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Rate-Diversity and Resource-Aware Broadcast and Multicast in Multi-rate Wireless Mesh Networks

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Abstract This paper focuses on the problem of increasing the traffic capacity (volume of admissible traffic) of broadcast and multicast flows in a wireless mesh network (WMN). We study and suggest routing strategies where the process of constructing the forwarding tree considers three distinct features: (a) the ability of individual mesh nodes to perform link-layer broadcasts at multiple rates, (b) the wireless broadcast advantage, whereby a single broadcast transmission covers multiple neighboring receivers and (c) the residual transmission capacity at a WMN node, subject to intereference-based constraints from existing traffic flows in its neighborhood. Our metric of interest is the the total number of broadcast and multicast flows that can be admitted into the network, without resulting in unacceptable degradation in metrics such as packet loss and dissemination latency. Our discrete event simulations show that the broadcast tree construction heuristic which takes both transmission rate and residual bandwidth into account out-performs those that do not. Building on our work on resource-aware broadcast tree construction, we propose a resource-aware multicast tree construction algorithm which exploits the multiple link-layer rates, the wireless broadcast advantage and the amount of resources available. Simulation results show that this algorithm performs better than heuristics based on pruning a broadcast tree or shortest path trees.

Keywords wireless mesh networks · broadcast · multicast · routing · admission control · rate-diversity

1 Introduction

Recent experiences with the deployment of Wireless Mesh Networks (WMNs; e.g., the Roofnet [5] and TFA [6] projects) attest to their significant promise as an alternative, low-cost, fault-tolerant wireless access infrastructure for many novel applications [2]. The traffic capacity of such multi-hop wireless networks [13], however, continues to be an area of concern. It is becoming increasingly clear that individual WMN nodes should utilize the link/MAC layer *multi-rate capability*,

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especially as commodity 802.11-based cards already dynamically adjust the transmission rate on any wireless link by varying the modulation scheme. Although this multi-rate capability has been exploited for unicast transmissions [4, 11], there is still limited research on the applicability of this capability to broadcast and multicast scenarios. Note that while the current 802.11a/b/g standards mandate the broadcast transmission of control frames (e.g. RTS/CTS/ACK) at the lowest possible rate (e.g.,1 Mbps for 802.11b and 6 Mbps for 802.11a), broadcast transmission rates for data packets are currently implementation-specific.

As part of our ongoing work on the Aiolos project [1], we are investigating how this multi-rate capability of wireless radios can be exploited to better support network-layer *broadcast* and *multicast* traffic. We believe that high-speed WMNs will eventually serve as the transport network in many communities for several broadcast/multicast consumer applications (such as IP-TV or local content delivery, streaming of rich sensor feeds from security/traffic cameras, and multiplayer games); it is thus necessary to devise traffic routing algorithms that maximize the volume of broadcast/multicast traffic that may be supported by a WMN. In our previous work [9], we had considered the case of *a single broadcast flow* and demonstrated how link-layer rate diversity could be exploited to reduce the *broadcast latency* (defined as the maximum delay between the transmission of a packet by the source node and its eventual reception by all receivers) in a single-channel WMN. While this work helped establish the importance of exploiting rate-diversity for link-layer broadcasts, it did not consider the question of how such rate diversity affects the total *admissible network load.*

In this paper, we consider the more practical case of having *multiple* broadcast or multicast flows present in a *single-channel* WMN and address the following two questions:

- How does the potential transmission rate diversity impact the notion of how much broadcast traffic load can be *feasibly admitted* into the network?
- What sort of broadcast and multicast routing strategies can increase the amount of broadcast/multicast traffic loads that a WMN can accommodate, and what benefit (if any) does the use of link-rate diversity offer over the conventional approach of performing link-layer broadcasts at the lowest possible rate?

In particular, we shall devise algorithms that consider (a) the multi-rate operation of an individual WMN, (b) *wireless broadcast advantage (WBA)* [25] (whereby a single transmission reaches multiple one-hop neighboring nodes), and (c) the availability of sufficient resources, in terms of *available air-time fraction* (note that a node which uses a link-layer transmission rate of R bps to forward a flow with an offered load of t bps is said to occupy an air-time fraction of $\frac{t}{R}$), for a broadcast or multicast flow to be feasibly admitted. The principal objective is to *perform admission control and routing to maximize the total amount of broadcast or multicast traffic load that may be feasibly supported on a given WMN topology*. Accordingly, we should route an individual broadcast or multicast flow to the destination nodes such that it uses the minimally feasible network resources. Given this objective, this paper makes the following three contributions:

1. We derive a condition to test whether a broadcast or multicast flow can be feasibly admitted in a multi-rate WMN assuming an ideal MAC layer. This condition also enables us to define a measure of the residual transmission resource at each node in terms of air-time fraction. This condition proves to be applicable even when applied to a realistic environment utilizing a contention-based distributed MAC.
2. For network-wide broadcast traffic, we present and evaluate four heuristic tree construction algorithms that exploit transmission rate diversity, WBA and the residual air-time fraction to increase the amount of *total* traffic load that a WMN can carry.
3. For the practically important case of multicast traffic, we present and evaluate a receiver-driven heuristic for tree construction that exploits transmission rate diversity, WBA and the residual air-time fraction. The proposed algorithm admits almost twice as much traffic as an algorithm that is based on pruning broadcast trees.

The rest of this paper is organized as follows. Section 2 reviews the relevant related work. Section 3 details the interference-related capacity constraints for multicast link-layer transmissions and provides a sufficient condition for the admissibility of a broadcast or multicast flow in a multi-rate WMN. Section 4 describes the heuristic algorithms for constructing resource-aware broadcast trees and presents their comparative performance, as evaluated by Qualnet-based simulations. Subsequently, Section 5 describes and evaluates an heuristic algorithm for resource-aware multicast tree construction in WMNs. Finally, Section 6 concludes the paper with the important observations and discussion of open work.

2 Related work

A significant body of research in MANETs (Mobile Ad Hoc Networks) has researched *efficient* network layer multicast and broadcast, typically focusing on metrics such as energy consumption [7, 25], the number of transmissions (which is equivalent to energy consumption if transmission power cannot be adjusted) [19] or the overhead in route discovery and management [12]. For WMN, where the mesh nodes are largely static (e.g., rooftop or electric pole mounted) and may often be powered from AC outlets, the total acceptable traffic load is a more critical performance metric than routing overhead or energy. QoS-aware MANET multicast routing algorithms have so far focussed on improving the delivery reliability (by either using resource reservation over multiple wireless paths (e.g., [3]), or constructing a delivery mesh instead of a tree (e.g., [24, 27])), rather than focusing on the opportunities and challenges associated with link rate diversity and interference.

The problem of high throughput routing in WMN has been studied only for the case of unicast flows. The authors of [11] proposed a routing metric which can be used for a multi-channel, multi-hop WMN. The proposed WCETT metric takes different transmission rates into account by defining WCETT to be inversely proportional to the transmission rate. The work in [4] shows that if the interference range is infinity, then the unicast routing path that minimizes the total path delay will also maximize the throughput between the source and destination. To deal with multi-rate links, Awerbuch et al. [4] defines the rate-dependent medium-time metric (MTM), which measures the time it takes to transmit a packet over a multi-rate links including the transmission delay, overheads of the RTS/CTS/ACK frames and channel contention. In contrast to our focus on the network layer, the problem of maximizing the MAC-layer throughput for multicast transmissions (in the presence of different quality links and stability constraints) has been analyzed in [8].

