A Novel Power-Efficient Broadcast Routing Algorithm Exploiting Broadcast Efficiency

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***Abstract*— It has been shown that the problem of finding a broadcast routing tree with minimum total transmit power is NP-hard. Hence, developing a heuristic power-efficient algorithm is crucial. The seminal work in this area is the well-known Broadcast Incremental Power (BIP) algorithm with a recent addition called Embedded Wireless Multicast Advantage (EWMA) algorithm. In this paper, we present yet another novel power-efficient algorithm for broadcast routing tree construction called Greedy Perimeter Broadcast Efficiency (GPBE) algorithm. We also compare the performance of these algorithms.**

I. Introduction

The problem of constructing a broadcast routing tree with minimum total transmit power has been shown to be NP-hard [1], [2], [7], [8]. Therefore, it becomes more crucial to investigate good heuristics which can lead to power-efficient algorithms. The most well-known power-efficient algorithms up to now include *Broadcast Incremental Power* (BIP) [1], and *Embedded Wireless Multicast Advantage* (EWMA) [2]. In both algorithms, a major theme in designing a power-efficient algorithm is to fully exploit the wireless broadcast advantage.

At each step of the BIP [1] and EWMA [2] algorithms, either *minimum incremental power* (required power to reach additional node) or *maximum gain* (reduction in transmit power of other nodes by increasing the transmit power of a node) is used as a decision criteria to determine the transmit power of each node, respectively. Previous simulation results confirmed that these are some of the good choices of decision metrics at each greedy decision process.

In this paper, we show that the *broadcast efficiency* can be another good choice of a greedy decision metric. 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 purpose of this paper is three-fold: (i) We first present that the broadcast efficiency is another viable metric of a greedy decision process. (ii) To demonstrate this, we provide a novel power-efficient algorithm utilizing the broadcast efficiency. (iii) We hope to spur the development of better power-efficient algorithms by analyzing this problem from a different perspective and providing more insights.

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The remainder of this paper is organized as follows. In the next section, we briefly define a network model and provide background. In Section III, we discuss previous representative work on the power-efficient broadcast routing problem. In Section IV, we present a detailed description of our new algorithm. Section V summarizes our simulation results and Section VI concludes this paper.

II. 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 $\in \{1, 2, \ldots, |N|\}$. The main objective is to construct a power-efficient (minimum total transmit power) broadcast routing tree rooted at the source node.

We assume that each node (host) is equipped with an omnidirectional antenna. The transmission power required to reach a node at a distance d is proportional to d^α assuming that the proportionality constant is 1 for notational simplicity and α is the path loss (attenuation) factor that satisfies $2 \leq \alpha \leq 4$. 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, the required *pairwise transmit power* P_{ij} to maintain a link $(i, j) \in T$ from node i to j is $P_{ij} = d_{ij}^\alpha$ where d_{ij} is the distance between the node i and j. The (node) *transmit power* assigned to node i by a routing algorithm is

$$P_{TX}(i) = \max_{j \in \Re_i} \{P_{ij}\}, \text{ for } i = 1, \ldots, N \tag{1}$$

where $\Re_i$ is a set of adjacent (child) nodes of node i in the tree.

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

Definition 2 (Physical and Logical Neighbor): If a node i is transmitting with power $P_{TX}(i)$, then the *physical neighbor*

$\aleph_i = \{k \mid 0 < P_{ik} \leq P_{TX}(i)\}$ of node i in a wireless network is a set of all the nodes within the communication boundary. The *logical neighbor* $\Re_i = adj(i) = \{k \mid \pi(k) = i\}$ of node i is a set of adjacent nodes in a routing tree.

In general, the physical neighbor determined by a network topology and (node) transmit power does not coincide with the logical neighbor determined by a routing algorithm. Note that $\aleph_j = \emptyset$ when $P_{TX}(j) = 0$ and $\Re_i \subseteq \aleph_i$.

