Link Layer II: Sharing the Wireless Medium, Link Layer Reliability

COS 463: Wireless Networks
Lecture 5

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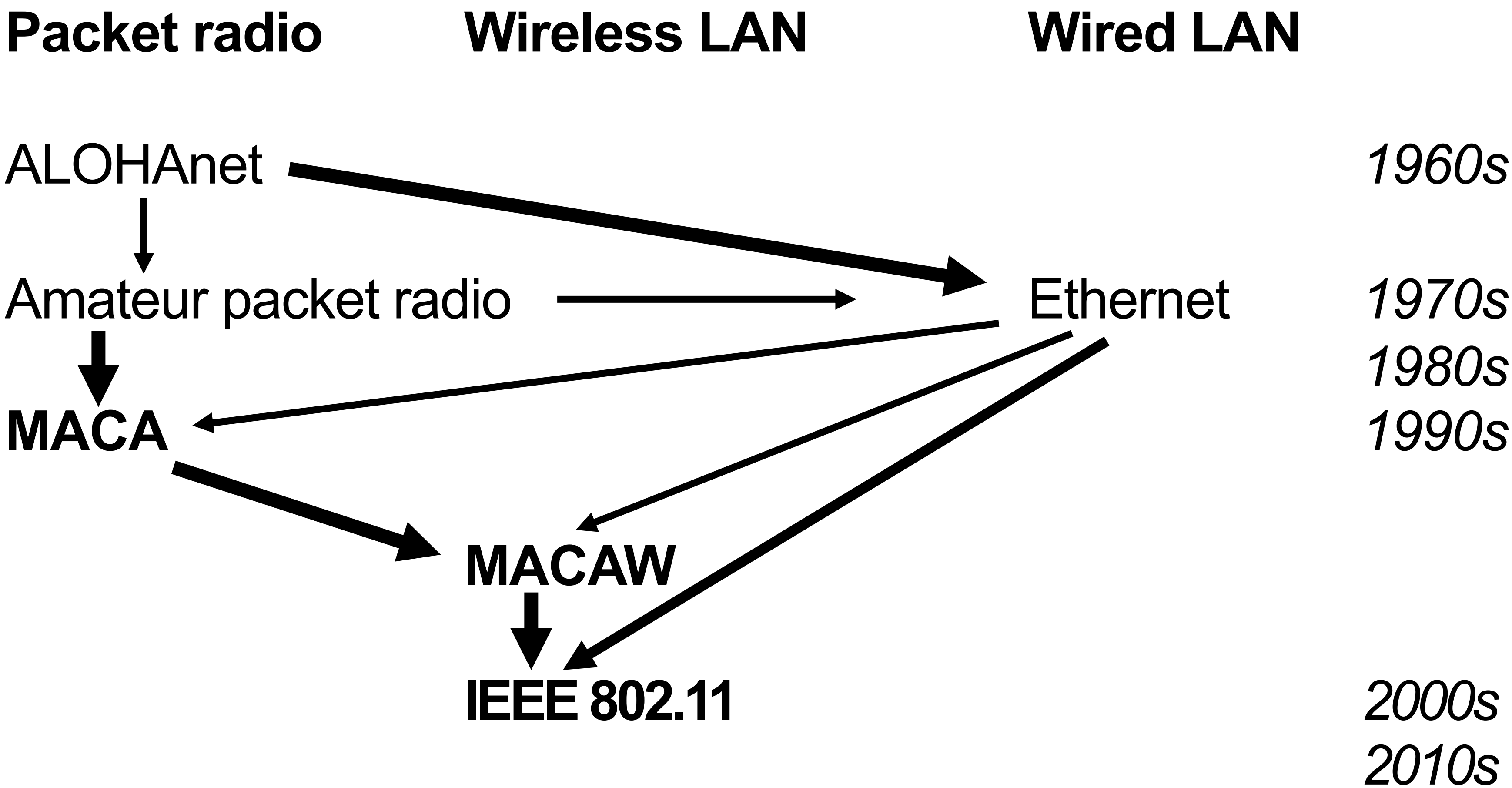
[Parts adapted from J. Kurose, K. Ross, D. Holmar]

Medium access: Timeline

Packet radio	Wireless LAN	Wired LAN	
ALOHAnet			*1960s*
Amateur packet radio		Ethernet	*1970s*

Medium access: Timeline



Today: Wi-Fi Above the PHY

1. **MACA**
   – Carrier sense in the wireless medium
   – Hidden and exposed terminal problems

2. MACAW

3. 802.11 MAC layer

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

Multi-channel

- Suppose we have **100 MHz of spectrum** to use for a wireless LAN

- **Strawman:** Subdivide into **50** channels of **2 MHz** each: FDMA, narrow-band transmission
  - Radio hardware simple, channels don't mutually interfere, **but**
  - **Multi-path fading** (mutual cancellation of out-of-phase reflections)
  - Base station can allocate channels to users. How do you support **arbitrary communication patterns?**

Idea: Use a single, shared channel

- Spread transmission across whole 100 MHz of spectrum
  - **Remove constraints** assoc. w/one channel per user
  - **Robust to multi-path fading**
    - Some frequencies likely to arrive intact
  - **Supports peer-to-peer communication**

- **Collisions:** Receiver must hear ≤1 strong transmission at a time

- So adopt **deference** from Ethernet
  - **Listen** before sending, **defer** to ongoing

MACA, MACAW: Assumptions and goals

- Assumptions
  - **Uniform, circular** radio propagation
    - Fixed transmit power, all same ranges
  - **Equal interference** and **transmit** ranges

Radios modeled as "conditionally connected" wires based on circular radio ranges

- Goals
  - Fairness in sharing of medium
  - Efficiency (total bandwidth achieved)
  - Reliability of data transfer at MAC layer

Concurrency versus Taking Turns

- **Far-apart** links should **send concurrently** (***spatial reuse***)

- Nearby links should **take turns:**

When Does CS Work Well?

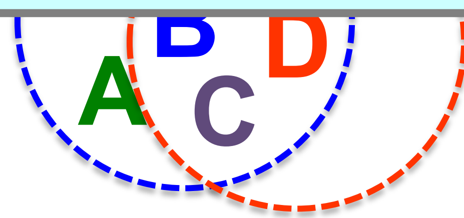
- Two transmission pairs are far away from each other
  - Neither sender carrier-senses the other

B transmits to A, while D transmits to C.

When Does CS Work Well?

