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.**

1 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, a popular feature widely available in commodity wireless cards is the ability to transmit at multiple transmission rates. WMN nodes can utilize the flexibility of multi-rate transmissions to make appropriate range and throughput/latency 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]. The limited research on using broadcast latency metric addressed single-rate networks in [10] and multi-rate networks in [3] [4] [11].

We define the efficiency of broadcast in terms of '*broadcast latency*' which we define as the maximum delay between the transmission of a packet by the source node and its eventual reception by all receivers. 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; this can lead to extreme and unacceptable communication cost, with broadcast forwarding structure being possibly recalculated with every change in topology (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 the coverage providing there is no packet loss caused by collision in the MAC layer. However, radio signals are likely to overlap with others in a geographical area, the straightforward flooding approach is usually very costly and results in serious redundancy, contention, and collision, a condition referred to as the broadcast storm problem in literature [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 is considering a setting of 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 the performance of centralized broadcasting (which requires global information).

2 Related Work

Our distributed algorithms are influenced from the centralized algorithms (*Weighted Connected Dominating Set* (WCDS) [3] and *Broadcast Increment Bandwidth* (BIB) algorithm [4]). In these works [3] [4], we had proposed *multi-rate multicast* in which a WMN node can adapt its link-layer transmission rate for multicast/broadcast traffic. We used the 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] [14] [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*'). Based on these insights, '*WCDS*' and '*BIB*' algorithms were presented in [3] [11] as heuristic solutions for 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 our work [3], we showed that the multiple distict-rate transmissions are not often used[1]; therefore, we do

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

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 [15] for use in MANETs. This protocol being a modification of ODMRP, an on-demand MANET multicast routing protocol, 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 static WMNs has been proposed in literature according to the best of our knowledge.

There are numerous distributed algorithms ([16] [17] [18] [19]) 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 [16] [20] and that of Adjih et al. [21]) 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 [19]) 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 forwarding-nodes set comes with increased complexity and reduced locality. We will be using only algorithms from the first class in our work, as for our work, increased transmission rates is more important than reduced CDS size (we shall come back to this discussion in in Section 5).

We will expand on the two algorithms: i.e. the algorithm of Wu and Li (referred to as WuLi hereafter after the authors' name) and the algorithm of Adijh (referred to as MPR (Multi-Point Relaying) hereafter) as we will adapt these algorithms in our work. WuLi algorithm is a simple, yet efficient, distributed pruning-based CDS construction [16], proposed in the context of ad hoc and sensor networks, that is completely localized and constructs CDS in general graphs. Given a network topology, initially all vertices (nodes) are unmarked. They exchange their open neighborhood information with their one-hop neighbors resulting in each node knowing all of its two-hop neighbors. 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 connected dominating set (albeit with a lot of redundant nodes as compared to MCDS (*Minimum Connecting Dominating Set*). Two pruning principles are provided to post-process the dominating set based on the neighborhood subset coverage. A node u can be taken out from S, the CDS, if there exists a node v with higher ID such that the closed neighbor set of u is a subset of the closed neighbor set of v. For the same reason, a node u will be deleted from S when two of its connected neighbors in S with higher IDs can cover all of u's neighbors. This pruning idea is generated to the following general rule [16]: 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. WuLi algorithm is composed of the following two steps:

1. Marking: The process marks every vertex in a given connected and unweighed graph $G = (V, E)$. The marking function $m(v)$ marks each vertex $v \in V$ either T (marked) or F (unmarked). We assume that all vertices are unmarked initially. $N(v) = \{u|v, u \in E\}$ represents the open neighbor set of vertex v. The marking process is following:

   (a) Initially assign marker F to every v in V.

   (b) Every v exchanges its open neighbor set $N(v)$ with all its neighbors as well as its rate of transmission $R(V)$.

   (c) Every v assigns its marker $m(v)$ to T if there exist two unconnected neighbors.

2. Pruning: The pruning rules for WuLi can be generalized [20] into the following Rule: Assume that node $u \in C$ and that a subset $S \leq k$ neighbors of u such that:

   (a) the subgraph spanned by S is connected

   (b) S is contained in C

   (c) each node in S has an ID larger than u

   (d) each neighbor of u is covered by the nodes in S

the node u, then, can then be pruned from C.

