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

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***Abstract*— This paper presents an integrated routing and MAC scheduling algorithm (IRMA)[1] 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.**

I. MOTIVATION

Reduction in the prices of commodity 802.11 products, their ready availability and an increasing demand for wireless access, has 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], DSR [9] or DSDV [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 routing and MAC scheduling (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 packet transmissions by replacing random access CSMA/CA with scheduled channel access.
2) Assignment of channel bandwidth to source-destination pairs is based on the actual traffic requirement, avoiding wastage of bandwidth arising in fixed TDMA slot assignment.
3) Selection of routing path based on link quality and available bandwidth, helping to 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 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. Section III gives an overview of the

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system model and interference model. In Section IV, our protocol framework to enable integrated routing and MAC is briefly described. In Section V, 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 VI discusses the simulation methodology and presents performance evaluation results for IRMA. Conclusions and future work are given in Section VII.

II. 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, these approaches tend to give equal channel access opportunities for each flow regardless of the traffic demand, which may not optimal for end-to-end performance.

In a recent work [29], the problem of scheduling a subset of transmission edges to maximize the aggregate MAC layer throughput is studied. Differs from this work, our work focuses on an optimized joint routing-scheduling scheme for all end-to-end traffic presented in the network. A theoretical basis for integrated optimization of routing and link scheduling on demand was first explored in [30]. More recently, the global optimization of link scheduling and routing has been studied by [31] [32], 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.

III. INTEGRATED MAC/ROUTING FRAMEWORK

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

A. 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 future, we plan to extend our model to multiple channels and multiple radios. 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.

Note that this model can be considered for a wireless backbone in a mesh network deployment with a relatively static infrastructure. Each mesh node may carry traffic from several mobile clients and we only consider *aggregated* traffic requests in our algorithm. Node mobility, arrival and departure of nodes manifest as changes in the traffic demand from the respective aggregation mesh nodes and we account for these changes by periodically sending traffic demand request messages. Based on those inputs, the centralized process runs 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.

B. 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* [33], a transmission is successful based on the signal-to-interference and noise ratio (SINR) at the receiver. Suppose node i wants to transmit to node j, we can calculate the SINR at receiver j as:

$$SINR_{ij} = \frac{G_{ij} P_i}{NW + \sum_{k \neq i} G_{kj} P_k} \tag{1}$$

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 (1) can be simplified as:

$$SINR_{ij} = \frac{G_{ij}}{\sum_{k \neq i} G_{kj}} \tag{2}$$

In the protocol interference model [31] [32], both communication range R and interference range R' are used. Generally,

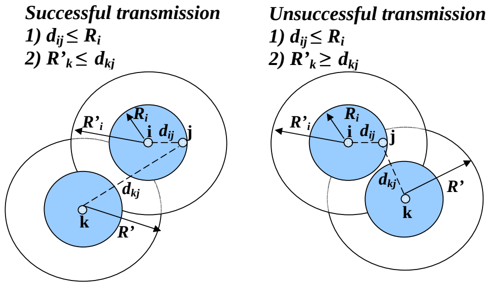


Fig. 1. Protocol Interference Model

$R' > R$ and as depicted in Figure 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)

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 scheduled 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 the distances between nodes. We use a relaxed model of interference to approximate the physical model as in [34]. 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,

$$G_{ij} \propto d_{ij}^{-\gamma} \tag{3}$$

where d_{ij} is the distance from node i to j and γ is the path loss index [35]. In the worst case d_{ij} is equal to R i.e. the receiver is at the edge of the transmission range. Substituting this in (2), the worst-case scenario requirement for R' is

$$R' \geq \sqrt[\gamma]{SINR_{thresh}}R \tag{4}$$

Then we choose n as the first integer which satisfies $n > R'/R$. Hence,

$$\sqrt[\gamma]{SINR_{thresh}} + 1 > n \geq \sqrt[\gamma]{SINR_{thresh}} \tag{5}$$

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 I

EXAMPLE OF THE MAPPING BETWEEN THE INTERFERENCE INDEX AND SINR THRESHOLD

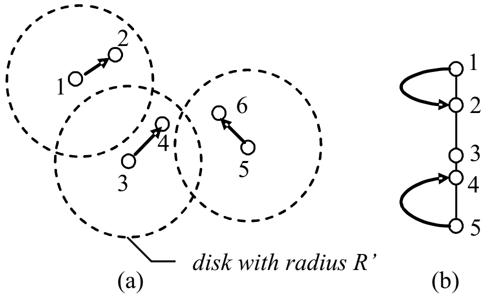


Fig. 2. Examples of deficiency of hop-based interference models

Note that equation (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.