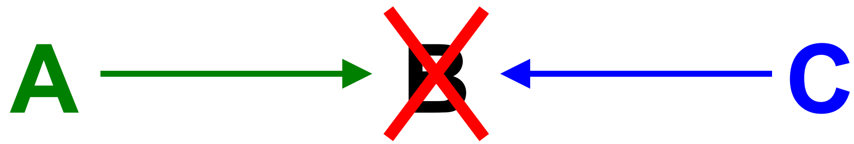
- **Both transmitters can carrier sense each other**
  - Carrier sense uses **thresholded correlation** value (like CDMA) to determine if medium occupied

But what about cases in between these extremes?



B transmits to A, D transmits to C, taking turns.

Hidden Terminal Problem



- **C** can't hear **A,** so **C** 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

- If C transmits, does it cause a collision at A?
  - **Yet C cannot transmit while B transmits to A!**

- **Same insight: Collisions spatially located at receiver**

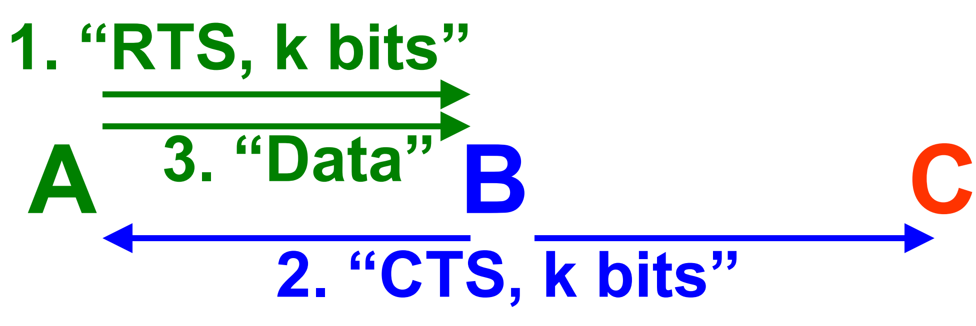
- One possibility: **directional antennas** rather than omnidirectional. **Why does this help? Why is it hard?**

MACA: Multiple Access with Collision Avoidance

- **Carrier sense** became adopted in packet radio
- But **distances** (cell size) remained large
- **Hidden and Exposed terminals abounded**
- **Simple solution:** use ***receiver's*** **medium state** to determine **transmitter** **behavior**

RTS/CTS

- Exchange of two short messages: ***Request to Send* (RTS)** and ***Clear to Send* (CTS)**
- **Algorithm**
  1. A sends an **RTS** (tells B to prepare)
  2. B replies an **CTS** (echoes message length)
  3. A sends its **Data**



Deference to CTS

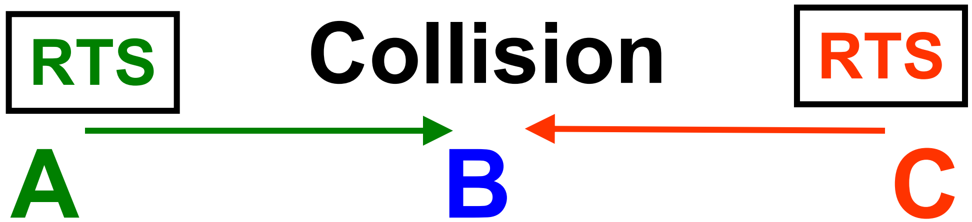
- **Hear CTS → Defer for length of expected data** transmission time
  - **Solves hidden terminal problem**

Deference to RTS, but not CS

- **Hear RTS →** Defer **one CTS-time** (*why?*)
- **MACA: No carrier sense before sending!**
  - Karn concluded useless because of **hidden** terminals
- So **exposed** terminals **B, C** **can transmit concurrently:**

Collision!

- **A's RTS** collides with **C's RTS, both are lost at B**
  - **B will not reply with a CTS**



- **Might collisions involving data packets occur?**
  – Not according to our **(unrealistic)** assumptions
  – But Karn **acknowledges interference range > communication range**

BEB in MACA

- When collisions arise, MACA senders **randomly backoff** like Ethernet senders then **retry the RTS**

- How long do collisions take to **detect** in the Experimental Ethernet?

- **What size** should we make MACA backoff slots?

BEB in MACA

- Current backoff constant: CW
- MACA sender:
  - $CW_0 = 2$ and $CW_M = 64$
  - Upon **successful** RTS/CTS, $CW \leftarrow CW_0$
  - Upon **failed** RTS/CTS, $CW \leftarrow \min[2CW, CW_M]$
- Before retransmission, wait a uniform random **number of RTS lengths** (30 bytes) in **[0, *CW*]**
  - 30 bytes = 240 μs

Today: Wi-Fi Above the PHY

1. MACA

2. **MACAW**

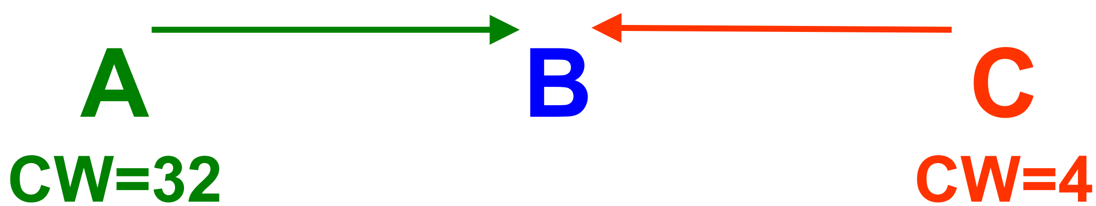
3. 802.11 MAC layer

MACAW: Context

- Published in SIGCOMM 1994, work ’93/’94
- Wi-Fi standards proceeded in parallel (IEEE standard ‘97)
  - 802.11 draws on MACAW, which draws on MACA
- **Assumptions and goals:** Same as MACA
- **Setting:** Wireless LAN
  - **Packet radio (MACA)** cell size: circa 100 mi. (**528 μs**)
  - **Wireless LAN (MACAW)** cell size: circa 100 ft. (**100 ns**)

Fairness in BEB/MACA

- MACA's BEB can lead to **unfairness:** backed-off sender has decreasing chance to acquire medium ("the poor get poorer")
- **Simple example: A, C** each sending at a rate that can alone saturate the network



- **C** more likely to win the backoff and set **minimum CW=2**
- **A** more likely to defer (maintain CW)

BEB in MACAW: Copy

- **MACAW proposal:** senders **write their *CW*** into packets
  – Upon hearing a packet, **copy and adopt** its *CW*

- **Result:** Dissemination of congestion level of “winning” transmitter to its competitors

Stretch break: Is this a good idea?

