S-GPBE: A Power-Efficient Broadcast Routing Algorithm Using Sectored Antenna

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ABSTRACT

In our previous work, we presented a power-efficient algorithm called Greedy Perimeter Broadcast Efficiency (GPBE) algorithm exploiting broadcast efficiency using an omnidirectional antenna. We showed that with remarkably simple code complexity (not computational complexity), we could derive an algorithm which is comparable to Broadcast Incremental Power (BIP) in terms of the total transmit power performance. The principle of broadcast efficiency holds even when we use an assumption that each node (host) is equipped with sectored antennas. In this paper, we extend our previous work to adapt to a sectored antenna case. A new algorithm called Sectored GPBE (S-GPBE) is proposed and the performance of this algorithm is compared with GPBE.

KEY WORDS

Broadcast, energy efficient, adhoc network, routing algorithm/protocol design and analysis, directional antenna.

1 Introduction

It has been shown that the problem of finding a broadcast routing tree using omnidirectional antennas with minimum total transmit power is NP-hard [1–3]. Hence, developing a heuristic power-efficient algorithm is crucial. The seminal work in this area is the well-known Broadcast Incremental Power (BIP) algorithm [1] with a recent addition called Embedded Wireless Multicast Advantage (EWMA) algorithm [2]. A major theme in designing a power-efficient algorithm is to fully exploit the wireless broadcast advantage.

In this paper, we address the problem of building a power-efficient broadcast routing tree using sectored antennas. We show that the *broadcast efficiency* can be a viable choice for a greedy decision metric [4], even when the directional antenna system is used in the network. The basic idea is as follows: over a whole deployed region, the wireless broadcast advantage is the most beneficial in a subregion where nodes are most densely deployed, because more nodes can be simultaneously reached with the same amount of transmit power.

The idea of using sectored antenna in wireless communications is not new. It has been already extensively used in the base stations of cellular networks for frequency reuse, to reduce interference, and to increase the capacity of allowable users within a cell [5]. However, the application of directional (smart) or sector antenna to wireless adhoc (or sensor) networks to reduce the transmit power of each node and hence to achieve the power-efficiency in routing problem is relatively new. The types of directional antenna of interest in this paper include the traditional (single element) sectored antenna (e.g., horn antenna [6]) and one class of smart antennas called switched beam antenna [7]. While the traditional sectored antenna has been used up to six sectors per cell in practice, a much larger number of sectors can be supported in switched beam antenna [7].

In [8], Wieselthier et al. first considered adaptation of directional antennas to the well-known Broadcast Incremental Power (BIP) algorithm, which was originally developed for omnidirectional antennas. Two algorithms called Reduced Beam BIP (RB-BIP) and Directional BIP (D-BIP) were introduced in [8]. In [8], the usage of adaptive array antenna (another class of smart antenna systems) is implicitly assumed, because RB-BIP or D-BIP algorithms require an unlimited number of antenna patterns and no assumption was given on the quantization of the beamwidth. RB-BIP algorithm is essentially same as BIP except that, after the BIP tree is constructed, the beamwidth of antenna is reduced to fit minimum possible angle to cover all child nodes of each node. On the other hand, D-BIP algorithm utilizes wireless broadcast advantage property [1] in the core of the algorithm while building a routing tree.

A natural extension to BIP algorithm using sectored antenna was presented in [9]. We will conveniently call this algorithm Sectored BIP (S-BIP). In S-BIP, minimum incremental power—additional power required to reach another node in the network—is calculated per-sector basis, and the transmit power level is increased only for the single sector with minimum incremental power. Although their focus is limited to traditional sector antenna systems, the same argument is also applicable to switched beam antenna systems. This shows that incremental power is a good choice for a decision metric at each greedy decision process, which is applicable to all classes of antennas. In this paper, we will show that broadcast efficiency is another good decision metric.

