Thesis Defence

The Feasibility and Usefulness of Link Abstraction in Wireless Networks

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What is ‘link abstraction’?

- Concept derived from ‘wired networks’
- If link abstraction exists –

![Graph showing the relationship between Packet Error Rate and Average RSSI (dBm).](image)

- Steep change in Error Rate
- Negligible error rates
If link abstraction is absent –

- It’s Existence simplifies
  - Complex routing metrics
  - Network protocols
  - Improves network performance
Introduction – Link Abstraction

- If link abstraction exists -

<table>
<thead>
<tr>
<th>Link</th>
<th>Exists</th>
<th>Doesn’t exist</th>
</tr>
</thead>
<tbody>
<tr>
<td>Error rate</td>
<td>Negligible (0%)</td>
<td>All packets lost (100%)</td>
</tr>
<tr>
<td>SNR and BER</td>
<td>Rapid change</td>
<td>Gradual change</td>
</tr>
</tbody>
</table>

- It’s Existence simplifies
  - Complex routing metrics
  - Network protocols
  - Improves network performance
We look for answers to:

- Is link abstraction feasible? Especially in:
  - Wireless Sensor Networks (WSNs)
  - Wireless Mesh Networks based on 802.11b (WMNs) – link distances < 500m
- Is there a method to engineer links with ‘link abstraction’?
- Is there a possibility of classifying existing links?
- Is there a factor / factors that invalidate ‘link abstraction’?
Related Work and Motivation
Related Work and Motivation: WMNs

Motivation

- Measurement study of WMNs motivated by FRACTEL (wi-Fi based Regional/Rural data Access and TELephony)

- FRACTEL : AIM
  
  "Extend the connectivity available at a single location in a village, to multiple locations while aiming to provide data, voice and video services over the links...."
### Related Work and Motivation: WMNs

- **Important wireless measurement studies** –
  - *Roofnet* – Community Mesh Network
  - *DGP* – Long Distance Network

### Setting:

<table>
<thead>
<tr>
<th></th>
<th>Community WMNs</th>
<th>Long Distance WMNs</th>
<th>FRACTEL (Presently)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>External Connectivity</strong></td>
<td>Multiple points</td>
<td>Single point</td>
<td>Single</td>
</tr>
<tr>
<td><strong>Link Distance</strong></td>
<td>Mostly &lt;500m</td>
<td>Up to few 10s of kms</td>
<td>Mostly &lt; 500m</td>
</tr>
<tr>
<td><strong>Network Architecture</strong></td>
<td>Unplanned, Omni antennas on rooftops</td>
<td>High gain directional antennas on tall towers</td>
<td>Avoid use of tall towers</td>
</tr>
<tr>
<td><strong>Environment</strong></td>
<td>Dense urban</td>
<td>Rural</td>
<td>Rural</td>
</tr>
</tbody>
</table>
### Related Work and Motivation: WMNs

#### Contrasting Results

<table>
<thead>
<tr>
<th></th>
<th>Community WMNs E.g.: Roofnet</th>
<th>Long Distance WMNs E.g.: DGP</th>
<th>FRACTEL (Presently)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Link Abstraction</strong></td>
<td>INVALID</td>
<td>VALID</td>
<td>To be determined</td>
</tr>
<tr>
<td><strong>Effect of Multi-path</strong></td>
<td>Strong Component observed</td>
<td>Less Susceptible</td>
<td>To be determined</td>
</tr>
<tr>
<td><strong>SNR / RSSI &amp; Link Quality</strong></td>
<td>Not useful to predict link quality</td>
<td>Has strong correlation with link quality</td>
<td>To be determined</td>
</tr>
</tbody>
</table>
Related Work and Motivation: WMNs

❖ **Roofnet Results** –
  - Intermediate delivery probabilities *(neither 0% or 100%)* on majority links
  - Multi-path is major cause of losses

