Exploiting Rate Diversity for Multicasting in Multi-Radio Wireless Mesh Networks

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***Abstract*: A multi-rate capable IEEE 802.11a/b/g node can utilize different link-layer transmission rates. Interestingly, multi-rate capability is defined by IEEE 802.11 standards only for unicast transmissions. In this paper, we consider a novel type of multi-radio multi-channel wireless mesh network (WMN) where a radio can mulicast at different link-layer transmission rates to its neighbors. Such *link-layer multi-rate multicast* capability will enable low-latency network-layer broadcast/multicast for multimedia.**

In our previous work, we assumed a "*fully multi-rate multicast*" (FMM) framework in which nodes can adjust link-layer multicast transmission rate for each link-layer frame. We propose a new framework called "*single best-rate multicast*" (SBM) that exploits the link-layer rate diversity by enabling each WMN to decide, depending on its topological properties, a single transmission rate for all its link-layer data multicasts. Although, FMM improves performance significantly, employing SBM is attractive since it can eliminate some undesirable features of practical multi-rate Media Access Control (MAC) protocols. We propose methods to determine the "best" link-layer transmission rate for the SBM framework. We also propose two heuristic broadcast solutions, using SBM framework, that can realize low-latency broadcast by exploiting inherent rate and interface diversity in multi-radio multi-channel WMN. Simulation results indicate that SBM broadcast heuristics give comparable performance to FMM broadcast heuristics, especially in dense networks.

I. INTRODUCTION

Wireless mesh networks (WMN) are multi-hop networks, composed of wireless links [1], that are typically composed of static wireless mesh routers and potentially mobile mesh clients. Such networks are envisioned as community networks or as broadband access networks for the Internet. WMN is considered a cost-effective alternative to wireless local area networks (WLAN) as it does not require any wired infrastructure. With the plummeting cost of 802.11-based hardware platforms, mesh networking is gaining ground as several industry players develop 802.11-based mesh networking platforms and services [2]. Current deployments of large-scale metropolitan-wide mesh networks suggest a promising future for WMN [3]. Nonetheless, wide-spread adoption of WMN as a viable access technology is still impeded by the relatively low spatial reuse, due to wireless interference, of a single radio channel in such multi-hop wireless environments. It has been shown that the capacity of single-channel wireless networks drops off as the number of nodes are increased [4].

With recent advancements in wireless technology rendering the usage of multiple radios affordable, a popular current trend is to equip each mesh node with multiple commodity wireless cards, with each card's radio tuned to a distinct channel. The usage of multiple radios significantly improves the capacity of the network by employing concurrent transmissions in the network [5] [6] [7]. Most commodity cards today also implement some rate-adaptation mechanism (e.g., RBAR [8]) to support different link transmission rates. WMN nodes can utilize the degree-of-freedom afforded by its multi-rate ability to make appropriate range and throughput tradeoffs across a wide range of channel conditions. While the degree-of-freedom afforded by multi-rate has traditionally been used for unicast only, we have recently proposed its use in broadcasting scenarios as well [9] [10] [11]. In the near future, multi-radio multi-channel multi-rate (*MR^2-MC*) WMNs are expected to gain a niche in the wireless market due to adoption and support from leading industry vendors and active research from the research community.

An important open question in MR^2-MC WMNs, that we address in this paper, is the minimum latency broadcasting[1] (MLB) problem. We determine the efficiency of broadcast in terms of '*broadcast latency*' which is defined as the maximum delay between the transmission of a packet by a source and its eventual reception by all receivers. The MLB problem, apart from its theoretical significance, is an important practical problem in WMN. The presence of several multi-party applications—e.g., software updates to all devices, local content distribution (e.g., video feeds) in community networks, and multimedia gaming—often impose stringent latency requirements on the underlying network and motivate a solution to our considered problem. The MLB problem has been studied earlier for single-radio single-channel (SR-SC) WMN—both for the single-rate [12] and the multi-rate case [13]—and for MR^2-MC WMN ([11]).

In our previous work [9] [10] [11] regarding multi-rate multicast, we assumed a "*fully multi-rate multicast*" (FMM) framework in which nodes could adjust link-layer multicast transmission rate for each link-layer frame. We showed that multi-rate link-layer multicast can significantly reduce broadcast latency. While using multi-rate multicast is desirable in an ideal case, it has been observed in practical MACs (such as 802.11) that the choice of a low transmission rate, even by an individual node, may substantially lower the total throughput achieved in that region (*due to the well-known paradigm of fairness in access attempts rather than bandwidth*) [14] [15]. Hence, it is worth studying the impact of broadcasting, in an ideal setting, using a single '*best*' rate, as opposed to the more powerful paradigm of broadcast transmission by different nodes at different rates. In particular, if it turns out that a single-rate broadcast strategy can provide latencies fairly close

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[1] We assume that multicast can be realised by pruning the broadcast tree.

to those provided by the multi-rate case, then an approach based on adopting a single system-wide link-layer broadcast rate may become worthy of consideration.

In this paper, we propose a new framework called "*single best-rate multicast*" (SBM) that exploits the link-layer rate diversity by deciding for a WMN, depending on its topological properties, a single transmission rate for all its link-layer data multicast. Using the SBM framework can simplify the broadcasting algorithms—e.g., the '*multicast grouping*' stage in broadcasting heuristics of [10] [11], that cater to the possibility of a transmitting node covering its neighbors in multiple transmissions (at different rates), is eliminated when SBM framework is used.

A. Our Contributions

The main contributions of this paper are detailed below:

1) Our work answers the following question: "*What is the 'best' link-layer transmission rate to use, given a multi-rate system with n different rates, when using the SBM framework*"?
2) We present two heuristic broadcast solutions, that use the SBM framework, to the MLB problem in MR^2-MC WMNs.
3) We present a joint '*interface grouping and transmission scheduling*' algorithm that schedules the broadcast transmissions at different nodes and also decides, when multiple interfaces are available, the interface to use that maximally exploits the channel diversity in the network.

