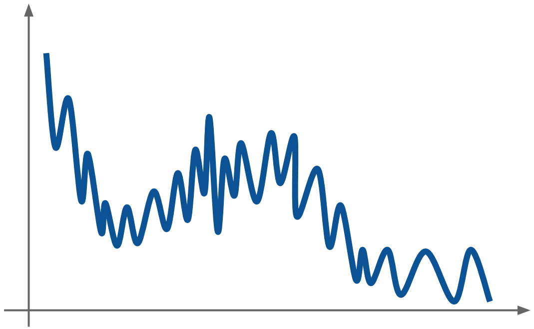
Lecture 26



Wireless

CS 168, Fall 2024 @ UC Berkeley

Slides credit: Prabal Dutta, Sylvia Ratnasamy, Rob Shakir, Peyrin Kao (and others)

Why is Wireless Different?

Lecture 26, CS 168, Fall 2024

Why is Wireless Different?

- Shared Medium
- Attenuation
- Changing Environments
- Collision Detection

MACAW Optimizations

- Acks for Reliability
- Backoff for Fairness
- DS for Synchronization
- RRTS for Synchronization

Brief History of Wireless Communication

Wireless communication predates the Internet!

- 1880s: Photophone *(Bell, Tainer)* sent data wirelessly using a light beam.
- 1890s: Wireless telegraph *(Marconi)* sent data using radio waves.
- 1890s: Experiments with millimeter waves *(Bose)*.
  - This is becoming an active area of research again!

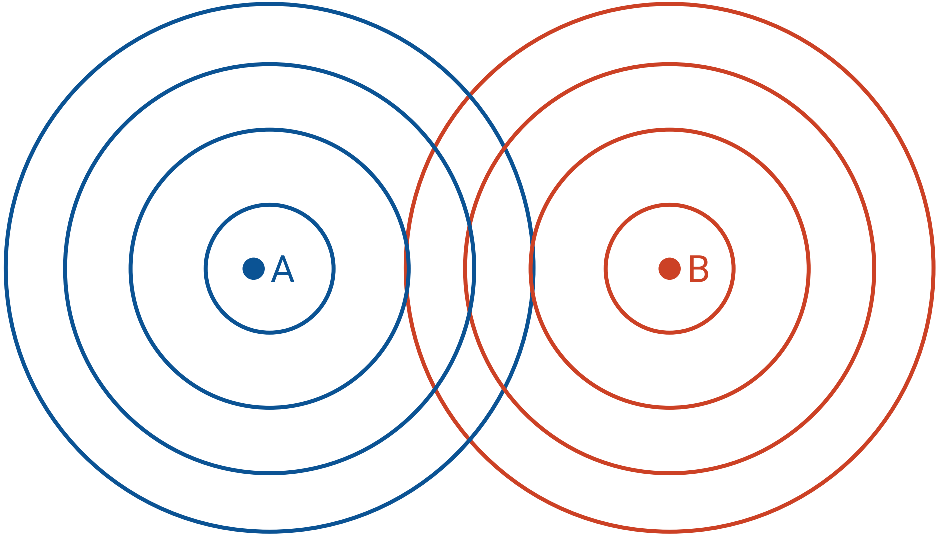
We now live in a world where wireless communication is everywhere.

Wireless Signals

Wireless signals are *not* packets of data floating in space.

Wireless signals are waves that propagate in all directions.

- Analogy: Ripples in a pond.
- Waves interact with each other, and with the environment.



Wired vs. Wireless: Key Differences

1. Wireless is fundamentally a shared medium. *(Wired is not.)*
2. Wireless signals attenuate significantly with distance. *(Wired signals do not.)*
3. Wireless environments can change rapidly. *(Wired environments do not.)*
4. Wireless packet collisions are hard to detect. *(Wired packet collisions are not.)*

Differences mostly affect Layer 1 (Physical) and Layer 2 (Link).

Difference: Wireless is a Shared Medium

Lecture 26, CS 168, Fall 2024

Why is Wireless Different?

- **Shared Medium**
- Attenuation
- Changing Environments
- Collision Detection

MACAW Optimizations

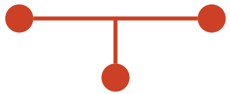
- Acks for Reliability
- Backoff for Fairness
- DS for Synchronization
- RRTS for Synchronization

Difference: Wired vs. Wireless Links

Wired links:

- Point-to-point (private) by default.

- Creating multi-point buses requires work.



- Fairly easy to shield from external interference.

- Uses electrical signals to transmit data.

Wireless links:

- Broadcast (shared) by default.

- Creating point-to-point private links requires work.
- Fairly hard to shield from external interference.
- Modulate electromagnetic fields to transmit data.

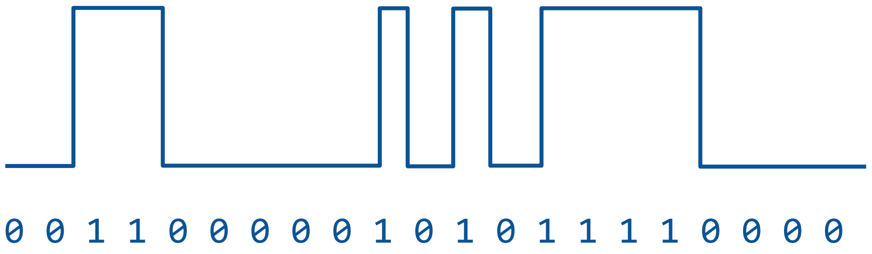
Encoding Data Over Wireless Links

Wired link: Encode bits as electrical signals.

- High voltage = 1.
- Low voltage = 0.

Wireless link:

- Draw the bits as a wave?
- Problem: Resulting wave is low-frequency, and hard to transmit.



Encoding Data Over Wireless Links – Modulation

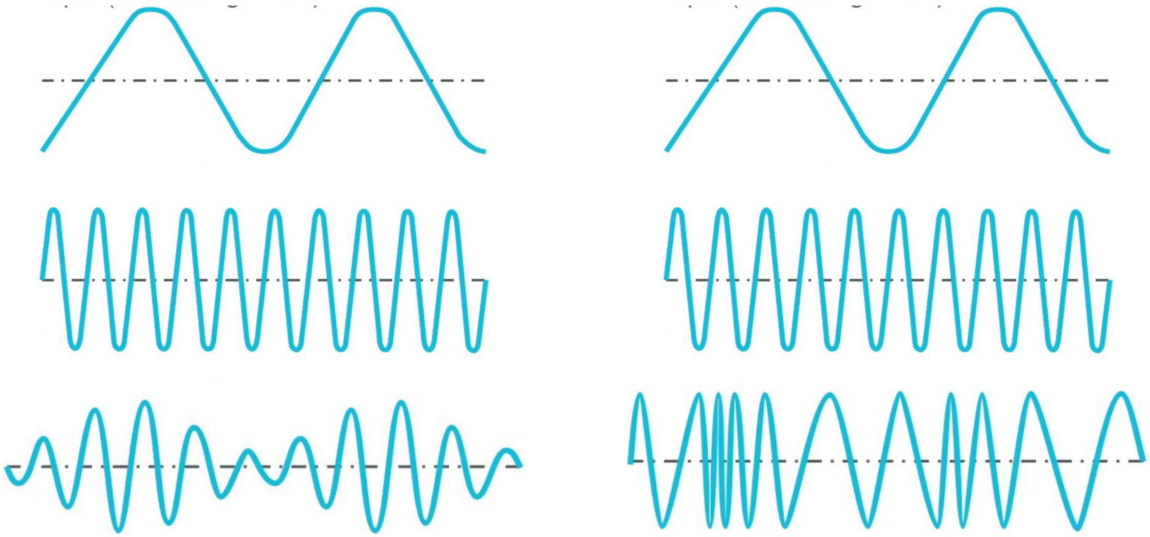
Modulation: Impose our data signal on top of a carrier signal.

- Carrier signal: A high-frequency, constant wave that contains no information.
- The combined wave is easy to transmit, and contains our data!

Original signal

+ Carrier signal

= Modulated signal



Amplitude Modulation (AM):
1 = Taller wave.
0 = Shorter wave.

Frequency Modulation (FM):
1 = Oscillate fast.
0 = Oscillate slow.

Other modulation strategies exist.

Measuring Noise and Interference – SINR

Shared medium → other signals can corrupt our data!

- **Noise**: Background, ambient signals.
- **Interference**: Another transmitter sending signals.

SINR (Signal to Interference and Noise Ratio) lets us measure connection quality:

$$\text{SINR} = \frac{P_{\text{signal}}}{P_{\text{interference}} + P_{\text{noise}}}$$

- Ratio of power to noise+interference at the the receiver.
- Higher SINR is better.
- If there's more noise+interference, the signal must be stronger.
- If signal is weak, can employ coding gain (error-correcting codes).

Measuring Noise and Interference – SINR

SINR is dimensionless (it's a ratio).

Decibels let us measure ratios on a logarithmic scale.

- Ratio is 10 times greater = increase of 10 dB.

Ratio	Ratio in dB
1	0 dB
10	10 dB
100	20 dB
1000	30 dB
10000	40 dB

SINR (measured in dB).

SINR formula.

$$\text{SINR}_{\text{dB}} = 10 \cdot \log_{10}\left(\frac{P_{\text{signal}}}{P_{\text{interference}} + P_{\text{noise}}}\right)$$

Measuring Noise and Interference – Noisy Channel Shannon Capacity

Shannon capacity: Theoretical limit of how much data can be sent on a noisy channel.

$$C = B \cdot \log_2(1 + \mathrm{SINR})$$

How much data can be sent? (bits/sec)

Bandwidth of channel (range of frequencies we can use).

Ratio of signal power to noise+interference.

- Higher bandwidth = can send more data.
- SINR increases = can send more data.
  - Stronger signal, or less noise+interference.

Measuring Noise and Interference – Noisy Channel Shannon Capacity

Shannon capacity: Theoretical limit of how much data can be sent on a noisy channel.

$$C = B \cdot \log_2(1 + \text{SINR})$$

How much data can be sent? (bits/sec)

Bandwidth of channel (range of frequencies we can use).

Ratio of signal power to noise+interference.

Example: The plain old telephone system:

- B = 3000 Hz. *(Telephones understand frequencies between 300 Hz and 3300 Hz.)*
- SINR = 100. *(20 dB signal-to-noise ratio.)*
- $C = 3000 \cdot \log_2(1 + 100) \approx 20000$ = 20 kbps.

Difference: Wireless Signals Attenuate

Lecture 26, CS 168, Fall 2024

Why is Wireless Different?

