Technical Report WINLAB-TR-289

IRMA: Integrated Routing and MAC Scheduling in Multi-hop Wireless Mesh Networks

Zhibin Wu, Sachin Ganu and Dipankar Raychaudhuri

Rutgers University

July, 2006

RUTGERS WIRELESS INFORMATION
NETWORK LABORATORY
Rutgers - The State University of New Jersey
Technology Centre of New Jersey
671 Route 1 South
New Brunswick, New Jersey 08902-3390
Phone: (732) 932-6857 Ext. 614
FAX: (732) 932-6882

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ABSTRACT

This paper presents an integrated routing and MAC scheduling algorithm (IRMA) for improving system performance in multihop wireless mesh networks. The IRMA approach is motivated by the fact that conventional contention-based MAC protocols such as 802.11 do not perform well in combination with independent ad hoc routing protocols such as DSR, DSDV or AODV due to interactions between neighboring nodes in the network. In IRMA, a centralized algorithm is used to allocate resources to each flow based on traffic flow specifications and the network compatibility graph based on a generalized n-hop interference model. Joint routing and MAC eliminates contention between radio nodes and assigns traffic flows to alternate paths based on actual traffic demand, thereby providing significant increases in network capacity. Two alternative algorithms are described and evaluated using ns-2 simulations: 1) Link Scheduling with Min Hop Routing (IRMA-MH) which uses real-time flow information to select paths and to set up complete end-to-end TDMA schedules; 2) Link Scheduling with Bandwidth-Aware Routing (IRMA-BR) which uses local information about available MAC bandwidth to route around congested areas. Simulation results for both schemes are presented, showing up to 300% improvement in network throughput when compared with baseline 802.11-based multihop networks with independent routing.

Acknowledgements

This work is supported in part by NSF NRT ORBIT Testbed Project, NSF NRT Grant ANI-0335244

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1. Introduction

1.1 Motivation

Recent “Moore’s Law” improvements in short-range radio cost performance have led to consideration of multi-hop “mesh networks” with extended range and network coverage. Such mesh networks may be used for applications such as community networks [1][2], rural telephony [3], urban broadband access [4] and home networks [5][6]. The IEEE 802.11s Task Group [7] is also currently involved in efforts to standardize protocols for wireless mesh networks and it may be expected that this technology will become mainstream over the next few years. The baseline design of a mesh network uses a layered implementation of MAC and routing protocols, for example 802.11 MAC in combination with routing protocols, such as AODV [8], [9] or [10].

However, the overall performance achieved by current layered implementations of multi-hop 802.11-based mesh networks is still significantly lower than the underlying channel capacity. This primarily arises from the fact that the wireless medium is inherently a shared resource where every station in a given neighborhood contends in a distributed manner to gain access to the medium. Several problems arise due to lack of coordinated access to the channel: hidden nodes contending for the channel [11], the exposed node problem resulting in poor spatial reuse due to channel sensing-induced backoffs in the extended neighborhood of an ongoing transmission [12], self-interference among packets of the same flow at each hop along the path [13].

The above considerations motivate the integrated MAC scheduling and routing (IRMA) approach proposed in this paper. The main idea is to avoid intra-flow and inter-flow contentions by creating a conflict-free schedule based on traffic demand across all end-to-end routed paths. Global optimality can be approached by allocating schedules and paths simultaneously for each of the source-destination pair traffic in the network. This approach eliminates the contention based channel access latencies and the multiple collisions that may occur due to hidden terminals in a multi-hop wireless networks. Joint route selection and link-scheduling has the following advantages for mesh networks:

1. Provides for contention-free transmissions by replacing random access with scheduled

access.

2. Assignment of channel bandwidth to source-destination pairs based on actual traffic requirements, thereby avoiding wastage of bandwidth with fixed TDMA slot assignments.

3. Selection of routing path based on the link quality and available bandwidth, thereby helping route around congested areas.

We consider two alternative joint MAC/routing algorithms: 1) Link Scheduling with Min Hop Routing (IRMA-MH) which uses real-time flow information to select paths and to set up complete end-to-end TDMA schedules; 2) Link Scheduling with Bandwidth-Aware (IRMA-BR) Routing which uses local information about available MAC bandwidth to route around congested areas. Using detailed simulation models with a generalized n -hop radio interference model, we will demonstrate significant performance improvements over baseline 802.11-based mesh networks.

The remainder of the paper is organized as follows: Section II describes prior work related to optimization of MAC scheduling and routing. Chapter II gives the system model, interference model and protocol overview. In Section IV, we formulate an optimization model for maximum achievable network throughput given input flow specifications and topology, and then propose two heuristic approaches that closely match the performance of the centralized optimization algorithm. Section V discusses the simulation methodology and presents performance evaluation results for IRMA. Conclusions and future work are given in Section VI.

1.2 Related Work

Several approaches have been proposed to improve the performance of mesh networks which use 802.11 CSMA/CA MAC [14] as the basis. These include tuning the carrier-sense range [15], enhancing local coordination [16][17][18] or using out-of-band control messages [19][20] to increase the utilization of the channel. Also, in parallel, there have been several cross-layer routing metrics proposed to incorporate MAC contention and interference effects into the path selection [21][22]. However, path selection using these metrics tends to mask the underlying inefficiencies of the MAC by finding an alternate path with a lower metric and does not succeed in eliminating the basic problem related to the interference.

Also, the problem of link scheduling across a single channel in a multi-hop radio networks has been long regarded as equivalent to either “vertex-coloring” or “edge-coloring” problems [23][24][25][26]. Several distributed MAC schemes [27][28] have been proposed to set-up interference-free TDMA schedules. However, those approaches tend to give equal channel access chances for each flow regardless of the traffic demand, which may not optimal for end-to-end performance.

