Energy Efficient Broadcasting Algorithms for Wireless Networks

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1 Introduction

Energy consumption and battery life is one of the most critical issues in ad hoc wireless networks. An ad hoc network is a decentralized type of wireless network that does not rely on a fixed pre-set infrastructure. The network consists of a collection of nodes that can send and receive signals using omnidirectional antennas.

Nodes can choose their transmission power taking into account that the required power for a node i to transmit a message to a node j at a distance of r_{ij} is proportional to ${r_{ij}}^{\alpha}$. α is the attenuation rate that typically takes a value between 2 and 4 depending on the communication medium properties. A key point to notice here is that since $\alpha > 1$, using a relay node between two nodes results in lower total transmission power than transmitting directly over a larger distance. This is shown in Figure 1. If we let $\alpha = 2$, the power required for node A to transmit directly to node C is proportional to AC^2. However, if node B is used as a relay node, the total required transmission power is proportional to $AB^2 + BC^2$. Since $AB + BC = AC$, $AB^2 + BC^2 + 2AB \times BC = AC^2$, and $AB^2 + BC^2 < AC^2$.

It is important to note the difference between broadcasting problem in wireless and wired networks. In wireless networks, assuming that all nodes use omnidirectional antennas, a single transmission to a distant node would be sufficient to reach all other nodes within the communication range of the sender without expending additional power. This property of wireless networks is known as the "wireless multicast advantage". In wired networks, transmission between each two nodes is over a connecting link, and the total cost of transmission to multiple nodes is the sum of the costs of the links. Therefore, the broadcasting problem can be viewed as a minimum(-cost) spanning tree (MST) problem. In wireless networks, however, the broadcasting problem is more challenging due to the wireless multicast advantage.

In this paper we are focusing on the broadcasting problem, where all network nodes except the source are destinations. Specificly, we are concerned with centralized broadcasting algorithms where each node has location information of all the network nodes as opposed to localized algorithms where nodes keep

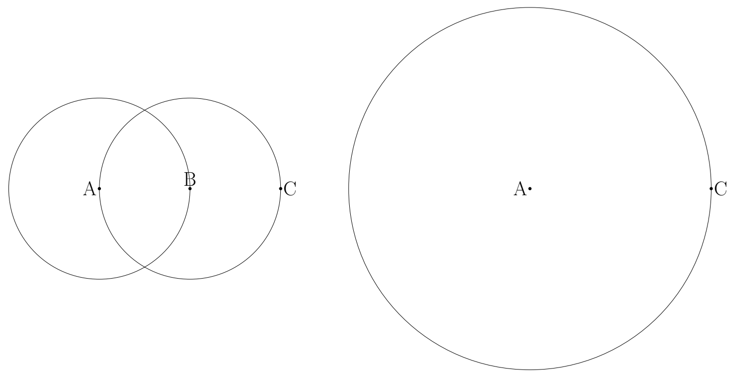

Figure 1: Node A wants to transmit to node C. On right, node A transmits directly to node C. On left, node B works as a relay node.

only limited neighborhood information. The multicasting problem can be solved by first solving the broadcasting problem and then eliminating transmissions to nodes that are not members of the multicast group. The unicasting problem where there is only one source and one destination can be viewed as a shortest path problem and solved in polynomial time complexity.

It has been shown in [vHE02] and [CCP$^+$01] that the minimum power broadcasting problem in wireless networks is NP-complete. Hence, it is crucial to develop heuristics.

Three greedy heuristic algorithms, namely Broadcast Incremental Power (BIP), Broadcast Least Unicast-cost (BLU), and Broadcast Link based MST (BLiMST) for the minimum energy broadcasting problem in wireless networks have been proposed in [WNE00] along with their performance analysis using simulations. Among these algorithms, only the first one (i.e. BIP) exploits the wireless multicast advantage and the other two (i.e. BLU and BLiMST), although scalable with polynomial time complexity, do not use the wireless multicast advantage and their performance is not as good as BIP. The analytical performance and approximation ratio of these algorithms are discussed in [WCL02].