We have previously studied the problem of low broadcast latency in multirate WMNs, for the single-channel case in [9] and for the multi-radio, multi-channel case in [22]. In particular, we presented an algorithm, based on the concept of *weighted connected dominating set (WCDS)*, that explicitly balances the wireless broadcast advantage (WBA) with rate diversity to achieve low-latency network-wide broadcast. However, Chou et al. [9] focused only on a single broadcast flow and does not address the problem of how individual flows should be routed to *maximize the total admissible volume of broadcast/multicast traffic* in the presence of inter-flow and intra-flow interference.

3 Interference modeling and feasibility analysis for rate-diverse transmissions

In this section, we present the impact of interference on the feasibility of broadcast flows for a single-channel WMN. The analysis presented here explains how a candidate node on the routing tree for a new broadcast flow F_j (with an associated offered load of L_j bits/s) can determine if it may feasibly forward the traffic for this flow using a link-layer broadcast rate ρ bit/s. This feasibility analysis will thus directly affect the formation of the broadcast forwarding tree (to be presented in Section 4). We make the following assumptions in our study:

- Each node is equipped with a single radio and operates on a single common channel.
- Each node transmits with a fixed maximum power but can transmit with different transmission rate by adjusting the modulation scheme. The transmission range is assumed to be a strictly decreasing function of the transmission rate. A binary packet reception model is assumed where, in the absence of interference, a node d can successfully receive a packet from a node s at rate r provided the distance between the two nodes d and s is less than or equal to the transmission range of transmission rate r.[1] This implies that, in the absence of interference, if a node d can correctly receive a packet from node s at rate r, then node d can also correctly receive a packet from node s using any available transmission rate lower than r. While we use a disc model for the transmission range as a basis for our discussion, the proposed algorithms are applicable to any generic, non-uniform or non-isotropic rate-range relationships. We assume that each node can transmit at rates chosen from $R = \{\rho_1, \rho_2, \rho_3, \ldots, \rho_k\}$, where the rates are arranged in ascending order such that $\rho_1 < \rho_2 < \rho_3 < \ldots < \rho_k$, and $d(\rho_i)$ denotes the transmission range for rate ρ_i.

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[1] The case where the channel condition is time-varying is left for future work.

- A node's "neighbors" are all the nodes that can be reachable using the lowest possible transmission rate ρ_1.
- Let $\{v_1, ..., v_l\}$ be a subset of the neighbors of a node v and the maximum rates that node v can use to reach these nodes individually are $\rho_1, ..., \rho_l$ respectively. The maximum rate that node v can use to reach $\{v_1, ..., v_l\}$ is $min(\rho_1, ..., \rho_l)$.
- We assume a binary interference model (which is similar to the protocol model of interference in [13]), where two nodes v_a and v_b mutually interfere if and only if $d(v_a, v_b) < \kappa \times d(\rho_1)$, where $\kappa > 1$. The distance $\kappa \times d(\rho_1)$ is known as the interference range. Again, this interference model is used solely for our simulation studies; alternative interference relationships do not affect our qualitative arguments.
- For formulating our feasibility criteria, we assume an ideal MAC layer as follows: Two nodes v_i and v_j can transmit at the same time iff node v_i's transmission does not interfere with the intended recipients of node v_j's transmission and vice versa.
- We assume that each network-layer broadcast and multicast flow consists of a constant bit rate flow.

We represent the entire WMN as a graph $G(V, E)$, with the mesh nodes forming the set of vertices V and the edge (which belongs to the set of edges E) representing the link between two neighboring nodes. A link $(v_a, v_b) \in E$ exists only if the distance $d(v_a, v_b)$ between nodes v_a and v_b is less than $d(\rho_1)$, and is associated with a rate ρ_{v_a,v_b}, the fastest feasible rate on (v_a, v_b). We denote multiple incoming point-to-multipoint flows as $F_1, F_2, F_3, \ldots, F_j, \ldots$, each with traffic load $L_1, L_2, L_3, \ldots, L_j, \ldots$ (where the traffic of a flow is modeled as a fluid arrival process[2]).[3] Each flow F_j represents the traffic generated from a given source node v_j to a set of destination nodes. If the destination set includes all mesh nodes except v_j, it is a *broadcast flow*; otherwise, it is called a *multicast flow*.

Definition 1 A link-layer multicast transmission $\tau(v_i, F_j)$ on node v_i for flow F_j is a two-tuple:

$$\tau(v_i, F_j) \triangleq \{\rho(v_i, F_j), N(v_i, F_j)\} \tag{1}$$

where $\rho(v_i, F_j) \in R$ denotes the transmission rate used by node v_i for flow F_j, and $N(v_i, F_j)$ denotes the set of *currently uncovered downstream* neighbors (uncovered set consists of nodes that v_i is trying to reach) that node v_i covers at rate $\rho(v_i, F_j)$ (i.e., the set of nodes $\{v_l : d(v_i, v_l) \leq d(\rho(v_i, F_j))$ and v_l is currently uncovered$\}$).

Note that a network flow (broadcast or multicast) consists of a number of such atomic link-layer multicast transmissions where each such atomic link-layer multicast transmission is associated with a non-leaf node (or transmitting node) on the flow-specific forwarding tree.

3.1 Definition and properties of broadcast interference

Given the broadcast nature of the wireless medium, the transmission $\tau(v_i, F_j)$ will interfere (or, equivalently, cannot occur simultaneously) with a set of other transmissions. In general, this set of interfering transmissions include transmissions by node v_i itself (i.e., transmissions for other flows where v_i is a non-leaf node), as well as transmissions by nearby interfering nodes. The inter-node interference for two transmissions $\tau(v_i, F_j)$ and $\tau(v_{\hat{i}}, F_{\hat{j}})$ (i.e. which means these two transmissions cannot occur simultaneously) occurs when $\tau(v_i, F_j)$ *interferes with the reception by any of the recipients* $N(v_{\hat{i}}, F_{\hat{j}})$, *or* $\tau(v_{\hat{i}}, F_{\hat{j}})$ *interferes with the reception by any of the recipients* $N(v_i, F_j)$. In particular, note that $F_{\hat{j}}$ and F_j may be the same flow—i.e., there may be intra-flow interference caused by different nodes on the forward tree for F_j.

Definition 2 For any link-layer multicast transmission $\tau(v_i, F_j)$, the interference set $Inter(\tau(v_i, F_j))$ denotes the set of other transmissions that cannot occur in parallel with transmission $\tau(v_i, F_j)$.

Figure 1 illustrates the nature of interference among several link-layer multicast transmissions, where circles of radius $R_I = \kappa \times d(\rho_1)$ represent the interference

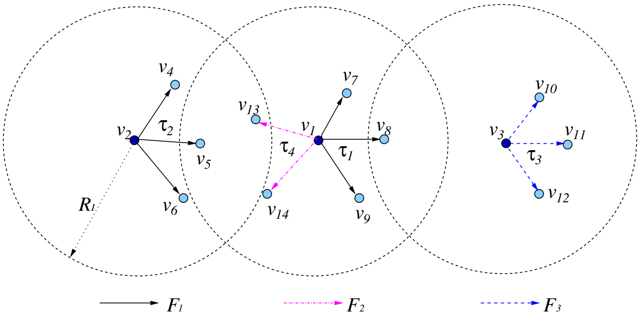

Figure 1 Example showing the interference among four link-layer multicast transmissions

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[2] Our analysis, which is aimed at understanding the fundamental issues associated with multi-rate transmissions, assumes that L_i represents the total traffic load of F_i, such that $\frac{L_i}{\rho}$ represents the total transmission time. For precise computation, L_i should be adjusted to include the various overheads (network, MAC, PHY) associated with a specific transmission technology.