- RTS failure rate at one node propagates far and wide
  – Ambient noise? Regions with different loads?

BEB in MACAW

- Integrates with MACAW's ACK mechanism
- Multiplicative increase, linear decrease (**MILD**)
- MACAW sender:
  - $CW_0 = 2$ and $CW_M = 64$
  - Upon **failed** RTS/CTS
    - $CW \leftarrow \min[1.5CW, CW_M]$
  - Upon **successful** RTS/CTS but **failed** ACK, **no change**
  - Upon **successful** RTS/CTS/DATA/ACK
    - $CW \leftarrow CW-1$

Reliability: ACK

- MACAW introduces an **ACK** after DATA packets (not in MACA)

- **Sender resends** if RTS/CTS succeeds but **no ACK returns**

- Sender resends RTS. **Two cases:**

1. DATA was lost
   - Receiver sends CTS, sender DATA

2. Receiver already has the DATA (reverse-link **ACK loss**)
   - Receiver sends **ACK**

ACK: Considerations

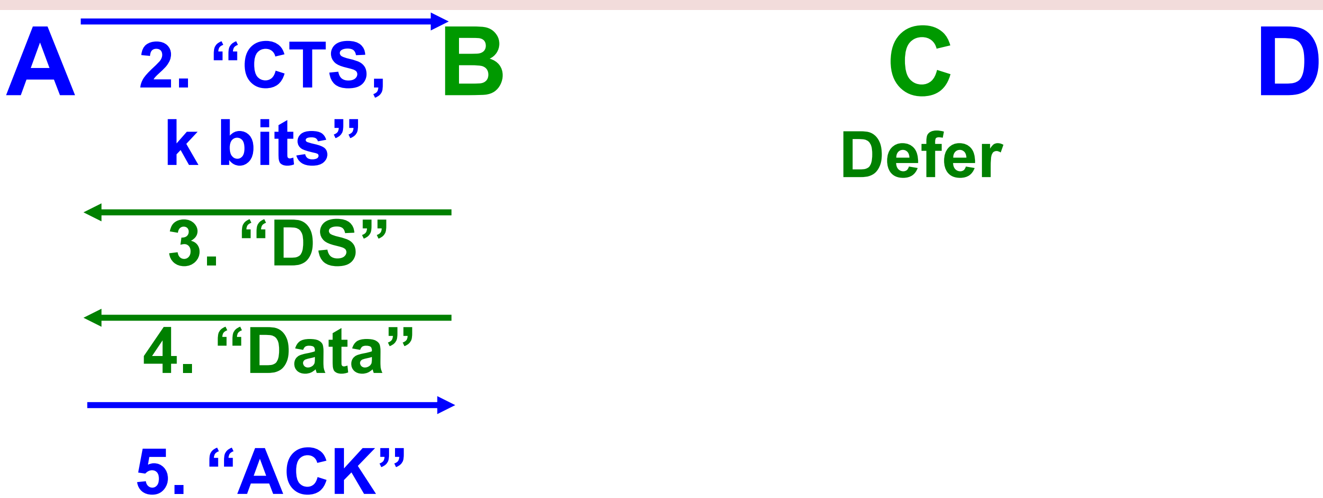
- **Avoid TCP window reductions** when interference
- Useful when there's **ambient noise** (microwave ovens…)
- Why are sequence numbers in DATA packets now important (not mentioned directly in paper!)
- Are ACKs useful for multicast packets? Consequences for, e.g., ARP?

MACAW and Exposed Terminals

- C can proceed only if it can hear a **CTS** from D
  - **But B's DATA will likely clobber D's CTS at C**
  - **C doesn't know if B's RTS/CTS exchange succeeded**

- So B sends a **Data Sending (DS)** packet after CTS
  - So C *knows* that B received a CTS
    - C **defers until after ACK**

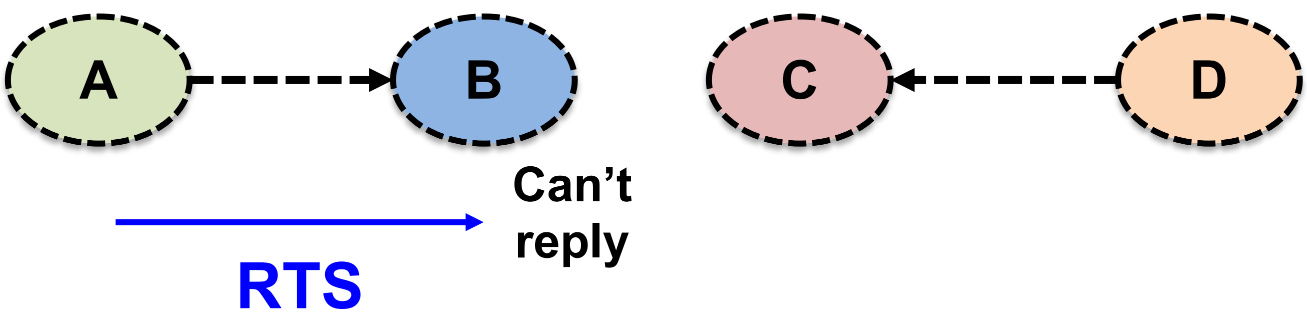
Conservative: Doesn't leverage exposed terminal opportunities for concurrency



