Energy-Efficient Broadcast and Multicast Trees for Reliable Wireless Communication

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***Abstract*— We define energy-efficient broadcast and multicast schemes for reliable communication in multi-hop wireless networks. Unlike previous techniques, the choice of neighbors in the broadcast and multicast trees in these schemes, are based not only on the link distance, but also on the error rates associated with the link. Our work is based on some existing techniques that create such trees which have a constant approximation ratio to optimal solutions. However, these existing techniques are applicable only to the ideal scenario where wireless links are error-free. Through simulations we show that our scheme achieves upto 45% improvement over previous schemes on realistic 100-node network topologies.**

I. INTRODUCTION

Algorithms to create energy-efficient broadcast or multicast trees in multi-hop wireless networks aim to exploit the inherent *wireless broadcast advantage*: when omnidirectional antennas are used, every transmission by a transmitting node can be received by *all nodes* within the transmission range. The problem of determining minimum aggregate transmission energy trees is known to be NP-Hard for the broadcast case [5]. Computation of similar minimum energy multicast trees in wired environments is equivalent to the Steiner tree problem, which is also known to be NP-Hard. Therefore, intelligent heuristic algorithms have been proposed for constructing such minimum-energy broadcast or multicast trees [5], [10]. All these algorithms, however, aim to minimize the transmission power required by a sender and intermediate nodes for a single packet transmission — they do not consider how possible link errors affect the energy costs for reliable delivery of the packet to the entire set of destination nodes.

In this paper, we focus on developing energy-efficient trees for *reliable* wireless multicasting or broadcasting. In wireless environments, where individual links often have high error rates, such reliable delivery potentially requires one or more retransmissions. Currently known minimum-energy tree formation algorithms assign costs to links based purely on the energy spent in a single transmission attempt to reach all their children. These techniques, therefore, do not provide the best performance from a reliable delivery standpoint. Since the number of retransmissions needed by a node to reliably deliver a packet to its children clearly depends on the error rates of the associated links, a retransmission-aware minimum cost algorithm must assign costs based on two parameters — the transmission power required by the node to reach its children on the delivery tree and *the error probability of its outgoing links*.

We had earlier studied the problem of energy-efficient reliable communication in the unicast case in [2] and had shown how the choice of routes based on retransmission-aware metrics can reduce the total transmission energy by as much as 70% over previous minimum-energy routing schemes (such as PAMAS [8]). The case of reliable broadcast or multicast is slightly different, since the probability of re-transmissions by a node depends not just on the error rate of a single downstream link, but on the combined effect of errors on *all the individual links* to each of its immediate child nodes.

We first consider the problem of reliable broadcasting in a multi-hop wireless network. Wieseltheir et al [10] had defined the following three broadcast tree formation algorithms which was shown to have constant approximation ratios to the optimal solution for error-free wireless links [9]:

1) Broadcast Incremental Power (BIP), which forms a tree using a modified version of Prim's algorithm.
2) Broadcast Least-Unicast-cost (BLU), which forms a tree by the superposition of the least-cost (minimum energy) unicast paths to each individual destination node.
3) Broadcast Link-based MST (BLiMST), which forms a minimum spanning tree by simply setting each link cost to the transmission energy needed to sustain communication over that link.

While BIP considers the wireless broadcast advantage in the tree formation process, BLU and BLiMST do not. In this paper, we present appropriate modifications to these algorithms to compute energy efficient data delivery trees that takes into account the costs for retransmissions necessary. By factoring in the individual link error probabilities in the cost, our modified algorithms avoid including poor quality links in the eventual tree, even if such links apparently incur lower transmission costs. Our formulation assumes that a transmitting node adaptively adjusts its power level during retransmissions to reach only the set of children nodes that have yet to correctly receive the packet. We use simulations to evaluate the relative performance of the reliable versions of the three algorithms with each other, and with their unreliable counterparts (as presented in [10]), to quantify the performance benefits.

We then discuss how the problem of energy-efficient reliable multicast delivery can be solved by simple modifications to the reliable broadcast algorithms, and ascertain the performance of these algorithms for varying multicast group sizes. Through simulation studies we observed that retransmission-aware schemes achieve upto 45% reduction in energy costs. In this paper, we first describe a centralized version of these algorithms. Subsequently, we describe how these techniques can be distributedly implemented in realistic multicast protocols. More specifically, we describe extensions to the Core Based Tree (CBT) multicast protocol [1] to make it retransmission-aware. Through packet-level simulations of this protocol we

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show that simple retransmission-aware metrics can be used to significantly reduce the energy costs of such protocols in error-prone wireless environments, even for of highly dynamic multicast groups.

