless nodes have the same initial energy reserves.

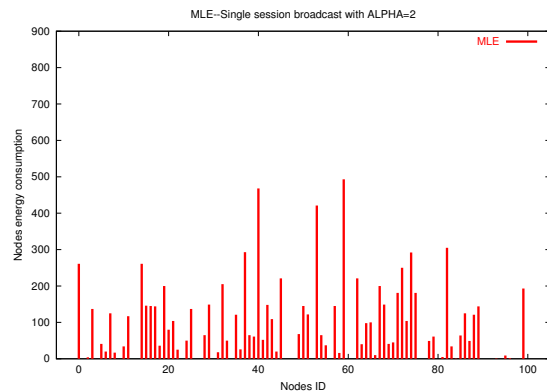
The objective of this work is to build a broadcast tree rooted at the source node such that the network lifetime is maximized. Since the broadcast is session-based, we found that the maximum duration of a session can be achieved by using a broadcast tree with the minimum longest edge. We assume the broadcast sessions are randomly generated, therefore it is reasonable to assume such a strategy will also work for multi session traffic. If the energy consumption is balanced in each session, then it is also balanced after multiple sessions.

The broadcast tree is constructed in two phases. In the first phase, we use Prim's MST algorithm to build a tree rooted at the source. In the second phase, we take into consideration the wireless broadcast nature to save energy by removing the unnecessary transmissions. Some relay node may become leaf node after the second phase, but for the remaining transmitting nodes, their transmission ranges won't increase. So the resulting broadcast tree still has the Minimum Longest Edge (hence the name MLE).

Phase 1: Given a complete undirected graph, we build a spanning tree rooted at the source. Initially, only the



(a) BIP



(b) MLE

Fig. 4. Nodes energy consumption in a single broadcast session

source node is included in the tree. At each step, the vertices in the tree define a cut of the graph. A light edge across the cut is selected and the node it connects is added into the tree. The edge weight is defined as the transmission power needed to reach the selected node. Figure 5.(a) shows a broadcast tree resulting from this algorithm.

Phase 2: Since the wireless communication is broadcasted in its nature, a node can be reached by many nodes. As long as the wireless network's connectivity is maintained, we can remove unnecessary transmissions to save the energy consumption. For example, if a node A's children can be reached by A's parent without increasing the parent node's transmission power, then node A's transmission can be eliminated. Figure 5.(b) shows the result of phase two. Node b 's child node becomes reachable from b 's parent node a after a increases its power, so node b becomes a leaf node as a result.

The first phase of this algorithm is to construct a Minimum Spanning Tree (MST) rooted at source node

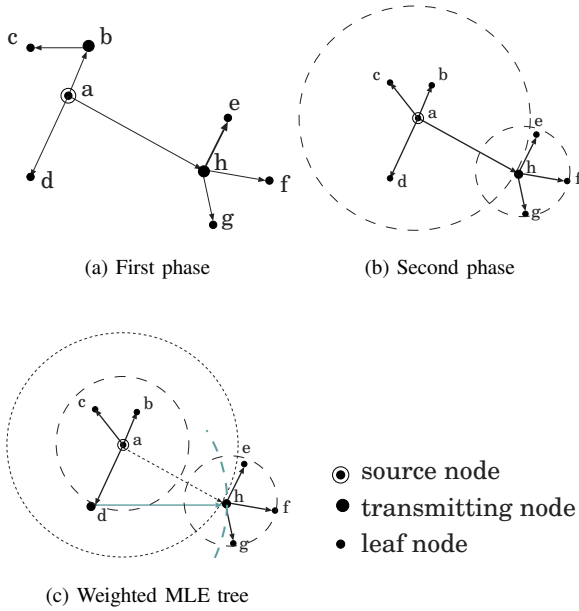


Fig. 5. MLE tree construction

in the same way as in wired network. We claim that this algorithm produces a tree with minimum longest edge (MLE). Since the edge length determines the transmission power level, a MST will no doubt minimize the maximum transmission power of all nodes. Recall that the network lifetime is defined as the earliest time that a node is drained out of energy. The node that is drained out first is usually the node that transmits at the maximum power level. If we minimize this transmission power, we definitely can extend the network lifetime.