The remainder of this paper is organized as follows. In the next section, we briefly define the network model we use and provide background. In Section 3, we present a detailed description of our new algorithm. Section 4 summarizes our simulation results and in Section 5 we discuss asymptotic behavior of the algorithm. Section 6 concludes this paper.

2 Background and Network Model

We denote a network as a weighted directed graph $G = (N, A)$ with a set N of nodes and a set A of directed edges (links), $A = \{(i, j)\}$. For a directed edge $(i, j) \in A$, let $\pi(j)$ denote the parent node of node j (i.e., $\pi(j) = i$). Each node is labeled with a node ID $\in \{1, 2, \ldots, |N|\}$. We assume that each node (host) is equipped with multiple sectored antennas. Let S be a set of sector IDs $S = \{1, 2, \ldots, m\}$, where $|S| = m$ is the number of sectors in each node. We denote s-th sector of node i as $i_{(s)}$ and all sectors of node i as $i_{(S)}$. If $C \subseteq N$, $C_{(S)}$ denotes all sectors of the subset C. For example, if C consists of node $\{1, 4, 7\}$ and each node has three 120° sectored antennas, then $C_{(S)} = \{1_{(1)}, 1_{(2)}, 1_{(3)}, 4_{(1)}, 4_{(2)}, 4_{(3)}, 7_{(1)}, 7_{(2)}, 7_{(3)}\}$. The main objective of this paper is to construct a power-efficient (minimum total transmit power) broadcast routing tree rooted at the source node using sectored antennas.

In this paper, we assume an idealized model of a sectored antenna: (i) All input power to the sectored antenna is converted to radiated power (100% antenna efficiency). (ii) s-th sector antenna covers a two dimensional plane over an angular region $[(s-1)\frac{2\pi}{|S|}, s\frac{2\pi}{|S|})$. (iii) Within each sector, the transmit power is uniformly distributed (constant gain) over the beam width $2\pi/|S|$. (iv) To be consistent with previous work [8, 9] and for a fair comparison of the performance of algorithms , we assume that the transmit power required to reach a node at a distance d is proportional to $d^\alpha/|S|$ assuming that the proportionality constant is 1 for notational simplicity, where α is the path loss (attenuation) factor that satisfies $2 \le \alpha \le 4$. (v) On the receiver side, using directional (including sectored) antennas will provide higher receiver gain. However, although it may not be accurate, for the same reason of valid comparison, we also assume the use of omnidirectional receiving antennas (unity gain) as in [8,9]. To avoid the undue complication of notation, we also assume the receiver sensitivity threshold as 1 (0 dB).

Definition 1 (Pairwise and Node Transmit Power) *Given a spanning tree T, when node j lies within a region covered by the s-th sector of node i, the required* pairwise transmit power *$P_{i_{(s)}\to j}$ to maintain a link $(i, j) \in T$ from node i to j is $P_{i_{(s)}\to j} = P_{i\to j}/|S| = d_{ij}^\alpha/|S|$, where d_{ij} is the distance between the node i and j, and $P_{i\to j} = d_{ij}^\alpha$ denotes the pairwise transmit power with omnidirectional antenna. The* sector beam transmit power *$P_{TX}(i_{(s)})$ of s-th sector of node i is*

$$P_{TX}\left(i_{(s)}\right) = \max_{j \in \Re_{i_{(s)}}} \left\{P_{i_{(s)}\to j}\right\} \text{ for } i \in N, \tag{1}$$

where $\Re_{i_{(s)}}$ is a set of adjacent (child) nodes of s-th sector of node i in the routing tree T.

The actual node transmit power *$P_{TX}(i)$ assigned to the node i by a routing algorithm is*

$$P_{TX}(i) = \sum_{s\in S} P_{TX}\left(i_{(s)}\right) \text{ for } i \in N. \tag{2}$$

Unlike conventional wired networks, there is no permanent connection between the nodes in wireless networks. The transmit power $\{P_{TX}(i_{(S)})\}$ assigned to each sector $i_{(S)}$ (and node mobility, if it is a mobile adhoc network) determines the network topology.