Need for Synchronization

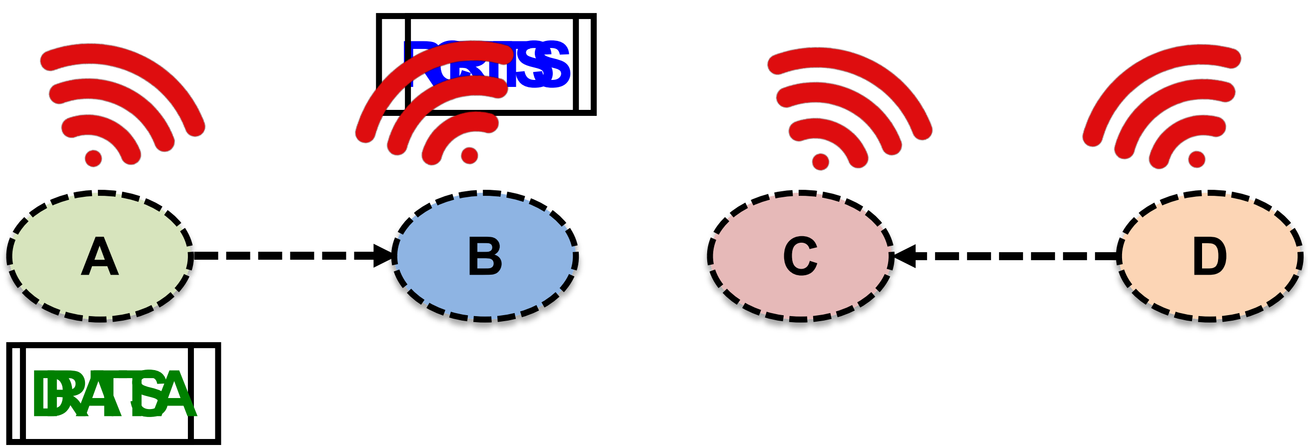
- Suppose **D** has a **smaller CW, ongoing transmission**
- B **cannot reply** to A's RTS
- **A doesn't know when** the contention periods are
  - So, A's backoff will increase: **unfair**

- **MACAW's approach:** let B contend **"on behalf of"** A



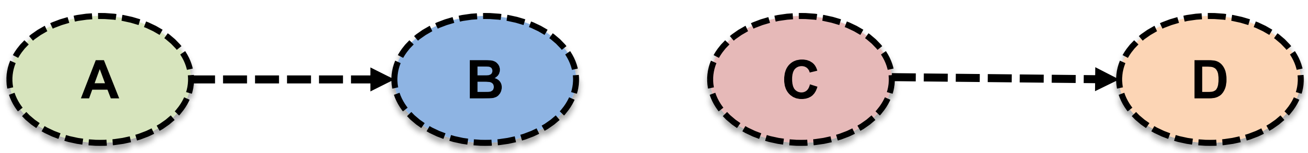
MACAW: RRTS

- **B knows** when the time gaps for contention are
- If B **can't reply to RTS,** it sends a **Request for RTS (RRTS)** packet to A when DATA completes (hears an ACK from C)
- C defers transmissions for two slot periods (*why?*)
  - On hearing RRTS, **A** sends **RTS** immediately without backoff



A Problem not Solved by RRTS

- **What happens in this scenario?**
  - Assume C is successful, ongoing transmission
  - When A sends RTS to B, B **just can’t hear it**
  - So this problem is not solved by RRTS



Today: Wi-Fi Above the PHY

1. MACA

2. MACAW

3. **802.11 MAC layer**
   - **Contention and backoff**
   - Frame aggregation
   - Selective retransmission and Acknowledgement

802.11's MAC

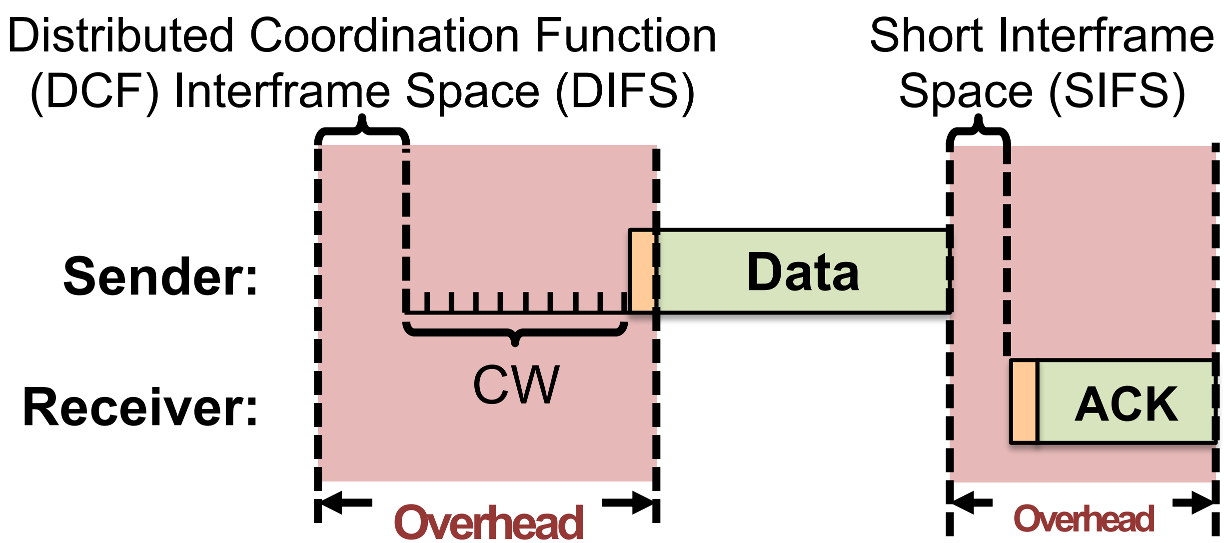
- Adopts **MACAW's MAC** from a high level:
  - **Same** RTS/CTS/DATA/ACK
    - RTS/CTS optional
  - **Different** **contention window** control

- Adopts **CS and Deference** from Ethernet:
  - But **not** **collision detection**
    - Transmit signal power ≫ receive signal power

- **Adds design elements** for high data rates, TCP above

Deference times for Prioritization

- Fixed-time deference + CS = **prioritization** (DIFS > SIFS)



- **So, overhead of fixed time duration** per Wi-Fi Frame:
  – RTS/CTS (if present), DIFS, CW, preamble, SIFS, ACK