II. BACKGROUND AND RELATED WORK

Broadcasting in wireless networks is a fundamentally different problem to broadcasting in wired networks due to the '*wireless broadcast advantage*' (WBA) [16]. 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 [16] [17], number of transmissions [18] [19], and route discovery and management overhead [20]. The limited research on using broadcast latency metric has focussed primarily on SR-SC meshes, with single-rate networks addressed in [12] and multi-rate networks in [9] [10] [13].

In our previous work [9], we 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 SR-SC multi-rate WMN in [10] [13]. The work in [10] [11] [13] exploits 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 [10] [13] as heuristic solutions for the MLB problem in SR-SC multi-rate mesh networks using the FMM framework. 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. We recently addressed the MLB problem for MR^2-MC [11] where we presented LMT and PAMT algorithms as *adaptive* broadcast heuristics. These algorithms improve the performance of the WCDS algorithm, designed for SR-SC WMN, by parallelizing it's transmissions by *adapting* itself to the interface (*or* channel) and rate diversity available in MR^2-MC WMNs. These aforementioned works, employing multi-rate multicast, all assume a FMM framework with the implicit requirement that a node be able to broadcast/multicast using *any* of the link-layer transmission rate. In our work for SR-SC WMNs [10], we showed that the multi-rate capability is not often used[2]. *This indicates that a broadcast algorithm with a single "well-chosen" multicast rate may offer fairly competitive performance.*

This work is similar to [12] in using a single-rate for all link-layer multicast. However, we use the SBM framework where the 'best' transmission rate is determined according to the topological properties of the WMN unlike [12] which uses a fixed rate regardless of the given WMN's topology. Also, the work done in [12] was specific for SR-SC WMNs while our work addresses *MR^2-MC* WMNs. We note that the other work addressing MLB problem for *MR^2-MC* WMNs [11] has assumed a framework (FMM) different to ours (SBM).

III. NETWORK AND INTERFERENCE MODEL

We use a network model similar to that described by [6]. We will use the notation introduced by [21] to represent our channel-assignment. Each node in the network can transmit at multiple-rates. There are totally C non-overlapping orthogonal frequency channels in the system and each node is equipped with Q radio interfaces where $Q \leq C$. The Q radio interfaces have omni-directional antennas. We assume a unit disk graph (UDG) model. In order to efficiently utilize the network resources, two radio interfaces, at the same node, are not tuned to the same channel. 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 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/b/g product [23] to perform sensitivity analysis of the broadcast performance with different rate-range relationships.

We use an undirected graph $G_T = (V, E_T, L_T)$ to model the given mesh network topology *before channel assignment*, where V is the set of vertices, E_T is the set of edges and L_T is the set of weights of edges in E_T. 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_T *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 latency of a link $l(u, v)$ is the latency of the '*quickest*' transmission rate that can be supported between nodes u and v. The set L_T contains the latencies of all links in E.

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

Channel assignment: A channel assignment $\mathcal{A}$ assigns each vertex v in V, Q different channels denoted by the set: $A(v) = \{a_1(v), a_2(v), \ldots, a_Q(v) : a_i(v) \neq a_j(v), \forall i \neq j;\ a_i(v) \in C, \forall i\}$ where $a_i(v)$ represents the channel assigned to i^{th} radio interface at node v.

The topology defined by $\mathcal{A}$ is represented by $G = (V, E, L, \Lambda)$ in the following natural way: There is an edge $e = (u, v, k)$ on channel $\lambda(e) = k$ between nodes u and v in G *if and only if* $d(u, v) \leq r$ (i.e. edge$(u, v) \in E_T$) and $\lambda(e) \in \mathcal{A}(u) \bigcap \mathcal{A}(v)$. The latency of the edge e is the latency of the fastest transmission rate supported on e. The set L contains the latency of each edge in E; similarly the set Λ contains the channel used on each edge in E. Note that G may be a *multi-graph*, with multiple edges between the same pair of nodes, when the node pair shares two or more channels. We use the same notation to refer to *vertices and nodes*, to *edges and links*, and to *weight of edges and latency of links* without confusion, the usage being clear from the context.

It is assumed that the *channel assignment* is done independently from our broadcasting framework. This design decision reflects the practical reality that the channel assignment strategy will likely be dictated by other factors, including the presence of *unicast* traffic on the WMN. We have used the '*common channel approach*' (CCA) channel assignment scheme [5] [7] for this work. CCA is a simple channel assignment scheme in which all nodes are assigned a common set of channels. The benefit of this approach is its simplicity and that the connectivity of the network, using CCA, is a multiple of the connectivity of a single channel mesh. We have also employed '*varying channel approach*' (VCA) [7] and '*interference survivable topology control*' (INSTC) [21] channel assignment schemes to perform sensitivity analysis of the results presented in this paper. We have earlier presented the effect of different channel assignment schemes on broadcast performance for MR^2-MC WMNs in our previous work [11].

Interference Model: We use a generalized conflict graph *based on transmissions* to model the effects of wireless interference between different multicast transmissions in MR^2-MC meshes. The conflict graph indicates which transmissions mutually interfere and hence cannot be active simultaneously. A transmission b_i interferes with a transmission b_j, if both transmissions b_i and b_j are taking place on the *same* channel, *and* the receivers of the transmission b_i are within the interference range of the transmitting node of b_j or *vice-versa*. The transmissions b_i and b_j do not interfere otherwise.

IV. HEURISTIC SOLUTIONS TO MLB PROBLEM

In this section, we present heuristic algorithms that solve MLB problem, using the SBM framework, in MR^2-MC WMNs. Broadly speaking, such heuristic algorithms must take *four* important decisions at each node. Firstly, it has to determine the 'best' transmission rate to use for *all* link-layer broadcasts (*this stems from our design choice to have only one broadcast rate*). Secondly, it has to decide whether a node should transmit (i.e., be a non-leaf node in the broadcast tree) or not. Thirdly, the 'interface grouping' decision must be made to decide the interface (*or alternatively the channel, since each interface is tuned to a distinct channel*) a transmitting node will use for its transmission. Lastly, each node's transmissions must be scheduled, while ensuring simultaneous transmissions (at different nodes) do not interfere, to minimize the broadcast delay.