❖ **Proposed routing metrics to work around** –
  - **ETX** –
    • Minimises expected time of transmission to ultimate destination


  - **WCETT** –
    • Chooses a channel diverse path

  *(Draves, R., Padhye, J., and Zill, B. Routing in Multi-Radio, Multi-Hop Wireless Mesh Networks. In MOBICOM (Sep 2004))*
Zhao and Govindan have shown:

- Absence of a *link abstraction*
- Presence of a ‘gray/transitional’ region
  - Outdoor – $1/5^{th}$ of total communication range
  - Indoor – $1/3^{rd}$ total communication range
  - Error rates – unpredictable, varying


- Problem addressed by
  - Routing metrics to differentiate between links
    - Multi-hop LQI (Link Quality Indicator)
    - $1/\text{PSR}$ (Packet Success Rate)
Related Work – Summary

❖ **Most literature reports** –
  ▪ The absence of link abstraction
  ▪ Links with intermediate delivery rates
  ▪ Routing metrics that choose the best link amongst them

❖ **Our work suggests** –
  ▪ Link abstraction is ‘feasible’
  ▪ It can be used to build predictable links
  ▪ This simplifies things like routing
Experimental Setup
And
Methodology
Experimental Setup – WMNs

❖ **Hardware** –
  - Senao 2511CD Plus 802.11b PCMCIA cards
  - Laptops
  - Antennas
    - Sector Antenna (\textit{Sector}) – 17 dBi
    - Omni Directional Antenna (\textit{Omni}) – 8 dBi

❖ **Software** –
  - Linux – kernel 2.6.11
  - Modified HostAP driver – ver 0.4.9
Experimental Setup: WMNs
Experiment Locations: WMNs

- **Experiment Locations** –
  - On Campus – 5
  - Village – 1

- Fixed one transmitter position

- Varied up to 6 receiver positions

- Receiver position classification –
  - Good – Avg. RSSI ≈ -70 dBm
  - Medium – Avg. RSSI ≈ -75 dBm
  - Bad – Avg. RSSI ≈ -80 dBm

- At each location – combination of Rx positions
Experiment Locations: WMNs

- ACES Type II – Apt
- Staff Ground – Gnd
- Hall 8 – dorm
- SBRA – Apt2dorm
- Academic Area – corridor
- Village Amaur – Vill

Images Source: http://earth.google.com
Experimental Setup – WSNs

- **Hardware** –
  - Tmote Sky motes
    - CC2420 Zigbee compliant 2.4GHz radio
  - Laptops
  - Antennas
    - Parabolic Grid Antenna *(Grid)* – 24 dBi
    - Sector Antenna *(Sector)* – 17 dBi
    - Omni Directional Antenna *(Omni)* – 8 dBi

- **Software** –
  - TinyOS – Open source OS
Experiment Locations: WSNs

- Dense Foliage – foliage
- Narrow road – road
- Hall 8 – dorm
- Structures Lab – lab
- Airstrip – airstrip
WMNs
Results and Implications
Controlled experiment – cards + RF cable

Experiments done at all 6 locations

6000 1400-byte broadcast pkts, 20ms gap between packets, 4 data rates

Average values for 100 pkt bins

Noise nearly constant (-94 to -95 dBm)
WMNs: Error Rate vs. RSSI

- ‘Threshold’ visible in interference free cases
- If RSSI > Threshold –
  - Error Rates – stable and low
- In ‘steep region’ –
  - Unpredictable error rates
- Intermediate Error Rates
  - Cause – Interference!
- Why different in Roofnet?
WMNs: Roofnet Data – A relook

- We observed high noise values in logs

- Our logs and DGP – Noise levels (-94 – -95 dBm)

- Noise floor reported by card –
  - Average Energy level sensed before pkt reception
  - Energy level averaged over a time duration

- In case of multipath, noise level should not be high

  Noise Band $\approx 16$ dB
  Maximum Noise $\approx -75$ dBm

  (Note: Data Rate: 1Mbps, Average RSSI > -80 dBm, 80%>Error Rate> 20 %)

- What is the cause of increased noise level

  Interference?