Assuming $d_{ik} > d_{ij}$, the *incremental power* ΔP^i_{jk} of node i is defined as the additional power required to reach another node k [1], i.e., $\Delta P^i_{jk} = P_{ik} - P_{ij}$. If we label every node in $\aleph_i$ as i_k in an increasing order of distance from node i (i.e., $i = i_0, i_1, \ldots, i_{|\aleph_i|}$ such that $P_{ii_p} < P_{ii_q}$ if $p < q$), then the transmit power $P_{TX}(i)$ of node i can be represented as the sum of incremental power

$$P_{TX}(i) = \sum_{k=0}^{|\aleph_i|-1} \Delta P^i_{i_k i_{k+1}}.$$

Given a spanning tree T with node i transmitting with power $P_{TX}(i)$, the *total transmit power* of this tree is

$$\mathcal{P}_{TX}(T) = \sum_{i \in N} P_{TX}(i) = \sum_{i \in N} \sum_{k=0}^{|\aleph_i|-1} \Delta P^i_{i_k i_{k+1}}. \quad (2)$$

We denote a tree with minimum total transmit power as

$$T^\circ = \underset{T \subset G(N,A)}{\arg\min}\, \mathcal{P}_{TX}(T) = \underset{T \subset G(N,A)}{\arg\min} \sum_{i \in N} P_{TX}(i) \quad (3)$$

$$= \underset{T \subset G(N,A)}{\arg\min} \sum_{i \in N} \sum_{k=0}^{|\aleph_i|-1} \Delta P^i_{i_k i_{k+1}}. \quad (4)$$

III. Related Work

In this section, we briefly discuss the underlying mechanisms of previous works leading to power-efficiency in broadcast routing.

A. Broadcast Incremental Power (BIP) Algorithm

As noted earlier in (2), the total transmit power is the same as the total incremental power. The BIP algorithm [1] effectively solves the constrained optimization problem (4) to find a solution to (3), where the constraint implicitly comes from the fact that all inner nodes (i_j for $j < k$) must be always included if an outer node i_k is included.

Other heuristics which further reduce the total transmit power *after* a routing tree is constructed were presented in [1]–[4] as postsweep [1] or perNodeMinimalize procedure [3]. An important characteristic of postsweep procedure [1] is that, while it is possible to reduce the transmit power of nodes, it is not allowed to increase. Suppose a node j and its logical neighbor $\Re_j$ (determined by a routing algorithm) lies within a transmission boundary of node i, i.e., $\{j\} \cup \Re_j \subset \aleph_i$. Because all child nodes of j can be reached by node i, the transmission from node j is redundant and hence can be eliminated giving the savings of $P_{TX}(j)$. We will call this class of algorithms as *inner postsweeping*, because the transmission range of a node is only allowed to shrink. Inner postsweeping can also be considered as an operation which makes a routing tree *consistent*, meaning the difference between the physical and logical neighbor is small.

B. Embedded Wireless Multicast Advantage (EWMA) Algorithm

The novel technique EWMA presented in [2] can also be considered as a postsweeping but the fundamental difference from the inner postsweeping is that the EWMA increases the transmit power of each node to check whether further reduction (gain) in total transmit power is possible. Hence, we will call this operation as *outer postsweeping*. Note that EWMA can be refined as $EWMA = (MST) + (inner\ postsweep) + (outer\ postsweep)$.[1] The outer postsweep procedure is a monotonic non-increasing function of a input tree: if there is gain, it changes the tree structure to accommodate it; otherwise, it leaves the tree intact.

Note that depending on the input to outer postsweep procedure, the outcome will be different in general. However, choosing $(MST) + (inner\ postsweep)$ as an initial starting point in [2] seems to be "natural" to achieve the most gain. In [5], we presented an extensive comparison study of known power-efficient algorithms with various performance measures, one of which includes the ratio of leaf nodes. Because MST has small ratio of leaf nodes (see Fig. 1), relatively high proportion of nodes (source and relay nodes) actively transmits with smaller power. This provides more search space to EWMA algorithm to test for gains at an added computational complexity.

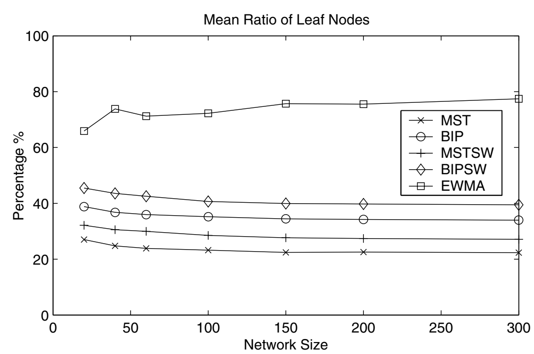


Fig. 1. Comparison of ratio of leaf nodes.