The MLB problem in MR^2-MC WMN is composed of many inter-related hard subproblems. The MLB problem is at least NP-hard since its specific instances (SR-SC single-rate WMN [12] and SR-SC multi-rate WMN [11]) are NP-hard. With the complexity of the problem in mind, we have decomposed our solution into *three* logically independent stages:

1) ***The 'best' link-layer multicast rate selection***: Since we have taken the design decision to use the SBM framework to simplify the broadcast heuristics and their implementation, we need to determine the single 'best'link-layer multicast rate. This rate, to be used for all link-layer multicast, is determined by each WMN, during the first stage of our solution, according to its topological properties.

2) ***Topology Construction***: The aim of this stage is to compute a broadcast tree (or a spanning tree of the given topology) T that exploits the WBA, the multi-rate transmission capability and the plurality of radio interfaces and channels available. The transmitting nodes and the children/parent relationships between different nodes are all decided during this stage.

3) ***Interface Grouping and Transmission Scheduling***: While the non-leaf nodes (transmitting nodes) of the tree are determined during the 'topology construction' stage, *the interface used for transmission at these non-leaf nodes is only decided during the interface grouping substage of the joint 'interface grouping and transmission scheduling' stage*. The interface grouping (or simply, grouping) substage must ensure that the interface chosen, at any transmitting node, shares its channel with the children node(s) of the transmitting node. *The transmission scheduling* (or simply, scheduling) *substage, on the other hand, determines the exact timing of the various transmissions*. The scheduling of the transmissions is done according to the following constraints: firstly, a node must transmit only after receiving its parent's transmission and secondly, the interfering transmissions must not be scheduled simultaneously. By having a joint '*grouping and scheduling*' stage, the channel diversity of the network can be utilized more efficiently.

V. DETERMINING THE SINGLE 'BEST' LINK-LAYER MULTICAST RATE AND "RAP" FORMULATION

We point out a key finding of our previous study, for SR-SC multi-rate WMN [10], that a transmission rate's broadcast efficiency (in reducing broadcast latency) can be predicted reasonably by the product of the transmission rate and its transmission coverage area (*rate-area product* or *RAP*) [10]. We propose using a similar approach for predicting a particular transmission rate's broadcast efficiency in MR^2-MC WMN. The RAP values for different transmission rates of the range-rate relationship of 802.11b in Qualnet [22] are provided in Table I. Similarly, the RAP values for transmission rates of our alternative rate-range relationship [23] are provided in Table II. *As a general rule-of-thumb, a transmission rate that has a higher RAP is more broadcast-efficient for SR-SC multi-rate WMNs* [10]. We investigate if this conjecture still holds for MR^2-MC WMNs.

We propose two methods of determining the 'best' link-layer multicast rate. For any given WMN, let R denote the set of transmission rates, which if used as the link-layer rate for all multicast, returns a connected network. *In the first method, we use the highest link-layer multicast rate in R as the chosen 'best' rate.* We call the transmission rate calculated by this method as the "*quickest*" rate. *In the second method, we use the transmission rate in R that that has the highest RAP value of all rates in R.* We call the transmission rate calculated by this method as the "*HRC*" (*highest-RAP-valued connected*) rate.

We will present results and analysis of these methods in Section IX.

VI. Topology Construction in MR^2-MC WMN using a single link-layer broadcast rate:

In this section, we present two heuristic algorithms for the topology construction. The first algorithm (Section VI-.1) exploits the WBA but fails to account for the interface diversity at individual nodes. The second algorithm (Section VI-.2) improves the first algorithm's performance by exploiting both the WBA and the interface-diversity.

The common input to both our algorithms is the channel assignment defined input topology $G = (V, E, L, \Lambda)$, broadcast source s in V, the 'best' broadcast transmission rate $\hat{l}$ (*chosen as described in the previous section*), and the channel assignments to all interfaces at each node $\mathcal{A}$.

*1) **Connected Dominating Set (CDS)**:* The topology construction in MR^2-MC WMN for the SBM framework is greatly simplified as compared to FMM framwork [10] [11]. To illustrate this, we note that the Weighted Connected Dominating Set (WCDS) problem [13]—which essentially is finding a connected dominating set that covers all nodes with minimum (latency) weighted sum—reduces to a problem of finding the Minimum Connecting Dominating Set (MCDS) when SBM framework is assumed. Unfortunately, MCDS in general graphs is also an NP-hard problem [24]. However, by assuming SBM framework, the algorithms are greatly simplified as we shall see later.

Algorithm 1 CDS construction

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Input: $[s, \mathcal{A}, C, G = (V, E, L, \Lambda), \hat{l}]$
$\mathcal{R} \leftarrow \{s\}$
while ($V \backslash \mathcal{R} \neq \emptyset$) do
  $(\hat{n}, \hat{l}, \hat{c}) = \arg\max_{n \in \mathcal{R}, c \in \mathcal{A}(n)} f(n, \hat{l}, c)$
  (where $f(n, \hat{l}, c) = (|N(n, \hat{l}, c) \backslash \mathcal{R}|)$)
  let the transmission of $\hat{n}$ be represented by $t$
  $A \leftarrow N(\hat{n}, \hat{l}, \hat{c}) \backslash \mathcal{R}$;
  if $\hat{n}$ can connect to $A$, using latency $\hat{l}$, on any of multiple
  channels (contained in set B), then $c(t) = B$
  $P_{CDS}(A) = \hat{n}$; $L_{CDS}(A) = \hat{l}$; $\Lambda_{CDS}(A) = \hat{c}$;
  $\mathcal{R} \leftarrow \mathcal{R} \cup A$
end while
Output: $[P_{CDS}, L_{CDS}, \Lambda_{CDS}]$
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We use a simple greedy heuristic called CDS, that is shown in in Algorithm 1, for constructing the broadcast topology. The algorithm starts by making the source node s eligible to transmit. This is done by moving s to the set $\mathcal{R}$ which keeps track of the eligible nodes (nodes that have received the transmission already and are eligible to transmit). A transmission $(n, \hat{l}, c)$ represents the transmission of node n on channel c (using the 'best' link-layer multicast rate $\hat{l}$). All eligible transmissions ($\forall n \in \mathcal{R}, \forall c \in \mathcal{A}(n)$) are given a 'priority' according to the number of new nodes (that have not yet received the transmission: $|N(n, \hat{l}, c) \backslash \mathcal{R}|$ *or* A) it covers. The algorithm works iteratively, and in each round finds the transmitting node $\hat{n}$ that can cover maximum number of nodes that have yet not received. If the transmission of $\hat{n}$ to reach its downstream nodes A is denoted by t, then $c(t)$ represents all the channels that $\hat{n}$ can use for this transmission. We delay the decision of the exact interface to use to a later (joint interface grouping and transmission scheduling) stage.

