Maximum Lifetime Broadcasting In Wireless Networks *

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Abstract

We consider the problem of broadcasting messages in a wireless energy-limited network so as to maximize network lifetime. An $O(e \log e)$ algorithm to construct a broadcast tree that maximizes the critical energy of the network following the broadcast is developed. Additionally, we propose two new greedy heuristics to construct minimum energy broadcast trees. We show how our maximum critical energy algorithm may be coupled with our proposed greedy heuristics as well as with the greedy heuristics proposed in [27, 28] for the construction of minimum energy broadcast trees. Extensive simulations performed by us show that this coupling improves network lifetime significantly (between 48.3% and 328.9%) when compared with network lifetime using the base greedy heuristics in isolation.

Keywords: Wireless networks, minimum energy broadcast trees, network lifetime.

1 Introduction

Battery-operated wireless sensor networks may be deployed in environments in which it is impractical to recharge/replace the battery of a sensor (e.g., in a battle field or at the bottom of an ocean). Hence, these networks must operate subject to the constraint that the energy available to a sensor isn't replenishable. In other wireless network applications, even though it is possible to recharge a node's battery (or replenish its energy supply), it is desirable to operate in an energy frugal manner so as to minimize the need for this recharge. With this need to conserve energy in many wireless network applications, several authors have developed energy-efficient algorithms for point-to-point communication [13, 14, 16, 22, 23, 24, 25], multicasting [1, 26, 27, 28, 29], and broadcasting [2, 3, 7, 8, 10, 15, 21, 26, 27]. The overall objective of these algorithms is to either maximize the lifetime (number of successful communications before first communication that cannot be done) or the capacity of the network (amount of data traffic carried by the network over some fixed period of time). Lifetime maximization is considered in [4, 5, 6, 30], for wireless sensor networks.

In this paper, we focus on algorithms to broadcast in wireless networks so as to maximize network lifetime. We assume the omnidirectional antenna model in which the wireless network is represented as

*This work was supported, in part, by the National Science Foundation under grant CCR-9912395.

a weighted directed graph G that has n vertices/nodes and e edges. Each node of G represents a node of the wireless network. The weight $w(i,j)$ of the directed edge (i,j) is the amount of energy need by node i to transmit a unit message to node j. Using an omnidirectional antenna, node i can transmit the same unit message to nodes $j_1, j_2, \cdots, j_k$, using

$$e_{wireless} = \max\{w(i,j_q) | 1 \leq q \leq k\}$$

energy rather than

$$e_{wired} = \sum_{q=1}^{k} w(i,j_q)$$

energy. Since, $e_{wireless} \leq e_{wired}$, the reduction in energy needed to broadcast from one node to several others in a wireless network over that needed in a wired network is referred to as the *wireless broadcast advantage* [27, 28].

In the most common model used for power attenuation in wireless broadcast, signal power attenuates at the rate a/r^d, where a is a media dependent constant, r is the distance from the signal source, and d is another constant between 2 and 4 [18]. So, for this model, $w(i,j) = w(j,i) = c * r(i,j)^d$, where $r(i,j)$ is the Euclidean distance between nodes i and j and c is a constant. In practice, however, this nice relationship between $w(i,j)$ and $r(i,j)$ may not apply. This may, for example, be due to obstructions between the nodes that may cause the attentuation to be larger than predicted. Also, the transmission properties of the media may be asymmetric resulting in $w(i,j) \neq w(j,i)$. In this paper, we assume the most general case in which edge weights may be asymmetric and may reflect the presence of obstructions in the broadcast path.

To broadcast from a source s to the remaining nodes of G, we use a *broadcast tree* T. The root of T is s and every other node of G is a descendent of s. The energy, $E(u)$, required by a node of T to broadcast to its children is

$$E(u) = \max\{w(u,v) | v \text{ is a child of } u\}$$

Note that for a leaf node u, $E(u) = 0$. The energy, $E(T)$, required by the broadcast tree to broadcast a unit message from the source to all other nodes is

$$E(T) = \sum_{u} E(u)$$

We use MEBT to denote the problem of finding a minimum-energy broadcast tree in a graph with general edge weights. MEBT is NP-hard, because it is a generalization of the connected dominating set problem, which is known to be NP-hard [11]. In fact, MEBT cannot be approximated in polynomial time within a factor $(1-\epsilon)\Delta$, where ϵ is any small positive constant and Δ is the maximal degree of a vertex, unless $NP \subseteq DTIME[n^{O(\log\log n)}]$ [12], where n is the number of vertices in the graph. Wieselthier et al. [27, 28] consider the case when $w(i,j) = c * r^d$. They develop a fast MEBT algorithm for the case of networks that have 3 nodes (a source broadcasting to 2 other nodes). For larger networks, they propose a recursive algorithm that "makes more than 51,000 calls" when there are 10 destination nodes. Since the proposed recursive algorithm is impractical for large networks, several heuristics are proposed. Four of the proposed heuristics are greedy heuristics that scale well as the network size increases. Wan et al. [26] provide a theoretical analysis of the performance of three of the greedy heuristics proposed in [27, 28]. They show that two of the proposed heuristics (link-based minimum spanning tree and broadcast incremental power) have constant approximation ratios and a third (shortest path spanning tree) has an approximation ratio that is at least $n/2$, where n is the number of nodes in the network (equivalently, number of vertices in the graph describing the network). These approximation ratios are for the case $w(i,j) = c * r^d$).