A theoretical basis for integrated optimization of routing and link scheduling on demand was first explored in [29]. More recently, the global optimization of link scheduling and routing has been studied by [30][31], which provides an upper bound to the capacity of specific multi-hop network topologies with specific traffic patterns and loads. However, these contributions are limited to upper-bound calculations rather than evaluation of a specific protocol and related integrated routing/scheduling algorithm. In this work, we outline a system model, protocol framework and related algorithms for integrated routing and scheduling in a mesh network with generalized radio interference models.

2. Integrated MAC/Routing Framework

In this chapter, we briefly introduce our system model, the radio interference model and its implications for joint MAC scheduling/routing design.

2.1 System Model and Assumptions

We consider a homogeneous wireless mesh network. Each node in the network only has one radio interface and shares a common channel. In the future, we plan to extend our model to multiple channels. Each radio has the same transmission power, P_{tx}, to cover the same transmission range and we also assume the network is globally synchronized. There is a central entity which collects the following information:

- Connectivity matrix of the network topology
- Source - destination pairs and their respective traffic demands.

Based on those inputs, the centralized process will run optimization algorithms to decide routes and link schedules for the nodes involved. We do not require the central entity to know the exact location of each node or the distance between nodes. In the next subsection, we describe how to approximate interference-free link scheduling given this limitation.

2.1.1 Modeling the Impact of Interference

In order to set up collision-free end-to-end transmission schedules, we first need to understand the interference model that is used to compute whether a packet collides or is successfully transmitted and received. We briefly discuss the two widely used interference models first.

In the *physical interference model* [32], a transmission is successful based on the signal-to-interference and noise ratio at the receiver. Suppose node i wants to transmit to node j, we can calculate the signal-to-interference and noise ratio SINR at receiver j as:

$$SINR_{ij} = \frac{G_{ij}P_k}{NW + \sum_{k \neq i} G_{kj}P_k} \tag{2.1}$$

where P_i denotes the transmit power of a node i and G_{ij} is the link gain from node i to j, which is mainly determined by the path loss of the wireless link. NW denotes the ambient noise and the second term in the denominator is the interference due to the other simultaneous transmissions in the network. The transmission is successful if $SINR_{ij} \geq SINR_{thresh}$, where $SINR_{thresh}$ is the necessary threshold for decoding the transmission successfully. Assuming all nodes are identical and ignoring the ambient noise, equation (2.1) can be simplified as:

$$SINR_{ij} = \frac{G_{ij}}{\sum_{k \neq i} G_{kj}} \tag{2.2}$$

In the protocol interference model [30][31], both communication range R and interference range R' are used. $R' > R$ and as depicted in Figure 2.1, a transmission is successful if both of the following conditions are satisfied:

1. $d_ij \leq R_i$ (i.e. receiver j is in the transmission range of sender i)
2. Any node k, such that $d_{kj} \leq R'_k$, is not transmitting (i.e. a receiver is not in the interference range of any other sender except the current sender)

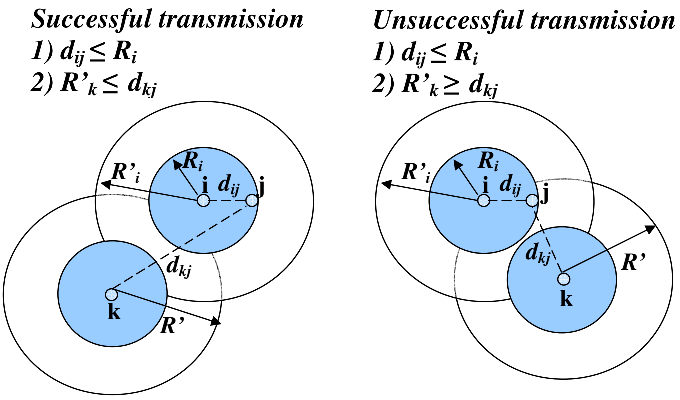

Figure 2.1: Protocol Interference model

Suppose a link i to j satisfies condition 1. It is denoted as e. For every e, $I(e)$ is the set of all transmissions (edges) that violate condition 2. A transmission is regarded to be interference-free as long as the edge u and any edge $v \subseteq I(u)$ can be arranged in different time slots.

It can be seen that neither of the above models are fully applicable to link scheduling in our system design because they require explicit global knowledge of either link gain characteristics or link distance. Here, we use a relaxed model of interference to approximate the physical model as in [33]. It is called the n-hop neighborhood protocol model of interference, where n is the interference index. In this model, we relax the distance-based interference constraints to hop-based ones. Thus, the condition (2) in the above protocol interference model refers to "any node k within the n-hop neighborhood of j is not transmitting". As this neighborhood information can be derived from the network connectivity graph easily, this can be used for a practical design.

To determine the appropriate interference index n for a certain $SINR_{thresh}$, we derive the following matching rules. Generally in wireless communication,

$$G_{ij} \propto d_{ij}^{-\gamma} \tag{2.3}$$

where d_{ij} is the distance from node i to j and γ is the path loss index [34]. According to (2.2), the worst-case scenario requirement for R' is

$$R' \geq \sqrt[\gamma]{SINR_{thresh}}R \tag{2.4}$$

where d_{ij} is equal to R. Then we choose n as the first integer which satisfies $n > R'/R$. Hence,

$$\sqrt[\gamma]{SINR_{thresh}} + 1 > n \geq \sqrt[\gamma]{SINR_{thresh}} \tag{2.5}$$

With this method, we give some example mapping of SINR threshold to the interference index in the following table.

$SINR_{thresh}$	$\gamma = 2$	$\gamma = 3$	$\gamma = 4$
5dB	2	2	2
10dB	4	3	2
15dB	6	4	3
20dB	11	5	4

Table 2.1: Example of the mapping between the interference index and SINR threshold

Note that equation (2.5) suggests that n should be at least 2 for any $SINR$ threshold larger than $0dB$. A common assumption that $n = 1$ in many "graph coloring" approaches [25][26][27] is actually an over-simplification that is unrealistic for the physical wireless mesh environment.