In section V, we proved that the Minimum Spanning Tree algorithm used in *Phase 1* outputs a broadcast tree of Minimum Longest Edge. Since only the shorter edges are removed, the *Phase 2* operation does not change the Minimum Longest Edge property of the broadcast tree.

B. MWIA Broadcast Tree Construction Algorithm

So far we have assumed that all the nodes have the same initial energy reserves. Since each node has different energy consumption rate, after a few sessions, some nodes may have less energy left than others. We need to modify the algorithm in consideration of this difference. In this section, we consider the energy-efficient broadcast tree construction with different initial energy reserves. We propose an algorithm that balances the energy consumption among all the nodes by using a weighted edge cost that is derived from the sending node's remaining energy.

Now we assume that each node is aware of its remaining energy, and this information is exchanged with other

nodes after each session. We associate each node with a weight, which is a function of its energy reserve. We define

$$\begin{aligned} E_i &= \text{the remaining energy of node } i \\ E_{max} &= \text{the maximum remaining energy} \\ &\quad \text{among all the nodes} \\ w_i &= E_{max}/E_i \end{aligned}$$

We associate each node i with a weight w_i and we use weighted link cost instead of the original link cost in the process of selecting candidates. In this sense, we model the wireless network as a complete directed graph, and each pair of nodes are connected by a pair of directed edges. We define

$$\begin{aligned} \text{weighted edge cost } p'_{ij} &= \text{link cost } p_{ij} * w_i \\ \text{weighted edge cost } p_{ji} &= \text{link cost } p_{ji} * w_j \end{aligned}$$

In the distributed implementation of this algorithm, to reduce the number of control messages for finding out E_{max} , the maximum remaining energy among all nodes, we can normalize it to 1, so there is no additional message overhead for using weighted edge cost.

Now the problem of building the broadcast tree with minimum largest edge-weight is formally defined as follows:

Definition 1: (Energy-efficient Broadcast Routing)

Given an edge-weighted directed graph G and a root node r , find a broadcast tree such that the maximum edge-weight in the tree is the minimum among all the broadcast trees.

To solve this problem, we introduce the *Minimum Weight Incremental Arborescence*. An *arborescence* is a tree with root r and paths from r to every node of G . To get a broadcast routing with the longest network life time, we need to find an arborescence rooted at r with the minimum largest edge-weight in the tree. The solution to this problem is a *Minimum Weight Incremental Arborescence* constructed as follows:

In the first phase, we build an arborescence rooted at the source node r . Initially, only r is included in the tree. At each step, we add a node to the tree on a minimum weight basis, that is, we find an edge with minimum weight from a vertex in the tree to a vertex not in the tree. If there are more than one such edges, the tie is broken randomly. We start from the source node and grow the tree one node at a time until all nodes are in the tree.

In the second phase, we use the same algorithm as described in section VI-A, Phase 2 to remove the unnecessary transmissions without increasing the transmission range of any node. Some edges are removed, and new edges are added to save the total energy, but the edge with the largest weight will remain untouched.

There may exist more than one MWIAs if there is a

tie. However, the following theorem tells us any MWIA will have the same maximum edge-weight.

Theorem 2: Every MWIA is an optimal solution for the *Energy-efficient Broadcast Routing Problem* defined above.

Proof.

Let $e(x, y)$ be an edge with the largest weight in a MWIA T . Let $T_{(x, y)}$ be the subtree at the time in the construction that edge $e(x, y)$ is added. Then $T_{(x, y)}$ is rooted at r and $e(x, y)$ is an outgoing edge with the minimum weight from any node in $T_{(x, y)}$ to a node not in $T_{(x, y)}$.