In [vHE02], an algorithm called Embedded Wireless Multicast Advantage (EWMA) was proposed that starts from a minimum spanning tree (MST) and then for each node checks whether an increase in its tramission power would result in inclusion of more nodes in a way that other node(s) do not need to transmit and the total transmission power of the broadcast tree is reduced.

In Section 2, these algorithms are discussed, and in Section 3 some new algorithms for the energy efficient broadcasting problem in wireless networks are proposed.

2 Algorithms Analaysis

2.1 Problem Model

The wireless networks are assumed to consist of a finite set of nodes with fixed locations (stationary) that are distributed over a 2D plane. We denote by N the number of nodes.

It is assumed that a large number of bandwith resources are available, and each node can choose to transmit at certain power levels. We further assume that all nodes use omnidirectional antennas, and therefore, all nodes that fall within the communication range of a transmitting node can receive its transmission.

The wireless network is modelled as a directed graph $G = (V, E)$ where V represents the set of nodes and E the set of communication links between the nodes. Node j is said to be connected to node i if node j falls within the communication range of node i. The link cost c_{ij} is the minimum power required to sustain the link between nodes i and j.

The goal is the construction of an energy-efficient broadcast tree, rooted at the source node.

2.2 Broadcast Incremental Power (BIP) Algorithm

2.2.1 Algorithm Description

The Broadcast Incremental Power (BIP) Algorithm has been proposed in [WNE00] as an algorithm that takes the wireless multicast advantage into account with a good performance.

The algorithm objective is to determine a minimum power tree rooted at source node.

The algorithm starts by a tree which only consists of the source, and at each step, the minimum incremental power to reach a new node from each node that are already in the tree is computed, and the corresponding new node is added to the tree. The minimum incremental power for an already transmiting node is the additional amount of power required to reach a nearest new node, and for a non-transmiting node is the amount of power required to transmit to a nearest new node. The total power associated with the tree is the sum of the powers of all transmitting nodes. As an example, Figure 2 shows a wireless network in which node 10 is the source.

At the beginning, the broadcast tree consists of only the source (node 10). Then the algorithm checks for every covered node (which at this stage is only node 10) and finds a new node that can be covered with the minimum additional power. Since node 9 is closest to node 10, the new node that will be added to the broadcast tree is node 9. Again, the algorithm checks for every covered node (which at this stage are nodes 10 and 9) and finds a new node that can be covered with the minimum additional power. There are two alternatives: either node 9 can transmit to a nearst node that is not covered yet, or node 10 can increase its transmission power from a level that only reaches node 9 to

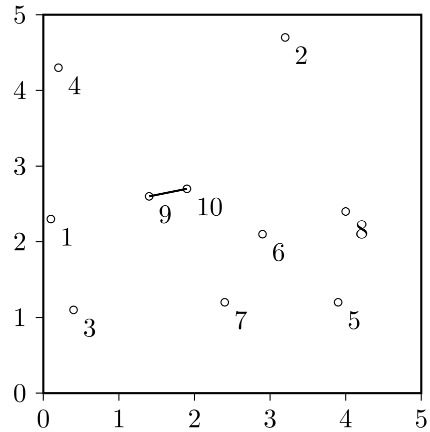

Figure 2: A wireless network with 10 nodes. Node 10 is the source [WNE00].

a level that also reaches a new node that is not covered yet. It is noted that the additional power for node 9 is the amount of power required for node 9 to transmit to a new node, but the additional power for node 10 is only the extra amount of power that is required for node 10 to transmit to a new node (Since node 10 is already transmitting with a certain power). Reaching node 6 from node 10 requires the minimum additional power, and hence, node 6 is added to the broadcast tree. Here, we can see that the BIP algorithm exploits the wireless multicast advantage since if the transmission power of node 10 is high enough to reach node 6, node 9 which is closer to node 10 is also covered without expending further power. Again, the algorithm checks the covered nodes (which at this stage are nodes 10, 9, and 6) and finds a new node that can be added to the tree with the minimum additional power expended by the covered nodes. This procedure is then repeated until all nodes are added to the broadcast tree (or simply all nodes are covered). The final broadcast tree is shown in Figure 3.

