Broadcast with Heterogeneous Node Capability

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Abstract— **In this paper, we investigate the power-efficient broadcast routing problem over heterogeneous wireless ad hoc or sensor networks where network nodes have heterogeneous capability. The network links between pairs of nodes can no longer be modeled as symmetric or bidirectional. We show that, while most previous power-efficient algorithms work in this setting with minor modifications, they are not designed to exploit such asymmetric constraints. We present a suitable algorithm which takes into account of the constraints and yet most power-efficient among all known algorithms.**

I. Introduction

In many real situations, RF transceivers take on various level of capabilities in terms of maximum transmission range, computational processing, and omnidirectional versus directional antennas, etc. Even transceivers that are supposed to meet certain common specifications may have different capabilities, because internal implementation details will vary from one manufacturer to another. Not to mention such scenario, certain networks such as cellular networks are inherently multi-tiered.

In case of wireless sensor networks (WSN), there exist many data-gathering stations which can also serve as gateway nodes to infrastructure networks. Also, as proposed in many research on localization [1], more powerful nodes called "anchors" are utilized to disseminate GPS or location information throughout the sensor nodes. Be it a gateway, an access point, an anchor or a data collection point, it is highly likely that they are orders of magnitude more powerful than tiny sensor nodes in terms of battery capacity, radio transmission range and processing power. Hence, it is imaginable that mixing up some fraction of such capable nodes with sensors can significantly boost the general characteristics of a network in a favorable way. For instance, it can transform an originally partitioned network into a connected one. Also by transferring most of the communication burden to the more capable nodes, it allows the network to survive much longer.

In this paper, we address the problem of constructing power-efficient broadcast routing tree over wireless multihop networks which consist of mixed types of network nodes of different capabilities. Finding a source-specific broadcast routing tree rooted at the source node with minimum overall power cost is commonly known as Minimum Energy Broadcast problem [4]. This problem has been proven to be NP-complete by several researchers [2], [3]. However, most previous work assumes flat architecture where network nodes possess homogeneous capability and hence bidirectional links are assumed.

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The objective of this paper is two-fold. First, we relax the assumption of bidirectionality of links to the asymmetric links and introduce an efficient heuristic algorithm for minimum energy broadcast problem which is suitable under such relaxed condition. Second, for heterogeneous or multi-tier networks, not only we can achieve this, but also we can better utilize the capable nodes by allowing them to exert more transmit power.

The remainder of this paper is organized as follows. In the next section, we present the network model and definitions that will be used throughout this paper. In Section III, we briefly review an efficient broadcast algorithm. In Section IV, we consider what modifications are required to make the previously proposed algorithms work. Section V summarizes our simulation results and Section VI concludes our paper.

II. Network Model

We assume that each node (host) in a wireless ad hoc network is equipped with an omnidirectional antenna. We assume each node acquires its location information either using GPS or other localization techniques [1]. Within a $1000{\times}1000$ m^2 network deploy region, the network configurations (locations of nodes) are randomly generated according to uniform distribution. All the generated nodes participate in the group of a single broadcast session. The source node S is chosen arbitrarily among them. The broadcast routing trees rooted at the source node are constructed.

We represent the amount of power consumption at node i as $P(i)$, and its corresponding transmission range as R_i. The maximum power a node can exert is bounded by $P(i) \leq P_{i,\max}$ and the maximum transmission range of node i is denoted $R_{i,\max}$. In general, we allow these maximum values to be different to account for the difference in radio transceivers. When the distance between node i and j is d_{ij}, the received power at a node varies as $d_{ij}^{-\alpha}$ where α is the path loss (attenuation) factor that usually satisfies $2 \leq \alpha \leq 4$. The required *pairwise RF transmit power* $\mathbf{P}_{ij}$ to maintain a link (i, j) from node i to j is $\mathbf{P}_{ij} = \Omega d_{ij}^{\alpha}$ where the proportionality constant Ω denotes the receiver sensitivity threshold. To avoid the undue complication of notations, we assume $\Omega = 1$ (0 dB). Clearly, the matrix $[\mathbf{P}_{ij}]$ is a constant matrix that is invariant over time, if locations of nodes do not change. Therefore, to reach node j from node i, the required RF transmit power of node i is $P_i^{RF} = \mathbf{P}_{ij}$.