Now, suppose there exists another arborescence T' such that every edge of T' has weight less than $w(x, y)$, the weight of edge $e(x, y)$. Since T' contains a path from r to y , it must contain an outgoing edge $e(x', y')$ from a node x' in $T_{(x, y)}$ to a node y' not in $T_{(x, y)}$. However, $w(x', y') < w(x, y)$ contradicts the above fact about edge $e(x, y)$. ■

To be consistent with the unweighted graph version, we sometimes use *weighed MLE* as an equivalence to *MWIA* in the following. As a result, the unweighted MLE is a special case of *MWIA*, where edge weights are equal in two directions and are all equal to the link cost.

In Figure 5, if MWIA algorithm is used, the broadcast tree after a time period will be like Figure 5.(c). The heavily loaded node a shifts the task to node d that has more energy left.

C. Multicast Tree Construction

In practice, multicast is implemented as *broadcast + prune*. We first use the *Phase 1* of the broadcast algorithms to construct a broadcast tree, and then we prune the broadcast tree to get a multicast tree. Unnecessary transmissions are removed as a result, and the longest edge in the broadcast tree may be removed if it is not on the path from the source to a member of the multicast group. But the remaining multicast tree still has the minimum largest edge-weight among all the pruned subtrees. Then we run the *Phase 2* algorithms to further optimize on the total energy consumption.

Theorem 3: The multicast tree obtained above is an optimal solution for the multicast routing with minimum largest edge-weight.

The property that the pruned multicast tree is still an optimal solution for multicast problem can be proved as follows:

Proof.

A multicast session is defined as a pair: (*source, multicast group*).

In any multicast tree, there must be a path from the source r to any member x in the multicast group. We can prove that the path from r to x in the multicast tree

T obtained by this algorithm has the minimum largest edge-weight among all such paths.

For contradiction, assume this is not true. Then we can find a path $r \rightsquigarrow i \rightarrow j \rightsquigarrow x$ in another multicast tree T' (Figure 6.(b)), and the largest edge-weight along this path is $w(i, j)$. Assume there is a path $r \rightsquigarrow u \rightarrow v \rightsquigarrow x$ in T and the largest weight along this path is $w(u, v)$ (Figure 6.(a)). If $w(i, j) < w(u, v)$, then we can find only two possibilities to connect x and v in the process of constructing broadcast tree following MLE or MWIA algorithm *Phase 1*:

- 1) If the largest weight on path $x \rightsquigarrow v \geq w(u, v)$ (Figure 6.(c)), then T contains paths $r \rightsquigarrow i \rightarrow j \rightsquigarrow x$ and $r \rightsquigarrow u \rightarrow v$ without path $v \rightsquigarrow x$, because path $r \rightsquigarrow i \rightarrow j \rightsquigarrow x$ exists before edge $u \rightarrow v$ is selected.
- 2) If the largest weight on path $x \rightsquigarrow v \leq w(u, v)$ (Figure 6.(d)), then T contains paths $r \rightsquigarrow i \rightarrow j \rightsquigarrow x \rightsquigarrow v$ and $r \rightsquigarrow u$ without edge $u \rightarrow v$, because path $r \rightsquigarrow i \rightarrow j \rightsquigarrow x \rightsquigarrow v$ exists before edge $u \rightarrow v$ is selected.

In either case, there should be no such path $r \rightsquigarrow u \rightarrow v \rightsquigarrow x$ in T . This contradicts the fact that T contains a path $r \rightsquigarrow u \rightarrow v \rightsquigarrow x$. ■

The union of these paths form a multicast tree, and the “minimum largest edge-weight” property will still hold.

