Acknowledgments: Lecture slides are from the graduate level Computer Networks course thought by Srinivasan Seshan at CMU. When slides are obtained from other sources, a reference will be noted on the bottom of that slide. A full list of references is provided on the last slide.
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
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

• 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

(Placelab: 28000 APs, MAC, ESSID, GPS)

<table>
<thead>
<tr>
<th>City</th>
<th>#APs</th>
<th>Max. degree</th>
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<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>
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</table>
Degree Distribution: Place Lab
Unmanaged Devices

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

Channel %age

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<th></th>
<th>6</th>
<th>51</th>
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</thead>
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<tr>
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<td>21</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>14</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>4</td>
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</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

**802.11 Client**

**Access Point**

**UDP flow**

**802.11 Interferer**

**Client**
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
Overview

- **802.11**
  - Deployment patterns
  - Reaction to interference
  - 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)
      - Omit beacon and BSSID (network ID)
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
Roofnet

![Roofnet Diagram]

- **NATed LAN**
- **Roofnet Nodes**
- **Wired Gateways**
- **Internet**
- **Roofnet to IP Proxy**
Lossy Links are Common
Delivery Probabilities are Uniformly Distributed

![Graph showing delivery probabilities as a function of node pair and broadcast packet delivery probability. The graph indicates that delivery probabilities are above two-thirds of links for more than 90% of the node pairs.]
• 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

![Graph showing delivery probability over time with two lines, one with higher variance and the other with lower variance.](image)
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
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 μs
    • 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 $\rightarrow$ B $\rightarrow$ C ?
  • A $\rightarrow$ B $\rightarrow$ C $\rightarrow$ 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)
- $P(\text{delivery}) = (d_f \times d_r)$ (ACK must be delivered too...)
- Link ETX = $1 / P(\text{delivery})$
- Route ETX = $\sum \text{link ETX}$
  - 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*
  - $\text{ETX} / \text{Link rate} = 1 / (P(\text{delivery}) \times \text{Rate})$
- What is best rate for link?
  - The one that minimizes 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
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  • Measurements

• White space networks
What are White Spaces?

- Each channel is 6 MHz wide.
- FCC Regulations:
  - Sense TV stations and Mics.
  - Portable devices on channels 21-51.

White Spaces are Unoccupied TV Channels.
The Promise of White Spaces

More Spectrum

Up to 3x of 802.11g

Longer Range

at least 3 - 4x of Wi-Fi
White Spaces Spectrum Availability

Differences from ISM (Wi-Fi)

Fragmentation

Variable channel widths

Each TV Channel is 6 MHz  Spectrum is Fragmented  nnels for more bandwidth
White Spaces Spectrum Availability

Location impacts spectrum availability ⇒ Spectrum exhibits spatial variation

Differences from ISM (Wi-Fi)

- **Fragmentation**: Variable channel widths
- **Spatial Variation**: Cannot assume same channel free everywhere

⇒ Spectrum exhibits spatial variation
White Spaces Spectrum Availability

Differences from ISM (Wi-Fi)

- Fragmentation
  - Variable channel widths

- Spatial Variation
  - Cannot assume same channel free everywhere

- Temporal Variation
  - Same Channel will not always be free
  - *Any* connection can be disrupted *any* time

Incumbents appear/disappear over time  ⇒  Must reconfigure after disconnection
Channel Assignment in Wi-Fi

Fixed Width Channels  $\Rightarrow$ 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 *potn*, *center channel* and *width*

Spatial Variation ⇒ BS must use channel iff free at client
Accounting for Spatial Variation

∪

∪

=
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
Discovering a Base Station

Can we optimize this discovery time?

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

Fragmentation \( \Rightarrow \) Try different center channel and widths

channels used by the BS?
SIFT, by example

5 MHz

ADC -> SIFT

SIFT
Does not decode packets
Pattern match in time domain

Time

Amplitude

Data -> ACK
SIFS