Max Noise Band in DGP / our expts $\approx 2$ dB, Max Noise = -94 dB
Controlled Interference Experiment

- **Experimental Setup**

  - **Source A**: 1400-byte packets, 2ms interval
  - **Source B**: 1300-byte packets, 2ms interval
  - **Source B**'s power fixed at -75 dBm
  - **Source A**'s power varied: -90, -85, -80, -75 dBm
Interference Experiment – Questions

❖ Does Interference increase the noise level reported by the card?

❖ Can packet loss be related to the number of foreign packets seen?

❖ Can the reported noise level be used to gauge the level of interference?

❖ *Can we estimate the link performance based on the ‘Average measured noise floor’?*
Interference Experiment – Answers

- Interference causes noise level to be high and variable
- Packet loss high even though number of observed foreign packets low
- Packet loss can be low even though number of observed foreign packets is high
- On this H/W, gauging level of interference is error prone
- It is not possible to estimate the link quality based on reported noise floor
## Controlled Interference Experiment

*Does Interference increase the noise level reported by the card?*

<table>
<thead>
<tr>
<th>Col-1</th>
<th>Col-2</th>
<th>Col-5</th>
<th>Col-8</th>
<th>Col-9</th>
</tr>
</thead>
<tbody>
<tr>
<td>Expt No</td>
<td>Src</td>
<td>Mean Noise (dBm)</td>
<td>Noise Band (dB)</td>
<td>Max Noise (dBm)</td>
</tr>
<tr>
<td>1</td>
<td>A</td>
<td>-93.26</td>
<td>4</td>
<td>-88</td>
</tr>
<tr>
<td>1</td>
<td>B</td>
<td>-92.1</td>
<td>6</td>
<td>-88</td>
</tr>
<tr>
<td>2</td>
<td>A</td>
<td>-92.53</td>
<td>9</td>
<td>-85</td>
</tr>
<tr>
<td>2</td>
<td>B</td>
<td>-89.34</td>
<td>9</td>
<td>-84</td>
</tr>
<tr>
<td>3</td>
<td>A</td>
<td>-90.85</td>
<td>14</td>
<td>-80</td>
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<tr>
<td>3</td>
<td>B</td>
<td>-85.16</td>
<td>14</td>
<td>-80</td>
</tr>
<tr>
<td>4</td>
<td>A</td>
<td>-93.06</td>
<td>2</td>
<td>-74</td>
</tr>
<tr>
<td>4</td>
<td>B</td>
<td>-90.18</td>
<td>19</td>
<td>-74</td>
</tr>
</tbody>
</table>
Controlled Interference Experiment

Controlled Experiment

[Graph showing packet statistics and signal strength]

Avg RSSI
- A : -85 dBm
- B : -75 dBm

Roofnet

[Graph showing packet statistics and signal strength]

Noise extends right up to -65 dBm

P1: Interference causes noise level to be high and variable
Controlled Interference Experiment

- Can packet loss be related to the level of interference seen?

<table>
<thead>
<tr>
<th>Expt No</th>
<th>Src</th>
<th>Loss %</th>
<th>Mean RSSI (dBm)</th>
<th>Mean Noise (dBm)</th>
<th>Col-6 5 %-ile (dBm)</th>
<th>Col-7 95 %-ile (dBm)</th>
<th>Col-8 Noise Band (dB)</th>
<th>Col-9 Max Noise (dBm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>A</td>
<td>99.2</td>
<td>-85.23</td>
<td>-92.53</td>
<td>-94</td>
<td>-85</td>
<td>9</td>
<td>-85</td>
</tr>
<tr>
<td>2</td>
<td>B</td>
<td>18.3</td>
<td>-74.68</td>
<td>-89.34</td>
<td>-94</td>
<td>-85</td>
<td>9</td>
<td>-84</td>
</tr>
</tbody>
</table>