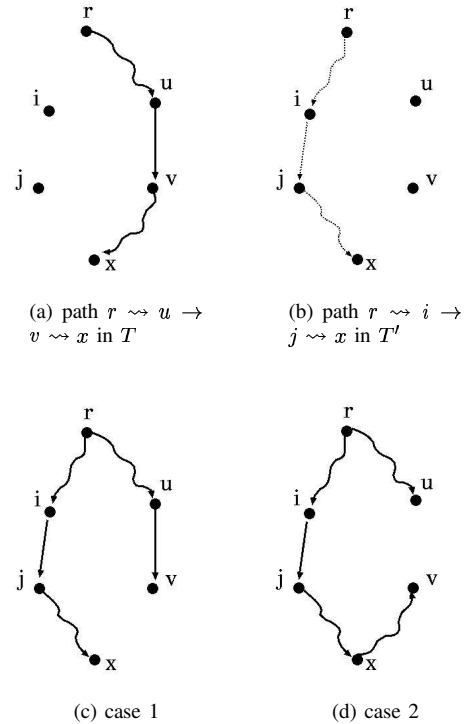


Fig. 6. proof of theorem VI-C

VII. DISTRIBUTED BROADCAST TREE CONSTRUCTION

A distributed Minimum Spanning Tree algorithm is presented in [5]. We can use the same message exchanging strategy to construct optimal broadcast tree in distributed environment. This strategy can be used for both MLE algorithm and MWIA algorithm.

Each node initially only knows the cost of the adjacent edges, all the nodes run the same algorithm and exchange messages with neighbors until the tree is constructed. We start with the source node as a fragment and successively enlarges the fragment until it spans the graph. The key point in the distributed algorithm is how a fragment finds its minimum weight ongoing edge to extend itself. In summary, each node in a fragment finds its minimum weight outgoing edge; Nodes in a fragment coordinate by sending *Report* messages to find the minimum weight outgoing edge of the entire fragment. In detail, it works as follows:

Each leaf node of the fragment finds its minimum weight outgoing edge and sends *Report(W)* message on its inbound branch, with W as the weight of the edge it found. Each interior node also finds its minimum weight outgoing edge and waits until it receives messages from all outbound fragment branches. The best edge is selected at the next step to extend the fragment. If no node has outgoing edge, the algorithm is done. Distributed implementation of BIP is just like distributed MLE or MWIA, it starts with a single node and successively enlarges the fragment until all the nodes are included in the fragment.

The distributed implementation of BIP algorithm and MLE/MWIA algorithm work equally well in terms of message complexity and time complexity. If the node identity is distinct, the total number of messages required is at most $5N \log_2 N + 2E$. Each message contains at most one edge weight, a level between 0 and $\log N$ and a few more bits to indicate message type. Since the energy consumption in message exchange is the same for both MLE/MWIA and BIP algorithm, and it is much smaller than that of data transmission, we do not include it in the energy consumption comparison.

VIII. SIMULATION RESULTS

We evaluate the performance of the proposed algorithms by simulations. The results from BIP provide a basis for comparison between these energy-efficient algorithms.

In this simulation study, we assume there is enough energy reserve at each node and we compare the energy consumption distribution. The numbers shown in the graph are normalized by the maximum energy capacity, which is the energy needed to cover the longest distance

in the network for a maximum duration. In the following simulations, a fixed value of $\alpha=2$ is used, which is a typical value for unobstructed environment.

Scenario I: Broadcast

We construct random network instances and compare the MLE algorithm with BIP with respect to mean, maximum and standard deviation of energy consumption among all the nodes for a single session broadcast traffic. Initially, every node has the same energy reserve, so unweighted MLE and BIP algorithms are used. The results are provided in Figure 7.

It is observed that both the maximum value and standard deviation in BIP are approximately 8% higher than those in MLE. In fact, when the network size is increased, the MLE algorithm shows more improvement.

Scenario II: Multicast

In this simulation study, we assume the initial energy reserves are sufficient, and we compare the energy consumptions of basic (unweighted) BIP, weighted MLE(or MWIA), and weighted BIP. The multicast session traffic is randomly generated, i.e., the source node, multicast group and session duration time are randomly chosen.

