15-744: Computer Networking

L-10 Wireless in the Real World

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 → 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

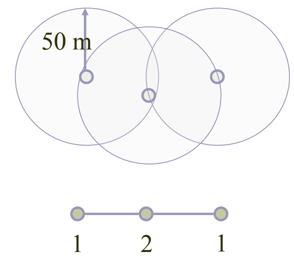
Characterizing Current Deployments

- 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

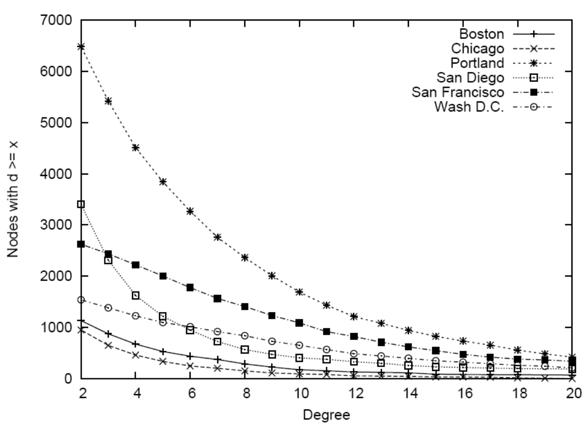
AP Stats, Degrees: Placelab

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

	#APs	Max. degree
Portland	8683	54
San Diego	7934	76
San Francisco	3037	85
Boston	2551	39



Degree Distribution: Place Lab



Unmanaged Devices

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

Channel	%age
6	51
11	21
1	14
10	4

- 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

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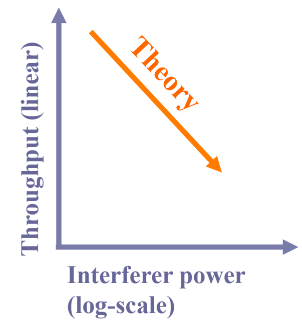
What do we expect?

- 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



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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?

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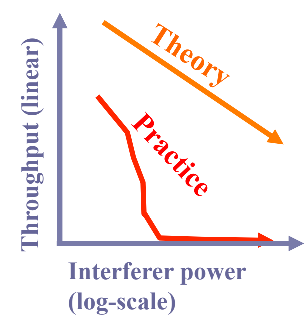
What we see

- Effects of interference more severe in practice
- Caused by hardware limitations of commodity cards, which theory doesn't model



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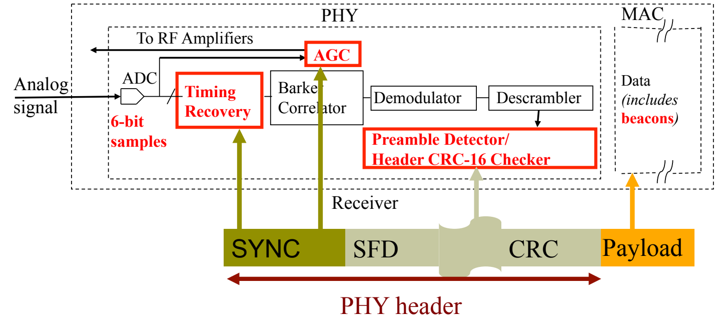
Experimental Setup

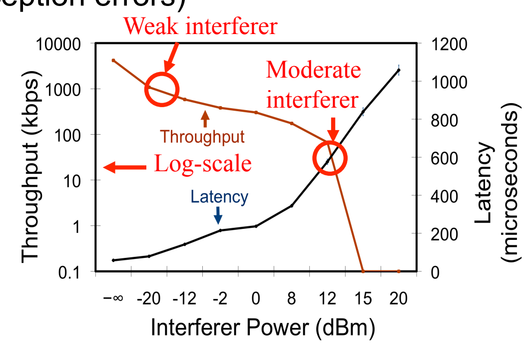
802.11 Receiver Path



- 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

Overview

- 802.11
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  - Interference mitigation
- Mesh networks
  - Architecture
  - Measurements
- White space networks

