Computer Networks X_400487

Lecture 5

Chapter 4: Medium Access Control

Lecturer: Jesse Donkervliet
Includes slides from Vlad Cursaru

IEEE 802.3

IEEE 802.11

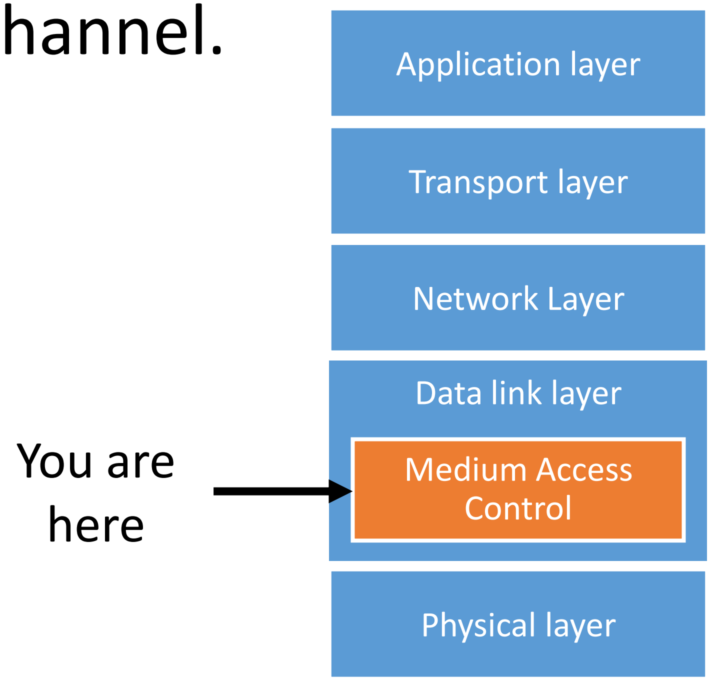
IEEE

WiFi

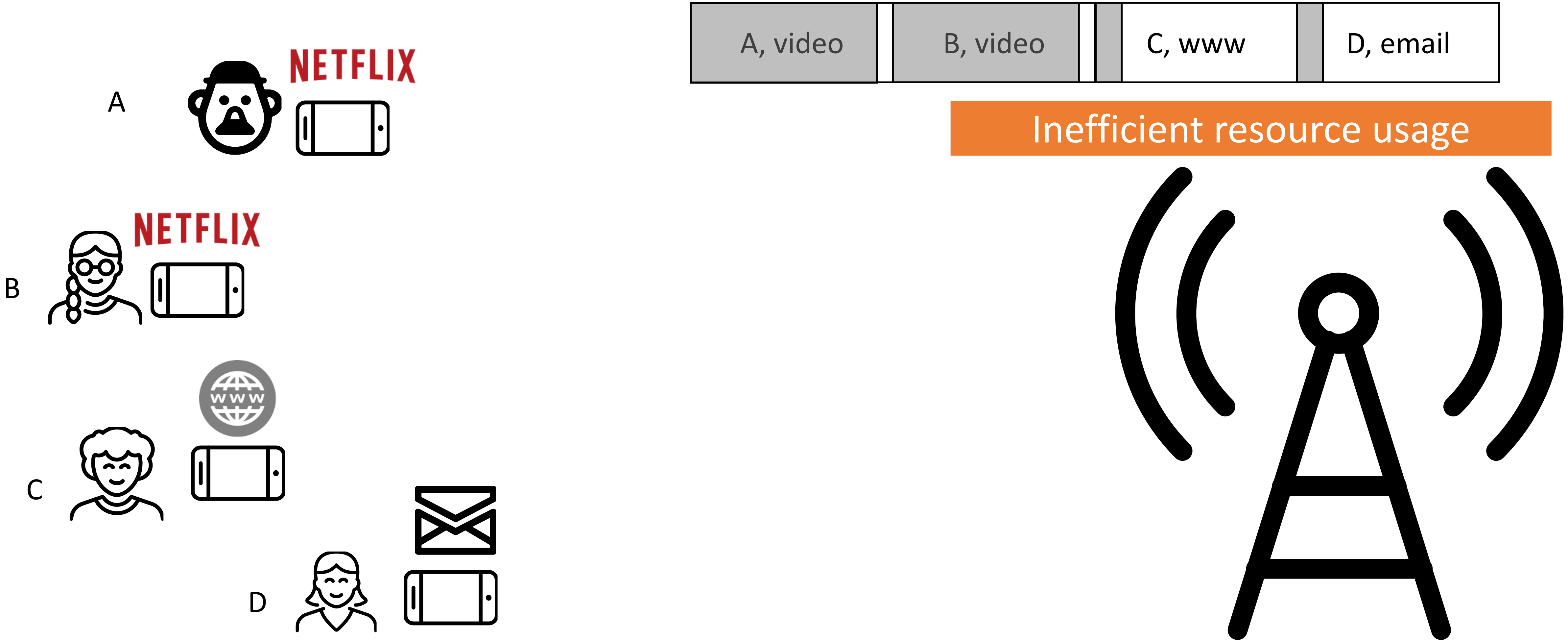
The MAC sublayer
Medium Access Control

Lower part of the Data link layer.