2.1.2 Implications of the hop-based interference model

At first glance, it seems that the n selected above would be a safe choice to avoid collisions completely. However, there is some "over-simplification" in the above relaxation process. There is still a small chance that collisions could occur. An example is given in Figure 2.2(a). In the network, the three transmissions, 1 → 2, 3 → 4 and 5 → 6 can be scheduled simultaneously according to the protocol interference model since all the receivers are in transmission range of their corresponding senders and out of the interference range of any other transmitter. However, at node 4, according to the physical interference model, the sum interference from both node 1 and 5 could make the $SINR_{14} < SINR_{thresh}$ and the transmission from 1 to 4 would fail.

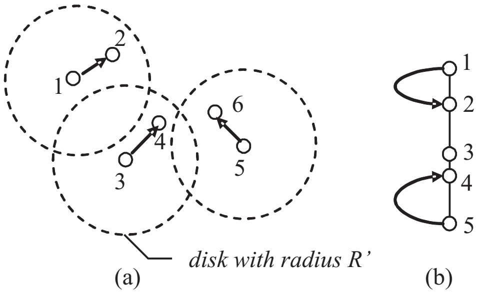

Figure 2.2: Examples of deficiency of hop-based interference models

Another potential problem is shown in Figure 2.2(b). This is a chain network topology which is determined by communication range R. If the interference index n is 2, then as node 5 and node 1 are 3-hops away from node 2 and 4 respectively, the transmission: 1 → 2 and 5 → 4 could be scheduled at the same time. However, node separation by n hops may not be equivalent to a physical separation by $n \times R$. The actual distance from 1 → 4 and 2 → 5 might be smaller than $2R$ because the nodes 3 and 4 are physically close together. Therefore, it is still possible for the two transmissions to interfere with each other. Hence, link scheduling does not ensure 100% interference-free schedules if the simplified n-hop interference model is used. If we change the equation (2.5) to choose a bigger n, the problem could be mitigated but the spatial reuse in the whole network will suffer. Hence, we use the n-hop interference model while determining link schedules for the flows, since this does not need knowledge of the distances or locations of the nodes. At the physical layer, however, we still use the $SINR$ based physical interference model. Note that a complete interference-free schedule may not be guaranteed in this case. We handle this problem by retaining the link layer acknowledgements and retransmissions in the TDMA MAC design.

2.2 Protocol framework

Our algorithm is based on the existence of a mechanism to disseminate and collect topology information and traffic specifications. This may be done using either a dedicated portion of the TDMA frame or a separate channel (using a different frequency) for control messaging. After receiving this information from the nodes, the centralized algorithm determines the routed paths and TDMA slot assignments for each source-destination pair. The problems associated with carrier-sense based random access, such as hidden node, exposed nodes, are eliminated by arranging conflicting transmissions in different time slots. Spatial reuse in the whole network can also be maximized by scheduling a maximum number of compatible transmissions simultaneously in the same timeslot.

In our design, as shown in Fig 3, each TDMA frame has N timeslots. The duration of each time slot will depend on the data rate of PHY layer and size of data unit. For each slot, the duration of the slot is: $T_{slot} = T_{data} + T_{ACK} + 2 \times T_{guard}$

The use of guard period is to accommodate the propagation delay and the Tx mode to Rx mode transition time in radio hardware. Each slot also accommodates the time required for the recipient to transmit an ACK to acknowledge the receipt of the data frame. As shown in Figure 2.3, a fixed part at the end of each time slot is used for this purpose. With this particular design, the collisions probability for ACK frames will be fairly small if their respective DATA transmissions do not collide [35].

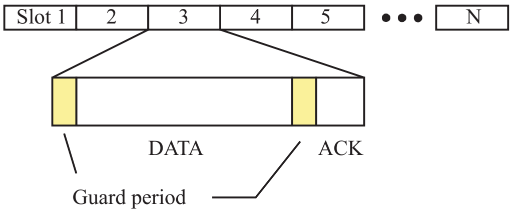

Figure 2.3: TDMA Frame Structure

For each directional link in the network, the link scheduling algorithm will mark a time slot for this link as one of the following:

- Scheduled: packet transmission for this link shall occur in this slot
- Occupied: this link cannot be used because of other ongoing transmissions.
- Free: unassigned idle slots

As explained in last subsection, collisions are not entirely avoided. Therefore, if a packet collides with other transmissions, the sender may perform random backoff before attempting its retransmission. Retransmissions are only allowed to use “free” slots. If the number of retransmissions exceeds the retry limit, the packet is dropped. “Free” slots are also used for broadcasting transmissions by a sender while “scheduled” slots are usually reserved for unicast transmissions in a directional link.

Note that even if link scheduling results are unavailable, all slots of all links will be marked as free by default. Then, the above TDMA MAC will work like a slotted-ALOHA MAC.

3. Problem Formulation and Algorithms

In this chapter, we first formulate the integrated MAC-Routing optimization to maximize the aggregate throughput of all end-to-end sessions over the whole network. Our LP formulation is similar in [30], but we divide our discussion in two cases: 1) route is known and 2) route is unknown. Moreover, the formulation to [30] does not consider fairness as a factor, therefore the optimal solution found would starve some flows to maximize the overall throughput. Here, we enhance the LP formulation with parameter controlling trade-off between throughput and fairness.

3.1 LP Formulation for link scheduling with known path

First, consider a wireless network with a group of nodes in a plane, which forms a network graph $G(V, E)$ given a communication range R. Each link has bandwidth b_u. There are M end-to-end flows in the network. Each pair of source and destination (s_i, d_i) generates a flow with rate $r_i, i = 1, 2, \ldots, M$. There are M link sequences $L_1, L_2, \ldots, L_M$, each corresponding to a path from the source to destination with path lengths $p_1, p_2, \ldots, p_M$ respectively. Thus, L_i is composed of p_i hops, . Assume each path segment l_{ij} to have a flow rate variable f_{ij}. The problem is formulated as:

$$Maximize \sum_{i=1}^{M} f_{i1}$$

Subject to three set of constraints:

1. $f_{ij} = f_{i,j+1}$, for $i = 1, 2, \ldots, M, j = 1, 2, \ldots, p_i - 1$
2. $r_i \geq f_{i1} \geq qr_i$, for $i = 1, 2, \ldots, M$.
3. $\sum_i \sum_j c_{ij} f_{ij} \leq b_u$, where $c_{ij} = 1$ if path segment l_{ij} coincides link edge e_u, otherwise 0.