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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

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Roofnet Design

- Deployment
  - Over an area of about four square kilometers in Cambridge, Messachusetts
  - Most nodes are located in buildings
    - 3~4 story apartment buildings
    - 8 nodes are in taller buildings
  - Each Rooftnet 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)

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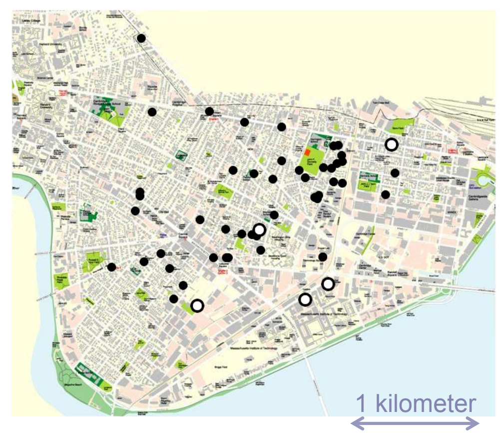
Roofnet Node Map



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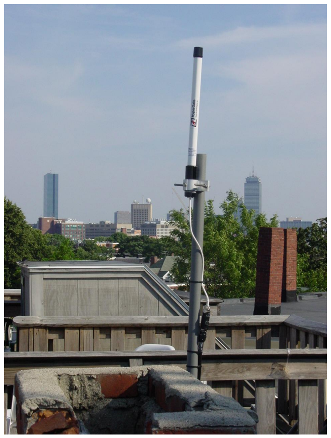
Typical Rooftop View



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

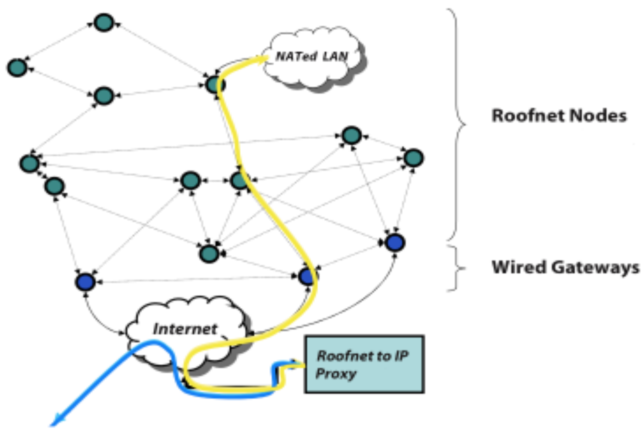
Software and Auto-Configuration

- 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



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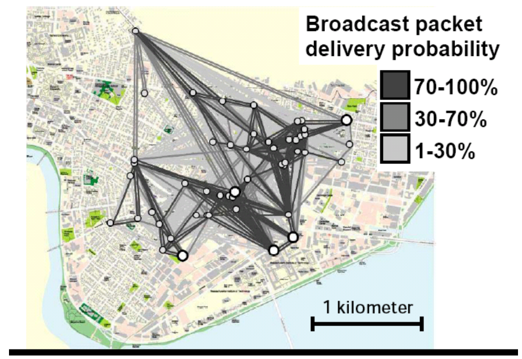
Lossy Links are Common



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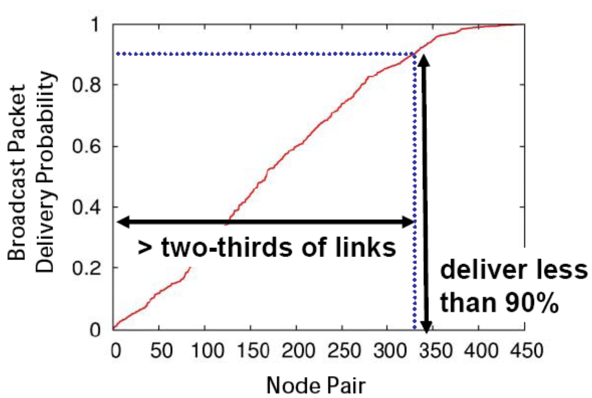
Delivery Probabilities are Uniformly Distributed