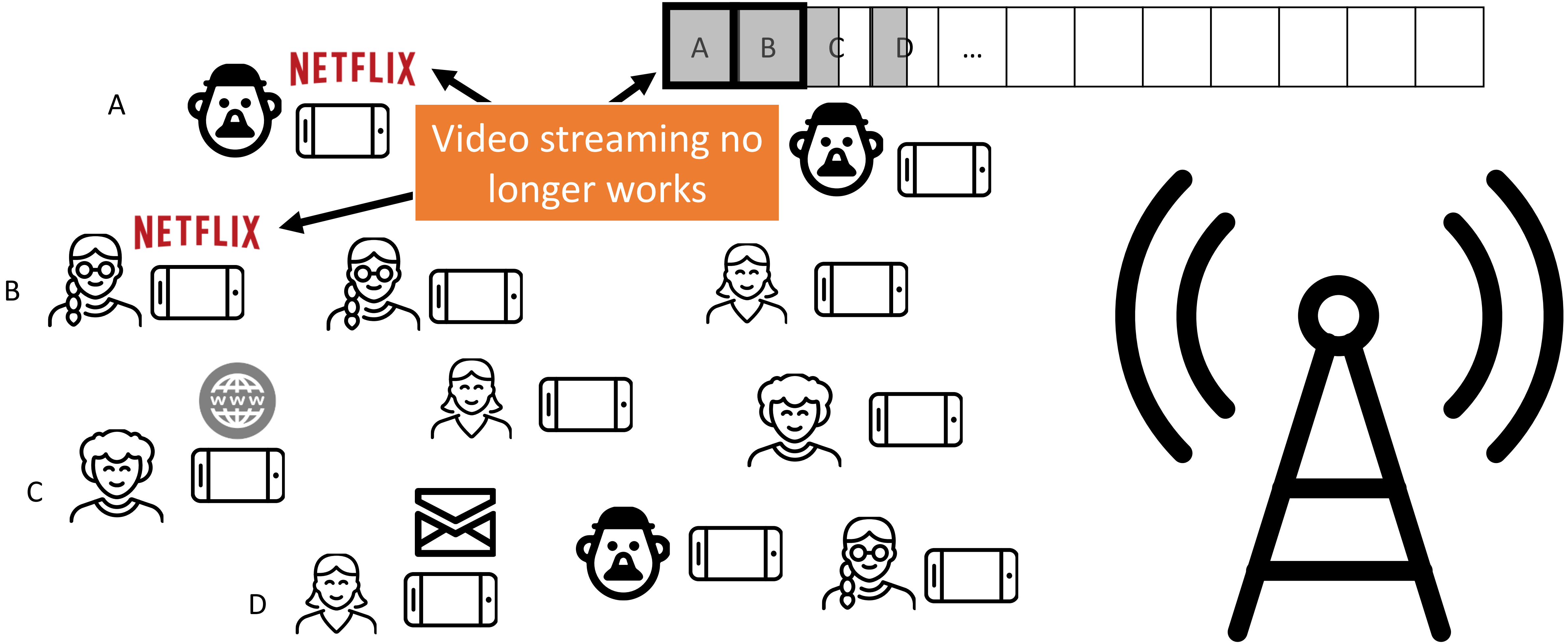
Responsible for deciding who can use the communication channel.



Didn’t we solve this at the Physical Layer???



Didn’t we solve this at the Physical Layer???



MAC Sublayer Outline

- ALOHA & Slotted ALOHA
- CSMA
  - 1-persistent
  - nonpersistent
  - p-persistent
- CSMA/CD
- **802.3 Ethernet**
- Ethernet Switching

- MAC for Wireless
  - Hidden Terminal
  - Exposed Terminal
- CSMA/CA
- **802.11 WiFi**
- Collision-Free Protocols
  - Basic Bit-Map
  - Token Ring
  - Binary Countdown

Two Approaches: Contend or Coordinate

Contend

- If there is data to send, send it!
- Collisions are a fact of life.
- Keep trying until sending succeeds.

Q: When to apply which strategy?

Coordinate

- If there is data to send, let other stations know.
- Send when it is your turn.
- Patiently wait while other stations are sending.