The first set of constraints is needed for guarantee that the flow-rate comes into a relay node is same as the flow rate going out. The second set of constraints are used to ensure each flow have at least q $(0 < q < 1)$ fraction of its offered load served. This allows a tradeoff between throughput and fairness. The third set of constraints considers that the flow supported by the link cannot exceed its bandwidth.

We denote the above formulation as the “basic problem”. The basic problem is similar to the formulation of a wired network when the path of each flow is known. Then the interference constraints derived from the radio interference model need to be augmented to the “basic problem”. This can be done by deriving “cliques” and “maximum independent sets” from the conflict graph of the network topology. Here, the conflict graph is derived from $G(V, E)$ and interference index n based on n-hop neighborhood interference model. We use a procedure similar to [30] to find those constraints based on the protocol interference model and solve the LP problem by converging its lower bound and upper bound. This converged objective value is the analytical throughput bound. The details of this method can be found in [30]. From the solution we can derive the link rates of each path segments and construct a TDM schedule to approximate those link rate allocations.

3.2 Link Scheduling-Minimum Hop Algorithm

Optimal scheduling using the above method is an NP-hard problem [30]. In practice, we cannot afford to run this procedure online in one of the nodes because there is no guarantee that optimal solution will be found in less than exponential time. Instead, we use a greedy algorithm named IRMA-MH (Link Scheduling with Min-Hop Routing) to get suboptimal solution. In the greedy algorithm, the path for each flow is found by Dijkstra algorithm [36] with hop-count metrics. Then each flow just schedules its transmissions based on its respective traffic demands one by one.

The objective of this algorithm is to determine the appropriate periodic schedule for every node in the network and allocate each flow a bandwidth $A_i (A_i \geq r_i)$. Suppose the links in the network all have the same bandwidth and there are N timeslots in a TDMA frame. Then the minimum bandwidth that can be allocated is $B_0 = B/N$. The centralized algorithm is described in Figure 3.1.

We use P_k to denote all path segments (links) which are scheduled in slot k, where $k = 1, 2, \ldots, N$. The algorithm schedules an edge e, in the first available time slot such that the slot does not already have the edge e scheduled (perhaps to serve another flow), and it does not have any edge that belongs to $I(e)$, where $I(e)$ is the set of potential interfering edges of e derived from $G(V, E)$ and the interference index n.

After the algorithm finds a feasible schedule, it will mark corresponding slots as “scheduled”for respective links. Also, it will determine those slots which will be marked as “occupied” for corresponding links in the interference neighborhood with transmitting links. After the slot

```
Sorting $F = \{F_i\}$ by ascending order of $r_i$
for each $F_i$
  Compute shortest path $L_i$
  $A_i = 0$
end for
while $F$ is not empty
  for each $F_i$
    if $A_i < r_i$
      for each $e$ in $L_i$
        Schedule $e$ to first available slot k such that
          $P_k \cap (e \cup I(e)) = \phi$
      end for
      $A_i = A_i + B_0$
    else
      Remove $F_i$ from $F$
    end if
  end for
end while
```

Figure 3.1: IRMA-MH Algorithm

assignments are disseminated to each sending node of the network, the network will work on this optimized link schedule. In our simulations, we found that this simple greedy algorithm was typically able to achieve 90% of the optimal value of the LP solution.

3.3 LP Formulation for integrated routing-link scheduling

As the route selection can itself be optimized for load-balancing and congestion control purpose, it is desirable to optimize routing and MAC scheduling jointly. In this case, since the paths for any given flow are unknown, the LP problem becomes more complicated. Because any edge $e_u \in E$ in $G(V, E)$ might support one or more flows possibly, the set of flow rate variables in the LP problem will be extended to every possible $f_{i,u}$. In addition, there are usually two implications based on different routing strategies:

1. Multi-path routing: Traffic is split over multiple paths to reach the destination node. This would results in out-of-order packets reception in the destination.
2. Single-path routing: Many existing routing algorithms [10][8][9] are confined to single path routing. This restriction can be reinforced by adding integer variables to the LP problem. This LP optimization is suboptimal compared to the multi-path routing case, but solving the integer programming problem is NP hard.

In either case, we can simply modify our previous formulation in Section 3.1 to adopt above changes. Interested readers can refer to [30] for detail. As those LP problems will cost a lot of

```
Sorting $F = \{F_i\}$ by ascending order of $r_i$
for each $F_i$
  $A_i = 0$
  Compute path $L_i$ with the Dijkstra algorithm
  while $A_i < r_i$
    for each $e$ in $L_i$
      Schedule $e$ to first available slot k such that
        $P_k \cap (e \cup I(e)) = \phi$
    end for
    $A_i = A_i + B_0$
  end while
  for each $e \in E$
    $w(e) = 0$
    for $m = 1, 2, \ldots, N$
      if $P_m \cap (e \cup I(e)) = \phi$ then $w(e) = w(e) + 1$
    end for
  end for
end for
```

Figure 3.2: IRMA-BR Algorithm

time to solve, we propose a heuristic algorithm for this problem instead.

3.4 Link Scheduling - Bandwidth Aware Routing

A common shortcoming of the distance-based routing algorithm is that it could create congested areas if many paths cross same neighborhood. Our solution is to include available bandwidth into metric, instead of using hop counts only.