Definition 2 (Physical and Logical Neighbor) *If a sector s of node i is transmitting with beam power $P_{TX}(i_{(s)})$, then the* physical neighbor *$\aleph_{i_{(s)}}$ of node i in a wireless network is a set of all the nodes within the communication boundary*

$$\aleph_{i_{(s)}} = \left\{k \mid 0 < P_{i_{(s)}\to k} \le P_{TX}\left(i_{(s)}\right)\right\}. \tag{3}$$

The logical neighbor *$\Re_{i_{(s)}}$ of sector $i_{(s)}$ is a set of adjacent nodes in a routing tree*

$$\Re_{i_{(s)}} = \{k \mid \pi(k) = i,\ k \text{ lies in } s\text{-th sector of } i\}. \tag{4}$$

In general, the logical neighbor determined by a routing algorithm need not coincide with the physical neighbor determined by a network topology and (node) transmit power. Given a spanning tree T, the *total transmit power* of this tree is

$$\mathcal{P}_{TX}(T) = \sum_{i\in N}\sum_{j\in S} P_{TX}\left(i_{(j)}\right). \tag{5}$$

3 S-GPBE Algorithm Description

In this section, we introduce another decision metric which captures the notion of wireless broadcast advantage well.

Definition 3 (Broadcast Efficiency) *The* wireless broadcast efficiency *$\beta_{i_{(j)}}$ is defined as the number of nodes reached per unit transmit beam power of sector s of node i*

$$\beta_{i_{(s)}} = \frac{\left|\aleph_{i_{(s)}}\right|}{P_{TX}\left(i_{(s)}\right)} \text{ for } i_{(s)} \in N_{(S)}, \tag{6}$$

where we assume that if $P_{TX}(i_{(s)}) = 0$, $\beta_{i_{(s)}} = 0$. Note that the transmit beam power, $P_{TX}(i_{(s)})$, is a continuous variable which can take an arbitrary value from 0 to $P_{\max}$, which is the maximum available transmit power of a transceiver. When we need to emphasize that transmit power is discretized (i.e., link (i, j) is established with minimum possible available power), we will use the notation

$$\beta_{i_{(s)}\to k} = \frac{\left|\aleph_{i_{(s)}}\right|}{P_{i_{(s)}\to k}} \text{ for } i_{(s)} \in N_{(S)},\ k \in N,\ i \ne k. \tag{7}$$

Note that assuming $\alpha = 2$, the broadcast efficiency is essentially the same as node density (up to a scale factor).

3.1 Location Dependence of Broadcast Efficiency When Using Omnidirectional Antennas

First, let's examine how broadcast efficiency is dependent on the location of a node when we use omnidirectional antenna. Assume that $|N|$ nodes are uniformly distributed

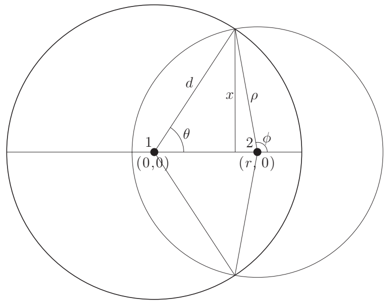

Figure 1. Dependence of broadcast efficiency on node location using omnidirectional antennas.