In a real application, the wireless network will be required to perform a sequence $B = b_1, b_2, \cdots$ of broadcasts. Broadcast b_i will specify a source node s_i and a message length l_i. In this paper, we assume that $l_i = 1$ for all i (our work is extended easily to the more general case of arbitrary l_is). For a given broadcast sequence B, the network lifetime is the largest i such that broadcasts $b_1, b_2, \cdots, b_i$ are successfully completed. The MEBT heuristics of [27, 28] may be used to maximize lifetime by performing each b_i using the broadcast tree generated by the heuristic (the broadcast trees are generated in sequence using the residual node energies). To perform a broadcast in an n node e edge network, $e \geq n-1$. So, all of our analyses assume this relationship between e and n.

We begin, in Section 2, by providing a brief description of the four MEBT heuristics of [27, 28]. Then, in Section 3, we describe two new heuristics to construct broadcast trees. In Section 4, an $O(e \log e)$ algorithm to determine the *maximum critical energy* (to be defined in Section 4) of a general network G following a broadcast from node s. In Section 5, we show how each of the heuristics of Sections 2 and 3 may be adapted to construct a broadcast tree with the property that the residual network has maximum critical energy. The adapted heuristics are called *optimal lifetime heuristics.* Simulation results (Section 6, show that the adaptation of Section 4 increases network lifetime regardless of which of the heuristics of Section 3 is used.

Heuristic $DSA(G, s)$ {

Step 1: Use Dijkstra's shortest paths algorithm (for example) to find a shortest path from s to every other vertex of G.

Step 2: Superimpose these shortest paths to obtain a broadcast tree rooted at s.

Step 3: Perform a sweep over the nodes, restructuring T to reduce total energy required by broadcast tree.

}

Figure 1: DSA minimum energy broadcast tree heuristic

2 Review Of Heuristics Of [27, 28]

In this section, we provide a brief description of the four greedy heuristics–DSA, MST, BIP, BIPPN–described in Wieselthier et al. [27, 28] to construct minimum energy broadcast trees. Later, in Section 5, we show how these heuristics may be modified to incorporate our maximum critical energy criterion.

The DSA Heuristic

The DSA (Dijkstra's shortest paths algorithm) heuristic[1] constructs a shortest path from the source node s to every other vertex in G. This, for example, could be done using Dijkstra's shortest paths algorithm [20]. The constructed shortest paths are superimposed to obtain a tree T rooted at s. Finally, a sweep is performed over the nodes of T. In this sweep, nodes are examined in ascending order of their index (i.e., in the order 1, 2, 3, $\cdots$, n). The transmission energy $\tau(i)$ for node i is determined to be the

$$\max\{w(i, j) | j \text{ is a child of } i \text{ in } T\}$$

If using $\tau(i)$ energy, node i is able to reach any descendents other than its children, then these descendents are promoted in the broadcast tree T and become additional children of i.

The DSA heuristic is summarized in Figure 1.

Wieselthier et al. [27, 28] note that performing the sweep operation results in a significant reduction in the energy required by the broadcast tree. They also note that although applying the sweep a second time results is some additional improvement, further applications of the sweep "provide little improvement"[2].

[1]This is the BLU heuristic of [27, 28] augmented with the sweep pass of [27, 28].

[2]In our implementation of the sweep method for the DSA heuristic as well as for each of the remaining heuristics dicussed in this paper, we apply the sweep once. Also, the sweep is done by examining the nodes of T from the root to the leaves rather than in order of node index.

Heuristic $MST(G, s)$ {

Step 1: T = minimum-cost spanning tree obtained using Prim's algorithm;

Step 2: Perform a sweep over the nodes, restructuring T to reduce total energy required by broadcast tree.

}

Figure 2: MST minimum energy broadcast tree heuristic

The MST Heuristic

The MST (minimum spanning tree) heuristic[3] uses Prim's algorithm [20] to construct a minimum-cost spanning tree (the cost of a spanning tree is the sum of its edge weights). The constructed spanning tree is restructured by performing a sweep over the nodes. The MST heuristic is summarized in Figure 2.