[3] We also assume that the load for all flows are fixed and known before hand at the time of admission control and route establishment.

range. There are three flows F_1, F_2, F_3, three transmitting nodes v_1, v_2, v_3, and four multicast transmissions $\tau_1 = \tau(v_1, F_1)$, $\tau_2 = \tau(v_2, F_1)$, $\tau_3 = \tau(v_3, F_3)$, $\tau_4 = \tau(v_1, F_2)$. The *currently uncovered downstream* neighbors of these four transmissions are as follows $N(v_1, F_1) = \{v_7, v_8, v_9\}$, $N(v_2, F_1) = \{v_4, v_5, v_6\}$, $N(v_3, F_3) = \{v_{10}, v_{11}, v_{12}\}$, $N(v_1, F_2) = \{v_{13}, v_{14}\}$. We observe that τ_1 interferes with τ_2 at node v_5. This interference is intra-flow interference since they are both transmissions for the same flow F_1. We further observe that τ_1 and τ_4 compete for resources (or equivalently, interfere with each other) at the same transmitting node v_1, and τ_3 interferes with τ_1 at node v_8. These interference constraints imply that the multicast transmission τ_1 cannot happen simultaneously with any of the other three multicast transmissions. Note that the interference effects are *not symmetric*—e.g., while τ_3 interferes with τ_1 (at node v_8), τ_1 does not cause any interference to any of the receivers of τ_3. Also note that different transmissions from the same node can have different relationship with another transmission. For example, τ_3 interferes with τ_1 but τ_3 does not interfere with τ_4.

In order to model the interference relationship for a given transmission, we construct the conflict graph for this *transmission* and compute the maximal cliques in the conflict graph. Recall that a *clique* in a graph is a subset of vertices such that each pair of vertices is connected by an edge, or in other words, the subgraph is a complete graph. A clique that is not contained in any other cliques is defined as a *maximal clique*. We further define the *conflict graph* for a given transmission τ as $CG(\tau)$, whose vertices (including τ) correspond to transmissions that may cause interference with τ or be interfered by τ, e.g., set $\{\hat{\tau},\ \forall \hat{\tau} \in Inter(\tau)\}$. The conflict graph of τ_1 in Fig. 1, $CG(\tau_1)$, as well as the resulted maximal cliques, are illustrated in Fig. 2. We can see that there are two maximal cliques in this graph: maximal clique 1 includes τ_1, τ_2, and τ_4; maximal clique 2 includes τ_1 and τ_3. The intuition of Fig. 2 is that only one transmission (among the members of a maximal clique) may be active at any instant. For example, only one of τ_1, τ_2 and τ_4 can take place at an instance. Similarly, only one of τ_1 and τ_3 can take place at an instance. However, note that τ_3 can happen simultaneously with either τ_2 or τ_4.

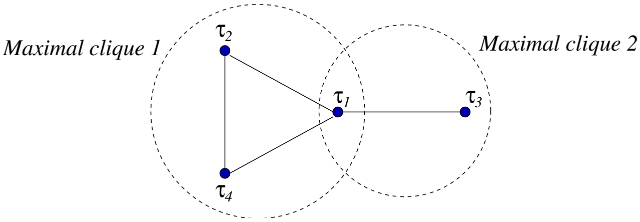

Figure 2 Conflict graph using maximal clique

It is important to note that this conflict graph is *transmission specific*—for example, if the transmission τ_1's transmission rate is modified such that $N(v_1, F_1) = \{v_7, v_9\}$, then it will no longer interfere with τ_3, resulting in a different conflict graph than Fig. 2. This is an important distinction from prior works such as [23, 26] on unicast traffic, where the vertices of conflict graphs represent *individual links* and the maximal cliques are transmission-independent. In the multicast environment, it is this dependency of the maximal cliques on the specific set of receivers (and thus, implicitly, on the link layer transmission rate chosen for the link-layer transmission) that makes the computation and enforcement of feasibility constraints harder.

To determine if transmission τ is feasible under this interference model, we transpose rate constraints to an *airtime constraint*—clearly, given the shared channel, the total fraction of airtime consumed by all the contending transmissions must be less than 1. To explicitly embody this constraint, we formally define the metric *transmission time fraction (TTF)* as follows:

Definition 3 Assuming that node v_i is a transmitting node of flow F_j, the transmission time fraction (TTF) for $\tau(v_i, F_j)$ is:

$$TTF(\tau(v_i, F_j)) = \frac{L_j}{\rho(v_i, F_j)} \tag{2}$$

where L_j denotes the load of flow F_j and $\rho(v_i, F_j)$ denotes the transmission rate selected by node v_i for flow F_j.

Given this definition, we can readily derive the *necessary* conditions on the airtime for the flows in Fig. 2 to be feasible:

$$TTF(\tau_1) + TTF(\tau_2) + TTF(\tau_4) \le 1 \tag{3}$$

$$TTF(\tau_1) + TTF(\tau_3) \le 1 \tag{4}$$

In general, these necessary conditions on the airtime for a set of flows in a conflict graph $CG(\tau)$ to be feasible can be expressed as follows:

$$\sum_{\tau' \in c} TTF(\tau') \le 1;\ \forall c \in C \tag{5}$$

where C is the set of all maximal cliques in conflict graph $CG(\tau)$.

The above conditions are necessary because we are using fluid approximation to a discrete problem. (similar necessary conditions exist also for unicast, see [17]). Alternatively, given a number of transmissions, it can readily be proved that these transmissions can take place simultaneously if and only if they belong to an independent set[4] of the CG. It was proved in [16] that a set of transmissions is feasible (or schedulable) if and only if it lies in the polytope of the independent sets of the CG. However, it is generally not feasible to apply this result in practice since the complexity to compute all independent sets grows exponentially with the number of nodes in a CG. Note that the number of nodes in a multicast CG is likely to be much larger than that of a unicast CG[5] and this makes the computation even harder.

In order to be able to determine the feasibility of a set of multicast transmissions, we will instead use a sufficient but not necessary condition. This condition may appear to be restrictive but our discrete event simulation (see Sections 4.2 and 5.1) shows that it can accurately predict the number of admission flows (observe that Eq. 5 ignores the fact that, in contention-based MACs [e.g., CSMA], channel accesscontention significantly reduces the capacity at high loads. Our restrictive admissibility criterion may thus prove to be less onerous than feared, as it implicitly compensates for our 'optimistic' ignoring of channel contention effects).

Theorem 1 *For a wireless mesh network with* p *point-to-multipoint flows* $F_1, \ldots, F_p$*. Flow* F_j *has a load of* L_j *and whose forwarding tree is* T_j*. Let* $\mathcal{NL}(T_j)$ *denote the set of non-leaf nodes for tree* T_j*. A sufficient condition for the flows* $F_1, \ldots, F_p$ *to be feasible is*

$$TTF\left(\tau\left(v_i, F_j\right)\right) \quad + \sum_{\tau' \in Inter\left(\tau\left(v_i, F_j\right)\right)} TTF(\tau') \leq 1 \qquad (6)$$

for all $v_i \in \mathcal{NL}(T_j)$ *and for all* F_j*. In other words, the feasibility of the flows requires that, for any link-layer multicast transmission* τ *in the network, the sum of TTF of the transmission* τ *and all of its neighbours in the conflict graph* $CG(\tau)$ *must be no more than* 1.

