Wireless in the Real World

- Real world deployment patterns
- Mesh networks and deployments
- Assigned reading
  - Modeling Wireless Links
  - Architecture and Evaluation of an Unplanned 802.11b Mesh Network
Wireless Challenges

- Force us to rethink many assumptions
- Need to share airwaves rather than wire
  - Don’t know what hosts are involved
  - Host may not be using same link technology
- Mobility
- Other characteristics of wireless
  - Noisy $\rightarrow$ lots of losses
  - Slow
  - Interaction of multiple transmitters at receiver
    - Collisions, capture, interference
    - Multipath interference

Overview

- 802.11
  - Deployment patterns
  - Reaction to interference
  - Interference mitigation

- Mesh networks
  - Architecture
  - Measurements
Characterizing Current Deployments

• Datasets
  • Place Lab: 28,000 APs
    • MAC, ESSID, GPS
    • Selected US cities
    • www.placelab.org
  • Wifimaps: 300,000 APs
    • MAC, ESSID, Channel, GPS (derived)
    • wifimaps.com
  • Pittsburgh Wardrive: 667 APs
    • MAC, ESSID, Channel, Supported Rates, GPS

AP Stats, Degrees: Placelab

<table>
<thead>
<tr>
<th></th>
<th>#APs</th>
<th>Max. degree</th>
</tr>
</thead>
<tbody>
<tr>
<td>Portland</td>
<td>8683</td>
<td>54</td>
</tr>
<tr>
<td>San Diego</td>
<td>7934</td>
<td>76</td>
</tr>
<tr>
<td>San Francisco</td>
<td>3037</td>
<td>85</td>
</tr>
<tr>
<td>Boston</td>
<td>2551</td>
<td>39</td>
</tr>
</tbody>
</table>
Unmanaged Devices

WifiMaps.com
(300,000 APs, MAC, ESSID, Channel)

<table>
<thead>
<tr>
<th>Channel %age</th>
<th>6</th>
<th>51</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>11</td>
<td>21</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>14</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>4</td>
</tr>
</tbody>
</table>

- Most users don’t change default channel
- Channel selection must be automated
Growing Interference in Unlicensed Bands

- Anecdotal evidence of problems, but how severe?
- Characterize how 802.11 operates under interference in practice

What do we expect?

- Throughput to decrease linearly with interference
- There to be lots of options for 802.11 devices to tolerate interference
  - Bit-rate adaptation
  - Power control
  - FEC
  - Packet size variation
  - Spread-spectrum processing
  - Transmission and reception diversity
Key Questions

• How damaging can a low-power and/or narrow-band interferer be?

• How can today’s hardware tolerate interference well?
  • What 802.11 options work well, and why?

What we see

• Effects of interference more severe in practice

• Caused by hardware limitations of commodity cards, which theory doesn’t model
Experimental Setup

- Extend SINR model to capture these vulnerabilities
- Interested in worst-case natural or adversarial interference
  - Have developed range of “attacks” that trigger these vulnerabilities
Timing Recovery Interference

- Interferer sends continuous SYNC pattern
- Interferes with packet acquisition (PHY reception errors)

Interference Management

- Interference will get worse
  - Density/device diversity is increasing
  - Unlicensed spectrum is not keeping up

- Spectrum management
  - “Channel hopping” 802.11 effective at mitigating some performance problems [Sigcomm07]
  - Coordinated spectrum use – based on RF sensor network

- Transmission power control
  - Enable spatial reuse of spectrum by controlling transmit power
  - Must also adapt carrier sense behavior to take advantage
Impact of frequency separation

- Even small frequency separation (i.e., adjacent 802.11 channel) helps

Transmission Power Control

- Choose transmit power levels to maximize *physical* spatial reuse
- Tune MAC to ensure nodes transmit simultaneously when possible
- Spatial reuse = network capacity / link capacity

![Diagram of APs and clients demonstrating spatial reuse](image)
Transmission Power Control in Practice

- For simple scenario $\rightarrow$ easy to compute optimal transmit power
  - May or may not enable simultaneous transmit
  - Protocol builds on iterative pair-wise optimization

- Adjusting transmit power $\rightarrow$ requires adjusting carrier sense thresholds
  - Echos, Alpha or eliminate carrier sense
  - Altrusitic Echos – eliminates starvation in Echos

