Wireless MACs: MACAW/802.11

Brad Karp
UCL Computer Science

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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

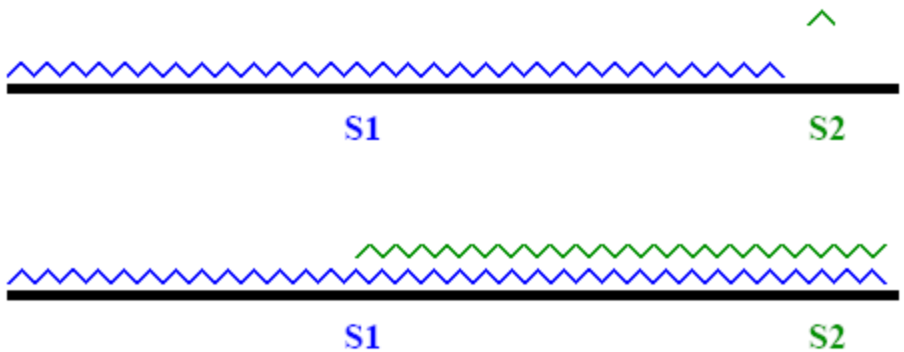
- Suppose we’ve 100 MHz of spectrum to use for a wireless LAN
- Subdivide into 50 channels of 2 MHz each: FDMA, narrow-band transmission
- Radio hardware simple, channels don’t mutually interfere
- Multi-path fading (mutual cancellation of out-of-phase reflections)
- Base station can allocate channels 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

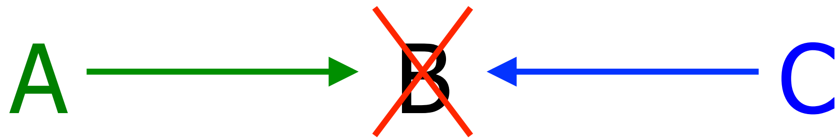


- Is CD possible on a wireless link? Why or why not?

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

A B C

- 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?

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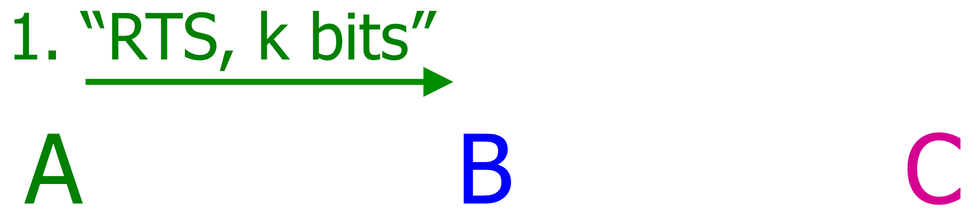

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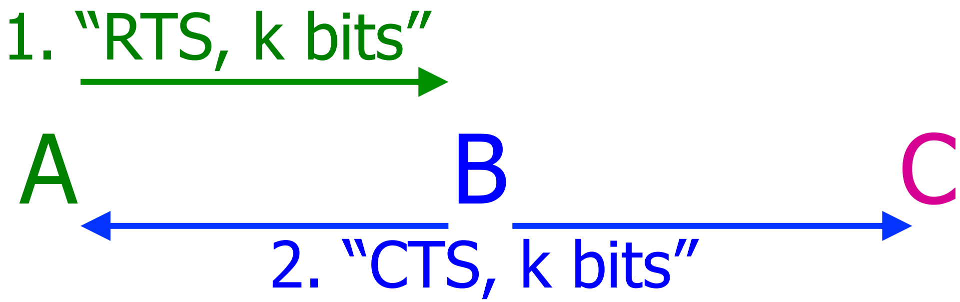

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BEB in MACA

- 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
- >= 12 non-overlapping channels in 802.11a

802.11 Variants and Bit-Rates

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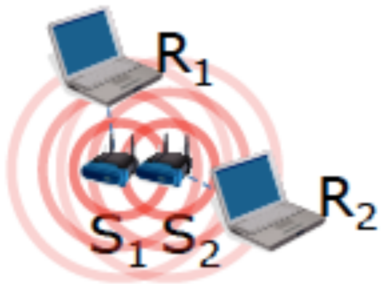
As bit-rate increases, SNR required at receiver to successfully decode signal increases

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

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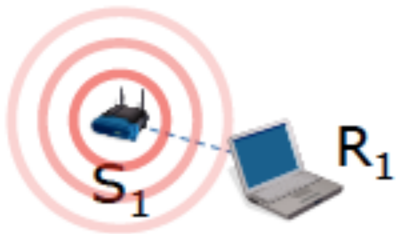


- Near links should time-multiplex:

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]

