

Energy Efficient Broadcast with Sectored Antennas in Wireless Ad Hoc Networks

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Abstract

In this paper we address the problem of energy-efficient broadcast in wireless ad hoc networks. We first extend the broadcast incremental power algorithm (BIP) [4] – an efficient algorithm to construct broadcast trees – to support sectored antennas. Secondly, we simulate and extensively compare the original BIP algorithm with the extended and modified BIP. The simulation shows drastic reduction in the total and average power consumption. Using three-sector antennas, for example, results in a 60-65% reduction in power consumption, and using six-sector antennas result in 80-82% power reduction. Moreover, we analyze the effects of sectoring, node density, and various attenuation exponents on the power consumption.

KEY WORDS

Broadcast, Energy, Routing, Sectored-Antennas, Wireless

1 Introduction

Broadcasting is a communication paradigm that allows to send data packets from a source to multiple receivers. Broadcasting and multicasting in wireless ad hoc networks are critical mechanisms in various applications such as information diffusion, sensor networks, and also for maintaining consistent global network information. Broadcasting is more efficient than sending multiple copies of the same packet through unicast. Wireless ad hoc networks are energy limited because the nodes are usually battery-powered. Therefore, it is highly important to use power-efficient broadcast algorithms for such networks.

Wieselthier, et al [4] proposed three power-aware broadcast tree construction algorithms. These algorithms construct a broadcast tree by: superimposing the shortest unicast paths; building the minimum spanning tree; or growing a tree by adding nodes that result in a minimal power increment. The last algorithm is called Broadcast Incremental Power algorithm (BIP). This algorithm

is similar to Prim’s algorithm to construct a minimum spanning tree (MST), starting from one set which initially contains only the source node, a new node with the minimum “incremental power” – the additional power necessary to reach the new node – is added to the set at each iteration. The algorithm stops when the set contains all the nodes. They also simulate and compare the performance (in terms of power consumption) of these different algorithms. The simulation comparison for randomly distributed nodes reveals that the difference in power consumption between these algorithms is not significant.

Wan, et al [3] introduced “Average BIP” (ABIP), a modified version of BIP. In ABIP, at each iterative step of the original BIP, multiple nodes are added to the broadcast tree. The set of added nodes is the one with minimum average incremental power. However, ABIP performs only slightly better than the original BIP in some cases, and can be worse in other cases. They have shown theoretical bounds on the power consumption on these various algorithms. Specially, the approximation ratio of BIP to the optimum is between $\frac{13}{3}$ and 12.

In this paper, we show that extending BIP to use sectored antennas can significantly reduce the energy consumption while keeping the algorithm very simple.

This paper is organized as follows. In section 2, we present our extension of BIP that takes advantage of sectored antennas. In section 3, we show the simulation results for sectored BIP under various node densities, propagation scenarios, and antenna types. Finally, we analyze our results and provide directions for future research.

2 BIP with sectored antennas

BIP assumes the use of an omnidirectional antenna. Using omnidirectional antennas results in energy waste for two main reasons. Firstly, in sparse or moderately crowded networks, not all sectors (directions) have receiving nodes. For example, in Figure 1), node A needs only one sector (upper-right) to broadcast to nodes B and C . Secondly, when a node B receives a broadcast packet from node A and retransmits it to D , the energy spent retransmitting in the opposite direction of reception, i.e., the lower sector of B , is generally wasted because the nodes located in that direction such as C have probably already received that packet from A ’s transmission (Figure 1). BIP is extended to multi-sector antennas by considering one sector at a time. To cover a new node only the power transmission level of a single sector “responsible” for that direction is increased. In the following we will model an omnidirectional antenna as a single sector antenna. The simulation results are presented in Section 3. They show that with 3-sector antennas, we reduce the average power consumption by at least 60%.

The implementation of our algorithm is similar to Prim’s algorithm [1]. Initially, the priority queue contains all the nodes, the queue is keyed on the minimal incremental power necessary to reach each node. At the start of the algorithm, we set the source node’s key to 0, and other nodes’ keys to ∞ . At each step, we remove a node v with the minimum key from the queue (with the minimal incremental power). If we denote the node responsible for v ’s removal as $\pi[v]$, which extends one of its sectored antennas to cover v , we update the keys of the remaining nodes in the priority queue based on the new transmission power levels of both v (with all sectored antennas transmitting at power level 0) and $\pi[v]$ (one of $\pi[v]$ ’s antenna transmission power has been raised in order to cover v).