The BIP Heuristic

The BIP (broadcast incremental power) heuristic[4] begins with a tree T that comprises only the source node s. The remaining nodes are added to T one node at a time. The next node u to add to T is selected so that u is a neighbor of a node in T and $E(T \cup \{u\}) - E(T)$ is minimum. Once the broadcast tree is constructed, a sweep is done to restructure the tree so as to reduce the required energy.

The BIP heuristic is summarized in Figure 3.

The BIPPN Heuristic

The BIPPN (broadcast incremental power per node) heuristic[5] begins with a tree T that comprises only the source node s and uses several rounds to grow T into a broadcast tree. To describe the growth procedure, we define $E(T, v, i)$, where $v \in T$, to be the minimum incremental energy (i.e., energy above the level at which v must broadcast to reach its present children in T) needed by node v so as to reach i of its neighbors that are not in T (of course, only neighbors j such that $ce(v) \geq w(v, j)$ are to be considered). Let $R(T, v, i) = i/E(T, v, i)$. Note that $R(T, v, i)$ is the inverse of the incremental energy needed per node added to T. In each round of BIPPN, we determine v and i such that $R(T, v, i)$ is maximum. Then, to T, we add the i neighbors of v that are not in T and can be reached from v by incrementing v's broadcast energy by $E(T, v, i)$. The i neighbors are added to T as children of v.

[3]This is the BLiMST heuristic of [27] augmented with a sweep pass.
[4]This is the BIP heuristic of [27, 28] augmented with a sweep pass.
[5]This is the node-based MST heuristic of [28] augmented with a sweep pass.

Heuristic $BIP(G, s)$ {

Step 1: // construct a broadcast tree T
$T = \{s\}$;
for $i = 1$ **to** $n - 1$ **do** {
Let u be a node that is not in T but is a neighbor of a node in T and such that $E(T \cup \{u\}) - E(T))$ is minimum.
$T = T \cup \{u\}$;
}

Step 2: Perform a sweep over the nodes, restructuring T to reduce total energy required by broadcast tree.

}

Figure 3: BIP minimum energy broadcast tree heuristic

Heuristic $BIPPN(G, s)$ {

Step 1: // construct a broadcast tree T
$T = \{s\}$;
while $|T| < n$ **do** {
Determine $v \in T$ and $i > 0$ such that $R(T, v, i)$ is maximum.
Add to T the i neighbors of v
not in T that can be reached using $E(T, v, i)$ incremental energy.
These i neighbors are added as children of v.
}

Step 2: Perform a sweep over the nodes, restructuring T to reduce total energy required by broadcast tree.

}

Figure 4: BIPPN minimum energy broadcast tree heuristic

Once the broadcast tree is constructed, a sweep is done to restructure the tree so as to reduce the required energy. The BIPPN heuristic is summarized in Figure 4.

3 Two New Heuristics For Broadcast Trees

We describe two new greedy heuristics–BIPWLA (broadcast incremental power with look ahead) and MEN (maximum energy node)–to construct broadcast trees. The first of these (BIPWLA) is an adaptation of the look ahead heuristic proposed by Guha and Khuller [12] for the connected dominating set problem. This heuristic, which also may be viewed as an adaptation of BIPPN, attempts to construct broadcast trees with smaller energy requirement by doing a limited look ahead. The second heuristic (MEN) doesn't explicitly attempt to construct boradcast trees with low energy requirement. Rather, it favors the use of high-energy nodes as relays (non-leaf nodes) of the broadcast tree so as to preserve the energy of low-energy nodes. This strategy is expected to increase lifetime.

The BIPWLA Heuristic

Let $ce(i)$ be the current energy at node i of the network before sending a message. In BIPWLA, we begin with a tree T that comprises the source node s together with all neighbors of s that are reachable from s using $ce(s)$ energy. Initially, the source node s is colored black, all other nodes in T are gray and nodes not in T are white. Nodes not in T are added to T in rounds. In a round, one gray node will have its color changed to black and one or more white nodes will be added to T as gray nodes. It will always be the case that a node is gray iff it is a leaf of T, it is black iff it is in T but not a leaf, it is white iff it is not in T. In each round, we select one of the gray nodes g in T; color g black; and add to T all white neighbors of g that can be reached using $ce(g)$ energy. The selection of g is done in the following manner. For each gray node $u \in T$, let n_u be the number of white neighbors of u reachable from u by a broadcast the uses $ce(u)$ energy. Let p_u be the minimum energy needed to reach these n_u nodes by a broadcast from u. Let,

$$A(u) = \{j|w(u,j) \leq ce(u) \text{ and } j \text{ is a white node}\}$$

We see that $n_u = |A(u)|$ and $p_u = \max\{w(u,j)|j \in A(u)\}$.