The algorithm completes its execution when all the nodes have been covered, i.e. when $V \backslash \mathcal{R} = \emptyset$. The algorithm returns the sets P_{CDS}, L_{CDS} and Λ_{CDS}, where $P_{CDS}(v_i)$ is the parent node of v_i, $L_{CDS}(v_i)$ is the latency of the link connecting v_i and $P_{CDS}(v_i)$, and $\lambda_{CDS}(v_i)$ is the channel used on the link connecting v_i and $P_{CDS}(v_i)$, $\forall v_i \in V$. The CDS tree can be constructed from these.

*2) **Parallelized Connected Dominating Set(PCDS)**:* In our previous work [11], we have shown that the *best performing trees in MR^2-MC WMNs, generally, adapt to the radio resources* (i.e., radio interfaces (Q) and channels (C)) *available*. It is desirable to construct similar adaptive trees when we use the SBM framework. The PCDS algorithm (depicted in Algorithm 2) is adapted from the PAMT algorithm that assumed a FMM framework [11]. *PCDS*—like the PAMT algorithm which improves WCDS tree's performance by parallelizing its transmissions—*improves CDS algorithm by exploiting the rate and interface-diversity available in MR^2-MC WMNs.* PCDS takes a different approach to CDS for calculating the priority f of each transmission. In an attempt to modify CDS to contain more parallel transmissions (when multiple radio interfaces are available), PCDS does not include downstream neighbors in a transmission that can be reached by *any other* eligible node, *on an alternative channel*, with a better path. The PCDS algorithm uses an extra parameter called *label* for each node, found using Dijkstra's algorithm, to represent the distance of this node to the source node (alternatively, instead of using *label*, the depth of the node can be used, since all nodes use the same rate).

PCDS begins by adding node s to the set $\mathcal{R}$ which contains nodes that are eligible to transmit during the next-round. The set $Y_{(n,\hat{l},c)} = N(n, \hat{l}, c) \backslash \mathcal{R}$ contains all hitherto 'uncovered nodes' that can be covered by a transmission $(n, \hat{l}, c)$. The label of this transmission (*label$_{trans}$*) is *label(n) + l*. During the calculation of priority of each transmission $(n, \hat{l}, c)$, all the yet not-reached neighboring nodes $Y_{(n,\hat{l},c)}$ of transmitting node n are contained in X. We search the neighborhood of each node in X to find if there are other eligible (to transmit) nodes in its vicinity that can cover this node on a channel different to that used by n. Such nodes are referred to as *nodes$_p$* in the algorithm. If the depth of any node in *nodes$_p$* is less than the depth of node n, then the considered node in X should be covered by this node instead of n. We, therefore, do not count this node as a covered-node for n. This node is deleted from the nodes that n shall cover: $Y_{(n,\hat{l},c)}$. After all nodes in X are checked in a similar manner, $Y_{(n,\hat{l},c)}$ contains the priority of the transmission $(n, \hat{l}, c)$. In case the transmitting node n can choose multiple interfaces to reach all downstream nodes $\mathcal{A}$, then the channels of these possible interfaces are stored in B. We represent the eligible channels for a transmission t by $c(t)$.

After completion of each round, covered-nodes A are added to $\mathcal{R}$. The algorithm completes its execution when all the nodes have been covered, i.e. when $V \backslash \mathcal{R} = \emptyset$. The algorithm returns the sets P_{PCDS}, L_{PCDS} and Λ_{PCDS}, where $P_{PCDS}(v_i)$ is the parent node of v_i, $L_{PCDS}(v_i)$ is the latency of the link connecting v_i and $P_{PCDS}(v_i)$, and $\Lambda_{PCDS}(v_i)$ is the channel used on the link connecting v_i and $P_{PCDS}(v_i)$, $\forall v_i \in V$. The PCDS tree can be constructed from these.

Algorithm 2 PCDS construction

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Input: $[s, \mathcal{A}, C, G = (V, E, L, \Lambda), \hat{l}]$
$\{label\}$ = Dijkstra's algorithm $(G)$
$\mathcal{R} = \{s\}$
while $(V \backslash \mathcal{R} \neq \emptyset)$ do
 $(\hat{n}, \hat{l}, \hat{c}) = \arg\max_{n \in \mathcal{R}, c \in \mathcal{A}(n)} f(n, \hat{l}, c)$

 where $f(n, \hat{l}, c)$ is calculated as:
 $X = Y_{(n,\hat{l},c)} = N(n, \hat{l}, c) \backslash \mathcal{R}$
 $label_{trans} = label(n) + \hat{l}$;
 if $X \neq \emptyset$ then
  for $x = 1$ to $|X|$ do
   $nodes_{tmp} = \cup_{(\forall c_{tmp} \in \mathcal{A}(n) \backslash \{c\})} N(X(x), \hat{l}, c_{tmp})$
   $nodes_p = nodes_{tmp} \cap \mathcal{R}$
   for $y = 1$ to $|nodes_p|$ do
    $label_{round}(y) = label(nodes_p(y)) + \hat{l}$
    if $label_{round}(y) < label_{trans}$ then
     $Y_{(n,\hat{l},c)} = Y_{(n,\hat{l},c)} \backslash \{X(x)\}$; break
    end if
   end for
  end for
 end if
 $f(n, \hat{l}, c) = |Y_{(n,\hat{l},c)}|$