C. 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(a). In the network, the three transmissions, $1 \rightarrow 2$, $3 \rightarrow 4$ and $5 \rightarrow 6$ 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 total interference from both node 1 and 5 could make the $SINR_{34} < SINR_{thresh}$ and the transmission from 3 to 4 would fail.

Another potential problem is shown in Figure 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: $1 \rightarrow 2$ and $5 \rightarrow 4$ 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 $1 \rightarrow 4$ and $2 \rightarrow 5$ might be smaller than $2R$ because the nodes 3 and 4 are in very close proximity. 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 relax the equation (5) to choose a bigger n, the problem could be mitigated but the spatial reuse in the whole network will suffer. Hence,

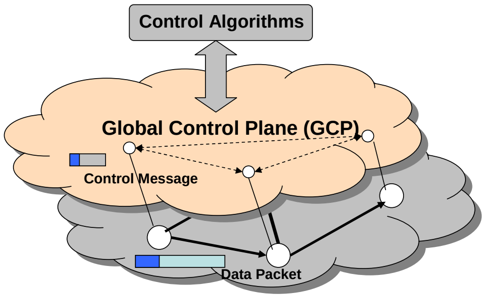


Fig. 3. CB-WMN Architecture

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.

IV. PROTOCOL FRAMEWORK

Our algorithm is based on the existence of a mechanism to disseminate and collect topology information and traffic specifications. In our protocol framework, we introduce a *control plane* for exchanging information related to co-ordination and scheduling the different flows.

Our control-based wireless mesh network architecture (CB-WMN) is shown in Figure 3. 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. 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 control "interfaces" of each node participate in the global control plane (GCP) which 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. GCP may be implemented using either a dedicated portion of the TDMA frame or a separate channel (using a different frequency) for control messaging. If a separate control radio is used, based on the choice of the radio, it could have a greater range (as shown in Figure 4 and lower data rate as compared to the radio in data channel. This is because the control plane only needs to support bursty and light traffic due to the sporadic nature of control signaling as compared to data plane which could support the transport of large amounts of bulk data.

Note that this gives rise to two virtual topologies at the control and data plane respectively as shown in Figure 5. The details of our bootstrapping and the discovery mechanism implementation have been omitted in the interest of space and we focus more on the control algorithms used by the centralized entity.

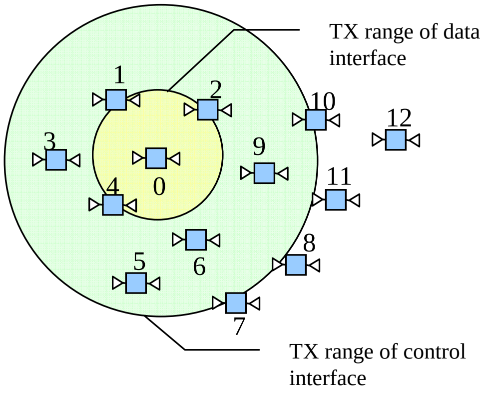
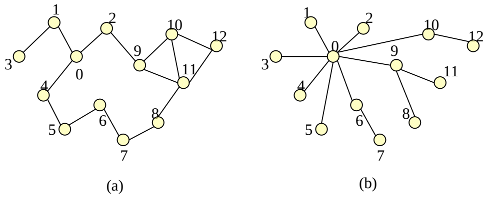


Fig. 4. Transmit ranges: control and data plane



(a) (b)

Fig. 5. Topology formation a) Data plane (Mesh) b) Control plane (Spanning Tree)

The control algorithms is run in a centralized manner. After the discovery in both the data plane and control planes, the traffic and topology information can be exchanged in the GCP either using a routing protocol or by other flooding mechanisms. After receiving this information from the nodes, then the 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.