The second technique our algorithm draws from is the 'Multipoint relaying' (MPR) technique initially devised by [17] in the context of flooding control to decrease protocol overhead in ad-hoc networks. The Multipoint relaying technique allows each node u select a minimum forwarding set [17] [22] from $N(u)$ to cover $N(N(u))$. Finding a multipoint relay set (MRS) with minimum size is NP-Complete [17]. Recently Adjih *et.al.* [23] proposed a localized heuristic to generate a CDS based on multipoint relaying. Their idea is sketched below. Each node first compute a multipoint relay set, a subset of one-hop neighbors that can cover all the two-hop neighbors. 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; *Rule 2: or* it is multipoint relay of its smallest neighbor.

3 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 $\pi(u, x) = k$; 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 $\rho_j : j > k$).

Using the Qualnet simulator [24] 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 the first two columns of Table I. We also employ an alterative rate-range relationship, shown in the first two columns of Table II, of a commercial IEEE 802.11a product [25] to perform sensitivity analysis of the broadcast performance with different rate-range relationships.

4 Distributed Broadcasting Algorithm

Our proposed distributed and localized broadcast algorithm for multi-rate WMN is composed of the following three stages:

1. **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 this stage are assumed to be taking place using the lowest possible rate i.e. $\forall\, v \in V'$; $\rho(v) = \rho_L$

2. **Neighbor-Grouping and Rate-Maximization**: the neighboring nodes to be covered by a particular node are decided during the substage of Neighbor-Grouping (NG). It is followed by the substage of Rate-Maximization which attempts to maximize the transmission rates across all the marked nodes (decided during Stage 1)

3. **Broadcast Tree construction**: the first two stages output the same result independent of the broadcast source; in the third stage, a broadcast tree is constructed taking into account the broadcast source and eliminating the redundant transmissions retained in 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 WuLi algorithm and differ on how and when the pruning operation is performed; we name these two protocols: *Multi-Rate Expedited-Pruning WuLi* (MEW) and *Multi-Rate Delayed-Pruning WuLi* (MDW). The third algorithm is based on the concept of MPR and is called *Multi-Point Rate-Maximized Relaying Algorithm* (MRRA). The working of these algorithms during different stages of our framework is described next:

4.1 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 1 and 2), 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 stages.

The MEW and MDW broadcast algorithms both employ the WuLi marking process (explained in Section 2 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 WuLi pruning rules as outlined in [20] and discussed in Section 2 earlier. Whereas, MEW (*Multi-Rate 'Expedited-Pruning' WuLi*) prunes away the redundant marked nodes *expeditiously* (during Stage 1) by following WuLi pruning rules (Section 2); MDW (*Multi-Rate 'Delayed-Pruning' WuLi*) does not perform the pruning as part of Stage 1 and omits the WuLi pruning altogether, the pruning of MDW is *delayed* and is now performed during a substage of Stage 2 called Rate-Maximization (discussed later) and then during Stage 3. The benefit of delaying the pruning would also be discussed when we reach the discussion about Rate-Maximization.

The MRRA algorithm, on the other hand, follows the approach suggested in [21] 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 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 [26] (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 relay sets choice also take 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; *Rule 2: or* 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, all marked nodes are assumed to forward at the lowest-rate, and 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.

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

Table 1: The rate-range and RAP relationship from Qualnet [24]

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

Table 2: The rate-range relationship and RAP of a commercial product [25]

4.2 Stage 2—Neighbor Grouping and Rate-Maximization:

4.2.1 Neighbor Grouping

In the step of Neighbor-Grouping, we decide the neighboring nodes a marked node has to cover. The intuition 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, at each node u, it is searched if there exists a one-hop neighboring node v which can be 'better' covered by w (another 1-hop neighbor of u; i.e. $w \in N1(u)$). v is said to be better covered by w is the aggregate throughput/rate of the path $u \to w \to v$ is better than the throughput of the path $u \to v$. 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 $v \in N1(u)$ **do**
  for each node $w \in N1(u)\backslash\{v\}$ **do**
    if $1/\pi(u,v) > 1/\pi(u,w) + 1/\pi(w,v)$ **then**
      remove v from neighbor-list of u at rate $\rho_{\pi(u,v)}$
    end if
  end for
end for

