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Multicasting of Connectionless Traffic in Resource-Limited Ad Hoc Wireless Networks

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Abstract— **In this work we address the problem of multicasting connectionless (packet oriented) traffic in energy and transceiver-limited ad hoc wireless networks. We first investigate the novel trade-offs caused by connectionless traffic as opposed to session-oriented traffic. Then we develop a new multicasting heuristic that is based on a minimum incremental** ***cost*** **logic. We also discuss the medium access (multicast scheduling) issues and propose a multicast scheduling scheme that works together with the proposed multicasting algorithm. Simulation results show that considerable improvement in energy and delay performance can be obtained by the proposed algorithms when compared with the ones that are originally designed for session based traffic.**

I. INTRODUCTION

Previous work on resource-limited multicasting was mostly done for the case of session (connection)-oriented traffic. Multicasting was first formulated from the viewpoint of energy efficiency in [1]. A key feature of the wireless medium is that topology can be changed by adjusting the RF transmission power; by using an omni-directional antenna all of the nodes in the communication range can hear the transmitted message. So in many situations instead of separately transmitting to all neighbor receivers, simultaneous transmission can be made in order to save energy. This is called the *wireless multicast advantage*[1]. In [2] the *Multicast incremental power algorithm (MIP)* was proposed for the construction of energy efficient multicast trees. This algorithm was a modification of Prim's MST algorithm [6] and it exploited the wireless multicast advantage. In [4],[5] and [7], more realistic network conditions were studied including a finite number of transceivers, limited bandwidth and limited energy.

Our main contribution in this work is adressing the energy-efficient multicasting problem for 'connectionless' (data-oriented) traffic as opposed to session-oriented. The network paradigm in the above referenced papers was such that, a multicast tree was formed and all of the nodes on this tree dedicated one of their available transceivers and frequency channels throughout the multicast session. In the connectionless case, however, a message is chunked into packets and each packet can be multicasted over different trees. Unless a packet finds a required set of transceivers and channel for transmission, it waits in the queue. Therefore queueing delay must also be taken into consideration. We assume a limited number of transceivers and finite initial energy, and propose a cost function that is used in the incremental cost algorithm. This cost function should take into account the limited energy resources and possible congestion.

In order to assess the complex trade-offs one at a time, we assume that there are unlimited bandwidth resources and that our topologies are static. Mobility effects can be relieved through the possibility of adjusting the transmission power. Nonetheless there are inherently static wireless networks (e.g. sensor networks) that involve no mobility. We also assume a centralized architecture, in which a central controller makes the multicasting and scheduling decisions. Distributed versions of the proposed algorithms is a subject of future research.

II. NETWORK MODEL

We consider a network, in which N nodes are randomly spread over a square area. The nodes are static and they are connected in the sense that any node can reach any other node through appropriate relays with the use of suitable power levels. Nodes can transmit with any transmission power P such that $P \leq P_{max}$. The received signal power is proportional to $Pd^{-\alpha}$, where d is the Euclidean distance between the transmitter and receiver and α is the path loss exponent. (Typically $2 \leq \alpha \leq 4$) Hence the RF power requirement to transmit through a link is given by:

$$P_{ij} = max\{d_{ij}^{\alpha}, P_0\} \tag{1}$$

where P_0 is the minimum required receive power error-free reception. Given the values of P_{max} and P_0, we can determine the maximum range of transmission, d_{max}. The resources of the network are modeled by:

- *Transceivers*: In this work, we assume that each node has $T_i = 1$ transceivers. A node can either choose to transmit or receive with this transceiver but cannot do both at the same time. The proposed algorithms can easily be modified for the case of multiple transceivers.
- *Energy*: $E_i(0)$ stands for the initial energy of node i. The residual energy of node i at time t is denoted

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by $E_i^r(t)$. When a node depletes its energy it can neither receive nor transmit new packets. Other than dissipating the RF power, energy is also spent at each transmission and reception by using constant amounts of $P_T = transmission$ and $P_R = reception$ processing powers. The node is assumed to spend no energy when it is idle.

