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Localized Minimum-Latency Broadcasting in Multi-rate Wireless Mesh Networks

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Abstract: **We address the problem of minimizing the worst-case broadcast delay in multi-rate wireless mesh networks (WMN) in a distributed and localized fashion. Efficient broadcasting in such networks is especially challenging due to the multi-rate transmission capability and the interference between wireless transmissions of WMN nodes. We propose connecting dominating set (CDS) based broadcast routing approach which calculates the set of forwarding nodes and the transmission rate at each forwarding node independent of the broadcast source. Thereafter, a forwarding tree is constructed taking into consideration the source of the broadcast. In this paper, we propose three distributed and localized rate-aware broadcast algorithms. We compare the performance of our distributed and localized algorithms with previously proposed centralized algorithms and observe that the performance gap is not large. We show that our algorithms greatly improve performance of rate-unaware broadcasting algorithms by incorporating rate-awareness into the broadcast tree construction algorithm process.**

I. INTRODUCTION

Wireless mesh networks (WMN) [1], where potentially-mobile mesh clients connect over a relatively-static multi-hop wireless network of mesh routers, are viewed as a promising broadband access infrastructure in both urban and rural environments [2]. With recent advancements in wireless technology, the ability to transmit at multiple transmission rates is a popular feature widely available in commodity wireless cards. WMN nodes can thus utilize the flexibility of multi-rate transmissions to make appropriate range vs. rate tradeoff choices across a wide range of channel conditions. While the flexibility afforded by multi-rate transmissions has traditionally been used for unicast, it has recently been proposed for use in broadcasting scenarios as well [3] [4].

The problem of 'efficient' broadcast is fundamentally different in wired and wireless networks due to the '*wireless broadcast advantage*' (WBA) [5]. The WBA originates from the broadcast nature of the wireless channel where a node's transmission can be received, assuming omni-directional antennas are being used, by all neighboring nodes that lie within its communication range. A lot of research has focussed on achieving efficient broadcast in multi-hop wireless networks and mobile ad-hoc networks. Typical metrics of broadcast performance are energy consumption [5] [6], number of transmissions [7] [8], and route discovery and management overhead [9]. While energy efficiency is important for battery-powered nodes, it is less relevant in many WMN scenarios, where the nodes are relatively static (e.g., mounted on rooftops) and directly connected to regular power outlets. In such networks, designers of broadcast algorithms can focus more on high-performance QoS-based metrics since energy-efficiency is no longer an overriding concern.

We evaluate the efficiency of broadcast in terms of '*broadcast latency*', defined as the maximum delay between the transmission of a packet by the source node and its eventual reception by all receivers. The broadcast latency metric has earlier been used for studies of single-rate WMNs in [10] and multi-rate WMNs in [3] [4] [11]. The problem of constructing trees that minimize the broadcast latency is referred to as the MLB (*minimum latency problem*) problem. The previous work on MLB problem [3] [4] [11] constructed low-latency broadcast trees in a centralized manner and required global information at a node for its operation. Centralized algorithms require global information of the entire network to be available at a centralized host; such algorithms thus have high communication cost and are often not robust, with the forwarding tree possibly needing to be recalculated with every change in topology (e.g., addition of new nodes).

When global information is not available, flooding is a simple approach to broadcasting in which a broadcast packet is forwarded by every node in the network exactly once. Simple flooding ensures network-wide coverage, provided there is no packet loss caused by MAC-layer collisions. However, the straightforward flooding approach is usually very costly and results in serious problems of redundancy, contention, and collision, a condition referred to as the "broadcast storm" problem[12] [13]. Despite its drawbacks, many protocol designers resort to flooding (or, some adaptation) for broadcasting in highly mobile networks like MANET (*mobile ad-hoc networks*) to ensure packet delivery. Nevertheless, since our work targets a predominantly static WMN, our objective is to perform broadcast in a distributed and localized manner (with limited k-hop topology information available, k being a reasonably small value) and produce performance close to

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the performance of centralized broadcasting (which requires global information).

II. RELATED WORK

Our distributed algorithms are influenced by the centralized algorithms (*weighted connected dominating set* (WCDS) [3] and *broadcast increment bandwidth* (BIB) algorithm [4]). In our earlier work on these algorithms, we had introduced the concept of *link-layer multi-rate multicast*, in which a WMN node can adapt its link-layer transmission rate for multicast/broadcast traffic. We used this link-layer multi-rate multicast concept to present low-latency broadcast algorithms for solving the MLB problem for single-radio single-channel multi-rate WMN in [3] [11]. The work in [3] [11] exploited two features that are present in multi-rate WMNs but not in a single-rate WMN. Firstly, if a node has to perform a link-layer multicast to reach a number of neighbors, then its transmission rate is limited by the smallest rate on each individual link, *e.g.,* if a node n is to multicast to two neighboring nodes m_1 and m_2, and if the maximum unicast rates from n to m_1 and m_2 are, respectively, r_1 and r_2, then the maximum rate n can use is the minimum of r_1 and r_2. Secondly, for a multi-rate WMN, the broadcast latency can be minimized by having some nodes transmit the same packet more than once, but at a different rate to different subsets of neighbors (called as '*distinct-rate transmissions*'). The '*WCDS*' and '*BIB*' algorithms utilized these insights to heuristically solve the MLB problem in single-radio multi-rate mesh networks. Both these algorithms consider the WBA and the multi-rate capability of the network, and also incorporate the possibility of multiple *distinct-rate* transmissions by a single node. In practice, however, multiple distict-rate transmissions were rarely used by any node [1]; therefore, we do not consider the possibility of having a node perform multiple distinct-rate transmissions in this work.