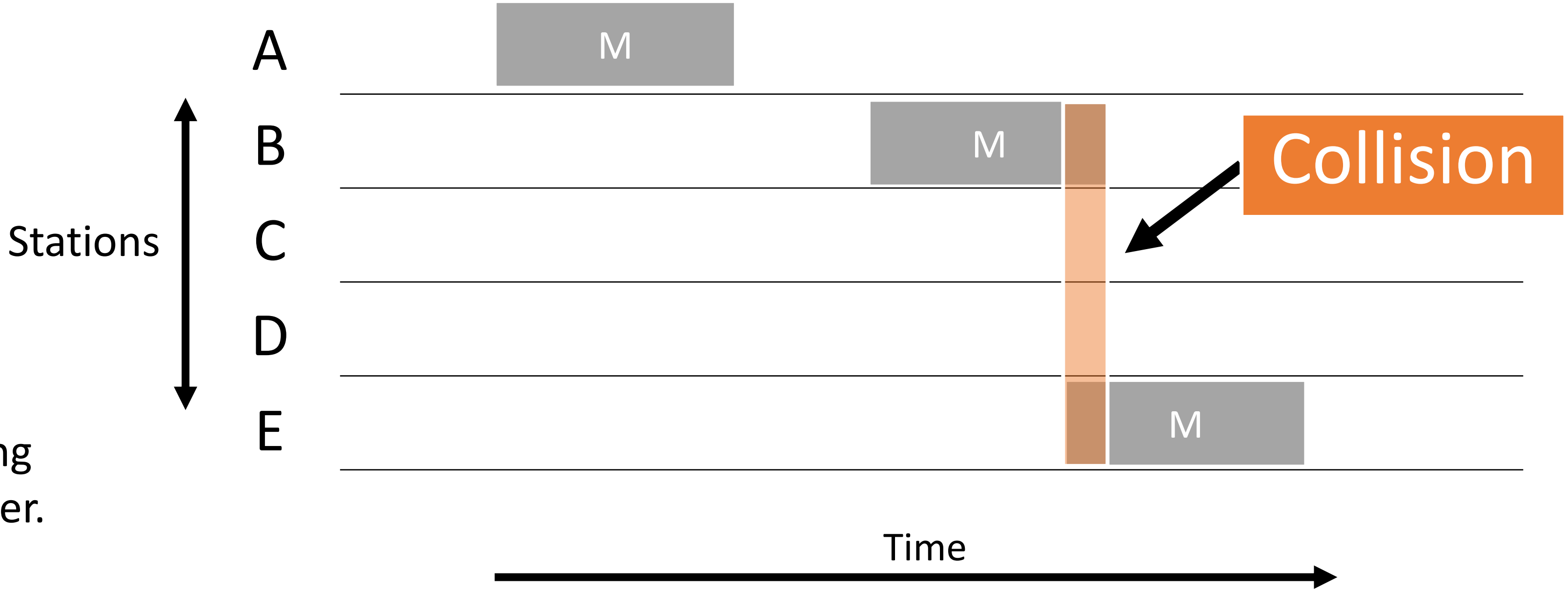
Protocols somewhere along the spectrum


HAWAII 1970
Lihue
OAHU
Honolulu
KAUAI
MAUI
Hilo
Kona
HAWAII

ALOHA

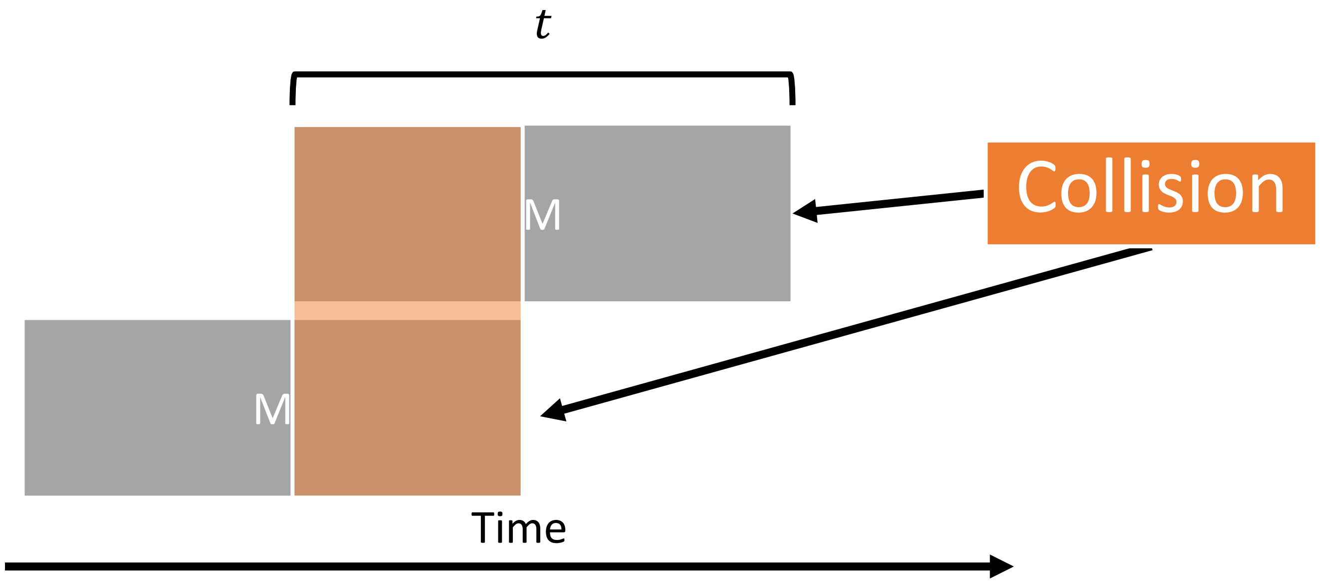
Q: When does ALOHA perform well/badly?