Note that Theorem 1 can also be expressed in terms of intra-flow and inter-flow interference. Equation 6 can equivalently be written as:

$$\begin{aligned} &TTF\left(\tau\left(v_i, F_j\right)\right) \\ &\quad + \sum\nolimits_{v_{\hat{i}}\,:\,v_{\hat{i}} \neq v \& v_{\hat{i}} \in \mathcal{NL}(T_j)\ \&\ \tau\left(v_{\hat{i}}, F_j\right) \in Inter\left(\tau\left(v_i, F_j\right)\right)} TTF\left(\tau\left(v_{\hat{i}}, F_j\right)\right) \\ &\quad + \sum\nolimits_{\hat{j}: 1 \leq \hat{j} \leq p \& \hat{j} \neq j} \sum\nolimits_{v_{\hat{i}}\,:\,v_{\hat{i}} \in \mathcal{NL}\left(T_{\hat{j}}\right)\ \&\ \tau\left(v_{\hat{i}}, F_{\hat{j}}\right) \in Inter\left(\tau\left(v_i, F_j\right)\right)} TTF\left(\tau\left(v_{\hat{i}}, F_{\hat{j}}\right)\right) \leq 1 \end{aligned} \qquad (7)$$

The second term in Eq. 7 accounts for the intra-flow interference experienced by the link-layer multicast transmission $\tau(v_i, F_j)$ while the third term accounts for the inter-flow interference.

The above theorem is a generalisation of Theorem 1 in [14] to the case of multi-rate multicast transmissions. The proof is similar to that in [14] and instead of providing a proof, we will discuss the insight behind the proof. The key idea behind the proof is to show that the vertex colouring problem of a corresponding graph $\tilde{G}$ can be solved provided that Eq. 6 holds. In fact, it can be showed that Eq. 6 implies that the number of colours available in the vertex colouring problem for $\tilde{G}$ is no less than the maximum node degree of $\tilde{G}$ plus one. Since the number of colours required for vertex colouring is upper bounded by the maximum node degree plus one, the vertex colouring problem can be solved.

An important consequence of our analysis is that determination of the *true feasibility* of a particular flow transmission requires maintenance of *flow-specific* state (knowledge of the conflict graph for each distinct separate transmission). In the next section, we shall see how this complicates the formation of a broadcast tree, by requiring each node to essentially maintain awareness of each distinct transmission that has been already scheduled within its interference region. Subsequently, in Section 5, we shall develop a less accurate node-centric feasibility metric for the case of multicast flows.

Finally, we would like to remark on two aspects of Theorem 1. Firstly, Theorem 1 gives a sufficient, but not necessary, condition for feasibility in scheduling

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[4] Given a graph (V, E) where V is the set of nodes and E is the set of edges. An independent set I is a subset of V such that no two elements in I are connected by an edge.

[5] Let Δ_i denote the out-degree of node v_i, then the maximum number of nodes in a unicast CG and multicast CG are, respectively, $\sum_{v_i \in V} \Delta_i$ (which is equal to the number of directed edges in the graph) and $\sum_{v_i \in V} (2^{\Delta_i} - 1)$.

link-layer transmissions. Secondly, Theorem 1 assumes perfect scheduling of link-layer multicast transmissions rather than distributed random access based on CSMA. In Sections 4 and 5, we will use discrete event simulations to demonstrate that the number of admissible flows predicted by Theorem 1 is close to the number of admissible flow in an IEEE 802.11 based WMN.

4 Heuristic broadcast algorithms

We first present the generic principle for the formation of a broadcast tree for a newly incoming flow. We assume that there are $j-1$ ($j \geq 1$) broadcast trees $\{T_1, \ldots, T_{j-1}\}$ already defined for the $\{F_1, \ldots, F_{j-1}\}$ flows in the network and describe the process of constructing the tree T_j for flow F_j. The broadcast tree formulation is top-down—i.e., we start from the source and selectively add forwarding (i.e. non-leaf) nodes to the broadcast tree.

The objective of the algorithms is to create *efficient* delivery trees in order to achieve the maximal *broadcast capacity*, where we define the *broadcast capacity* as *the total amount of network load (cumulatively over multiple flows) that can be feasibly admitted into the WMN*. As the load for all the flows are $L_1, L_2, L_3, \ldots, L_j, \ldots$, the metric for evaluating the 'goodness' of an algorithm is given by $\sum_{j\in\{1,2,3,\ldots J\}} L_j$ where F_J is the last flow to be feasibly admitted (satisfies the constraints of Eq. 6 at all forwarding nodes) and F_{J+1} cannot be feasibly admitted.

We defer for now the question of *selection metric*, i.e., the question of how to pick the next relaying node given an existing set of nodes for the partial tree T_j. Rather, we first demonstrate the process of verifying whether a new node (transmitting at a specific rate to a set of child nodes) is feasible. *Our philosophy is thus to incrementally build a top-down broadcast tree T_j that is feasible at all times*, avoiding the addition of any transmission τ that violates Eq. 6.

Let us assume that a number of nodes have been selected as transmitting nodes for flow F_j in previous tree construction steps. This means for a selected node $v_{i'}$, the transmission rate $\rho(v_{i'}, F_j)$ and the downstream neighbors $N(v_{i'}, F_j)$ for transmission $\tau(v_{i'}, F_j)$ have been determined. We are now trying to determine if node v_i can be selected as next transmitting node, i.e., if $\tau(v_i, F_j)$ with a transmission rate $\rho(v_i, F_j)$ and downstream neighbor $N(v_i, F_j)$ can be permitted. To verify this process, we consider all the possible transmissions of $\tau(v_i, F_j)$ with transmission rates $\rho_1, \ldots, \rho_k$. For any ρ_l, $l = \{1, \ldots, k\}$ to be feasible, it is essential that the corresponding airtime constraint for $\tau(v_i, F_j)$ be satisfied, i.e.,

$$\frac{L_j}{\rho_l} + \sum_{\tau' \in Inter(\tau(v_i, F_j))} TTF(\tau') \leq 1 \tag{8}$$

Given our desire to try to 'pack' as many flows into the WMN, it is natural to prefer nodes where the residual airtime fraction is higher (nodes whose neighborhood is less busy). Accordingly, we define the metric *residual transmission time fraction (RTTF)* for rate ρ_l associated with transmission $\tau(v_i, F_j)$ for flow F_j at node v_i as:

$$RTTF\left(\tau\left(v_i, F_j\right)|\rho_l\right) = 1 - \frac{L_j}{\rho_l} - \sum_{\tau' \in Inter(\tau(v_i, F_j))} TTF(\tau') \tag{9}$$

Note that, as before, the computation of $RTTF(\tau(v_i, F_j)|\rho_l)$ is dependent on not just the choice of the node v_i, but also the associated rate ρ_l (as $Inter(\tau(v_i, F_j))$ depends on ρ_l). It is also worth to note the difference between $\tau(v_i, F_j)$ in Eq. 9 and τ in Eq. 6. τ in Eq. 6 is a fixed transmission and hence its rate and downstream neighbors have been determined. In contrast, $\tau(v_i, F_j)$ in Eq. 9 is not fixed and we are in the process of determining if it is feasible on node v_i with a possible rate ρ_l. For feasibility of the candidate transmission $\tau(v_i, F_j)$, we need to check that

$$RTTF(\tau(v_i, F_j)|\rho_l) \geq 0 \tag{10}$$

Moreover, when selecting among alternative nodes for possible inclusion in the tree, we should clearly prefer "less congested nodes", i.e., nodes with higher $RTTF(\tau(v_i, F_j)|\rho_l)$.

4.1 Heuristic metrics for broadcast tree formation

Given our goal of maximizing the amount of admitted broadcast load, we should try to reduce the consumption of airtime by individual transmissions. In general, we thus want that (a) each transmission $\tau(v_i, F_j)$ by v_i uses as high a transmission rate as possible, and (b) the number of transmissions required to complete broadcast or multicast be minimized. Clearly, these two desires are mutually conflicting, since a faster rate implies a smaller coverage area, and consequently a larger number of individual transmissions.