Bandwidth: In this work, for simplicity, we assume unlimited number of frequency channels so that frequency assignment,which is a difficult combinatorial problem, can be avoided.

Communication is source-initiated and each node generates new multicast packets with independent *Poisson* distribution of rate λ. All multicast requests are admitted i.e. there is no admission control. The number of desired destinations (multicast set) of a packet is a random number with uniform distribution between 1 and N-1. Every node has equal chance of being in the desired multicast set. Service time of a packet over a single hop is constant and it is denoted by $1/\mu$, where μ is the service rate. Time is slotted and one slot length is equal to service time of one packet $(1/\mu)$. The nodes are synchronized to start their transmission at the beginning of the slots. Transmissions are done with omni-directional antennas, so all nodes within the range of the transmitting node can receive it. If node i depletes its energy reserves, all packets destined to node i and waiting in the adjacent queues of i are dropped.

Throughout this work we are considering connectionless traffic; hence there is no 'end-to-end' reservation of transceiver resources. All node i has to do as a relay node is to decide on the best feasible set of nodes to transmit the incoming and its own generated packets. If the packet can not be transmitted due to the lack of transceivers it is placed in the queue. We assume a *First Come First Serve* (FCFS) queue at each node. At each slot a node either transmits one of its packets to a number of neighbors or receives a packet from one of its neighbors or stays idle. A decision mechanism (scheduler) should exist in order to make the decisions of which one to do.

III. RESOURCE-LIMITED MULTICASTING OF PACKET TRAFFIC

When a node receives or generates a packet, it should know the intended multicast set for that packet, and according to that set, it should be able to decide which set of neighbors (transmission set) to forward the packet. Let S_i denote the set of neighbor nodes, to which node i has to forward its packet. Then, node i can make a transmission if and only if:

- Node i and each of the nodes in set S_i have at least one available transceiver.
- Node i and its intended set of neighbors have sufficient energy to complete data transfer.

The most common approach to multicasting is to form a *multicast tree*. Previous work on multicast trees assume session-based traffic; a multicast tree is formed for each generated packet and nodes on the tree allocate their transceivers for the duration of the session. In data-oriented case however, it may not be feasible to find a tree for every single packet. Moreover, some additional performance considerations arise from the limited energy and transceiver resources, which are discussed below:

A. Performance Considerations

1) Energy per Packet: The RF power required for error-free transmission *from node i to j* is given by (1). Additionally, if node i transmits to a set of nodes in the set S_i, it uses transmission processing power P_T and each of the nodes in the set S_i spends receive processing power P_R. These powers are dissipated in the duration of one time slot $(1/\mu)$. Therefore at this transmission a total of $(\max\{P_0, {d_{ij}}^{\alpha}\} + P_T + |S_i| P_R) 1/\mu$ units of energy is spent. Here node 'j' is the furthest node in the set S_i.

Now consider Figure 1, in which there are three nodes. Node 1 is the transmitter and nodes 2 and 3 are in the multicast set. Multicasting can be done in two ways as shown in Figures 1.a and 1.b: Direct transmission can be done to both nodes in one step; or multicast can be done in two steps, respectively . Choosing method (a) requires ${d_{13}}^{\alpha} + P_T + 2P$ units of power, while choosing method (b) requires ${d_{12}}^{\alpha} + {d_{23}}^{\alpha} + 2P_T + 2P$ units of power. First, suppose P_T and P are zero. Then, if ${d_{13}}^{\alpha} \leq {d_{12}}^{\alpha} + {d_{23}}^{\alpha}$ choosing (a) is a better option in terms of energy efficiency. Now lets assume that P_T and P are greater than zero. Then choosing (a) is even more advantageous because only P_T units of transmission power is enough instead of $2P_T$ units. We can call this as *wireless multicast advantage for energy*.This advantage is special to wireless medium and should be exploited in order to decrease the energy expenditure.