4.2.2 Rate Maximization

The marked nodes at the completion of Stage 1 (Initial Marking) represent the forwarding nodes transmitting using the lowest-rate only. In Stage 2 (Neighbor-Grouping and Rate-Maximization), after the completion of the Neighborhood-Grouping substage, each marked node knows the 1-hop neighboring nodes it is responsible to cover. We recall that the aim of the Neighborhood-Grouping was to ensure that the transmission rate at a marked node is not reduced to cover a 'distant' node that is 'better' covered by another marked node. The objective of the next substage, called Rate-Maximization, is to maximize the transmission rates across all marked nodes by utilizing higher-rate links. In particular, we can use the Rate-Area-Product (RAP) maximization principle [3] to either increase the rate of certain transmissions, or even completely eliminate certain transmissions. In general, this implies that the transmission rate of some marked nodes will increase, as well as some subset of marked nodes can become unmarked[2]. The challenge, of course, is to achieve these changes while preserving the connectivity of the resulting marked nodes (dominating set). In particular, since the approach subsequently creates a shared tree spanning the set of marked nodes, it is important to ensure that the resulting set of nodes is connected, independent of the location of the broadcast source. As noted, the key challenge comes from the impact of rate diversity (two marked nodes A and B may end up with rates ρ_A and ρ_B, such that A's transmission reaches B, but not vice versa).

As a simple example to illustrate this point, consider two marked nodes u and v within transmission range of each other. The neighboring nodes of u are nodes $\{v, x, w\}$ at transmission rate r_1 i.e $Neigh(u, r_1) = \{v, x, w\}$, similarly, $Neigh(u, r_2) = \{x, w\}$ where $r_2 > r_1$. Also, assume that $Neigh(v, r_1) =$

[2]Our results seem to indicate that although rate increase is very common, un-marking of nodes, in Stage 2, does not happen too frequently

$\{u, z\}$ and $Neigh(v, r_2) = \{z\}$. We note that the transmission rate at u is limited to r_1 because it must cover v at this rate, the other two of its neighboring nodes i.e. x and w can be covered at the quicker rate of r_2. Assuming v has a higher-ID than u, u can try to export the neighboring node v to the adjoining marked node v (being in the closed-neighbor set of v, another marked node). By doing this operation, it can increase its own rate to r_2. However, the pitfall in such an approach would be that in such a network if x or w were a broadcast source, we would not be able to span all nodes (i.e. create a connected spanning tree) using the rates/ forwarding nodes decided (x or w would be able to connect to u at r_2, assuming that the broadcast source can transmit even when not in the CDS, however, the transmission at u was chosen to be r_2 which cannot now cover v). Note that if v or z are chosen as broadcast source, the forwarding nodes/forwarding rates can create a spanning tree using these decided rates.

Since our distributed topology construction algorithm (Stage 1 and 2) calculated is agnostic of the broadcast source, the transmission rates chosen for each marked node should ensure that there is never an instance of a partitioned network, if certain nodes are broadcast source. This requirement is due to the multi-rate nature of multi-rate WMNs (WuLi algorithm does not consider this asymmetry as it is designed for single-rate networks). If we have directed graph $D = (V, E)$ in which V is the CDS or the set of marked nodes, and there is an out-going edge at each marked node connecting to its neighbors that are reachable at the transmission rate for that marked node. Our objective is to determine the transmission rates at the nodes in CDS such that we obtain a *strongly connected graph* (path from any vertex to any other vertex in the directed graph D). Strong connectivity would ensure that the rate is chosen such that irrespective of the broadcast source, we can have a connected tree resulting from the rates chosen at the marked nodes. An approach to ensure strong connectivity is to increase a forwarding node's rate only if the nodes loaned out (to a higher-ID marked node) do not include a marked node. By excluding the possibility of loaning out a marked node, we constrain a forwarding node to use a maximum rate that must cover all its neighboring marked nodes. This can lead to large CDS and/or large number of forwarding nodes. We solve the problem of strong connectivity by enforcing an extra condition that the 'loaning-node', at its higher increased rate as well, should be able to connect to the 'loaned-to' node. This condition is necessary to ensure that we are able to form a broadcast tree from the rates decided at the transmitting nodes irrespective of the broadcast source.