within a circular region of radius d as in Fig. 1.[1] Although the real situation should be modeled with a probability mass function, we will approximate with a uniform probability density function. Comparing the two nodes, one located at the center $(0,0)$ (node 1) and the other located at $(r,0)$ (node 2), we can intuitively infer that node 1 has larger broadcast efficiency than node 2. This is because more nodes can be simultaneously covered with the same transmit power from node 1 than from node 2. Considering the boundary effect of a deployed region, the broadcast efficiency of node 2 can be expressed as a function of distance from the center of the deployed region $r < d$ and the transmission range ρ of node 2 as follows:

$$\beta_2(\rho) = \begin{cases} \frac{\pi\rho^2}{\rho^2}\frac{|N|}{\pi d^2} = \frac{|N|}{d^2} & \text{if } 0 \le \rho \le d-r \\ \frac{A_1+A_2}{\rho^2}\frac{|N|}{\pi d^2} & \text{if } d-r < \rho \le d+r \\ \frac{\pi d^2}{\rho^2}\frac{|N|}{\pi d^2} = \frac{|N|}{\rho^2} & \text{if } \rho > d+r \end{cases} \tag{8}$$

where

$$A_1 = \pi\rho^2 - \rho^2\cos^{-1}\left(\frac{-r+\frac{d^2+r^2-\rho^2}{2r}}{\rho}\right)$$

$$A_2 = d^2\cos^{-1}\left(\frac{d^2+r^2-\rho^2}{2\,d\,r}\right) - d\,r\sqrt{1-\frac{\left(d^2+r^2-\rho^2\right)^2}{4\,d^2r^2}}$$

Using (8), we can get the curves shown in Fig. 2. Because of symmetry, without loss of generality, the relation in fact holds for all locations within the boundary region. Note that node 2 has the same constant broadcast efficiency $|N|/d^2$ as node 1 only in a limited range, $0 \le \rho \le d-r$.

Fig. 2 coincides with the intuition that the node located at the center has the largest broadcast efficiency. As a node moves away from the center, the broadcast efficiency is a monotonic non-increasing function of distance from the center location. From Fig. 2, we can observe that when we use an omnidirectional antenna, *the broadcast efficiency is location dependent* and *the center of symmetric deploy region is the optimal place where the broadcast efficiency can be best utilized*.

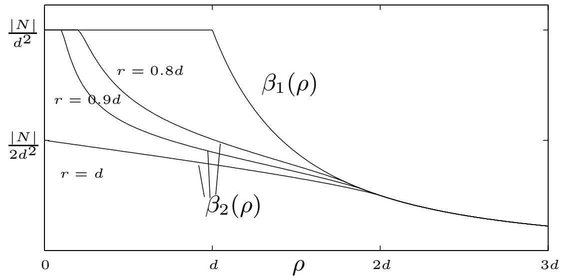

Figure 2. Comparison of broadcast efficiency of node 1 and 2 when omnidirectional antennas are used.

3.2 Less Dependence of Broadcast Efficiency on Location When Using Multiple Sectored Antennas

When omnidirectional antennas are used, we showed that the broadcast efficiency is heavily location dependent. The most illustrative example can be chosen when a node lies at the boundary of the deploy region. Whenever the node tries to reach other nodes, it is guaranteed that at least more than half of the transmit power is wasted to cover outside area of the deploy region, which is clear in Fig. 2 (refer the curve $\beta_2(\rho)$ with $r = d$).

However, this is not the case when multiple sectored antennas are used by each node. Among the sectors of a node, there always exists one sector which faces toward the center of the deploy region. Also any inefficient sectors in broadcast efficiency can be adaptively turned off. Hence, the dependence of broadcast efficiency on location is not as severe as in an omnidirectional antenna case.

3.3 Effect of Broadcast Efficiency on Routing Decision

Before we proceed further to the detailed decription of the algorithm, let's first look at a few examples of how broadcast efficiency impacts the routing decision. To account for the constraint that a directed rooted tree should be constructed, we use a slightly modified definition of broadcast efficiency. Let a set C denote the collection of nodes covered by the transmission range of other sectors of nodes. Because any node in C need not be covered again, we count only the number of newly added nodes, i.e., $\left|\aleph_{i_{(j)}} \backslash C\right|$ instead of $\left|\aleph_{i_{(j)}}\right|$ in (6).