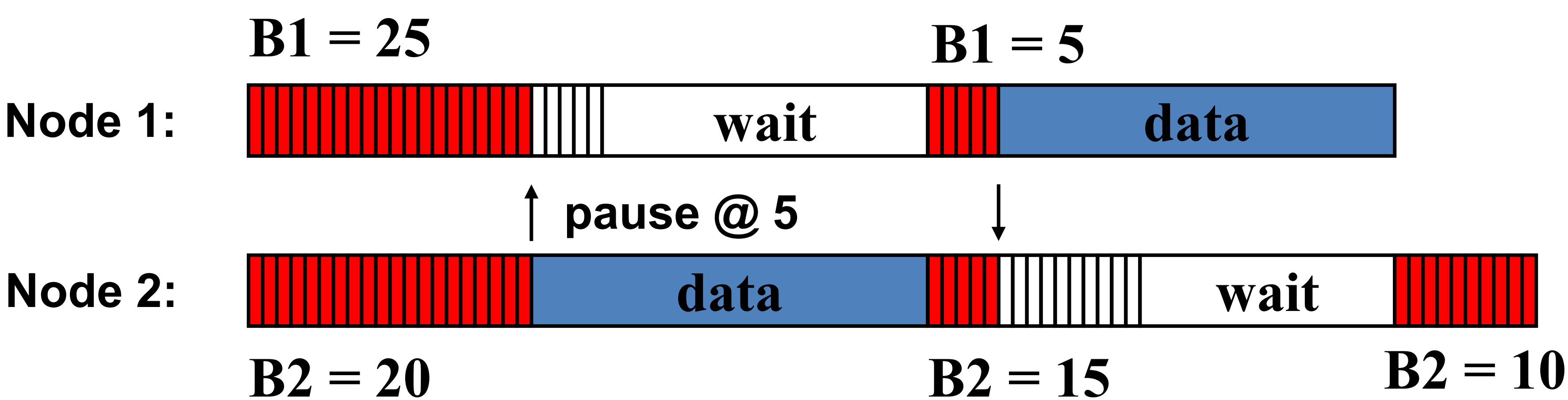
802.11 ac: SIFS = 16 μs, DIFS = 34 μs

Backoff: Pausing and Resuming

- **802.11 backoff slot time** = Physical **CS** time + **propagation** time + time to **switch radio** from receive to transmit

802.11 ac:
slot time = 9 μs

- **No MACAW:** No "copy," no MILD, no DS, no RRTS



CW = 31

B1 and B2 are backoff intervals at nodes 1 and 2

802.11's Pause

- Adaptively sets CW with **BEB**
  - Start with CW = 31, **double** if no CTS or ACK received
  - **Reset to 31** on **successful transmission**

- **Not fair** in the short term
  - Under contention, losers will use larger CW than winners (winners reset)
  - Winners may be able to **transmit several packets** while unlucky nodes are **still counting down**

- Could adopt MACAW's copy & MILD, but has drawbacks

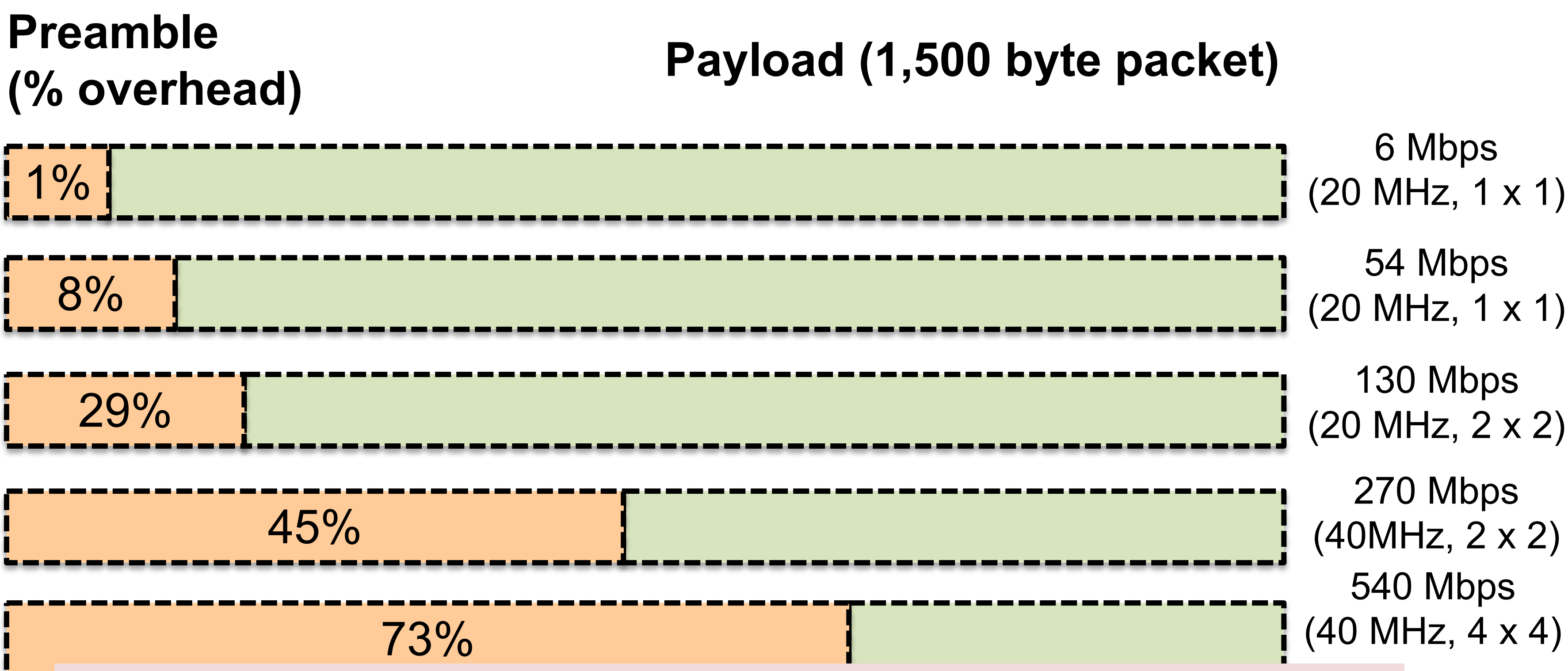
Today: Wi-Fi Above the PHY

1. MACA

2. MACAW

3. **802.11 MAC layer**
   – Contention and backoff
   – **Frame aggregation**
   – **Selective retransmission and Acknowledgement**

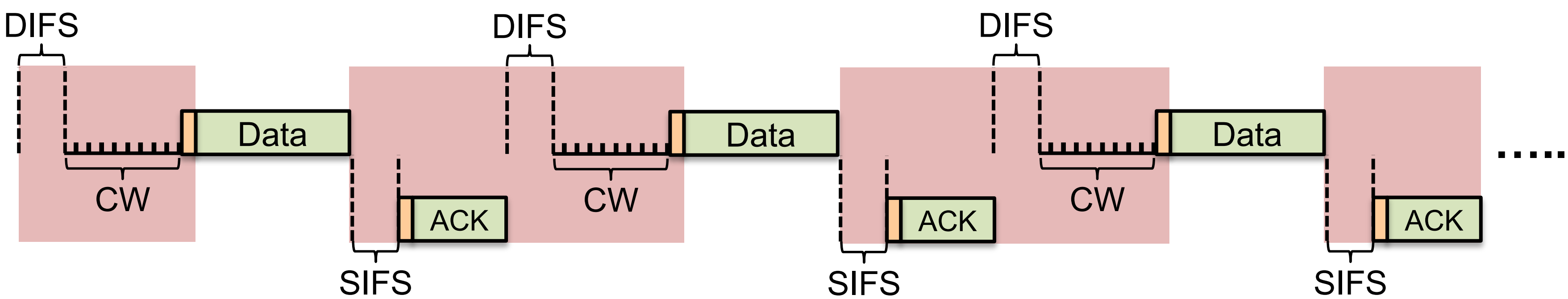
Motivation: MAC Scaling Incommensurate with PHY Bitrate