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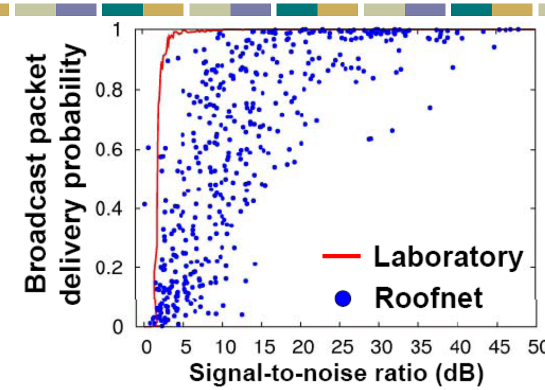
Delivery vs. SNR



- SNR not a good predictor

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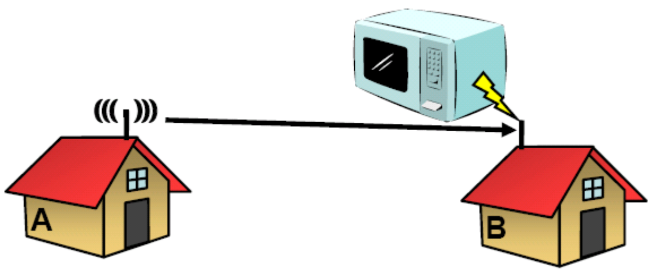
Is it Bursty Interference?

- May interfere but not impact SNR measurement



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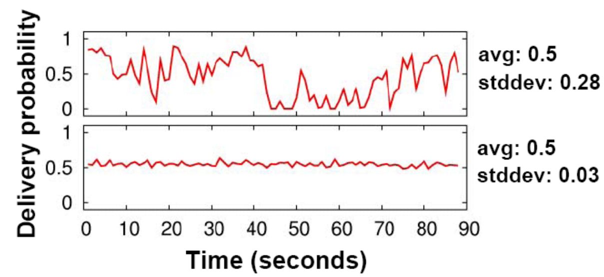
Two Different Roofnet Links

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



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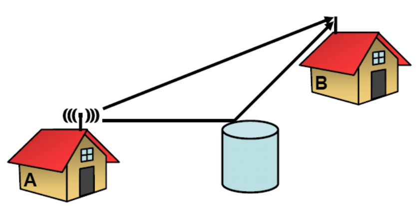
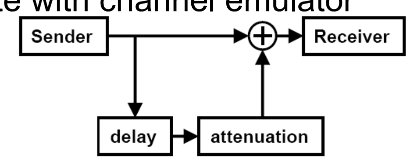
Is it Multipath Interference?



- Simulate with channel emulator



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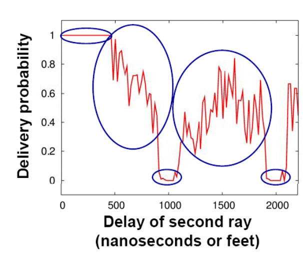
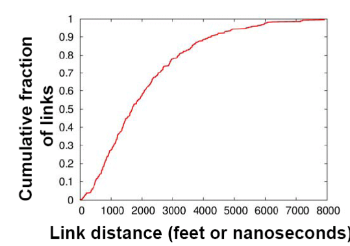
A Plausible Explanation

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





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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

$$t = \frac{1}{\sum_i \frac{1}{t_i}}$$

- Routing Metric
  - ETT (Estimated Transmission Time) metric
    - 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 interferece)
    - 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(delivery) = (d_f * d_r)   (ACK must be delivered too…)
- Link ETX = 1 / P(delivery)
- Route ETX = Σ 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*
  - ETX / Link rate = 1 / (P(delivery) * Rate)
- What is best rate for link?
  - The one that maximizes ETT for the link!
  - SampleRate is a technique to adaptively figure this out.