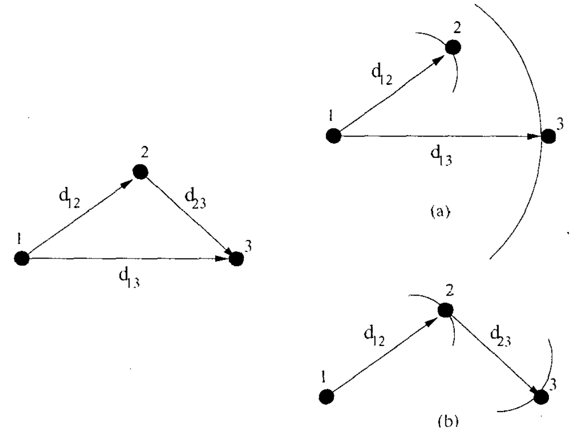

Fig. 1. An example topology: (a) and (b) shows two different alternative multicast trees. In (a) wireless multicast advantage for energy can be exploited. However consequences for network lifetime and packet delay depends on the residual energy and congestion states.

2) Network Lifetime: In this work, we define the network lifetime as the time until the first node dies. Recent work on the *energy-limited* routing and multicasting indicate that after death of the first node, other nodes are loaded more heavily; node deaths occur much faster, which degrades the data throughput of the network.

Consider again Figure 1. Assume that the processing powers are zero. We mentioned before that if $d_{13} \geq d_{12}{}^{\alpha} + d_{23}{}^{\alpha}$, then (a) is a better option in terms of energy efficiency. Suppose that the residual energy of node i is so small that it wont be enough for the energy expended for simultaneous transmission $((d_{13}^{\alpha} + P_T)1/\mu)$. Then it would be better to make the multicasting in two hops, as in (b), sacrificing wireless multicast advantage for energy.

Briefly, the nodes having small residual energy should be discouraged from transmitting with long range. Additionally the nodes that are not in the multicasting set should be discouraged from acting as relay, if they have small residual energy.

3) Stability and Delay: Delay is a very important performance criterion for queueing networks. Wireless medium presents novel trade-offs also for the delay. This can be illustrated by an example in Figure 1. In the example network, if multicast tree (a) is chosen, the transceiver of node 1 is used once and the transceivers of nodes 2 and 3 are also used once (total three transceiver usage). However if multicast tree (b) is chosen, transmission is made two times and reception is also made two times (total four transceiver usage). Therefore choosing tree (a) results in better transceiver utilization. Moreover; if (b) is chosen multicasting can be done in at least two time slots, whereas in (a) it can be done in a single slot , which decreases delay. This can be called as *wireless multicast advantage for delay.*

IV. ALGORITHMS

Multicasting scheme can be summarized as 1) Forming the broadcast tree. 2) Pruning the broadcast tree in order to form the multicast tree.

Each node stores the broadcast tree originating from itself. Each packet to be transmitted contains a set of destination nodes. The broadcast tree is then pruned such that the leaf nodes that aren't in this destination set are removed from the tree. Then the node determines which set of nodes to forward the packet to. Each node receiving this packet forwards the packet to the neighbors corresponding to the set of destinations. This continues until all of the destination nodes receive the packet. Below described are two algorithms for forming a broadcast tree:

A. Data-Oriented Link-Based MST (D-LiMST) Algorithm

This algorithm is based on the link-cost-based MST. Link cost is assigned to each link and Prim's algorithm is applied in order to find the minimum-cost link-based broadcast tree. The node adjusts its transmission power so that it reaches simultaneously all of its child nodes receiving its packet. Therefore the wireless multicast advantage is partially taken into consideration in the power control part of the algorithm.