- B’s loss = 18.3%; A’s loss = 99.2%
- Even if B stops, A’s loss = 99%

P2: Packet loss high even though number of observed foreign packets low
**P3:** Packet loss can be low even though number of observed foreign packets is high.
Controlled Interference Experiment

P2
Packet loss high
Foreign Packets low

P3
Packet loss low
Foreign Packets high

Roofnet
No Correlation between loss rate & rate of foreign packet reception
Controlled Interference Experiment

- Can the reported noise level be used to gauge the level of interference?
  - Instantaneous noise levels show variability
  - Noise levels reported differ from known level
  - Reason?

- Method the card measures the noise floor.
- Timing decides reported value.

**P4:** On this H/W, gauging level of interference is error prone.
Controlled Interference Experiment

- Can we estimate the link performance based on the ‘Average measured noise floor’?

**P5:** It is not possible to estimate the link quality based on reported noise floor.
### WMNs: RSSI Stability and Error Variability

<table>
<thead>
<tr>
<th>Location</th>
<th>Rx Posn</th>
<th>LoS? (Y/N)</th>
<th>Dur. (hrs)</th>
<th>RSSI 95%-ile (dBm)</th>
<th>RSSI 5%-ile (dBm)</th>
<th>RSSI Band (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Apt</td>
<td>1</td>
<td>Y</td>
<td>48</td>
<td>-66</td>
<td>-69</td>
<td>3</td>
</tr>
<tr>
<td>Apt</td>
<td>2</td>
<td>N (foliage)</td>
<td>48</td>
<td>-69</td>
<td>-77</td>
<td>8</td>
</tr>
<tr>
<td>Apt</td>
<td>3</td>
<td>N (foliage)</td>
<td>48</td>
<td>-76</td>
<td>-82</td>
<td>6</td>
</tr>
<tr>
<td>Apt2Dorm</td>
<td>1</td>
<td>Y</td>
<td>24</td>
<td>-75</td>
<td>-77</td>
<td>2</td>
</tr>
<tr>
<td>Apt2Dorm</td>
<td>2</td>
<td>Y</td>
<td>24</td>
<td>-70</td>
<td>-71</td>
<td>1</td>
</tr>
<tr>
<td>Apt2Dorm</td>
<td>3</td>
<td>N (foliage)</td>
<td>24</td>
<td>-79</td>
<td>-81</td>
<td>2</td>
</tr>
</tbody>
</table>

RSSI Band over long term mostly below 5 dB (LoS)
WMNs: RSSI Stability and Error Variability

- **Interest: RSSI stability**
  - Short term
  - Long Term
  - Short term stability – within 3 – 4 dB
  - Long term stability – within 5 dB (LoS)
  - Close to the steep region
    - RSSI overlaps steep region
    - Error rates – unpredictable, varying

![Error Rate vs Bin Number](image)

Error Rate vs Bin Number
Village, Avg RSSI = -80.5 dBm
WMNs: Summary of Results

- **Interference**: Major cause of intermediate error rates (neither close to 0% nor 100%)
- **RSSI Threshold** exists in absence of interference.
- Above the threshold, ‘link abstraction’ holds.
- **RSSI is stable over long and short durations**
- **Error Rate is unpredictable and varies (close to the steep region)**
- Difficult to **gauge interference** using available hardware
Design Implications – Link Abstraction

- Allows us to plan links with predictable performance. How?