 $A \leftarrow Y_{(\hat{n},\hat{l},\hat{c})}$ ($Y$ computed in $f$)
 let the transmission of $\hat{n}$ be represented by $t$
 if $\hat{n}$ can connect to $A$, using latency $\hat{l}$, on any of
 multiple channels (contained in set B)
 then $c(t) = B$
 $\mathcal{R} \leftarrow \mathcal{R} \cup A$
 $P_{PCDS}(A) = \hat{n}$; $L_{PCDS}(A) = \hat{l}$; $\Lambda_{PCDS}(A) = \hat{c}$
end while
Output: $[P_{PCDS}, L_{PCDS}, \Lambda_{PCDS}]$
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VII. Interface Grouping and Transmission Scheduling

The broadcast performance of MR^2-MC WMN can be improved by combining interface grouping and transmission scheduling sub-stages into a joint stage. By delaying the choice of the interface to use till the scheduling stage, the WMN can maximally exploit the channel diversity in the system. This is done by either choosing an interface (for a transmission) that is tuned to a currently unused channel *or* alternatively to a channel on which the transmission can take place alongside existing transmissions due to lack of interference. Clearly, having disjoint stages of grouping and scheduling can easily lead to a non-optimal choice of the interface to use causing broadcast performance deterioration.

For joint *grouping and scheduling*, the topology construction stage instead of deciding the single interface it will use (alternatively, the channel it will use) picks all candidate interfaces and postpones the actual decision about the interface to use until scheduling. During scheduling, an appropriate choice of the interface to use, depending on the other transmissions at that time, is made to fully exploit the channel diversity available. This substantially improves performance especially for large number of radio interfaces Q (and channels C).

The joint grouping and scheduling algorithm is shown in Algorithm 3. The algorithm's aim is to find the start-time (τ) and end-time (δ) of each transmitting node. The algorithm works iteratively in rounds. The algorithm begins by initializing *time*, depicting current time, to zero and E, depicting eligible transmissions, to contain source node's transmission. In each round, the eligible transmissions (E) are descending-order sorted according to the *height* of respective transmitting nodes. The height of a node n is the length of the path from the node n to its furthest leaf. For all eligible transmissions $t \in E$, the function $c(t)$ represents the possible channels (channels on eligible interfaces) for this transmission. These values are available from the topology construction stage. The set C contains eligible channels for the current eligible-transmission being checked (t). The choice of channel (*or interface*) to be used for a particular transmission is dictated by our desire to include as many *parallel* transmissions as possible. A channel c is found amongst the eligible channels (C) that is either not currently being used (i.e., it is not in the set of used channels U) or is being used by some transmission(s), but these transmission(s) do not interfere with t. The channel decided for a transmission t is denoted by $\lambda(t)$. If it is decided that transmission t is to use channel c, t is added to the set T_c that contains ongoing transmissions on c. The channel c is then added to U containing channels currently being used. As soon as the channel (and interface) of the transmission has been decided, we can schedule the transmission at the current time *time*. The start-time of t, denoted by $\tau(t)$, is set to *time*; while the end-time of t, denoted by $\delta(t)$, is set to *time* + l. *T_sel_round* contains the transmissions selected in the current round; while *T_decided* contains all transmissions whose start-time and end-time have already been determined.

After each round, the transmissions selected during that round (*T_sel_round*) are added to decided transmissions (*T_decided*) and deleted from eligible transmissions (E). *T_not_finished* contains all yet unfinished transmissions. The earliest finishing time for transmissions in *T_not_finished* is called *NextStop*; all transmissions completing at *NextStop* are called *NextTrans*. Let $\hat{c}$ be the channel used by a transmission in *NextTrans*. This transmission (in *NextTrans*) must be removed from $T_{\hat{c}}$ as the transmission is going to finish. If $T_{\hat{c}}$ becomes empty after removing this transmission, then $\hat{c}$ can be removed from U. We represent the transmissions of nodes reached by the finishing transmissions as E_{next}. These transmissions are eligible now, and thus they are added to E. The *time* is then set equal to *NextStop*. The algorithm schedules all transmissions similarly, and completes execution when $E = \emptyset$ (i.e., there is no eligible transmission) and $U = \emptyset$ (i.e, there is no ongoing transmission).

VIII. Maximum end-to-end throughput

The results of broadcast latency are directly applicable to low throughput data flows (e.g., control traffic) as the metric applies to a *single* packet. However, for higher throughput data flows, an important metric is the maximum achievable end-to-end throughput. We essentially employ a generalization of the method used in [9], for throughput calculation in SR-SC multi-rate networks, to determine the throughput of MR^2-MC wireless mesh. An important distinction between SR-SC multi-rate WMN and MR^2-MC WMN is that interfering transmissions can take place simultaneously (on orthogonal channels) in MR^2-MC WMN. The algorithm for throughput calculation [9] is modified to adapt to our interference model (presented in Section III). The throughput results for our heuristic algorithms are provided in Section IX.

IX. Simulation Results

In this section, we present simulation results to evaluate the performance of our algorithms. We consider static wireless mesh networks of nodes randomly located in an area of 1000×1000 m^2 region. The broadcast latency of our heuristics are all shown by normalizing it against the broadcast latency