In addition to the RF transmit power, other signal processing powers for transmission, reception, and other computational

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processing denoted p_i^T, p_i^R and p_i^C, respectively, contribute to the battery energy drain [4]. We assume $p_i^T = p^T$, $p_i^R = p^R$ and $p_i^C = p^C$ for all i. Then, the general form of power consumption $P(i)$ at node i is

$$P(i) = P_i^{RF} + p^T I_{\{P_i^{RF}>0\}} + \sum_{j\in N\setminus\{i\}} p^R I_{\{d_{ij}\le R_j\}} + p^C$$

where $I_{\{\cdot\}}$ denotes an indicator function. That is, $I_{\{P_i^{RF}>0\}} = 1$ only if $P_i^{RF} > 0$, i.e., transmission with nonzero RF power always incurs transmit signal processing power p^T. Similarly, $I_{\{d_{ij}\le R_j\}}$ means that receive signal processing power p^R is required for node i, if it is within the transmission range of node j. For clarity of presentation, we set $p^T = p^R = p^C = 0$ in this paper, but in [5] we showed that considering these factors in a similar setting can only make our results even stronger.

A network is represented as a weighted directed graph $G = (N, A)$ with a set N of $n = |N|$ nodes and a set A of $m = |A|$ directed edges (links). A directed edge $(i, j) \in N^2$ exists if and only if $d_{ij} \le R_{i,\max}$. Note that existence of (i, j) does not necessarily mean (j, i) exists, since the ranges of node i and j can be different, i.e., $R_i \ne R_j$ in general. We define a network is *connected*, if there exists a directed path from the source node S to every node $i \in N$. Given transmission ranges $\{R_i\}_{i\in N}$, the *topology* τ *induced by* $\{R_i\}$ is a mapping $\tau : G \longrightarrow G'$ from a directed graph $G = (N, A)$ to a subgraph $G' = (N', A') \subset G$ satisfying $N' = N$ and $A' = \{(i, j) \mid (i, j) \in A(G),\ d_{ij} \le R_i\}$.

For a directed graph, a directed spanning tree rooted at a source node is called an *arborescence*. From now on, when we refer a (directed) tree, it denotes an arborescence rooted at the source node. Given a spanning tree T, the actual (node) *transmit power* assigned to the node i is $P(i) = \max_{j\in\delta(i)} \{\mathbf{P}_{ij}\}$ where $\delta(i)$ denotes the *logical neighbor* of node i which is a set of adjacent (child) nodes of node i in the directed tree T such that $\delta(i) = \{k \mid (i, k) \in T\}$. The cardinality of $\delta(i)$ corresponds to outdegree of node i. For a directed tree, the indegree of a node is always 1 except the root, for which indegree is 0. Hence, there exists a unique parent node $\pi(i)$ for each node i, except the root node ($\pi(S) = \phi$). For an arbitrary set $C \subseteq N$, $\pi(C) = \bigcup_{i\in C} \pi(i)$. The *physical neighbor* $\mathcal{N}_i(j)$ of node i is a set of all the nodes covered within the communication range $R_i = d_{ij}$ such that $\mathcal{N}_i(j) = \{k \mid 0 \le d_{ik} \le d_{ij},\ k \in N\}$. Clearly, the *total transmit power* $\mathcal{P}_{TX}(T)$ corresponding to a spanning tree T is the sum of all node transmit power $\mathcal{P}_{TX}(T) = \sum_{i\in N} P(i)$.

III. LESS: Search for Hidden Sweep

In this section, we briefly present a new broadcast routing algorithm called the *Largest Expanding Sweep Search* (LESS). It is a heuristic centralized algorithm within the framework of local search that improves upon some of the shortcomings of *Embedded Wireless Multicast Advantage* (EWMA) [2] which used to be the state-of-the-art algorithm in terms of performance. The basis idea of EWMA is that in exchange for slight increase in transmit power of a node, multiple nodes can eliminate their transmission, and hence the overall transmit power can be reduced. We call this operation as Expanding Sweep Search (ESS). The net difference called the *gain* in EWMA is always to remove a transmitting node. We generalize this notion to include reduction as well as elimination of transmit power. We believe this is the first attempt to systematically define the concept of generalized gain. The major design principle of LESS is that, instead of relying on a specific pre-determined starting location such as source or center [6], *search* the right location to build a tree which is likely to produce an efficient tree in the end. For full analytical details, readers are referred to [7]. In this paper, we will focus our attention to how LESS algorithm performs in the heterogeneous network case. Now we introduce the generalized ESS operation.