A multi-rate multicast algorithm called RAM (*rate adaptive multicast*) based on ODMRP (*on-demand multicast routing protocol*) was proposed in [14] for use in MANETs. Being a modification of ODMRP, RAM is designed primarily for highly mobile networks. The RAM protocol does not explicitly exploit the WBA and has a large overhead for static WMNs since it neither attempts to minimize the 'forwarding group' size nor does it attempt to maximize the transmission rates at the forwarding nodes. No distributed broadcast algorithm addressing the case of static WMNs that exploits muli-rate feature and WBA has been proposed in literature according to the best of our knowledge.

There are numerous distributed algorithms ([15] [16] [17] [18]) that attempt reduction of the forwarding-node set required to reach each node in the network. These algorithms, sometimes referred to as backbone-based routing algorithms, construct a small set of nodes that form a connected dominating set (CDS) of all nodes. CDS of the nodes of the network, whose topology is represented by a graph $G = (V, E)$, is a connected subgraph of G spanned by the nodes of $V' \subseteq V$ such that every node in the network is at most one hop distant from a node in V'. A good backbone, traditionally, is minimal in size; however, in case of multi-rate WMNs, it should have other characteristics such as high transmitting rates at the chosen nodes (in the backbone) to ensure low broadcast latency.

There are two major classes of protocols that calculate the CDS. Algorithms in the first class (e.g. the algorithm of Wu and Li [15] [19] and that of Adjih et al. [20]) initially compute a large CDS and then attempt to prune away redundant nodes by means of local optimizations. The second class of algorithms (e.g. the algorithm proposed in [18]) firstly calculate a small dominating set and then connect it up. The CDS calculated by the second class of algorithms is generally smaller than the CDS calculated by the first class of algorithms; however, the smaller cardinality of the set of forwarding-nodes set comes at the expense of increased complexity and reduced locality. In our work, we shall see that the ability to exploit increased transmission rates is more important than reduced CDS size (this assertion is discussed in detail in Section V). Accordingly, we will only consider algorithms from the first class in this paper.

Our heuristics are based on significant modifications to two underlying (rate-diversity unaware) techniques that both calculate a 'small' CDS by first computing a large CDS and then pruning away redundant transmissions. The first technique, called the ***Wu-Li*** algorithm [15], is a simple localized technique that uses only 2-hop neighborhood information to compute a CDS as follows. Initially, all vertices (nodes) are unmarked. The marking process uses the following simple rule: any vertex having two unconnected neighbors (not connected directly) is marked as a dominator. The set of marked vertices form a rather large CDS V'. Two pruning techniques are then used to reduce the CDS size. A node u can be removed from V' if there exists a higher-id node $v \in V'$ such that the closed neighbor set[2] of u is a subset of the closed neighbor set of v. For the same reason, a node u will be deleted from V' when two of its connected neighbors in V' with higher IDs can cover all of u's neighbors. This pruning idea is generalized to the following rule [15]: a node u can be removed from S if there exist k connected neighbors with higher IDs in S that can cover all u's neighbors. The second technique to locally compute a CDS is called "multi-point relaying" (***MPR***) [20]. The MPR technique allows each node u to first elect a 'multi-point relay set' (*MRS*) [21] [16] from its one-hop neighbors to cover its two-hop neighbors. Finding a MRS with minimum size is NP-Complete [16]. The CDS is calculated as follows [20]: each node first compute a MRS, a subset of one-hop neighbors that can cover all its two-hop neighbors. After each node has determined its MRS, a node decides that it is in the connected dominating set by matching either *Rule 1:* the node is smaller than all its neighbors *or Rule 2:* it is the multipoint relay of its smallest neighbor. Although neither of these two relatively simple algorithms necessarily form the smallest CDS, we shall use them in the Initial Marking stage, since the subsequent stage of Neighbor-Grouping and Rate-Maximization (which we introduce) turn out to be much more important for multi-rate networks than the optimal computation of the initial CDS itself.