Details of Power Control

- Hard to do per-packet with many NICs
  - Some even might have to re-init (many ms)
- May have to balance power with rate
  - Reasonable goal: lowest power for max rate
  - But finding this empirically is hard! Many \{power, rate\} combinations, and not always easy to predict how each will perform
  - Alternate goal: lowest power for max needed rate
    - But this interacts with other people because you use more channel time to send the same data. Uh-oh.
    - Nice example of the difficulty of local vs. global optimization
Rate Adaptation

• General idea:
  • Observe channel conditions like SNR (signal-to-noise ratio), bit errors, packet errors
  • Pick a transmission rate that will get best goodput
    • There are channel conditions when reducing the bitrate can greatly increase throughput – e.g., if a \( \frac{1}{2} \) decrease in bitrate gets you from 90% loss to 10% loss.

Simple rate adaptation scheme

• Watch packet error rate over window (K packets or T seconds)
• If loss rate > thresh\(_{\text{high}}\) (or SNR <, etc)
  • Reduce Tx rate
• If loss rate < thresh\(_{\text{low}}\)
  • Increase Tx rate
• Most devices support a discrete set of rates
  • 802.11 – 1, 2, 5.5, 11, etc.
Challenges in rate adaptation

- Channel conditions change over time
  - Loss rates must be measured over a window
- SNR estimates from the hardware are coarse, and don’t always predict loss rate
- May be some overhead (time, transient interruptions, etc.) to changing rates

Power and Rate Selection Algorithms

- Rate Selection
  - Auto Rate Fallback: ARF
  - Estimated Rate Fallback: ERF

- Goal: Transmit at minimum necessary power to reach receiver
  - Minimizes interference with other nodes
  - Paper: Can double or more capacity, *if done right.*

- Joint Power and Rate Selection
  - Power Auto Rate Fallback: PARF
  - Power Estimated Rate Fallback: PERF
  - Conservative Algorithms
    - Always attempt to achieve highest possible modulation rate
Power Control/Rate Control summary

- Complex interactions…
  - More power:
    - Higher received signal strength
    - May enable faster rate (more S in S/N)
      - May mean you occupy media for less time
    - Interferes with more people
  - Less power
    - Interferes with fewer people
    - Less power + less rate
      - Fewer people but for a longer time

- Gets even harder once you consider
  - Carrier sense
  - Calibration and measurement error
  - Mobility

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Community Wireless Network

- Share a few wired Internet connections
- Construction of community networks
  - Multi-hop network
    - Nodes in chosen locations
    - Directional antennas
    - Require well-coordination
  - Access point
    - Clients directly connect
    - Access points operates independently
    - Do not require much coordination

Roofnet

- Goals
  - Operate without extensive planning or central management
  - Provide wide coverage and acceptable performance
- Design decisions
  - Unconstrained node placement
  - Omni-directional antennas
  - Multi-hop routing
  - Optimization of routing for throughput in a slowly changing network
Roofnet Design

- Deployment
  - Over an area of about four square kilometers in Cambridge, Massachusetts
  - Most nodes are located in buildings
    - 3~4 story apartment buildings
    - 8 nodes are in taller buildings
  - Each Roofnet node is hosted by a volunteer user
- Hardware
  - PC, omni-directional antenna, hard drive …
  - 802.11b card
    - RTS/CTS disabled
    - Share the same 802.11b channel
    - Non-standard “pseudo-IBSS” mode
      - Similar to standard 802.11b IBSS (ad hoc)
      - Omit beacon and BSSID (network ID)
Roofnet

Typical Rooftop View
A Roofnet Self-Installation Kit

Antenna ($65)
8dBi, 20 degree vertical

Computer ($340)
533 MHz PC, hard disk, CDROM

802.11b card ($155)
Engenius Prism 2.5, 200mW

50 ft. Cable ($40)
Low loss (3dB/100ft)

Miscellaneous ($75)
Chimney Mount, Lightning Arrestor, etc.