IV. GPBE Algorithm Description

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

Definition 3 (Broadcast Efficiency): Let C denote a set nodes currently covered by the transmission range of other nodes. The number of newly covered nodes by node i, transmitting with power $P_{TX}(i)$, is $|\aleph_i \backslash C|$. The *wireless broadcast*

[1]MST denotes the minimum weight spanning tree.

efficiency β_i is defined as the number of newly covered nodes reached per unit transmit power

$$\beta_i = \frac{|\aleph_i \backslash C|}{P_{TX}(i)} \text{ for } i \in N. \quad (5)$$

When we need to emphasize that an edge (i, j) is established, i.e., node i transmits to node j with transmit power $P_{TX}(i) = P_{ij}$, we will use the notation

$$\beta_{ij} = \frac{|\aleph_i \backslash C|}{P_{ij}} \text{ for } i, j \in N, i \neq j. \quad (6)$$

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

A. Location Dependence of Broadcast Efficiency

Let's examine how broadcast efficiency is dependent on the location of a node. Assume that $|N|$ nodes are randomly distributed with the following uniform probability density function (pdf) $f_{XY}(x, y) = |N| / (2d)^2$ over $0 \leq x, y \leq 2d$ region as shown in Fig. 2(a).[2] Then, the average number of covered nodes $E\{|\aleph_i(r)|\}$ as a function of transmission range r becomes

$$E\{|\aleph_i(r)|\} = A \cdot |N| / (2d)^2 \quad (7)$$

where A is the area of intersection between the square deploy region and the circle of radius r centered at node i. Comparing the two nodes, one located at the center (node 1) and the other located at the corner (node 2), we can intuitively infer that node 1 has 4 times the expected broadcast efficiency than node 2 at the corner. This is because, on average, 4 times the number of nodes can be simultaneously covered with the same transmit power from node 1. Considering the boundary effect of deployed region, the exact form of the average broadcast efficiency of node 2 can be expressed as a function of radius r as follows:

$$E\{\beta_2(r)\} = \begin{cases} \frac{\pi r^2/4}{r^2} \frac{|N|}{4d^2} = \frac{\pi |N|}{16d^2} & \text{if } r \leq 2d \\ \frac{\frac{1}{4}\pi(2d)^2 + I_1}{r^2} \frac{|N|}{4d^2} & \text{if } 2d < r \leq 2\sqrt{2}d \\ \frac{4d^2}{r^2} \frac{|N|}{4d^2} = \frac{|N|}{r^2} & \text{if } r > 2\sqrt{2}d \end{cases} \quad (8)$$

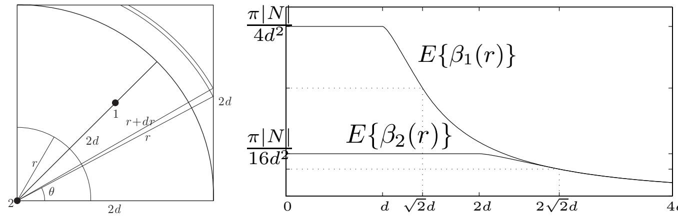
$$\text{where } I_1 = \int_{2d}^{r} \int_{\cos^{-1}(2d/\rho)}^{\pi/2 - \cos^{-1}(2d/\rho)} \rho \, d\theta d\rho$$

and $\alpha = 2$ is used. For $2d < r \leq 2\sqrt{2}d$ case, $E\{\beta_2(r)\}$ can be simplified as

$$\begin{aligned} E\{\beta_2(r)\} &= \frac{\pi d^2 + \int_{2d}^{r} \left(\pi/2 - \cos^{-1}(2d/\rho)\right) \rho \, d\rho}{r^2} \frac{|N|}{4d^2} \quad (9) \\ &= \left[\frac{1}{4}\pi - \cos^{-1}\left(\frac{2d}{r}\right) + \frac{2d}{r^2}\sqrt{r^2 - 4d^2}\right] \frac{|N|}{4d^2}. \end{aligned}$$

By repeating the same analysis for node 1, we can get the curves shown in Fig. 2(b). Note that node 1 has consistently higher average broadcast efficiency.