In pure ALOHA, users transmit frames *whenever they have data*; if a collision occurs, *users retry after a random delay.*

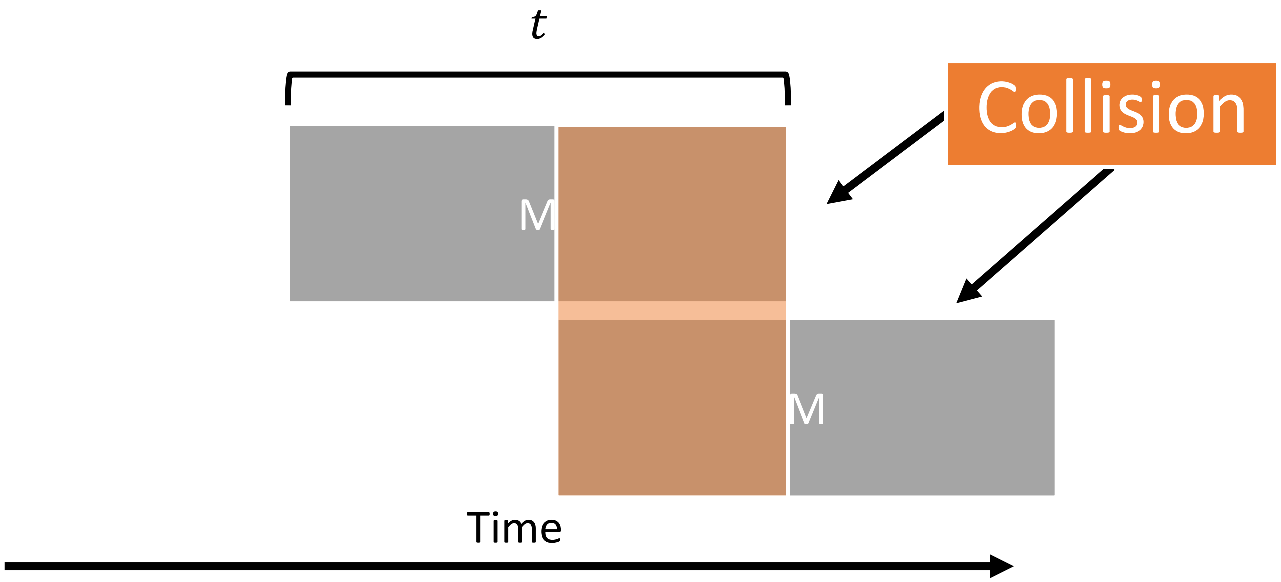


These stations use the same channel *without* mutiplexing on the physical layer.

Collisions in ALOHA

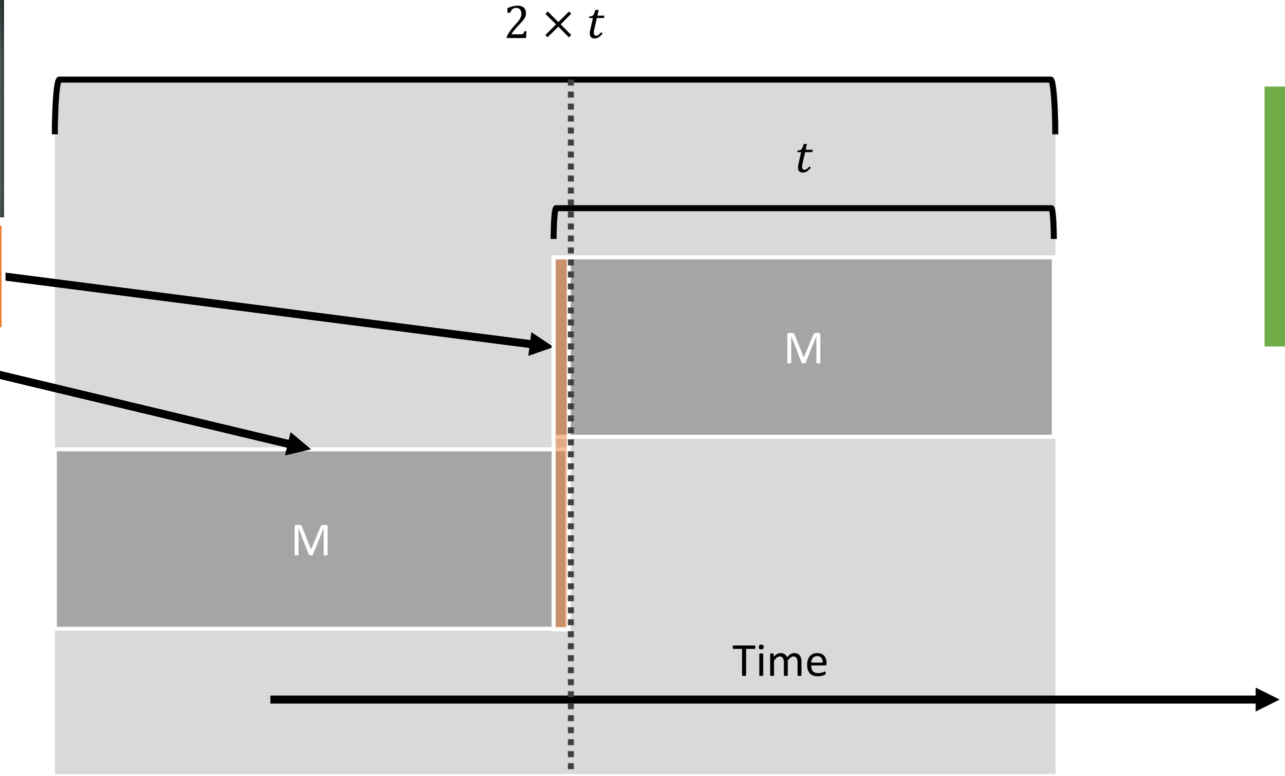


Collisions in ALOHA



Collisions in ALOHA

Frame collisions can occur anywhere within 2 times duration of transmission.