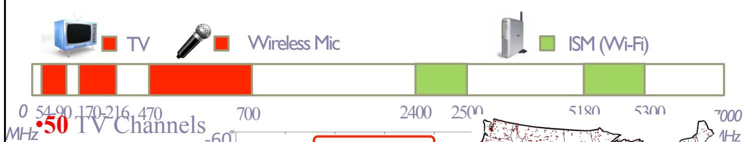
Discussion

- 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

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

What are White Spaces?



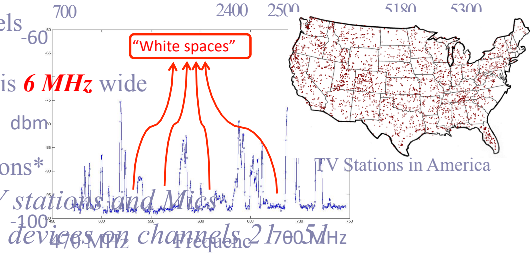
•50 TV Channels

•Each channel is *6 MHz* wide

•FCC Regulations*

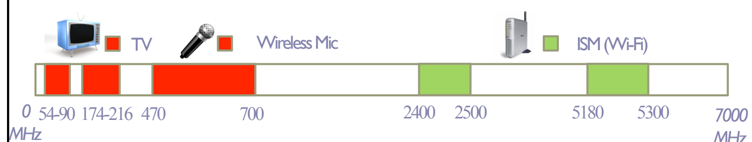
•*Sense TV stations and Mics*

•*Portable devices on channels 21 - 51*



White Spaces are *Unoccupied* TV Channels

The Promise of White Spaces



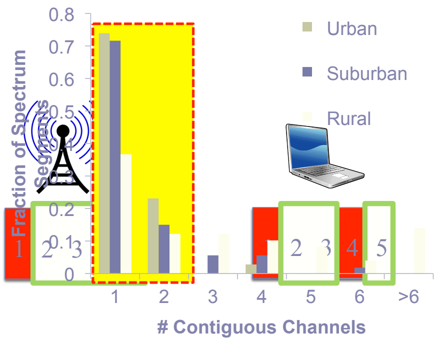
Up to 3x of 802.11g

More Spectrum

Longer Range

at least 3 - 4x of Wi-Fi

White Spaces Spectrum Availability

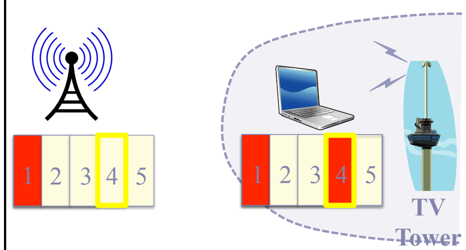


Differences from ISM(Wi-Fi)

Fragmentation
→ Variable channel widths

Each TV Channel is 6 MH Spectrum is Fragmented nnels for more bandwidth

White Spaces Spectrum Availability



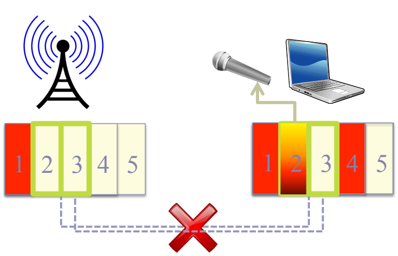
Differences from ISM(Wi-Fi)

Fragmentation
→ Variable channel widths

Spatial Variation
→ Cannot assume same channel free everywhere

Location impacts spectrum availability ⇒ Spectrum exhibits spatial variation

White Spaces Spectrum Availability



Differences from ISM(Wi-Fi)