In the proposed IRMA-BR (Link Scheduling - Bandwidth Aware Routing) algorithm, the local information about the potential MAC bandwidth is measured before selecting a route for each flow. The available bandwidth is measured by the number of free slots. The metric of a link e: $w(e)$ is the number of *occupied* and *scheduled* slots in a given TDMA frame. Then, when the Dijkstra algorithm is used to select a shortest path, both the hop counts and available bandwidth will be factored in. The centralized algorithm for IRMA-BR is given in Figure 3.2. With this heuristic algorithm, a path with more available bandwidth will be preferred over a short congested path.

4. Simulation Results

In this chapter, we present the simulation results using the above integrated MAC/routing design. The upper bound for throughput is obtained by solving the LP problem in Section 3.1 with MATLAB. This is the analytical upper bound for any scheduling algorithm with known paths for end-to-end flows. We use the ns-2 simulator [37] for the greedy algorithms. The simulation parameters are listed in Table 4.1.

Topology size	1000x1000 m^2
Number of nodes	40
TX range	250m
Carrier sense range	550m
Channel rate	1Mbps
SINR threshold	10 dB
Propagation Model	TwoRayGround
Path loss index (γ)	4
MAC slot duration	8.4 msec
Slots per frame	20

Table 4.1: Simulation Parameters

We modified the default *ns-2* PHY model to approximate the physical interference model described in section III.A. Note that the integrated MAC-routing algorithms still use the hop-based interference model as commented earlier. Based on the above parameters and Table 2.1, the interference index n is set to 2. Hence, a transmission can only affect a node within the 2-hop neighborhood of the sender.

For a certain topology, we compare the following scenarios results with the analytical bound:

1. Baseline scenario 1: single radio, single channel. The routing protocol is AODV [8] and IEEE 802.11 w/o RTS/CTS is used for MAC.

2. Baseline scenario 2: Same as above except the routing protocol is DSDV [10].

3. Integrated MAC/Routing scenario: The default algorithm for integrated MAC-Routing is IRMA-MH. The TDMA MAC has a 20-timeslot frame. The length of each slot allows a transmission of a packet of as large as 1000 bytes (excluding the size of IP layer and MAC layer headers).

The “maximum throughput” of the system is measured in the following manner: each end-to-end flow in the network generates CBR traffic with an offered load r. Each flow runs for the same duration of 120 seconds. The network throughput is regarded as a valid measurement only when all flows can successfully transmit a fraction q of the offered load r. We keep increasing offered load until the network saturates. Then the maximum valid measurement is taken as the network throughput given the uniform load of those source-destination pairs. In the following experiments, q is set to 0.8.

4.1 Scenario with Single-hop Flows

In this experiment, we use a set of ten 40-node random topologies. In each topology, 10 randomly chosen source-destination pairs are selected and used to generate end-to-end CBR sessions with flow rates specified as a parameter. The simulation results are shown in Figure 4.1, all with 1 Mbps PHY rates for each link. The two baseline schemes (DSDV and AODV plus IEEE 802.11 MAC) only achieve 20-50% of analytical bound. The IRMA-MH scheme proposed here achieves about 90% of the analytical bound even though it is a simple greedy algorithm. This result shows that when that topology and traffic information are available, optimization in MAC layer only can have as much 100-200% improvement with 1-hop flows. This is because the centralized TDMA scheduling algorithm effectively eliminates MAC collisions.

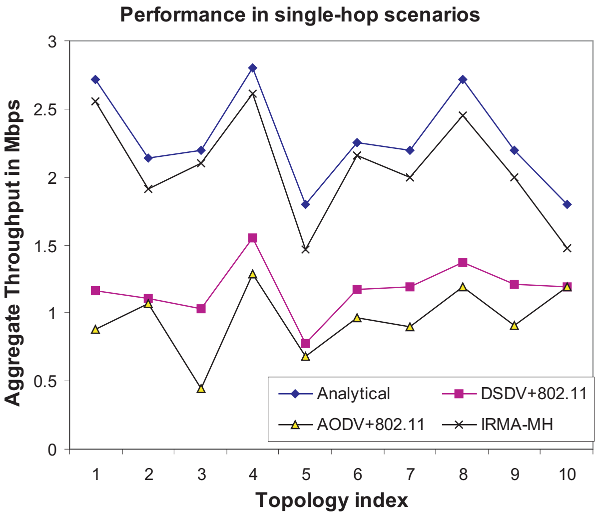

Figure 4.1: Simulation Results for Single-hop scenarios

4.2 Scenario with Multi-hop Traffic

In this experiment, we use a set of five 40-node random topologies. In each topology, 10 randomly chosen source-destination pairs are selected and used to generate end-to-end CBR sessions with flow rates specified as a parameter. The number of hops in each flow varies from 1 to 8, with an average number of 3.22 hops.

Similar to the results above, the IRMA-MH algorithm yields a sustainable throughput between 2-4 times the net throughput of the baseline mesh scenarios and approximately 60-90% of the analytical optimal scheduling bound, as shown in Figure 4.2.

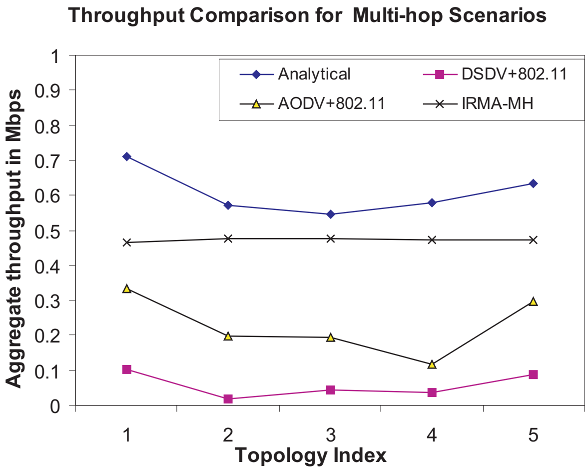

Figure 4.2: Simulation Results for Multi-hop scenarios

The reason why the IRMA-MH algorithm always yields a throughput of around 0.5 Mbps is because the TDMA frame has only 20 timeslots. Therefore, a single slot assignment to any link (at a data rate of 1 Mbps) corresponds to a bandwidth allocation as 0.05 Mbps. As we have 10 flows in the topology, so the aggregated throughput of around $10 \times 0.05 = 0.5$ Mbps is achieved. This can be further improved by extending the TDMA frame length to accommodate more slots.