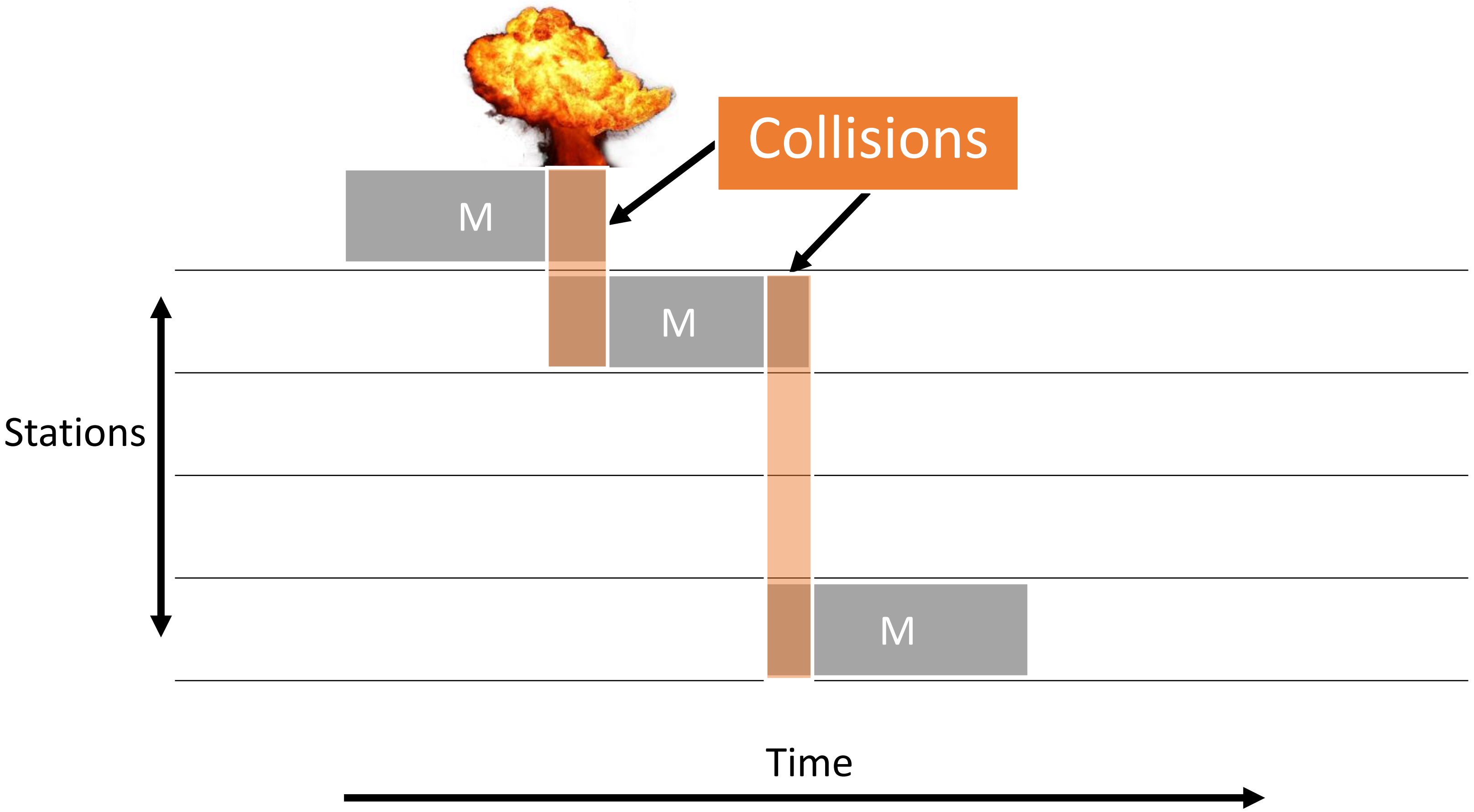


If another frame is sent anywhere in this period, a collision occurs

Pure ALOHA

All of these messages will have to be retransmitted!