2.2.2 Implemented Code

The BIP code has been developed in C++ and has been submitted alongside this report. 2D vectors from C++ standard library is used to store the locations of the nodes. The nodes are divided into two groups: covered and non-covered nodes. Initially, only the source node is considered to be covered. The covered nodes also divide into two groups: transmitting and non-transmitting nodes. When trying to add a new node to the tree, both transmittig nodes and non-transmitting nodes increase their transmission power and the node with the minimum additional power consumption is added to the tree. At the end of program execution, the transmitting nodes with their transmission power and the total cost of the broadcast tree is shown in the console. Also, the transmis-

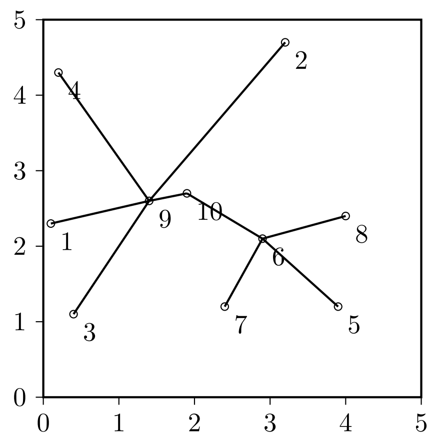

Figure 3: The final broadcast tree from the BIP algorithm [WNE00].

sion path which indicates which transmitting nodes and with which powers are transmitting is shown.

2.2.3 The Sweep Operation

The performance of the BIP algorithm can be further improved by the so called "sweep" operation which eliminates unnecessary transmissions. Here, likely a more accurate description of the sweep operation is given than the original paper [WNE00]. The idea is that if node k is the furthest node in the communication range of node i, and node j's transmission power reaches node k, then the transmission of node i to node k can be eliminated. For example, in Figure 3, which shows the resulting broadcast tree of the BIP algorithm, the communication range of node 9 is high enough to reach node 6 (which is the furthest node that node 10 transmits to). Therefore, the transmission of node 10 to node 6 can be eliminated. The resulting broadcast tree after the sweep operation is shown in Figure 4.

2.2.4 Complexity Analysis

As described in Section 2.2.1 and implemented in the code provided with this project, the algorithm has a most outer loop which iterates until all nodes are included one by one in the broadcast tree. This takes $O(N)$. To do this, every node in the broadcast tree either already transmitting or not (which at most takes $O(N)$) needs to check every other node not yet included in the broadcast tree (which at most takes $O(N)$) and selects the node that can be added with the minimum amount of additional power. Therefore, overall, the time complexity of the BIP algorithm is $O(N^3)$.

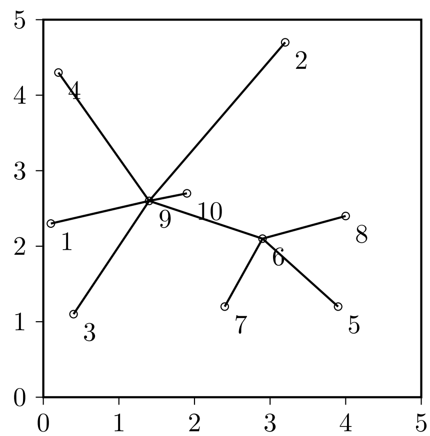

Figure 4: The resulting broadcast tree after the sweep operation [WNE00].

The time complexity of the sweep operation is $O(N^2)$. This is because every node i (and hence N nodes) check to see if every other node j (and hence N) has a transmission receiving node k at node j's furthest communication range that also falls within the communication range of node i. If this is the case, then the transmission power of node j is reduced until node k is excluded from node j's communication range.

