Cross-Layer Design for Multi-Power, Multi-Interface Routing Protocol in Wireless Mesh Networks

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1. Introduction
   - Background
   - Motivation
2. Related Work
4. Simulation and Analysis
5. Conclusion & Future Work
Background

- Wireless mesh networks (WMNs) have received increased attention over the last years.
- WMNs consist of two types of nodes
  - Mesh routers
    - Equip with multiple wireless interface
    - Form the infrastructure/Backbone of WMNs
    - Increase the transmission range/coverage
  - Mesh clients
    - Usually have only one wireless interface
    - Access the network through mesh routers as well as directly meshing with other mesh clients
• The characteristics of WMNs
  – Multi-radio, Multi-channel, Multi-hop
  – Support for ad hoc networking, and capability of self-forming, self-healing, and self-organization
  – Multiple types of network access
  – Compatibility and interoperability with existing wireless networks support

• IEEE 802.11 TGs develops a flexible and extensible standard for WMNs based on original IEEE 802.11. [8]
  – The default routing protocol is HWMP and the optional routing protocol is RA-OLSR
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<tbody>
<tr>
<td>ID</td>
<td>Length</td>
<td>Version</td>
<td>Active Protocol ID</td>
<td>Active Metric ID</td>
<td>Peer Capacity</td>
<td>Power Save capability</td>
<td>Synchronization Capability</td>
<td>MDA Capability</td>
<td>Channel Precedence</td>
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<tr>
<td>OUI</td>
<td>Protocol Identifier</td>
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<tr>
<td>OUI</td>
<td>Metric Identifier</td>
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<table>
<thead>
<tr>
<th>OUI</th>
<th>Value</th>
<th>Meaning</th>
</tr>
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<tbody>
<tr>
<td>00-0F-AC</td>
<td>0</td>
<td>Hybrid Wireless Mesh Protocol (default path selection protocol)</td>
</tr>
<tr>
<td>00-0F-AC</td>
<td>1</td>
<td>Radio Aware OLSR (optional path selection protocol)</td>
</tr>
<tr>
<td>00-0F-AC</td>
<td>2-254</td>
<td>Reserved for future use</td>
</tr>
<tr>
<td>00-0F-AC</td>
<td>255</td>
<td>Null protocol</td>
</tr>
<tr>
<td>Vendor OUI</td>
<td>Other</td>
<td>Vendor specific</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>OUI</th>
<th>Value</th>
<th>Meaning</th>
</tr>
</thead>
<tbody>
<tr>
<td>00-0F-AC</td>
<td>0</td>
<td>Airtime path metric (default path metric)</td>
</tr>
<tr>
<td>00-0F-AC</td>
<td>1-254</td>
<td>Reserved for future use</td>
</tr>
<tr>
<td>00-0F-AC</td>
<td>255</td>
<td>Null metric</td>
</tr>
<tr>
<td>Vendor OUI</td>
<td>Other</td>
<td>Vendor specific</td>
</tr>
</tbody>
</table>
• In IEEE 802.11s draft list some usage models for wireless mesh networks
Transmit power control is essentially an cross-layer design problem.

The power control problem is complex since the choice of the power level affects many aspects of the networks:

- Signal quality
- Transmission range
- Interference
- Connectivity
- Throughput capacity
• Current wireless network interface cards also capable of multiple transmit power level setting
  – Cisco Aironet 350 series access points allow different transmit power settings (1, 5, 20, 30, 50, and 100mW)
  – An ideal power control protocol should follow the troughs of these curves [7]
Motivation

• Most of routing protocol design in WMNs focus on single layer of network stacks
• The theoretical [5] studies and simulation results demonstrates [6] the appropriate transmission power selection tightly affects network performance
• Original TPC in ad hoc networks only apply to single hop routing or use minimum hop counts as routing metric
• Based on MiRii [1], we proposed the $M^2iRi^2$ routing protocol to support multiple power levels transmission