Simulations are run over 100-node graphs generated by GT-ITM. We observe the energy consumption as the multicast group size increases.

Each simulation was run over 100 network instances and the results averaged. The simulation results are provided in Figure 8. In average, the mean energy consumption in weighted MLE is increased by 10%, max value decreased by 15%, and the standard deviation decreased by 6% over basic BIP. While in weighted BIP, the average energy consumption is only increased by 3.7%, and maximum value decreased by 13%, and standard deviation decreased by 5% over basic BIP. Despite the randomness of the network instances and multicast sessions, the performance results of weighted MLE(or MWIA) and weighted BIP are very close. This indicates that the energy-balancing strategy by use of energy related weights can be used to improve both BIP and MLE.

Another observation from the simulation study is that in broadcast traffic, as the number of participants increases, the energy consumption is decreased in general. This is due to the fact that when more nodes are involved, the nodes are getting closer, therefore the transmitting power needed are decreased. But in the multicast case, where the total number of nodes is fixed, increasing the size of multicast group can only make the energy consumption increase.

We also observed that when we choose $\alpha = 4$, the two algorithms produce the same broadcast tree in some network instances, and the overall performance is very close. This is because when α is high, the penalty of using long edges becomes significant. When the cost of

using relaying nodes is much cheaper than using a single hop long edge, BIP algorithm becomes in favor of the short edges during the tree construction, this is similar to MLE algorithm.

In summary, the unweighted MLE algorithm is good for long lasting session where the energy drain out of individual nodes is likely to occur in a single session; Weighted BIP and weighted MLE are good for multi session traffic where each session is relatively short. These two weighted algorithms have roughly the same performance, with the latter being better in minimizing the maximum power consumption. It is also observed that when the path loss exponent α is high, the MLE and BIP algorithms tend to produce the same results.

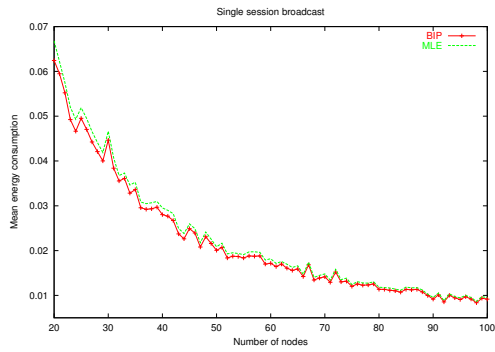
IX. SUMMARY AND FUTURE WORK

In this study, energy-efficient broadcast routing algorithms called Minimum Longest Edge(MLE) and Minimum Weight Incremental Arborescence(MWIA) are introduced. MLE achieves longer network lifetime by minimizing the maximum transmission power of individual nodes. The probability that a node is overused is decreased significantly. We further extended the idea to consider the situation where nodes have different energy reserves, and introduced edge weights based on remaining energy of sending nodes. We proved the Minimum Weight Incremental Arborescence (MWIA) is the optimal solution for broadcast routing with the minimum largest edge-weight.

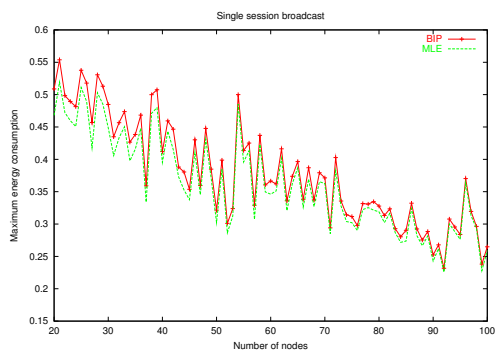
Simulation results show that the energy expenditure of MLE and MWIA are more evenly distributed than BIP for random multi-session multicast traffic, while the total energy consumptions are not increased significantly as a trade-off. To our knowledge, this is the first work to address the broadcast and multicast problem in multihop wireless *Ad hoc* networks toward a balanced energy consumption.