Definition 1 (Sweeping Gain): Given an arborescence as an input, the (generalized) sweeping gain $SG_{i\to j}$ by a transmission range from node i to node j such that $R_i = d_{ij}$ is defined using the following notations:

$$\begin{aligned} \Pi_{i\to S} &= \{\text{all nodes in a path from } i \text{ to } S\} \\ \mathcal{Q}_i(j) &= \pi(\mathcal{N}_i(j))\setminus\{i\} \\ \mathcal{M}_i(j) &= \mathcal{N}_i(j)\setminus\Pi_{i\to S}, \end{aligned} \tag{1}$$

where $\Pi_{i\to S}$ represents the set of nodes encountered in the path from node i to the source node S following the parent pointer, $\mathcal{Q}_i(j)$ represents all the involved nodes in testing for expanding sweep search, $\mathcal{N}_i(j)$ denotes the physical neighbor of node i when the range is $R_i = d_{ij}$, $\pi(\mathcal{N}_i(j))$ denotes the set of parent nodes of $\mathcal{N}_i(j)$, and $\mathcal{M}_i(j)$ stands for all would-be child nodes of node i, if the range $R_i = d_{ij}$ is finally selected after the sweep operation. Using these notations, the (generalized) sweeping gain is defined as

$$SG_{i\to j} = \sum_{u\in\mathcal{Q}_i(j)} \left(P(u) - \max_{k\in\delta(u)\setminus\mathcal{M}_i(j)} \{\mathbf{P}_{uk}\} \right). \tag{2}$$

Definition 2 (Gain): Let $\Delta P_{i\to j} = \mathbf{P}_{ij} - P(i)$ denote the incremental power of node i when $\mathbf{P}_{ij} \ge P(i)$. Then, the *generalized gain* (or simply *gain* henceforth) is defined as

$$G_{i\to j} = SG_{i\to j} - \Delta P_{i\to j} \tag{3}$$

which can take a positive or negative value.

The generalized sweeping gain defined as above includes both *eliminating* and *reducing* the transmit power of nodes.

Largest Expanding Sweep Search (LESS) Algorithm
Input: minimum spanning tree T_{MST}
STEP 1: For the given input tree T, find (i^*, j^*) s.t.

$$\bar{C}_i := \{k \mid d_{ik}^{\alpha} \ge P(i)\}, \quad \forall i \in N$$

$$(i^*, j^*) := \underset{(i,j)\in N\times\bar{C}_i\setminus\Pi_{i\to S}}{\arg\max} \{G_{i\to j}\}$$

$P(i^*) := \mathbf{P}_{i^*j^*}$ // assign transmit power to node i^*

$\pi(\mathcal{M}_{i^*}(j^*)) := i^*$ // update parent node to node i^*

STEP 2: Repeat STEP 1 while the gain $G_{i^*\to j^*}$ is positive.

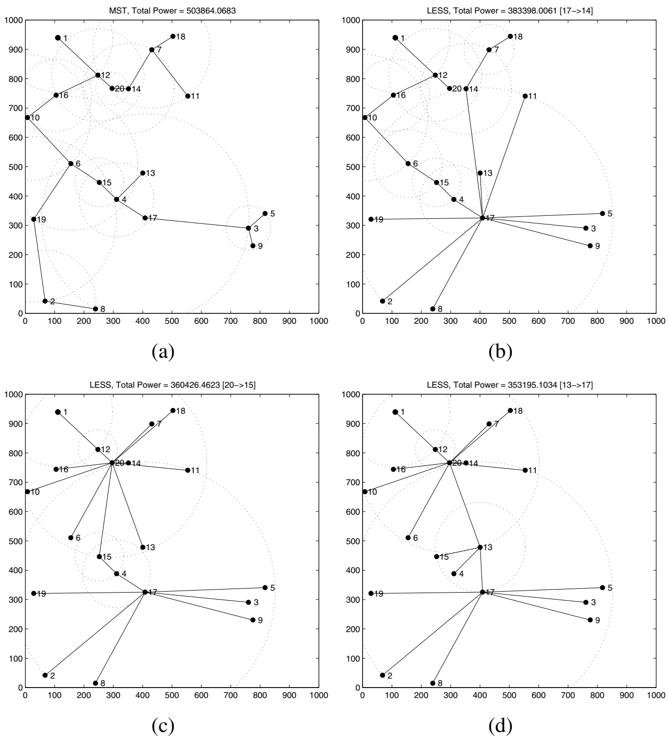


Fig. 1. $n = 20$, $\alpha = 2$. (a) Input MST tree, (b) LESS tree after first iteration, (c) LESS tree after second iteration, (d) LESS tree after third iteration.