We now present a selective set of heuristics for computing the tree T_j based on the notion of a connected

```
Input  : $G(V, E)$, $s$ – source node for the given flow $F_j$,
         $R = \{\rho_1, \rho_2, \rho_3, \ldots, \rho_k\}$.
Output: The broadcast tree $T$ for the given flow $F_j$.
$Z = \{s\}, T = \emptyset$ ;
while ($V \setminus Z \neq \emptyset$) do
    $candidate = \emptyset$ ;
    for $v_i \in Z$ do
        for each possible $\rho(v_i, F_j) \in R$ do
            $\rho = \rho(v_i, F_j)$;
            Compute $f(\tau(v_i, F_j))$; /* Different $f(.)$ for WCMA, MRA and RCA. */
            if $\tau(v_i, F_j)$ is feasible for rate $\rho$; then
                $candidate = candidate \cup \tau(v_i, F_j)$
            end
        end
    end
    $\hat{\tau}(v_{\hat{i}}, F_j) = \text{argmax}_{\tau(v_i,F_j)\in candidate} f(\tau(v_i, F_j))$;
    if $\hat{\tau}(v_{\hat{i}}, F_j) = \emptyset$ (no feasible transmission found) then
        return $\{T = \emptyset\}$; /* The flow cannot be admitted */
    else
        Select $\hat{\tau}(v_{\hat{i}}, F_j) = \{\hat{\rho}(v_{\hat{i}}, F_j), N(v_{\hat{i}}, F_j)\}$ as next transmission for flow $F_j$
        $Z \leftarrow Z \cup N(v_{\hat{i}}, F_j)$;
        $T \leftarrow T \cup (\cup_{a \in N(v_{\hat{i}}, F_j)} \{(\hat{i}, a)\})$;
    end
end
```

Algorithm 1 The broadcast tree formation process

dominating set (CDS). Recall that for a graph $G(V, E)$ with set of vertices V and set of edges E, a CDS Z of G is a subset of V such that (1) Every element (node) of $V \setminus Z$ is in the neighborhood of at least one node in Z; (2) The set Z is connected. In this paper, we extend the WCDS (Weighted CDS) algorithm presented in [9] for constructing an minimum CDS-based broadcast tree in a multi-rate WMN. Our heuristic algorithms start by making the source node s for F_j eligible to transmit, and setting Z (denoting the set of covered nodes) to $\{s\}$. We say that a node is 'covered' if it is within the transmission range of a node $v \in Z$, given v's current link rate. In each round of the algorithm, we choose the $\tau(v_i, F_j)$ combination for a node $v_i \in Z$ that *maximizes* some objective function $f(\tau(v_i, F_j))$ (and, of course, does not violate the constraints of Eqs. 10). Algorithm 1 illustrates the overall design for all the algorithms, with the computation of $f(\tau(v_i, F_j))$ being the sole point of difference among all the heuristics. In all cases, the tree formation process may terminate at an intermediate point if no additional feasible transmission is found. In such a case, we reject the admission of incoming flow F_j.

We have evaluated 6 different choices of the metric $f(\tau(v_i, F_j))$ in our study. We will present the results on four of them below; for results on the other metrics, the reader can refer to [18]. The first algorithm, called the *weighted coverage maximization algorithm (WCMA)*, calculates the cost of a candidate transmission $\tau(v_i, F_j)$ as follows:

$$f_{WCMA}\left(\tau\left(v_i, F_j\right)\right) = \left|N\left(v_i, F_j\right)\right| \times \rho\left(v_i, F_j\right) \qquad (11)$$

This is identical to the WCDS metric in [9], except for the additional step of verifying that the chosen rate satisfies the feasibility constraints.

The second algorithm considers only the effect of interference on a single transmission. The transmission rate is fixed with the lowest rate (e.g., 6 Mbps for IEEE 802.11a radio). This algorithm is called the *maximum RTTF algorithm (MRA)* and tries to select the transmission that results in the maximum residual airtime.

Table 1 Radio range for IEEE802.11a

Transmission rate (Mbps)	Transmission range (m)
6	170.62
9	152.07
12	120.79
18	95.95
24	67.93
36	42.86
48	27.04
54	24.10

Table 2 Average number of admissible broadcast flows for each heuristic

Heuristic	Average number of admissible broadcast flows
WCMA	6.5
MRA	3.7
WMRA	6.5
RCA	8.2

Accordingly, the cost of a candidate transmission $\tau(v_i, F_j)$ is given by:

$$f_{MRA}\left(\tau\left(v_i, F_j\right)\right) = RTTF\left(\tau\left(v_i, F_j\right) \mid \rho\left(v_i, F_j\right)\right) \qquad (12)$$

By selecting the (node, rate) combination with the largest $RTTF$ value, this heuristic tries to maximize the *residual* airtime, with the expectation that this will eventually allow more future transmissions to be admitted.

The third algorithm, called the *weighted maximum RTTF algorithm (WMRA)* balances the desire to select the transmission with the maximum residual airtime and higher transmission rate. The cost function of a candidate transmission $\tau(v_i, F_j)$ is thus computed as:

$$f_{WMRA}\left(\tau\left(v_i, F_j\right)\right) = \rho\left(v_i, F_j\right) \times RTTF\left(\tau\left(v_i, F_j\right) \mid \rho\left(v_i, F_j\right)\right) \qquad (13)$$

Note that in WMRA, the rate selected must cover at least one uncovered neighbor. WMRA may be viewed as the generalized, rate-diversity aware, version of MRA.

Finally, the fourth algorithm, called the *RTTF-aware coverage algorithm (RCA)*, computes the cost of a candidate transmission $\tau(v_i, F_j)$ as follows:

$$f_{RCA}\left(\tau\left(v_i, F_j\right)\right) = \left|N\left(v_i, F_j\right)\right| \times \rho\left(v_i, F_j\right) \times RTTF\left(\tau\left(v_i, F_j\right) \mid \rho\left(v_i, F_j\right)\right) \qquad (14)$$

Intuitively, the RCA algorithm tries to balance the competing objectives of interference minimization (favoring nodes with larger $RTTF$), link rate maximization (to reduce broadcast latency), and coverage of currently uncovered nodes (favoring transmissions that cover more nodes in the broadcast tree).

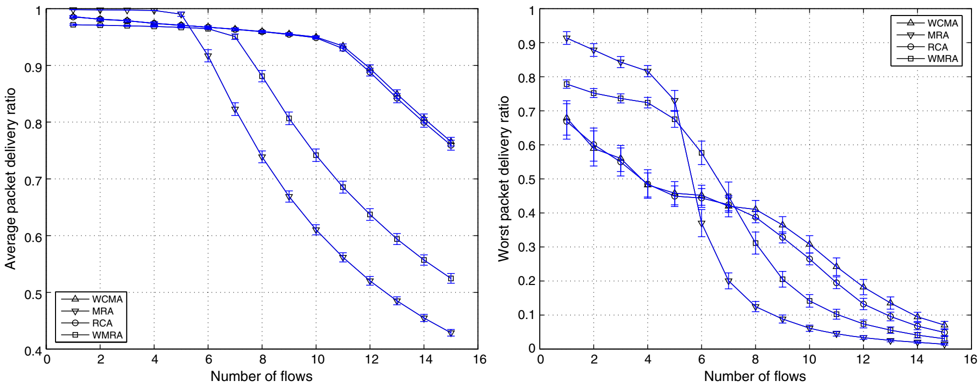
4.2 Simulations with IEEE 802.11a

In this section, we present results on using discrete event simulator Qualnet [20] with IEEE 802.11a radios on: (1) The comparison of performance (in terms of throughput, packet delivery rate and latency) of the three heuristics WCMA, MRA and RCA proposed earlier; and, (2) The accuracy of using Eq. 10 to determine the number of admissible flows.