• $M^2iRi^2$ routing protocol jointly coordinates the transmission power selection at each traffic flow and route selection among multi-interface nodes

• The goals of our proposed cross-layer routing protocol
  – Per-flow power control to establish routing path
  – To suppress the interference that impacting the ongoing transmission
  – To look after both network throughput and average end-to-end delay
Intra-flow interference

Inter-flow interference

Flow1

Flow2

Flow3

Route 1

Route 2

A

B
Outline

1. Introduction

2. Related Work
   - MiRii - Routing Protocol [1]


4. Simulation and Analysis

5. Conclusion & Future Work
Related Work

  - WCETT metric takes intra-flow interference into consideration (Intra-flow interference)
  - LBAR calculates nodal activity and traffic interference for choosing a path (Inter-flow interference)

\[ MiRii = \alpha \sum_{i=1}^{n} ETT_i + \beta \max_{1 \leq j \leq k} chanETT_j + \gamma\sum_{K \in path}^{AT_K}_{K \neq src,dst} \]

, where \( \alpha + \beta + \gamma = 1 \)
• **WCETT**: Weighted Cumulated ETT

\[
ETX = \frac{1}{d_f \times d_r}
\]

\[
ETT = ETX \times \frac{S}{B}
\]

\[
WCETT = \sum_{i=1}^{n} ETT_i
\] \hspace{1cm} \ldots \ldots (1)

\[
X_j = \sum_{\text{Hop on channel} j} ETT_i, 1 \leq j \leq k
\]

\[
WCETT = \max_{1 \leq j \leq k} X_j
\] \hspace{1cm} \ldots \ldots (2)

* S: packet size
* B: bandwidth (raw data rate)

• Equation (1) represents the sum of end-to-end delay over a \( n \) hops path

• \( X_j \) is the sum of transmission time of hops on channel \( j \)

• Equation (2) means the bottleneck channel

Combine equations (1) and (2):

\[
WCETT = (1 - \beta) \times \sum_{i=1}^{n} ETT_i + \beta \times \max_{1 \leq j \leq k} X_j
\]
• **Load-Balanced Ad Hoc Routing (LBAR)**
  
  - LBAR defines a new metric for routing known as the degree of **nodal activity** to represent the load on a node
    - \( A_i \): the number of active paths through node \( i \)
    - \( TI_i \) (Traffic interference): the sum of activity of neighboring nodes of node \( i \), where \( j \) is a neighbor node of node \( i \).
      
      \[
      TI_i = \sum_{j \neq i} A_j
      \]
    
  - The **Cost** of routing path \( k \): \( i \) is a node on path \( k \) other than source and destination, \( j \) is a neighboring node of node \( i \)
      
      \[
      C_k = \sum_{i \in k} (A_i + TI_i)
      \]
The average time in each node of a packet called Activity Time (AT)

Activity Time is derived from Little’s result.

\[ T(\text{average\_time}) = \frac{N(\text{average\_number})}{\lambda(\text{average\_arrival\_rate})} \]

\[ AT_K = \frac{N_K + \sum_{nb=1}^{m} N_{nb}^K}{\lambda_K + \sum_{nb=1}^{m} \lambda_{nb}^K} \]

\( N_k \): the average queue length

\( \lambda_k \): average packet receiving rate
• [2] A power controlled multiple access protocol for wireless packet networks
  
  – PCMA generalizes the transmit-or-defer “on/off” collision avoidance model to a “variable bounded power” collision suppression model

  – The protocol design is based on CSMA/CA and modifies the RTS/CTS to RPTS/APTS (Request-Power-To-Send / Acceptable-Power-To-Send)
- Nodes transmit the packets with the power level that does not disturb the ongoing receptions of its neighbors.
- To avoid the potential transmitter disturbing the ongoing reception, each receiver sends busy tone pulses to announce its noise tolerance.
• PCMA protocol steps