The IRMA control algorithms in the GCP depend on the signaling messages to exchange essential information, such as topology information, traffic updates and schedules. As an example, we present the format for the traffic update message used in the centralized scheme in Figure 6. This is sent out by the mesh nodes to notify a traffic event.

After running the IRMA algorithm, an appropriate TDMA schedule assignment is sent back to the node. In our design, as shown in Figure 7, 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: $T_{slot} = T_{data} + T_{ACK} + 2 \times T_{guard}$

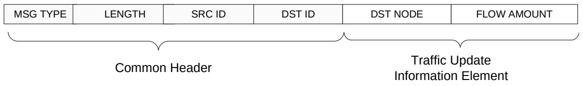


Fig. 6. A Typical Signaling Format

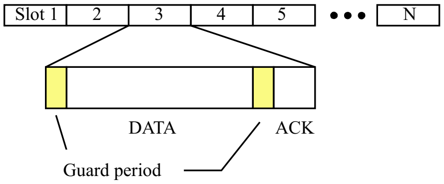


Fig. 7. TDMA Frame Structure

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 7, 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 [36]. 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 may not be entirely eliminated. 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 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.

The global synchronization required by TDMA MAC can be implemented either by having a GPS signal feed into each nodes of the network or selecting a central entity with accurate clock to distribute precise timing over the global control plane. For the latter case, a protocol like IEEE 1588 [37] can be applied.

V. PROBLEM FORMULATION AND ALGORITHMS

In this section, 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 to the one described in [31], but we consider two separate cases: 1) route is known and 2) route is unknown. Moreover, the formulation in [31] does not consider fairness as a factor, therefore the optimal solution found could starve some flows to maximize the overall throughput. Here, we enhance the LP formulation with the parameter, q, that controls the trade-off between throughput and fairness.

A. 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. The capacity of each directional link e is upper bounded by the link bandwidth $b(e)$. 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 a source to a destination with path lengths $p_1, p_2, \ldots, p_M$ respectively. Thus, each L_i is composed of p_i hops. We define an edge set $L \subseteq E$, which contains all edges used by those paths. Assume each path segment l_{ij} to have a flow rate variable f_{ij}, where $j = 1, 2, \ldots, p_i - 1$. 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) $r_i \geq f_{i1} \geq q r_i$, for $i = 1, 2, \ldots, M$.
3) $\sum_i \sum_j c_{ij} f_{ij} = f(e) \leq b(e)$, where $c_{ij} = 1$ if path segment l_{ij} coincides link edge $e \in L$, otherwise 0.

The first set of constraints is needed to guarantee flow conservation at each intermediate node. The second set of constraints are used to ensure each flow has at least q $(0 < q < 1)$ fraction of its offered load served. The parameter, q, allows a tradeoff between throughput and fairness. The third set of constraints considers that the total flow amounts supported by the link edge, denoted as $f(e)$, cannot exceed the edge capacity.

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" to extend the problem for wireless networks. A procedure similar to the one used in [31] is used. The work is briefly summarized here for the sake of clarity.

To account for wireless interference in the optimization problem, a *conflict graph* G' is used, where the vertices of the conflict graph are the edges in the original graph. Based on an n-hop neighborhood interference model, there exists an edge between two vertices of G' that interfere with each other. A *clique* in a conflict graph is a set of edges which conflict with each other. The cliques can be found by searching G'. Each edge e could belong to one or more cliques and the total usage of the links in each clique is at most 1. Therefore, if the clique set found in G' is defined as $X_k, k = 1, 2 \ldots, K$, the interference constraints can be written as:

$$\sum_{e \in X_k} \frac{f(e)}{b(e)} \leq 1, k = 1, 2 \ldots, K, e \in L$$

Substituting the third constraint set of the basic problem with this stronger set of constraints, the LP formulation can be used to find a reasonable "upper bound" of the scheduling problem with wireless interference.