Operating Assumptions

Nodes are assumed to be able to adapt their transmission power to the minimum necessary to sustain communication over a particular link. Since the attenuation suffered over a wireless link typically varies with distance D as D^{α}, the transmission power, $T_{i,j}$, needed for communication between nodes i and j separated by a distance $D_{i,j}$ is assumed to be $\propto D_{i,j}^{\alpha}$. The exponent, α, is typically around 2 for short-distances, and around 4 for larger distances (over 100 meters). Accordingly, when a transmitter node i intends to reach all the nodes in a set C with a single direct transmission, it needs to transmit at a power P_i given by

$$P_i \propto D_{i,k}^{\alpha}, \quad \text{where} \quad k = \arg\max_j D_{i,j} \quad j \epsilon C \qquad (1)$$

Since we are merely concerned with the relative performance of different algorithms, we can assume the proportionality constant to be 1 without any loss of generality. The error rate for any link (i, j) is denoted as $p_{i,j}$ — in the wireless environment, these error rates can often be as large as $30 - 40\%$. We do not consider the effects of node mobility in this paper.

We also assume that a node is capable of *intelligently* and efficiently adapting its power-level during retransmissions to the level necessary to reach only those children that have so far not received the packet correctly. This implies that the children are able to send acknowledgment messages to the parent node. However to avoid the ack implosion problem, wireless link layers recommend disabling acknowledgment in response to multicast packets [3]. To avoid this situation, many reliable multicast schemes use a negative acknowledgment (NAK) based solution (e.g. SRM [4]). Our proposed technique can also be adapted to this NAK-based wireless multicast environment with simple modifications.

II. RELATED WORK

While several algorithms have been proposed for minimum-energy unicast routing in wireless networks (e.g., [8], [7]), the minimum-energy multicasting problem is relatively recent and much harder. The problem was proved in [5] to be NP-Hard.

The BIP, BLU and BLiMST heuristic algorithms for computing energy-efficient trees for unreliable wireless broadcasting and multicasting, as described in Section I were presented in [10]. This work was subsequently extended in [11], which considered operation under additional constraints such as limited bandwidth and limited node energy. Iterative Maximum-Branch Minimization (IMBM) algorithm is an alternative heuristic algorithm suggested in [5] to construct minimum-energy broadcast trees, and was shown to outperform BIP for smaller values (close to 2) of the propagation exponent α.

Reliable multicasting have typically been addressed for the wired environment, where the primary focus has been to solve the ack implosion problem using pure end-host mechanisms (e.g. SRM [4]) or using router support (e.g. RMTP [6]). Our focus is more on understanding the fundamental aspects of energy-aware reliable multicasting for wireless ad-hoc environments. Hence, for the sake of simplicity we assume that the intermediate nodes implement reliable forwarding mechanisms to its immediate children using hop-by-hop ACK or NAK-based techniques.

III. RETRANSMISSION-AWARE MINIMUM ENERGY TREES

In this section, we develop the algorithms to create minimum energy trees for reliable data transfer. We start with the broadcast case, where all nodes are destination nodes. Subsequently we extend the technique for the multicast case, where only a subset of the total nodes are intended recipients.

Consider a wireless link, $\langle i, j \rangle$, between two nodes i and j. Let $E_{i,j}$ denote the energy required to transmit a packet from i to j, where $E_{i,j} \propto D_{i,j}^{\alpha}$. If the link has a packet error probability, $p_{i,j}$, then the expected number of transmissions (including retransmissions as necessary) to reliably transmit a single packet across this link is $1/(1 - p_{i,j})$. Hence, the expected energy requirements to reliably transmit a packet across the link is given by

$$E_{i,j}(\textit{reliable}) = \frac{E_{i,j}}{1 - p_{i,j}} \qquad (2)$$

We use this measure of energy requirements as a link cost metric for the different reliable broadcast algorithms.