Algorithm 3 Interface grouping and Transmission Scheduling

```
$time = 0$;
$E$= all transmissions of $s$;
while $E$ = $\emptyset$ or $U$ = $\emptyset$ do
  $E$= descending-sort ($height(E)$)
  $T\_sel_{round} = \emptyset$;
  for $x = 1$ to $|E|$ do
    $t = E(x)$;
    $c(t)$ = The channels $t$ can use to transmit to its neighbors
    $C = c(t)$
    for $j = 1$ to $|C|$ do
      $c = j^{th}$ element of $C$;
      if $c \notin U$ or ($c \in U$ and if ($t$ and $T_c$) do not interfere) then
        $\lambda(t)$ = $c$; $T_c = T_c \cup t$; $U = U \cup c$;
        $\tau(t) = time$; $\delta(t) = time + l$;
        $T\_sel\_round = T\_sel\_round \cup t$;
      end if
    end for
  end for
  $T\_decided = T\_decided \cup T\_sel\_round$;
  $E = E \backslash \{T\_sel\_round\}$;
  $T\_not\_finished$ = $\{t\} : \delta(t) > time$ ;
  $NextStop = \min(\delta(T\_not\_finished))$;
  $NextTrans = \{t\} : \delta(t) = NextStop, \forall t$;
  for $v = 1$ to $|NextTrans|$ do
    $\hat{c} = \lambda(NextTrans(v))$
    $T_{\hat{c}} = T_{\hat{c}} \backslash \{NextTrans(v)\}$
    if $T_{\hat{c}} = \emptyset$ then
      $U = U \backslash \{\hat{c}\}$;
    end if
  end for
  $E_{next}$ = transmissions enabled by $NextTrans$;
  $E = E \cup E_{next}$;
  $E = E \backslash \{T\_decided\}$;
  $time = NextStop$;
end while
```

performance of the Dijkstra's tree[3]. We employ the rate-range relationships derived from Qualnet (Table I) and from the specifications of a commercial product (Table II) in our study.

A. Sensitivity of broadcasting framework to rate-range relationship

We present the sensitivity analysis of our broadcasting framework to the rate-range relationship of the WMN using the rate-range relationships shown in Table I and II. We have observed that, for both considered rate-range relationships, the performance of SBM broadcast heuristics (CDS and PCDS) is comparable to performance of FMM broadcast heuristics (WCDS [10] and PAMT [11]), *especially for dense WMNs*. For the rate-range relationship as shown in Table I, the broadcast latency, for varying Q (and C), is depicted in Figure 1 and the throughput results in Figure 2. Similarly, for the rate-range relationship as shown in Table II, the broadcast latency result is shown in Figure 3, whereas the throughput result is shown in Figure 4. Both the latency and throughput results, for both rate-range relationships, show a similar trend where the SBM broadcast heuristics perform comparably to FMM broadcast heuristics, especially at high node densities.

B. The performance of different topology construction algorithms

The performance of PCDS and PAMT is identical to the performance of CDS and WCDS, respectively, for SR-SC

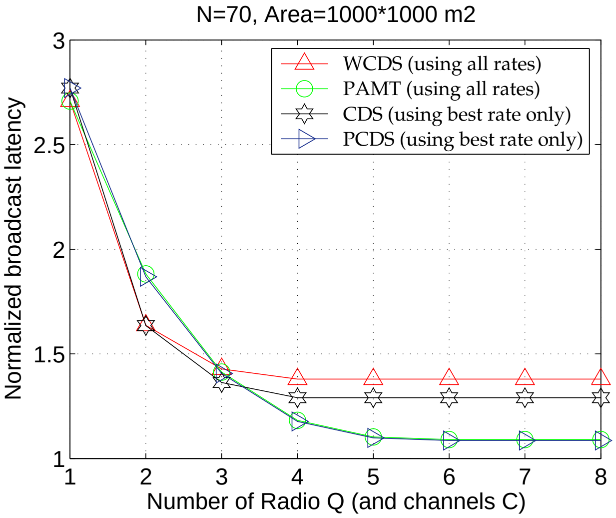

Fig. 1. The normalized broadcast latency against Q (and C) for N=70 and Area= 1000 × 1000 m^2 *(rate-range relationship as in Table I)*

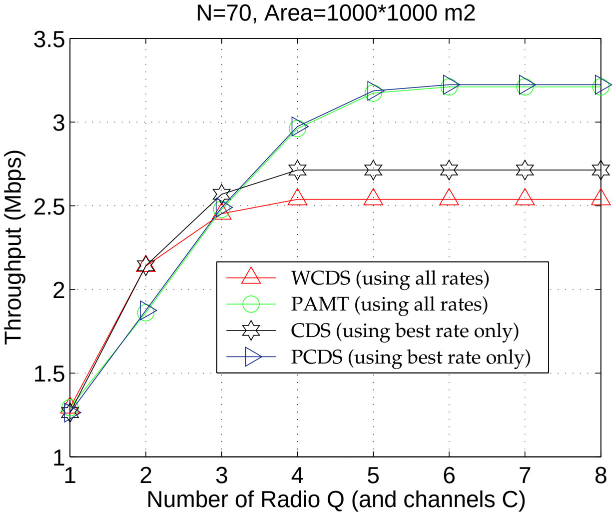

Fig. 2. The throughput (in Mbps) against the number of radio interfaces Q (and the number of channels C) for N=70 and Area= 1000 × 1000 m^2, *(rate-range relationship as in Table I)*

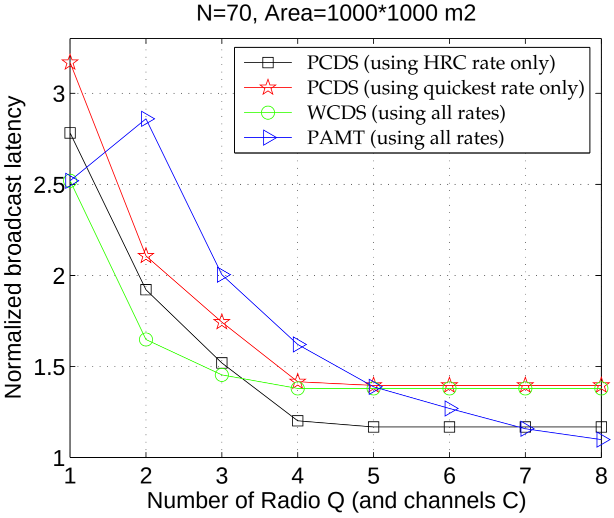

Fig. 3. The normalized broadcast latency against Q (and C) for N=70 and Area= 1000 × 1000 m^2, *(rate-range relationship as in Table II)*

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[3] Since determining the actual optimal is NP-hard, we use Dijkstra tree's performance as a theoretical lower bound on the optimal achievable latency in a corresponding wired network