Initially, the transmission rate at a marked node is maximized subject to the maximum rate that it can use to connect to *all* its neighboring nodes decided in the Neighbor-Grouping substage. The maximum rate is the slowest of individual link rate to any of the downstream node. Each node, thereafter, attempts to exploit what we call the '*neighbor coverage relief*'. The intuition behind neighbor coverage relief is that a marked node u can be connecting to neighboring at different rates. If the neighboring nodes (called rate-limiting nodes) are already covered by a higher-ID neighboring marked node v at its current transmission rate and if it satisfies the RAP condition (explained later), then the rate-limiting nodes can be exported to be covered by v. Rate-Maximization can be thought of as a generalization of the pruning step of WuLi's algorithm.

To mathematically represent the Rate-Maximization algorithm, 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, for notational compactness, assume $\rho_0 = \infty$ (setting the rate to ρ_0 implies that a marked node has 'unmarked itself'). Also, at any stage of the iterative algorithm, $\rho(u)$ denotes the current transmission rate associated with node u. Let $N_k(u) : k = 1, ..., L$ denote the set of neighboring nodes that node u reaches at rate ρ_k (but cannot reach at any higher rate $\rho_j : j > k$). Also, assume that $N_k(u)$ cannot be a empty set, i.e. for the algorithm, L does not have to represent all the possible broadcast transmission rates but should merely represent the subset of rates for which u has one (or more) neighbors. Let $|N_k(u)|$ denote the number of elements in $N_k(u)$. The Rate-Maximization algorithm is described in Algorithm 2 and works as follows: The rate-limiting nodes of node u, whose current rate of transmission $\rho(u)$ is indexed by k in the algorithm, has an initial transmission rate k equal to L. The node u can increase its rate each time the *RAP Condition for transfer* is satisfied. The Rate-Area-Product or the RAP condition for the transfer ensures that the WBA is maximized. Assuming that the current-rate at u is k. We represent the quickest-rate supported between two nodes u and v by $\pi(u, v)$. $N_k(u)$ represents all nodes v s.t. their quickest rate to connect to u is k (i.e., $\pi(u, v) = k$). Node u wishes to export the rate-limiting nodes at the current-rate i.e. $N_k(u)$ to some neighboring node and thereby increase rate. The RAP attempts to balance the rate-change (possibly rate loss) of the 'exported' nodes and the rate-gain of the remaining nodes. If we represent the node, a rate-limiting node N_{ki} can be exported to as $\delta(N_{ki})$, then, the rate-change of the exported nodes is represented by $\sum_{i=1}^{|N_k(u)|} \rho(\delta(N_{ki}(u))) - \rho(u)$ and the rate-gain of the remaining nodes is represented by $|N(u) \backslash \{N_k(u)\}| \times (\rho_{k-1}(u) - \rho_k(u))$. The RAP condition for a successful transfer is satisfied if the sum of the rate-change of the exported nodes and the rate-gain of the remaining node is positive. If $N_{ki}(u)$ cannot be exported to any 1-hop higher-ID higher-marked neighboring node i.e. $\delta(N_{ki}(u)) = \emptyset$ or the exported-to node can not connect to u on rate $k-1$, then $\rho(\delta(N_{ki}(u)))$ is taken as $-\infty$. Thus, in such cases, the RAP condition would never be satisfied if even one rate-limiting node is non-exportable. The Rate-Maximization algorithm would keep on exporting the rate-limiting nodes (and thereby increasing its rate) until all the nodes have been exported, at which it can unmark itself.