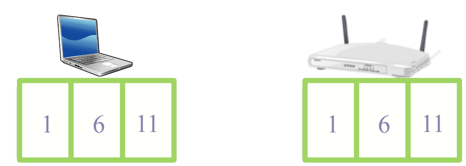
Fragmentation
→ Variable channel widths

Spatial Variation
→ Cannot assume same channel free everywhere

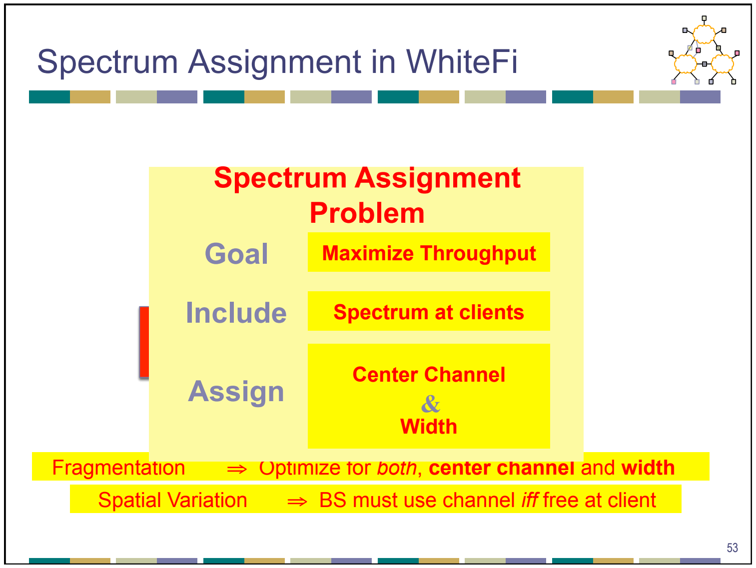
Temporal Variation
→ Same Channel will not always be free
→ *Any* connection can be disrupted *any* time