Transmission rate (Mbps)	Transmission range (m)	20 nodes	30 nodes	40 nodes	50 nodes	60 nodes	70 nodes	80 nodes	RAP (Mbps-km^2)
1	483	3.7527	4.9654	6.0404	6.0581	6.8685	7.2944	7.6121	0.73
2	370	3.1943	3.8988	4.2859	4.4506	4.9467	5.0476	5.0275	0.86
5.5	351	1.7585	2.146	2.2224	2.4239	2.6947	2.8111	2.8019	2.13
11	283	1.3572	1.4739	1.5991	1.6652	1.8205	1.8615	2.0036	2.77

TABLE I

Broadcast latency of PCDS, (for Q=2, C=2, Area= 1000 × 1000 m^2), using SBM framework, CCA channel-assignment and the rate-range relationship from Qualnet [22], also see probability of a connected network for this table in Figure 7

Transmission rate (Mbps)	Transmission range (m)	20 nodes	30 nodes	40 nodes	50 nodes	60 nodes	70 nodes	80 nodes	RAP (Mbps-km^2)
1	610	4.559	6.591	7.5292	7.3821	7.8563	8.0737	8.2701	1.17
6	396	1.7714	2.0259	2.1964	2.2626	2.3385	2.3496	2.4012	2.96
11	304	1.4436	1.6392	1.7638	1.9037	1.9563	2.0248	2.0773	3.19
18	183	N/A	N/A	N/A	2.5746	2.6788	2.7648	2.7033	1.89
54	76	N/A	N/A	N/A	N/A	N/A	N/A	N/A	0.98

TABLE II

Broadcast latency of PCDS, (Q=2, C=2, Area= 1000 × 1000 m^2), using SBM framework, CCA channel-assignment, and the rate-range relationship of a commercial product [23], also see probability of having a connected network in Figure 8

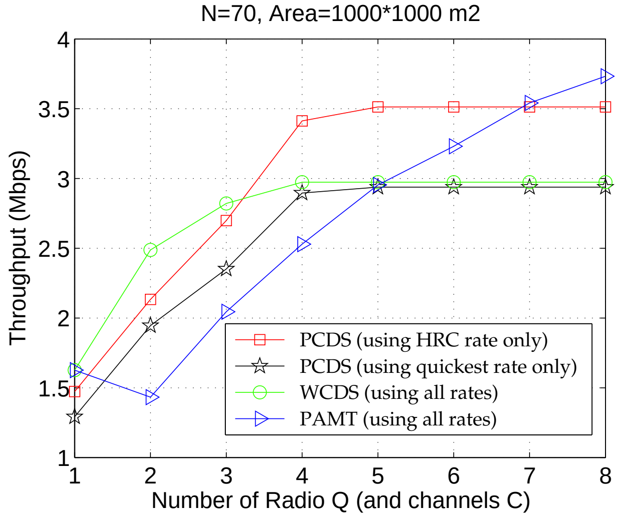

Fig. 4. The throughput (in Mbps) against the number of radio interfaces Q (and the number of channels C) for N=70 and Area= 1000 × 1000 m^2, *(rate-range relationship as in Table II)*

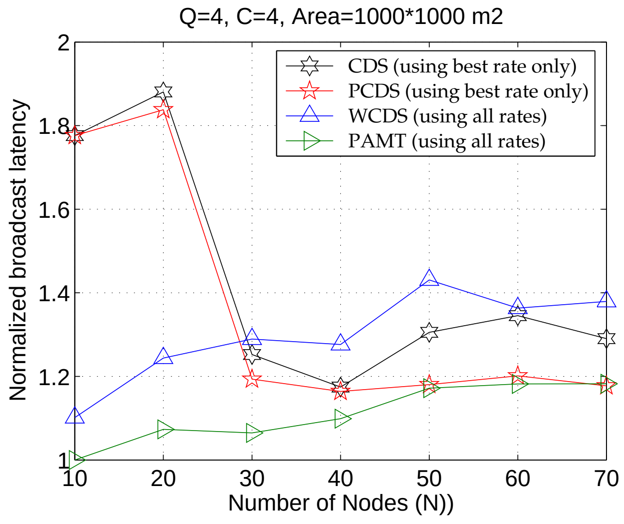

Fig. 5. The normalized broadcast latency against the number of nodes N for Q=4, C=4; Area= 1000 × 1000 m^2, *(rate-range relationship as in Table I)*

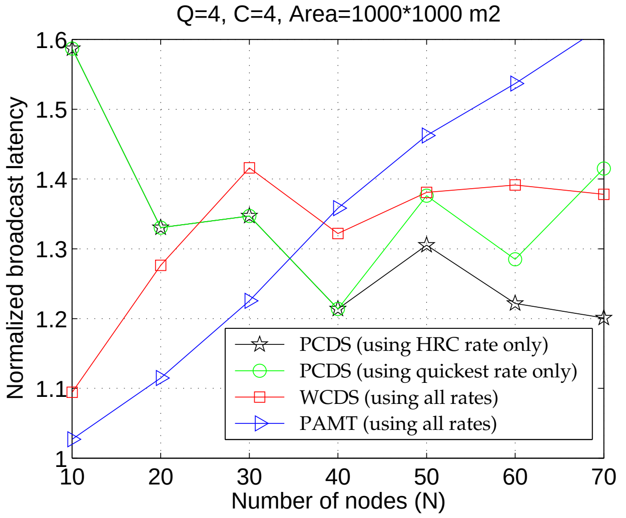

Fig. 6. The normalized broadcast latency against the number of nodes N for Q=4, C=4; Area= 1000 × 1000 m^2, *(rate-range relationship as in Table II)*

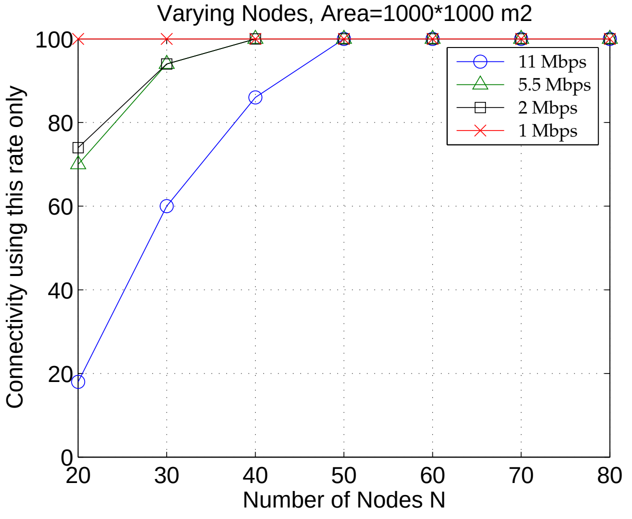

Fig. 7. The probability of having a connected network using the *rate-range relationship of Table I*