One of the future research topics is to incorporate the limitation of finite number of transceivers at each node and limited number of frequencies available. So far we used an “admit all” policy. In order to increase the network throughput, the admission control policy needs to be changed.

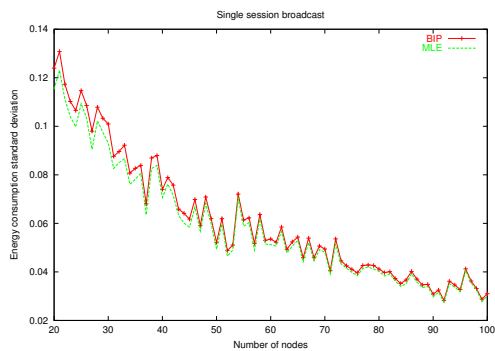
We are also interested in further investigating the performance of the distributed broadcast routing algorithm in mobile environment, and conclude if it is a reasonable price to pay for gathering global information in order to achieve the optimal solution. A future research topic results from this is to develop suboptimal solution when node mobility is high, and thus to gather global information in order to find the optimal solution is likely to be infeasible. A localized search mechanism will be needed and global information should be used as less as possible.



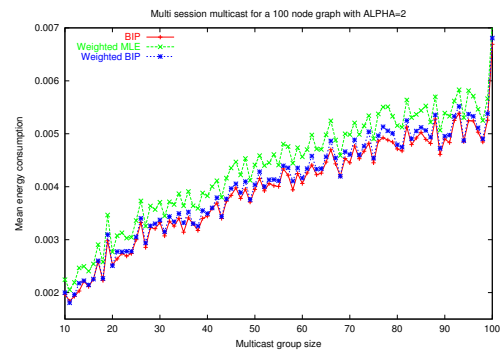
(a) Mean energy consumption for broadcast



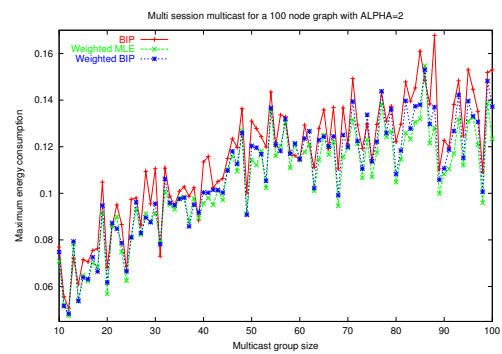
(b) Maximum energy consumption for broadcast



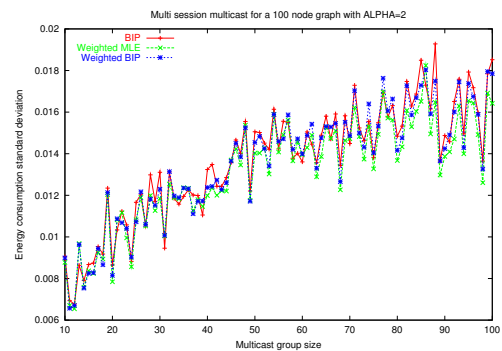
(c) Energy consumption stdDev for broadcast



(a) Mean



(b) Max



(c) StdDev

Fig. 7. Broadcast simulation results. Pictures show the comparison between basic BIP and unweighted MLE.

Fig. 8. Multicast simulation results. Pictures show the comparison of basic BIP, Weighted MLE(or MWIA) and Weighted BIP.