For each $j \in A(u)$, we define the following analogous quantities

$$B(j) = \{q|w(j,q) \leq ce(j) \text{ and } q \text{ is a white node}\}$$

$$n_j = |B(j)|$$

$$p_j = \max\{w(j,q)|q \in B(j)\}$$

Node g is selected to be the gray node u of T that maximizes

$$n_u/p_u + \max\{n_j/p_j|j \in B(u)\}$$

Once the broadcast tree is constructed, a sweep is done to restructure the tree so as to reduce the required energy.

The BIPWLA heuristic is summarized in Figure 5.

Heuristic $BIPWLA(G, s)$ {

Step 1: // construct a broadcast tree T

$T = \{s\} \cup \{j | w(s, j) \leq ce(s)\}$;

Color s black, and all other nodes of T gray, all nodes not in T white.

while $|T| < n$ **do** {

Let g be the gray node u of T that maximizes $n_u/p_u + \max\{n_j/p_j | j \in B(u)\}$.

Make g a black node.

Add the nodes of $A(g)$ to T as children of g.

Color the nodes of $A(g)$ gray.

}

Step 2: Perform a sweep over the nodes, restructuring T to reduce total energy required by broadcast tree.

}

Figure 5: BIPWLA minimum energy broadcast tree heuristic

The MEN Heuristic

The MEN (maximum energy node) heuristic attempts to use nodes that have more available energy as non-leaf nodes of the broadcast tree thereby preserving the energy of low-energy nodes, which become leaves of the broadcast tree (recall that the leaves of a broadcast tree expend no energy in our model). In MEN, we start with $T = \{s\}$. At each step, we determine Q such that

$$Q = \{u | u \text{ is a leaf of } T \text{ and } u \text{ has a neighbor } j,\ j \notin T, \text{ for which } w(u, j) \leq ce(u)\} \tag{1}$$

From Q, we select the node u that has maximum energy $ce(u)$. All neighbors j of u not already in T and which satisfy $w(u, j) \leq ce(u)$ are added to T as children of u. This process of adding nodes to T terminates when T contains all nodes of G (i.e., when T is a broadcast tree).

Finally, a sweep is done to restructure the tree so as to reduce the required energy. The MEN heuristic is summarized in Figure 6.

4 The Maximum Critical Energy Algorithm

In this section, we first define the maximum critical energy problem and state its relevance to maximum lifetime brodcasting. Then, we develop a polynomial-time algorithm to solve this problem.

Heuristic $MEN(G, s)$ {

Step 1: // construct a broadcast tree T
$T = \{s\}$;
while $|T| < n$ **do** {
Let Q be as defined in Equation 1.
Let $u \in Q$ be such that $ce(u)$ is maximum.
$T = T \cup \{$neighbors j of u not in T for which $w(u, j) \leq ce(u)\}$;
}

Step 2: Perform a sweep over the nodes, restructuring T to reduce total energy required by broadcast tree.

}

Figure 6: MEN minimum energy broadcast tree heuristic

4.1 Problem Definition

Let T be a broadcast tree. Following a broadcast using the broadcast tree T, the residual energy, $re(i, T)$, at node i is

$$re(i, T) = ce(i) - \max\{w(i, j) | j \text{ is a child of } i \text{ in } T\} \geq 0$$

The critical energy, $CE(T)$, following the broadcast is defined to be

$$CE(T) = \min\{re(i, T) | 1 \leq i \leq n\}$$

In the *maximum critical energy problem* (MCEP), we are given a network and a source node s and are to find a broadcast tree T rooted at s such that $CE(T)$ is maximum. This maximum value of $CE(T)$ is called the *maximum critical energy* and is denoted $MCE(G, s)$.

Intuitively, by using a broadcast tree T that maximizes $CE(T)$, we maximize our chances of being able to complete the next broadcast request. Hence, we expect to prolong network lifetime by maximizing $CE(T)$ following each broadcast.

4.2 Algorithm for $MCE(G, s)$

Given a source node s, our strategy to determine $MCE(G, s)$ is to first obtain a sorted list, L, of candidate values for MCE. Next, we perform a binary search on the values in L to determine $MCE(G, s)$.

Determine Candidate List L

For each node i of G, define the set $a(i)$ of residual energy values as below

$$a(i) = \{ce(i) - w(i,j) | (i,j) \text{ is an edge of } G \text{ and } ce(i) \geq w(i,j)\}$$

Let $l(i)$ denote the set of all possible values for $re(i)$ following the broadcast. We see that

$$l(i) = \begin{cases} a(i) & \text{if } i = s \\ a(i) \cup \{ce(i)\} & \text{otherwise} \end{cases}$$

Consequently, the sorted list of all possible values for $MCE(G,s)$ is given by

$$L = sort(\cup_{1 \leq i \leq n} l(i))$$

We assume that G is represented using adjacency lists [20]. Since each $l(i)$ may be computed in $O(d_i^{out})$ time, where d_i^{out} is the out-degree of node i, all $l(i)$ may be computed in $O(n+e) = O(e)$ time. From the $l(i)$s, L may be computed in $O(e \log e)$ time using a sort method such as merge sort [20]. So, the total time needed to compute L is $O(e \log e)$. Note that $|L| = O(e)$. Let *computeL*(G,s) denote an algorithm that determines the sorted list L using the strategy just described.

