Wireless MACs: MACAW/802.11

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Fundamentals: Spectrum and Capacity

• A particular radio transmits over some range of frequencies; its **bandwidth**, in the physical sense
• When we’ve many senders near one another, how do we allocate spectrum among senders? Goals:
  – Support for arbitrary communication patterns
  – Simplicity of hardware
  – Robustness to interference
• Shannon’s Theorem: there’s a fundamental limit to channel capacity over a given spectrum range:

\[
C = B \log_2 (1 + S/N)
\]

• $C =$ capacity (bits/s), $B =$ bandwidth (Hz), $S/N =$ signal/noise power ratio (linear W)
• Multiple simultaneous senders OK, but no free lunch!
Multi-Channel

• Suppose we’ve 100 MHz of spectrum to use for a wireless LAN
• Subdivide into 50 channels of 2 MHz each: FDMA, narrow-band transmission
• Radio hardware simple, channels don’t mutually interfere
• Multi-path fading (mutual cancellation of out-of-phase reflections)
• Base station can allocate channels to users. How do you support arbitrary communication patterns?
• Other possibilities: FHSS
Single, Shared Channel

- Spread transmission across whole 100 MHz of spectrum
- Robust to multi-path fading (some frequencies arrive intact)
- Simple: symmetric radio behavior
- Supports peer-to-peer communication
- Collisions: a receiver must only hear one strong transmission at a time
Review: Ethernet MAC

• “Ethernet is straight from God.”
  - H.T. Kung, Harvard networks course lecture
• **CS (Carrier Sense):** listen for others’ transmissions before transmitting; defer to others you hear
• **CD (Collision Detection):** as you transmit, listen and verify you hear exactly what you send; if not, back off random interval, within exponentially longer range each time you transmit unsuccessfully

- Is CD possible on a wireless link? Why or why not?
MACAW: Context

• Published in SIGCOMM 1994, work 93-94
• 802.11 standardization proceeded in parallel (IEEE standard in 1997)
• 802.11 draws on MACAW, which draws on MACA
• No real research paper on 802.11 design; MACAW covers same area well
• Assumptions: uniform, circular radio propagation; fixed transmit power; equal interference and transmit ranges
• What are authors’ stated goals?
  – Fairness in sharing of medium
  – Efficiency (total bandwidth achieved)
  – Reliability of data transfer at MAC layer
Hidden Terminal Problem

- Nodes placed a little less than one radio range apart
- CSMA: nodes listen to determine channel idle before transmitting
- C can’t hear A, so will transmit while A transmits; result: collision at B
- Carrier Sense insufficient to detect all transmissions on wireless networks!
- Key insight: collisions are spatially located at receiver
Exposed Terminal Problem

- B sends to A; C sends to a node other than B
- If C transmits, does it cause a collision at A?
- Yet C cannot transmit while B transmits to A!
- Same insight: collisions are spatially located at receiver
- One possibility: directional antennas rather than omnidirectional. Why does this help? Why is it hard?
- Simpler solution: use receiver’s medium state to determine transmitter behavior
RTS/CTS in MACA and MACAW

- Sender sends short, fixed-size RTS packet to receiver
- Receiver responds with CTS packet
- RTS and CTS both contain length of data packet to follow from sender
- Solves hidden terminal problem!
- Absent CTS, sender backs off exponentially (BEB) before retrying
- RTS and CTS can still themselves collide at their receivers; less chance as they’re short; any help on short data packets?
RTS/CTS in MACA and MACAW

1. “RTS, k bits”

A B C

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1. “RTS, k bits”

A  B  C

2. “CTS, k bits”

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RTS/CTS in MACA and MACAW

1. “RTS, k bits”

A \rightarrow B \rightarrow C \text{defers}

2. “CTS, k bits”

- Sender sends short, fixed-size RTS packet to receiver
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RTS/CTS in MACA and MACAW

1. "RTS, k bits"

A defers B 3. "Data"

C

2. "CTS, k bits"

• Sender sends short, fixed-size RTS packet to receiver
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BEB in MACA

- Current backoff constant: $B$
- Maximum backoff constant: $B_M$
- Minimum backoff constant: $B_0$
- MACA sender:
  - $B_0 = 2$ and $B_M = 64$
  - Upon successful RTS/CTS, $B \leftarrow B_0$
  - Upon failed RTS/CTS, $B \leftarrow \min[2B, B_M]$
- Before retransmission, wait a uniform random number of RTS lengths (30 bytes) in $[0, B]$
- No carrier sense! (Karn concluded useless because of hidden terminals)
BEB in MACAW

• BEB can lead to unfairness: backed-off sender has decreasing chance to acquire medium ("the poor get poorer")
• Simple example: two senders sending to the same receiver, each sending at a rate that can alone saturate the network
• MACAW proposal: senders write their $B$ into packets; upon hearing a packet, adopt its $B$
• Result: dissemination of congestion level of "winning" transmitter to its competitors
• Is this a good idea?
• RTS failure rate at one node propagates far and wide
• Ambient noise? Regions with different loads?
Reliability: ACK