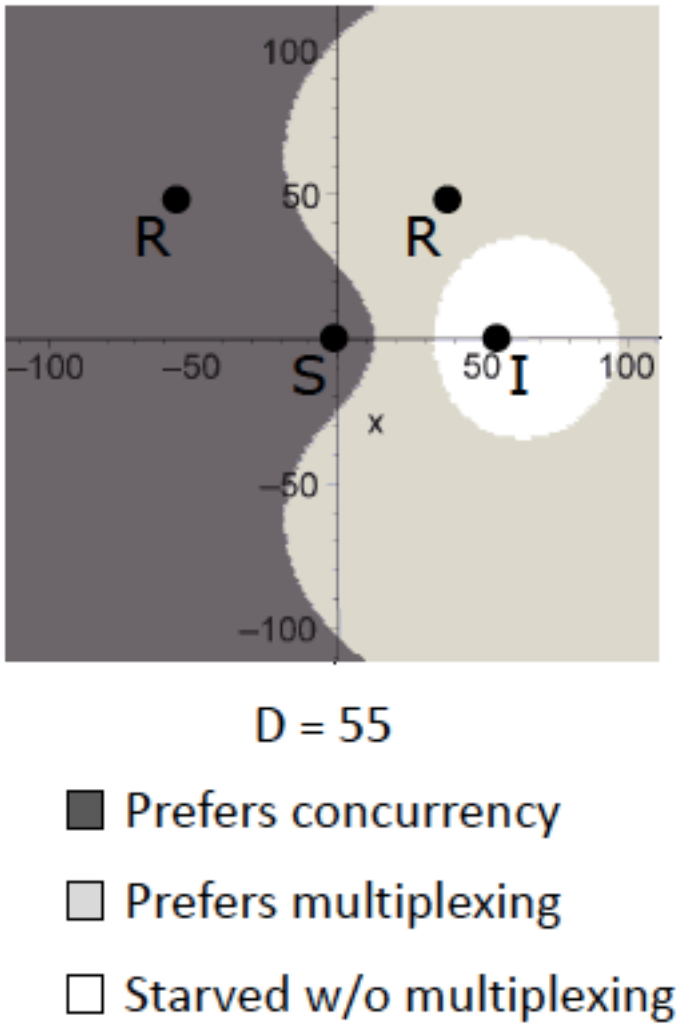
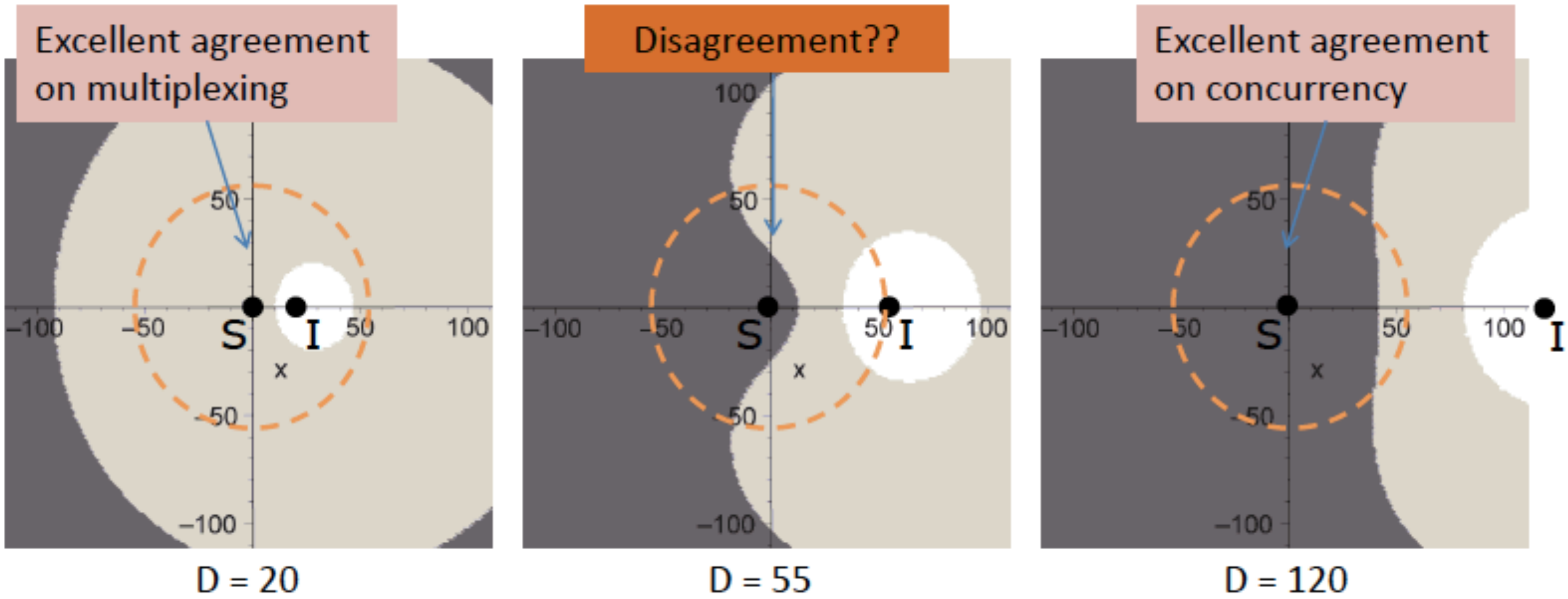


figure [Micah Brodsky]

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

Receiver preference vs. position:



- Prefers concurrency
- Prefers multiplexing
- Starved w/o multiplexing

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…)