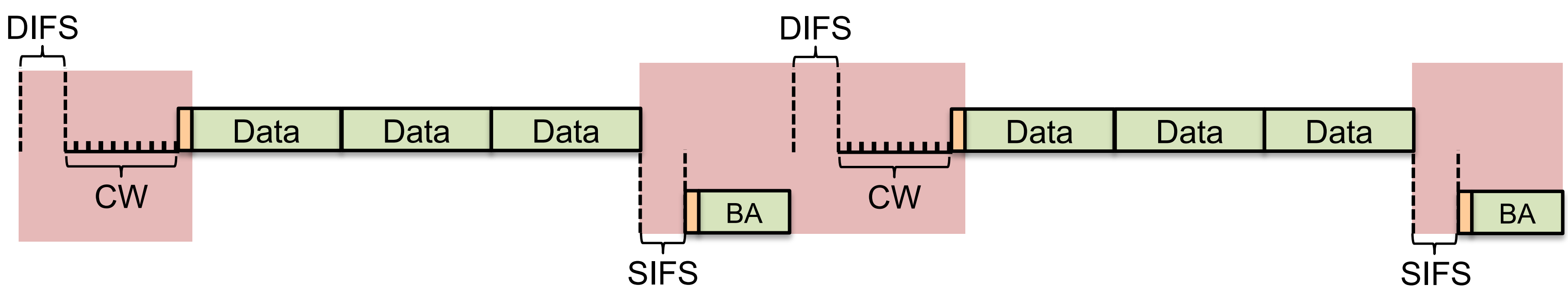
Problem: Drop in efficiency with increasing data rate from fixed overheads in the preamble and inter-frame spaces

Aggregation Amortizes Fixed Overheads

- **Without aggregation:**



- **With aggregation:** Multiple frames/channel acquisition
  – ***Block ack (BA)*** tells sender which arrived



802.11: Selective Retransmission

- 802.11 adopts TCP's selective retransmission, but:
  - Primary consideration is **performance** at the link layer
  - Protocol is only **semi-reliable:** may drop packets

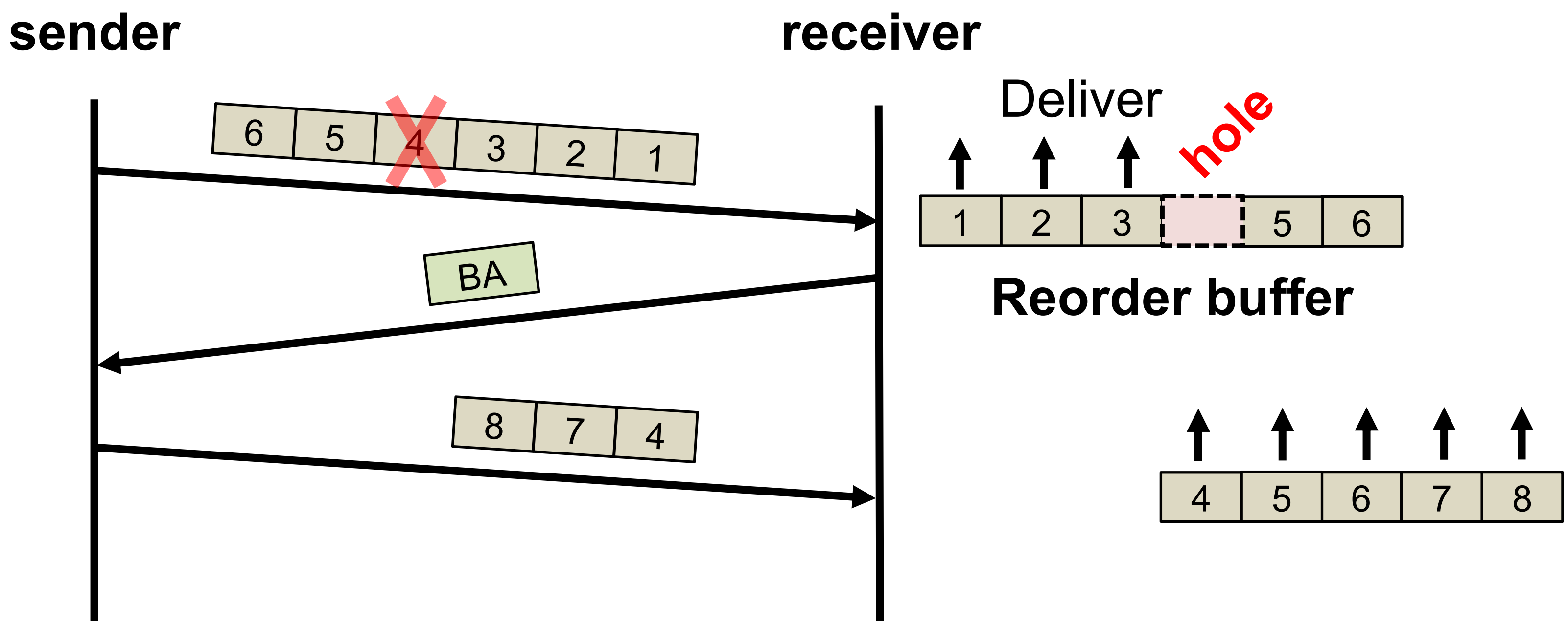
- Receiver-side **reorder buffer** for in-order delivery

- Receiver-side **scoreboard** for feedback to sender

- Sender transmits ***Block ACK request (BAR)*** frames:
  1. If needed, sender can solicit a ***Block ACK response*** (***BA response***) from receiver