- Shared Medium
- **Attenuation**
- Changing Environments
- Collision Detection

MACAW Optimizations

- Acks for Reliability
- Backoff for Fairness
- DS for Synchronization
- RRTS for Synchronization

Difference: Attenuation

Wireless signals **attenuate** – they get much weaker over longer distances.

- Our design must account for attenuation.
- Wired signals also attenuate, but effect is far smaller.

Trade-off:

- Maximize performance: Accuracy, speed, range.
- Minimize resource use: Power, use less of the frequency spectrum (costs money).
- Trade-off: Better signal requires more resources.

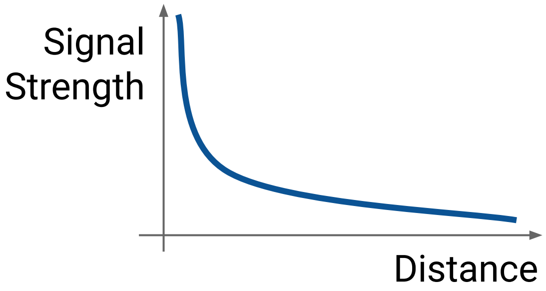
Measuring Attenuation – Free-Space Model

Free-space model (aka **line-of-sight model**):

- Transmitter and receiver exist in empty space.
- No obstacles, not even Earth's surface.

In this model, the **inverse square law** applies.

- 10 times as far = signal is 100 times weaker.
- k times as far = signal is k^2 times weaker.



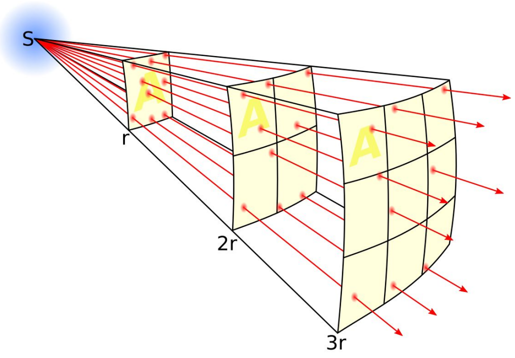
"is proportional to"

$$P_r \propto \frac{P_t}{d^2}$$

Transmitter power

d = distance between transmitter and receiver

Receiver power



Intuition: Signal propagates out like a sphere.
Signal power is spread over surface of sphere.
Surface area of sphere = $4\pi d^2$.

The **Friis equation** accounts for:

- Gain of the transmitter and receiver antennas.
- Aperture (area) of the receiver antenna. Proof omitted.
  - Intuition: Larger antenna can capture more signal.
- Distance between antennas (inverse-square law).

$$\underset{\text{Receiver power}}{P_r} = \underset{\text{Transmitter power}}{P_t} \cdot \overbrace{G_t \cdot G_r}^{\text{Gains of antennas}} \cdot \overset{\text{Aperture of receiver antenna}}{\left(\frac{\lambda^2}{4\pi}\right)} \overset{\text{Distance (inverse square law)}}{\left(\frac{1}{4\pi d^2}\right)}$$

Measuring Attenuation – Friis Equation, Rewritten

The equation is sometimes written like this:

$$P_r = P_t \cdot G_t \cdot G_r \cdot \left(\frac{\lambda^2}{4\pi}\right)\left(\frac{1}{4\pi d^2}\right)$$
$$= P_t \cdot G_t \cdot G_r \cdot \left(\frac{\lambda}{4\pi d}\right)^2$$

Or in terms of decibels (logarithmic scale):

$$P_r^{\mathrm{dB}} = P_t^{\mathrm{dB}} + G_t^{\mathrm{dB}} + G_r^{\mathrm{dB}} + 20\log_{10}\left(\frac{\lambda}{4\pi d}\right)$$

Measuring Attenuation – Link Budget

How do we know if the link will actually work?

- Compute a **link budget**: Add all gains, subtract all losses.

$$P_r^{\mathrm{dB}} = P_t^{\mathrm{dB}} + \sum \mathrm{gains} - \sum \mathrm{losses}$$

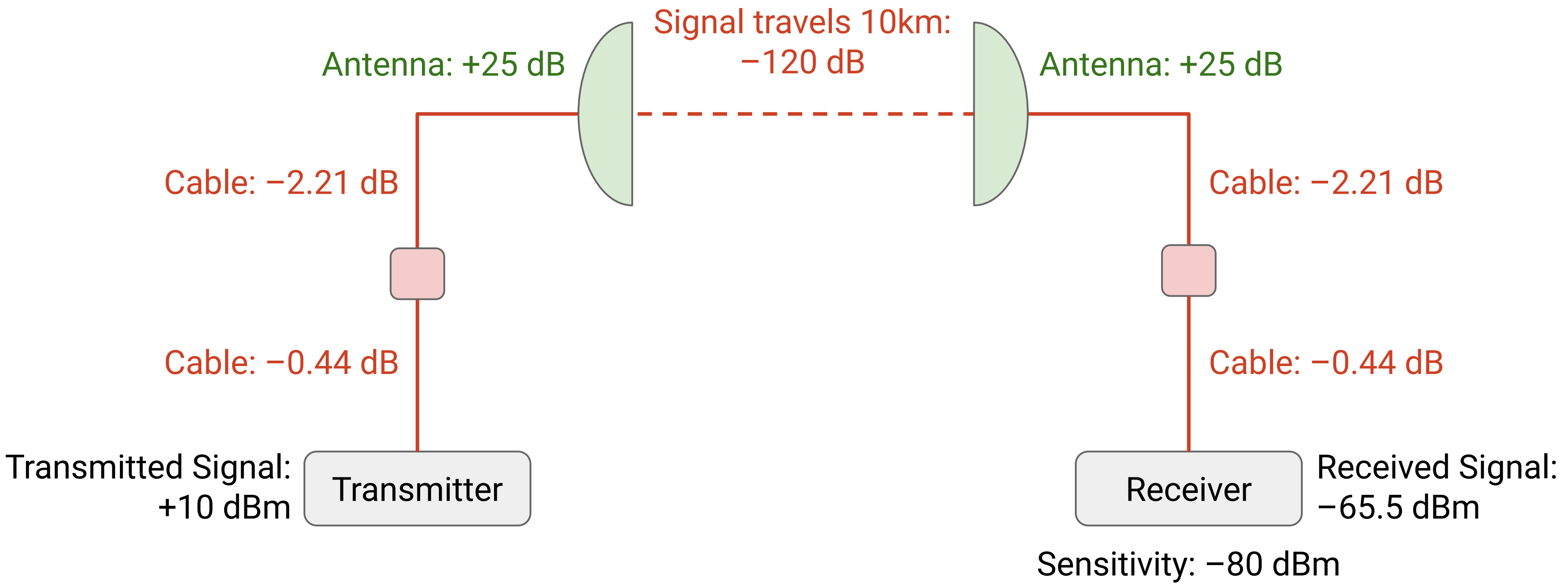
- Compare:
  - Signal power at receiver.
  - Receiver **sensitivity** (minimum signal the receiver can hear).
- If link budget is positive: P_r > Sensitivity. Link works!
- If link budget is negative: P_r < Sensitivity. Link doesn't work!

Link margin is difference between receiver signal and sensitivity.

- Bigger link margin = more robust signal.

Measuring Attenuation – Link Budget

Example of computing link budget:



Link margin = 14.5 dBm > 0.
Our connection works!

Note: dBm = Power relative to 1 milliwatt.

Difference: Changing Environments

Lecture 26, CS 168, Fall 2024

Why is Wireless Different?

- Shared Medium
- Attenuation
- **Changing Environments**
- Collision Detection

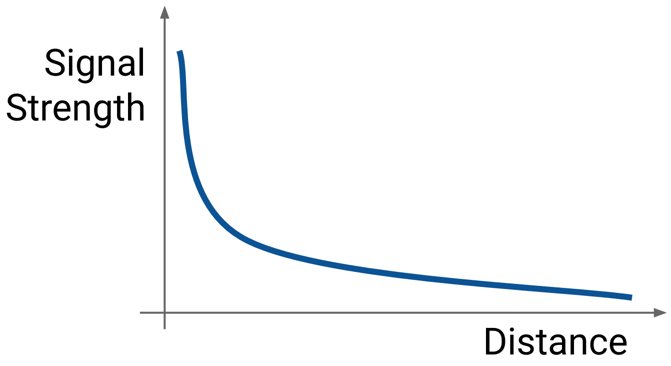
MACAW Optimizations

- Acks for Reliability
- Backoff for Fairness
- DS for Synchronization
- RRTS for Synchronization

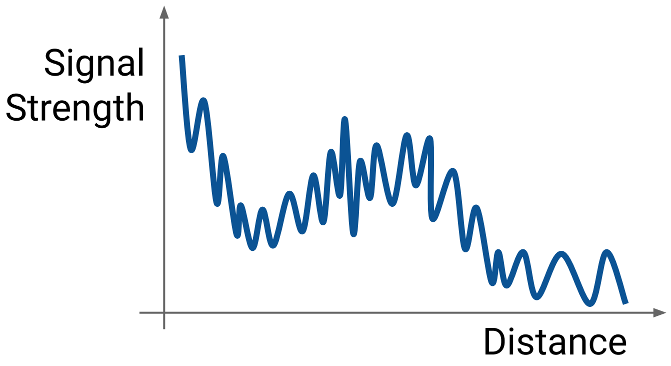
Difference: Environments Change

Wireless environments change rapidly.

- Devices move around.
- Signals reflect and refract off physical obstacles (e.g. buildings, Earth's surface).



Free-space model:
Signal weakens over distance.

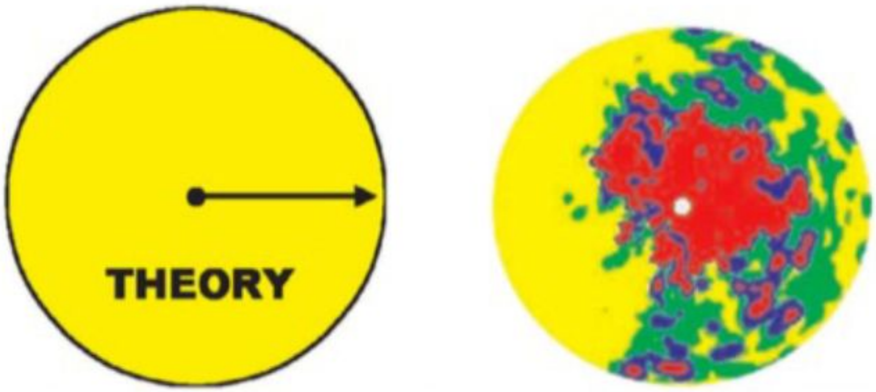


After accounting for obstacles:
Signal strength fluctuates!

