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

Wireless in the Real World
- Real world deployment patterns
- Mesh networks and deployments
- Assigned reading
  - Architecture and Evaluation of an Unplanned 802.11b Mesh Network
  - White Space Networking with Wi-Fi like Connectivity

Overview
- 802.11
  - Deployment patterns
  - Reaction to interference
  - Interference mitigation
- Mesh networks
  - Architecture
  - Measurements
- White space networks
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

(Place Lab: 28000 APs, MAC, ESSID, GPS)

<table>
<thead>
<tr>
<th>City</th>
<th>#APs</th>
<th>Max degree</th>
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</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

WifiMaps.com

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

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

- Access Point

- 802.11 Client

- UDP flow

- 802.11 Interferer

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**Timing Recovery Interference**

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

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**802.11 Receiver Path**

- To RF Amplifiers
- ADC
- 16-bit samples
- Timing Recovery
- Barker Correlator
- Preamble Detector
- Header CRC-16 Checker
- Descrambler
- Demodulator
- Data (includes beacons)

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**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
Overview

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  - Interference mitigation

- Mesh networks
  - Architecture
  - Measurements

- White space networks

Roofnet

- Share a few wired Internet connections

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)
      - Omits beacon and BSSID (network ID)

Roofnet Node Map

1 kilometer
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

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
Roofnet

Lossy Links are Common

Delivery Probabilities are Uniformly Distributed

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

Roofnet Design

- Routing Metric
  - ETT (Estimated Transmission Time) metric
    \[ t = \frac{1}{\sum \frac{1}{x_i}} \]
  - 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

ETX measurement results

- Delivery is probabilistic
  - A 1/r^2 model wouldn’t really predict this!
  - Sharp cutoff (by spec) of “good” vs “no” reception. Intermediate loss range band is just a few dB wide!

- Why?
  - Biggest factor: Multi-path interference
    - 802.11 receivers can suppress reflections < 250ns
    - Outdoor reflections delay often > 1 \mu sec
    - Delay offsets == symbol time look like valid symbols (large interference)
    - Offsets != symbol time look like random noise
    - Small changes in delay == big changes in loss rate
Deciding Between Links

• Most early protocols: Hop Count
  • Link-layer retransmission can mask some loss
  • But: a 50% loss rate means your link is only 50% as fast!
• Threshold?
  • Can sacrifice connectivity. 😊
  • Isn’t a 90% path better than an 80% path?
• Real life goal: Find highest throughput paths

Is there a better metric?

• Cut-off threshold
  • Disconnected network
• Product of link delivery ratio along path
  • Does not account for inter-hop interference
• Bottleneck link (highest-loss-ratio link)
  • Same as above
• End-to-end delay
  • Depends on interface queue lengths

ETX Metric Design Goals

• Find high throughput paths
• Account for lossy links
• Account for asymmetric links
• Account for inter-link interference
• Independent of network load (don’t incorporate congestion)

Forwarding Packets is Expensive

• Throughput of 802.11b =~ 11Mbits/s
  • In reality, you can get about 5.
• What is throughput of a chain?
  • A → B → C
  • A → B → C → D
  • Assume minimum power for radios.
• Routing metric should take this into account! Affects throughput
**ETX**

- Measure each link’s delivery probability with broadcast probes (& measure reverse)
- \( P(\text{delivery}) = (d_t \ast d_r) \) (ACK must be delivered too…)
- Link ETX = 1 / \( P(\text{delivery}) \)
- Route ETX = \( \Sigma \) link ETX
  - Assumes all hops interfere - not true, but seems to work okay so far

**ETX: Sanity Checks**

- ETX of perfect 1-hop path: 1
- ETX of 50% delivery 1-hop path: 2
- ETX of perfect 3-hop path: 3

- (So, e.g., a 50% loss path is better than a perfect 3-hop path! A threshold would probably fail here…)

**Rate Adaptation**

- What if links @ different rates?
- ETT – expected *transmission time*
  - \( \text{ETX} / \text{Link rate} = 1 / (P(\text{delivery}) \ast \text{Rate}) \)
- What is best rate for link?
  - The one that maximizes ETT for the link!
  - SampleRate is a technique to adaptively figure this out.

**Discussion**

- Value of implementation & measurement
  - Simulators did not “do” multipath
    - Routing protocols dealt with the simulation environment just fine
    - Real world behaved differently and really broke a lot of the proposed protocols that worked so well in simulation!
  - Rehash: Wireless differs from wired…
  - Metrics: Optimize what matters; hop count often a very bad proxy in wireless
  - What we didn’t look at: routing protocol overhead
    - One cool area: Geographic routing
Overview

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What are White Spaces?

- Each channel is 6 MHz wide
- FCC Regulations:
  - Sense TV station and Mic
  - Portable devices on channels
- Unoccupied TV Channels

The Promise of White Spaces

- More Spectrum
- Longer Range
  - up to 3-4x of Wi-Fi
White Spaces Spectrum Availability

Differences from ISM (Wi-Fi)

Fragmentation
Variable channel widths

Location impacts spectrum availability  ➔ Spectrum exhibits spatial variation

Channel Assignment in Wi-Fi

Fixed Width Channels  ➔ Optimize which channel to use
Spectrum Assignment in WhiteFi

**Spectrum Assignment Problem**

- **Goal**: Maximize Throughput
- **Include**: Spectrum at clients
- **Assign**: Center Channel & Width

**Fragmentation** ⇒ Optimize for both, center channel and width

**Spatial Variation** ⇒ BS must use channel if free at client

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**Intuition**

- Use widest possible channel
- But
- Limited by most busy channel

  - Carrier Sense Across All Channels
  - All channels must be free
    - $\rho_{BS}(2 \text{ and } 3 \text{ are free}) = \rho_{BS}(2 \text{ is free}) \times \rho_{BS}(3 \text{ is free})$

**Tradeoff between wider channel widths and opportunity to transmit on each channel**

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**Accounting for Spatial Variation**

- 1 2 3 4 5
- 1 2 3 4 5

**Discovering a Base Station**

- Discovery Time = $O(B \times W)$

  - Fragmentation ⇒ Try different center channel and widths
  - channels used by the BS?
SIFT, by example

SIFT

Pattern match in time domain

ADC

SIFT

Time

Amplitude

Evaluation

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

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)
  • 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 (kbps/sec)</th>
<th>Latency (ms)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>12</td>
<td>2762</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>
<td>27</td>
</tr>
<tr>
<td>4</td>
<td>7</td>
<td>379</td>
<td>43</td>
</tr>
<tr>
<td>5</td>
<td>1</td>
<td>80</td>
<td>37</td>
</tr>
<tr>
<td>Avg: 2.3</td>
<td>Total: 33</td>
<td>Avg: 1350</td>
<td>Avg: 22</td>
</tr>
</tbody>
</table>
• **Link Quality and Distance (Single-hop TCP, Multi-hop TCP)**
  - Most available links are between 500m and 1300m and give 500 kbits/s

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

• **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

  - **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