On the Cost and Quality Tradeoff in Constructing Minimum-Energy Broadcast Trees in Wireless Ad Hoc Networks

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I. Introduction

A wireless ad hoc network consists of a collection of wireless mobile nodes, dynamically forming a temporary network without the use of any centralized administration. Typically, each node in such a network has limited energy resources. Consequently, energy-efficiency is an important design consideration for such networks. In such networks, broadcast communication provides a bandwidth efficient mechanism to communicate information between a source and a group of nodes. Broadcast can be used for data dissemination from a single data source, coordination and control among the nodes in the network, resource discovery, and as a primitive operation in on-demand unicast protocols such as DSR [4] and AODV [6].

Recently, minimum-energy broadcast communication in wireless ad hoc networks have been shown to be NP-complete [3], [5], [1]. Several heuristics have been proposed [7], [1], each having a different complexity and producing a broadcast tree with a different energy cost. Thus, there has been a lack of understanding of the tradeoffs involved in designing these heuristic algorithms. To understand these tradeoffs, we first isolate three key ingredients that constitute any such heuristic: (a) how the basic tree is constructed, (b) how wireless multicast advantage (WMA) is exploited to reduce the total energy consumption, and (c) how often to apply the WMA exploitation. We analyze six heuristics to identify the contribution of each building block in terms of complexity added and the improvement to the quality of the trees constructed.

II. Building Blocks

The three ingredients that constitute any minimum-energy broadcast heuristic algorithm are:

a) Tree Formation: It is a step by step procedure of adding new nodes to a partially built tree. For example, one can add nodes by following a MST algorithm [2] which gives an optimal solution if WMA is disregarded. Similarly, one can use BIP [7] heuristic algorithm for the same when WMA is not disregarded.

b) WMA Correction: The correction process is used to reduce the overall broadcast energy of the partially or completely built tree. The correction algorithm repeatedly applies expansion steps. Each such step increases some node's transmission power and as a result many other nodes are shut off or made to transmit at a lower power. The value by which the total broadcast power gets reduced is called the *gain* of the step. In our taxonomy, we consider EWMA [1] and propose NWMA, which is an extension of EWMA, as the two major correction algorithms. EWMA has two restrictions: First, in an expansion step, a node A gains from another node B if and only if it is able to reach all the children of node B and thereby shut off node B completely (and not just reduce its power to some lower value by not reaching the far-off children of B). Second, EWMA does not expand a node B if it has already been shut down or expanded in some previous expansion step. In contrast, in NWMA, none of the above constraints are followed which helps obtain better broadcast trees.

c) When to apply WMA Correction: The two general ways of applying WMA correction are: (i) To apply it every time a new node is added to the tree by a tree formation step; (ii) To apply it after a complete tree is built using only tree formation steps.

Decoupling the three building blocks of minimum-energy broadcast heuristic algorithms allows us to categorize different heuristics based on the variations in the building blocks described above. A taxonomy is given in Table I.

III. Experimental Results

We simulated the different heuristics and compared them against each other. We varied the network size between 10, 20, 50, 100, and 200. For each network size, 50 network instances were generated and simulated. For each instance, the nodes were randomly generated on a grid. We used a propagation constant $\alpha = 2$ in these simulations. We measured the total transmission power of the broadcast trees constructed. The results are plotted using the notion of *normalized tree power* [7]. Let $p_i(m)$ denote the total power of the broadcast tree for a network instance m, generated by algorithm i. Let

Heuristic	Tree form	WMA Corr.	WMA Corr. Appl.
MST_EWMA_End	MST	EWMA	At the end
BIP_EWMA_End	BIP	EWMA	At the end
MST_EWMA_Inc	MST	EWMA	Incremental
BIP_EWMA_Inc	BIP	EWMA	Incremental
MST_NWMA_End	MST	NWMA	At the end
BIP_NWMA_End	BIP	NWMA	At the end
MST_NWMA_Inc	MST	NWMA	Incremental
BIP_NWMA_Inc	BIP	NWMA	Incremental