A. *Reliable Broadcast Incremental Power (RBIP)*

Like the BIP algorithm, RBIP is also a modified version of the Prim's algorithm, in that it greedily adds links to an existing tree such that the incremental cost is minimized. Additionally, both these algorithms dynamically modify the costs associated with the individual links during this iterative process. However since RBIP works on reliable transmission costs, these costs are a function of both the link distances and link error rates. Therefore, RBIP does not start by necessarily choosing the closest nodes.

Before proceeding further, it is necessary to quantify the actual energy costs for reliable packet transmission by a node i to its children on the broadcast tree. In this paper, we focus only on a positive acknowledgment scheme. In this scheme node i transmits the first packet with sufficient power to reach all its children. In subsequent re-transmissions, it chooses a transmission power which is sufficient to reach all those children which did not acknowledge the reception of this packet. The average energy costs for reliable transmission is computed by Procedure *ComputeTxtCost*(i, S), shown in Figure 1, where S is the set of children nodes.

If a negative acknowledgment scheme is used, node i will be required to re-transmit the packet with a power level necessary to reach all its children as long as it receives NAKs from any of them.

The RBIP algorithm iteratively adds the minimum cost link (from the set of eligible links) to an existing tree. The algorithm is initiated with a tree, T, consisting of only the source node, r, as root and the cost for each other node is given by Equation 2.

```
Procedure : ComputeTxCost$(i, S)$
$S_{sort} \leftarrow$ SortByDistance$(i, S)$
    { $S_{sort}$ is sorted by decreasing order of distance from $i$ }
$n_{tot} \leftarrow 0$; $cost \leftarrow 0$
for $j \in S_{sort}$ in the decreasing sequence
    $n_j \leftarrow \frac{1}{1-p_{i,j}}$
    if $n_{tot} < n_j$
        $n_{extra} \leftarrow n_j - n_{tot}$
        $cost \leftarrow cost + n_{extra}.E_{i,j}$
        $n_{tot} \leftarrow n_{tot} + n_{extra}$
return $cost$
```

Fig. 1. Computing the average energy requirements for reliable transmission a packet from a node i to the set of nodes, S, which are within the transmission range of i. $E_{i,j}$ is the energy required for a single transmission from node i to node j, and $p_{i,j}$ is the associated packet error probability for the link $\langle i, j\rangle$. If a NAK-based reliability scheme is used in the link layer, then the cost increment in the **for** loop should always be done by $n_{extra}.E$, where E is the transmission energy required to transmit to that node in S that is farthest from i.

```
Procedure : UpdateCost$(\langle i, j\rangle, k)$
    { Let $S$ be the current set of children of $i$ in the tree }
$c \leftarrow$ ComputeTxCost$(i, S \cup \{k\})$ − ComputeTxCost$(i, S)$
if $(cost_k > c)$
    $cost_k \leftarrow c$; $\pi_k \leftarrow i$
```

Fig. 2. Update the cost of node k (which is a neighbor of node i) after a new link$\langle i, j\rangle$ is added to the tree in the modified Prim's algorithm for RBIP. Node k is not currently part of the tree. π_k is set to indicate the current candidate parent of k.

The algorithm in pseudo-code is presented in Figure 3. In each step of **while** loop in the algorithm, the minimum cost node, x is added to the tree, and π_x denotes the parent node which is already part of the tree. Additionally, for each neighbor, y of π_x which is not currently in the tree, the cost is updated using the Procedure *UpdateCost*$(\langle \pi_x, x\rangle, y)$ shown in Figure 2. The *incremental* cost for node π_x to reliably transmit a packet to node y is the updated cost for y if it is lower than the current cost of y. If subsequently the node y is added to the tree with no further change to its cost, then its parent in the tree will be node π_x. The parent pointer is, therefore, also updated in the *UpdateCost* procedure.

The computational complexity of an efficient implementation of the *PrimRBIP* algorithm (e.g. using a Fibonacci heap, presorting all neighbors by distance, etc.) is $O((m+n)\log n)$, where n is the number of nodes in the topology and m is the number of edges on the corresponding communication graph.