Path Loss is Messy

Wireless propagation is messy.

- In theory: Signal propagates in all directions.
- In real life: Signal strength depends on environment.



Color = strength of signal.

Characteristics of Path Loss

3 characteristics affect signal strength:

Free-space loss:

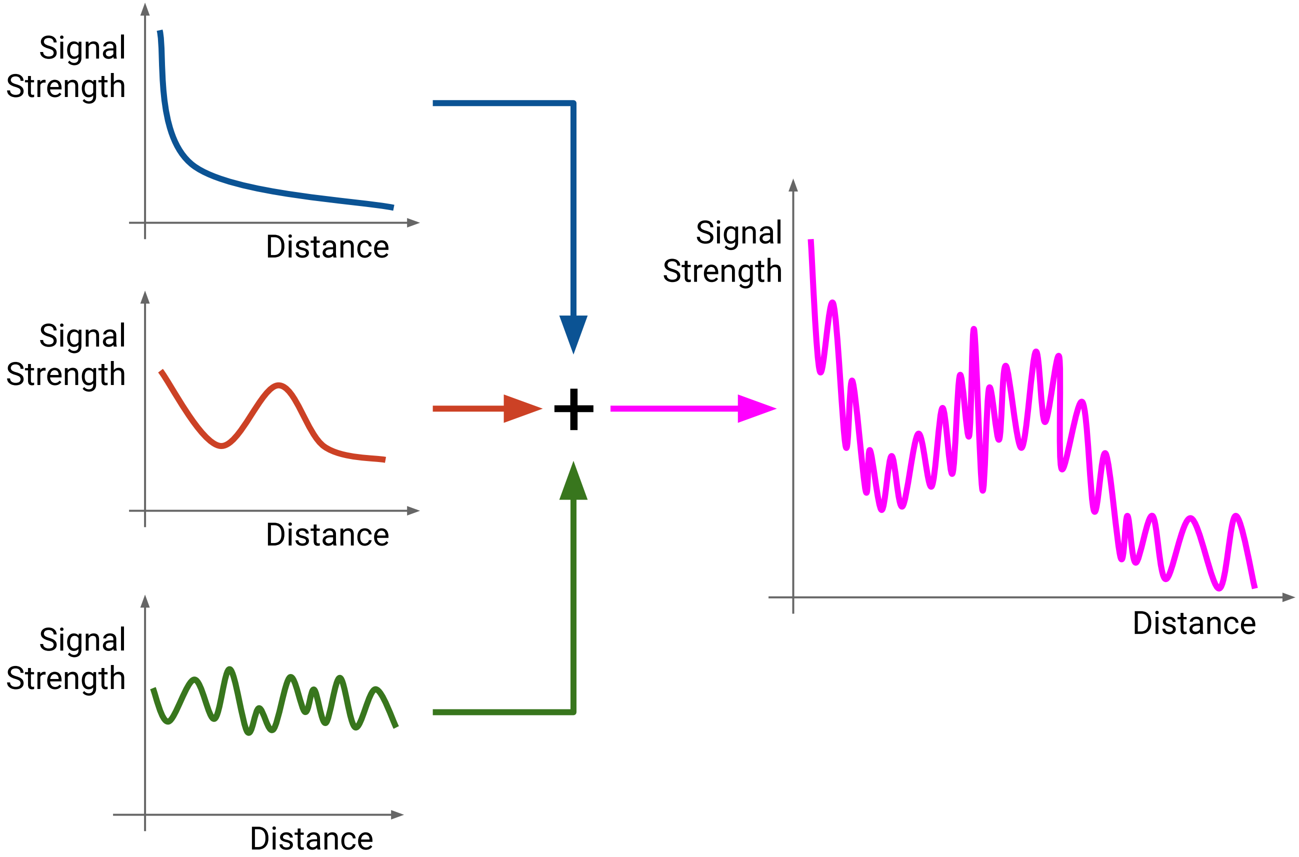
– Due to inverse square law.
– Fluctuates very slowly.

Shadowing:

– Due to obstructions.
– Fluctuates quickly.

Multipath fading:

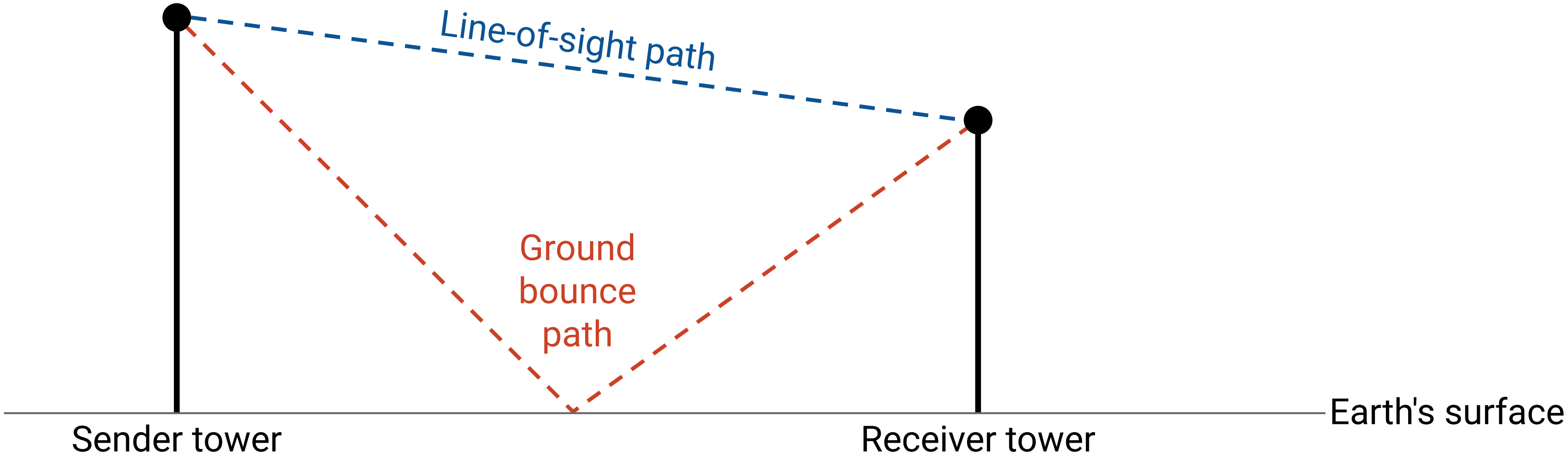
– Due to signal colliding with itself.
– Fluctuates very quickly.



Modeling Path Loss – Two-Ray Model

Two-ray model assumes the signal waves travel along two paths:

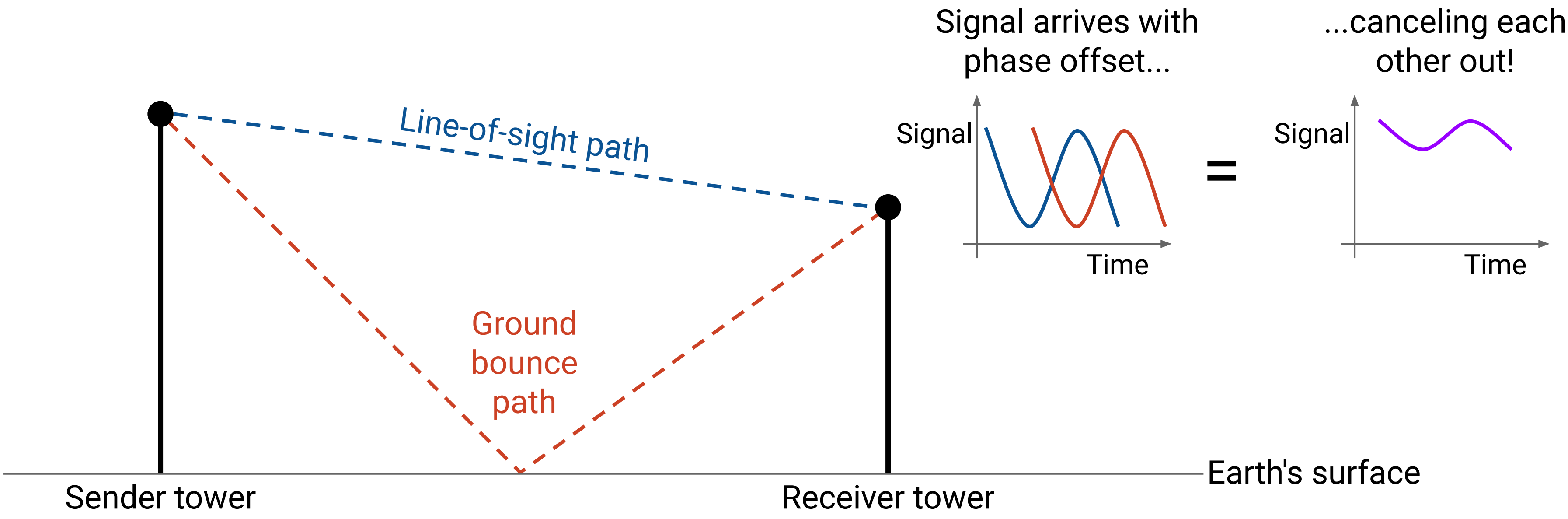
- Line-of-sight path: Wave arrives with no obstacles.
- Ground-bounce path: Wave reflects off the Earth's surface.



Modeling Path Loss – Two-Ray Model

Assuming sender and receiver are far enough:

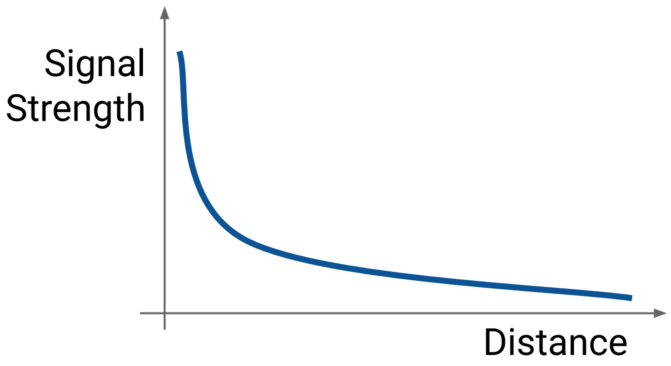
- Waves arrive phase-shifted at the receiver, causing destructive interference.
- Signal strength ∝ $1/d^4$. Drops off much faster than inverse-square law!