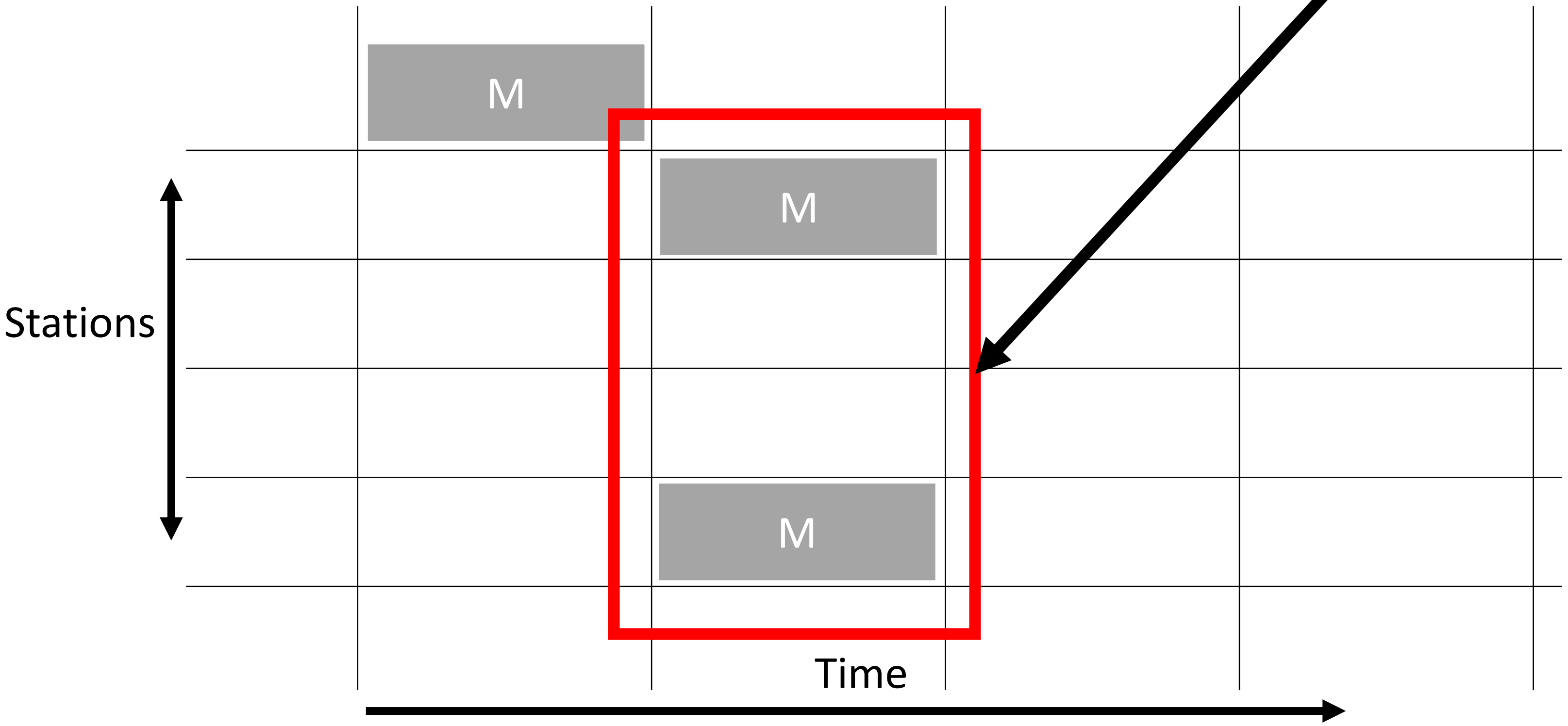
Q: How can we reduce the risk of collision?



Slotted ALOHA

First frame sent successfully

These messages will have to be retransmitted!



Probability of frame collisions is reduced. Frames now overlap completely, or not at all.

