CS434/534: Topics in Networked (Networking) Systems

Wireless Foundation:
Wireless Mesh Networks

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Outline

- Recap
- Wireless background
  - Frequency domain
  - Modulation and demodulation
  - Wireless channels
  - Wireless PHY design
  - Wireless MAC design (one hop)
    - wireless access problem and taxonomy
    - wireless resource partitioning dimensions
    - media access protocols
  - From single-hop MAC to multi-hop mesh
    - wireless mesh network capacity
    - maximize mesh capacity
Admin.

- PS2 questions
- Project first check point
  - Due Thursday after break
Recap: The Hidden Terminal Problem

- A is sending to B, but C cannot detect the transmission.
- Therefore C sends to B.
- In summary, A is “hidden” from C.
Recap: 802.11 RTS-CTS-data-ACK

- RTS
- CTS
- NAV (RTS)
- NAV (CTS)
- data
- ACK
- DIFS
- SIFS
- defer access
- new contention
Recap: 802.11 CSMA/CA

B1 and B2 are backoff intervals at nodes 1 and 2

cw = 31
Recap: PIFS

D: downstream poll, or data from point coordinator
U: data from polled wireless station
Recap: Wireless Link Access Control

- Problem: single shared medium, hence if two transmissions overlap on all dimensions [time, space, frequency, and code], then it is a collision
  +CS+CD+EB

- Slotted ALOHA \( \rightarrow \) Ethernet
  +CA
  +ACK
  +RTS/CTS

- Zigzag decoding
- Hidden-terminal Collision detection/prevention
Recap: ZigZag Decoding

Exploits 802.11’s behavior

- Retransmissions
  - Same packets collide again
- Senders use random jitters
  - Collisions start with interference-free bits

\[ \Delta_1 \quad \Delta_2 \]

\[ P_a \quad P_b \]
while (exists a chunk that is interference-free in one collision and has interference in the other) {
    decode and subtract from the other collision
}
How Does ZigZag Work?

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\[ \Delta 1 \neq \Delta 2 \]
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How Does ZigZag Work?

Delivered 2 packets in 2 timeslots
As efficient as if the packets did not collide
Outline

- Admin. and recap
- Media access control
  - Slotted Aloha
  - Hidden terminal
  - Example: 802.11
  - Hidden terminal with 802.11 revisited
    - Overall idea
    - Technical issues
      - Collision detection
Collision Detection: How does the AP know it is a Collision and Where the Second Packet Starts?
Detecting Collisions and the Value of $\Delta$

AP received signal

Correlate

Packets start with known preamble

AP correlates known preamble with signal

$\Delta$

Correlation

Time
Matching Collision

Question to think offline: Given \((P_1 + P_2(\Delta))\) and \((P_1', P_2'(\Delta'))\), how to determine that \(P_1 = P_1'\) and \(P_2 = P_2'\)
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      - Subtracting chunks
How Does the AP Subtract the Signal?

- Channel’s attenuation or phase may change between collisions
- Can’t simply subtract a chunk across collisions

Alice’s signal in first collision

Alice’s signal in second collision
Subtracting a Chunk

- **Decode** chunk into bits
  - Removes effects of channel during first collision

- **Re-modulate** bits to get channel-free signal

- **Apply effect of channel** during second collision
  - Use correlation to estimate channel despite interference
What if AP Makes a Mistake?
What if AP Makes a Mistake?

Bad News: Errors can propagate

Can we deal with these errors?
What if AP Makes a Mistake?

**Good News: Temporal Diversity**

A bit is unlikely to be affected by noise in both collisions

Get two independent decodings
Errors propagate differently in the two decodings

Which decoded value should the AP pick?

For each bit, AP picks the decoding that has a higher PHY confidence
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      - Deployment
Acknowledgement

- Use as much synchronous acknowledgement as possible for backward compatibility
Implementation

- USRP Hardware
- GNURadio software
- Carrier Freq: 2.4-2.48GHz
- BPSK modulation
Testbed

• 10% HT,
• 10% partial HT,
• 80% perfectly sense each other
Throughput Comparison

CDF of concurrent flow pairs

Throughput

802.11

Perfectly Sense
Partial Hidden
Hidden Terminals

Terminal$
**Throughput Comparison**

ZigZag Exploits Capture Effect

Hidden Terminals get high throughput

Throughput CDF of concurrent flow pairs
Capture Effect

- Subtract Alice and combine Bob’s packet across collisions to correct errors

\[ \Delta_1, \Delta_2 \]

3 packets in 2 time slots $\rightarrow$ better than no collisions
Summary

- **Basic lesson:**
  - Traditional thinking was on avoiding collisions
  - Zigzag changed the way of thinking: decoding collisions

- **Many extensions of the Zigzag idea:**
  - decoding collisions, instead of avoiding collisions
    - See Remap in Backup Slides
    - A good area for creative thinking
Infrastructure Mode Wireless

802.11 by default operates in infrastructure mode.