Feasibility Check

We may determine whether G has a broadcast tree rooted at s such that $CE(T) \geq q$ by performing either a breadth-first or depth-first search [20] starting at vertex s. This search is forbidden from using edges (i,j) for which $ce(i) - w(i,j) < q$. Breadth-first (depth-first) search modified to not use forbidden edges is called a *pruned breadth-first (depth-first) search*. It is easy to verify that G has a broadcast tree rooted at s such that $CE(T) \geq q$ iff the pruned search reaches all n vertices of G. When G is represented using the adjacency list representation, a breadth-first (depth-first) search, and hence also the pruned search, takes $O(n+e) = O(e)$ time. Let $feasibile(G,s,q)$ be an algorithm that performs either a pruned breadth-first or pruned depth-first search and returns the value **true** iff the search reaches all vertices of G.

The MCE Algorithm

Figure 7 gives the algorithm to determine $MCE(G,s)$. As stated earlier, this algorithm first determines L, the sorted list of possible values for $MCE(G,s)$, and then performs a binary search over the values in L to determine $MCE(G,s)$.

As noted earlier, the complexity of *computeL* is $O(e \log e)$ and that of $feasible$ is $O(e)$. Since $|L| = O(e)$, the binary search invokes $feasible$ $O(\log e)$ times. So, the overall complexity of algorithm MCE is $O(e \log e)$.

Algorithm $MCE(G, s)$ {
$L = computeL(G, s)$; // sorted list of possible MCE values
// binary search on L
$left = 0$; $right = |L| - 1$;
$MCE = -1$;
while $left \leq right$ **do**
$middle = (left + right)/2$;
if $feasible(G, s, L[middle])$
$\{MCE = L[middle];\ left = middle + 1;\}$
else $right = middle - 1$;
}
return MCE;
}

Figure 7: Compute maximum critical energy

5 Optimal Lifetime Heuristics

To service a large and unknown sequence of broadcast requests we need to reduce the probabilty of depeleting the energy in any node. Two heuristics to accomplish this are–(1) for each broadcast request, use a broadcast tree that maximizes the critical energy and (2) use a minimum energy broadcast tree. The down side to using the second strategy is that following the very first broadcast, we may be left with nodes with very small (or zero) residual energy (i.e., the critical energy becomes small); causing future broadcasts to fail. Although the first strategy maximizes the critical energy following a broadcast, there are several broadcast trees that have the same maximum critical energy $MCE(G, s)$. Intuitively, we expect to maximize lifetime if from the set of broadcast trees that maximize the critical energy, we use a broadcast tree that uses minimum total energy. Hence we propose coupling the two proposed strategies.

Each of the heuristics described in Sections 2 and 3 may be modified so as to construct a low-energy broadcast tree T for which $CE(T) = MCE(G, s)$. For this modification, we first compute $MCE(G, s)$ using Algorithm MCE (Figure 7). Next, we run a pruned version of the desired heuristic. In this pruned version, the use of edges for which $ce(i) - w(i, j) < MCE(G, s)$ is forbidden. The modified heuristic, called an *optimal lifetime heuristic* is summarized in Figure 8. We use the letter H to denote any of the heuristics of Sections 2 and 3. For example, when $H = BIP$, OLH is $OLBIP$ and $prunedH$ is $prunedBIP$ (the pruned version of Heuristic BIP).

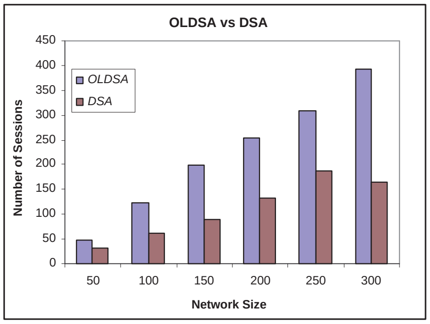
Heuristic $OLH(G, s)$ {
  $mce = MCE(G, s)$;
  $prunedH(G, s, mce)$;
}