Software (“free”)
Our networking software based on Click

Total: $685

Takes a user about 45 minutes to install on a flat roof

Software and Auto-Configuration

• Linux, routing software, DHCP server, web server …
• Automatically solve a number of problems
  • Allocating addresses
  • Finding a gateway between Roofnet and the Internet
  • Choosing a good multi-hop route to that gateway
• Addressing
  • Roofnet carries IP packets inside its own header format and routing protocol
  • Assign addresses automatically
  • Only meaningful inside Roofnet, not globally routable
  • The address of Roofnet nodes
    • Low 24 bits are the low 24 bits of the node’s Ethernet address
    • High 8 bits are an unused class-A IP address block
  • The address of hosts
    • Allocate 192.168.1.x via DHCP and use NAT between the Ethernet and Roofnet
Software and Auto-Configuration

• Gateway and Internet Access
  • A small fraction of Roofnet users will share their wired Internet access links
  • Nodes which can reach the Internet
    • Advertise itself to Roofnet as an Internet gateway
    • Acts as a NAT for connection from Roofnet to the Internet
  • Other nodes
    • Select the gateway which has the best route metric

Roofnet currently has four Internet gateways

Evaluation

• Method
  • Multi-hop TCP
    • 15 second one-way bulk TCP transfer between each pair of Roofnet nodes
  • Single-hop TCP
    • The direct radio link between each pair of routes
  • Loss matrix
    • The loss rate between each pair of nodes using 1500-byte broadcasts
  • Multi-hop density
    • TCP throughput between a fixed set of four nodes
    • Varying the number of Roofnet nodes that are participating in routing
Evaluation

- Basic Performance (Multi-hop TCP)
  - The routes with low hop-count have much higher throughput
  - Multi-hop routes suffer from inter-hop collisions

<table>
<thead>
<tr>
<th>Hops</th>
<th>Number of Pairs</th>
<th>Throughput (kbits/sec)</th>
<th>Latency (ms)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>158</td>
<td>2451</td>
<td>14</td>
</tr>
<tr>
<td>2</td>
<td>303</td>
<td>771</td>
<td>26</td>
</tr>
<tr>
<td>3</td>
<td>301</td>
<td>362</td>
<td>45</td>
</tr>
<tr>
<td>4</td>
<td>223</td>
<td>266</td>
<td>50</td>
</tr>
<tr>
<td>5</td>
<td>120</td>
<td>210</td>
<td>60</td>
</tr>
<tr>
<td>6</td>
<td>43</td>
<td>272</td>
<td>100</td>
</tr>
<tr>
<td>7</td>
<td>33</td>
<td>181</td>
<td>83</td>
</tr>
<tr>
<td>8</td>
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<td>159</td>
<td>119</td>
</tr>
<tr>
<td>9</td>
<td>4</td>
<td>175</td>
<td>182</td>
</tr>
<tr>
<td>10</td>
<td>1</td>
<td>182</td>
<td>218</td>
</tr>
<tr>
<td>no route</td>
<td>132</td>
<td>0</td>
<td>—</td>
</tr>
<tr>
<td>Avg: 2.9</td>
<td>Total: 1332</td>
<td>Avg: 84</td>
<td>Avg: 39</td>
</tr>
</tbody>
</table>

TCP Throughput (kiloths/second)

Evaluation

- Basic Performance (Multi-hop TCP)
  - TCP throughput to each node from its chosen gateway
  - Round-trip latencies for 84-byte ping packets to estimate interactive delay

<table>
<thead>
<tr>
<th>Hops</th>
<th>Number of nodes</th>
<th>Throughput (kbits/sec)</th>
<th>Latency (ms)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>12</td>
<td>2752</td>
<td>9</td>
</tr>
<tr>
<td>2</td>
<td>8</td>
<td>940</td>
<td>19</td>
</tr>
<tr>
<td>3</td>
<td>5</td>
<td>552</td>
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<td>4</td>
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<td>379</td>
<td>43</td>
</tr>
<tr>
<td>5</td>
<td>1</td>
<td>89</td>
<td>37</td>
</tr>
<tr>
<td>Avg: 2.3</td>
<td>Total: 33</td>
<td>Avg: 1320</td>
<td>Avg: 22</td>
</tr>
</tbody>
</table>
Evaluation

• Link Quality and Distance (Single-hop TCP, Multi-hop TCP)
  • Most available links are between 500m and 1300m and 500 kbits/s