[2] We can similarly repeat the same analysis for a circulur topology.



(a) (b)

Fig. 2. (a) Dependence of broadcast efficiency on node location (b) Comparison of average broadcast efficiency on node 1 and 2.

Although only two extreme cases are compared, it is intuitively clear that the node located at the center has the largest average broadcast efficiency. As a node moves away from the center, the broadcast efficiency is monotonic decreasing function of a distance from the center location. From Fig. 2(b), we can observe that *the average broadcast efficiency is location dependent* and *the center of symmetric deploy region is the optimal place where the broadcast efficiency can be probabilistically best utilized.*

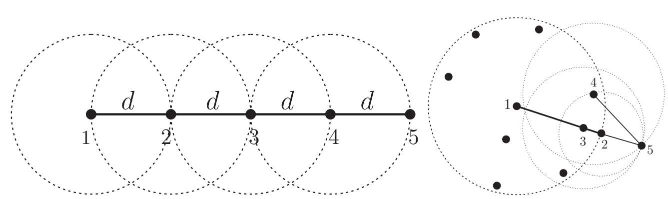
B. Effect of Broadcast Efficiency on Routing Decision

Before we proceed further to detailed algorithm description, we examine a few examples how routing decisions can be made using broadcast efficiency as a decision criterion.

Example 1 (Colinear topology): Consider a simple topology where all nodes lie within a line segment. Node 1 tries to broadcast to other nodes. It was shown in [9] that the transmission range assignment shown in the Fig. 3(a) is the optimal strategy in terms of total transmit power, which can be proved with Jensen's inequality. The decision by the node 1 is as follows: The broadcast efficiency is $\beta_{12} = 1/d^2, \beta_{13} = 2/(2d)^2, \ldots, \beta_{15} = 4/(4d)^2$. In general, when there are $|N|$ colinear nodes, the broadcast efficiency becomes

$$\beta_{1k} = \frac{k-1}{((k-1)\,d)^2} = \frac{1}{(k-1)d^2} \text{ for } k \geq 2. \quad (10)$$

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(a) can be constructed, which is also optimal.



(a) (b)

Fig. 3. (a) Routing decision for a colinear topology. (b) Routing decision at a boundary.

Example 2 (General boundary behavior): Now let's look at another example shown in Fig. 3(b). At the first iteration, suppose node 1 is transmitting with power d_{12}^{α} and node 5 has yet to be covered. Node 2, 3 and 4 are some of the candidate nodes for transmission. From this figure, $d_{25} < d_{35}$ and $d_{25} < d_{45}$. Hence, broadcast efficiency has $\beta_{25} > \beta_{35}$ and $\beta_{25} > \beta_{45}$. Therefore, node 2 decides to transmit with power d_{25}^{α}. This is the general behavior of using broadcast efficiency as a decision criterion, which results in reasonable choice (shortest distance).

C. Algorithm Description

In this section, we introduce our new algorithm, *Greedy Perimeter Broadcast Efficiency* (GPBE). Let S denote the source node. The GPBE algorithm maintains two sets: C and F. The set C represents the nodes currently covered by the transmission range of nodes. The set F represents the set of nodes transmitting with nonzero transmit power such that $F \subseteq C$.

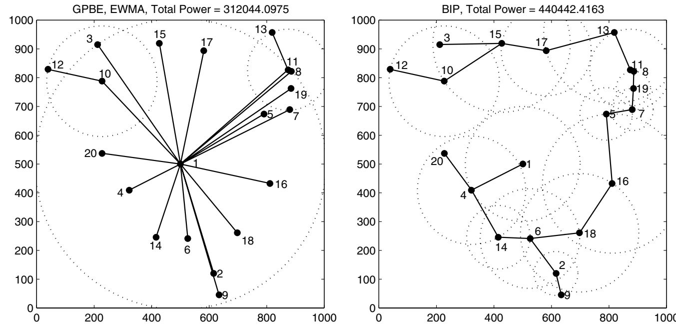
GPBE (Greedy Perimeter Broadcast Efficiency) Algorithm
$C := \{S\}, \quad F := \phi$
$P_{TX}(i) := 0$ for all $i \in N$
while $(C \neq N)$
  for each node $i \in C$ and $j \in N \backslash C$
    find a pair (i^*, j^*) such that