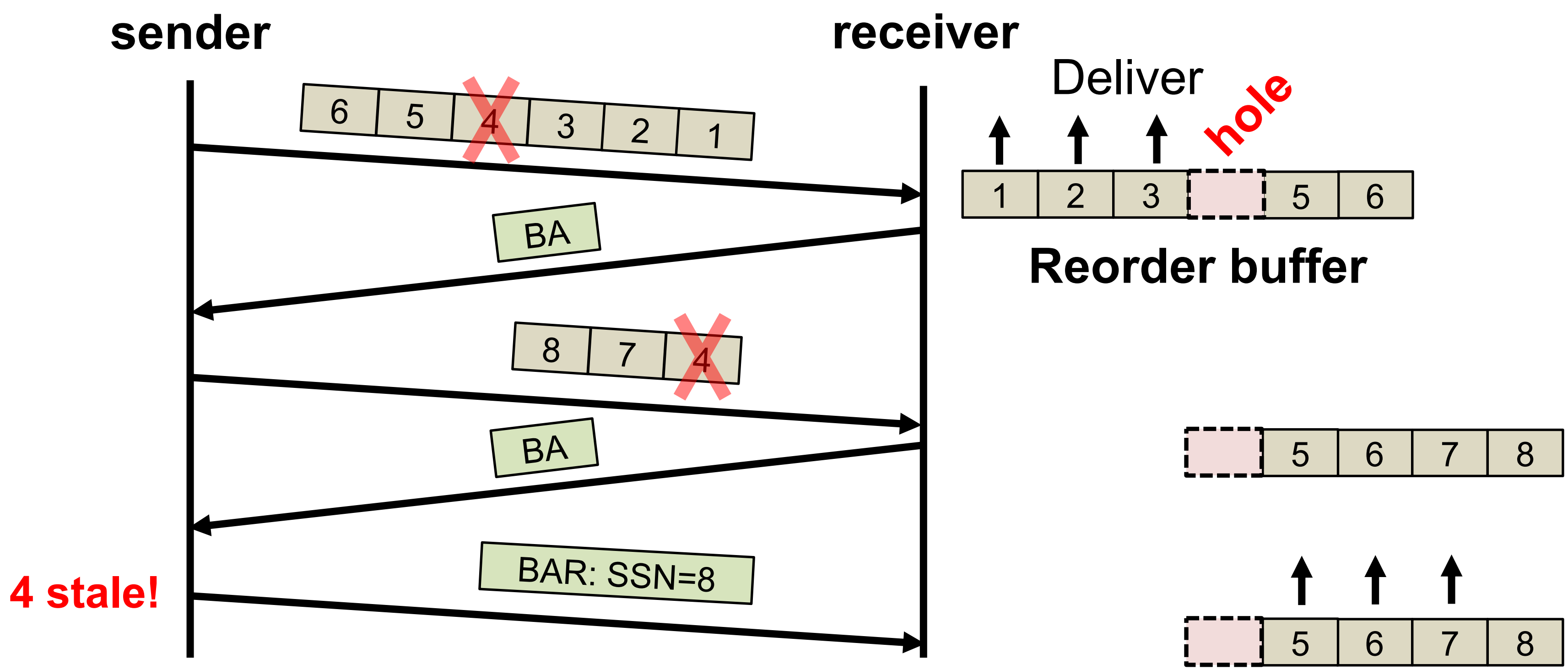
  2. Sender may direct receiver to **drop (*i.e.,* fail to deliver to the network layer)** frames **it deems old**

Reorder Buffer Operation



- Like TCP, 802.11's reorder buffer guarantees in-order delivery to the layer above
- But **at most once** instead of exactly-once semantics

Flushing the Reorder Buffer

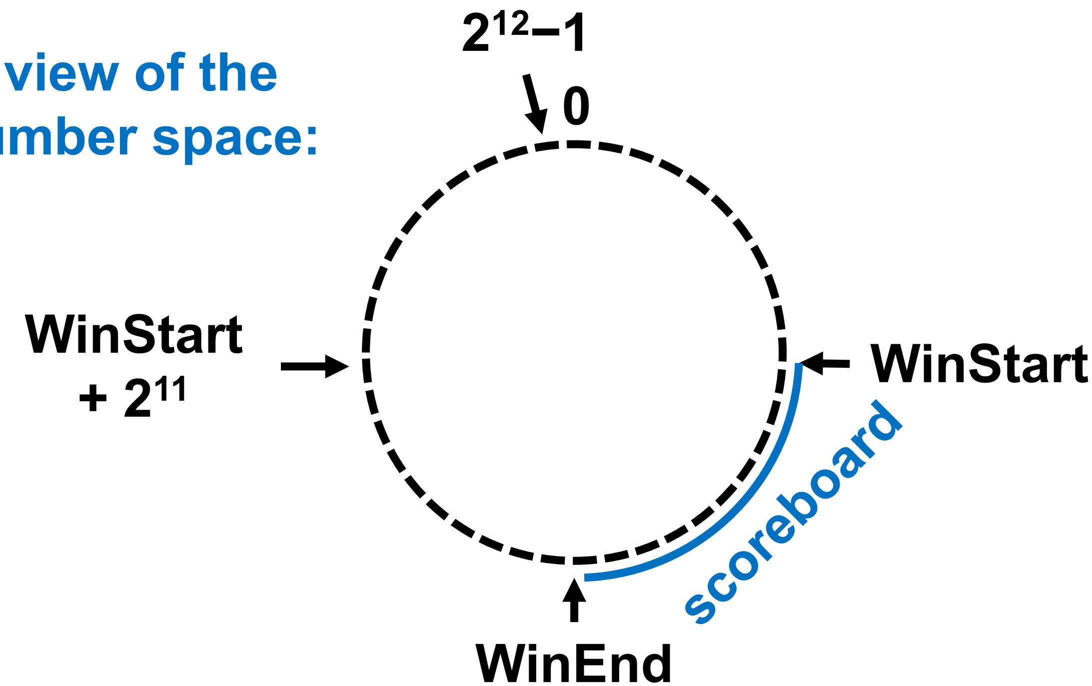


- On receiving a BAR containing ***starting sequence number*** **SSN:**
  - **Deliver** all frames with **sequence number < SSN**

The Scoreboard

(All arithmetic modulo 2^{12})