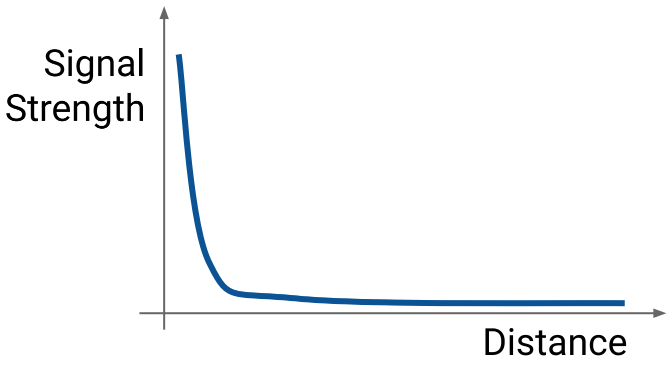


Modeling Path Loss – Two-Ray Model

If sender and receiver are far enough:

- Waves arrive phase-shifted at the receiver, causing destructive interference.
- Signal strength ∝ $1/d^4$. Drops off much faster than inverse-square law!





Free-space model:

– Signal strength ∝ $1/d^2$.
– Idealized, no obstacles.

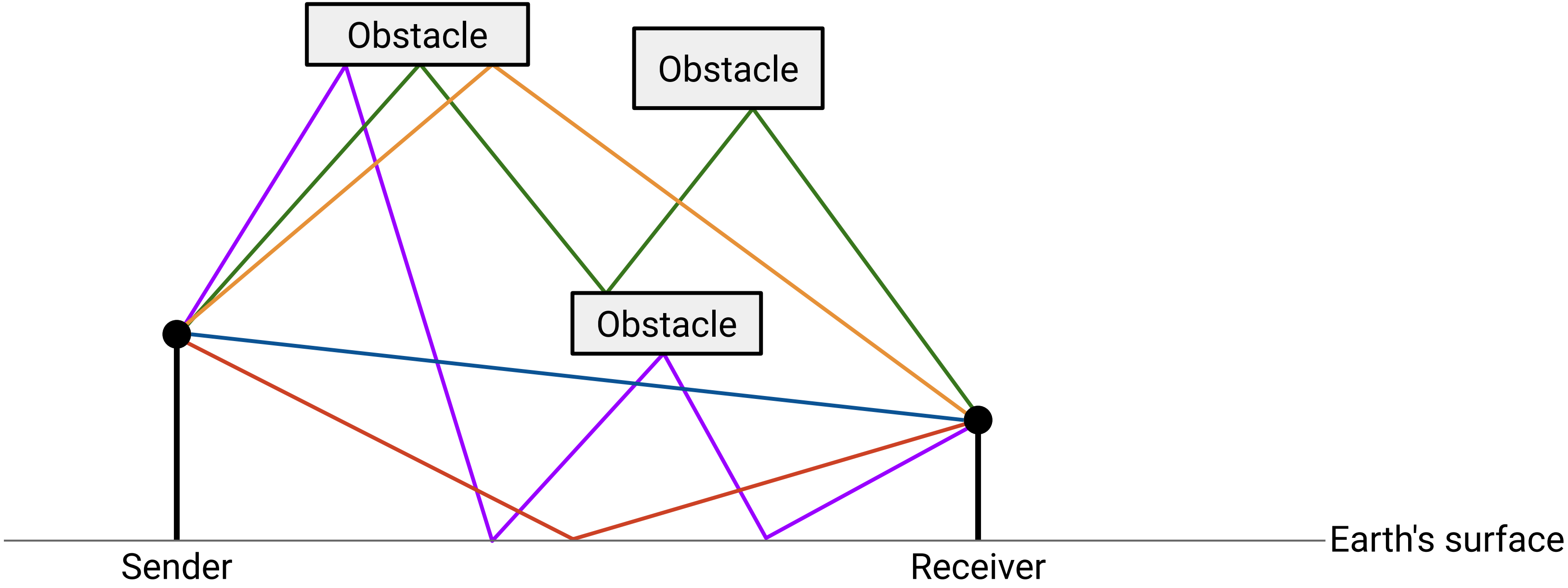
Two-ray model:

– Signal strength ∝ $1/d^4$.
– Signal bounces off ground. Causes destructive interference.

Modeling Path Loss – General Ray Tracing Models

General **ray tracing** models account for other obstacles.

- Signals reflect, scatter, and diffract.
- Most signals arriving at receiver are reflections.
- Run simulations in software. Requires information about environment.



Modeling Path Loss – General Ray Tracing Models

Free-space model: Signal strength $\propto 1/d^2$.

Two-ray model: Signal strength $\propto 1/d^4$.

General ray tracing model:

Receiver power

Transmitter power

Distance

$$P_r = P_t K d^\gamma$$

K and γ are empirically determined by the model.

- Signal dominated by reflections.
- Exponent γ is determined empirically. Usually between −2 and −8.

Difference: Collision Detection

Lecture 26, CS 168, Fall 2024

Why is Wireless Different?

- Shared Medium
- Attenuation
- Changing Environments
- **Collision Detection**

MACAW Optimizations

- Acks for Reliability
- Backoff for Fairness
- DS for Synchronization
- RRTS for Synchronization

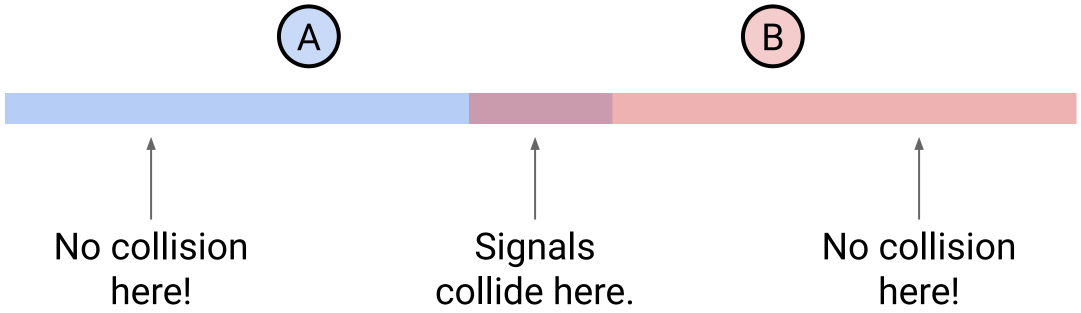
Difference: Collision Detection

Wired collisions are easy to detect.

- On a point-to-point link, collisions might not happen at all.
- There's just one signal on the wire to sense.

Wireless collisions are much harder to detect.

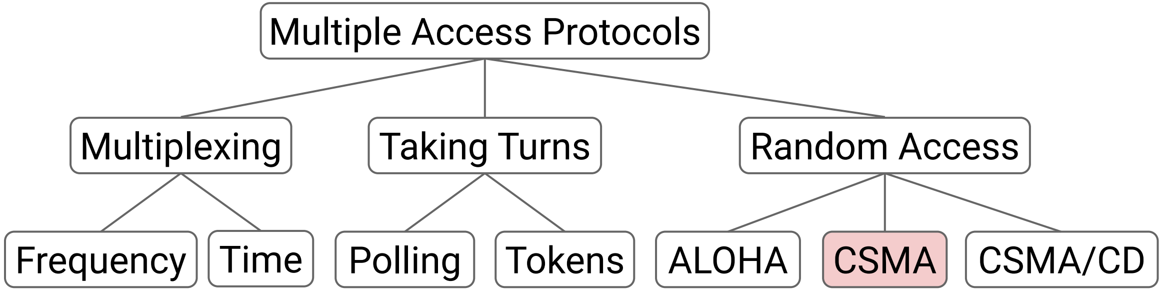
- There's a spatial aspect to collisions.
- Signals can collide in one place, but not another place.



Recall: Multiple Access Protocols

Recall: Many ways for devices to share a link.

- Let's start with CSMA: Listen, and transmit when it's quiet.
- Then we'll design some protocols for wireless networks.



If pairs are well-separated, no problem!

- Goal: A→B and C→D.
- A transmits to B.
- C transmits to D at the same time.
- No collisions!

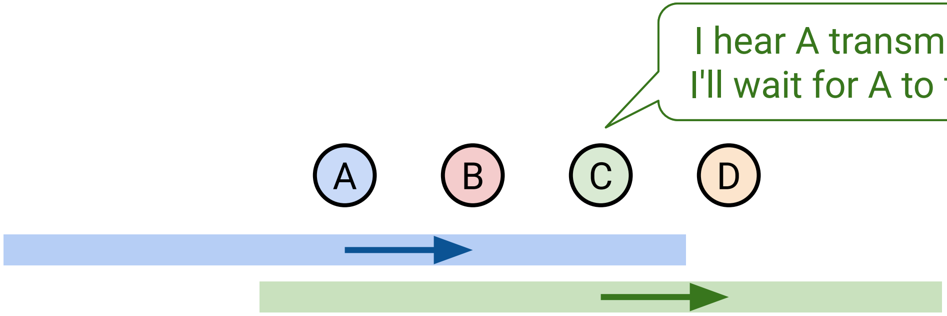
Notice: Signals propagate in all directions (not just toward the destination).

- Arrows are just drawn for convenience.

CSMA in Wireless Networks

If pairs are in range of each other, no problem!

- Goal: A→B and C→D.
- A transmits to B.
- C detects transmission. Must wait to transmit to D.
- No collisions! A–B and C–D take turns.

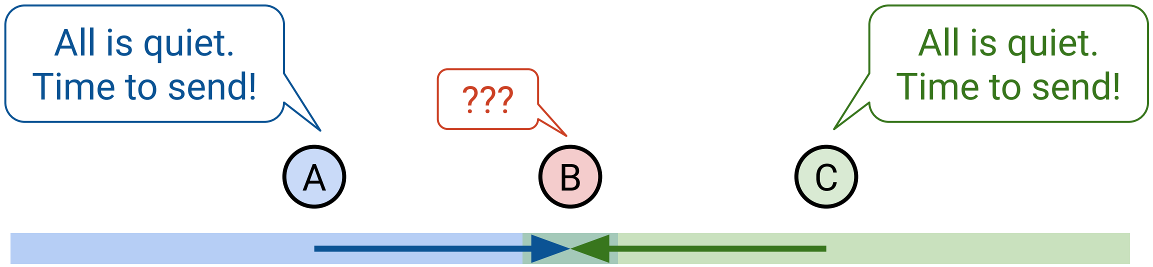


CSMA in Wireless Networks – Hidden Terminal Problem

Hidden terminal problem:

- Goal: A→B and C→B.
- A senses quiet, and starts transmitting.
- C senses quiet, and starts transmitting.
- Collision at B!