The link-based cost metric used with this algorithm is as follows:

$$C_{ij} = \begin{cases} (\frac{P_{ij}}{P_{max}})(\frac{E_0}{E_i^R})^{\beta} L(Q_i + Q_j)^{\gamma} & \forall i, j s.t i \in \mathcal{R}(j) \\ \infty & otherwise \end{cases} \tag{2}$$

where P_{ij} is the RF power required for transmission from node i to j, E_0 is the initial energy of node i and E_i^R is the remaining energy of node i. Q_i is the *congestion* of node i; it is the sum of the number of neighbors corresponding to each packet waiting in the queue of node i. The function $L(x)$ is equal to $max\{1, x\}$, it prevents the metric from being equal to zero. This link metric is composed of three terms, as seen. β and γ are the coefficients that are adjusted to weigh the terms appropriately. This link cost metric addresses all of the performance issues that were discussed before. At the beginning of the network operation there are no packets in any queue and each node has equal residual energy (E_0). Link costs are equal to transmission power requirements over the links. As time goes on nodes on the minimum power paths begin to get congested and energy of the nodes on those paths begin to deplete. The second and third terms begin to increase. Low-energy and congested nodes are discouraged in multicasting. As a result some fairness is introduced to the network in terms of the consumed energy and experienced flow.

B. Data-Oriented Multicast Incremental Cost (D-MIC) Algorithm

Although the previous algorithm captures somewhat the wireless multicast advantage, we can better exploit by a change in the multicast tree algorithm. The Multicast Incremental Power [2] idea was previously designed for this purpose and uses the Broadcast Incremental Power Algorithm (BIP) to form a broadcast tree.

For our case we replace the logic of incremental power, with *incremental cost.* The logic of the algorithm is as follows: We first determine the next node that can be reached with minimum cost from the source node. We then determine "new" node to be added to the tree at a minimum additional cost - either a node already transmitting can increase its transmission power, or a non transmitting node, that has already been added to the tree can use one of its transceiver to start transmitting to the "new" node. We can define an incremental cost metric as follows:

$$C_{ij} = (\frac{P_{ij}}{P_{max}})(\frac{E_0}{E_i})^{\beta} L(Q_i + Q_j)^{\gamma} - (\frac{P(i)}{P_{max}})(\frac{E_0}{E_i})^{\beta} L(Q_i)^{\gamma} \tag{3}$$

Here $P(i)$ is the power that node i is already using. The incremetal cost metric equals infinity if nodes i ad j are not neighbors. The subtracted part of the metric denotes the cost that is already incurred if node i is an already transmitting node. When there is no congestion and residual energy is high, this metric equals to the Incremental Power Metric in [2]; therefore it exploits wireless multicast advantage. Besides, this incremental cost metric discourages the congested nodes from being added to the tree as a relay node. It also discourages the nodes with low residual energy from increasing their tranmission power.

Since the network conditions (residual energy and congestion states) change throughout the network operation, the broadcast trees should also be updated periodically. In this work, we assume that at every time slot, new broadcast trees are formed.

V. MEDIUM ACCESS CONTROL PROBLEM

A. *Assumptions and Definitions*

Introducing packet queueing brings along the problem of interacting queues. At each time slot there will be a number of nodes that are waiting to transmit and transmitting at the same time would cause a conflict and collision. Hence, in this work we consider scheduled medium access schemes as opposed to random access. Our aim is establishing a conflict-free scheduling scheme that determines the set of transmissions to be activated at each slot. If transmission set S_i is active this means that there is a transmission from node i to to the nodes in set S_i and transceivers of those nodes are allocated to that transmission. Next, we define the Scheduling Constraint that avoids conflict in scheduling.

Definition 1 (Scheduling Constraint): Suppose two transmission sets S_i and S_j are to be activated in the same time slot. Two transmission sets can't have a common node i.e. $(S_i \cap S_j \neq 0)$.