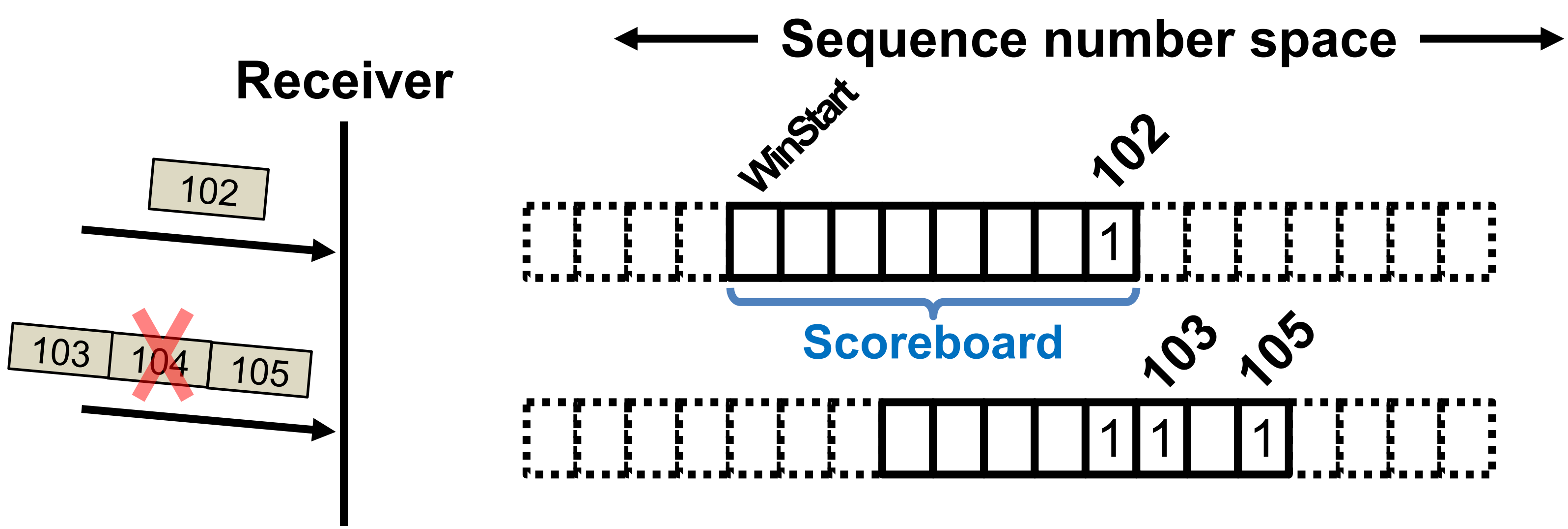
Receiver's view of the sequence number space:



- Each bit in **BA frame *scoreboard*** bitmap corresponds to receipt of frames in **[WinStart, WinEnd)** interval
- Data and BAR frames **move the scoreboard**

Scoreboard Dynamics

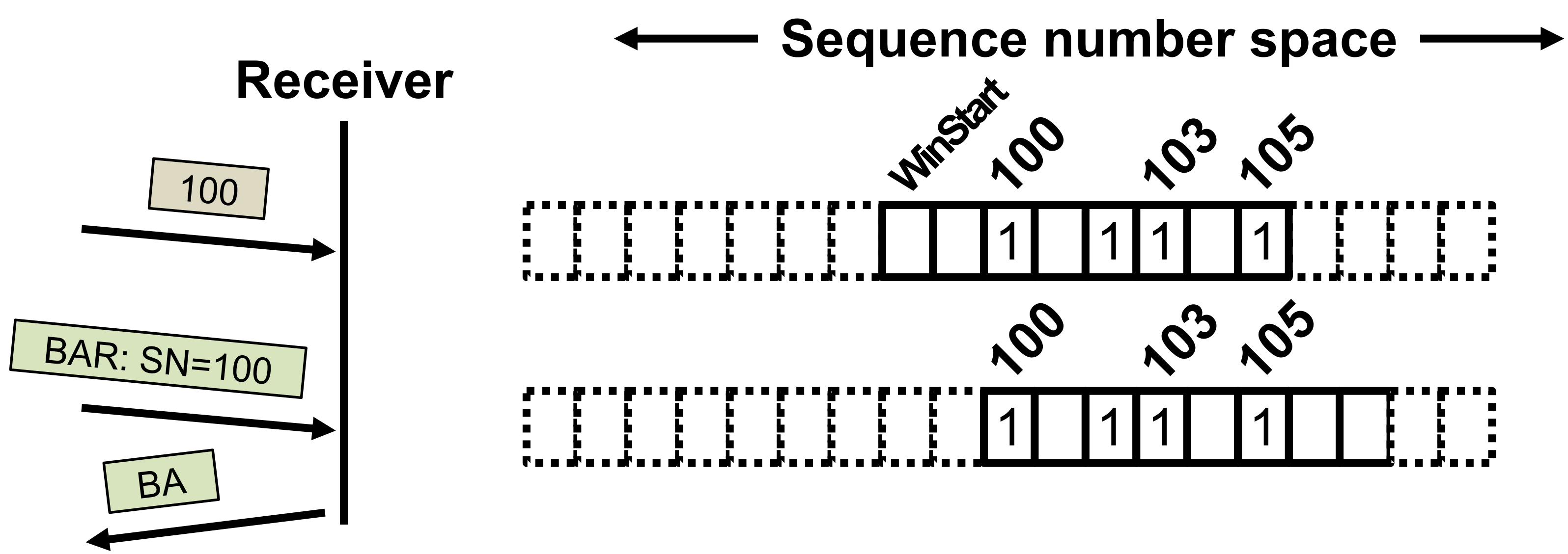
(All arithmetic modulo 2^{12})



- Receive frame (seq. # SN) **from new sender:**
  - **Set WinEnd ← SN**
- Receive frame **WinEnd < SN ≤ WinStart + 2^{11}:**
  - **Shift scoreboard** to accommodate SN

Scoreboard Dynamics

(All arithmetic modulo 2^{12})



- Receive frame, **WinStart < SN ≤ WinEnd:** **Set SN's bit**
- Receive BAR (seq. # SN): **Shift scoreboard right** (WinStart ← SN)
- Receive frame, **WinStart + 2^{11} < SN < WinStart:** **no-op**

Wi-Fi Above the PHY: Concluding Thoughts

- Hard to understate the **influence of ALOHAnet, Ethernet, MACA, and MACAW** on **Wi-Fi**
  - CS, deference, RTS/CTS, BEB...
- Wi-Fi's **scoreboarding & selective retransmission** serve as an example of the corollary to the **E2E Principle**
  - Implement *just enough* of a function at the lower layer to get a **performance advantage**

Thursday Topic:

Bit Rate Adaptation

Mesh Networks: Roofnet

Friday Precept:

Introduction to Lab 2:

HackRF MAC Protocols