Problems of infrastructure mode wireless networks?
Mesh Networks

Benefits
- Fast and low-cost deployment
- No central point of failure
- No APs overhead for users who can reach each other

Issues?
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    - understanding: wireless mesh network capacity
Capacity of Mesh Networks

* The question we study: how much traffic can a mesh wireless network carry, assuming an oracle to avoid the potential overhead of distributed synchronization (MAC)?

* Why study capacity?
  * learn the fundamental limits of mesh wireless networks
  * separate the spatial reuse perspective and system design perspective
  * gain insight for designing effective wireless protocols
Mesh Transmission Constraints

Interference constraint
- transmission successful if there are no other transmitters within a distance \((1+\Delta)r\) of the receiver

Radio interface constraint
- a single half-duplex transceiver at each node:
  - either transmits or receives
  - transmits to only one receiver
  - receives from only one sender
Model

- Domain is a disk of unit area
- There are $n$ nodes in the domain
- The transmission rate is $W$ bits/sec
Capacity of Mesh Wireless Network

- Consider two types of networks
  - arbitrary networks: place nodes optimally to derive overall upper bound
  - random network: nodes are placed randomly
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      - setting
      - arbitrary networks: place nodes optimally to derive overall upper bound
Transmission Model: Bit-time Perspective

- Chop time into a total of WT bit-times in T seconds
- The transmission decision is made for each bit time

Diagram:
- Bit time 1
- Bit time 2
- Bit time t
- Bit time WT
Transmission Model: End-to-end Perspective

- Assume the network sends a total of $\lambda T$ end-to-end bits in $T$ seconds
- Assume the $b$-th bit makes a total of $h(b)$ hops from the sender to the receiver
- Let $r_{bh}$ denote the hop-length of the $h$-th hop of the $b$-th bit
Hop-Count Constraint

Since there are a total of $WT$ bit-times, and during each bit-time there are at most $n/2$ simultaneous transmissions, we have

$$\sum_{b=1}^{\lambda T} h(b) \leq \frac{WTn}{2}$$
Area Constraint

- Consider two simultaneous transmissions at a bit-time

\[
D_{jm} + r \geq D_{im} \geq (1+\Delta)r' \\
D_{jm} + r' \geq D_{jk} \geq (1+\Delta)r \\
\Rightarrow \\
D_{jm} \geq (r+r') \Delta /2
\]
Area Constraint

- For each transmission with distance $r$ from sender to receiver, we draw a circle with radius $\frac{1}{2} \Delta r$
- These circles do not overlap
Area Constraint: Global Picture

$s1$

\[ r_1^1 \quad r_1^2 \]

receiver

$s2$

\[ r_2^1 \quad r_2^2 \]

receiver

\[ r_{\lambda T}^1 \quad r_{\lambda T}^2 \]

receiver

\[ r_{\lambda T}^{h(\lambda, T)} \]
**Area Constraint: Global Picture**

\[ \text{sum over all circles, since each circle has at least } \frac{1}{4} \text{ of its area in the unit disk,} \]

\[
\sum_{b=1}^{\lambda T} \sum_{h=1}^{h(b)} \frac{1}{4} \pi \left( \frac{\Delta r_b^h}{2} \right)^2 \leq WT \rightarrow \sum_{b=1}^{\lambda T} \sum_{h=1}^{h(b)} \left( r_b^h \right)^2 \leq \frac{16 WT}{\pi \Delta^2}
\]
Summary: Two Constraints

Radio interface constraint
- a single half-duplex transceiver at each node

\[ \sum_{b=1}^{\lambda T} h(b) \leq WT \frac{n}{2} \]

Interference constraint
- transmission successful if there are no other transmitters within a distance \((1+\Delta)r\) of the receiver

\[ \sum_{b=1}^{\lambda T} \sum_{h=1}^{\lambda h} (r^h_b)^2 \leq \frac{16WT}{\pi \Delta^2} \]
Capacity Bound

Let $L$ be the average (direct-line) distance for all $\lambda T$ end-to-end bits.

\[ \lambda TL \leq \sum_{b=1}^{\lambda T} \sum_{h=1}^{h(b)} r_b^h \]

\[ \Rightarrow \]

\[ \lambda TL \leq \sum_{b=1}^{\lambda T} \sum_{h=1}^{h(b)} r_b^h \leq \sqrt{\sum_{b=1}^{\lambda T} h(b)} \sqrt{\sum_{b=1}^{\lambda T} \sum_{h=1}^{h(b)} (r_b^h)^2} \]

\[ \Rightarrow \]

\[ \lambda TL \leq \sqrt{\frac{WTn}{2}} \sqrt{\frac{16WT}{\pi \Delta^2}} = \sqrt{\frac{8}{\pi}} \frac{WT}{\Delta} \sqrt{n} \]

\[ \Rightarrow \]

\[ \lambda L \leq \sqrt{\frac{8}{\pi}} \frac{W}{\Delta} \sqrt{n} \]