Source i  Destination j  Potential interference transmitter k

RPTS  APTS  DATA

Send Busy Tone Pulses

ACK
• Node j sends busy tone power depending on its “noise tolerance”, $E_j$.

$$E_j = \frac{Pr_j}{\text{SINR\_threshold}} - Pn_j$$

• When node k receives the busy tone power, it calculates its transmission power bound imposed by node j.

$$Pt\_bound = \min\{\min_j \left\{ \frac{E_j}{G_{jk}} \right\}, Pt\_max\}$$
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Cross-Layer Routing Protocol Architecture

- The cross-layer routing protocol coordinate network layer and physical layer
  - iTolerance calculation
  - iTolerance information exchange
  - TxPower level selection
  - Link quality measurement
  - MiRii routing protocol
• A packet transmission from node $i$ to node $j$ is successful reception if the received SINR is above a certain threshold.

\[
SINR_j = \frac{P_i G_{ij}}{\sum_{l \neq i} P_l G_{lj} + N_j} \geq SINR\_Threshold
\]

• By allowing vicinity nodes to transmit concurrently, the interference power increases and decreases the SINR
• *iTolerance* is the interference tolerance of any receiver node $j$ that is receiving an ongoing transmission and derives as follow:

\[
iTolerance_j = \frac{P_i G_{ij}}{\text{SINR}_{\text{threshold}}} - \left( \sum_{l \neq i} P_l G_{lj} + N_j \right)
\]

• We use the *iTolerance* to constrain the transmission power
• The node broadcasts *iTolerance* to its one-hop neighbors through probe packet
  – The probe packet broadcast interval is 1 second
### D’s iTolerance list

<table>
<thead>
<tr>
<th></th>
<th>A 0</th>
<th>4.0368e-10</th>
</tr>
</thead>
<tbody>
<tr>
<td>A 1</td>
<td>3.2152e-10</td>
<td></td>
</tr>
</tbody>
</table>

### C’s iTolerance list

<table>
<thead>
<tr>
<th></th>
<th>A 0</th>
<th>4.0368e-10</th>
</tr>
</thead>
<tbody>
<tr>
<td>A 1</td>
<td>3.2152e-10</td>
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</table>

### B’s iTolerance list

<table>
<thead>
<tr>
<th></th>
<th>A 0</th>
<th>4.0368e-10</th>
</tr>
</thead>
<tbody>
<tr>
<td>A 1</td>
<td>3.2152e-10</td>
<td></td>
</tr>
</tbody>
</table>

### E’s iTolerance list

<table>
<thead>
<tr>
<th></th>
<th>A 0</th>
<th>4.0368e-10</th>
</tr>
</thead>
<tbody>
<tr>
<td>A 1</td>
<td>3.2152e-10</td>
<td></td>
</tr>
</tbody>
</table>
• Transmission power control can be used to influence the routing by controlling the power level of route request packets

• The traffic flows use iTolerance to constrain the transmission power selection which suppress the interference producing to the ongoing transmissions
• When route discovery starts
  – The transmitter node $i$ looks over its neighbor $l$’s $iTolerance$
  – The node $i$ chooses the appropriate $TxPower$ level to send RREQ or forward RREQ messages
  – The lowest power is selected if no power level satisfy the constraint

$$\max\{TxPower \_ level \mid TxPower \_ level \leq \min_l\{\frac{iTolerance_l}{G_{il}}\}\}$$

• At the same time, the MiRii routing metric is utilized to evaluate the routing path

$$\text{MiRii} = \alpha \sum_{i=1}^{n} ETT_i + \beta \max_{1 \leq j \leq k} \text{chanETT}_j + \gamma \sum_{K \in \text{path}} \sum_{K \neq \text{src, dst}} AT_K$$