To find the optimal schedule, however, more strict constraints need to be reinforced, because the edges involved in the transmission scheduling solution also have to be schedulable. To realize this, all edges utilized in the same time slot have to belong to the same *independent set* of G', where any edge in this set does not conflict with any other edges. If the collection of all independent sets is defined as $Y_k, k = 1, 2 \ldots, K'$ and suppose each independent set only becomes active for a portion, λ_k, of a TDMA frame, we have the following new constraints:

1) $\sum_k \lambda_k \leq 1, k = 1, 2 \ldots, K'$
2) $\frac{f(e)}{b(e)} \leq \sum_{e \in Y_k} \lambda_k$, for each e $\in L$

Adding above constraints to the basic problem would complete the LP formulation of the optimal scheduling problem with known path. From the above solution, the link rates of each path segments can be derived and an optimal TDM schedule can be constructed to approximate those link rate allocations. However, the problem of finding maximal independent set is NP-hard. In practice, only a limit number of independent sets are found and the corresponding LP solution only yields a *lower bound* of the problem.

In this paper, with different mesh topologies, we apply the above method to find reasonably good upper and lower bounds by conducting a certain large number of iterations. If the upper bound and lower bound converges, then the converged value is regarded as the analytical throughput of the LP solution. Otherwise, the upper bound is used.

B. Link Scheduling-Minimum Hop Algorithm

Optimal scheduling using the above method is an NP-hard problem, because finding the “maximal clique” and “maximal independent set” are both NP-hard problems. 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 a sub-optimal solution. In the greedy algorithm, the path for each flow is found by Dijkstra algorithm [38] with hop-count metrics. Then, each flow 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 B and there are N time slots in a TDMA frame. Then the minimum bandwidth that can be allocated is $B_0 = B/N$. The centralized algorithm is described in Figure 8.

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', the conflict graph. 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 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.

```
Given $F = \{F_i\}$
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
```

Fig. 8. IRMA-MH Algorithm

C. 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 $e \in E$ might support one or more flows possibly, the set of flow rate variables in the LP problem will be extended to every possible $f(i, e)$. 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 and other complexities for practical implementation.
2) Single-path routing: Traffic always follow the same unique path from the source to destination. Many existing routing algorithms [8] [9] [10] are confined to single path routing. In this paper, we focus on single-path routing solutions.

According to [31], in order to limit path selection to single path routing for each flow $< s_i, d_i >$, there exists new constraints:

1) $f(i, e) \leq b(e) z(i, e)$, where $z(i, e) \in \{0, 1\}, e \in E$
2) $\sum_{e \in S(v)} z(i, e) \leq 1$, where $S(v)$ contains all edges originating at node v.

```
Given $F = \{F_i\}$
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
```

Fig. 9. IRMA-BR Algorithm

$\{z(i, e)\}$ is a set of binary variables introduced to the LP formulation to reinforce the single-path requirements. However, solving the integer programming problem is NP-hard. Instead, we propose a heuristic algorithm for single path routing as described next in Section V-D.

D. 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 the 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 9. With this heuristic algorithm, a path with more available bandwidth will be preferred over a short congested path.

VI. SIMULATION RESULTS

In this section, we present the simulation results using the above integrated MAC/routing design. The upper bound for system throughput is obtained by solving the LP problem in Section V-A with MATLAB, unless otherwise mentioned. This is the analytical upper bound for any scheduling algorithm with known paths for end-to-end flows. We use the ns-2 simulator [39] for simulating the proposed GCP framework and control algorithms. The simulation parameters are listed in Table II.

Topology size	1000x1000 m^2
Number of nodes	40
TX range	250m
Carrier sense range	550m
Data Channel rate	1Mbps
Control Channel rate	100kbps
SINR threshold	10 dB
Propagation Model	TwoRayGround
Path loss index (γ)	4
MAC slot duration	8.4 msec
Slots per frame	20

TABLE II

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 I, the interference index n is set to 2. Hence, a transmission is assumed to 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 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 2*: Same as above except the routing protocol is DSDV [10].
3) *IRMA*: 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.