Example 1 (Colinear topology) *Let's start with a simple topology where all nodes lie within a line segment. Node 1 tries to broadcast to other nodes. The decision by the node 1 is as follows: The broadcast efficiency is* $\beta_{12} = 3/d^2, \beta_{13} = 6/(2d)^2, \ldots, \beta_{15} = 12/(4d)^2$. *In general, when there are* $|N|$ *colinear nodes, the broadcast efficiency*

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[1] We can bound any arbitrary deploy region with the smallest circular region enclosing every node in the network.

becomes

$$\beta_{1k} = \frac{3\,(k-1)}{((k-1)\,d)^2} = \frac{3}{(k-1)d^2} \text{ for } k \geq 2. \qquad (9)$$

Because β_{1k} monotonically decreases as k gets larger, β_{12} is maximum. Hence, node 1 picks node 2 as a destination node. By repeatedly applying this greedy decision algorithm to other nodes, the routing tree shown in Fig. 3 can be constructed, which is also optimal.

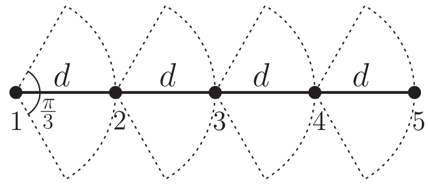

Figure 3. Routing decision for a colinear topology.

3.4 Algorithm Description

While some probabilistic analyses on broadcast efficiency were given in Section 3.1 and 3.2 by approximating a node distribution using a uniform probability density function, any specific instance of network should be modeled with probability mass function. In this case, the broadcast efficiency is not constant inside the deploy region. The algorithm presented in this section takes advantage of random fluctuations in node distribution to construct a broadcast routing tree. The basic idea is to treat each sector as a node.

Without loss of generality, let node 1 be the source node. The S-GPBE algorithm maintains four different sets: $C, C_{(S)}, F$, and R. The set C represents the nodes covered by its own transmission range or by others. $C_{(S)}$ denotes the set of all sectors of covered nodes. The set F represents the set of sectors of nodes transmitting with nonzero transmit beam power. The set R is set difference of $C_{(S)}$ and F, i.e., $R = C_{(S)} \backslash F$.

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S-GPBE Algorithm (Greedy Perimeter Broadcast Efficiency using Sectored Antenna)
$C := \{1\},\ C_{(S)} := 1_{(S)},\ F := \phi,\ R := C_{(S)} \backslash F$
$P_{TX}\left(i_{(j)}\right) := 0$ for all $i \in N$ and $j \in S$
while $(N \backslash C \neq \phi)$
    for each sector $i_{(j)} \in R$ and $k \in N \backslash C$
        find a sector and node pair $(i_{(j)}, k)$ which has the best broadcast efficiency such that
        $\left(i^*{}_{(j^*)}, k^*\right) = \underset{(i_{(j)},k) \in R \times N \backslash C}{\arg\max} \left\{ \frac{\left|\aleph_{i_{(j)}} \backslash C\right|}{P_{i_{(j)} \to k}} \right\}$    (10)
    end
    $P_{TX}\left(i^*{}_{(j^*)}\right) := P_{i^*{}_{(j^*)} \to k^*} = P_{i^* \to k^*} / |S|$
    $\Re_{i^*_{(j^*)}} := \aleph_{i^*_{(j^*)}} \backslash C$
    $F := F \cup \{i^*_{(j^*)}\}$
    $C := C \cup \aleph_{i^*_{(j^*)}}$
    $C_{(S)} := \bigcup_{i \in C} \{i_{(S)}\}$
    $R := C_{(S)} \backslash F$
end
return $\mathcal{P}_{TX}(T) := \sum_{i \in F} \sum_{j \in S} P_{TX}\left(i_{(j)}\right)$
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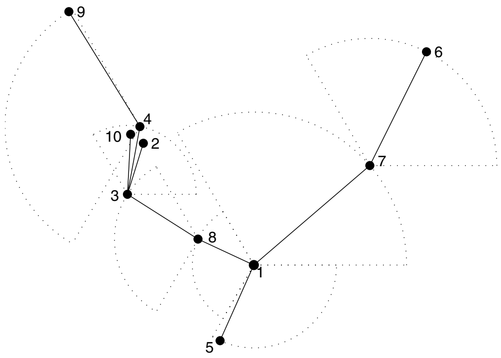

Figure 4. A sample S-GPBE tree with $|N| = 10$.