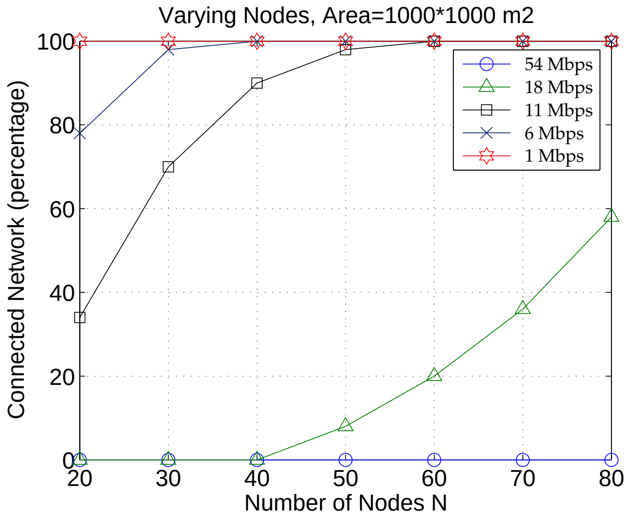

Fig. 8. The probability of having a connected network using the *rate-range relationship of Table II*

WMNs.[4] This can be observed (for $Q = 1$) in Figure 1. For the MR^2-MC WMN scenario (i.e., for $Q > 1$ in Figure 1), PCDS and PAMT improve the performance of CDS and WCDS, respectively, by *parallelizing* their transmissions.

Referring to Figure 5 and Figure 6, the performance of SBM heuristics (i.e., CDS and PCDS) becomes comparable to the performance of FMM heuristics (i.e., WCDS and PAMT) with increasing node density. We note that in sparse WMN, the SBM heuristics might be hindered by its design choice of only employing a single link-layer multicast rate as the network might have to decide a lower rate as the 'best' multicast rate to maintain connectivity. This can lead to lower performance for SBM heuristics compared to FMM heuristics in sparse networks. This is, however, not a problem for dense networks.

C. Using RAP for 'best' rate prediction in MR^2-MC WMNs

To study the viability of using RAP as a rule-of-thumb for measuring the broadcast efficiency of different rates for the SBM framework, we have performed simulations to calculate the broadcast latency—for varying number of nodes in an area of $1000 \times 1000\ m^2$ using the rate-range relationship shown in Table I and Table II—for PCDS algorithm. The data in Table I and II is to be observed together with Figure 7 and 8, respectively, which displays the probability of having a connected network (calculated using 1500 sample topologies), for shown rates. The lowest rate (1 Mbps in Table I and II) has the maximum connectivity probability of 1—since we only consider networks that are connected using the lowest rate. Figures 7 and 8 indicate that connectivity probability, using a particular rate, decreases with increasing rates. We note that the quicker rates (e.g., 18 Mbps and 54 Mbps in Figure 8) have very low connectivity probability. The average broadcast latency (geometric mean of the normalized broadcast latency of 50 random topologies) of PCDS, using the CCA channel-assignment and SBM framework (Q and $C = 2$), is displayed for different rates and node densities in Table I and Table II for different rate-range relationships. A N/A value describes the case where a rate does not return a connected network. *It is seen from that the highest RAP-value transmission rate (11 Mbps for both Table I and II) has the best average broadcast latency.*

D. Methods for calculating the "best" multicast rate

We now evaluate the viability of the methods, proposed in Section V, for determining the 'best' link-layer multicast rate . Considering the range-rate relationship shown in Table I, since the RAP values are monotonically increasing with increasing rate, both the 'quickest' and 'HRC' (highest RAP-valued connected) rate methods give the same rate. We refer to this rate as the 'best' rate in Figures 1, 2 and 5. The normalized broadcast latency and throughput for varying number of Q (and C) with $N = 70$ are shown in Figures 1 and 2, respectively. Similarly, for varying number of nodes (using Q and $C = 4$), results are displayed in Figure 5. For the range-rate relationship shown in Table II, Figure 6—displaying the normalized broadcast latency for varying number of nodes (using Q and $C = 4$) in 1000×1000 m^2 area—shows that the 'quickest' rate and the 'HRC' rate methods perform comparably for low node densities. For low node density, 'HRC' rate is *likely* to be the same as the 'quickest' rate according to the connectivity data in Table I (for $N \leq 40$).

For higher node densities, however, 'HRC' rate method performs much better than than the 'quickest' rate method as shown in Figure 6 (for N more than 40). Figure 3 and Figure 4 also show that latency and throughput performance of our heuristics—for $N = 70$ in 1000×1000 m^2 area—using 'HRC' rate method is much better than 'quickest' rate method across the range of Q and C. This is also illustrated in Table II for Q and C = 2 for varying number of nodes. *Hence on the basis of these experimental results, we can conclude that using the 'HRC' rate method is an efficient way of selecting the 'best' rate to be used in SBM framework broadcast heuristics.*

X. CONCLUSIONS

In this paper, we proposed a new broadcast/multicast framework called SBM that uses a single "best" link-layer rate for all multicast. We also proposed low latency broadcast heuristics that utilize SBM framework, and suggested methods that can select the "best" rate to be used with our framework. Our analysis of SBM showed that, in dense settings, its performance is comparable to the more powerful FMM framework that can adapt the link-layer multicast rate of each frame. Although the single layer-rate multicast approach appears attractive, there are some important practical issues to be resolved. For one, the SBM approach requires centralized knowledge of the entire topology, also SBM requires improvements to make it less vulnerable to dynamic topologies.

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