It can also be noted that conventional routing protocols have very poor performance in this mesh scenario, especially with DSDV. While the simulation with the AODV routing protocol achieves about 30% of the analytical bound, the DSDV case usually yields just 5%-10% of the bound. This is because DSDV uses proactive route maintenance messages even in the absence of data traffic.

4.3 Comparison of IRMA-MH and BR

We use an example to show that how IRMA-BR routing could select better routes with the help of global bandwidth information. In the 6x6 grid topology shown in Figure 8, there are two flows: $A \rightarrow B$ and $C \rightarrow D$. With shortest-path routing, two adjacent paths will be used as indicated in Figure 4.3(a). However the IRMA-BR algorithm finds an alternate path to route around the congested area. As shown in Figure 4.3(b), the flow $C \rightarrow D$ uses a path that has more hops but less interfered by the flow $A \rightarrow B$. The corresponding throughput results for the above two algorithms, compared with the baseline scenario, are shown in Figure 4.4. The results show that the network throughput can be further improved by carefully selecting a route with less interference.

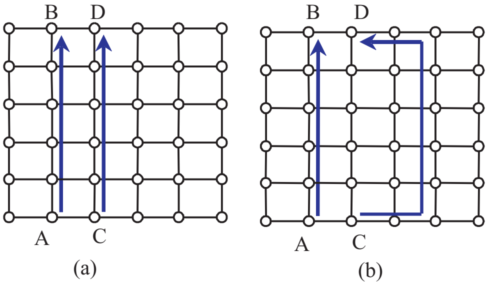

Figure 4.3: Different routes used by (a) IRMA-MH and (b) IRMA-BR in a 6x6 grid for two vertical flows

Another simulation experiment is conducted to compare the IRMA-BR and IRMA-MH algorithms with more general topologies. A set of five 40-node random topologies are used. In

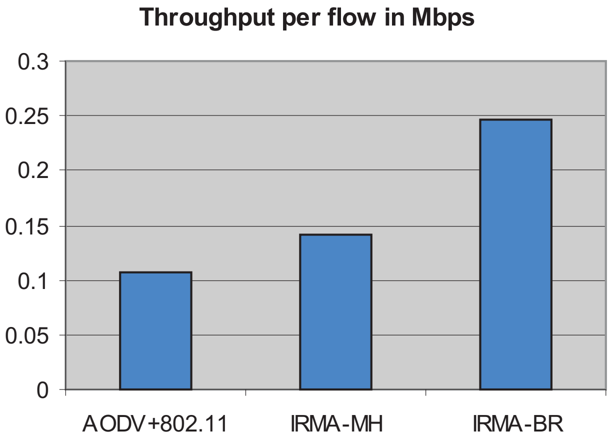

Figure 4.4: Simulation Results for 6x6 Grid Topology

each topology, 5 randomly chosen source-destination pairs are selected and used to generate end-to-end CBR. The results are shown in Figure 4.5. As can be seen, in 2 out of 5 scenarios, IRMA-BR algorithm yields better performance than IRMA-MH.

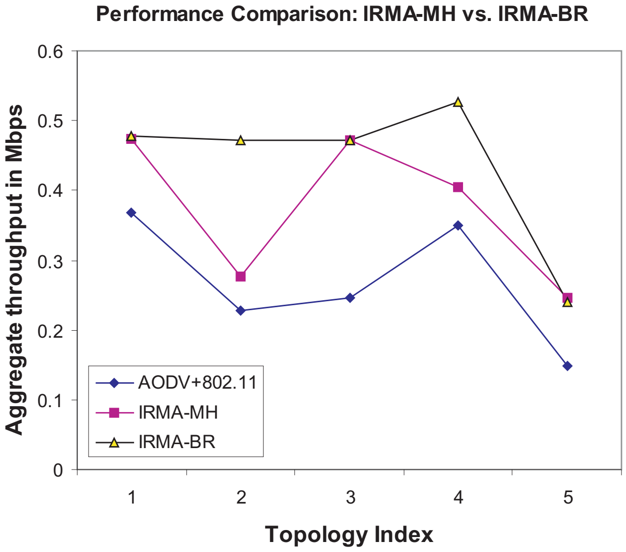

Figure 4.5: Simulation results for random topologies with 5 multi-hop flows

5. Conclusions and Future work

In this technical report, we proposed and evaluated an integrated routing and link scheduling (IRMA) mechanism for improving system performance in multi-hop wireless mesh networks. Simulation results were presented for two alternative centralized algorithms (IRMA-MH and IRMA-BR) for realizing integrated MAC/routing. The results show that the proposed IRMA schemes offer as much as 2-3x performance gain over traditional 802.11 MAC with ad-hoc routing baselines for wireless mesh networks. In future, we plan to integrate MAC and routing considered here with channel assignment algorithms for multi-radio mesh scenarios. At the same time, protocol design and validation work for IRMA will be carried out using the ORBIT testbed [38] for proof-of-concept prototyping.

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A. CB-WMN ARCHITECTURE

To realize the IRMA scheme, we also proposed a control-based wireless mesh network framework. (CB-WMN).