$$(i^*, j^*) = \underset{(i,j) \in C \times N \backslash C}{\arg\max} \left\{ \frac{|\aleph_i \backslash C|}{P_{ij}} \right\} \tag{11}$$

  end
  $P_{TX}(i^*) := P_{i^*j^*}$
  $F := F \cup \{i^*\}, \ C := C \cup \aleph_{i^*}$
end
return $\mathcal{P}_{TX}(T) := \sum_{i \in F} P_{TX}(i)$

Fig. 4(a) shows the final tree GPBE algorithm produces for a specific topology of 20 nodes. The source node 1 is located at the center of deploy region $(500, 500)$. Initially, $C = \{1\}, F = \phi$. At the first iteration, node 1 (i^* in the pseudocode) picks the node 11 (j^* in the pseudocode) as a destination node, because $P_{TX}(1) = P_{1,11}$ gives maximum broadcast efficiency. At this stage, each set becomes $C = N \backslash \{12, 13\}, F = \{1\}$. Notice how multiple nodes can be added to C simultaneously with a single iteration. At the next stage, all combinations of broadcast efficiency β_{ij} for $(i, j) \in C \times \{12, 13\}$ are tested. With the same reasoning provided in Example 2, $\beta_{11,13}$ has the maximum broadcast efficiency. Now each set changes to $C = N \backslash \{12\}, F = \{1, 11\}$. Similarly, at the final stage, $\beta_{10,12}$ is selected and the algorithm terminates in 3 iterations, because $C = N$. Usually, the greedy decision (maximum broadcast efficiency) is made at the perimeters of transmission range, that is why it is called GPBE. In this specific example, EWMA produces the same result.

For the same topology, we also applied BIP algorithm which results in Fig. 4(b). Clearly, BIP could not exploit the



(a) (b)

Fig. 4. A sample broadcast routing tree by (a) GPBE and EWMA and (b) BIP.

underlying broadcast efficiency in this case.[3] Also note that the outer postsweeping on BIP will produce exactly the same result as in Fig. 4(a).

Due to limited space, we can not provide the results for directional antenna case. Instead, interested readers are referred to [6], where we discussed that the same principle utilizing the broadcast efficiency can be equally well suitable for traditional sectored antennas or switched beam smart antenna systems.

V. Simulation Model and Results

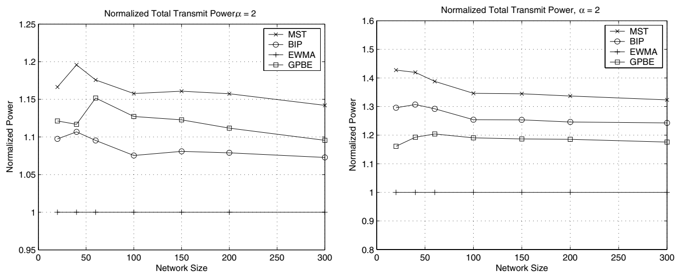
In this section, we perform simulations with the following model. Within a 1×1 km^2 square region, the network configurations (locations of nodes) are randomly generated according to uniform distribution. The same random seeds are used for a valid comparison of each algorithm. The transmit power is calculated with normalized proportionality constant (hence, $P_{ij} = d_{ij}^{\alpha}$) and the receiver sensitivity threshold is assumed to be 0 dB. As a path loss factor, $\alpha = 2$ is used. Broadcast routing trees rooted at the source node (also located randomly in the grid) are constructed using various algorithms. The simulation results are for stationary (non-mobile) network topologies. We do not limit on the maximum transmit power $P_{\max}$ as in [1], [2].