As noted earlier, due to the constraint that a directed tree rooted at the source node should be constructed, we use a slightly modified version of broadcast efficiency (10) from the original (6).

Fig. 4 shows the final tree produced by S-GPBE algorithm using 3 sectored antennas in each node for a specific topology of 10 nodes. Initially, $C = \{1\}, C_{(S)} = \left\{1_{(1)}, 1_{(2)}, 1_{(3)}\right\}, F = \phi, R = C_{(S)}$. At the first iteration, sector $1_{(2)}$ ($i^*_{(j^*)}$ in the pseudocode) picks the node 8 (j^* in the pseudocode) as a destination node, because $P_{TX}\left(1_{(2)}\right) = P_{1_{(2)} \to 8}$ gives maximum broadcast efficiency. At this stage, each set becomes $C = \{1, 8\}$, $C_{(S)} = \left\{1_{(1)}, 1_{(2)}, 1_{(3)}, 8_{(1)}, 8_{(2)}, 8_{(3)}\right\}$, $F = \left\{1_{(2)}\right\}$, $R = \left\{1_{(1)}, 1_{(3)}, 8_{(1)}, 8_{(2)}, 8_{(3)}\right\}$. At the second and third iteration, the links $\left(1_{(3)} \to 5\right)$ and $\left(8_{(2)} \to 3\right)$ are added and $C = \{1, 3, 5, 8\}$. At each stage, all combinations of broadcast efficiency $\beta_{i_{(j)} \to k}$ for $(i_{(j)}, k) \in R \times N \backslash C$ are tested. At the fourth iteration, the links $\left(3_{(1)} \to 2\right)$, $\left(3_{(1)} \to 4\right)$, and $\left(3_{(1)} \to 10\right)$ are added. Notice how multiple nodes can be added to C simultaneously with a single iteration. The following steps are straightforward and the algorithm terminates in 7 iterations when $C = N$. As is evident from Fig. 4, the greedy decision (broadcast efficiency) is usually made at the perimeters of transmission range, that is why it is called S-GPBE, and provides reasonable choices (shortest paths).

4 Simulation Model and Results

In this section, we perform simulations using the following model. Within a 1×1 km^2 square region, the network configurations (locations of nodes) are randomly generated according to a uniform distribution. The same random seeds

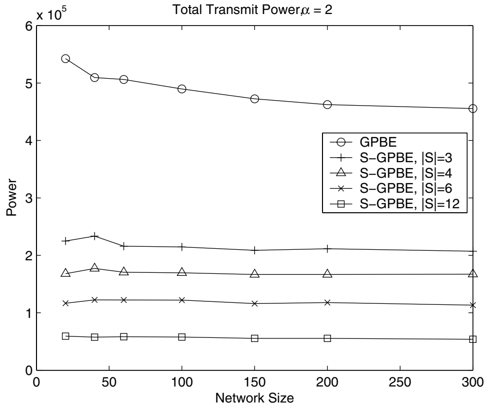

Figure 5. Comparison of total transmit power of GPBE and S-GPBE. Mean of 100 random topologies for $|S| = 1, 3, 4, 6$ and 12, where $|S| = 1$ corresponds to GPBE.

are used for a valid comparison of each algorithm. The transmit power is calculated with normalized proportionality constant (hence, $P_{ij} = d_{ij}^{\alpha}$). $\alpha = 2$ is used as a path loss factor. Broadcast routing trees rooted at the source node are constructed using the algorithm presented in the previous section. The simulation results are for stationary (non-mobile) network topologies. We place no limit on the maximum transmit power $P_{\max}$ as in [1, 2, 9].