B. Reliable Broadcast Least-Unicast-cost (RBLU)

The RBLU algorithm is a simple extension to the BLU algorithm in [10]. The link costs for each link $\langle i, j\rangle$ is given by Equation 2. Using these link costs, we compute the minimum cost unicast routes from the source node to all other nodes, and the "minimum energy" tree is computed as the superimposition of all these paths. Thus, the RBLU more accurately models the energy costs of reliable packet transmissions, as compared to the BLU algorithm, but neither of these algorithms consider the multicast advantage of the wireless links.

```
Procedure : PrimRBIP$(r, S)$
for $(x \in S)$
    $cost_x \leftarrow E_{r,x}(reliable)$; $\pi_x \leftarrow r$
$cost_r \leftarrow 0$; $\pi_r \leftarrow NULL$; $R \leftarrow S - \{r\}$; $T \leftarrow \emptyset$
while $(R \neq \emptyset)$
    $x \leftarrow$ ExtractMinCostNode$(R)$
    $T \leftarrow T \cup \{\langle \pi_x, x\rangle\}$
    for $(y \in \{$NeighborSet$(x) \cap R\})$
        if $(cost_y > \frac{E_{x,y}}{1-p_{x,y}})$
            $cost_y \leftarrow \frac{E_{x,y}}{1-p_{x,y}}$; $\pi_y \leftarrow x$
    for $(y \in \{$NeighborSet$(\pi_x) \cap R\})$
        UpdateCost$(\langle \pi_x, x\rangle, y)$
```

Fig. 3. The modified Prim's algorithm for RBIP, where r is the root node for the broadcast tree, and S is the entire set of nodes. The routine *ExtractMinCostNode*(R) returns the node, x in the set R with the minimum cost, and also deletes the node from the set. *NeighborSet*(q) indicates the set of nodes that are within the transmission range of q. The broadcast tree is the set of links in the set T.

C. Reliable Broadcast Link-based MST (RBLiMST)

The RBLiMST is, similarly, a simple extension of the BLiMST algorithm. Again the link costs for each link is given by Equation 2. The minimum spanning tree rooted at the source is computed using this metric.

D. Sweep Algorithm and Tree Costs

The performance of the algorithms can be improved by using a "sweep" operation that eliminates or reduces the transmission energy requirements of some nodes. The benefits and mechanisms for the sweep protocol was presented in [10] for the unreliable packet transmission case. In our reliable transmission case, we perform the sweep operations in a post-order traversal of the tree. A node, x is transferred from being a child of its parent, $y = \pi_x$ to being a child of its grand-parent $z = \pi_y$ if doing so reduces overall energy requirements for reliable packet transmission costs. The change in costs for the nodes y and z can be computed as follows:

$$\Delta_y = \textit{ComputeTxCost}(y, C_y - \{x\}) - \textit{ComputeTxCost}(y, C_y)$$
$$\Delta_z = \textit{ComputeTxCost}(z, C_z \cup \{x\}) - \textit{ComputeTxCost}(z, C_z)$$

where C_y and C_Z denote the children set of the nodes respectively. Node x is transferred from y to z, if and only if, x is within the transmission range of z and

$$\Delta_y + \Delta_z < 0 \qquad (3)$$

Unlike the unreliable case, a node cannot be transferred merely based on the distance information between the nodes. The link error rates need to be considered as defined in Equation 3 in making this decision.

The expected energy requirements for reliable packet broadcast using a tree created by any of the reliable tree building protocols is given by:

$$\textit{Cost}_T = \sum_{x \in \textit{NodeSet}} \textit{ComputeTxCost}(x, C_x) \qquad (4)$$

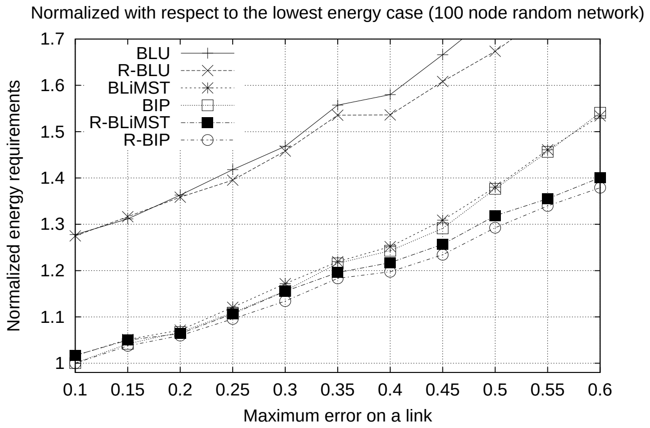

Fig. 4. Normalized energy requirements for the different broadcast schemes on the 100 node random network for varying maximum link error probabilities.