- **MACAW** introduces an ACK after DATA packets; not in **MACA**
- Sender retransmits if RTS/CTS succeeds but no ACK returns; doesn’t back off
- **Avoid TCP window reductions when interference**
- Useful when there’s **ambient noise** (microwave ovens...)
- Why are **sequence numbers** in DATA packets now important (not mentioned directly in paper!)
- Are **ACKs** useful for multicast packets? Consequences for, *e.g.*, **ARP**?
MACAW and 802.11 Differences

- 802.11 uses **physical CS** before transmissions **and** defers a uniform random period, in \([0, B]\)
  - Sets timer to count down random period
  - Timer pauses when carrier sensed, continues when channel idle
  - Packet transmitted when timer reaches zero

- 802.11 combines physical CS with **virtual CS** from RTS/CTS packets in the **Network Allocation Vector (NAV)**

- 802.11 uses BEB when an ACK doesn’t return
802.11 Variants and Bit-Rates

- **802.11a**: 5 GHz, 20 MHz channel; 6, 9, 12, 18, 24, 36, 48, 54 Mbps
- **802.11g**: 2.4 GHz, 20 MHz channel; 6, 9, 12, 18, 24, 36, 48, 54 Mbps
- **802.11b**: 2.4 GHz, 20 MHz channel; 1, 2, 5.5, 11 Mbps
- 3 non-overlapping channels in 802.11b/g
- \( \geq 12 \) non-overlapping channels in 802.11a
802.11 Variants and Bit-Rates

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- **802.11b**: 2.4 GHz, 20 MHz channel; 1, 2, 5.5, 11 Mbps

As bit-rate increases, SNR required at receiver to successfully decode signal increases.

*Sender adapts bit-rate to maximize throughput*
Two Regimes in Wireless: Concurrency vs. Time-Multiplexing

- Far-apart links should *send concurrently*:

- Near links should *time-multiplex*:

figures [Micah Brodsky]
Two Regimes in Wireless: Concurrency vs. Time-Multiplexing

• Far-apart links should send concurrently:

• Near links should time-multiplex:

Carrier sense attempts to distinguish these cases
Uses energy threshold to determine if medium occupied
What about cases in between these extremes?
When Does CS Work Well?

• Agreement:
  – If two senders and two receivers, and both receivers achieve highest throughput when both use concurrency or both use multiplexing, they agree

• Far-apart links agree on concurrency

• Near links agree on time-multiplexing

• In between, risk links don’t agree; CS may not work well
Simulation Study of CS
[Brodsky and Morris, 2009]

- Place sender S and interferer I at fixed locations
- Place receiver from S uniformly at random within some radius of S
- Compare throughputs at receiver over all locations
- Vary distance between sender and interferer
Individual Receivers
[Brodsky and Morris, 2009]

figure [Micah Brodsky]
Receiver Preference as Interferer Distance Varies [B&M, 2009]

Receiver preference vs. position:

- Excellent agreement on multiplexing
- Disagreement??
- Excellent agreement on concurrency

D = 20
D = 55
D = 120

figures [Micah Brodsky]
802.11: A Dose of Reality

• The canonical wireless link in the research community. Why?
  – Hardware commoditized, cheap
  – First robust (DSSS) wireless network with LAN-like bitrate
• Many wireless system papers based on simulations of 802.11 networks
• *Caveat simulator*: simulating a real link layer doesn’t mean realistic simulations. Reflection, absorption, and interference models? Traffic patterns? Mobility patterns?
• Have I been wasting your time? *In practice no one uses RTS/CTS!* *(Note from prior slides: CS works pretty well)*
• Why? Are MACAW and the hidden terminal problem irrelevant?
802.11, Base Stations, and Hidden Terminals

- To first order, everyone uses base stations, not peer-to-peer 802.11 networks.
- When base station transmits, there can be no hidden terminals within one LAN. Why?
- Clients can be hidden from one another. But what’s the usual packet output stream of a wireless client (e.g., laptop)? Packet sizes? TCP ACKs; short packets.
- What’s the cost of RTS/CTS? How big are RTS and CTS packets? Greatest cost when RTS/CTS same size as data.
- 802.11 end-user documentation recommends disabling RTS/CTS “unless you are experiencing unusually poor performance”.
- Drivers leave it off by default.
802.11, Peer-to-Peer Traffic, and Hidden Terminals

• In MACAW, successful communication and interference ranges equal
• In 802.11, interference range often more than double successful communication range
• How useful is RTS/CTS in 802.11?
  – Consider A → B ← C classic hidden terminal case
  – When A transmits, C may often sense A’s carrier directly; often no need for RTS/CTS
• Studies show RTS/CTS does not improve throughput in multi-hop 802.11 networks (see Roofnet paper in M038/GZ06 next term...)