The difference between our algorithm and the original BIP is that our nodes have multiple sectors,

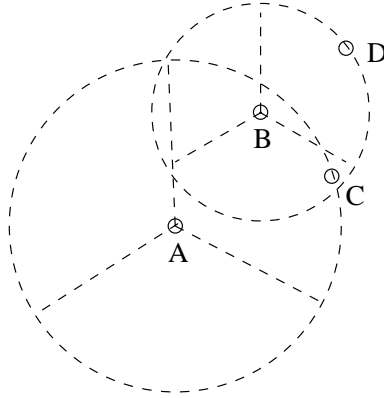


Figure 1: An example where sectored antenna is better than omnidirectional antenna

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MST-PRIM( $G, r$ )
1  $Q := V[G]$ 
2 for each  $u \in Q$ 
3   do  $\text{key}[u] := \infty$ 
4  $\text{key}[r] := 0$ 
5  $\pi[r] := \text{NIL}$ 
6 while  $Q$ 
7 do  $u := \text{EXTRACT-MIN}(Q)$ 
8   for each  $v \in Q$ 
9     do if  $\min\{\text{BIP}(u, v), \text{BIP}(\pi[u], v)\} < \text{key}[v]$ 
10        then  $\pi[v] := \text{BIP}(u, v) < \text{BIP}(\pi[u], v) ? u : \pi[u]$ 
11            $\text{key}[v] := \min\{\text{BIP}(u, v), \text{BIP}(\pi[u], v)\}$ 

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each covering some non-overlapping region, so $\pi[v]$ needs to pick one of its sectors, the one in v 's direction, raise its transmission power to cover v , while keeping the other sectors unchanged. BIP uses only one antenna sector (omnidirectional) for each node and the transmission power level in all directions is raised as a result of $\pi[v]$'s trying to cover v .

The complexity of our algorithm depends on the data structures used to implement the priority queue, as Prim's algorithm [1]. If binary heap is used to implement the priority queue, the complexity will be $O(N^2 \lg N)$, where N is the number of nodes. Note that we are assuming that every node can reach other nodes, thus the graph is fully connected, with $O(N^2)$ edges.

3 Simulation and Results

In this section, we present the simulation results of BIP with omni-directional antennas, and BIP with multi-sector antennas. The nodes are randomly placed within a square of dimension 600×700 . The nodes density is varied by taking $N = \{20, 40, 60, 100, 200, \dots, 1000\}$. The source node is randomly selected. The number of antenna sectors S is taken within $\{1, 3, 6\}$. The path loss attenuation factor α is taken within $\{2, 3, 4\}$. For each combination of N , S , and α , we take the average of 100 different input sets of N nodes.

For an antenna with S sectors, each sector's covering angle is $2\pi/S$, evenly divided between 0 and

2π . For simplicity, we assume that the antennas are broadcasting in two dimensional space. The antennas orientation is static. Since the nodes are randomly picked, and the orientation is static, the initial orientation of the antennas should have no effects on our result.

We compute the power consumption for transmission between nodes s and d with distance $d(s, t)$ as specified in [2]:

$$P(s, t) = \frac{1}{S \times d(s, t)^\alpha}$$

For multi-sector antenna ($S > 1$), the gain achieved by optimizing BIP, for example, using the “sweep” post-processing discussed by Wieselthier, et al [4], is very small. And for omnidirectional antenna, the improvement is about 20% (data not shown), much smaller compared to the gain with multiple antennas, for example, 3–sector, which results in more than 60% in the saving of power consumption.

We normalize average power consumption as:

$$P^l(sector) = \frac{P(sector)}{P(omnidirectional)}$$

where $P(sector)$ is the average power consumption using BIP with sectored antenna and $P(omnidirectional)$ is the average power consumption for BIP using omnidirectional antennas. These two values are computed using the same node topology.

Table 1: $\alpha = 2$, normalized power consumption.

N	omni	3-sector	6-sector
20	1	0.394	0.208
40	1	0.382	0.203
60	1	0.387	0.206
100	1	0.381	0.203
200	1	0.384	0.204
300	1	0.384	0.204
400	1	0.384	0.204
500	1	0.384	0.204
600	1	0.384	0.204
700	1	0.385	0.204
800	1	0.384	0.204
900	1	0.385	0.204
1000	1	0.384	0.204

Figure 2 shows the total power consumption with various node densities for $\alpha = 2$ and Table 1 shows the normalized power consumption.

Figure 3 shows the total power consumption with various node densities for $\alpha = 3$ and Table 2 shows the normalized power consumption.

Figure 4 shows the total power consumption with various node densities for $\alpha = 4$ and Table 3 shows the normalized power consumption.

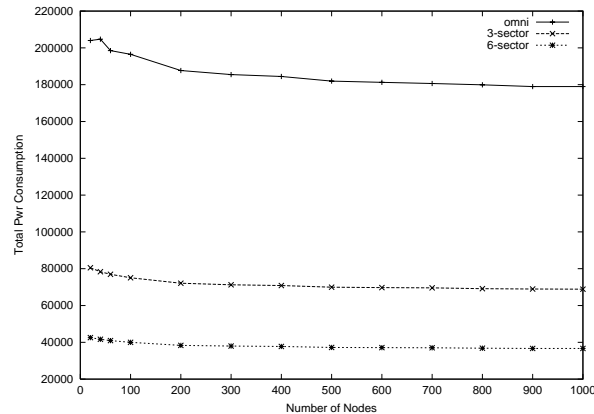


Figure 2: Total power consumption using different number of antenna sectors with various node densities, $\alpha = 2$.

Table 2: $\alpha = 3$, normalized power consumption.