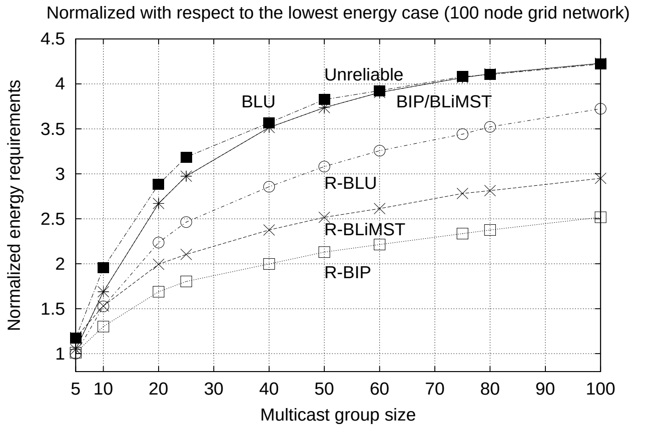

Fig. 6. Normalized energy requirements for the different multicast schemes on the 100 node grid network for varying group sizes for maximum link error probability of 0.4.

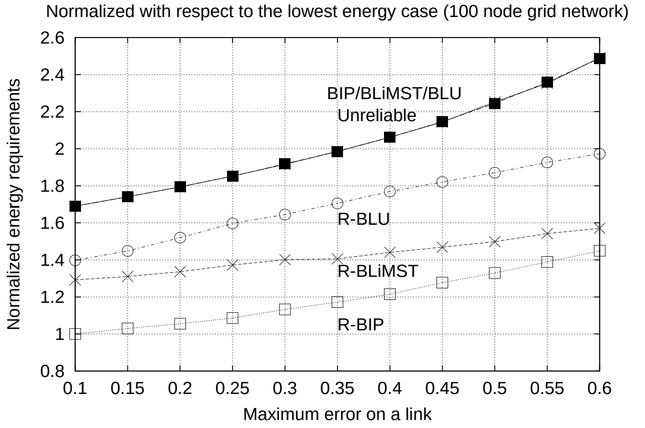

Fig. 5. Normalized energy requirements for the different broadcast schemes on the 100 node grid network for varying maximum link error probabilities.

E. *Multicast Trees*

The computation of a minimum cost multicast tree in wired networks is also known as the Steiner tree problem which is known to be NP-Hard. In this section, we present heuristics to compute minimum energy reliable multicast trees. The heuristics are direct analogs of the reliable broadcast tree algorithms.

We first compute the broadcast tree for the entire set of nodes but do not apply the sweep algorithm. Next, we prune those nodes from the tree that do not lead to any multicast group member. This processing is performed in a single post-order traversal. Finally, the sweep operations are performed on the remaining tree in post-order. The three multicast algorithms are correspondingly named Reliable Multicast Incremental Power (RMIP), Reliable Multicast Least-Unicast-cost (RMLU) and Reliable Multicast Link-based MST (RMLiMST) analogous to their broadcast counterparts.

F. *Performance Comparisons*

We have analyzed the performance of these different schemes through detailed simulations. In different experiments we study the algorithms over different topologies with varying sizes. In this section, we present the results for 100 node topologies. To get good confidence bounds we present averages of 100 separate runs for each result.

We present results for random and grid topologies. In the random topologies, the wireless nodes are randomly located in a 100×100 square grid. We vary the transmission range of the nodes to create topologies with different number of edges. Like in [10], in this paper we only present results for the case where the transmission range is large enough to reach all other nodes, for ease of comparison. For the grid topology, the 100 nodes are placed 10 units apart of a rectangular grid. The nature of the results on these two topologies provide an interesting insight to the re-transmission aware metric. The error probability of the different links are chosen uniformly at random between 0 and a maximum value.

Broadcast for Random Topology: In Figure 4 we present the energy requirements for the different schemes for as the maximum link error probability is varied. The energy is normalized with respect to the experiments that led to the lowest energy requirements (RBIP for the case when the maximum link error probability was 0.1).

We summarize the observations of these experiments as follows: The retransmission-aware algorithms show a relative improvement over their unreliable counterparts which varied between 5-10% in all the scenarios. The RBIP algorithm has the lowest energy costs among all the schemes and is closely followed by the RBLiMST scheme. The reliable and unreliable BLU schemes have significantly higher costs (about 30% more) than the other schemes. As expected there is an increase in the energy requirements for all the different schemes with increase in link error probabilities.