Problem: A and C are out-of-range. They can't detect each other sending.

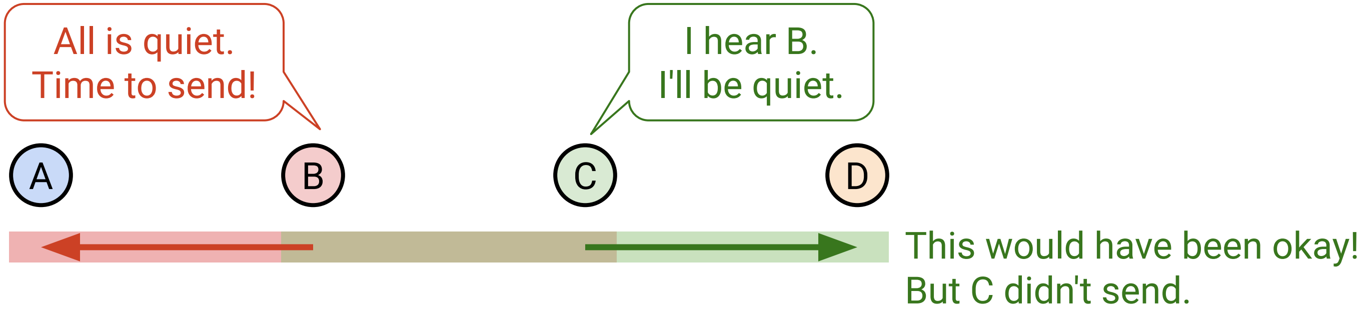


Exposed terminal problem:

- Goal: B→A and C→D.
- B senses quiet, and starts transmitting.
- C senses a collision and doesn't send.

Notice: We could have actually sent simultaneously.

- Some areas have collision, but we don't care. No collisions at the receivers.



MACA (Multiple Access with Collision Avoidance)

Key problem: CSMA detects collisions at the *sender*.

- But we only care about collisions at the *receiver*.

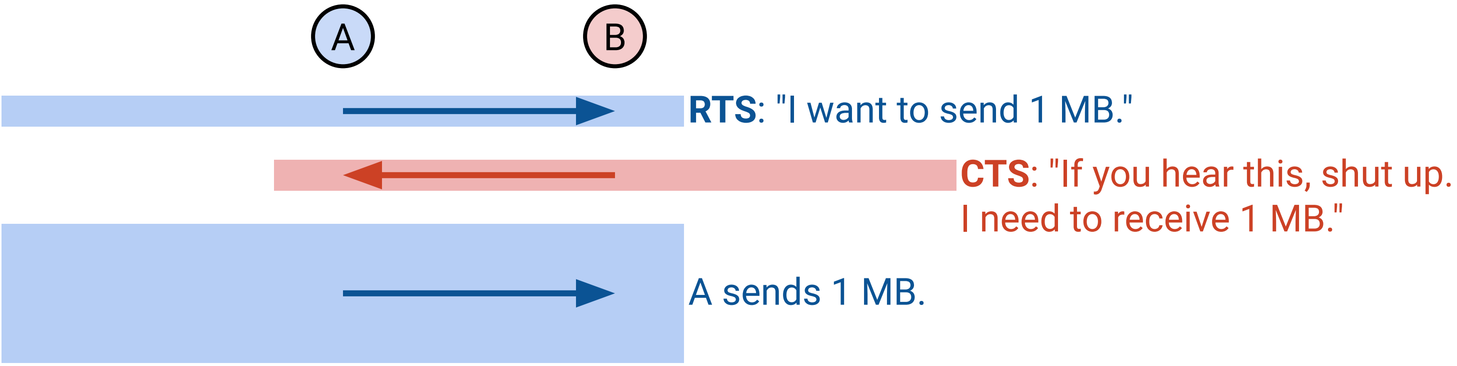
Solution: Let's have the receiver announce if it detects collisions.

- New protocol for shared medium:
  MACA (Multiple Access with Collision Avoidance).
- Note: In this new protocol, we're not doing carrier sense anymore.

MACA (Multiple Access with Collision Avoidance)

To communicate over MACA:

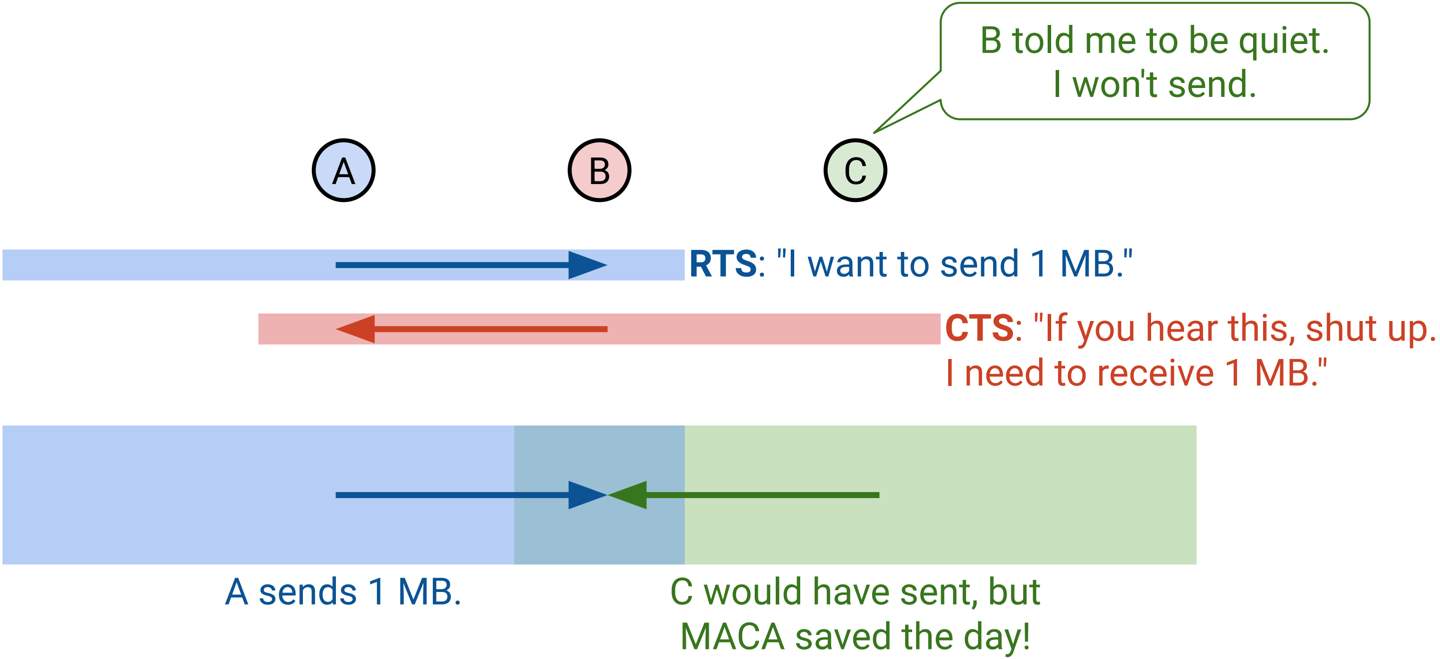
1. Sender transmits **Request to Send (RTS)** with length of data.
2. Receiver transmits a **Clear to Send (CTS)** with length of data.
    - This tells sender that it's safe to send. No collisions at receiver.
    - This tells everyone in receiver's range to be quiet.



MACA (Multiple Access with Collision Avoidance) – Solving Hidden Terminal Problem

MACA solves the hidden terminal problem.

- Goal: A→B, C→B.
- B now tells everyone in its range to be quiet, using the CTS.
- C won't send anymore. Collision avoided!



MACA (Multiple Access with Collision Avoidance) – Rules

If you hear a CTS, be quiet until the data is sent.

- CTS contains length of data.
- You can use data length to estimate how long you need to wait.

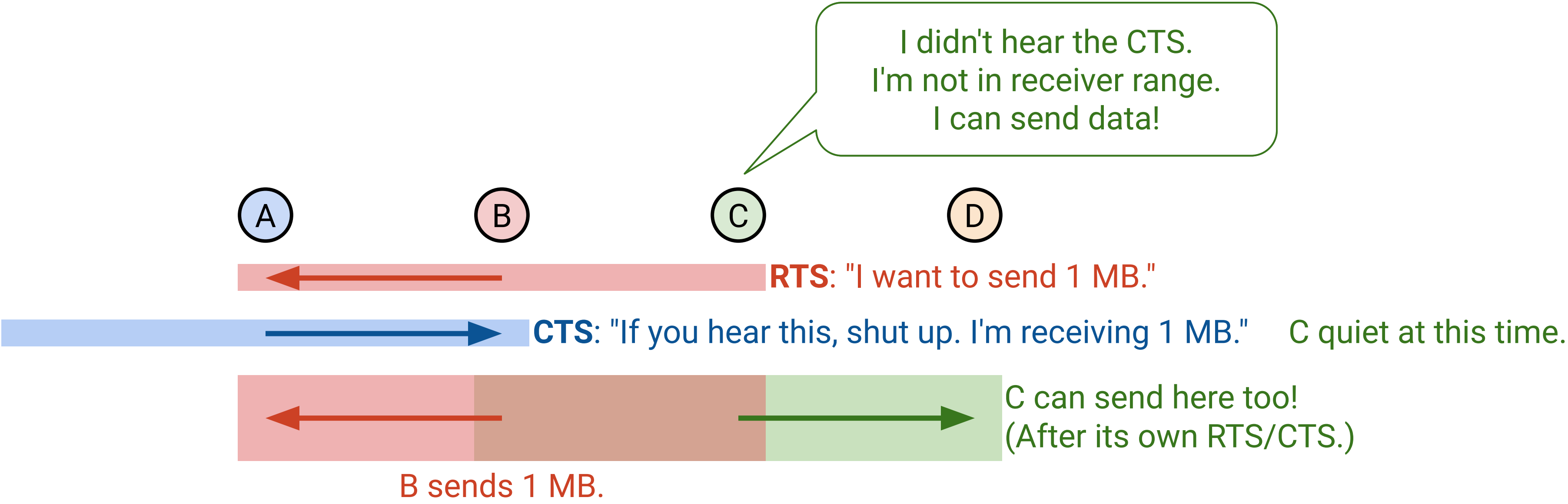
If you hear an RTS, be quiet for one time slot.

- Give the receiver time to send the CTS.
  - If you don't be quiet, you might clobber out the CTS.
- After waiting:
  - If you hear the CTS: You're in receiver range. Be quiet.
  - If you don't hear the CTS: You're not in receiver range. You can send again.