Fig. 5(a) summarizes the performance comparison of static trees, MST, BIP, EWMA and GPBE in terms of total transmit power for various sizes of the networks $|N| = \{20, 40, 60, 100, 150, 200, 300\}$. Each point in Fig. 5(a) and 5(b) 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. To facilitate easy comparison with previous work [1], [2], we use the *normalized total transmit power* [1] as a metric:

$$\mathcal{P}_{TX}^{norm}(T_{\text{algorithm}}) = \frac{\mathcal{P}_{TX}(T_{\text{algorithm}})}{\min_{i \in \text{algorithm}} \{\mathcal{P}_{TX}(T_i)\}},$$

where algorithm = {MST, BIP, EWMA, GPBE}. The curves in Fig. 5(a) coincide with the results presented in the performance evaluation section of [2], which verifies the correctness of

[3]We have chosen this topology to facilitate the explanation of our algorithm. BIP algorithm performs comparably in general, if not better.



(a) (b)

Fig. 5. Comparison of total transmit power of MST, BIP, EWMA and GPBE. Mean of 100 random topologies. (a) Source S is located at random (b) Source S is chosen as the closest node from the center (500,500).

implementation. In addition, our new algorithm GPBE is compared together. In terms of total transmit power performance, on average, it lies in between BIP and MST. The EWMA produced the best performance in all cases.

In Fig. 5(b), we pick the node nearest to the center (500,500) as the source node S to test the effect of broadcast efficiency, while leaving all other conditions unchanged. In this case, we can observe that GPBE produced better performance than BIP, because GPBE exploits the broadcast efficiency. Therefore, GPBE can be considered within the regime of a power-efficient algorithm. This result also suggests that there is some correlation between the broadcast efficiency and the construction of power-efficient broadcast routing problem. Hence, it is worth further exploration.

In our simulation results, we observed that about half of the cases out of 100 different topologies, GPBE performed better than BIP. But the variance of total transmit power of GPBE was larger. Hence, this contributed to slightly worse average performance than BIP, when the location of the source node is random. This happens especially when the source node is located at the corner of the deploy region. In such case, a lot of transmit power is wasted before reaching some nodes near the center, because at the initial stages of GPBE algorithm, there is less competition among the nodes to find better broadcast efficiency. In fact, GPBE algorithm makes the most aggressive choice at each step. We expect some mechanism to control the aggressiveness at the initial stage, what we call a *slow start mode*, will improve the performance of the algorithm. Also, the problem can be somewhat remedied if each node is equipped with a directional antenna. This is because, when each antenna beam is pointed into the deploy region, the broadcast efficiency is almost uniform regardless of node location.

On the other hand, when the source is located near the center of deploy region, as observed in Section IV-A, the broadcast efficiency plays an important role and GPBE performs better than BIP. This suggests that GPBE algorithm is more suitable for base station or access point (e.g., such as in IEEE 802.11b wireless LAN standard) scenarios, where nodes are aggregated around access points at the center.

From a different perspective, we can consider the GPBE algorithm as a generalization of MST algorithm. Consider a strategy of choosing a node with maximum broadcast efficiency so that only a single new node is covered, i.e., in (11), fix $|\aleph_i \backslash C| = 1$. With this constraint, picking a node to maximize the broadcast efficiency is equivalent to choosing a node which can be reached with minimum transmit power, which is the basically the operation of MST. What is interesting in the simulation results is that GPBE is an enhancement to MST algorithm using more general cost metric. This point immediately raises an interesting question: will it be possible to enhance the performance of BIP algorithm by relaxing the cost metric of BIP algorithm, analogously? Note that BIP algorithm uses the incremental power ΔP^i_{jk} as a cost metric. We can imagine the relaxed cost metric as $|\aleph_i \backslash C| / \Delta P^i_{jk}$, which we refer as *incremental broadcast efficiency*. We intend to study this cost metric in the near future.

VI. Conclusions

In this paper, we presented a novel power-efficient broadcast routing algorithm which effectively exploits the broadcast efficiency. We demonstrated that GPBE algorithm has the property that adaptively assigns transmit power to each node depending on how densely nodes are distributed, and has the favorable ability of choosing multiple nodes at the same time. Although our algorithm GPBE is based on a different philosophy, the performance of it is comparable to the one of the most prominent power-efficient algorithm in the literature, BIP.

Our future research direction includes the analysis of computational complexity of GPBE, a distributed implementation, the reduction of search space using the perimeter behavior and further enhancement of the algorithm to achieve better performance.

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