A. 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 10, 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

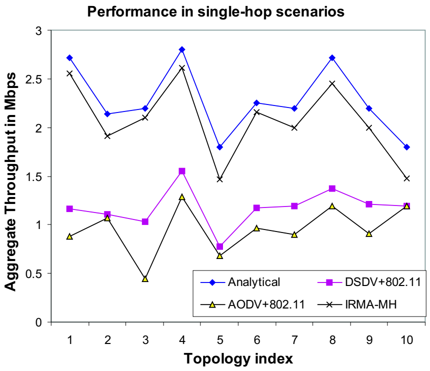


Fig. 10. Simulation Results for Single-hop scenarios

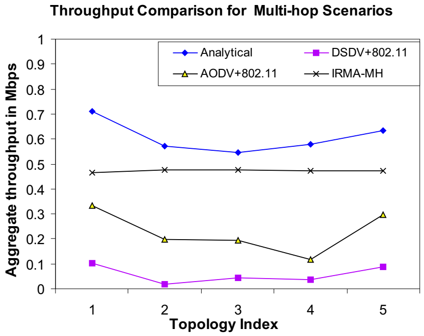


Fig. 11. Simulation Results for Multi-hop scenarios

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.

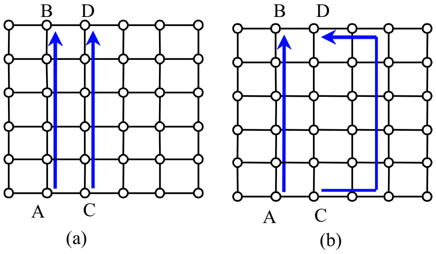
B. Scenario with Multi-hop Traffic

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 11.

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, the aggregated throughput of around $10 \times 0.05 = 0.5$ Mbps is achieved. This artifact can be alleviated 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.



(a)

(b)

Fig. 12. Different routes used by (a) IRMA-MH and (b) IRMA-BR in a 6×6 grid for two vertical flows

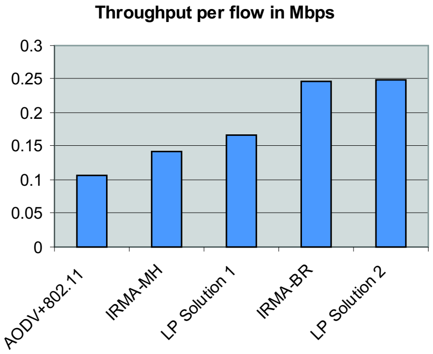


Fig. 13. Simulation Results for 6×6 Grid Topology: the first LP solution corresponds to the LP problem with known min-hop path, the second LP solution corresponds to the LP problem with any single-path routing

C. 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 12, 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 12(a). However the IRMA-BR algorithm finds an alternate path to route around the congested area for one of the flows. As shown in Figure 12(b), the flow $C \rightarrow D$ uses a path that has more hops but less interfered by the flow $A \rightarrow B$.

The throughput results for the above two algorithms, compared with the baseline scenario and optimal analytical solutions, are shown in Figure 13. The two differnt optimal solutions contrasted here are obtained with the method described in Section V-A and V-C respectively. The comparison of LP solutions show that the network throughput achieved by optimal routing is 50% higher than the min-hop path selection. Correspondingly, the IRMA-BR algorithm which selects a bandwidth(interfererence)-aware path yields more throughput than the IRMA-MH algorithm. This example shows that a non-trivial network performance improvement can be gained

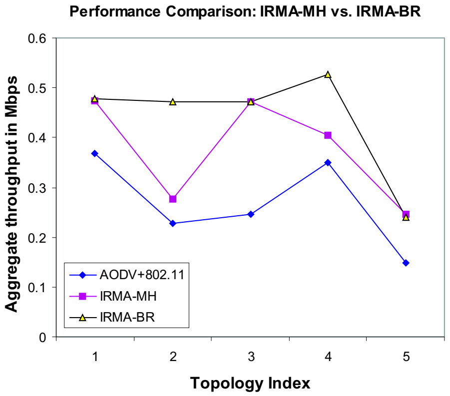


Fig. 14. Simulation results for random topologies with 5 multi-hop flows

by approximating the joint optimal route/scheduling solution in this scenario.