MACA (Multiple Access with Collision Avoidance) – Solving Exposed Terminal Problem

MACA solves the exposed terminal problem, under certain assumptions.

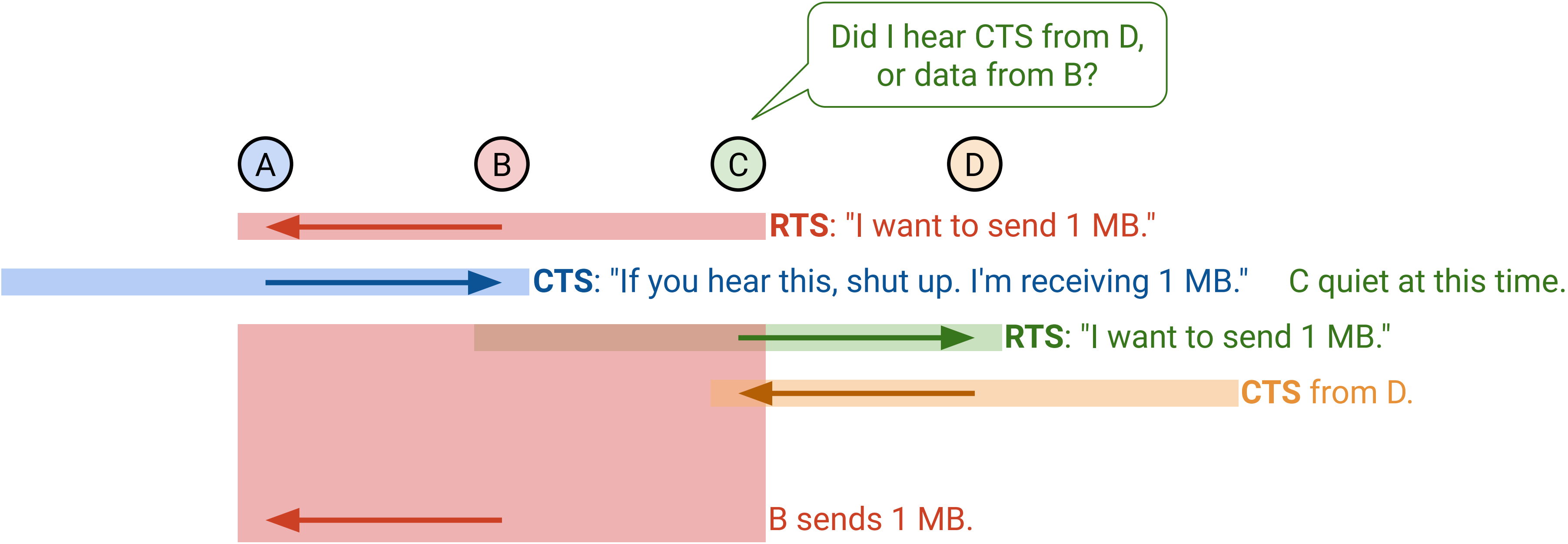
- Goal: B→A and C→D.
- C hears the RTS and defers for one time slot.
- C doesn't hear the CTS, so it's out-of-range of the other receiver, and can send.



MACA (Multiple Access with Collision Avoidance) – Solving Exposed Terminal Problem

MACA solves the exposed terminal problem, **under certain assumptions**.

- Assumes that C can hear the CTS over A's data.
- Key problem: MACA requires the sender to listen (for the CTS).
    - Contrast with CSMA: Sender just sends.



MACA (Multiple Access with Collision Avoidance) – Collisions

If we send RTS, but don't hear CTS, that means there was a collision!

Apply *exponential backoff* and wait up to twice as long before sending another RTS.

- Each device maintains a *CW* (Contention Window) value.
- Pick a random number in [0, *CW*]. Wait that long before re-sending RTS.

Rules for adjusting *CW*:

- Minimum value: *CW* = 2.
- Maximum value: *CW* = 64.
- On successful RTS/CTS: Set $CW \leftarrow 2$.
- On failed RTS/CTS: Set $CW \leftarrow 2 \times CW$, clamped at 64.

Optimization: Acks for Reliability

Lecture 26, CS 168, Fall 2024

Why is Wireless Different?

- Shared Medium
- Attenuation
- Changing Environments
- Collision Detection

MACAW Optimizations

- **Acks for Reliability**
- Backoff for Fairness
- DS for Synchronization
- RRTS for Synchronization

Introducing MACAW (Multiple Access Collision Avoidance for Wireless)

MACAW *(Multiple Access Collision Avoidance for Wireless)* offers improvements over MACA.

- Acks for reliability.
- Better backoff for fairness.
- DS packets for synchronization.
- RRTS packets for synchronization.

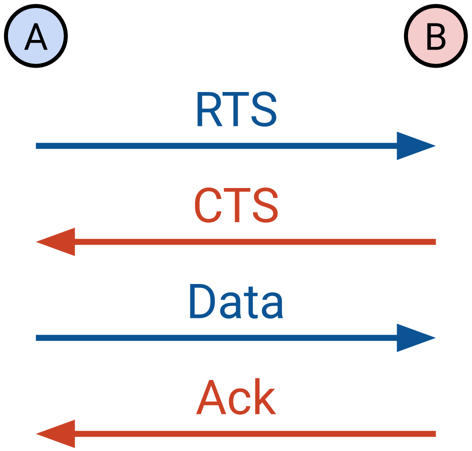
MACAW Feature: Acks for Reliability

MACAW implements acks for reliability:

- If data is lost: No ack! Sender tries again, starting over with a new RTS.
- If ack is lost: No ack! Sender tries again, starting over with a new RTS.
  - Since receiver already got data, it can immediately ack, instead of CTS.

Recall end-to-end principle: Reliability implemented at end hosts for correctness.

- We're adding acks as a performance optimization, not for correctness.



Optimization: Better Backoff for Fairness

Lecture 26, CS 168, Fall 2024

MACAW Feature: Better Backoff for Fairness

MACA is unfair: Winners keep winning. Losers keep losing.

	A	B	
	CW = 2	*CW* = 2	

A and B try to reserve simultaneously.
Suppose A wins.

A wins and sets *CW* = 2.	*CW* = 2	*CW* = 4	B loses and doubles *CW*.

A has lower *CW*, will try again sooner.
A wins again!

A wins and sets *CW* = 2.	*CW* = 2	*CW* = 8	B loses and doubles *CW*.

A has lower *CW*, will try again sooner.
A wins again!

A wins and sets *CW* = 2.	*CW* = 2	*CW* = 16	B loses and doubles *CW*.

MACAW Feature: Better Backoff for Fairness

MACAW solution: Have everybody share the same *CW*.

- Packet header has a field with *CW* value.
- If you receive a packet, set your *CW* to value in the packet.

MACAW solution: Change *CW* update rules to be more gentle.

- Multiplicative Increase, Linear Decrease (MILD).
- On successful RTS/CTS/data/ack: ***CW* ← *CW* – 1**, clamped at 2.
  - Contrast with MACA, setting *CW* = 2.
- On failed RTS/CTS: ***CW* ← 1.5 × *CW***, clamped at 64.
  - Contrast with MACA, setting *CW* ← 2 × *CW*.

We're simplifying a bit. Technically, this slide is only true if all devices are in range of each other.

Optimization: DS for Synchronization

Lecture 26, CS 168, Fall 2024

Why is Wireless Different?

- Shared Medium
- Attenuation
- Changing Environments
- Collision Detection

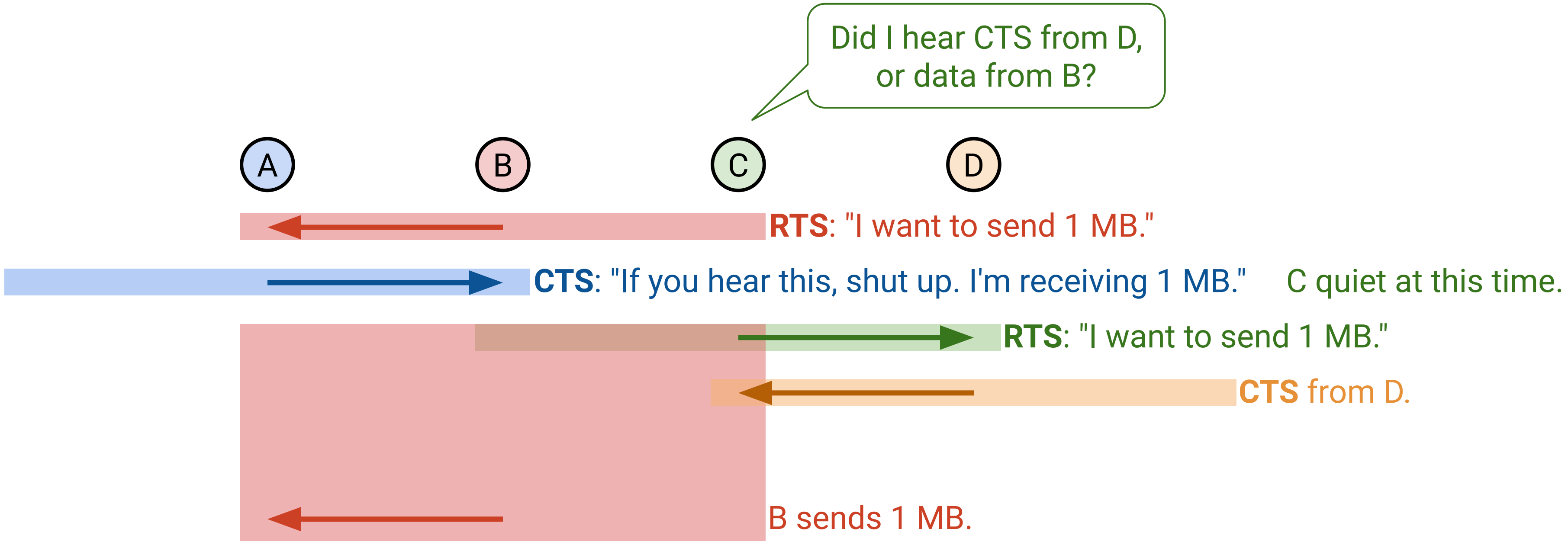
MACAW Optimizations

- Acks for Reliability
- Backoff for Fairness
- **DS for Synchronization**
- RRTS for Synchronization

MACAW Feature: Admit Defeat on Exposed Terminals

Recall the exposed terminal problem.