Carrier Sense Multiple Access

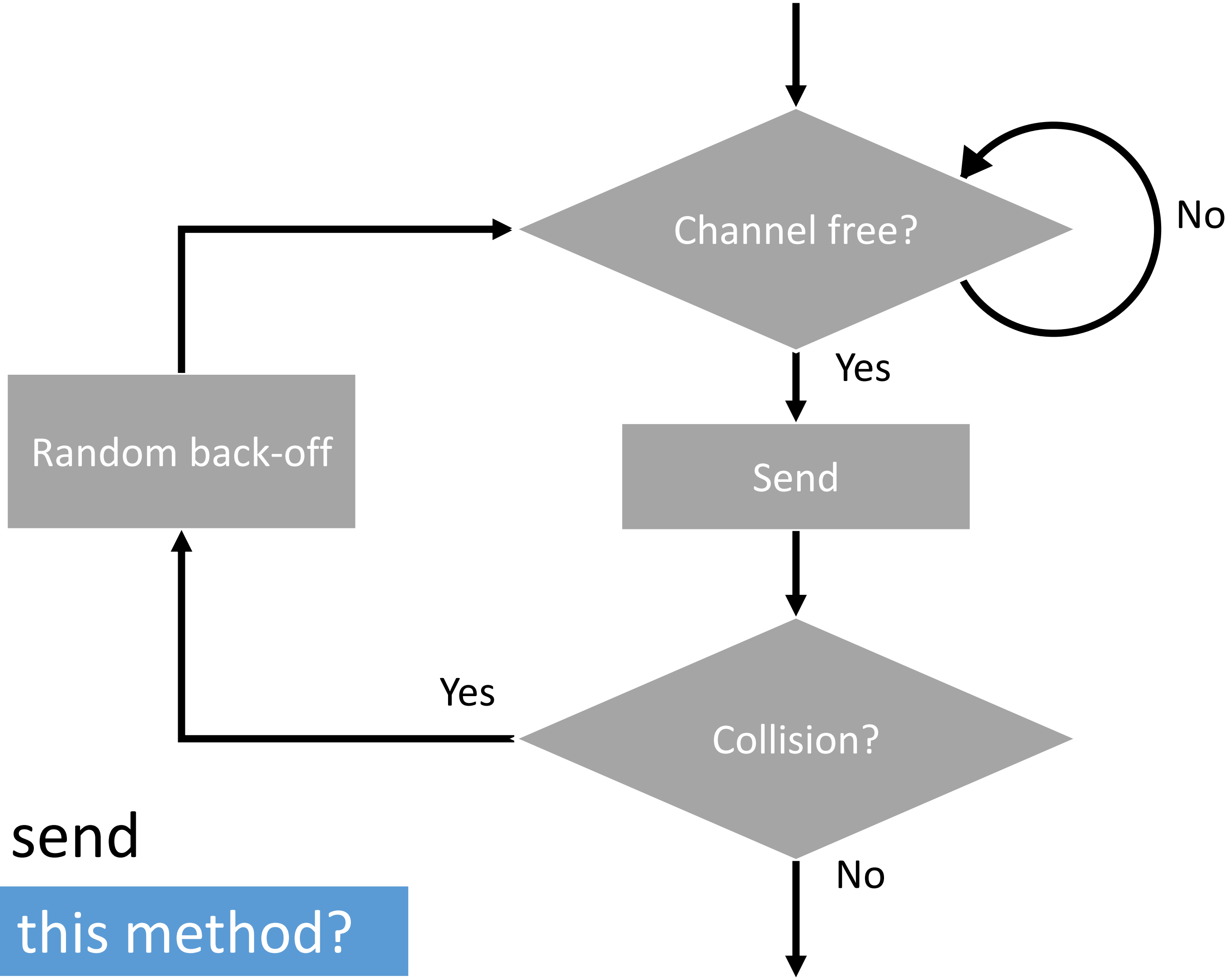
Carrier-Sense Multiple Access

Senders detect ("sense") if the channel is in use

Protocols that apply CSMA:

1. 1-persistent: wait for idle, then send. If collision, random back-off.
2. Nonpersistent: if busy, random back-off. Try again
3. p-persistent: if busy, wait for next slot
   if idle, send with probability p