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[1] only a few ($\sim$ 20%) simulation topologies used multiple distinct-rate transmissions at an individual node

[2] closed neighbor set is the union of the node itself and its neighbors

V	Set of vertices (or, nodes)	E	Set of edges (or, links)
Π	Set of transmission-rate of links in E	Λ	Set of channel of links in E
ρ_i	i^{th} highest transmission rate supported by MAC	N	Total number of nodes in network (=$\|V\|$)
$\rho(u)$	Current transmission-rate of u	ρ_0	Rate of a non-transmitting interface
$N(u)$	1-hop neighbors that u is currently covering	$N_{\rho_k}(u)$	1-hop neighbors of u (on rate ρ_k)
$r(u)$	Set of rates u having a "rate-limiting-node"	L	Number of distinct rates supported by MACg
$\pi(u,v)$	Highest transmission-rate link (u,v) can use	$\lambda(u,v)$	Channels link (u,v) can use
m	Number of marked-nodes	d	maximum number of neighbors of a marked-node

TABLE I
INDEX OF MATHEMATICAL SYMBOLS USED

III. NETWORK MODEL

We use an undirected graph $G = (V, E, \Pi)$ to model the given mesh network topology, where V is the set of vertices, E is the set of edges and Π is the set of weights of edges in E. The vertex v in V corresponds to a wireless node in the network with a known location. An undirected edge (u, v), corresponding to a wireless link between u and v, is in the set E if and only if $d(u, v) \leq r$ where $d(u, v)$ is the Euclidean distance between u and v and r is the range of the lowest-rate transmission. The transmission rate of a link $\pi(e)$ ($e = (u, v) \in E$) is the quickest transmission rate that can be supported on link represented by e. The set Π contains the rates of all links in E. Let us assume that each node has a choice of L different rates: $\rho_1, \ldots, \rho_L$, with $\rho_1 > \rho_2 \ldots > \rho_L$. Also, let $\rho(u)$ denote the transmission rate of node u. Recall that $\pi(u, v)$ denotes the quickest-rate transmission supported between u and v. $N_k(u)$ denotes all nodes x such that $\pi(u, x) = \rho_k$; alternatively, $N_k(u) : k = 1, ..., L$ denotes the set of neighboring nodes that node u reaches at rate ρ_k (but cannot reach at any higher rate $\rho_j : j > k$). The mathematical symbols used in this paper are tabulated in Table I.

Using the Qualnet simulator [22] as a reference (assuming a two-ray propagation model), we obtain the transmission rate versus transmission range (rate-range) relationship (for 802.11b) shown in Table II. We also employ an alterative rate-range relationship, shown in the first two columns of Table III, of a commercial IEEE 802.11a product [23] to perform sensitivity analysis of the broadcast performance with different rate-range relationships.

IV. DISTRIBUTED BROADCASTING ALGORITHM

Our proposed distributed and localized broadcast algorithm for multi-rate WMN is composed of three stages. In the first stage named '*initial marking*', we use any of the existing broadcast algorithms for single-rate wireless networks to calculate a sufficiently small-sized (rate-unaware) CDS; all transmissions at the end of the first stage of 'initial marking' are assumed to be taking place using the lowest possible rate. The second stage called the '*neighbor-grouping* and *rate-maximization*' stage itself is itself composed of two substages: the decision of the the neighboring nodes a particular node must cover is made during Neighbor-Grouping (NG) substage, whereas the Rate-Maximization substage attempts to maximize transmission rates across all the marked nodes (recall that nodes are marked during Stage 1). The third and last stage, called broadcast '*tree-construction*' constructs a broadcast source-independent tree and eliminates redundant transmissions that were retained during the earlier two stages.

In this section, we will present three new distributed and localized broadcast algorithms. The first two of these algorithms are based on the Wu-Li algorithm and differ on how and when the pruning operation is performed; we name these two protocols: *multi-rate expedited-pruning Wu-Li* (MEW) and *multi-rate delayed-pruning Wu-Li* (MDW). The third algorithm is based on the concept of MPR and is called *multi-point rate-maximized relaying algorithm* (MRRA). We next describe the working of these algorithms during the three different stages of our framework.

A. ***Stage 1***–*Initial Marking:*

During Stage 1, we determine a rough measure of the forwarding set (or CDS) by following a marking process using the lowest-rate transmission only. As different transmission rates have different transmission ranges (see Tables II and III), different rates have different neighbor sets. At the end of Stage 1, we have a forwarding set (or CDS) and the transmission rate at each of these forwarders is set to be the lowest-rate. The actual decision of rates (and attempts to increase them) is made in subsequent stage of Neighbor-Grouping and Rate-Maximization.

The MEW and MDW broadcast algorithms both employ the Wu-Li marking process (explained in Section II earlier) in which a node is marked if it has two neighbors that are not directly connected. A node u is considered a neighbor of v if distance between u and v is less than or equal to the range of the lowest-rate transmission i.e. $d(u, v) \leq r$ where r is the range of rate ρ_L. The MEW and MDW algorithms differ in their implementation of Wu-Li pruning rules as outlined in [19] and discussed in Section II earlier. Whereas MEW (*multi-rate 'expedited-pruning' Wu-Li*) prunes away the redundant marked nodes *expeditiously* (during Stage 1) by following Wu-Li pruning rules (Section II), the MDW algorithm (*multi-rate 'delayed-pruning' Wu-Li*) does not perform the pruning as part of Stage 1. Thus, in MDW, the pruning process is *delayed* and performed later, during a substage of Stage 2 called Rate-Maximization (discussed later) and then again during Stage 3. We shall enumerate the potential benefits of such delayed pruning when we reach the discussion about Rate-Maximization.