Figure 8: Generic optimal lifetime heuristic

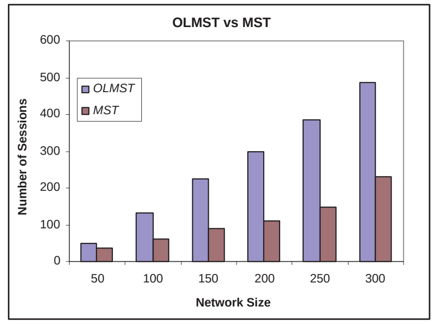
6 Simulation Results

The performance of all of the heuristics described in this paper was evaluated using random graphs generated in a manner similar to that used in [27, 28] to generate test graphs. We experimented with networks that have $n \in \{50, 100, 150, 200, 250, 300\}$ nodes. For each n, we generated 10 random graphs. Each random graph was generated by randomly assigning the n nodes to points in a 20×20 grid. The maximum permissible transmission energy for a node was set to $P_{max} = 25$. We computed $w(i, j) = r(i, j)^d$, where $r(i, j)$ is the Euclidean distance between nodes i and j, and d was set to 2. Edges with $w(i, j) > P_{max}$ were discarded. The initial energy available to a node was randomly assigned as an integer in the range $[300, 600]$. For each network, we generated 10 random broadcast sequences $B = b_1, b_2, \cdots$ (each b_i is just a source node index for a unit-length broadcast). The maximum lifetime for each network-broadcast sequence combination (G, B) was determined by running the appropriate heuristic with source vertices in the order $b_1, b_2, \cdots$ until the first b_j for which a broadcast tree could not be constructed. Following the successful construction of a broadcast tree, the energy of each node was updated to its residual energy. The lifetime for (G, B) is $j - 1$. In this way, for each heuristic and each value of n, 100 lifetime values were obtained. Figures 9, 10 and 11 (line 1 of each table) give the average value of these lifetimes. Figure 11 gives the minimum (line 2), maximum (line 3), and mean (line 4) percentage increase in lifetime provided by the optimal lifetime version of each base heuristic for the cases $n = 100$ and 200 and Figure 12 gives the average lifetimes and percent increase in average lifetime for all networks in our test set. The standard deviation in this percentage improvement also is provided (line 5).

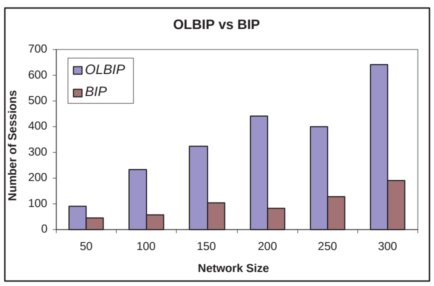
We see that for each of the six minimum-energy heuristics considered in this paper, the average lifetime of OLH is significantly more than that of H. For example, the average lifetime of $OLDSA$ is 98.7% more than that of DSA. For $H = MST$, BIP, $BIPPN$, MEN, and $BIPWLA$, the improvement in lifetime obtained by OLH is, respectively, 111%, 280.1%, 328.9%, 48.3%, and 355.8%. As far as lifetime is concerned, the best heuristic is $OLBIPPN$. It is interesting to note that the worst OL heuristic, $OLMEN$ with an average lifetime of 213 is significantly superior to the best minimum-energy broadcast tree heuristic MEN; for MEN, the average lifetime is 143.7. This indicates the value of coupling the



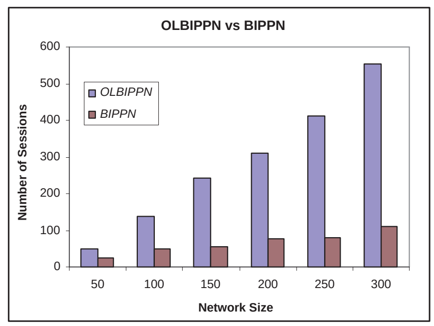
(a) OLDSA vs DSA



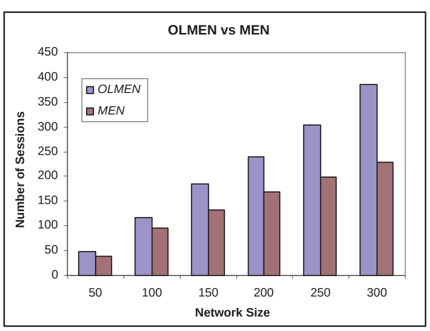
(b) OLMST vs MST



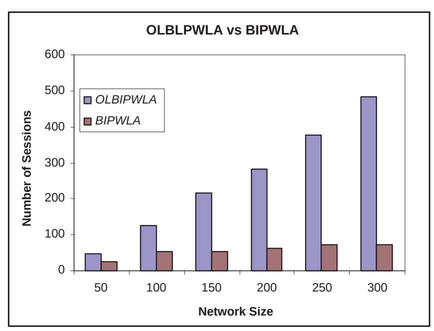
(c) OLBIP vs BIP



(d) OLBIPPN vs BIPPN



(e) OLMEN vs MEN



(f) OLBIPWLA vs BIPWLA

Figure 9: Average lifetimes

MCE algorithm with a minimum-energy broadcast tree heuristic, as is done in OLH.