• Link Quality and Distance (Multi-hop TCP, Loss matrix)
  • Median delivery probability is 0.8
  • 1/4 links have loss rates of 50% or more
  • 802.11 detects the losses with its ACK mechanism and resends the packets
Evaluation

• Architectural Alternatives
  • Maximize the number of additional nodes with non-zero throughput to some gateway
  • Ties are broken by average throughput

<table>
<thead>
<tr>
<th>GWs</th>
<th>Conn</th>
<th>Multi-Hop Throughput (kbits/sec)</th>
<th>Single-Hop Throughput (kbits/sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>37</td>
<td>781</td>
<td>23</td>
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<td>2</td>
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<td>4</td>
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<td>37</td>
<td>2355</td>
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<td>6</td>
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<td>7</td>
<td>37</td>
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<td>9</td>
<td>37</td>
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</tr>
<tr>
<td>10</td>
<td>37</td>
<td>2795</td>
<td>37</td>
</tr>
<tr>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>15</td>
<td>37</td>
<td>3197</td>
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<td>20</td>
<td>37</td>
<td>3508</td>
<td>37</td>
</tr>
<tr>
<td>25</td>
<td>37</td>
<td>3721</td>
<td>37</td>
</tr>
</tbody>
</table>

Evaluation

• Inter-hop Interference (Multi-hop TCP, Single-hop TCP)
  • Concurrent transmissions on different hops of a route collide and cause packet loss
Roofnet Summary

• The network’s architectures favors
  • Ease of deployment
  • Omni-directional antennas
  • Self-configuring software
  • Link-quality-aware multi-hop routing

• Evaluation of network performance
  • Average throughput between nodes is 627kbits/s
  • Well served by just a few gateways whose position is determined by convenience
  • Multi-hop mesh increases both connectivity and throughput

Roofnet Link Level Measurements

• Analyze cause of packet loss

• Neighbor Abstraction
  • Ability to hear control packets or No Interference
  • Strong correlation between BER and S/N

• RoofNet pairs communicate
  • At intermediate loss rates
  • Temporal Variation
  • Spatial Variation
Lossy Links are Common

Delivery Probabilities are Uniformly Distributed

Broadcast packet delivery probability

70-100%
30-70%
1-30%

1 kilometer

> two-thirds of links deliver less than 90%

Node Pair
Delivery vs. SNR

- SNR not a good predictor

Is it Bursty Interference?

- May interfere but not impact SNR measurement
Two Different Roofnet Links

- Top is typical of bursty interference, bottom is not
- Most links are like the bottom

Is it Multipath Interference?

- Simulate with channel emulator
A Plausible Explanation

• Multi-path can produce intermediate loss rates
• Appropriate multi-path delay is possible due to long-links

Key Implications

• Lack of a link abstraction!
  • Links aren’t on or off… sometimes in-between

• Protocols must take advantage of these intermediate quality links to perform well

• How unique is this to Roofnet?
  • Cards designed for indoor environments used outdoors
Roofnet Design - Routing Protocol

• **Srcr**
  - Find the highest throughput route between any pair of Roofnet nodes
  - Source-routes data packets like DSR
  - Maintains a partial database of link metrics

• **Learning fresh link metrics**
  - Forward a packet
  - Flood to find a route
  - Overhear queries and responses

• **Finding a route to a gateway**
  - Each Roofnet gateway periodically floods a dummy query
  - When a node receives a new query, it adds the link metric information
  - The node computes the best route
  - The node re-broadcasts the query
  - Send a notification to a failed packet’s source if the link condition is changed

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Roofnet Design

• **Routing Metric**
  - ETT (Estimated Transmission Time) metric
    - **\[ t = \frac{1}{\sum_i \frac{1}{t_i}} \]**
    - Srcr chooses routes with ETT
    - Predict the total amount of time it would take to send a data packet
    - Take into account link’s highest-throughput transmit bit-rate and delivery probability
    - Each Roofnet node sends periodic 1500-byte broadcasts

• **Bit-rate Selection**
  - 802.11b transmit bit-rates
    - 1, 2, 5.5, 11 Mbits/s
  - **SampleRate**
    - Judge which bit-rate will provide the highest throughput
    - Base decisions on actual data transmission
    - Periodically sends a packet at some other bit-rate