Note:
\[ \left( \sum_{i=1}^{n} x_i \right)^2 \leq n \sum_{i=1}^{n} x_i^2 \]

Discussion: what does the result mean?
Discussion

- $L$ depends on
  - traffic pattern (who needs to talk to whom) and
  - positions of the end-to-end (application-level) senders and (application-level) receivers

- If end-to-end senders and receivers are spread out throughout the network, $L$ is large
  - per node capacity $\propto \frac{1}{\sqrt{n}}$

- Otherwise, $L$ will be small as network becomes denser
Achieving Capacity: Example

- n/2 senders and receivers:

\[ r = \frac{1}{1 + 2\Delta} \frac{1}{\sqrt{\frac{n}{4}} + \sqrt{2\pi}} \]

- \( \lambda L = \)

\[ \frac{W}{1 + 2\Delta} \frac{n}{\sqrt{n} + \sqrt{8\pi}} \]
Results: Arbitrary Networks

Protocol Model

\[ \frac{W}{1 + 2\Delta \sqrt{n + \sqrt{8\pi}}} \leq \text{Best case capacity for Protocol Model} \leq \sqrt{\frac{8}{\pi \Delta}} \sqrt{n} \text{ bit-meters/sec} \]
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      - setting
      - arbitrary networks: place nodes optimally to derive overall upper bound
      - random networks: uniform distribution of nodes and senders/receivers
Uniform Random Networks

- Uniform distribution of n nodes
- n origin-destination (OD) pairs
- Each node chooses same power level P, and thus equal radius r(n)
- Equal throughput λ(n) bits/sec for all OD pairs
Random Networks: Required Bits

- Assume: average length of each OD pair is \( L \)

- Average number of hops:
  \[
  \frac{L}{r(n)}
  \]

- Total required bit transmissions per second to support \( \lambda(n) \):
  \[
  n\lambda(n)\frac{L}{r(n)}
  \]
Random Networks: Offered Bits

- Required bit transmissions per second: \( n \lambda(n) \frac{L}{r(n)} \)

- What is the maximum number of transmissions (of bits) in one second?
  - space used per transmission (interference limited):
    - at least \( \frac{1}{4} \pi [\Delta r(n)/2]^2 = \pi \Delta^2 r^2(n)/16 \)

- number of simultaneous transmissions at most (interference limited):
  \[
  \frac{1}{\pi \Delta^2 r(n)^2 / 16} = \frac{16}{\pi \Delta^2 r(n)^2}
  \]

- total bits per second
  \[
  \frac{16W}{\pi \Delta^2 r(n)^2}
  \]
Random Networks: Capacity

Required $\leq$ offered

$\Rightarrow$

$$n\lambda(n) \frac{L}{r(n)} \leq \frac{16W}{\pi \Delta^2 r(n)^2}$$

$\Rightarrow$

$$\lambda(n) L \leq \frac{16W}{\pi \Delta^2 nr(n)}$$
Connectivity Constraint

- Need routes between origin-destination pairs - places a lower bound on transmit range $r(n)$

To maintain connectivity with a high probability, requires $r(n)$ on the order: $\sqrt{\frac{\log n}{n}}$
Random Networks: Capacity

Required \leq offered

\[ n\lambda(n) \frac{L}{r(n)} \leq \frac{16W}{\pi\Delta^2 r(n)^2} \]

\[ \Rightarrow \lambda(n)L \leq \frac{16W}{\pi\Delta^2 nr(n)} \]

\[ r(n) \propto \sqrt{\frac{\log n}{n}} \]

\[ \Rightarrow \lambda(n)L \propto \frac{1}{\sqrt{n \log n}} \]
Measurement

- Measured scaling law: throughput declines worse with $n$ than theoretically predicted: $1/n^{1.68}$

- Remaining story line
  - wireless mesh networks may have low scalability, and need techniques to increase capacity
Improving Wireless Mesh Capacity

Radio interface constraint
- A single half-duplex transceiver at each node

\[ \sum_{b} \lambda T h(b) \leq WT \frac{n}{2} \]

Interference constraint
- Transmission successful if there are no other transmitters within a distance \((1+\Delta)r\) of the receiver

\[ \sum_{b=1}^{\lambda T} \sum_{h=1}^{h(b)} (r_b^h)^2 \leq \frac{16WT}{\pi \Delta^2} \]

Rate*distance capacity:

\[ \lambda L \leq \sqrt{\frac{8W}{\pi \Delta}} \sqrt{n} \]