The MRRA algorithm, on the other hand, follows the approach suggested in [20] to determine the initial CDS. It employs the concept of multi-point relaying to calculate, at each node, all its one-hop neighbors that should forward to

Transmission rate (Mbps)	Transmission range (m)
1	483
2	370
5.5	351
11	283

TABLE II
THE RATE-RANGE AND RAP RELATIONSHIP FROM QUALNET [22]

Transmission rate (Mbps)	Transmission range (m)
1	610
6	396
11	304
18	183
54	76

TABLE III
THE RATE-RANGE RELATIONSHIP AND RAP OF A COMMERCIAL PRODUCT [23]

cover its two-hop neighborhood. We have adapted multipoint relaying to include rate-diversity available in WMN. This is done by using the WCDS algorithm [3] (which is a rate-aware broadcast algorithm for SR-SC multi-rate WMNs) to generate the multi-point relay set (MRS) of each node i.e. each node would execute the WCDS algorithm with itself as the source/root on its 2-hop subgraph to determine the set of its one-hop neighbors that should act as the MRS to cover all of its 2-hop neighbors. By utilizing rate-aware localized MRS decisions, we ensure that the choice of the relay set at each node takes into consideration the inherent rate-diversity available in the WMN. After each node has determined its MRS, a node decides that it is in the connected dominating set if and only if: *Rule 1:* the node is smaller than all its neighbors; *or Rule 2:* it is multipoint relay of its smallest neighbor. Note that at the end of this marking process, only the initial forwarding set (or CDS) is calculated and all marked nodes are assumed to forward at the lowest-rate. The actual rates of transmission would be decided in the next stage.

The only differences between our three algorithms are confined to their differences in the Stage 1. Since, the next two stages (Stage 2 and Stage 3) are common to all three of our proposed algorithms (MEW, MDW and MRRA), we shall, therefore, give a general description of these two stages, which should be assumed to apply to all our algorithms.

B. ***Stage 2****—Neighbor-Grouping and Rate-Maximization:*

1) Neighbor-Grouping: In the step of Neighbor-Grouping, we decide the neighboring nodes a marked node has to cover. The logic employed is straight-forward: a marked node should not be reducing its rate to cover a node that can be, alternatively, be 'better' covered by another node. This step ensures that transmission rate at marked nodes is not constrained to a lower-rate because it has to cover all its possible neighbors.

The neighborhood-grouping algorithm is explained in Algorithm 1. In the algorithm, each node u searches to see if there exists a one-hop neighboring node v which can be 'better' covered by w (another 1-hop neighbor of u; i.e. $w \in N(u)$). v is said to be better covered by w is the aggregate throughput/rate of the path $u \rightarrow w \rightarrow v$ is better than the throughput of the path $u \rightarrow v$. At the end of the algorithm, the 1-hop neighborhood of each marked node has been decided. Each marked node is responsible for ensuring that its 1-hop neighborhood is covered (by itself, or through another marked node, as we shall later see).

Algorithm 1 Neighborhood Grouping function at node u

```
for each one-hop neighbors $v \in N(u)$ do
    for each node $w \in N(u)\backslash\{v\}$ do
        if $1/\pi(u,v) > 1/\pi(u,w) + 1/\pi(w,v)$ then
            remove $v$ from neighbor-list of $u$ at rate $\pi(u,v)$
        end if
    end for
end for
```

Message Complexity: Assuming that 2-hop neighborhood information has been established prior to the NG stage, no message needs to be exchanged during the NG stage. Let us represent the maximum neighbors of a marked node by d and the number of marked nodes by m. After the NG stage completes, each marked node will broadcast a packet for a total maximum of m packets. The maximum size of the sent packet is (1 + $(L)d$) times the bytes required to represent a node-id since the packet sent by a marked node conveys the sending marked node's node-ID, its neighbors on different rates. We note that L is a small (constant) value since typically limited rates are supported; the total message-complexity of the NG stage, therefore, is $O(md)$.

2) ***Rate-Maximization (RM):*** Before discussing the RM stage, we introduce the concept of "*rate-limiting-nodes*". We note that a lower-rate transmission can cover all nodes reachable at a higher-rate but not vice-versa; this implies that the maximum rate a node u can use to reach all its 1-hop neighbors $N(u)$ collectively, is the minimum of the (maximum) rate u can use to reach each individual node in $N(u)$. To illustrate this concept, assuming a single radio interface, refer to Figure 1 for an example topology. Although, u can reach nodes v and w with rate of 54 Mbps, u is constrained to transmit at a lower rate of 11 Mbps to reach nodes x, v and w collectively. Node x, for this topology, is referred to as a rate-limiting-node of node u, for its presence limits u's rate to 11 Mbps, with its absence the rate of u can be increased to 54 Mbps.