The simulations are carried out using 50 different topologies with 150 nodes randomly distributed in an area of 1 km^2. We first determine the number admissible flows predicted by Eq. 10 for each heuristic. This is done by first determining the transmission range and interference range for each transmission rate of IEEE 802.11a. The transmission range for each given rate is given in Table 1 and is derived from Qualnet [20] with two-ray ground propagation model and fixed transmission power of 16 dBm (note: this is equivalent to 40 mW, which is the standard maximum power for 5.15–5.25 GHz band [15]). For each topology, we generate 15 broadcast flows with an offered load of 0.1 Mbps by randomly picking their source node. We then apply the flows one by one to the network until Eq.10 is violated. The average number of admissible flows for each heuristic over the 50 topologies is summarised in Table 2.

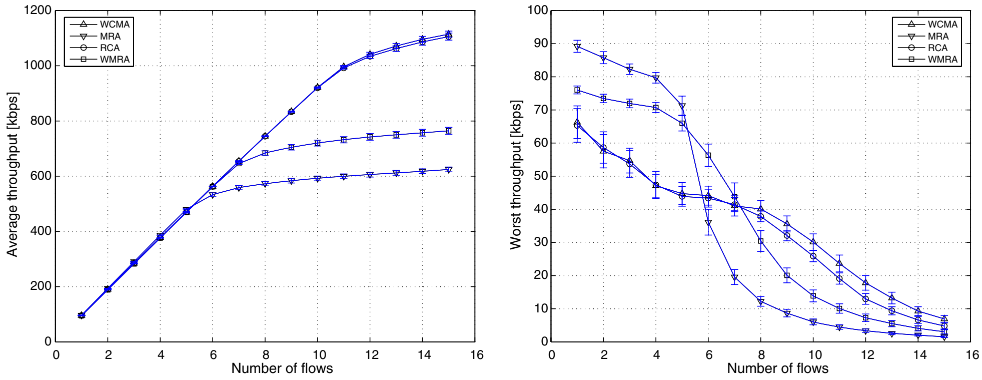
In order to test the accuracy of using Eq. 10 for admission control, we import the topology and flow data (which is discussed in the previous paragraph) into the discrete event simulator Qualnet. In our simulation,

Figure 3 Packet delivery ratio comparison



a Average packet delivery ratio **b** Worst packet delivery ratio

Figure 4 Network throughput comparison



a Average network throughput **b** Worst network throughput

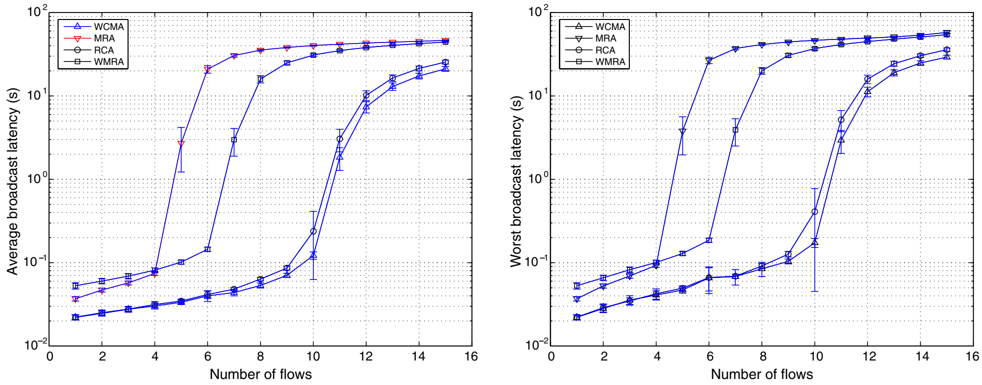
for each topology, we study the network performance as the number of flows varies from 1 to 15 where the two extremes are, respectively, well below and well above, the network's capacity. Note that in order to test the network performance when the number of flows exceeds the number of admissible flows, we have suspended the use of using Eq. 10 when the number of flows is greater than what is admissible.

We use three performance metrics—*packet delivery ratio, broadcast latency, and network throughput*—in our simulation study. We will show both the average (i.e. over all flows and all nodes) and worst case performance. For packet delivery ratio (or throughput), the worst case performance occurs at the node with the lowest packet delivery ratio (or throughput) for all flows. Figures 3, 4 and 5 show the behaviour of these three performance metrics with number of flows varying from 1 to 15. It can be seen from these figures that the three heuristics that use multiple transmission rates (i.e. WCMA, RCA and WMRA) out-perform MRA (which uses the lowest rate only) in all the three performance metrics. Although the performance of WCMA and RCA are very similar for all three performance metrics as the number of broadcast flows is varied in the simulation, the application of the feasibility constraint in Eq. 10 results in the admission of a significantly smaller number of flows by WCMA, compared to RCA. In other words, the application of the admission control strategy is much more accurate and robust under RCA, compared to its use under WCMA. Of course, the performance gains from RCA are not as spectacular for broadcast traffic: as, by definition, a broadcast flow must reach *all* WMN nodes, we do not have the ability to *route around* areas of high load. The results illustrate two important points:

- *Using link-layer transmission rate diversity as part of the broadcast routing process (i.e, WCMA, RCA, WMRA) achieves significantly higher capacity, as opposed to rate diversity unaware algorithms (i.e., MRA).*
- *A rate diversity-aware approach (i.e. WCMA or WMRA) that does not factor in the existing level of traffic load on the wireless channel will admit a smaller amount of broadcast traffic that a scheme (i.e., RCA) that is additionally intereference-aware.*

If we use the on-set of sudden increase latency in Fig. 5 to determine the number of admissible flows as

Figure 5 Broadcast latency comparison



a Average broadcast latency **b** Worst broadcast latency given by discrete event simulation, then both WCMA and RCA can admit 9 broadcast flows in the network. A comparison against Table 2 shows that the RCA accurately predict the number of flows that would be admissible in practice (before the performance degradation increases rapidly), while WCMA under-estimates the number of flows that can actually be admitted. We therefore conclude that RCA is the best broadcast algorithm out of all those that we have studied because it gives an accurate prediction on the number of flows admitted and it gives the best performance under practical MAC layers.

Finally, note that we have also performed similar studies using 802.11b radios; the results obtained are qualitatively similar and omitted here for reasons of space.

5 Rate and contention aware multicast

We now consider the more practical problem of constructing similar routing trees for multicast flows. Unlike all earlier work on multicasting, we aim to build a multicast tree that explicitly factors in the three unique WMN features—(a) the ability of nodes to operate at different link rates; (b) the impact of interference on the available (bandwidth) capacity of a WMN node, and (c) the WBA. While the capacity gains in multicasting are expected to be higher, the key difficulty in extending the accurate interference-aware approach (embodied by the RTTF metric of Eq. 9) to multicast flows is that the broadcast tree formation algorithms are *greedy*—i.e., they compute the tree starting at the source and greedily select add nodes to the tree, corresponding to the "best subsequent" transmission. In contrast, the multicast tree cannot be built greedily, since nodes should only be added if they extend the tree towards one of the receivers (most distance-vector algorithms, such as Dijkstra, cannot solely compute the shortest path to a specific destination node v_d from a source v_s, but instead, reconstruct the shortest path by backward traversal after computing a larger set of shortest paths). While one approach for multicasting may thus be based on pruning (i.e., first create the broadcast tree, and then simply prune all unnecessary edges), this is likely to be unsatisfactory. In particular, by assuming that all neighboring nodes need to receive a transmission, the broadcast tree formation process may have incorrectly excluded some (link, rate) combinations.