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 each topology, 5 randomly chosen source-destination pairs are selected and used to generate end-to-end CBR. The results are shown in Figure 14. As can be seen, in 2 out of 5 scenarios, IRMA-BR algorithm yields better performance than IRMA-MH.

D. Signaling Overhead on the Control Channel

In the implementation of GCP, a unicast routing mechanism is run on the control channel to collect and disseminate all control signaling. Using an example, we calculate the signaling overhead in IRMA scheme and compare it with the signaling overhead of other conventional approaches. For those conventional schemes, the overhead includes both the routing signaling and IEEE 802.11 RTS/CTS frame exchanges which are used to avoid collision. For IRMA schemes, the overhead is represented by the all control packets exchanged in the global control plane. To make a fair comparison, all signaling overheads are measured in layer 2. We conduct a simulation on a 4×4 grid topology. Ten traffic sessions of random source-destination pairs are started at random time. The duration of the traffic sessions is exponentially distributed with an average of 30 seconds. The total simulation time is 80 seconds and the first traffic session starts at t=20 seconds. We conduct the same simulation procedure with 10 different traffic scenarios. The results are averaged over those 10 simulations. We report both the signaling overhead measurement (in bps) and the normalized overhead (ratio of control traffic in bytes to the actual data delivered end-to-end in bytes) for each scheme.

The signaling overhead of IRMA scheme is much smaller than other schemes. It is mainly due to the fact that IRMA scheme uses much less signaling to arrange collision-free MAC scheduling than the per-packet RTS/CTS signaling used in IEEE 802.11 MAC protocol. This can be more clearly seen from the Figure 15. In this figure, we plot the change of signaling overhead in timeline for one of the simulation experiments. While the conventional schemes spent significant overhead to conduct per-packet reservation (RTS/CTS), the curve of the overhead of IRMA scheme has only several *spikes* associated with the changes of traffic profile. From these simulation results, we can see the integrated routing/scheduling scheme would not only improve the end-to-end throughput, but also reduce the signaling overhead in protocols for static wireless mesh networks, comparing to the conventional approaches.

Scheme name	Overhead (in bps)	Normalized Overhead
IRMA-MH	18646	1.499%
DSDV + 802.11	55117	6.1962%
AODV + 802.11	67558	7.0517%

TABLE III

COMPARISON OF SIGNALING OVERHEAD

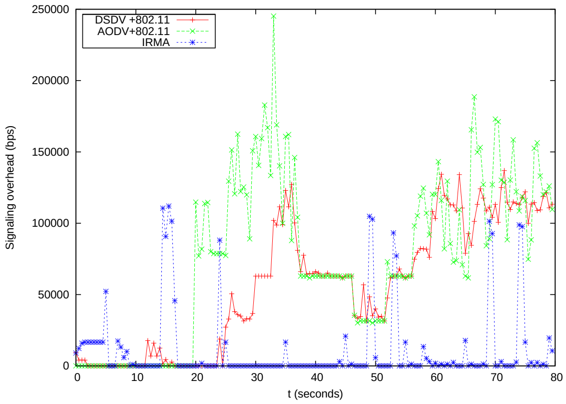


Fig. 15. Measurement of Signaling Overhead

VII. CONCLUSIONS AND FUTURE WORK

In this paper, 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 [40] for proof-of-concept prototyping.

REFERENCES

[1] "Champaign-Urbana Community Wireless Network, http://www.cuwireless.net."

[2] "LocustWorld Mesh project, http://www.locustworld.org."

[3] P. Bhagwat, B. Raman, and D. Sanghi, "Turning 802.11 inside-out," *SIGCOMM Comput. Commun. Rev.*, vol. 34, no. 1, pp. 33–38, 2004.

[4] S. Ganu and D. Raychaudhuri, "Integrating short-range ad-hoc radio technologies into next generation wireless networks," in *ICCC 2005, Proceedings of the International Conference and Exposition on Communication and Computing*, IEEE Press, 2005.