The objective of the RM sub-stage is to find, for a node u, neighboring forwarding nodes to whom u's rate-limiting-nodes can be 'exported'. The utility of an export can be determined using, in particular, the "rate-area-product" (RAP) maximization principle described in [3]. The export of rate-limiting-nodes, in general, will increase an interface's transmitting rate, with a node unmarking itself if all its neighbors have been exported. The challenge faced by RM, due to the potential danger of link assymmetry [3] that arises due to rate diversity, is to maximize the rates at a node's interfaces while preserving the *strong* connectivity of the resulting dominating set. Since our framework determines forwarders and rates irrespective

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[3] e.g. it is possible for node u to reach v but not vice-versa (where $\rho(u) < \rho(v)$) due to different ranges for different rates

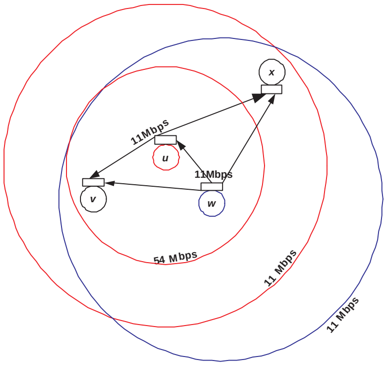

Fig. 1. Before Rate-Maximization at u

of the broadcast source (i.e., until Stage 3), it is important to ensure strong connectivity irrespective of the broadcast source.

To illustrate the concepts employed by RM, we refer to Figure 1 for an example topology comprising of three nodes. Node u can reach nodes $\{v, w\}$ and $\{x\}$ in a 54 Mbps and 11 Mbps transmission, respectively. Node w, however, can reach nodes $\{v,u\}$ and $\{x\}$ in a 54 and 11 Mbps transmission. We will study RM sub-stage at node u. Node u is constrained to use a lower rate (of 11 Mbps) if both neighbors of u (v and x) are to be covered in a single transmission. The rate-limiting-node of u is x. Node u will look for an higher-id marked node[4] that can cover u's rate-limiting-node using its current rate and be reachable from u after u increases its rate; also, the sum of the uplink rates of u's neighbors should improve after an export. We check now if u's rate-limiting-node x can be exported to w. Firstly, x is reachable through w's current transmission; secondly, w is reachable from u even after u's rate is increased to 54 Mbps; lastly, the sum of rates of u's neighbor increases with this transfer (54+11=65 instead of 11+11=22 before). Since all conditions are satisfied, the export of x can take place increasing the transmitting rate of u to 54 Mbps as shown in Figure 2.

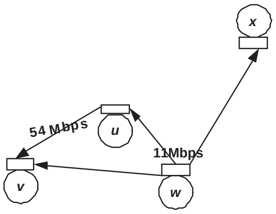

Fig. 2. After Rate-Maximization at u

The RM algorithm, for any node u, is mathematically described in Algorithm 2. Node u will attempt to increase its rate if it is currently a transmitting node (i.e. it has some rate-limiting-nodes). The token *continue* is initially equal to 1 which indicates that rate-increase can be attempted; a token *continue* valued 0, on the other hand, implies that the rate-limiting-nodes of the current rate are non-exportable and further rate-increase must not be attempted. Initially, E (denoting the rate gain for the exported nodes) is set to zero.

Algorithm 2 Rate-maximization function at node u

```
continue = 1
while $continue$ and $\rho(u) \neq 0$ do
    $E = 0$; $continue = 0$;
    $r(u)$ = rates at $u$ sorted in descending order
    $k$ = index of $\rho(u)$ in $r(u)$
    if $k = 1$ then
        $RLN = N_{r_k(u)}(u) \cup u$
    else
        $RLN = N_{r_k(u)}(u) \backslash N_{r_{k-1}(u)}(u)$
    end if
    $H$= all higher-ID marked neighbors of $u \setminus \{RLN\}$
    ————————————————————-
    {This part aims to find a neighbor to export nodes in RLN while satisfying RAP condition}
    ————————————————————-
    for $m$ = 1 to $|RLN|$ do
        $rln$= $RLN(m)$; $rate\_new = -\infty$;
        for $n = 1$ to $|H|$ do
            $h = H(n)$
            if $rln \in N(h)$ and $u \in N(h)$ and $\rho(h) > rate\_new$ then
                $rate\_new = \rho(h)$
            end if
        end for
        $rate\_diff = rate\_new - r_k(u)$
        $E$ = $E$ + $rate\_diff$
    end for
    ————————————————————-
    if $E \geq 0$ then
        $continue = 1$; $\rho(u) = r_{k-1}(u)$
    end if
end while
```