The LESS algorithm presented as above works as follows: apply the generalized ESS operation from every node regardless of transmitting or leaf nodes, find the node i^* with the largest gain and its associated transmission range, and update the transmit power of the node $P(i^*)$ and update the parent node of the covered nodes except the path nodes $\Pi_{i^* \to S}$ to node i^*. After one iteration, the input tree structure changes to a new one. Repeat the same operation with the updated tree as an input to STEP 1, while there is a positive gain.

Let us explain the algorithm with an example comprised of 20 nodes with $S = 1$. The initial input tree to LESS algorithm is the minimum spanning tree (MST) shown in Fig. 1(a). The operation of LESS works quite differently from EWMA. Also the definition of gain in LESS is different from EWMA. In the first iteration shown in Fig. 1(b), node 17 has the maximum gain when it transmits to node 14. The corresponding sets are:

$$\begin{aligned}
\mathcal{N}_{17}(14) &= \{2,3,4,5,6,8,9,11,13,14,15,17,19\} \\
\pi(\mathcal{N}_{17}(14)) &= \{19,17,15,3,10,2,3,7,4,20,6,4,6\} \\
&= \{2,3,4,6,7,10,15,17,19,20\} \qquad (4) \\
\Pi_{17 \to S} &= \{17,4,15,6,10,16,12,1\} \\
\mathcal{Q}_{17}(14) &= \{2,3,4,6,7,10,15,19,20\} \\
\mathcal{M}_{17}(14) &= \{2,3,5,8,9,11,13,14,19\}
\end{aligned}$$

Using (4) and (2), the corresponding sweeping gain is

$$\begin{aligned}
SG_{17 \to 14} = \mathbf{P}_{28} + \mathbf{P}_{35} + \mathbf{P}_{19,2} + \mathbf{P}_{20,14} + (\mathbf{P}_{6,19} - \mathbf{P}_{6,15}) \\
+ (\mathbf{P}_{4,13} - \mathbf{P}_{4,17}) + (\mathbf{P}_{7,11} - \mathbf{P}_{7,18})
\end{aligned}$$

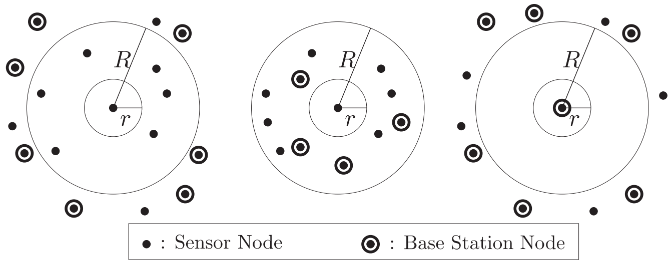
The first four terms correspond to the sweeping gain by *removal* of transmitting nodes in the original input tree (node 2, 3, 19 and 20), and the next three terms in parenthesis correspond to the sweeping gain by *reduction* of the transmit power of nodes 6, 4 and 7. The required incremental power is $\Delta P_{17 \to 14} = \mathbf{P}_{17,14} - P(17) = \mathbf{P}_{17,14} - \mathbf{P}_{17,3}$. Hence the gain is $G_{17 \to 14} = SG_{i \to j} - \Delta P_{i \to j} = 1.2047 \cdot 10^5$. This generalized ESS is repeated while there exists a positive gain.

Following the same way, in the second iteration shown in Fig. 1(c), the operation in STEP 1 is repeated using the tree in Fig. 1(b) as an input. $G_{20 \to 15}$ is the maximum gain with value $2.2972 \cdot 10^4$. In the third iteration, node 13, which was originally a leaf node in Fig. 1(c), decides to transmit to node 17. The testing for gain is performed as follows: $\mathcal{N}_{13}(17) = \{4,13,15,17\}$, $\pi(\mathcal{N}_{13}(17)) = \mathcal{Q}_{13}(17) = \{4,15,20\}$, $\Pi_{13 \to 1} = \{20,12,1\}$, and $\mathcal{M}_{13}(17) = \{4,15,17\}$. As a result, the gain is $G_{13 \to 17} = \mathbf{P}_{4,17} + \mathbf{P}_{15,4} + (\mathbf{P}_{20,15} - \mathbf{P}_{20,13}) - (\mathbf{P}_{13,17} - 0) = 7.2314 \cdot 10^3$. Notice that this is not possible in either EWMA [2] or post sweep operation [4]. Since there is no further gain, LESS algorithm stops here.