Algorithm 2 Rate-Maximization function at node u

$\rho(u)$ is the current transmission rate at u
$N_k(u)$ = all nodes v s.t. $\pi(u, v) = k$
———————————————
for $k = L; k > 0; k--$ **do**
    if (condition) **then**
        $N_k(u) = 0;$
        $\rho(u) = \rho_{k-1}$
    end if
end for
———————————————
RAP improvement condition:
Exported: $\sum_{i=1}^{|N_k(u)|} \rho(\delta(N_{ki}(u))) - \rho(u)$
Remaining: $|N(u) \backslash \{N_k(u)\}| \times (\rho_{k-1}(u) - \rho_k(u))$
Exported + Remaining > 0
———————————————
where $\delta(N_{ki}(u))$ is a 1-hop higher-ID marked neighbor
of u which can cover $N_{ki}(u)$ at its current rate
and which u cover at its increased rate $k-1$.
(if multiple, choose 1-hop neighbor of higher rate)
if $N_{ki}(u)$ cannot be exported i.e. $\delta(N_{ki}(u)) = \emptyset$
then $\rho(\delta(N_{ki}(u))) = -\infty$

4.3 Stage 3—Tree construction:

Although the forwarding set (CDS) and the transmission rates calculated do not change with different broadcast sources i.e. the same nodes (in the CDS) will forward and at the same decided rate. However, the tree (i.e., the parent/children relationship) is different based 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 i.e. topology construction algorithm 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 the current stage ensuring that there are no unnecessary transmissions.

5 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 $1 \times 1\ km^2$. Using each count of network nodes, we generate 100 topologies where nodes are uniformly randomly distributed 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 are using Dijkstra tree performance 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

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 $N_{Rate(u)}(u)$
end if
if received $RREP$ and $RREP.nexthop = u$ **then**
    Activate $Forwarder$ flag
    $RREP.nexthop = Parent(u)$
    $send(RREP)$
end if

relationships depicted in Table I (obtained from Qualnet [24]) and Table 2 (obtained from a commercial product [25]) are assumed. The interference range is assumed to be 1.7 times the lowest transmission rate's range.

5.1 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 1 and 2. The WuLi 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 1 and 2 for the rate-range curves in Table 1 and 2, 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.

5.2 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 algorithms against the centralized algorithm's performance. The results of this comparision can also be observed in Figures 1 and 2. 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, however, the performance gap between WCDS and the distributed algorithm, particularly MDW, is not large. The performance MDW, however, improves the performance of rate-unaware broadcast manifold. The performance of MDW, in terms of broadcast latency, is better than MRRA's performance.

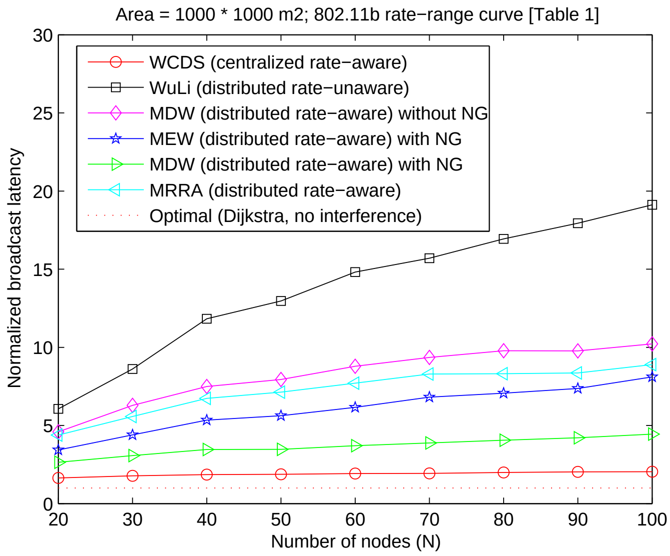

Figure 1: Normalized broadcast latency against varying number of nodes N (Area=1000*1000 m^2) for 802.11b rate-range curve [Table 1]