$\alpha=0.3, \beta=0.3, \gamma=0.4$
<table>
<thead>
<tr>
<th>Node</th>
<th>iTolerance</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>B</td>
<td>0</td>
<td>4.0368e-10</td>
</tr>
<tr>
<td>B</td>
<td>1</td>
<td>6.0211e-09</td>
</tr>
<tr>
<td>C</td>
<td>0</td>
<td>4.0368e-10</td>
</tr>
<tr>
<td>C</td>
<td>1</td>
<td>6.1325e-09</td>
</tr>
<tr>
<td>D</td>
<td>0</td>
<td>2.0368e-11</td>
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<tr>
<td>D</td>
<td>1</td>
<td>6.1578e-09</td>
</tr>
<tr>
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<td>0</td>
<td>5.0368e-10</td>
</tr>
<tr>
<td>E</td>
<td>1</td>
<td>7.9351e-08</td>
</tr>
</tbody>
</table>

**Diagram:**
- RREQ
- Low TxPower level
- High TxPower level
The power control is based on per-flow and routing protocol is designed for flow-based routing

- Original AODV routing protocol is a destination-based routing protocol, we modify it to a flow-based routing protocol
  - The flow-based routing solve route flapping problem which take place in destination-based routing protocol.

- Each traffic flow select difference $TxPower$ at each hop according to neighbors’ $iTolerance$ constraint
  - The traffic flow is identified by fid and has it corresponding $TxPower$ recording at routing table
B's Routing Table

<table>
<thead>
<tr>
<th>dst</th>
<th>nexthop</th>
<th>fid</th>
<th>TxPower</th>
<th>MiRii</th>
</tr>
</thead>
<tbody>
<tr>
<td>E</td>
<td>C</td>
<td>1</td>
<td>100mW</td>
<td>200</td>
</tr>
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</table>

Flow1
(200)

Flow1
(205)
<table>
<thead>
<tr>
<th>dst</th>
<th>nexthop</th>
<th>fid</th>
<th>TxPower</th>
<th>MiRii</th>
</tr>
</thead>
<tbody>
<tr>
<td>E</td>
<td>C</td>
<td>1</td>
<td>100mW</td>
<td>200</td>
</tr>
<tr>
<td>A</td>
<td>A</td>
<td>2</td>
<td>30mW</td>
<td>100</td>
</tr>
<tr>
<td>E</td>
<td>D</td>
<td>2</td>
<td>30mW</td>
<td>210</td>
</tr>
</tbody>
</table>
The implementation of the proposed routing protocol is based on Ad Hoc On-demand Distance Vector Routing Protocol (AODV).

- The probe packets are used to measure the link quality (ETT, chanETT, and AT) and piggyback the iTolerance information.
- RREQ, RREP packet are modified to conform with design goals.
Probe Packet Format

• The packet format of Probe packet
  - iTolerance table
  - Neighbor link quality table
  - Little’s result table

\[ \text{ratio}(t) = \frac{\text{count}(t - w, t)}{w/\tau} \]

\( \text{Count}(t-w, t) \) is the number of probes received during window \( w \)

\( w/\tau \) is the number of probes that should have been received
# RREQ Packet Format

<table>
<thead>
<tr>
<th>Type</th>
<th>J</th>
<th>R</th>
<th>G</th>
<th>D</th>
<th>U</th>
<th>Reserved</th>
<th>Hop Count</th>
</tr>
</thead>
<tbody>
<tr>
<td>RREQ ID</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Destination IP Address</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Destination Sequence Number</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Originator IP Address</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Originator Sequence Number</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- **MiRii routing metric**
  - $\Sigma ETT_{\text{link}}$
  - $\Sigma \text{chanETT}_{\text{link}}$
  - $\Sigma A T_{\text{node}}$

- **Per-flow power control**
  - Fid
  - TxPower
RREP Packet Format

<table>
<thead>
<tr>
<th>Type</th>
<th>R</th>
<th>A</th>
<th>Reserved</th>
<th>Hop Count</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Destination IP Address</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Destination Sequence Number</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Originator IP Address</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

\[ \Sigma_{\text{ETT}} \text{link} \]

\[ \Sigma_{\text{chanETT}} \text{link} \]

\[ \Sigma_{\text{AT}} \text{node} \]

