IRMA: Integrated Routing and MAC Scheduling in Multihop Wireless Mesh Networks

Zhibin Wu, Sachin Ganu and Dipankar Raychaudhuri
WINLAB, Rutgers University
Contents

- Motivation
- Theoretical Background
- System Model and IRMA Algorithms
- Simulation Results
- Conclusion and Future Work
WMN (Wireless Mesh Network)

- Mesh routers form a core network serving as an infrastructure for clients

Motivations for IRMA Design

- WMN is different from ad-hoc and sensor networks
  - Minimal mobility, no power consumption constraints.
  - Performance focus: resource (channel) utilization efficiency

- Problems with layered approaches (802.11 + AODV, etc. …)
  - The performance of 802.11 MAC degrades with the increasing number of clients and number of hops
  - Routing protocols not take care of wireless characteristics.

- Cross-layer designs
  - Incorporate MACPHY parameters (e.g. link loss rate, bandwidth) into routing metrics, do not solve MAC inefficiency directly.

- Our approach: IRMA
  - Merge routing and MAC layer into an integrated component
  - Optimize MAC/routing parameters to maximize the end-to-end system throughput with multi-hop flows
IRMA Concept

IRMA determines good routes and schedules together

- Link transmissions are scheduled at different timeslots (shown as different colors)
- Eliminate interference and maximize spatial reuse
Theoretical background

- Maximize end-to-end throughput: multi-commodity network flow problem (linear programming)

- Interference-free scheduling: coloring problem (graph theory)
  - Finding maximal independent set in the conflict graph
LP Formulation of Integrated Routing and MAC Scheduling (1)

Maximize \[ \sum_{i=1}^{M} f_i \]

Subject to:

1) Flow conservation
   \[ f_i \text{ keeps same along the path for } <s_i,d_i> \]

2) Link capacity
   \[ f(e) = \sum_i f_i \leq BW(e), \text{ for each } e \in L \]

3) Fairness tradeoff
   \[ qr_i \leq f_i \leq r_i, \quad 0 \leq q \leq 1 \]

- \( M \) concurrent flows from \( s \) to \( d \)
- \( L \): link set selected as paths
- \( r \): offer-load/demands for each flow

Constraints for link conflict based on “conflict graph” in interference model
LP Formulation of Integrated Routing and MAC Scheduling (2)

- Find the analytical throughput bounds
  - Min-hop routing + link Scheduling
    - The path for each \(<s, d>\) is known as the min-hop path.
  - Joint routing/scheduling
    - Single path routing, but path is uncertain.
    - Mixed integer programming problem

(\textit{Method is similar to the LP optimization method presented in [K. Jain et. al. 03]})

- Observations and conclusions from previous and our LP analysis
  - It’s NP-hard to find all link conflict constraints in LP formulation.
  - Possible optimal routing paths can be found to yield better throughput than min-hop paths.
  - Optimal solution needs global knowledge.

- Our contribution: Offline Optimization \rightarrow Online algorithms
Interference-free Scheduling

- Protocol Model of Interference
  
  Transmission range: $R$
  Interference range: $R'$

  **Conditions for a successful transmission:**
  1) $d_{ij} \leq R_i$
  2) any node $k$, such that $d_{kj} \leq R'_k$ is not transmitting

- Scheduling requires
  - to know exactly whose interference affect whom
  - node distance to be known or measured. *Not practical!*

- Our proposed solutions
  - Using a “k-hop” range to approximate the interference range
  - Using a control radio to reach all interfering hidden nodes.
IRMA System Model

- **Global control plane and data plane**
  - All control signaling on a separate plane
  - Each node uses another radio interface over a dedicated control channel
  - Parameters of IRMA component in data plane is determined by control algorithms

Protocol stacks in IRMA system
IRMA System Control Cycle

- A central control entity running in one of the nodes, discovering global topology and link bandwidth information
- Control Cycle:
  - Detection and report of new or changed traffic demands.
  - IRMA optimization determine the paths and conflict-free TDMA schedules for each node.
  - IRMA components (Routing and MAC) transform and work with the new working parameters to ensure QoS.
IRMA Algorithms: IRMA-MH