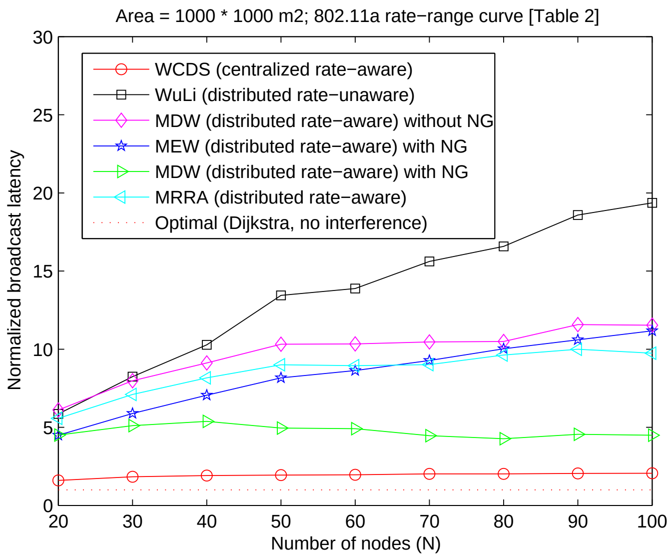

Figure 2: Normalized broadcast latency against varying number of nodes N (Area=1000*1000 m^2) for 802.11a rate-range curve [Table 2]

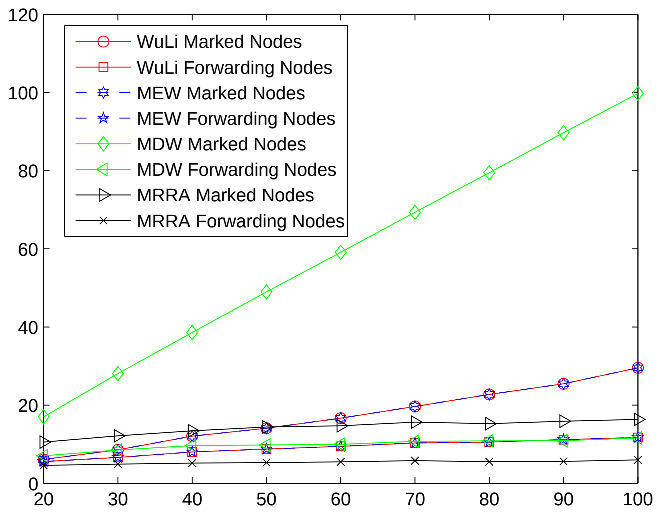

Figure 3: Number of marked-nodes/or forwarders against varying number of nodes N (Area=1000*1000 m^2) for our algorithms (assuming rate-range curve of Table 1)

5.3 Effects of Delayed-Pruning and Neighbor-Grouping

It should be observed in Figures 1 and 2 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* WuLi) with Neighbor-Grouping (NG) is better than the performance of MEW (Multi-Rate *Expedited-Pruning* WuLi) 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.

5.4 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 3. 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.

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

We have performed simulations on the Qualnet [24] simulator to see the performance of our broadcast algorithms 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 4. The results in Figure 4 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.

6 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 rate-diversity of the underlying network

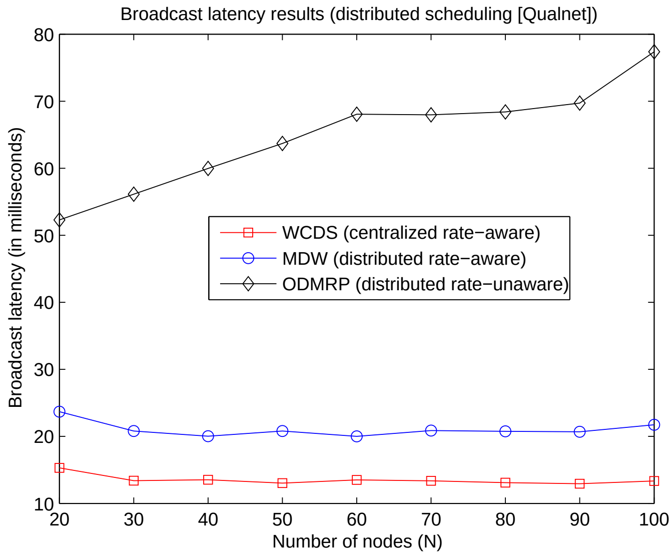

Figure 4: Normalized broadcast latency against varying number of nodes N (Area=1000*1000 m^2) using 802.11b simulation in Qualnet

into the metric of our broadcasting algorithm. We showed through simulations that manifold increase over existing broadcast algorithms is realized by exploiting the available rate-diversity. We 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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