RSSI Threshold
- 79 dBm, 11Mbps

RSSI Variation
3 – 4 dBm

Modified RSSI Threshold Value
-75 dBm
Link Measurement

Also useful to determine transmit powers between 2 nodes
Routing

- Proposed metrics like ETX and WCETT are unstable

Error Rate vs Bin Number
Village, Avg RSSI = -80.5dBm
Opportunistic Routing (EXOR)

- Tries to work in presence of interference
- Tries to take advantage of any abnormal link range that may be achieved
- Source broadcasts packet
- Based on who received packet, chooses who forwards packet on next hop
- Difficult to achieve predictable performance

Better to avoid interference.
Design Implications – Routing

❖ Interference Aware Routing –
  ▪ Methods proposed in literature
  ▪ Use the value of SNR to gauge level of interference

❖ Our measurements using our H/W indicate that reported noise floor unreliable for:
  ▪ Inference of interference
  ▪ Estimation of link quality

❖ Possible with appropriate H/W ?
Design Implications – MAC protocols

❖ **CSMA / CA MACs:**
  ▪ Use CS and CA to avoid interference
  ▪ RTS/CTS to overcome hidden node cases
  ▪ However, not foolproof as Interference Range > Signal Range

❖ **TDMA MAC**
  ▪ Possible solution
  ▪ May be suitable for FRACTEL
WSNs
Results and Implications
WSNs – Calibration Experiment

- 5000 packets, 20 ms interval
- TOSBase on mote connected to laptop
- Received packets logged on laptop


WSNs – Calibration

- Error rate rises sharply for small change in SNR. Gives rise to the ‘steep region’
- Link abstraction holds
- Error Rate varies in the steep region
- Variability – Operation close to sensitivity of radio

![Graph showing Packet Error Rate vs Avg RSSI](image-url)
Real Life Experiments: Error Rate vs RSSI

- RSSI threshold exists
  - RSSI > threshold –
    - error rates are stable and low
    - Link Abstraction holds
  - Spread of points with intermediate error rate increases

- Spread of points with intermediate error rate increases
Temporal Variability – RSSI

- RSSI is variable over small (20 ms) and long durations (20 sec).
- RSSI variability: 4 to 5 dB across days.

- Foliage, 20 ms, Bin Size=1
- Foliage, 2 sec, Bin Size=100
- Foliage, 20 sec, Bin Size=1000
### Temporal Variability – Error Rate

Error rate varies, and unpredictable.

- RSSI overlaps steep region
- Similar variability in other environments:
  - Foliage, BinSz=100, -87 dBm
  - Foliage, BinSz=1000, -87 dBm
  - Road, Omni, BinSz=100, -89 dBm

<table>
<thead>
<tr>
<th>Environment</th>
<th>BinSz</th>
<th>RSSI</th>
<th>Error Rate (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Foliage-40m</td>
<td>100</td>
<td>-87</td>
<td>70</td>
</tr>
<tr>
<td>Corridor-60m</td>
<td>100</td>
<td>-84</td>
<td>38</td>
</tr>
<tr>
<td>Corridor-60m</td>
<td>100</td>
<td>-84</td>
<td>70</td>
</tr>
<tr>
<td>Corridor-60m</td>
<td>1000</td>
<td>-87</td>
<td>67</td>
</tr>
<tr>
<td>Lab Loc. 2</td>
<td></td>
<td></td>
<td>74</td>
</tr>
<tr>
<td>Lab Loc 2</td>
<td></td>
<td></td>
<td>73</td>
</tr>
<tr>
<td>Road, Omni, BinSz=100</td>
<td>-89dBm</td>
<td></td>
<td>7</td>
</tr>
</tbody>
</table>
WSNs: Implications

- RSSI Threshold exists

- Planning Links – to build predictable links
  - Take sample measurements
  - Allow worst case leeway in RSSI band
  - Operate link at such a point

- Classify links in an existing network

- Effect of variation (Time Scale)
  - Small – Routing metrics
  - Large – Old measurements invalid
Conclusion
In the absence of interference

- If RSSI > Threshold
  - Error rates are stable and low
  - ‘Link abstraction’ is feasible