REFERENCES

- [1] Internet engineering task force(ietf) mobile ad hoc networks(manet) working group charter.
- [2] Jae-Hwan Chang and Leandros Tassiulas. Energy conserving routing in wireless ad-hoc networks. In *INFOCOM (1)*, pages 22–31, 2000.
- [3] T. S. Cormen, C. E. Leiserson, and R. L. Rivest. *Introduction to Algorithms*. MIT Press and McGraw-Hill Book Company, 1976.
- [4] Omer Egencioglu and Teofilo F. Gonzalez. Minimum-energy broadcast in simple graphs with limited node power. In *Proc. IASTED International Conference on Parallel and Distributed Computing and Systems (PDCS 2001)*, Anaheim, CA, pages 334–338, August 2001.
- [5] R. G. Gallager, P. A. Humblet, and P. M. Spira. A distributed algorithm for minimum-weight spanning trees. *ACM Transactions on Programming Languages and Systems (TOPLAS)*, 5(1):66–77, 1983.
- [6] J. Jubin and J.D. Tornow. The darpa packet radio network protocols. *Proceedings of the IEEE*, 75(1):21–32, January 1987.
- [7] Sung-Ju Lee, William Su, Julian Hsu, Mario Gerla, and Rajive Bagrodia. A performance comparison study of ad hoc wireless multicast protocols. In *INFOCOM (2)*, pages 565–574, 2000.
- [8] T. S. Rappaport. *Wireless Communications: Principles and Practices*. Prentice Hall, 1996.
- [9] Peng-Jun Wan, Gruia Calinescu, Xiangyang Li, and Ophir Frieder. Minimum-energy broadcast routing in static ad hoc wireless networks. In *INFOCOM*, pages 1162–1171, 2001.
- [10] Jeffrey E. Wieselthier, Gam D. Nguyen, and Anthony Ephremides. On the construction of energy-efficient broadcast and multicast trees in wireless networks. In *Proceedings of IEEE INFOCOM*, pages 585–594, March 2000.
- [11] Jeffrey E. Wieselthier, Gam D. Nguyen, and Anthony Ephremides. Algorithms for energy-efficient multicasting in static ad hoc wireless networks. In *Mobile Networks and Applications(MONET)6*, pages 251–263, 2001.
- [12] Jeffrey E. Wieselthier, Gam D. Nguyen, and Anthony Ephremides. Energy-efficient multicasting of session traffic in bandwidth-and transceiver-limited wireless networks. *Cluster Computing*, 5:179–192, 2002.



Manki Min received his Ph.D. in Computer and Information Sciences from University of Minnesota in 2004. He is currently a Post Doc Associate in University of Florida, working with Dr. Pardalos. His current research interests include polynomial time approximation schemes (PTAS) and its applications to wireless mobile ad hoc network topologies.

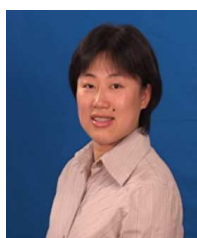


Yingshu Li is a PhD candidate in the Department of Computer Science and Engineering at the University of Minnesota, Twin Cities. She received the BS degree in computer science from Beijing Institute of Technology, China, in 2001, and the MS degree in computer science from the University of Minnesota, Twin Cities, USA, in 2003. Her current research interests include mobile wireless network and mobile ad-hoc network Database Systems. She is a student member

of the IEEE.



Weili Wu is an Assistant Professor in the Department of Computer Science at the University of Texas at Dallas. She received her Ph.D. in Computer Science from the University of Minnesota in 2002, and M.S. in 1997 respectively. Her current research areas are database systems, spatial data management, geo-spatial data mining, clustering and information retrieval, and distribute database systems.



Maggie Cheng received her Ph.D in Computer Science from the University of Minnesota at the Twin Cities in 2003. She is currently an assistant professor at the Computer Science Department in the University of Missouri, Rolla. Her current research interests include wireless networking and mobile computing, sensor networks, network security and combinatorial optimization. She is a member of the IEEE.



Jianhua Sun is a Ph.D. candidate in the Department of Computer Science and Engineering, University of Minnesota, under the supervision of Professor Ding-zhu Du. Her research interest includes optical networks, ad-hoc and wireless networks. She received a MS degree in Computer and Information Science from the Univ. of Minnesota in 1995, and a BS degree in Computer Science from the University of Science and Technology of China in 1992.