TABLE I

A TAXONOMY OF MINIMUM-ENERGY BROADCAST HEURISTIC ALGORITHMS

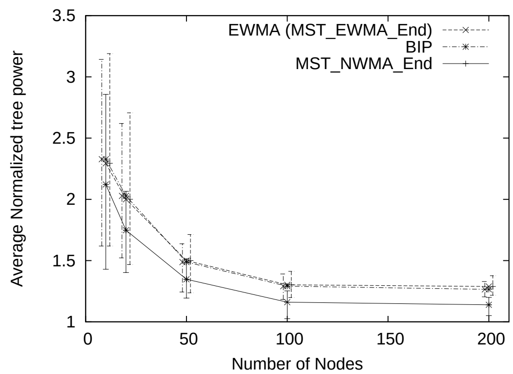

Fig. 1. Normalized tree power for 50 network instances and 10 and 90 percentiles.

p_0 be the power of the lowest-power broadcast tree among the set of algorithms performed and all network instances (50 in our case). Then the normalized tree power associated with algorithm i and network instance m is defined as $p'_i(m) = \frac{p_i(m)}{p_0}$.

Figure 1 shows the normalized tree power for BIP, EWMA (MST_EWMA_End), and MST_NWMA_End. It shows that the tree powers generated by BIP and EWMA are comparable while MST_NWMA_End generates trees with much lower powers than BIP and EWMA. Since EWMA and MST_NWMA_End only differ in the correction algorithm, these results confirm that *NWMA is a better correction algorithm than EWMA*.

Figure 2 shows that using the same correction algorithm, namely NWMA, MST_NWMA_Inc, BIP_NWMA_Inc, MST_NWMA_End, and BIP_NWMA_End generate broadcast trees with comparable transmission powers. Also, the variations of normalized tree powers for all the four algorithms are very similar. This shows that (i) *the impact of the tree formation algorithm is not significant*, (ii) *applying WMA correction incrementally does not have any advantage over applying it once in the end*, and (iii) this result combined with the observations made from Figure 1 confirm that *the correction algorithm employed is the single most important factor in deciding the quality of the broadcast trees obtained*. We do not consider MST_EWMA_Inc, BIP_EWMA_Inc and BIP_EWMA_End further as they differ only in the tree formation method employed and the frequency of application of WMA correction, neither of which has any significant impact

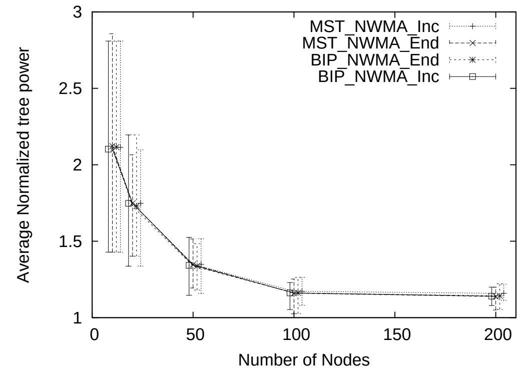

Fig. 2. Normalized tree power for 50 network instances and 10 and 90 percentiles.

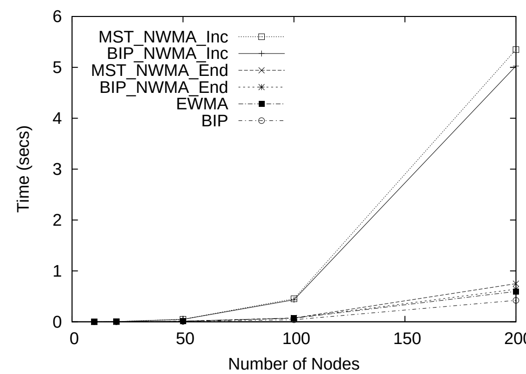

Fig. 3. Execution time of the six heuristics running on a 2Ghz Intel Pentium 4 PC.

on the quality of the broadcast trees obtained.

Figure 3 shows the execution time of each of the six heuristics. It shows that *MST_NWMA_End and BIP_NWMA_End which apply the correction algorithm at the end have much shorter running times than the ones that apply the correction algorithm incrementally, and the choice of tree formation algorithms has little effect on the running time*.

ACKNOWLEDGMENT

I am thankful to Prof. Y. C. Hu for his guidance. This work is supported in part by a Tellabs Foundation fellowship and by NSF grant ANI-0338856.

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