Incumbents appear/disappear over time ⇒ Must reconfigure after disconnection

Channel Assignment in Wi-Fi



Fixed Width Channels ⇒ 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 iff free at client
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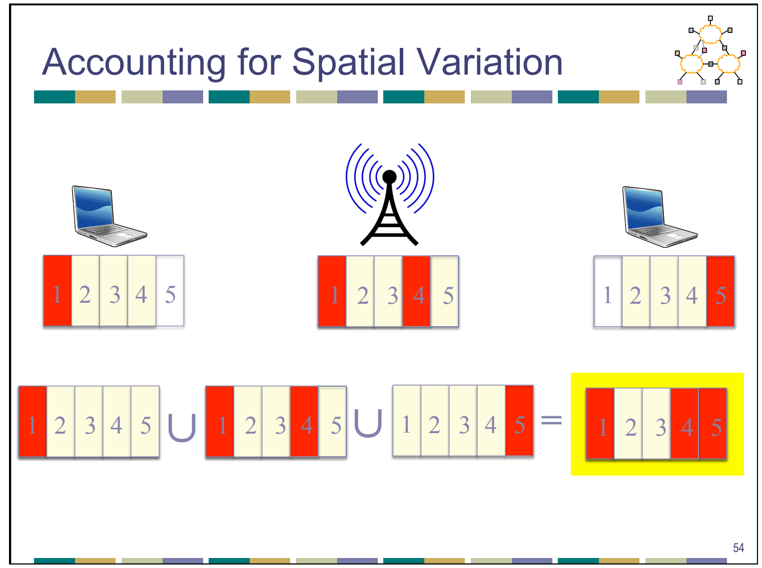
Accounting for Spatial Variation
1 2 3 4 5
1 2 3 4 5
1 2 3 4 5
1 2 3 4 5 ∪ 1 2 3 4 5 ∪ 1 2 3 4 5 = 1 2 3 4 5
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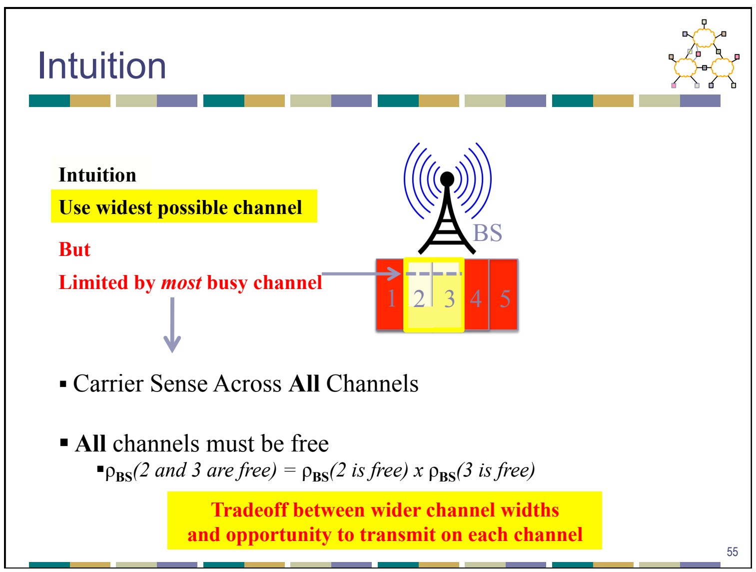
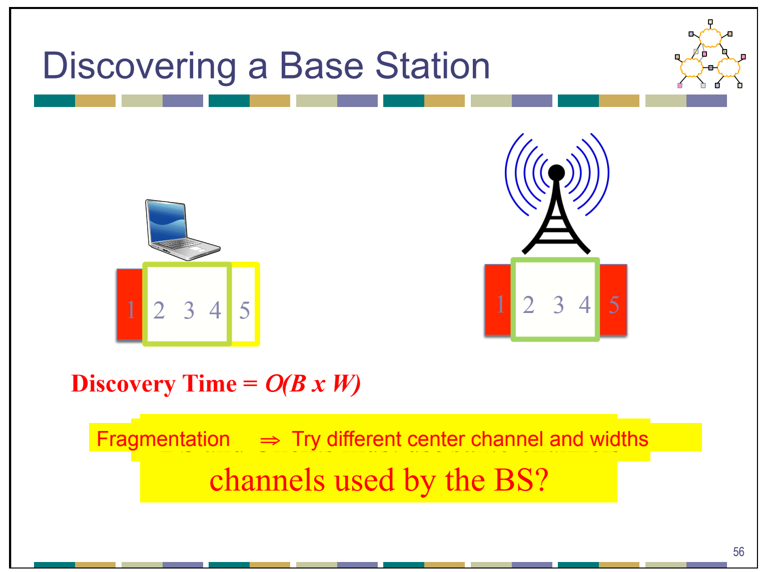

Intuition
Intuition
Use widest possible channel
But
Limited by most busy channel
BS
1 2 3 4 5
▪ Carrier Sense Across All Channels
▪ All channels must be free
▪ρBS(2 and 3 are free) = ρBS(2 is free) x ρBS(3 is free)
Tradeoff between wider channel widths and opportunity to transmit on each channel
55


Discovering a Base Station
1 2 3 4 5
1 2 3 4 5
Discovery Time = O(B x W)
Fragmentation ⇒ Try different center channel and widths
channels used by the BS?
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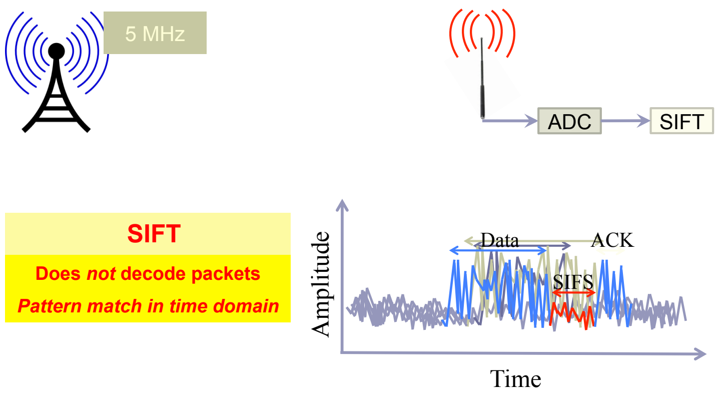
SIFT, by example