Although the reliable schemes show an improvement over the unreliable schemes, the relative benefits vary between 5-10%. This is because of the nature of the variation of the link cost metric with distance and link error probabilities. The link cost (and hence, the energy requirements) increase as D^α with increase in distance, D and as $1/(1-p)$ with increase in link error probability, p. For example, for $\alpha = 2$, doubling the distance increases the energy costs by a factor of 4, while doubling the link error probability (e.g. from 0.2 to 0.4) increases the energy costs by a factor of 1.33. Therefore, the distance component plays a more significant role in energy costs. For a complete graph (which has the maximum number of edges), the energy costs are primarily determined by the distance component, which are same for both the reliable and unreliable schemes.

Therefore, to study the effect of link error probability only, we next present some results on a grid topology.

Broadcast for Grid Topology: In the grid topology, the nodes are arranged equispaced on a two-dimensional rectangular grid, with the space between adjacent nodes being 10 units. Additionally, we restrict the transmission range of each node to 15 units. This implies that a node is able to reach one neighbor along each axis direction, and one neighbor along each diagonal direction. The distance between nodes is thus restricted to just two different values (10 units and 14.14 units).

In Figure 5 we plot the energy costs for the different schemes for grid topologies. We make the following observations: The reliable protocols perform significantly better than their unreliable counterparts. For example, the RBIP algorithm has upto 45% lower energy costs than the BIP algorithm. The performance of the unreliable algorithms are very similar to each other (the plots for the three unreliable schemes are practically indistinguishable). The RBIP algorithm performs the best among all the algorithms. The performance benefits of the reliable versions increases with increase in the size of the network.

Multicast groups for Grid Topology: Finally, in Figure 6 we present the energy requirements for the different algorithms for mutlticast trees. In these experiments, the link error probabilities were chosen uniformly at random to vary between 0 and 0.4. For each of these experiments, we chose a random subset of the 100 nodes to form a multicast group, and apply the technique outlined in Section III-E to create the multicast trees. The results are similar to the broadcast case. The plot shows the aggregate energy costs over all the transmitting nodes; therefore we see an increasing cost for larger group sizes. It is also interesting to note that the marginal increase in costs for increase in the group size decreases as the group gets larger.

IV. DISTRIBUTED IMPLEMENTATION

Due to space constraints, we briefly describe a distributed implementation of a re-transmission aware multicast protocol based on our described schemes. This new protocol is an extension of the CBT multicast protocol [1], where joining nodes unicast *group_join* messages towards a "core" node in the network and all nodes in the path of this message is added to the multicast group. We assign the re-transmission-aware cost metric (Equation 2) to the links which is used by the unicast routing protocol to compute shortest paths. Each node, x, on the tree periodically (once every 3 seconds) checks for potential sweep operations as described in Section III-D.

We have implemented these protocols in our packet level simulator. In Table IV we compare the performance of two protocols for varying rate of changes in the group membership. CBT(Dist) uses only a distance-based cost metric for join path determination and sweeps. CBT(Error) is our proposed scheme. The energy costs are normalized with respect to the specific experiment which required maximum energy to transmit the same number of multicast packets to the group. The average join/leave interval specifies the average gap (in s) between successive changes to the group membership. For very frequent changes to the group, the multicast delivery path does not stabilize to energy efficient delivery paths. The energy costs therefore increase with increasing frequency of changes to the group. In fact for an average join/leave interval of 0.5 second the energy requirements of the CBT(Error) scheme exceeds the CBT(Dist) scheme. At this high rate of change the results are effectively random.

Avg. Join/Leave Interval (in s)	Normalized Energy Costs	
	CBT(Dist)	CBT(Error)
256.0	0.54	0.48
32.0	0.56	0.52
4.0	0.60	0.57
2.0	0.70	0.61
0.5	0.97	1.0

TABLE I

COMPARISON OF ENERGY EFFICIENT MULTICAST PROTOCOLS FOR THE 100 NODE GRID TOPOLOGY.

V. CONCLUSIONS

In this work we present energy-efficient reliable broadcast and multicast schemes for multi-hop wireless environments. The schemes can be easily integrated to current well-known distributed multicast protocols (e.g. CBT). In this paper, we assumed a wireless link layer that uses hop-by-hop positive acknowledgments for reliability. However, our scheme is extensible to a NAK-based scheme by a simple modification to Procedure *ComputeTxCost*.

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