In summary, the LESS algorithm relies on a generalized definition of sweeping gain. As evidenced in Fig. 1(b)–(d), as long as there exists gain, whether visible or hidden, it can find it and reduce the total transmit power. As in EWMA, the LESS algorithm is an one-way operation in that it always reduces total power if possible: if it finds the gain, change the tree structure, otherwise, leave it as it is. Even if we use the EWMA tree as initial feasible solution, we observed there is still a significant gain over EWMA, but not vice-versa. Applying EWMA on LESS tree has no effect, because LESS finds every possible gain.

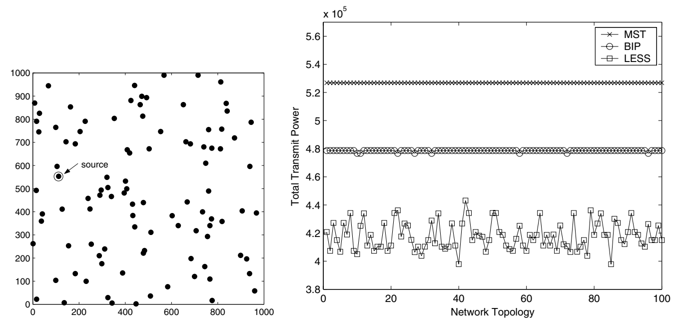
IV. Modification Required to Previous Algorithms

In most analytic work on connectivity [8], [9], the homogeneous range assignment problem for strong (1-)connectivity is considered. The strong connectivity is defined as, given any two nodes, there exist a directed path from one node to the other. We can not use previous results due to the following reasons. First, the connectivity used in minimum energy broadcast problem is not strong connectivity but reachability from the source to every node. Second, we consider heterogeneous range assignment problem. Many previous results no longer hold due to these differences in assumptions. For instance, the existence of an isolated node, a sufficient condition for network disconnectedness, was the basis for all analysis [8]. However, when the network is heterogeneous, the notion of isolatedness should change accordingly. For simplicity, let us consider 2-tier network case where tier 1 nodes are called the sensor nodes with transmission range r and tier 2 node are called the base station (BS) nodes with transmission range $R(> r)$. As shown in Fig. 2(a), a node is rx-isolated if it can not receive message from any other node. A node is tx-isolated if it can not transmit to any other node. A tx-isolated sensor node may not be rx-isolated as in Fig. 2(b). An rx-isolated BS node may not be tx-isolated.



(a) (b) (c)

Fig. 2. (a) rx-isolated node (b) tx-isolated sensor node (c) tx-isolated base station node.



(a) (b)

Fig. 3. (a) Simulation setup. $n = 100$ nodes are randomly distributed. Source node is indicated. (b) Performance comparison in terms of total transmit power ($\alpha = 2$).

While most previous work assume finite maximum transmit power $P_{\max}$, in simulation results, all of them assumes $P_{\max} = \max_{(i,j)\in N^2} \mathbf{P}_{ij}$ for each topology. This is equivalent to $P_{\max} = \infty$ regardless of specific topology, and the underlying graph is always a fully connected graph. In this paper, we address the impact of various different maximum transmit power $P_{i,\max}$ which is dependent on each node's transceiver. Nevertheless, the modification required to original algorithms (MST, Broadcast Incremental Power (BIP) [4] and LESS) are minimal. By defining the pairwise RF transmit power as

$$\mathbf{P}_{ij} = \begin{cases} d_{ij}^{\alpha} & \text{if } d_{ij}^{\alpha} \leq P_{i,\max} \\ \infty & \text{otherwise} \end{cases} \quad (5)$$

most issues due to asymmetric links are solved. In case of Prim's algorithm for MST and BIP, because these algorithms add one node at a time, it just need to check outgoing edges at each step until every node is added. Otherwise, the network is not connected. In case of LESS, the ESS operation does not disturb network connectivity even for heterogeneous network. Therefore, we can use it directly in conjunction with (5).

V. Simulation Scenarios and Results

Even for 2-tier network model, the parameter space to explore is very large. The parameters of interest are: (i) the number of nodes in the network including tier 1 and tier 2 nodes, denoted n_1 and n_2 respectively, and let the total number of nodes be $n = n_1 + n_2$; (ii) the ratio of tier 1 and 2 nodes denoted $\rho = n_2/n_1$ or equivalently the percentage of tier i nodes $p_i = n_i/(n_1 + n_2) \times 100 = n_i/n \times 100$ for $i = 1, 2$; (iii) the maximum range r of tier 1 node and the maximum range R of tier 2 nodes. Without loss of generality, we assume $r \leq R$. Path loss factor $\alpha = 2$ is used in our simulations.