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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

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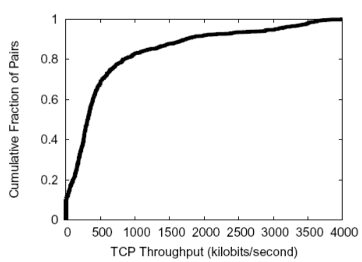
Evaluation

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



Hops	Number of Pairs	Throughput (kbits/sec)	Latency (ms)
1	158	2451	14
2	303	771	26
3	301	362	45
4	223	266	50
5	120	210	60
6	43	272	100
7	33	181	83
8	14	159	119
9	4	175	182
10	1	182	218
no route	132	0	–
Avg: 2.9	Total: 1332	Avg: 627	Avg: 39

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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

Hops	Number of nodes	Throughput (kbits/sec)	Latency (ms)
1	12	2752	9
2	8	940	19
3	5	552	27
4	7	379	43
5	1	89	37
Avg: 2.3	Total: 33	Avg: 1395	Avg: 22

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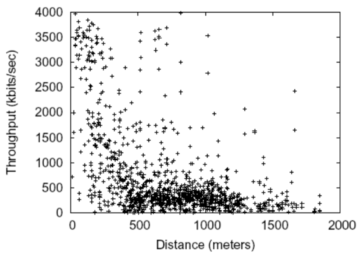
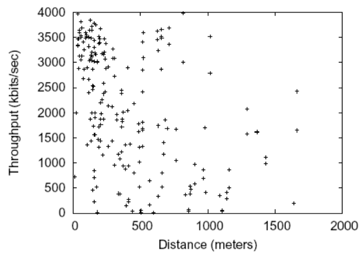
Evaluation

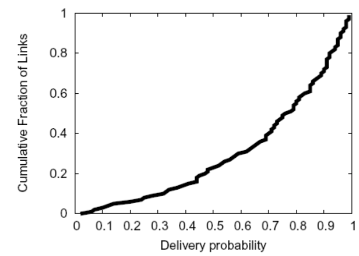
- Link Quality and Distance (Single-hop TCP, Multi-hop TCP)
  - Most available links are between 500m and 1300m and give 500 kbits/s





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

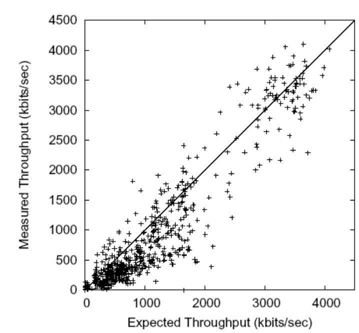
- Architectural Alternatives
  - Maximize the number of additional nodes with non-zero throughput to some gateway
  - Ties are broken by average throughput

GWs	Multi-Hop Conn	Multi-Hop Throughput (kbits/sec)	Single-Hop Conn	Single-Hop Throughput (kbits/sec)
1	37	781	23	174
2	37	1450	32	824
3	37	1871	34	1102
4	37	2131	36	1140
5	37	2355	37	1364
6	37	2450	37	2123
7	37	2529	37	2312
8	37	2614	37	2475
9	37	2702	37	2564
10	37	2795	37	2659
⋮	⋮	⋮	⋮	⋮
15	37	3197	37	3180
20	37	3508	37	3476
25	37	3721	37	3658

GWs	Multi-Hop Conn	Multi-Hop Throughput (kbits/sec)	Single-Hop Conn	Single-Hop Throughput (kbits/sec)
1	34	760	10	535
2	35	1051	17	585
3	35	1485	22	900
4	35	2021	25	1260
5	36	1565	28	1221
6	36	1954	30	1192
7	36	1931	31	1662
8	37	1447	32	1579
9	37	1700	33	1627
10	37	1945	34	1689
⋮	⋮	⋮	⋮	⋮
15	37	2305	36	1714
20	37	2509	36	2695
25	37	2703	37	2317

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