Accordingly, we have devised the *rate and contention aware multicast algorithm* (*RCAM*) (mathematically outlined in Algorithm 2) with the following intuition. The multicast tree will be constructed incrementally taking into account the rate, time fraction usage, and WBA. We assumed that the set of Q multicast receivers $\{mr_1, ..., mr_Q\}$ are known at the start of the tree formation process. In the first step, we find the least-cost unicast path from source s to any member, say mr_α, of the set of Q receiver nodes, assuming, for now, an arbitrary link cost $c(v_a, v_b)$ for any link (v_a, v_b) (the actual definition of the link cost $c(.)$ will be provided shortly). In general, the higher the rate for the edge (v_a, v_b), the smaller should be the link cost. However, to balance the link cost with the level of channel contention, $c(v_a, v_b)$ needs to also account for the amount of residual airtime in the neighborhood of (v_a, v_b). The most accurate determination of this contention is given by the metric $RTTF$ (see Eq. 9), which however, depends on the precise receiver set for a specific transmission $\tau(.)$. As this is not possible for multicast as the relevant downstream receivers are not known a-priori, we instead define a *flow-independent* metric *cumulative transmission time fraction (CTTF)* for a node v_i as:

$$CTTF(v_i) = \sum_{l=1}^{j-1} \sum_{v_m \in V} \frac{L_l}{\rho(v_m, F_l)} I(v_i, v_m, F_l) \tag{15}$$

where $I(v_i, v_m, F_l)$ is an indicator function that equals 1 (otherwise 0) if: (v_m is a transmitting node for tree T_l) $\wedge$ (v_m or at least one of the receivers in $N(v_m, F_l)$ is within the interference range of v_i). In other words, $CTTF(v_i)$ defines the cumulative airtime usage (across all prior scheduled transmissions) in the interference range of v_i.

To account for interference, the link cost $c(v_a, v_b)$ is modified to be a function of both the link speed $\rho(v_a, v_b)$ and the most critical airtime constraint in v_a's vicinity. Thus,

$$c(v_a, v_b) = \frac{1}{\rho(v_a, v_b)} \times \frac{1}{1 - \max_{d(v_a, v_l) \leq \kappa \times d(\rho_1)} CTTF(v_l)} \tag{16}$$

Moreover, if $CTTF(v_i) + \frac{L_j}{\rho(v_a, v_b)} > 1$, then $c(a, b)$ should equal ∞ to reflect the fact that this link, although physically present, is unusable due to airtime constraints.

While such a formulation accounts for the rate diversity, RCAM also needs to account for the WBA. In particular, if a node v_a has already been chosen to as a forwarding node of the tree T_j, it follow that any node v_b in the neighborhood of $\tau(v_a, F_j) = \{\rho(v_a, F_j), N(v_a, F_j)\}$ (i.e., $v_b \in N(v_a, F_j)$ iff $\rho(v_a, v_b) \geq \rho(v_a, F_j)$), can receive the packet for free due to WBA. This is reflected by setting their cost $c(v_a, v_b)$ to 0 (label 1 in

```
**Input** : $G(V, E)$, source node $s$, list of receivers $\{mr_1, mr_2, \ldots, mr_Q\}$, load $L$, cumulative
            transmission time fraction $\{CTTF(v)\}$
**Output**: The multicast tree $T$
$T = \emptyset$, $A = \{s\}$ ;
for $v \in V$ do
    $CTTFmax(v) = \max_{u:\text{ (v, u) interfere}} CTTF(u)$ ;
end
for $(a, b) \in E$ do
    maxCont= max(CTTFmax(a), CTTFmax(b)) ;
    if maxCont + $\frac{L}{\rho(a,b)}$ < 1 then
        $c(a, b) = 1/(r(a, b) \times (1 - maxCont))$
    else
        $c(a, b) = \infty$
    end
end
for p = 1 to $Q$ do
    /*$SP$ computes the shortest path from the set $A$ to $m_p$, using $c(a, b)$
      as the cost function.                                              */
    minpath = $SP(A, m_p, \{c(a, b)\})$;
    $T = T \cup \{(v, u) \in minpath\}$;
    for $(v, u) \in E : v \in T$ && $d(v, u) \leq d(\rho(v))$ do
        label 1: $c(v, u) = 0$; $A = A \cup u$;
    end
end
if $T$ is valid i.e., if $T$ does not violate airtime constraints then
    Return $T$;
else
    Return $\emptyset$; //No valid multicast tree found
end
```

Algorithm 2 RCAM algorithm

Algorithm 2). After this adjustment, the RCAM algorithm proceeds iteratively by selecting the next receiver node having the least-cost unicast path among the remaining receivers (e.g., selecting mr_β next) and grafting this path onto the existing multicast tree (the set A in Algorithm 2). To perform this grafting, RCAM selects the least-cost feasible path from the receiver to any member of A. Note that due to the inaccurate formulation of $CTTF(v_i)$, it is possible that the final computed tree T_j may actually be infeasible (i.e., it may violate one of the constraints of Eq. 6). In particular, this may happen when a (node,rate) pair selected to be part of the tree at a later point in the tree formation process turns to cause the Eq. 6 to be violated at some previously chosen forwarding node. Accordingly, RCAM performs a final feasibility check on the whole tree T; if it is found to be infeasible, the entire multicast flow is rejected.

5.1 Simulations with IEEE 802.11a

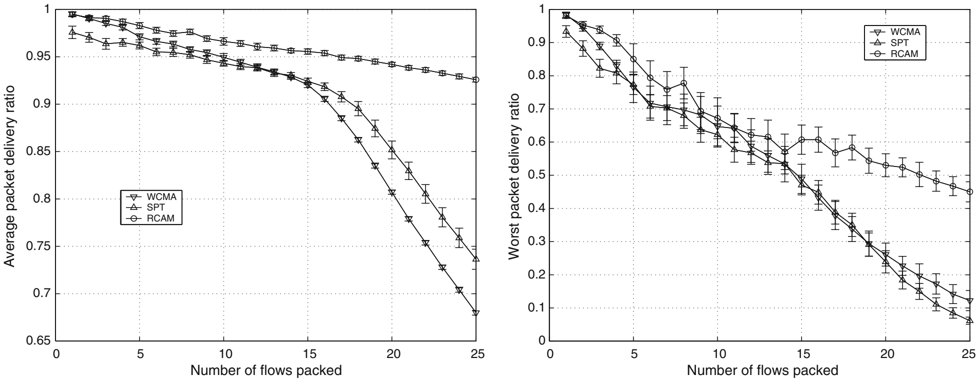
In this section, we compare the performance of RCAM against two alternative algorithms that do not consider interference effects: (a) The *Pruning* algorithm, where the broadcast tree is first constructed by WCMA and all un-necessary nodes are subsequently pruned. (b) The conventional *shortest path tree (SPT) algorithm*, where the tree is formed by merging the shortest unicast path (with a link's cost being the inverse of its transmission rate) from source to each individual multicast receiver.

Similar to the study carried out in Section 4.2, we are interested to compare the performance of these heuristics in terms of packet delivery ratio, throughput, latency as well as their ability to predict the number of admissible flows. We perform simulation with 50 network topologies with 400 nodes uniformly randomly

Table 3 Average number of admissible multicast flows for each heuristic

Heuristic	Average number of admissible multicast flows
WCMA followed by pruning	10.0
SPT	14.0
RCAM	24.5

Figure 6 Multicast packet delivery ratio comparison



a Average packet delivery ratio **b** Worst packet delivery ratio

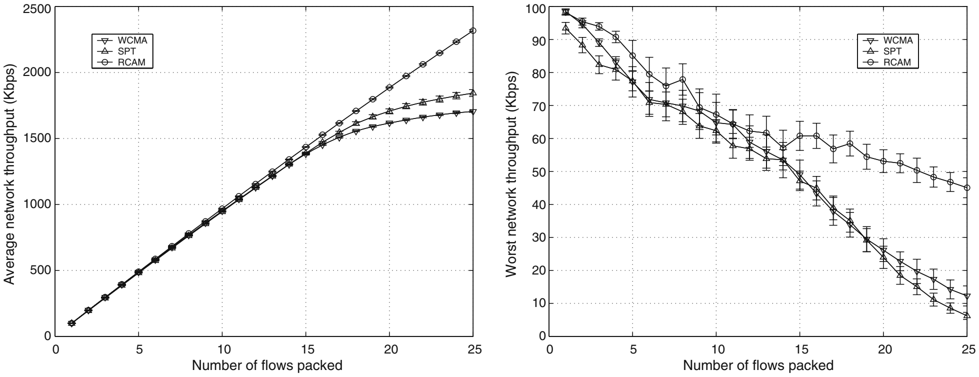
distributed on a 1.5 × 1.5 km area. In order to test how well the heuristics predict the number of admissible multicast flows, we vary the number of flows from 1 to 25. Each flow has an offered load of 0.1 Mbps and has 5 multicast receivers which are randomly selected from the mesh nodes. By using the transmission ranges and interference range of IEEE 802.11a (see Table 1), the average number of admissible multicast flows for each of the heuristics is summarised in Table 3.