Fid

TxPower

MiRii routing metric

Per-flow power control
Flow chart for **send** a RREQ message

Start Route Discovery

1. \( \text{rt\_flags == RTF\_UP} \) or
2. \( \text{rt\_req\_timeout > \text{CURRENT\_TIME}} \)

- No
  - \( \text{rq\_ETT} = 0 \)
  - \( \text{rq\_chan\_ETT} = 0 \)
  - \( \text{rq\_AT} = 0 \)
  - \( \text{Flow\_ID = fid} \)
  - \( \text{TxPower = TxPower}_{\text{high}} \)

Set \( \text{TxPower = TxPower}_{\text{low}} \)

If \( \text{TxPower}_{\text{high}} \leq \min (i\text{Tolerance}_{\text{nb}} / \text{Gain}_{\text{nb}}) \)

- Yes
  - Send RREQ

Drop RREQ

return
Flow chart for receive a RREQ message (1/2)

Input data: rreq_pkt, rtable

1. **Drop rreq**
   - Drop rreq
   - Return

2. **rq_src == self**
   - Yes
   - Create an entry for the reverse route
   - Reverse route for rq_src exits or not?
     - Yes
     - Compute MiRii value
     - return No
     - No
     - Cache rq_src & rq_id
     - recently heard this rreq
       - Yes
       - Compute MiRii value
       - return No
       - No
       - Start

3. **ETT = rq_ETT + ETTi**
   - chanETT = {rq_chanETT, (chani, ETTi)}
   - AT = rq_AT + ATself
     (i is the link from self to pre_hop)
   - Compute MiRii value
Flow chart for receive a RREQ message (2/2)

1. fresher seq no for rq_src or 
2. lesser #MiRii for 
the same seq.no.

Update reverse route
rrt_ETT = ETT
rrt_chanETT = chanETT
rrt_AT = AT
rt_MiRii = MiRii

Check rq_dst == self

sendReply
rp_ETT = ETT
rp_chanETT = { (chani, ETTi) }
rp_AT = 0
(i is the link from self to next_hop)
Flow_ID = fid
rp_TxPower = rq_TxPower

Have a fresh enough route to 
rq_dst

sendReply
rp_ETT = rt_ETT + ETTi
rq_chanETT = { (rt_chanETT),(chani, ETTi) }
rp_AT = rt_AT
(i is the link from self to next_hop)
Flow_ID = fid
rp_TxPower = rq_TxPower

If TxPower_high <= 
min (iTolerance_nb / Gain_nb )

Set TxPower =TxPower_low

Yes

Set TxPower =TxPower_high

No

Forward RREQ

Update RREQ
rq_ETT = rrt_ETT
rq_chanETT = rrt_chanETT
rq_AT = rrt_AT
Flow_ID = fid
TxPower = rq_TxPower
Flow charts for \textbf{send} RREP message

\begin{itemize}
\item Start
\item $rp_{-}ETT = ETT$
\item $rp_{-}chanETT = chanETT$
\item $rp_{-}AT = AT$
\item $Flow\_ID = fid$
\item $TxPower = rq\_TxPower$
\item Send RREP
\end{itemize}
Flow charts for receive RREP message

1. newer route or 2. lesser MiRii for the same seq no.

Yes

Update forward route
rt_ETT = rp_ETT
rt_chanETT = rp_chanETT
rt_AT = AT
rt_MiRii = MiRii

No

Forward data pkt

If this rrep is for node self

Yes

Discard rrep pkt

No

Reverse route for rq_src exits ?

Yes

Forward rrep
rp_ETT = rt_ETT + ETTi
rp_chanETT = {rt_chanETT, (chani, ETTi) }
rp_AT = rt_AT
(i is the link from self to next_hop)
Flow_ID=fid
TxPower = rt_TxPower

No

Start

AT = rp_AT + ATself
Compute MiRii

Yes

Forward route to rp_dst exits or not ?