[5] "http://www.bdt.co.nz/thomson/press/berlin_ifa_show_2003.asp."

[6] "http://wireless-networks.philips.com/."

[7] IEEE 802.11 Task Group S, "Mesh networking standard, http://grouper.ieee.org/groups/802/11/reports/tgs_update.htm."

[8] C. E. Perkins and E. M. Royer, "Ad hoc On-demand Distance Vector routing," in *Proceedings of the IEEE Workshop on Mobile Computing Systems and Applications*, pp. 90–100, 1999.

[9] D. B. Johnson and D. A. Maltz, "Dynamic source routing in ad hoc wireless networks," in *Mobile Computing* (T. Imielinski and H. Korth, eds.), vol. 353, Kluwer Academic Publishers, 1996.

[10] C. Perkins and P. Bhagwat, "Highly Dynamic Destination-Sequenced Distance-Vector Routing (DSDV) for mobile computers," in *ACM SIGCOMM'94 Conference on Communications Architectures, Protocols and Applications*, pp. 234–244, 1994.

[11] S. Xu and T. Saadawi, "Does the IEEE 802.11 MAC protocol work well in multihop wireless ad hoc networks?," *Communications Magazine, IEEE*, vol. 39, no. 6, pp. 130–137, 2001.

[12] J. Li, C. Blake, D. S. D. Couto, H. I. Lee, and R. Morris, "Capacity of ad hoc wireless networks," in *MobiCom '01: Proceedings of the 7th annual international conference on Mobile computing and networking*, (New York, NY, USA), pp. 61–69, ACM Press, 2001.

[13] M. Gerla, K. Tang, and R. Bagrodia, "TCP performance in wireless multi-hop networks," in *WMCSA '99: Proceedings of the Second IEEE Workshop on Mobile Computer Systems and Applications*, (Washington, DC, USA), p. 41, IEEE Computer Society, 1999.

[14] IEEE 802 LAN/MAN Standards Committee, "Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications, IEEE Standard 802.11," 1999.

[15] J. Deng, B. Liang, and P. K. Varshney, "Tuning the carrier sense range of IEEE 802.11 MAC," in *Proceedings of IEEE Global Telecommunications Conference - Wireless Communications, Networks, and Systems (Globecom'04)*, 2004.

[16] A. Acharya, A. Misra, and S. Bansal, "Design and analysis of a cooperative medium access scheme for high-performance wireless mesh networks," in *Proceedings of 1st IEEE International Conference on Broadband Networks*, 2004.

[17] A. Acharya, A. Misra, and S. Bansal, "A label-switching packet forwarding architecture for multi-hop wireless lans," in *WOWMOM '02: Proceedings of the 5th ACM International Workshop on Wireless Mobile Multimedia*, (New York, NY, USA), pp. 33–40, ACM Press, 2002.

[18] Z. Wu and D. Raychaudhuri, "D-LSMA: Distributed Link Scheduling Multiple Access Protocol for QoS in ad-hoc networks," in *Proceedings of IEEE Global Telecommunications Conference - Wireless Communications, Networks, and Systems (Globecom'04)*, vol. 3, pp. 1670–1675, Novemeber 2004.

[19] Y. Li, H. Wu, D. Perkins, N.-F. Tzeng, and M. Bayoumi, "MAC-SCC: Medium access control with a separate control channel for multihop wireless networks," in *Proceedings of ICDCSW'03*, May 2003.

[20] P. Kyasanur, J. Padhye, and P. Bahl, "On the efficacy of separating control and data into different frequency bands," in *Proceedings of 1st IEEE International Conference on Broadband Networks*, 2005.

[21] S. Zhao, Z. Wu, A. Acharya, and D. Raychaudhuri, "PARMA: A PHY/MAC aware routing metric for ad-hoc wireless networks with multi-rate radios," in *Proceedings of IEEE International Symposium on a World of Wireless, Mobile and Multimedia Networks (WoWMoM 2005)*, 2005.