In addition to the experiments just reported, we conducted experiments with random graphs on 20×20 grids under each of the following scenarios:

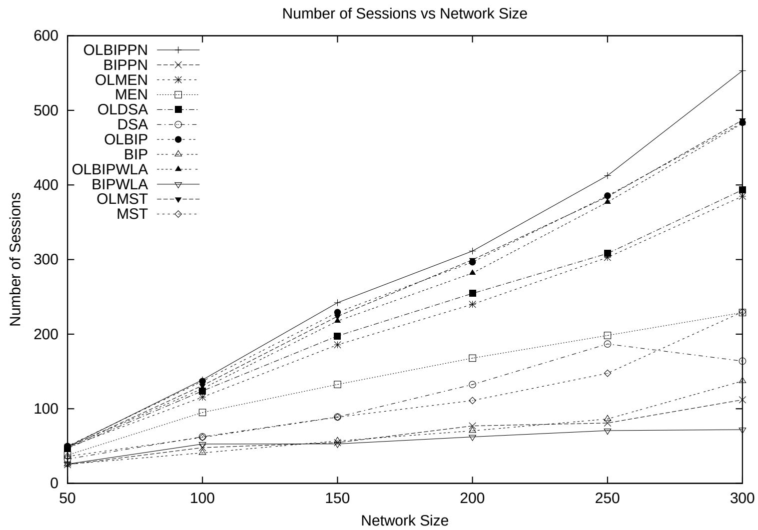


Figure 10: Average network lifetime

1. $P_{max} = 25$, $d = 2$, and initial node energy a random number in the range [1000,2000].

2. $P_{max} = \infty$, $d = 2$, and initial node energy a random number in the range [1000,2000].

3. $P_{max} = 625$, $d = 4$, and initial node energy a random number in the range [3000,6000].

Also, random graphs on a 100×100 grid with $P_{max} = 625$, $d = 2$ and initial node energy being a random number in the range [15000,30000] were used. The conclusion from these additional experiments is the same–the OLH version of each heuristic H has a much larger lifetime.

Although the OLH heuristics improve lifetime, they generally do this at the expense of increased energy utilization. Figures 13 and 14 give the energy used per broadcast session. As can be seen, each optimal lifetime heuristic generates broadcast trees that use more energy, on average, than the broadcast trees produced by its non-optimal lifetime counterpart. For example, $OLDSA$ uses about 6.4% more energy per broadcast than does DSA. The corresponding percentages for MST, BIP, $BIPPN$, MEN and $BIPWLA$ are 18%, 12.9%, 19.8%, 12.2% and 5.7%. Of the heuristics we tested, $BIPPN$ generated broadcast trees that used the least energy. Despite this, the network lifetime using $BIPPN$ is lower than that with any other of the tested heuristics; an exception being $BIPWLA$. By coupling the MCE algorithm with $BIPPN$ to obtain $OLBIPPN$, network lifetime is increased 328.9%, while energy consumption increases 19.9%; $OLBIPPN$ has the best lifetime of the tested heuristics.

	OLDSA	*DSA*	*OLMST*	*MST*	*OLBIP*	*BIP*
Avg	123.8	61.7	131.1	61.6	139.3	40.6
Min	38.5		90.5		176.6	
Max	151.6		178.6		312.2	
Mean	101.6		118.9		244.7	
Std Dev	36.4		56.7		46.2	
	OLBIPPN	*BIPPN*	*OLMEN*	*MEN*	*OLBIPWLA*	*BIPWLA*
Avg	139.4	48.3	115.5	95.0	127.3	53.4
Min	64.8		9.4		71.7	
Max	259.6		45.2		221.3	
Mean	185.0		21.4		140.8	
Std Dev	53.9		13.4		57.5	

(a) $n = 100$

	OLDSA	*DSA*	*OLMST*	*MST*	*OLBIP*	*BIP*
Avg	254.5	132.0	299.7	111.0	296.6	71.4
Min	40.0		137.4		233.3	
Max	181.4		225.8		395.5	
Mean	107.4		176.7		317.5	
Std Dev	59.2		47.7		57.2	
	OLBIPPN	*BIPPN*	*OLMEN*	*MEN*	*OLBIPWLA*	*BIPWLA*
Avg	311.4	77.0	240.0	167.9	281.9	62.4
Min	217.6		24.0		223.5	
Max	404.3		53.3		408.2	
Mean	307.1		42.9		359.1	
Std Dev	63.1		9.8		59.5	

(b) $n = 200$

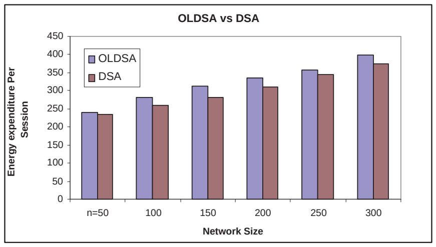
Figure 11: Network lifetime statistics for $n = 100$ and 200