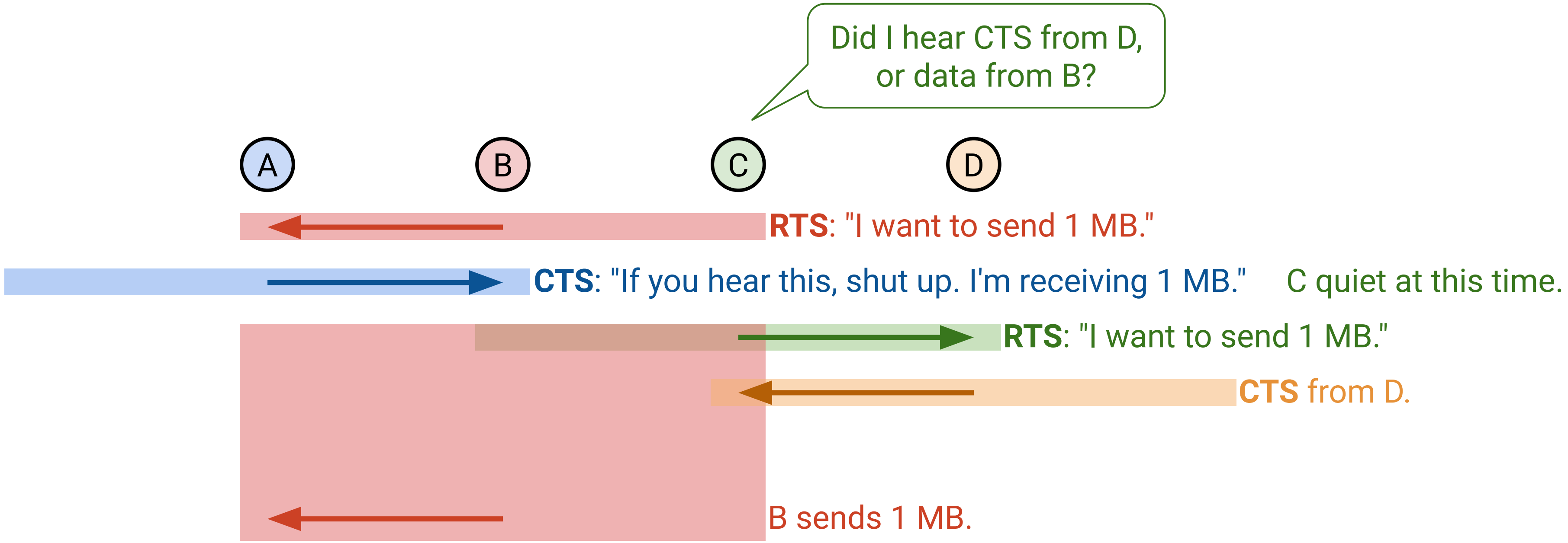
- Goal: B→A, C→D.
- C must hear an CTS from D before it can start sending.
- But C can't hear the CTS. Gets clobbered by the data from B!



MACAW Feature: Admit Defeat on Exposed Terminals

MACAW (and MACA) admits defeat on the exposed terminal problem.

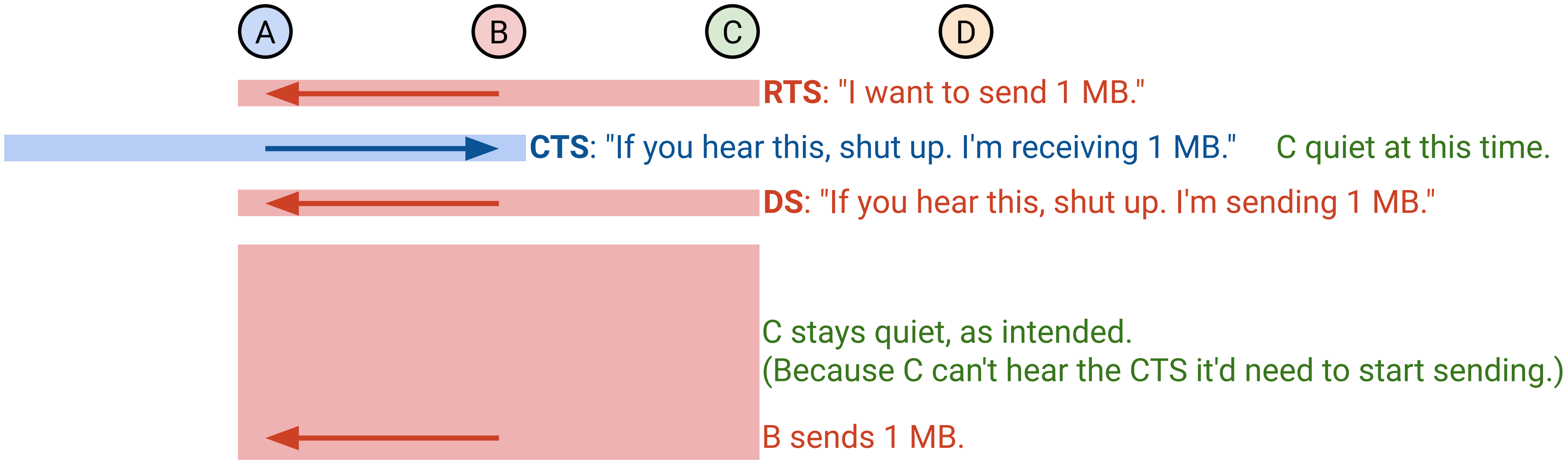
- Ideally, B→A and C→D send simultaneously. In reality, they must take turns.
- Punchline: If you're in range of sender, you need to be quiet.
    - Because you can't hear the CTS you'd need to start sending yourself.



MACAW Feature: Admit Defeat on Exposed Terminals

Punchline: If you're in range of sender, you need to be quiet.

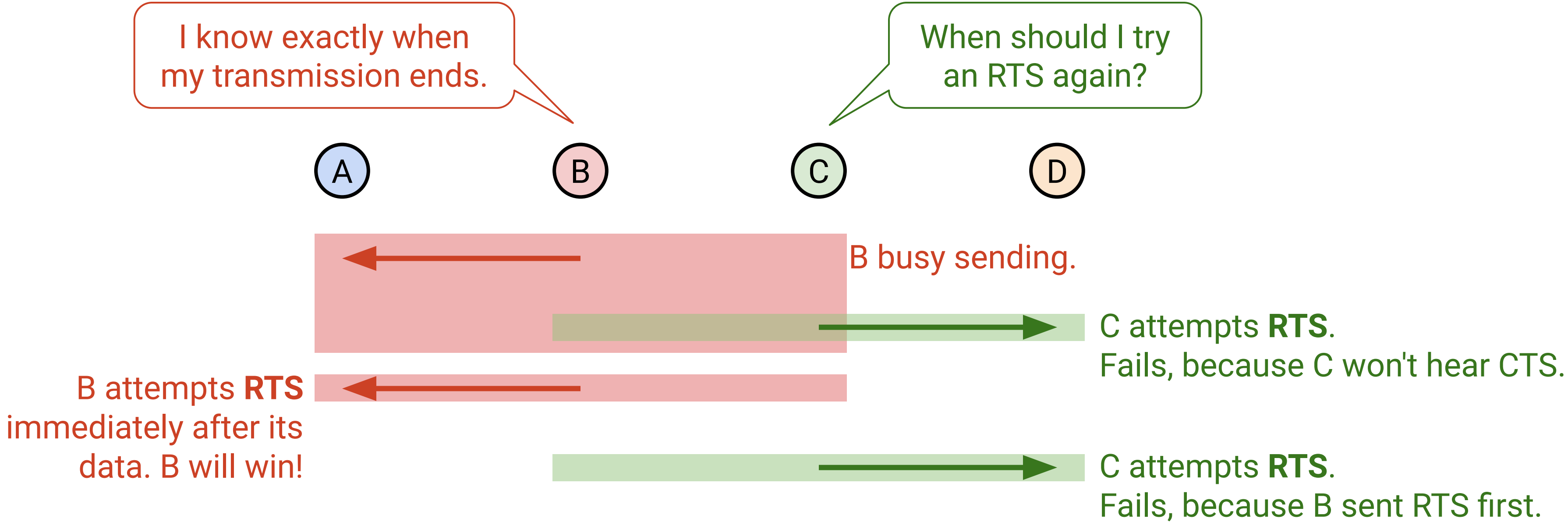
- Solution: Sender transmits a **Data Sending (DS)** packet before the data.
- Warns everyone in sender's range to be quiet.



MACAW Feature: DS Packet for Fairness

The DS packet also helps with synchronization for fairness.

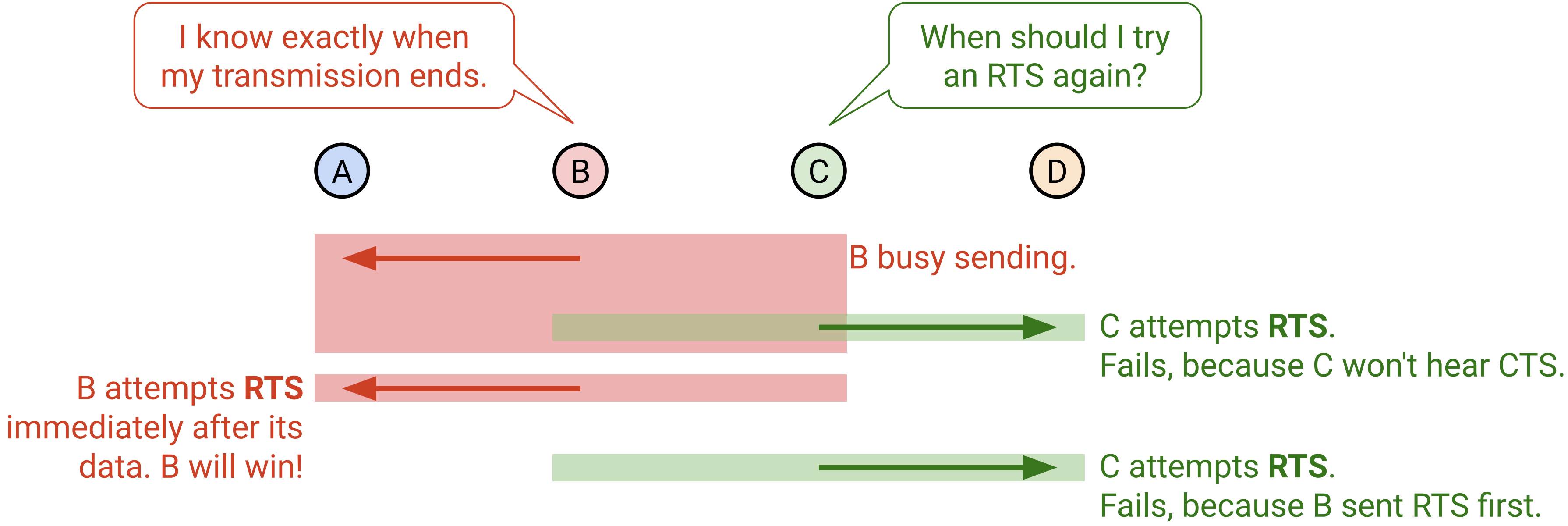
- To see why, let's see what happens *without* the DS packet.
- Goal: B→A, C→D.