A. Scenario 1—Capability to Exploit BS Nodes

In the first scenario, we investigate whether MST, BIP, and LESS can exploit the existence of BS nodes to further minimize the total transmit power. Over 1000x1000 m^2 deploy region, $n = 100$ nodes are randomly distributed. Fig. 3(a) shows the sample topology for which we run simulations. Among 100 nodes, we randomly select $n_2 = 10$ nodes (or equivalently $p_2 = 10\%$) as BS nodes. The transmission ranges of sensor and BS nodes are set to $r = 170$ and $R = 500$, respectively, with units in meters. By varying the choice of 10 BS nodes, 100 different network topologies are generated. Note that location of nodes including the source node in Fig. 3(a) does not change, but which role each nodes takes (sensor or BS) varies from one topology to another. In this setup, BS nodes are allowed to increase their transmit power quite liberally. Whenever advantageous in reducing total transmit power, it is better for the BS nodes to enlarge their transmit power since the communication burden can be relieved from the sensor nodes. For a given topology, it is a well-known fact that the maximum edge weight of MST is the critical range [8], [9]. In this example, the critical range is $R_{critical} = 162.4$. Hence, if $r \geq R_{critical}$, the network will be connected regardless of the existence of BS nodes [8].

Fig. 3(b) summarizes the simulation results for 100 different topologies. In case of MST, the existence of BS has no effect on the choice of links at each step of the Prim's algorithm we used, since only the node which can be added with the minimum power value is chosen. Therefore, the curve corresponding to MST is flat. The BIP behaves slightly differently. At each step, a new node which can be added with the minimum incremental power is selected. While there are BS nodes which can generously increase its power, BIP algorithm takes advantage of the condition only for several limited occasions. In Fig. 3(b), only 8 cases out of 100 network topologies are affected. Nevertheless, the effect on the average performance result is negligible.

While MST and BIP are insensitive to the existence of BS nodes, LESS is adaptive to the choice of BS nodes. The values of total transmit power can vary as much as 10% as shown in Fig. 3(b). This result suggests that LESS algorithm is suitable for networks consisting of nodes with heterogeneous capabilities, while MST or BIP are not. Furthermore, LESS produces the best performance.

B. Scenario 2—Impact of Percentage of BS Nodes

In Scenario 1, the percentage of BS nodes was fixed at $p_2 = 10\%$. In this section, we address the impact of the ratio (or percentage p_2) of BS nodes on the performance of each algorithms. The number of sensor and BS nodes are $n = 100$, among which p_2 percent of the nodes are randomly chosen as