Fig. 5 summarizes the performance comparison of S-GPBE in terms of total transmit power for various sizes of the networks $|N| = \{20, 40, 60, 100, 150, 200, 300\}$ and for sector sizes $|S| = \{1, 3, 4, 6, 12\}$, where $|S| = 1$ corresponds to GPBE. Each point in Fig. 5 represents an average value of 100 different randomly generated network topologies. Note that the total transmit power of these algorithms depends solely on the locations of nodes.

In Table 1, specific values of *normalized total transmit power* $\mathcal{P}_{TX}^{norm}\left(T_{\text{S-GPBE}}\right)$ (refer to equation 5)

$$\mathcal{P}_{TX}^{norm}\left(T_{\text{S-GPBE}}\right) = \frac{\mathcal{P}_{TX}\left(T_{\text{S-GPBE}}\right)}{\mathcal{P}_{TX}\left(T_{\text{GPBE}}\right)}$$

are listed for different sector sizes. Fig. 5 together with Table 1 clearly show that there are improvements of about 55%, 65%,76% and 88% for $|S| = 3, 4, 6,$ and $12, respectively.$ Ideally, $\mathcal{P}_{TX}^{norm}\left(T_{\text{S-GPBE}}\right) = 1/|S|$ or less is desirable but the simulation results show that each value slightly deviates from the ideal case.

5 Asymptotic Behavior

In this section, we discuss the asymptotic behavior of S-GPBE and S-BIP trees as the beamwidth θ of each sector becomes smaller (or $|S|$ becomes larger).[2] As $\theta \to 0$, link characteristics become dominant over node characteristics, because the wireless links in wireless networks tend to exhibit more wire-like characteristics such as better guided electromagnetic waves and less co-channel interference as in straight wire links .

Table 1. Normalized total transmit powers, $\alpha = 2$

$\lvert N\rvert$	$\lvert S\rvert = 3$	$\lvert S\rvert = 4$	$\lvert S\rvert = 6$	$\lvert S\rvert = 12$
20	0.414	0.309	0.215	0.109
40	0.458	0.347	0.240	0.113
60	0.426	0.337	0.241	0.115
100	0.438	0.346	0.249	0.117
150	0.441	0.352	0.245	0.117
200	0.457	0.360	0.254	0.119
300	0.454	0.367	0.248	0.118

Note that in original BIP [1], one of the two strategies, either multihop (MH) or broadcast advantage (BA), are chosen depending on whether there is wireless broadcast advantage available in the node configuration. Whenever there is broadcast advantage, BA strategy is chosen by incrementing the transmit power of a node. Otherwise, MH strategy is chosen by newly assigning a transmit power to a node. In a three node configuration, these are the optimal strategies to get minimum total transmit power. As $\theta \to 0$, the probability of choosing BA becomes negligible and for a small value of θ (say $5^\circ \sim 10^\circ$), almost always MH strategy is chosen.

Similarly in S-GPBE with a 3 node configuration, if the node nearest to the source node is d distance apart and the other node lies within $\sqrt{2}d$, BA strategy is chosen; otherwise, MH strategy will be chosen. In both algorithms, the resulting trees asymptotically converge to the minimum weight spanning tree (MST) as $\theta \to 0$, where the total transmit power is calculated per-link basis. (In omnidirectional antenna case, the transmit power of each node is calculated per-node basis by choosing the maximum power among the links.) However, BIP converges to MST faster than S-GPBE, because BIP is based on an optimal strategy for a three node configuration. This can be easily proved with simple probabilistic arguments. Fig. 6 illustrates how S-GPBE converges to MST as the beamwidth becomes smaller. When $|S| = 36$ or the beamwidth of each sector is $\theta = 10^\circ$, S-GPBE becomes the same tree as MST. (Note that the structure of MST does not change whether omnidirectional or directional antennas are used.)