- MH (Min-hop) routing
- TDMA link scheduling based on the path selection
- **Inputs** of the algorithm:
  - Topology \((G(V,E))\)
  - Traffic Profile (source-destination, bandwidth requirement) and
  - Interference-index \(k\)
  - TDMA frame length \(T\) (Number of slots in a frame)
- **Output**: route selection and MAC TDMA slot assignments

```
IRMA-MH Algorithm:
1. *Find the shortest route with hop metric*
2. *For each link \(e\) in each flow \(F_i\), assign earliest available slot \(x\) for this link as long as it does not conflict with the links already scheduled in this slot \(x\)*
3. *Repeat step 2 until all bandwidth requirements are fulfilled or no more slots are available.*
```
IRMA-BR

- Min-hop routes are not optimal, cause local congestions
- Better paths can be found and yield higher throughput than MH paths
- Joint TDMA Link Scheduling and Bandwidth Aware Routing (BR)

IRMA-BR Algorithm:
1. Sorting the flow in ascending order by bandwidth requirements
2. For each flow $F_i$, $i = 1, 2, ..., M$
   a) Generate link Metric based on available “free” TDMA Slots
   b) finding shortest path for flow $F_i$ with the “bandwidth” metric.
   and assign conflict-free TDMA slots for this flow
Performance Evaluation

- Implement the GCP and IRMA algorithms in ns-2.28
- Introduce the calculation of aggregated interference signal strength
- A separate control radio and channel in GCP
- Compare the performance
  - IRMA algorithms
  - Analytical bounds solved by LP
  - Baseline approaches
    - DSDV+802.11
    - AODV+802.11

### Simulation Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Topology size</td>
<td>1000x1000 m²</td>
</tr>
<tr>
<td>TX range</td>
<td>250m</td>
</tr>
<tr>
<td>Data channel rate</td>
<td>1Mbps</td>
</tr>
<tr>
<td>Control Channel rate</td>
<td>100kbps</td>
</tr>
<tr>
<td>SINR threshold</td>
<td>10 dB</td>
</tr>
<tr>
<td>Propagation Model</td>
<td>TwoRayGround</td>
</tr>
<tr>
<td>Path loss index</td>
<td>4</td>
</tr>
<tr>
<td>MAC slot duration</td>
<td>8.4 msec</td>
</tr>
<tr>
<td>Slots per frame</td>
<td>20</td>
</tr>
</tbody>
</table>

Based on $\text{SINR}_{\text{thresh}}$, 2-hop interference model is adopted in IRMA
A Typical Simulation Topology
Performance of IRMA-MH algorithm

- 5 Multi-hop flows
- Average Hop length: 3.22
- IRMA-MH algorithm supports much higher throughput (200%-400%) than baseline scenarios with conventional approaches
- Resource utilization is more efficient with conflict-free TDMA scheduling
IRMA-MH vs. IRMA-BR

IRMA-BR algorithm chooses a detour path to route around possible congested areas by using available bandwidth measurement as metric.

Different routes used by (a) IRMA-MH and (b) IRMA-BR in a 6x6 grid for two vertical flows.
Evaluation of the Signaling Overhead

Overhead Statistics
- Baseline: RTS/CTS + routing overhead
- IRMA: All control signaling in GCP

Simulation Topology:
- 4x4 grid
- 10 random start/end traffic sessions
- Traffic duration: exponential distributed.
- Results normalized by end-to-end throughput

<table>
<thead>
<tr>
<th>Scheme</th>
<th>normalized overhead</th>
</tr>
</thead>
<tbody>
<tr>
<td>IRMA-MH</td>
<td>1.499%</td>
</tr>
<tr>
<td>AODV+802.11</td>
<td>6.1962%</td>
</tr>
<tr>
<td>DSDV+802.11</td>
<td>7.0517%</td>
</tr>
</tbody>
</table>

IRMA approach reduce signaling overhead as well as improve throughput performance
Conclusion and Future Work

- We proposed IRMA for wireless mesh networks and discussed:
  - Interference-free scheduling
  - Realistic system model
  - Online algorithms
- Simulation results show that IRMA design improve end-to-end throughput significantly with modest signaling overhead
- Fundamental need to integrate routing and MAC scheduling for wireless mesh network design
- Ongoing and Future Work
  - Distributed IRMA algorithms
  - Extension to Multi-Channel Multi-Radio (MCMR) Mesh Networks
  - CSMA/TDMA overlay MAC emulation and ORBIT validation
Questions & Answers