Interference destroys correlation between error rate and RSSI / SNR

Close to steep region error rate becomes variable and unpredictable
Conclusion – Summary

- **Link Abstraction simplifies:**
  - Routing
  - Allows planning predictable links
  - Classifying existing links for predictable ops.
  - Helps achieve better and predictable network performance
  - ‘BriMon’ uses the concept of link abstraction.
Future Work

- Specific experiments to rule out multipath
- Experiments in the 5 GHz band
  - De-licensed in India in Jan 07
- Achieve finer time synchronisation and over multiple hops
- Effect of Interference on WSN links
Motivation and Related Work

- Measurement studies show ‘absence of link abstraction’

- Implications of absence -
  - Intermediate error rates on a link
  - State of link needs to be tracked. Why?
  - Complex routing metrics required. Especially in multi-hop.
WSNs: Link Range Measurements

- Predictable Operation $\rightarrow$ Lower Ranges

- Number of ways to Increase Range
  - Increase Transmit Power
  - Use Multiple Hops
  - Use External Antennas

- Link Range Experiments:
  - Environments – Foliage, Road
  - Antenna Combinations (Tx – Rx)
    - Internal – Internal
    - Omni – Internal
    - Sector – Omni
    - Grid – Omni
## WSNs: Link Range Measurements

<table>
<thead>
<tr>
<th>Environment</th>
<th>Location – Distance</th>
<th>Avg Pkt Error (Std Dev) (%)</th>
<th>Avg RSSI (Std Dev) (dBm)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Foliage</strong></td>
<td>Internal – 35m</td>
<td>0.3 (1.25)</td>
<td>-78.79 (3.43)</td>
</tr>
<tr>
<td></td>
<td>Sector – 30m</td>
<td>0.53 (2.6)</td>
<td>-80.77 (3.55)</td>
</tr>
<tr>
<td></td>
<td>Grid – 70m</td>
<td>1.6 (4.08)</td>
<td>-85.05 (4.19)</td>
</tr>
<tr>
<td><strong>Road</strong></td>
<td>Omni – 75m</td>
<td>0 (0)</td>
<td>-80.64 (2.47)</td>
</tr>
<tr>
<td></td>
<td>Sector – 210m</td>
<td>0 (0)</td>
<td>-81.92 (0.49)</td>
</tr>
<tr>
<td><strong>Airstrip</strong></td>
<td>Grid – 500m</td>
<td>0 (0)</td>
<td>-85.67 (0.94)</td>
</tr>
</tbody>
</table>

فيلم: Substantial increase in range achieved
Implications

- In WSNs, use of external antennas –
  - Provides substantial increase in communication range
  - Allows predictable performance
  - Simplifies network architecture
  - Simplifies routing
  - Can help to increase network lifetime by reducing message overhead
Diagram

All Locations
5 locations

Interference Prone
- No Correlation between SNR and Error Rate

Interference Free
- Threshold exists
- Error rates low and stable
- Close to steep region -- Error rates varying and stable
<table>
<thead>
<tr>
<th>Expt No</th>
<th>Src</th>
<th>Mean RSSI (dBm)</th>
<th>Loss %</th>
<th>Mean Noise (dBm)</th>
<th>5 %-ile (dBm)</th>
<th>95 %-ile (dBm)</th>
<th>Noise Band (dB)</th>
<th>Max Noise (dBm)</th>
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<tbody>
<tr>
<td>1</td>
<td>A</td>
<td>-89.74</td>
<td>100</td>
<td>-93.26</td>
<td>-94</td>
<td>-90</td>
<td>4</td>
<td>-88</td>
</tr>
<tr>
<td>1</td>
<td>B</td>
<td>-75.59</td>
<td>0.5</td>
<td>-92.1</td>
<td>-94</td>
<td>-88</td>
<td>6</td>
<td>-88</td>
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<tr>
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<td>-75</td>
<td>19</td>
<td>-74</td>
</tr>
</tbody>
</table>