6 Conclusions

In this paper, we have presented another power-efficient broadcast routing algorithm, S-GPBE, which can be used in conjunction with directional antenna systems including traditional sectored antenna and switched beam smart antenna. This algorithm effectively exploits the broadcast efficiency in broadcast routing tree construction. Especially because the research on power-efficient routing using direc-

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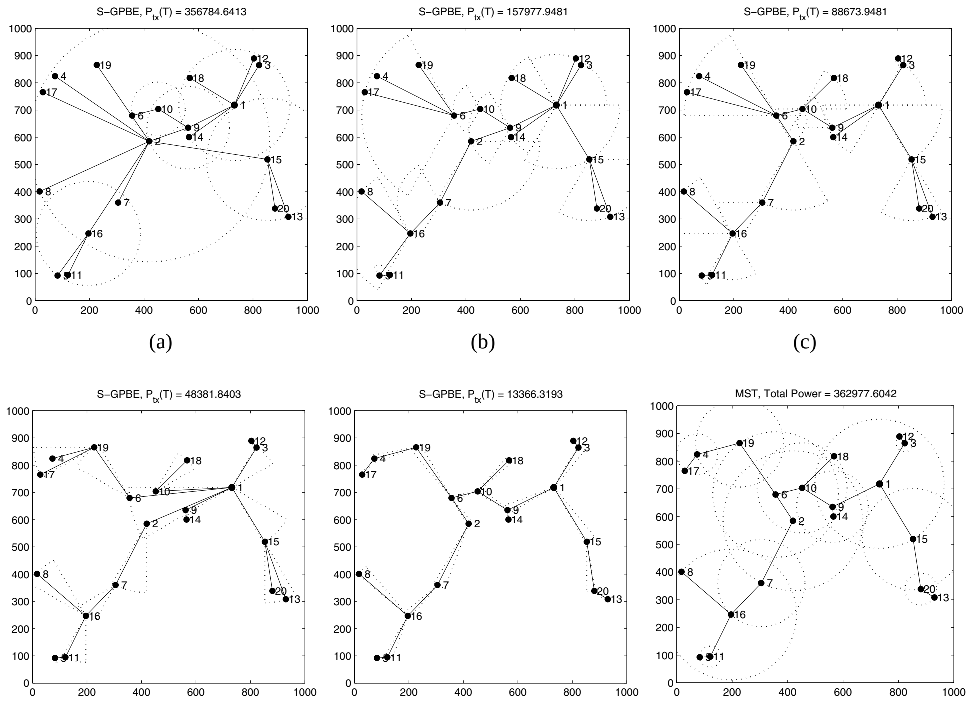
[2] As noted earlier, up to 6 sectors per cell have been used in practice. When $|S| > 6$, we can consider it as switched beam antenna systems.



(a) (b) (c)

(d) (e) (f)

Figure 6. The convergence of S-GPBE to MST as $\theta \to 0$. A sample broadcast routing tree by (a) GPBE, (b) S-GPBE with 3 sectors, (c) S-GPBE with 6 sectors, (d) S-GPBE with 12 sectors, (e) S-GPBE with 36 sectors, and (f) MST.

tional antenna is still at its early stage, we believe richness in various approaches to solve a given problem will provide more insights into the problem and, hopefully, better algorithms and heuristics can be developed.

The greedy decision criteria used in MST and BIP can be considered as the most "conservative" greedy metrics, because only a single node is allowed to be added to a tree at each iteration. In this paper, we presented a more "aggressive" greedy metric, broadcast efficiency, which allows the addition of multiple nodes at the same time. The simulation results imply that this metric may be too aggressive: because in the current version of algorithm, once the transmit power is determined, it is not allowed to change afterwards. Further enhancement of the algorithm by relaxing this constraint to achieve better performance is one of our future research directions.

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