15-744: Computer Networking

L-10 Wireless in the Real World

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 → 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

Wireless in the Real World

• Real world deployment patterns
• Mesh networks and deployments
• Assigned reading
  • Self-Management in Chaotic Wireless Deployments
  • Architecture and Evaluation of an Unplanned 802.11b Mesh Network
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: Place Lab

<table>
<thead>
<tr>
<th>City</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>

Degree Distribution: Place Lab

Unmanaged Devices

- Most users don’t change default channel
- Channel selection must be automated

WNDFM.com

(300,000 APs, MAC, ESSID, Channel)

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

802.11 Access Point

UDP flow

802.11 Interferer

802.11 Client

802.11 Receiver Path

Timing Recovery Interference

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

Throughput (kbps) vs. Interferer Power (dBm)

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

Transmission Power Control in Practice

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

- Adjusting transmit power → 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$_{high}$ (or SNR <, etc)
  • Reduce Tx rate
• If loss rate < thresh$_{low}$
  • 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

**Overview**

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  - Interference mitigation

- Mesh networks
  - Architecture
  - Measurements

**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 operate 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)
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

• 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

• 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

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>Hop</th>
<th>Number of Paths</th>
<th>Throughput (kbits/sec)</th>
<th>Latency (ms)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>154</td>
<td>114</td>
<td>11</td>
</tr>
<tr>
<td>2</td>
<td>301</td>
<td>771</td>
<td>26</td>
</tr>
<tr>
<td>3</td>
<td>301</td>
<td>382</td>
<td>45</td>
</tr>
<tr>
<td>4</td>
<td>223</td>
<td>266</td>
<td>59</td>
</tr>
<tr>
<td>5</td>
<td>120</td>
<td>219</td>
<td>60</td>
</tr>
<tr>
<td>6</td>
<td>24</td>
<td>795</td>
<td>108</td>
</tr>
<tr>
<td>7</td>
<td>33</td>
<td>181</td>
<td>83</td>
</tr>
<tr>
<td>8</td>
<td>14</td>
<td>150</td>
<td>129</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>238</td>
</tr>
<tr>
<td>Avg 2.3 hops</td>
<td>132</td>
<td>Avg: 133</td>
<td>Avg: 38</td>
</tr>
</tbody>
</table>

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>Hop</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>27/32</td>
<td>9</td>
</tr>
<tr>
<td>2</td>
<td>8</td>
<td>9/40</td>
<td>19</td>
</tr>
<tr>
<td>3</td>
<td>5</td>
<td>8/2</td>
<td>27</td>
</tr>
<tr>
<td>4</td>
<td>7</td>
<td>37/9</td>
<td>43</td>
</tr>
<tr>
<td>5</td>
<td>1</td>
<td>80/3</td>
<td>37</td>
</tr>
<tr>
<td>Avg: 2.3 Total: 33</td>
<td>Avg: 1309</td>
<td>Avg: 22</td>
<td></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

Evaluation

- **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>GW</th>
<th>Multi-Hop Conn</th>
<th>Multi-Hop Throughput (kbits/sec)</th>
<th>Single-Hop Conn</th>
<th>Single-Hop Throughput (kbits/sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>37</td>
<td>522</td>
<td>35</td>
<td>398</td>
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<td>2</td>
<td>37</td>
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<td>8</td>
<td>37</td>
<td>2402</td>
<td>37</td>
<td>2123</td>
</tr>
<tr>
<td>9</td>
<td>37</td>
<td>2402</td>
<td>37</td>
<td>2123</td>
</tr>
<tr>
<td>10</td>
<td>37</td>
<td>2402</td>
<td>37</td>
<td>2123</td>
</tr>
</tbody>
</table>

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

Inter-hop Interference (Multi-hop TCP, Single-hop TCP)

• Concurrent transmissions on different hops of a route collide and cause packet loss
Lossy Links are Common

Delivery Probabilities are Uniformly Distributed

Delivery vs. SNR

Is it Bursty Interference?

- SNR not a good predictor

- 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