We denote the rates on which a node u has rate-limiting-nodes as $r(u)$. The total rates in $r(u)$ is not necessarily equal to the total number of rates L and is specific to the node u. The rates in $r(u)$ are arranged in a descending order, i.e., $r_1(u) > r_2(u)$ and so forth. For mathematical compactness, $r_0(u)$ denotes the fact that u would not be transmitting since a non-transmitting node has rate of zero. The index of u's current transmission rate, $\rho(u)$, in $r(u)$ is represented as k in Algorithm 2. The rate-limiting-nodes (RLN) is calculated as the difference between the neighbors of u at the current rate $(N_{r_k(u)}(u))$ and the next higher rate in $r(u)$ (i.e., $N_{r_{k-1}(u)}(u)$, if $r_{k-1}(u) \neq r_0(u)$). For each node rln in RLN, it is checked for every node $h \in H$ where H comprises of higher-ID marked neighbors of u excluding RLN if, *firstly*, rln is a neighbor of h (i.e., $\pi(h, rln) \geq \rho(h)$ and, *secondly*, if u is a neighbor of h (to ensure strong-connectivity). The maximum uplink rate rln can receive from a node $h \in H$ fulfilling these conditions is stored in a variable called $rate\_new$ (that is initialized with -∞). The difference between the initial rate of rln and the $rate\_new$ is maintained in $rate\_diff$. The variable E contains the sum of $rate\_diff$ of all nodes in RLN. The nodes that cannot be exported have $rate\_diff$ of -∞. Thus, even for a single non exported rate-limiting-node at a particular rate, the value of E would be -∞. For each interface, if $E > 0$, its rate is increased and *continue* is set to 1; otherwise, if $E < 0$, *continue* is set to zero. The algorithm completes when increase in rate is not possible either due to export of all nodes, or due to *continue* token equal to zero.

Message Complexity: During the RM sub-stage, each time

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[4] the restrictive condition of only exporting to higher-ID neighbors is to avoid circular hand-offs

a marked node u is successful in increasing its rate, it would broadcast its new rate $\rho(u)$ to its neighbors in a message. The maximum number of these messages exchanged is $((m-1) \times L)$ with the size of a these messages being the sum of the bytes used to represent node-ID and rate-ID. Since L is a constant, total message-complexity of RM is $O(m)$.

C. *Stage 3—Tree-Construction:*

The forwarding set (CDS) and the transmission rates calculated are *independent* of the broadcast source, i.e., the same nodes (in the CDS) will forward at the same decided rate in all cases. However, the tree (i.e., the parent/children relationship among these nodes) will vary depending on the broadcast source. Redundant transmissions can be pruned (e.g. if a forwarding node can determine that all of its neighbors can also receive from another node of higher-priority, then this node can unmark itself). Thus, redundant transmission can be pruned away, based on the broadcast source, in Stage 3. We present our Stage 3 of Tree-Construction mathematically in Algorithm 3. Initially, the $label$ of all nodes is equal to ∞. The source node, represented by s, starts by sending out a $RREQ$ message to its neighbors with $RREQ.label$ set to its transmission latency i.e. $\frac{1}{\rho(s)}$. Any node u that receives a $RREQ$ message will check if its label i.e. $RREQ.label$ is less than its current label; if so, then u will choose the sender of the $RREQ$ (represented by $RREQRcvd.sender$ in the algorithm) as its parent, send a $RREP$ back to it (setting $RREP.nexthop$ to $RREQRcvd.sender$) and modify its label to the received label. Furthermore, u would generate a new $RREQ$ message with itself in the $RREQ.sender$ field and increment its label with its transmission latency i.e. $\frac{1}{\rho(u)}$ and transmit it to its neighbors. When any node, represented by u again, receives a $RREP$ message and $RREP.nexthop$ is equal to u, it would active the $Forwarder$ flag and set the $RREP.nexthop$ to its parent ($Parent(u)$) and re-send the $RREP$. In this manner, the Forwarding or Non-Forwarding status of each node is determined. During the actual data broadcast, each node that has its Forwarding flag activated will forward the message forward at its predetermined rate. In the next section, we shall see that most of the redundant transmissions (retained in CDS during Stage 2) are eliminated during this Tree-Construction stage.

Message Complexity: The maximum number of $RREQ$ messages sent in the network is contingent on the number of marked nodes chosen in earlier steps. The worst-case message complexity of the Tree-Construction stage is $O(md)$.

V. SIMULATION RESULTS:

We compare the performance of our three algorithms using random topologies of different network sizes (measured by the number of nodes) in an area of 1×1 km^2. We generate 100 topologies for varying number of nodes using a uniform random distribution in the network area. We then apply our algorithms to each topology to compute the broadcast latency. We normalized the broadcast latency by the delay given by the Dijkstra's algorithm which is the shortest delay possible when there is no limit to the number of radios, channels and times a node can transmit a packet. Since determining the actual optimal is NP-hard, we use the Dijkstra metric as a theoretical lower bound on the optimal achievable latency in a corresponding wired network. Thus the minimum value of normalized delay is unity. The result that we will show is the average normalized broadcast latency over 100 network instances. The transmission rate-range relationships depicted in Table II (obtained from Qualnet [22]) and Table III (obtained from a commercial product [23]) are assumed. The interference range is assumed to be 1.7 times the lowest transmission rate's range.