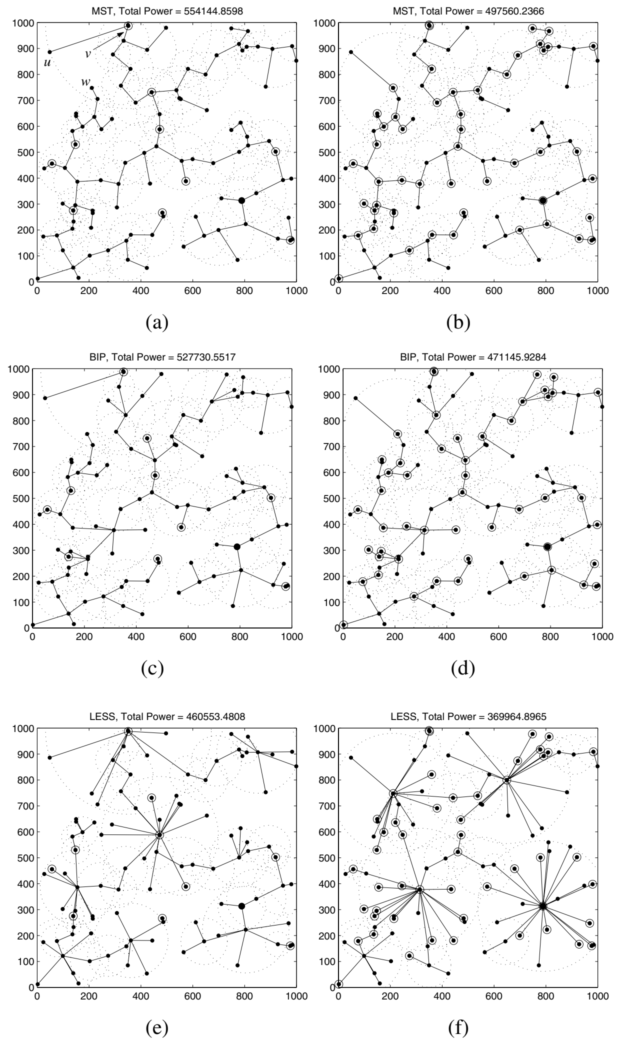


Fig. 4. Sample trees with paremeter $n = 100$, $\alpha = 2$, $r = 170$, and $R = 340$ corresponding to algorithms: (a) MST ($p_2 = 10$) (b) MST ($p_2 = 50$) (c) BIP ($p_2 = 10$) (d) BIP ($p_2 = 50$) (e) LESS ($p_2 = 10$) (f) LESS ($p_2 = 50$). Small dots represent the sensor nodes. A large dot represents the source node. Small dots with a circle represent base station nodes.

BS nodes. The value of p_2 is varied from 0 to 100. When $p_2 = 0$, none of the nodes are BS nodes and hence the maximum range of all (sensor) nodes corresponds to r. On the other hand, when $p_2 = 100$, every node corresponds to BS node and hence the maximum range is R for all nodes.

Before we proceed further, it is instructive to consider sample examples illustrated in Fig. 4. The figures in the first column of Fig. 4 correspond to the broadcast trees produced by MST, BIP and LESS algorithms for the parameters mentioned earlier, i.e., $n = 100$, $p_2 = 10\%$, $r = 170$ and $R = 340$. Similarly, second column corresponds to $p_2 = 50\%$ keeping other parameters unchanged. Note that if $p_2 = 0\%$ ($r = R = 170$), this network will not be connected. (This case is not shown in the figure.) For instance, node u lying in the upper left corner of Fig. 4(a) is an isolated node and hence the cost of the tree will be infinite, $\mathcal{P}_{TX}(T) = \infty$. By introducing

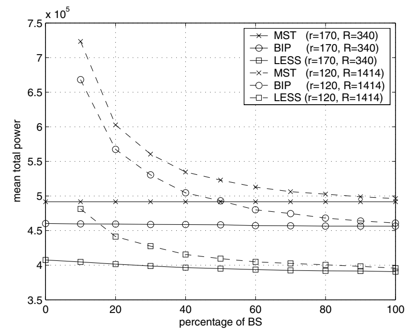


Fig. 5. Total transmit power vs. percentage of base station nodes. Dashed lines represent average performance results of each algorithm corresponding to parameters $r = 120$ and $R = 1414$. Solid lines are for $r = 170$ and $R = 340$.

$p_2 = 10\%$ BS nodes with $R = 340$ as in the first column, node u can now be connected from the BS node v, and the total cost becomes finite. By further increasing the percentage of BS nodes to $p_2 = 50\%$ as in the second column, a better link from the closer BS node w can be chosen and the total cost becomes reduced (see Fig. 4(b)). We can observe from Fig. 4(a)–(d) that, except the links involving node u, v and w, other links in MST and BIP trees have not changed. On the other hand, LESS in Fig. 4(e) and (f) is reactive to the locations of BS nodes.

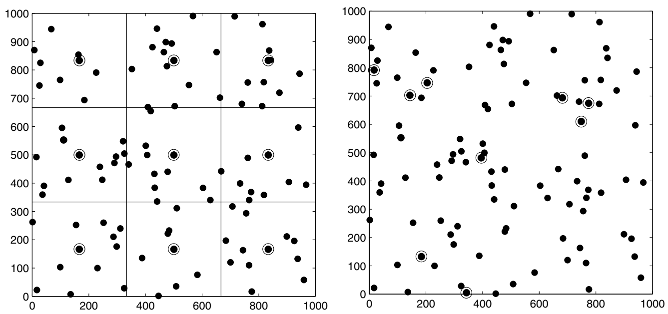
Fig. 5 summarizes the average performance result of total transmit power as a function of p_2. Each point in Fig. 5 is average of 100 randomly generated topologies. Since increasing the fraction of BS nodes can make a disconnected network connected, the cost of tree can become finite from infinite. This makes the performance analysis difficult.