2.3 Embedded Wireless Multicast Advantage (EWMA) Algorithm

2.3.1 Algorithm Description

The Embedded Wireless Multicast Advantage (EWMA) algorithm starts with a feasible broadcast tree for the network, then the solution is improved by removing some existing branches and establishing some new branches such that the total energy of the broadcast tree is reduced. The difference in the total energies of the trees before and after the branch exchange is called a gain. In [vHE02], a minimum spanning tree (MST) is used as the initial feasible solution. To describe the algorithm, first some notations are introduced: C denotes the set of covered nodes in a network, F is the set of transmitting nodes of the final broadcast tree, and E is the set of excluded nodes. A node is called excluded node if it is a transmitting node in the initial solution but it is not a transmitting node in the final solution. Initially, $C = s$, where s is the source node. and F and E are empty. Initially, $C = \{s\}$, and sets F and E are empty.

A propagation constant of $\alpha = 2$ is assumed.

Figure 5 shows an example network and the MST as the initial solution. In this network, node 10 is the source. After the MST is built, the transmitting nodes are 10, 9, 6, 1, 8, and their transmission energies are 2, 8, 5, 4, and 4, respectively, and the total energy of the MST is $e_{MST} = 23$. At this stage, $C = \{10\}$, and $F = E = \{\emptyset\}$. In the second stage, the algorithm tries to build a broadcast tree from nodes in the set $C - F - E$. The gain of a node i is the amount of energy obtained in total from increasing node i's transmission power in exchange of excluding some nodes in the MST. For example, in the network in order to exclude node 8, the source node 10 has to increase its transmission power by $\Delta e_{10}{}^{8} = 13 - 2 = 11$. The gain obtained by doing so is $g_{10}^{8} = e_6 + e_8 + e_9 - \Delta e_{10}{}^{8} = 6$. We note that when the transmitting power of node 10 is high enough to exclude node 8, nodes 6 and 9 can also be excluded. Similarly,

$$g_{10}^{1} = e_1 + e_6 + e_8 + e_9 - \Delta e_{10}^{1} = 5$$

$$g_{10}^{6} = e_6 - \Delta e_{10}^{6} = -2$$

$$g_{10}^{9} = e_6 + e_8 + e_9 - \Delta e_{10}^{9} = 6$$

Once the gains for all nodes from C-F-E are calculated, the algorithm selects a node with the highest positive gain in the set F. In this example, the node with the highest positive gain is node 10, and hence, at this stage, $C = \{1, 2, 4, 5, 6, 7, 8, 9, 10\}, E = \{6, 8, 9\}$ and $F = \{10\}$.

Since node 3 is not covered yet, this procedure is repeated again. In this stage, $C - F - E = \{1, 2, 4, 5, 7\}$. The algorithm chooses the next transmitting node from this set. The gain corresponding to having each node from this set as the transmitter is computed, and the node with the highest gain is selected. Node 1 has the highest gain (since it expends the minimum power to reach node 3) and is selected as the next transmitting node. Now, all nodes are covered and the algorithm terminates with $C = \{1, 2, 3, 4, 5, 6, 7, 8, 9, 10\}, E = \{6, 8, 9\}$ and $F = \{1, 10\}$. Figure 6 shows the resulting broadcast tree. The total energy of this broadcast tree is $e_{EWMA} = 17$ which is lower then the cost of the MST ($e_{EWMA} = 23$).

2.3.2 Complexity Analysis

Now we determine the time complexity of the EWMA algorithm. Assume N is the number of nodes. As mentioned previously, every node (hence $O(N)$) starting from the source node checks if it can get some gain from increasing its transmission power and excluding some neighboring nodes. To do this, not only the neighboring nodes must be considered ($O(N^2)$ up to now) but also all neighbors of each neighboring node that are connected to it must be checked ($O(N^3)$). As this process is repeated n times for all iterations, the total time complexity is $O(N^4)$.