A.1 Network Architecture

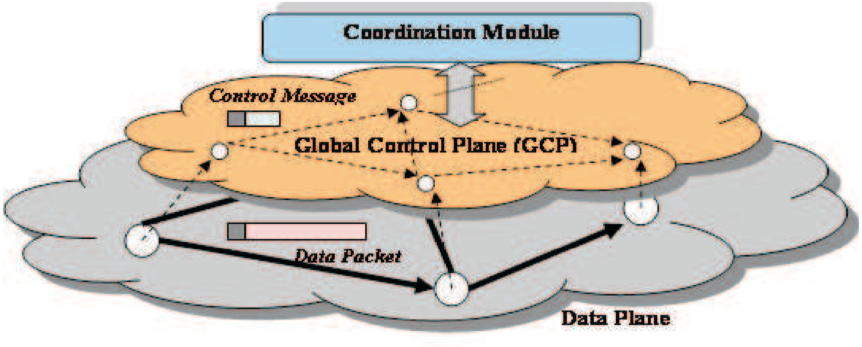


Figure A.1: CB-WMN Architecture

In the control-based wireless mesh network (CB-WMN), each node has a dedicated control interface and one (or more) data interfaces. The radio interfaces working on the data channel form a normal mesh communication infrastructure, which is defined as the data plane of this network. The control interfaces of all the nodes form a different single or multi-hop wireless network. We call it "global" control plane (GCP) that helps to optimize the system performance of the data plane. A few nodes may be actually connected to the Internet and we call them as gateway nodes (similar to the mesh portals described in the IEEE 802.11s specification).

The global control plane (GCP) is responsible for reservations and allocations of radio resource utilized in the data channel. In addition, it assists the initial bootstrapping and topology discovery phase when new nodes join the network. Usually, the data radio equipped in CB-WMN is a high data-rate short-range radio which could support the transport of large amounts of bulk data. The control radio, on the contrary, only needs to support bursty and light traffic due to the sporadic nature of control signaling. A typical control channel (based on the choice of the radio) could have about 5x the transmission range of the data channel and $\frac{1}{10}$ of the data rate as shown in Figure A.2.

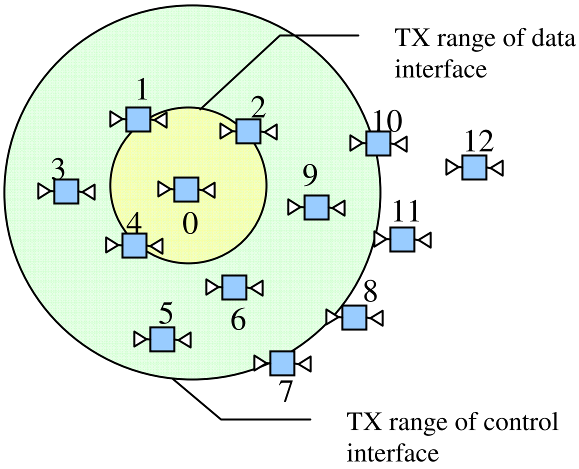


Figure A.2: CB-WMN Radio Range: Control and Data Plane

Note that this gives rise to two virtual topologies at the control and data plane respectively.

A.2 Protocol Stack in Control Plane and Data Plane

The protocol stack for both the control and the data plane at each node is as shown in the Figure A.3. The control plane employs a low bit rate, long range radio. This could be an IEEE 802.11 radio using the 1 Mbps data rate or a separate radio at lower frequency. A simplified CSMA based MAC is used for channel access. The simple MAC uses a fixed contention window size and disables virtual carrier sense. All the control messages flow from the agents towards the control master or vice-versa. Hence, a tree-based approach is used to form a spanning tree with the control master at the root of the tree. We skip the details of the spanning tree formation in the interest of space. The master collects information from the control agents and issues link scheduling as well as routing commands to the agents.

The data plane may have one (or more) physical interfaces as shown in the Figure 3. The data plane has a TDMA based MAC (described in section III.B.1) that is controlled by the control master. Routing is done based on the tables populated by the control master using signaling in the control plane.

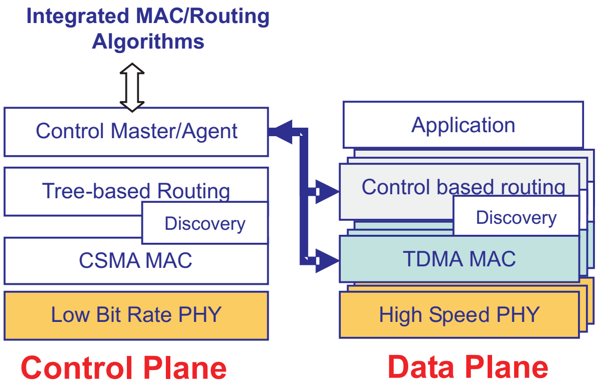


Figure A.3: CB-WMN Protocol Stack

A.2.1 TDMA MAC in Data Plane

The TDMA based MAC provides deterministic control over flow throughputs/delays. Moreover, because of the introduction of the control channel, TDMA scheduling can be realized by the control master with global knowledge. The problems associated with carrier-sense based random access, such as hidden node, exposed nodes, can be eliminated by arrange conflicting node's schedule in different time slots. Spatial reuse in the whole network can also be maximized by scheduling a maximum number of transmissions simultaneously in the same timeslot. The detail of this MAC design can be found in Section 2.2.

B. CB-WMN Messages and Protocols

B.1 Signaling in the Control Plane

Currently, there are six signaling messages designed for control plane. There are:

- *HELLO_BEACON*. This is used for discovery and spanning tree algorithm.
- *MASTER_DECLARE*. The master node is pre-selected and configured with some network-wide parameters, such as TDMA frame size, slot length etc. Whenever a node is discovered in the control plane, the control agent of that node receives these parameters from the master through this message.
- *LINK_UPDATE* This message is to let the agent report neighborhood information discovered in the data plane.
- *ROUTE_UPDATE*. The route update message is used by the control master to disseminate routing table entries to be used by that node in the data plane.
- *TRAFFIC_REPORT*. Using the traffic update report, the individual nodes can inform the control master of the expected traffic flow and the intended recipient.
- *TDMA_ASSIGN*. The control master distributes the TDMA slot assignment to the individual agents using this message.

All the above messages, except the it HELLO_BEACON, are unicast and need to be acknowledged in the link layer.