	OLDSA	*DSA*	*OLMST*	*MST*	*OLBIP*	*BIP*
Avg	220.8	111.2	262.2	124.3	264.2	69.5
Increase	98.7%		111.0%		280.1%	
	OLBIPPN	*BIPPN*	*OLMEN*	*MEN*	*OLBIPWLA*	*BIPWLA*
Avg	284.5	66.3	213.0	143.7	256.0	56.2
Increase	328.9%		48.3%		355.8%	

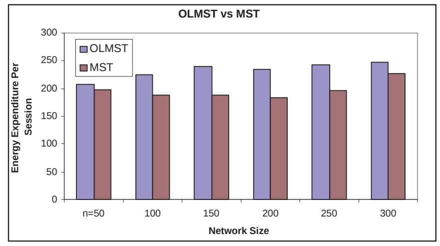
Figure 12: Average lifetime over all test networks

7 Conclusion

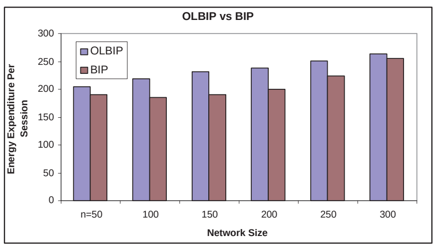
We have developed an $O(e \log e)$ algorithm to construct a broadcast tree that maximizes the critical energy of the network following the broadcast. When this algorithm is coupled with a heuristic for



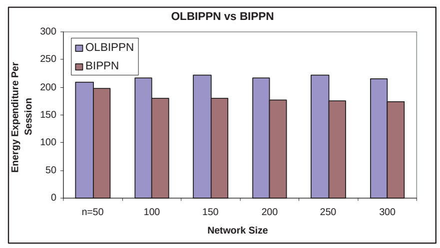
(a) OLDSA vs DSA



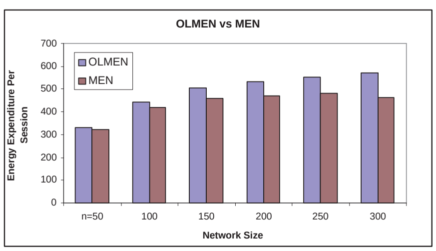
(b) OLMST vs MST



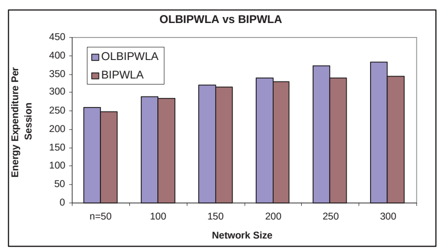
(c) OLBIP vs BIP



(d) OLBIPPN vs BIPPN



(e) OLMEN vs MEN



(f) OLBIPWLA vs BIPWLA

Figure 13: Average energy per session

minimum-energy broadcast trees, the result is a heuristic that significantly increases lifetime relative to that obtained by the original heuristic. For the 6 minimum-energy broadcast tree heuristics of Section 3, lifetime improved, on average, by a low of 48.3% for the MEN heuristic to a high of 328.9% for the $BIPPN$ heuristic. In the absence of the critical energy constraint, our newly proposed heuristic, MEN, yields maximum lifetime (from among the 6 heuristics considered in this paper).

Our work shows that although minimum-energy broadcast tree heuristics result in low-energy broadcast trees, the use of these broadcast trees doesn't result in good network lifetime. Network lifetime is enhanced significantly by incorporating the critical energy constraint into each minimum-energy broad-

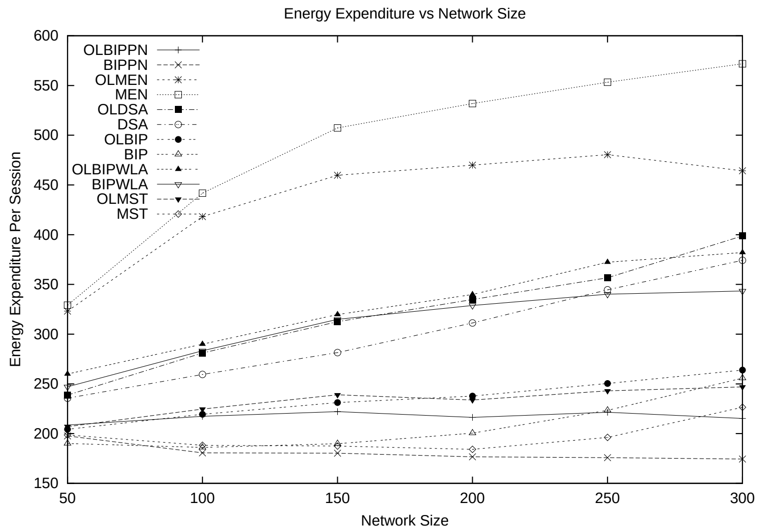


Figure 14: Average energy expenditure per session

cast tree heuristic.

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