Algorithm 3 Distributed Tree-Construction, broadcast source is s

```
Initially, $label(v) = \infty, \forall v \in V$
$u = id(node)$
if $u = s$ then
    Send $RREQ$ with $RREQ.label = \frac{1}{\rho(s)}$
end if
------------------------------------------------
if $RREQRcvd.label < label(u)$ (non-duplicate) then
    $Parent(u) = RREQRcvd.sender$
    $RREP.nexthop = RREQRcvd.sender$
    $send(RREP)$ to $RREQRcvd.sender$
    $RREQ.sender = u$
    $RREQ.label = RREQRcvd.label + \frac{1}{\rho(u)}$
    $send(RREQ)$ to $N_{\rho(u)}(u)$
end if
if received $RREP$ and $RREP.nexthop = u$ then
    Activate $Forwarder$ flag
    $RREP.nexthop = Parent(u)$
    $send(RREP)$
end if
```

A. *Rate-Unaware vs. Rate-Aware Distributed Broadcast*

We present the performance of our rate-aware distributed broadcast algorithm against the performance of rate-unaware distributed broadcast algorithm in Figures 3 and 4. The Wu-Li algorithm is an algorithm that does not take multi-rate capability into account during its operation, therefore, we would expect its performance to be poorer than MEW, MDW, with and without Neighbor-Grouping, and MRRA algorithms, all of which are rate-aware algorithms. The performance results are shown in Figures 3 and 4 for the rate-range curves in Table II and III, respectively. It is observable that rate-aware broadcast algorithms have better performance than rate-unaware broadcast algorithms across the range of number of nodes (N) and for both rate-range curves. The performance of rate-unaware broadcasting is particularly poor for higher values of N. We can conclude therefore that Stage 2 of our broadcasting framework enables our algorithms to perform better than rate-unaware by maximizing transmission rates at the forwarding nodes, after grouping the neighboring nodes to minimize some redundancy.

B. *Distributed versus centralized topology construction algorithms (assuming centralized scheduler)*

In this subsection, we use the ideal centralized scheduler proposed in [3] to compare the performance of our distributed

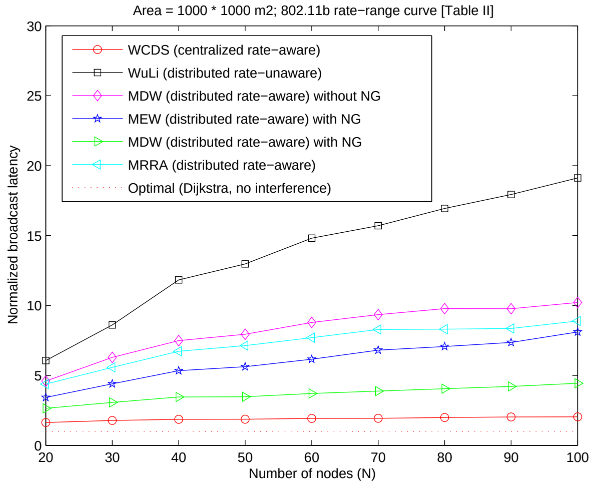

Fig. 3. Normalized broadcast latency against varying number of nodes N (Area=1000*1000 m^2) for 802.11b rate-range curve [Table II]

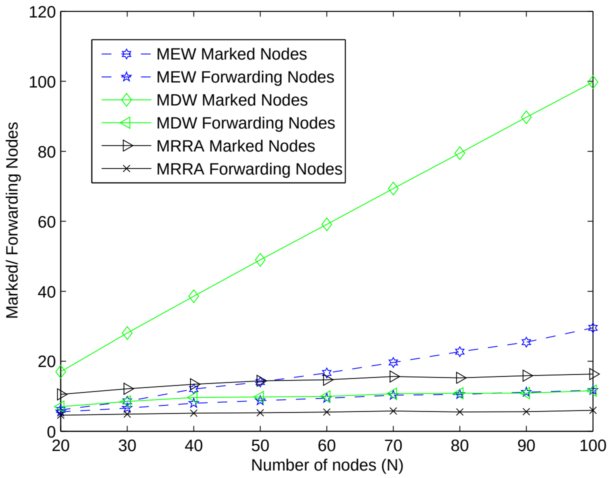

Fig. 5. Number of marked-nodes/or forwarders against varying number of nodes N (Area=1000*1000 m^2) for our algorithms (assuming rate-range curve of Table II)

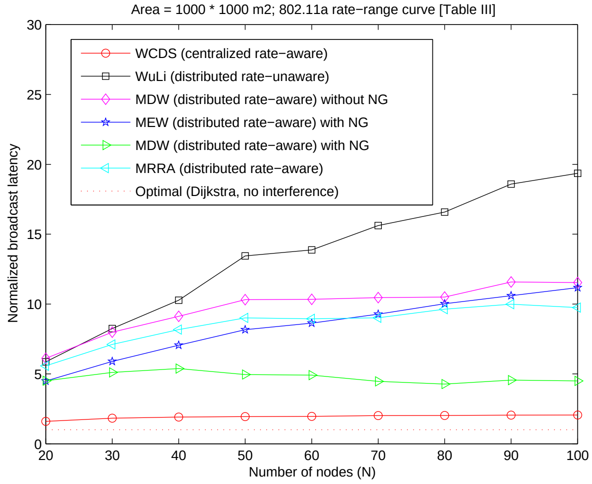

Fig. 4. Normalized broadcast latency against varying number of nodes N (Area=1000*1000 m^2) for 802.11a rate-range curve [Table III]

algorithms against the centralized algorithm's performance. The results of this comparision can also be observed in Figures 3 and 4. We observe that the performance of WCDS [3], which is an example of a centralized multi-rate broadcast algorithm, is quite close to the 'optimal' value (Dijkstra tree on an equivalent wired formulation). As is to be expected, the performance of our distributed algorithm cannot match the performance of the centralized algorithm. The performance gap between WCDS and the MDW algorithm is, however, not large. The performance of MDW, in terms of broadcast latency, is better than MRRA's performance.