The set of nodes that can be activated in a conflict-free manner is called a *conflict-free activation set*($\mathcal{S}$). Our goal is to find an activation set that maximizes communication performance of the network.

B. *Algorithmic Solution*

Communication performance can be understood as a utility. One possible way of assessing the overall utility would be assigning each node a dynamically changing utility value according to a predefined activation utility metric (W_i). For the execution of the algorithm, we assume that the central controller knows every node waiting to be served and their corresponding utility values. The central controller does simply the following:

- Initialize activation set as $\mathcal{S} = \emptyset$.
- Repeat:
  - Activate the transmission set S_i such that $i = argmax_{i \in V}\{W_i | S_i \cap \mathcal{S} = \emptyset\}$, where V is the set of nodes.
  - Update activation set as $\mathcal{S} = \mathcal{S} \cup S_i$
- Until there is no more possible conflict-free activation.

So the nodes with highest utility values are prioritized in scheduling. We propose the transmission set activation utility metric as $W_i = Q_i$, where Q_i is the congestion of node i as defined before. By using this utility metric we prioritize congested nodes in scheduling in order to reduce congestion. We can call the resulting scheme as the *Congestion Avoiding Scheme.* Another simple but less efficient solution would be to select nodes in a random manner. We refer to this as the *Random Scheme.* It will serve as a benchmark for our scheduling scheme in the performance evaluation.

VI. SIMULATIONS

We have simulated the proposed algorithms D-MIC and D-LiMST for different link metric coefficients, using a number of network examples. For each set of simulations, 10 networks with 15 nodes are randomly generated on a square region of 100 meters length. Path loss exponent (α) is taken as 2 and the maximum transmission range (a_{max}) is taken as 50 meters. Transmission and Receive processing powers are taken as zero for simplicity. Time slot length is equal to 1 msec. In the simulations we test the performance of the D-MIC algorithm for $(\beta, \gamma) = (0, 0)$ (which corresponds to the MIP algorithm [2]), $(\beta, \gamma) = (0, 1)$ (that considers energy expenditure and congestion) and $(\beta, \gamma) = (1, 0)$ (that considers energy expenditure and network lifetime.). We also list the performance results for the D-LiMST algorithm for the same set of coefficients.

Figure 2 shows the average delay per packet for changing network load and different link metric coefficients. The graph shows that D-MIC $((\beta, \gamma) = (0, 1))$ achieves by far the best delay performance with respect to the cases in which congestion is *not* considered. Because it prevents congested nodes from being a relay node in the multicast tree. D-LiMST$(((\beta, \gamma) = (0, 1)))$ is also worse than D-MIC since it doesn't exploit wireless multicast advantage for delay.

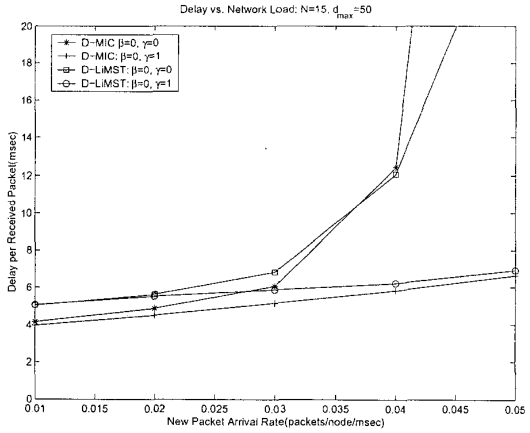

Fig. 2. Average delay per packet (multicast algorithms).

Figure 3 depicts the average energy expenditure per received packet. D-MIC$((\beta, \gamma) = (0, 0))$ which is equivalent to MIP has the best energy performance since it exploits wireless multicast advantage and its only consideration is energy. If congestion is considered in multicasting, energy expenditure increases since simultaneous transmission are more preferred in order to avoid congestion.