N	omni	3-sector	6-sector
20	1	0.374	0.193
40	1	0.370	0.191
60	1	0.373	0.193
100	1	0.370	0.192
200	1	0.372	0.193
300	1	0.372	0.193
400	1	0.372	0.193
500	1	0.372	0.193
600	1	0.372	0.193
700	1	0.373	0.193
800	1	0.373	0.194
900	1	0.374	0.194
1000	1	0.372	0.193

4 Analysis and Discussion

It is obvious from the simulation results shown above that the use of sectored antennas drastically reduces the average energy consumption by more than 60% for BIP with 3-sector antennas, and 80% for BIP with 6-sector antennas. In the following we will attempt to provide an explanation for such energy saving.

Claim: The average number of sectors used per node is less than 1.

Proof: Assume that there are N nodes, and we color the node black if it is covered by some other node, white otherwise. Initially, the source node is colored black and all the other nodes are colored white. From the algorithm, the node will stay black once it is colored that way, but a white node can become black. At each step of our algorithm, at least one new node will be covered, thus the number of black nodes increases at least by one, but at most one new sector is used. Thus, the algorithm will

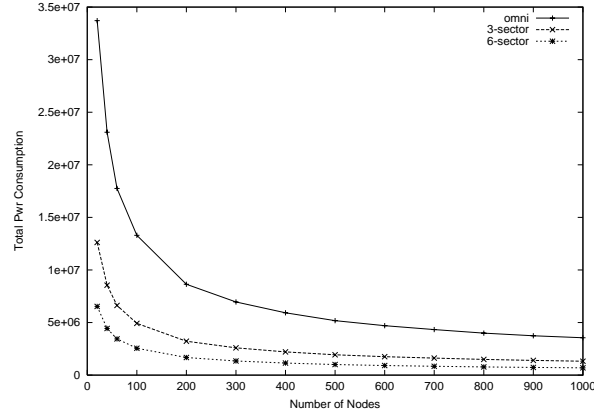


Figure 3: Total power consumption using different number of antenna sectors with various node densities, $\alpha = 3$.

Table 3: $\alpha = 4$, normalized power consumption.

N	omni	3-sector	6-sector
20	1	0.361	0.185
40	1	0.359	0.184
60	1	0.362	0.186
100	1	0.361	0.185
200	1	0.364	0.187
300	1	0.363	0.186
400	1	0.363	0.186
500	1	0.363	0.186
600	1	0.364	0.187
700	1	0.365	0.187
800	1	0.365	0.187
900	1	0.365	0.187
1000	1	0.364	0.187

terminate within $N - 1$ steps because by that time, all the nodes will be black, and we are using at most $N - 1$ sectors. So the average number of sectors per node is at most $\frac{N-1}{N} < 1$. \square

So if the broadcast tree constructed by our modified BIP results in roughly the same broadcasting paths as those by BIP, the saving in energy will be about $1 - 1/S$, where S is the number of sectors each node has. For $S = 3$, the saving is about 67%, and for $S = 6$, the saving would be 83%, which agrees well with our simulation results.

Another observation is that when the nodes density is increased, the total power consumption (i.e., summation over all nodes) tends to decrease as shown in Figures 3 and 4. The node density is increased by keeping the same simulation area (600×700) and increasing the number of nodes from 20 to 1000. Increasing the node density results in a shorter average distance between nodes. Whenever the average distance between two nodes is reduced by a factor of h , the average power increment is also reduced by a factor of h^α (where $\alpha \geq 2$). Thus when the number of nodes

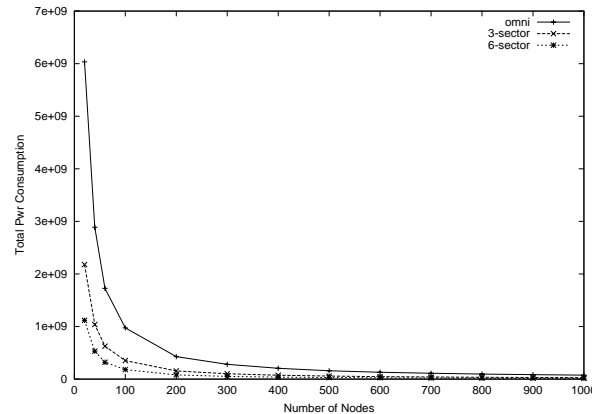


Figure 4: Total power consumption using different number of antenna sectors with various node densities, $\alpha = 4$.

increases, the average power decreases at a faster rate.

5 Conclusions

In this paper we have extended the "Broadcast Incremental Power" algorithm to handle multi-sector antennas. We have shown through extensive simulation that this results in drastic energy saving (e.g., more than 60% for a 3-sectored antenna). We also simulated the extended algorithm under various propagation constraints and node densities. We plan to extend this algorithm to handle multicast communication. In this case we plan to consider both power consumed due to transmitting packets but also due to receiving packets. This has not been addressed in the past. However, this is a major difference between multicast and broadcast since not all nodes are required to be awake to receive multicast packets. Another interesting question to be considered is the energy saving that can be obtained when considering smart antennae that can create directional beams.

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