C. Effects of Delayed-Pruning and Neighbor-Grouping

It should be observed in Figures 3 and 4 that delayed-pruning and Neighbor-Grouping substage improves the performance appreciably. Firstly, to see the effect of delayed pruning, we note that the performance of MDW (multi-rate *delayed-pruning* Wu-Li) with Neighbor-Grouping (NG) is better than the performance of MEW (multi-rate *expedited-pruning* Wu-Li) with NG, across the range of N for both the considered rate-range curves. Secondly, the effect of NG can be seen by seeing the improvement in MDW with NG over MDW without NG across the range of N for both the considered rate-range curves.

D. Number of Marked nodes and Forwarders

We make the distinction that marked nodes are the nodes marked for transmission before Stage 3, whereas, the nodes actually chosen to forward after Stage 3 are referred to as forwarders. The graph depicting number of marked nodes and forwarders for the different algorithms is depicted in Figure 5. It is interesting to note the effect of delayed-pruning on the number of marked nodes (or, the CDS set); although, the delayed pruning produces better broadcast latency results, it does this at the expense of a bigger CDS. Whereas MEW prunes away a substantial portion of the CDS before invoking the Rate-Maximization process, MDW does not have this explicit pruning step before Rate-Maximization. This implies that relatively few nodes are able to prune themselves completely during Rate-Maximization in Stage 2. More importantly with delayed pruning (and a larger CDS), there are more opportunities to increase transmission rates as a marked node has more neighboring marked nodes to export nodes to. Note that the actual nodes that would transmit for MDW are a lot lesser than the marked nodes (or, the size of CDS). This is because Stage 3 will eliminate the redundancy in the transmissions and ensure that the number of nodes that will actually forward is not large. The number of forwarders (after Stage 3) of MDW is comparable, though still slightly higher, to the number of forwarders for MEW.

E. Distributed vs. Centralized topology construction algorithms (assuming distributed 802.11 MAC scheduler)

We have performed simulations on the Qualnet [22] simulator to see the performance of our broadcast algorithms

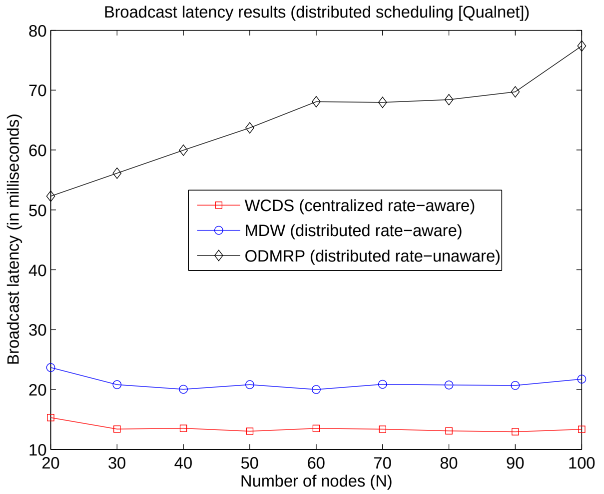

Fig. 6. Normalized broadcast latency against varying number of nodes N (Area=1000*1000 m^2) using 802.11b simulation in Qualnet

with a practical MAC scheduler (we have used 802.11b as our MAC scheduler). We implemented PHY 802.11b at the physical layer, which uses a pre-configured BER-based packet reception model. The MAC802.11 with Distributed Coordination Function (DCF) was chosen as the medium access control protocol. All default parameters are assumed unless stated otherwise. We have used MDW (with NG) as representative of our distributed multi-rate algorithm and compare it against WCDS (a centralized multi-rate algorithm) and ODMRP (a distributed rate-unaware algorithm). Note that since ODMRP is a rate-unaware protocol, all its transmission are assumed to be at the lowest rate of 1 Mbps. The broadcast latency results (in milliseconds) of the simulations are shown in Figure 6. The results in Figure 6 are consistent with the results discussed earlier; MDW improves the performance of ODMRP across all values of N but does slightly worse than the centralized algorithm.

VI. CONCLUSIONS AND FUTURE WORK

We have presented three localized and distributed algorithms to construct broadcasting trees in static wireless mesh networks (WMN). We also proposed techniques to incorporate the rate-diversity of the underlying network into the metric of our broadcasting algorithm. We showed through simulations that appropriate use of the available rate diversity can provide a significant (often a three-fold) reduction in the broadcast latency. More importantly, we have also demonstrated that the gap between the performance of our distributed algorithms, which operate in a distributed manner with limited topology information, and centralized algorithms, which operate with great operational overhead and global topology information, is not large for practical purposes. As our future work, we plan to extend our work to multi-radio multi-channel multi-rate WMNs by incorporating interface-diversity-awareness into the existing distributed algorithms.

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