Therefore, in the first case, we consider only network topologies which are already connected without BS nodes, i.e., $R_{crit} \leq r$ for parameters $r = 170$ and $R = 2r = 340$. The results are presented as solid line curves in Fig. 5. As already observed in Scenario 1, if we consider only connected topologies when $p_2 = 0\%$, changing the ratio of BS nodes has no impact on MST. We can observe that BIP is also marginally affected. Only LESS exhibit visible reduction in total transmit power, which is still not a dramatic change. Implication from the results of Fig. 4 and 5 is that, once a network is connected, the percentage of BS nodes in the network is less important. A more crucial factor seems to be whether BS nodes lie at the proper locations where the wireless broadcast advantage property can be better exploited. For instance, placing BS nodes at the outer boundary of the deploy region has almost no impact on the results, because it will induce excessive out of boundary power loss [6]. Also, as shown in Fig. 4(f), only 4 BS nodes instead of 50 may have been enough to produce the same tree as long as they are located correspondingly.

In the next case, we run simulations with parameters $r = 120$ and $R = 1414$. In this setup, because r is smaller, more network topologies tend to be disconnected. However, by setting a very large value of R, as long as there exist a path from the source to any of the BS nodes, the network will be connected. The results are presented as dashed line curves in Fig. 5. When the percentage of BS nodes are small, many suboptimal links are chosen just to make the network connected. As more fraction of BS nodes having larger ranges are added, better links are likely to be chosen. Therefore, the total transmit power decreases rapidly as p_2 increases.

C. Scenario 3—Random vs. Regular BS Placement

The observations made in the previous section lead us to investigate how to place the BS nodes over the deploy region. In this section, we consider two strategies including random and regular deployment of BS nodes in the network. Specifically, $n_2 = 9$ BS nodes are placed either randomly or regularly at the center of each 3×3 grid and the rest of the $(n - n_2)$ sensor nodes are randomly distributed as shown in Fig. 6. The maximum ranges of sensors and BS nodes are set to $r = 170$ and $R = 340$, respectively.



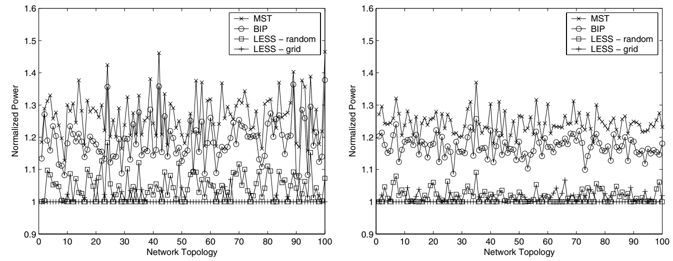
(a) (b)

Fig. 6. Simulation setting for scenario 3. (a) whole deploy region is divided into 3x3 grid. A base station node is placed in the center of each grid, (b) The base station nodes are randomly distributed.

Fig. 7(a) and (b) summarizes the simulation results for $n = 100$ and $n = 250$, respectively. The vertical axis in the figures corresponds to the normalized total transmit power. That is, for each network topology, the total transmit power of each algorithm is divided by the minimum value among the algorithms. We can observe that LESS algorithm outperforms MST and BIP in both deployment strategies. Savings in energy is approximately 20∼30% compared to MST and BIP. Also, if the BS nodes are regularly placed in each grid, the performance of LESS algorithm is better in most of the network topologies than random placement. This implies that, if we are allowed to place BS nodes regularly over the deploy region as in grid structure, it is likely to give better chance to build a more power-efficient broadcast tree.

We note that simulation results provided in this paper are far from exhaustive, especially because the parameter space is too large. However, with limited scenarios, we could still derive valuable insights which include:

- for a given maximum transmission range r of sensor nodes, it is beneficial to spread enough number of sensors so that the network can be connected without the aid of BS nodes.



(a) (b)

Fig. 7. Comparison of regular vs. random base station placement. (a) $n = 100$, (b) $n = 250$.

- once this condition is satisfied, further including BS nodes can be only helpful. Not only BS nodes help reducing the overall power of the network, but also much of the communication burden can be alleviated from the sensors so that the network can survive longer.

VI. Conclusions

We considered power-efficient broadcast problems over wireless ad hoc networks where nodes have different capability. For the clarity of presentation, we specifically considered a two-tier network model which can be considered as a sensor network consisting of sensors and base stations. We presented previously developed algorithms such as MST or BIP has minimal impact with the introduction of more capable base station nodes. On the other hand, we observed that our recently developed LESS algorithm can take advantage of such situation successfully and gives best performance among the known broadcast algorithms.

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