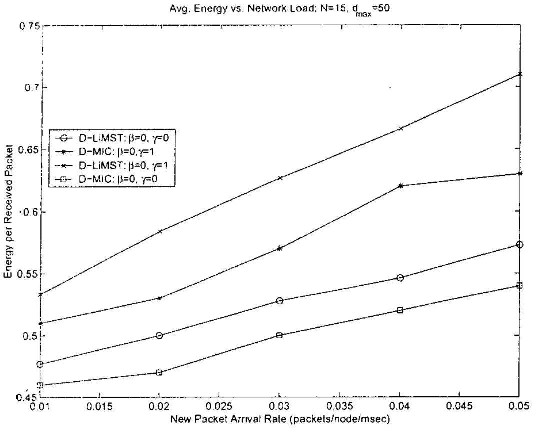

Fig. 3. Average expended energy per packet (multicast algorithms).

Delivered volume of packets vs time characteristics is shown in Figure 4. In this case energy resources are stricter and some nodes start to die after a period of network operation, which results in the decrease of succesful transmission rate with time. D-MIC$((\beta,\gamma) = (1,0))$, has the best performance because it considers the residual energy state, and simulatenous transmissions are encouraged, which causes transmission of more data at the same time.

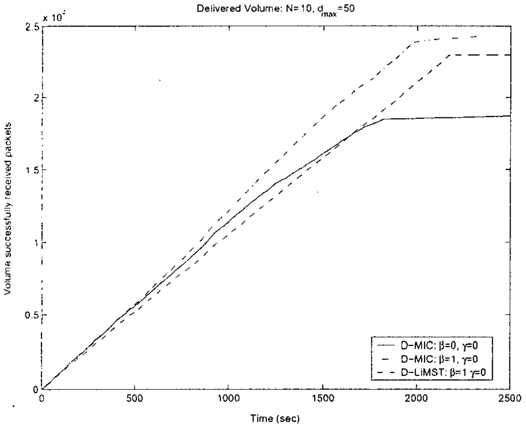

Fig. 4. Succesfully received volume of packets (multicast algorithms).

Figure 5 shows the delay performance of the proposed Congestion Avoiding Scheduling Scheme compared with the benchmark Random Scheduling Scheme. Here we use D-MIC as the multicasting algorithm. Congestion Avoiding Scheme, with D-MIC$(((\beta,\gamma) = (1,1)))$ has the better performance because it prioritizes congested transmission sets and avoid congestion.

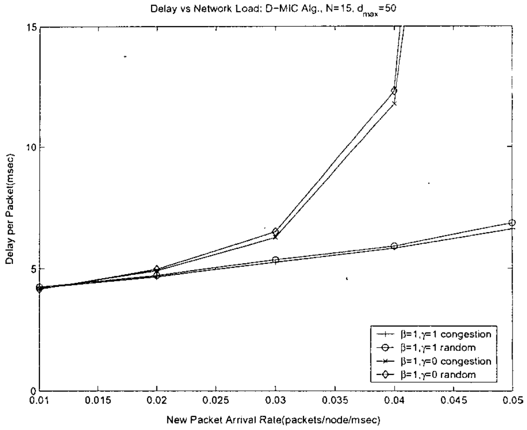

Fig. 5. Average delay per packet (scheduling algorithms).

VII. CONCLUSIONS

In this paper, we proposed and evaluated the Data-oriented Multicast Incremental Cost (D-MIC) algorithm, which considers the power, congestion, and network lifetime issues that arise with the limited resources. D-MIC algorithm provides considerable performance improvement with respect to the algorithms previously developed for session based traffic, in terms of energy per packet, delay per packet and aggregate transmitted volume of traffic. We also developed a MAC layer transmission scheduling scheme that prioritizes the congested nodes in serving, which leaded to a significant performance improvement in delay and energy performance, when compared with a benchmark random scheduling. Work is currently in progress on the distributed implementation of these multicasting and scheduling schemes.

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