B.2 Network Bootstrap and Discovery

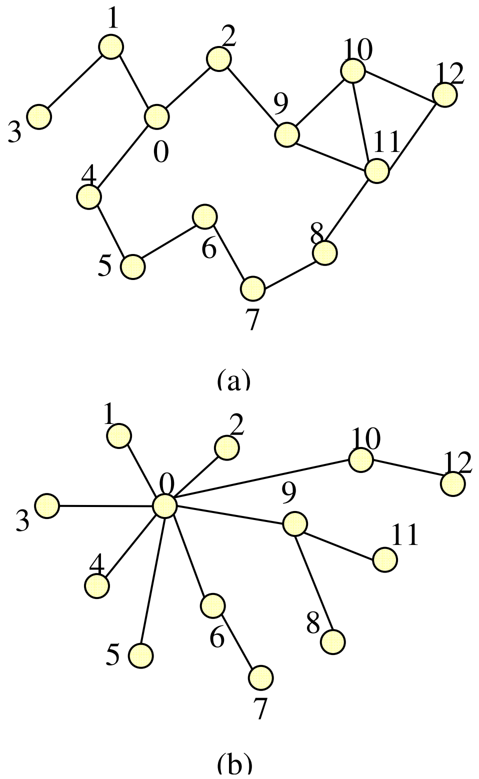
B.2.1 Discovery in the control plane

During the initial bootstrapping phase, all nodes broadcast *HELLO_BEACON*s to announce their presence. Through the exchange of these messages, nodes discover their neighbors in the control plane. After the master node declares its identity in the *HELLO_BEACON*, all the agents form a spanning tree with the root at the master (as shown in b) of Figure B.1). In

CB-WMN, a node is first discovered in the control plane before any traffic can be sent out. So, the discovery for the data plane will be deferred (proportional to the network size) by a certain period until the discovery is finished in the control plane.

B.2.2 Discovery in the data plane

For discovery in the data plane, all the nodes use a default interface (in the case of multiple data interfaces) and channel to broadcast *HELLO_BEACON*s. Upon hearing this message in the data channel from other neighbors, each node sends a *LINK_UPDATE* message in the control plane to the master to report a unidirectional link. If no new *LINK_UPDATE* messages are heard by the master node during a "topology stable period", the master node creates a global topology view considering only symmetric links (that have been discovered and reported by both end-points of the link).



(a)

(b)

Figure B.1: Topology formation a) Data plane (Mesh) b) Control plane (Spanning Tree)

Based on this topology, a shortest-path routing algorithm is executed in the master to generate routing table for each node. This table is given to the control agent using *ROUTE_UPDATE* signaling. Finally, the control agent sets the corresponding layer-3 routing table for data interface in each node. Now, for each node, there is a working MAC and routing table to support flows of any end-to-end source-destination node pairs. We also assume that the topology changes due to node mobility in both planes are much less than the frequency of HELLO beacons.

B.3 Slot Requests and Assignment Phase

The control agent attaches a traffic monitor to the layer-3 of the data-plane to monitor the start of every end-to-end session. Once the traffic is detected, the control agent will notify the master node about the traffic flow specifications. Note that for a wireless mesh network, it is expected that the traffic demand at each mesh node will be an aggregate request for all the client nodes that it is serving. The agent monitors the flow and sends new a report if the traffic variation is larger than a certain threshold. The master will wait for a certain "traffic stable period" after the reception of each *TRAFFIC_REPORT* signaling. The entire message exchange sequence is shown in Figure B.2.

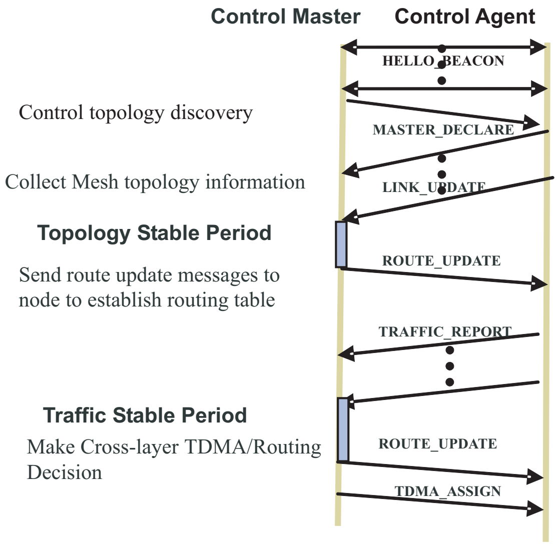


Figure B.2: Message Sequence in the Control Plane

With the knowledge of flow information about end-to-end sessions and global topology, the master node utilizes the cross-layer optimization algorithms, described in Chapter 3, to optimize the settings of route selection, TDMA scheduling or both. Control agents are notified of the slot assignments and routing paths using *TDMA_ASSIGN* and *ROUTE_UPDATE* messages respectively.

B.4 Dynamic Behavior of CB-WMN Network

When a new node wants to join the network, it will first be discovered in the control plane. After the reception of *MASTER_DECLARE* message, the new node will be instructed by the master node that whether it shall proceed to perform discovery in data plane or not. The decision is largely dependent on the busy degree or slot occupation ratio in the data plane. The new node would need to check additional information in the *MASTER_DECLARE* message to see if one or more particular slots are open for it to access data channel. This is to ensure the node's traffic (such as HELLO messages) will not collide with ongoing traffic activities. After this node is discovered in the data plane, the control master will receive one or more *LINK_UPDATE* messages related to this new node. Then, additional routing table will be generated for this new node and depends on the current traffic flow information, *TDMA_ASSIGN* messages will be sent to the new node. When a node leaves or has broken radio, the corresponding hello beacons in the data plane will disappear. And if this persists a certain time duration, the *LINK_UPDATE* signaling will be triggered and reported to the control master by its previous neighbors. Then corresponding new routing table and TDM scheduling scheme will be generated based on this new topology information. Only the differential part of the new schemes are sent back to the nodes affected. This will help to reduce the signaling overhead in the control channel. Similar procedures will apply when a new session starts or ends. Due to the size limit of this writing, we don't elaborate them.