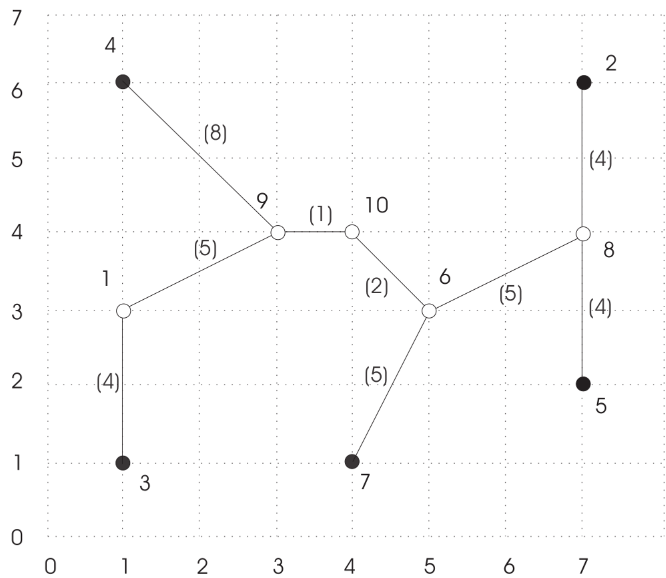

Figure 5: A sample network and the MST as the initial solution. [vHE02]

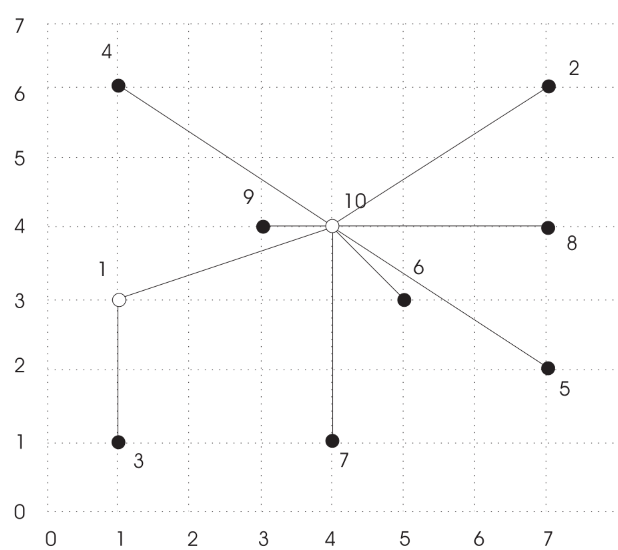

Figure 6: The resulting broadcast tree from EWMA algorithm. [vHE02]

3 New Algorithms And Modifications of Previously Studied Algorithms

In this section, some new suggestions (that to the best of my knowedge are not mentioned in the literature and might be worth investigating) to improve the previously studied algorithms are proposed.

3.1 BIP With Decreasing Source Range

Range is defined as the maximum distance over which a node transmits signals. The BIP algorithm studied in Section 2.2 starts from the source node and incrementally increases its transmission power (and hence range) until nodes are included one by one. At any stage, if using a relay node would result in inclusion of an additional node with less transmission power, the relay node is used. An alternative approach is what we might call reverse BIP. In this approach the range of the source starts from a value which is high enough to reach the furthest node i. Then the source transmission power is decreased until node i is excluded, and instead the nearest node to node i acts as a relay node and transmission is done through that relay node. If this will result in lower total power cost then the transmission is done via the relay node. The same procedure is then repeated for the second furthest node up until the nearest node to the source.

3.2 EWMA with BIP as Initial Feasible Solution

In Section 2.3, the EWMA algorithm is described for the minimum power broadcast problem in wireless networks. The EWMA starts with an MST as an initial feasible solution and then tries to reduce the total power consumption by eliminating some nodes in the MST in exchange for increasing the transmission power of some other nodes. A new idea might be to use the resulting broadcast tree from the BIP algorithm instead of the MST as the initial feasible solution.

4 Conclusions

Energy efficiency is crucial for wireless ad hoc networks since they rely on batteries with a finite lifetime. Two energy efficient broadcasting algorithms, namely the BIP and the EWMA, alongwith their complexity analysis are described in this report. Two new ideas have been suggested for more energy efficient broadcasting algorithms. Also, the BIP algorithm is implemented in C++ and has been tested with successful results for small and large network sizes.

References

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