[22] R. Draves, J. Padhye, and B. Zill, "Routing in multi-radio, multi-hop wireless mesh networks," in *MobiCom '04: Proceedings of the 10th annual international conference on Mobile computing and networking*, (New York, NY, USA), pp. 114–128, ACM Press, 2004.

[23] I. Cidon and M. Sidi, "Distributed assignment algorithms for multihop packet radio networks," *IEEE Transactions on Computers*, vol. 38, no. 10, pp. 1353–1361, 1989.

[24] R. Ramaswami and K. Parhi, "Distributed scheduling of broadcasts in a radio network," in *Proceedings of IEEE Conference on Computer Communications (INFOCOM)*, vol. 2, pp. 497–504, IEEE Comput. Soc. Press, 1989.

[25] A. Ephremides and T. Truong, "Scheduling broadcasts in multihop radio networks," *IEEE Transactions on Communications*, vol. 38, pp. 456–460, April 1990.

[26] S. Gandham, M. Dawande, and R. Prakash, "Link scheduling in sensor networks: distributed edge coloring revisited," in *Proceedings of IEEE Conference on Computer Communications (INFOCOM)*, 2005.

[27] C. X. Zhu and M. S. Corson, "Five-phase reservation protocol for mobile ad-hoc networks," in *Proceedings of IEEE Conference on Computer Communications (INFOCOM)*, pp. 322–331, 1998.

[28] L. Bao and J. J. Garcia-Luna-Aceves, "A new approach to channel access scheduling for ad hoc networks," in *MobiCom '01: Proceedings of the 7th annual international conference on Mobile computing and networking*, (New York, NY, USA), pp. 210–221, ACM Press, 2001.

[29] G. Sharma and N. Shroff, "On the complexity of scheduling in wireless networks," in *MobiCom '06: Proceedings of the 12th annual international conference on Mobile computing and networking*, 2006.

[30] L. Tassiulas and A. Ephremides, "Jointly optimal routing and scheduling in packet radio networks," *IEEE Transactions on Information Theory*, vol. 38, pp. 165–168, January 1992.

[31] K. Jain, J. Padhye, V. N. Padmanabhan, and L. Qiu, "Impact of interference on multi-hop wireless network performance," in *MobiCom '03: Proceedings of the 9th annual international conference on Mobile computing and networking*, (New York, NY, USA), pp. 66–80, ACM Press, 2003.

[32] M. Kodialam and T. Nandagopal, "Characterizing the capacity region in multi-radio multi-channel wireless mesh networks," in *MobiCom '05: Proceedings of the 11th annual international conference on Mobile computing and networking*, (New York, NY, USA), pp. 73–87, ACM Press, 2005.

[33] P. Gupta and P. R. Kumar, "The capacity of wireless networks," *IEEE Transactions on Information Theory*, vol. 46, March 2000.

[34] A. Raniwala and T. Chiueh, "Architectures and algorithms for an IEEE 802.11-based multi-channel wireless mesh network," in *Proceedings of IEEE INFOCOM*, 2005.

[35] T. S. Rappaport, *Wireless Communications: Principles and Practice*. Upper Saddle River, NJ, USA: Prentice-Hall, Inc., second ed., 1994.

[36] K. Oikonomou and I. Stavrakis, "Analysis of a probabilistic topology-unaware TDMA MAC policy for ad-hoc networks," *IEEE Journal on Selected Areas in Communications*, vol. 22, no. 7, pp. 1286–1300, 2004.

[37] IEEE 1588 Standards Committee, "IEEE 1588 Standard for a Precision Clock Synchronization Protocol for Networked Measurement and Control Systems," 2002.

[38] T. Cormen, C. Leiserson, and R. Rivest, *Introduction to Algorithms*. MIT Press, 1989.

[39] "The network simulator ns-2, http://www.isi.edu/nsnam/ns."

[40] D. Raychaudhuri, I. Seskar, M. Ott, S. Ganu, K. Ramachandran, H. Kremo, R. Siracusa, H. Liu, and M. Singh, "Overview of the orbit radio grid testbed for evaluation of next-generation wireless network protocols," in *Proceedings of the IEEE Wireless Communications and Networking Conference (WCNC 2005)*, 2005.