Figures 6, 7 8 show the performance of three heuristics in terms of packet delivery rate, throughput and latency. Both the average and worst case scenarios are plotted in these figures. It can be seen from these Figures that RCAM out-performs both SPT and WCMA followed by pruning. We attribute this performance gain to RCAM's ability to route around hotspots by taking $CTTF$ (note that $(1 - CTTF)$ used in Algorithm 2 has similar meaning as $RTTF$) into account when choosing forwarding nodes on a new multicast tree. As a consequence, congestion 'bottlenecks' are significantly reduced, leading to the ability to accommodate higher loads without significant performance degradation. On the contrary, WCMA and SPT cannot route around the network 'hotspots' or bottlenecks during the multicast tree formation process because they do not consider $CTTF$ (or more accurately, $(1 - CTTF)$). Consequently, as the number of flows increases, the network is subject to several contention 'bottlenecks'; as is well known, channel contention significantly increases the frequency of collision-induced losses and MAC-layer backoffs, leading to sharply higher packet loss rates and latency.

Figure 9 shows how the network throughput changes according to the number of multicast receivers. The dashed lines show the network throughput predicted by using Eq. 10 while the solid lines show the throughput obtained from the discrete event simulation. It can be seen that the prediction by Eq. 10 is very accurate and that RCAM again outperforms the other two algorithms. The figure also shows that the network throughput achievable for higher number of multicast receivers is smaller. This occurs because there are fewer opportunities for the algorithm to route around 'hotspots' when the number of receivers is higher.

Finally, Figs. 3 and 6 highlight an important performance problem for broadcast and multicast flows in multi-hop WMN. For example, even though the

Figure 7 Multicast network throughput comparison



a Average network throughput **b** Worst network throughput

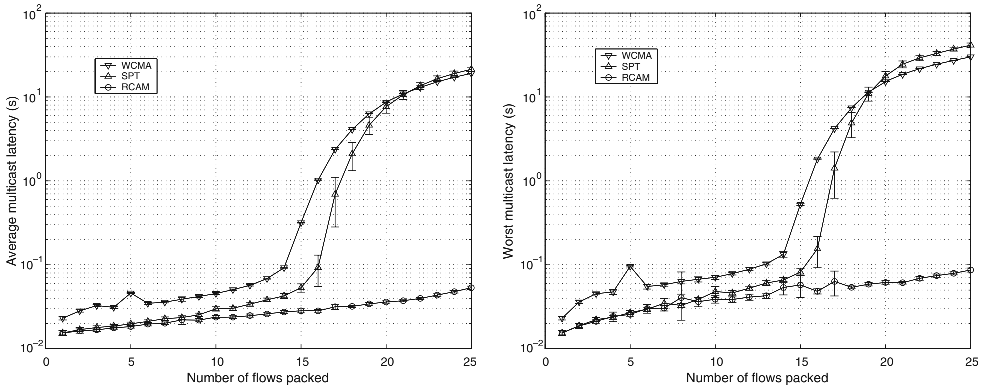


Figure 8 Multicast latency comparison

a Average multicast latency

b Worst multicast latency

average packet delivery rate for broadcast flows in Fig. 3a can remain high (above 90%), the corresponding *worst case* packet delivery rate can be low (about 70-80%). Figure 6 shows similar behaviour for multicast flows. This performance problem is due to the lack of reliable link-layer multicast delivery mechanism in IEEE 802.11 (Note: IEEE 802.11 uses 4-way handshake consisting of RTS/CTS/DATA/ACK to enhance the reliability of link-layer unicast frame transmissions, but a link-layer multicast transmission in IEEE 802.11 uses only carrier sensing to avoid collision.) and the accumulation of packet loss as packets propagate down the delivery tree. We plan to address this performance deficiency in our future work by developing a more reliable MAC layer broadcast technique and a multicast algorithm which exploits this reliable MAC layer broadcast technique.

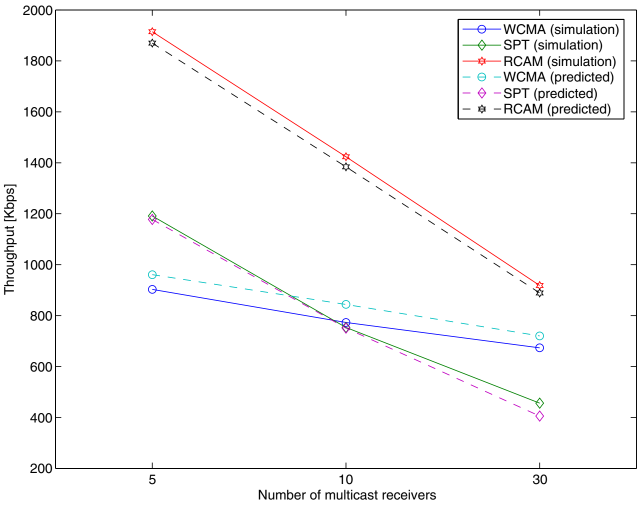


Figure 9 This plot shows how network throughput varies with the number of multicast receivers

6 Concluding remarks and future work

We have demonstrated that the combined consideration of link-rate diversity and channel interference can significantly increase the amount of broadcast/multicast traffic load that may be feasibly admitted and routed within a WMN. From a theoretical standpoint, we have established how the accurate formulation of contention-aware capacity constraints for wireless multicast involves the notion of maximal cliques in a conflict graph, where each vertex of the graph represents a specific (node, flow) transmission, instead of a 'link'. As a consequence, the accurate computation of feasibility requires the maintenance of per-flow state at every WMN node, and consequently incurs high computation complexity. For network-wide broadcast traffic, the RCA heuristic algorithm provides up to 78% of improvement in the total broadcast capacity (total feasible load) by choosing transmissions that balance between high link rates, greater node coverage and low channel contention. Extensive simulation studies with both 802.11a and 802.11b models confirm that the joint utilization of link-layer transmission rate diversity and interference-aware residual capacity is vital for maximizing the broadcast traffic load in WMN environments.

For multicast flows, we have presented the RCAM algorithm, which is able to significantly increase the amount of admissible multicast traffic on a WMN by exploiting both the transmission rate and the available (contention-free) airtime at individual nodes. This result is of great practical significance to many real-life applications (e.g., games, video-conferencing). We are currently working to develop more practical, *distributed tree formation* algorithms based on the heuristics presented in this paper. In addition, the development of *robust* multicasting and broadcasting strategies, that exploit rate diversity to improve latency but are also less vulnerable to wireless packet losses, is another aspect of our future research. Finally, for the case where all the nodes in a network can use only one link-layer transmission rate (similar to the framework introduced in [21]), we have studied the impact of the choice of the network-wide link-layer transmission rates on the performance of broadcast and multicast in [10].

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