No
Create an entry for the forward route

No
Input data: rrep pkt

Drop rrep pkt

exit

exit

Yes

start
Outline

1. Introduction
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• Change original NS-2
  – Cumulative interference in SINR computation
  – Per flow power control
  – MiRii Routing metric

• Use two power levels (100mW and 30mW) for power selection

<p>| | |</p>
<table>
<thead>
<tr>
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<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Packet Size</td>
<td>1000 Bytes</td>
</tr>
<tr>
<td>Channel carrier frequency</td>
<td>2.472e9</td>
</tr>
<tr>
<td>Radio propagation model</td>
<td>TwoRayGround</td>
</tr>
<tr>
<td>SINR threshold</td>
<td>6.02dB</td>
</tr>
<tr>
<td>Noise Floor</td>
<td>-120dBm</td>
</tr>
<tr>
<td>CS_Thresh</td>
<td>-94dBm</td>
</tr>
<tr>
<td>RX_Thresh</td>
<td>-94dBm</td>
</tr>
<tr>
<td>Pt_level1</td>
<td>30mW</td>
</tr>
<tr>
<td>Pt_level2</td>
<td>100mW</td>
</tr>
</tbody>
</table>
A simple topology

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>MiRii 30mW</td>
<td>Average e-e delay (ms)</td>
<td>14.00</td>
<td>37.92</td>
<td>102.29</td>
</tr>
<tr>
<td></td>
<td>Throughput (Kbps)</td>
<td>511.05</td>
<td>884.73</td>
<td>1118.93</td>
</tr>
<tr>
<td>MiRii 100mW</td>
<td>Average e-e delay</td>
<td>11.75</td>
<td>16.84</td>
<td>141.46</td>
</tr>
<tr>
<td></td>
<td>Throughput</td>
<td>510.21</td>
<td>1003.79</td>
<td>1057.09</td>
</tr>
</tbody>
</table>
A uniform network topology
Traffic Type: CBR, Average Flow Number: 5 flows

Average End-to-End Delay (msec)

- CBR: 512Kbits/s
- CBR: 1Mbits/s

M²iR², Mirii 30mW, Mirii 100mW, AODV 30mW, AODV 100mW
A random network topology
Traffic Type: CBR, Average Flow Number: 5 flows

Throughput (Kbps)

<table>
<thead>
<tr>
<th>Traffic Type</th>
<th>M^2iRi^2 30mW</th>
<th>Mirii 100mW</th>
<th>AODV 30mW</th>
<th>AODV 100mW</th>
</tr>
</thead>
<tbody>
<tr>
<td>CBR:512Kbits/s</td>
<td>4000</td>
<td>3000</td>
<td>2000</td>
<td>1000</td>
</tr>
<tr>
<td>1Mbits/s</td>
<td>3000</td>
<td>2000</td>
<td>1000</td>
<td>500</td>
</tr>
</tbody>
</table>
Traffic Type: CBR, Average Flow Number: 5 flows

Average End-to-End Delay (msec)

- M²iR²
- Mirii 30mW
- Mirii 100mW
- AODV 30mW
- AODV 100mW

CBR: 512Kbits/s
CBR: 1Mbits/s
Outline

1. Introduction
2. Related Work
4. Simulation and Analysis
5. Conclusion & Future Work
Conclusion

• We proposed $M^2iRi^2$ routing protocol for multi-interface WMNs which coordinate the physical layer and the network layer.

• The iTolerance is introduced into power control and incorporate it to route discovery.

• The MiRii routing metric is utilized to evaluate the routing path.

• The power control is based on per-flow and routing protocol is designed for flow-based routing.

• $M^2iRi^2$ routing protocol can look after both network throughput and end-to-end delay.
Future Work

• We may incorporate M²iRi² with the traffic flow admission control
• The transmission data rate control is another issue in the protocol design
• In the future, we consider evaluating the protocol in an actual system


Thank you!