MACAW Feature: DS Packet for Fairness

B has a huge advantage, because B knows when its data transmission ends.

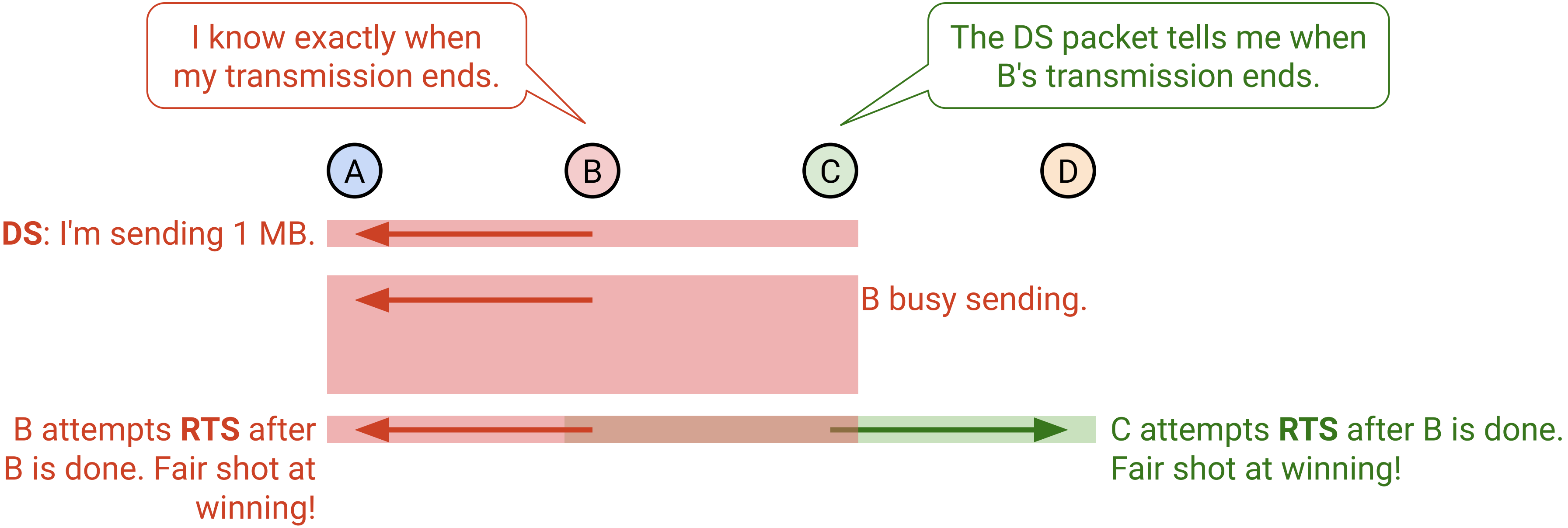
- B can immediately recapture the channel with another RTS.
- C must guess when to send the RTS.



MACAW Feature: DS Packet for Fairness

The DS packet synchronizes by telling everybody when the transmission ends.

- Now C can also send the RTS after B is done.
- C and B both have a fair shot at winning!



Optimization: RRTS for Synchronization

Lecture 26, CS 168, Fall 2024

Why is Wireless Different?

- Shared Medium
- Attenuation
- Changing Environments
- Collision Detection

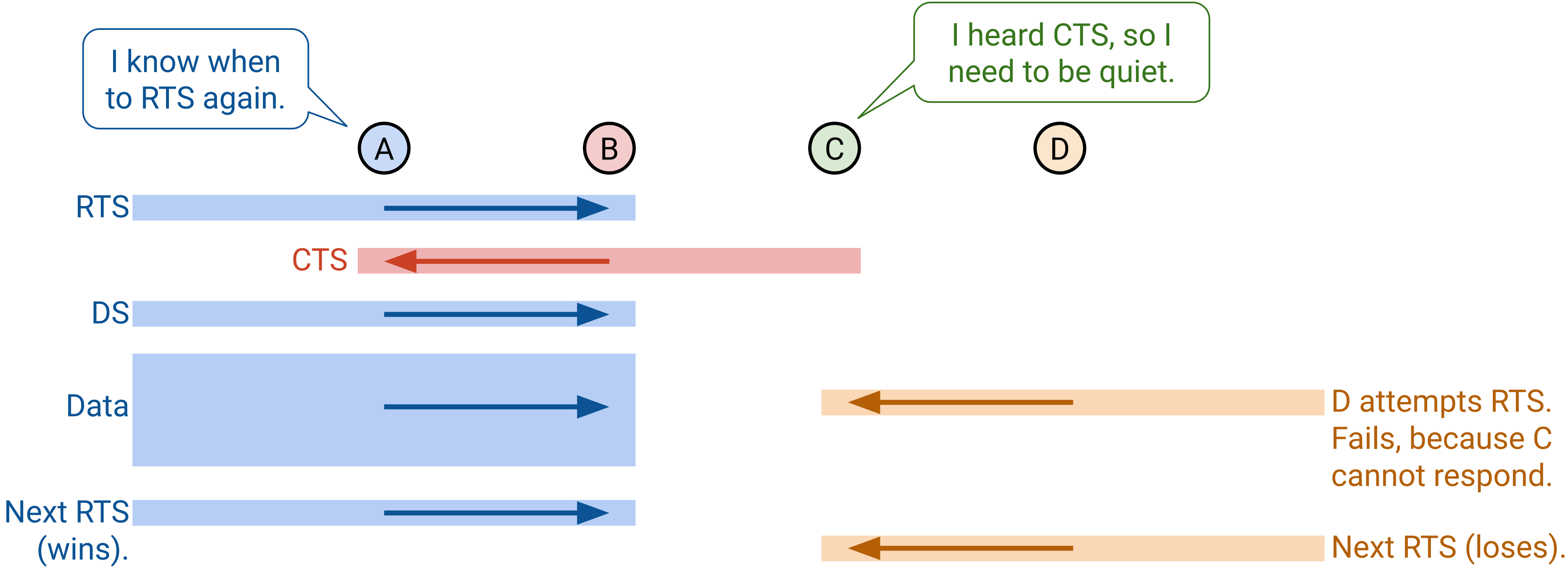
MACAW Optimizations

- Acks for Reliability
- Backoff for Fairness
- DS for Synchronization
- **RRTS for Synchronization**

MACAW Feature: RRTS Packet for Fairness

Another case where we need synchronization for fairness:

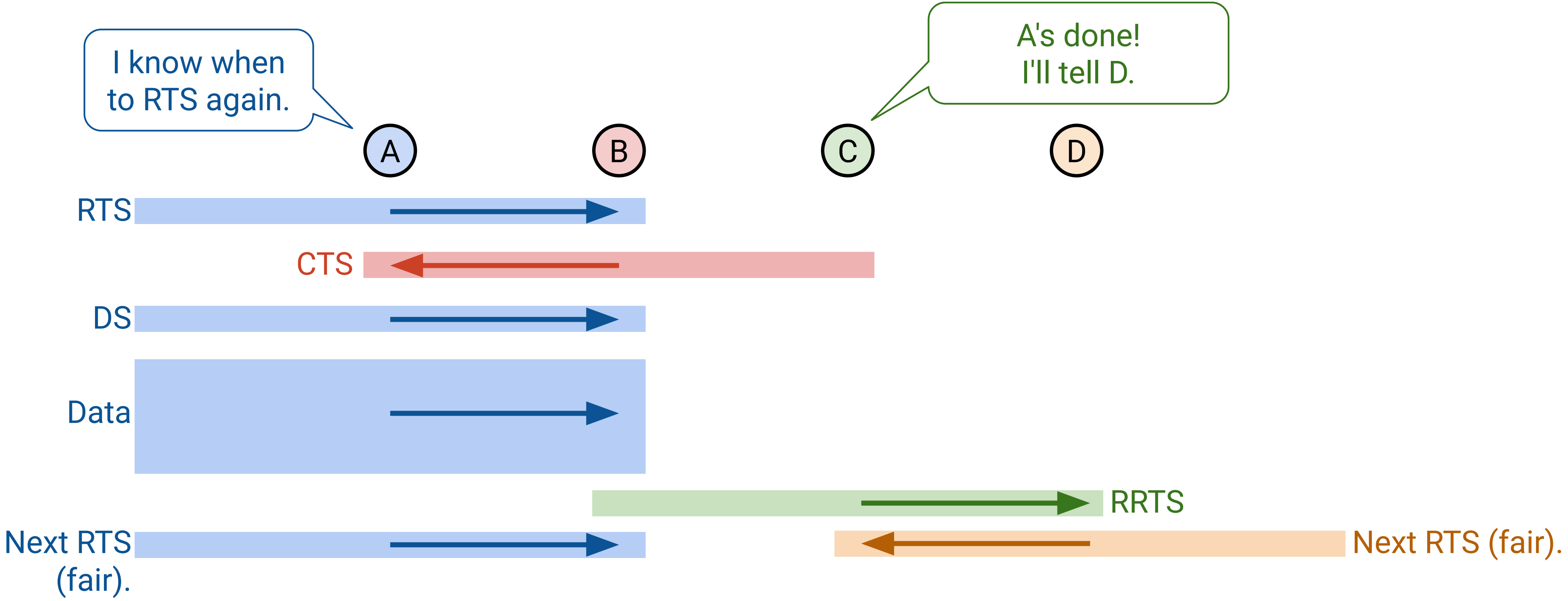
- Goal: A→B, D→C.
- D is doomed. D can't hear the CTS or the DS, and has no idea when to try again.



MACAW Feature: RRTS Packet for Fairness

Solution: Let C contend on behalf of D.

- Goal: A→B, D→C.
- C sends an **RRTS** to tell D: Now's a good time to send a RTS.



MACAW Feature: RRTS Packet for Fairness

If C hears an RTS, but can't respond: Send an RRTS when channel frees up.

- This tells D to immediately send an RTS.
- If you hear an RRTS: Be quiet for 2 time slots so the RTS/CTS can happen.