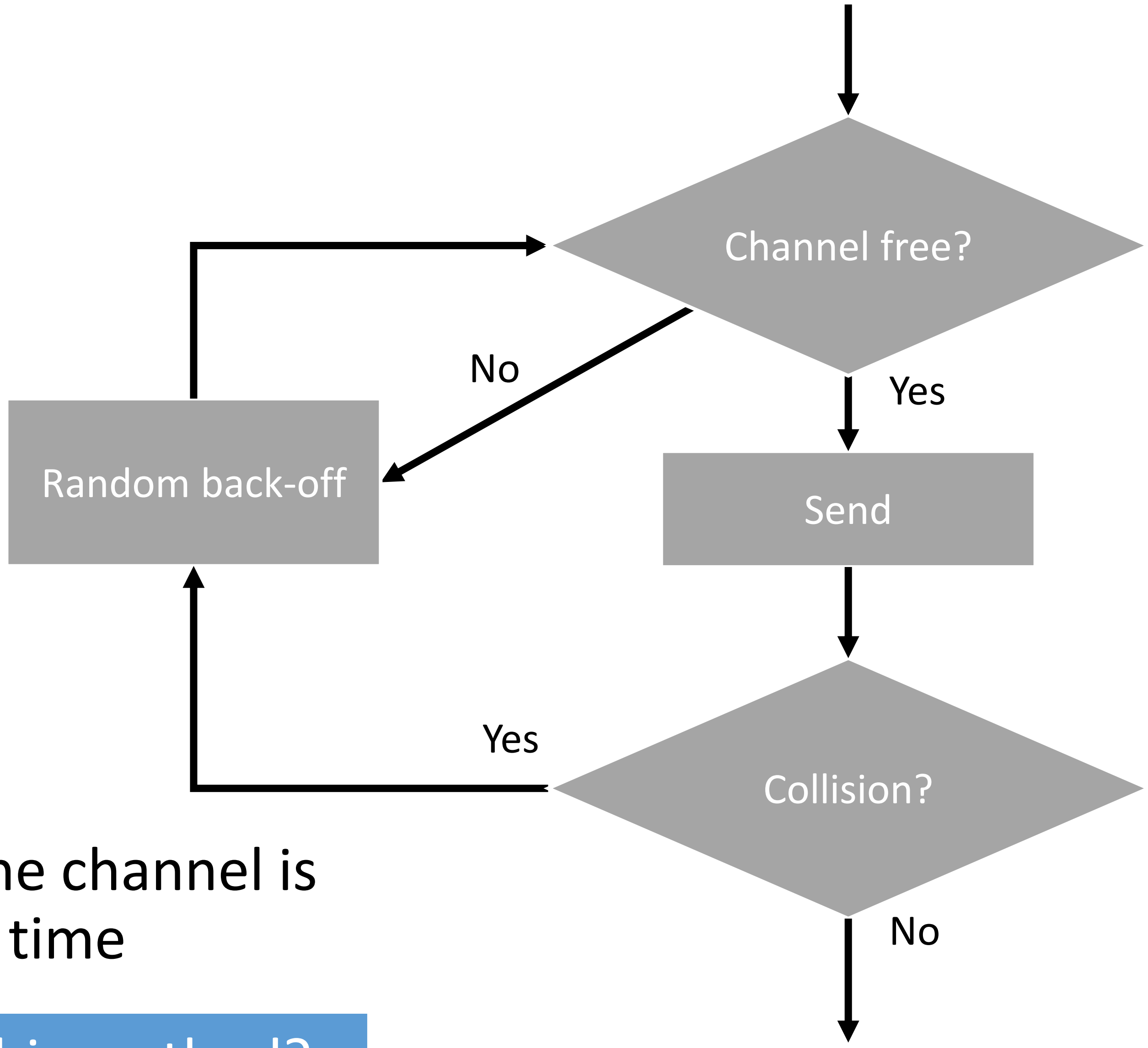
1-persistent CSMA



Wait until the channel is idle, then send

Q: Can you think of a problem with this method?

Nonpersistent CSMA

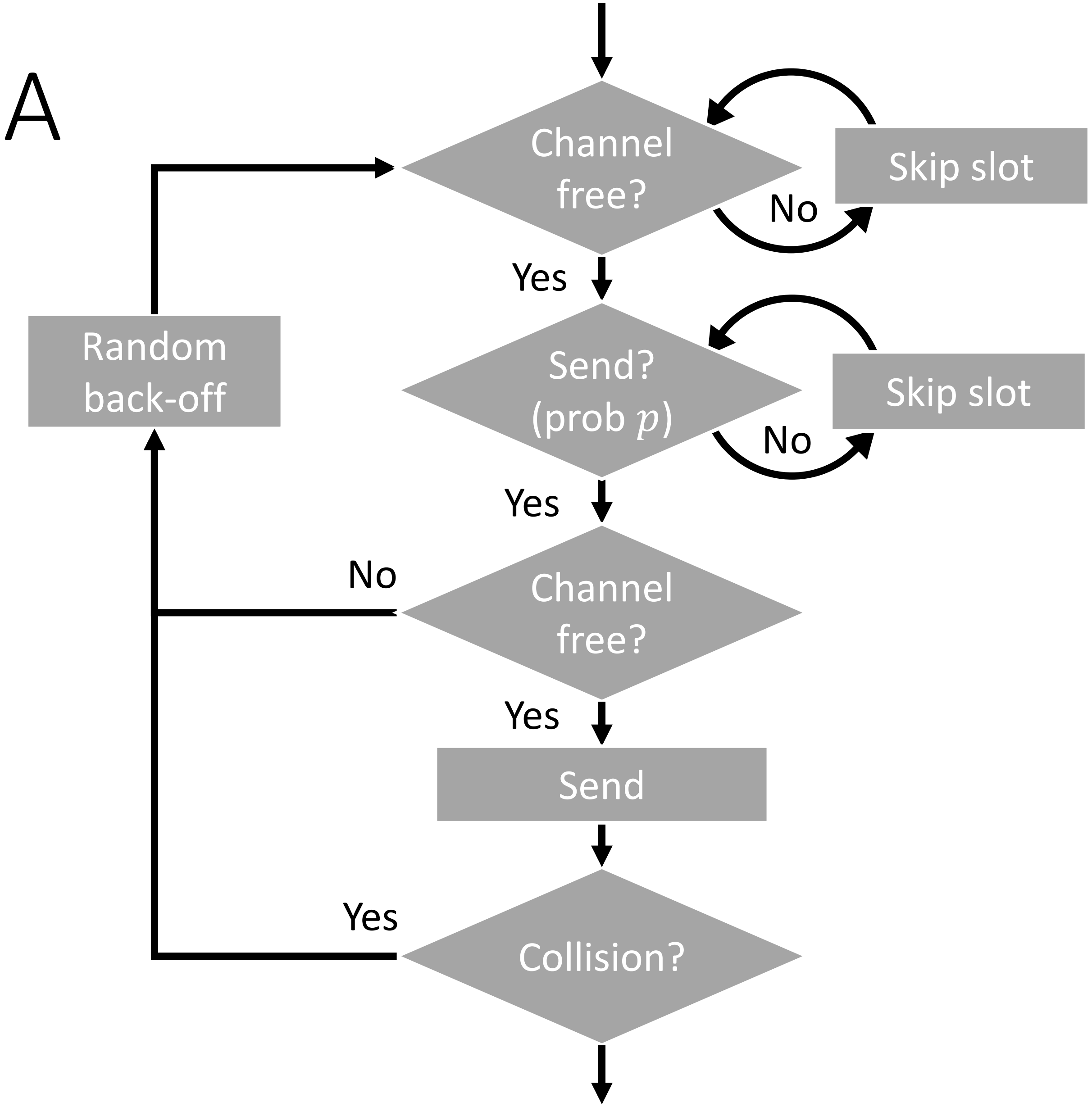


Nonpersistent CSMA is less greedy. If the channel is occupied, it waits a random amount of time

Q: Can you think of a problem with this method?

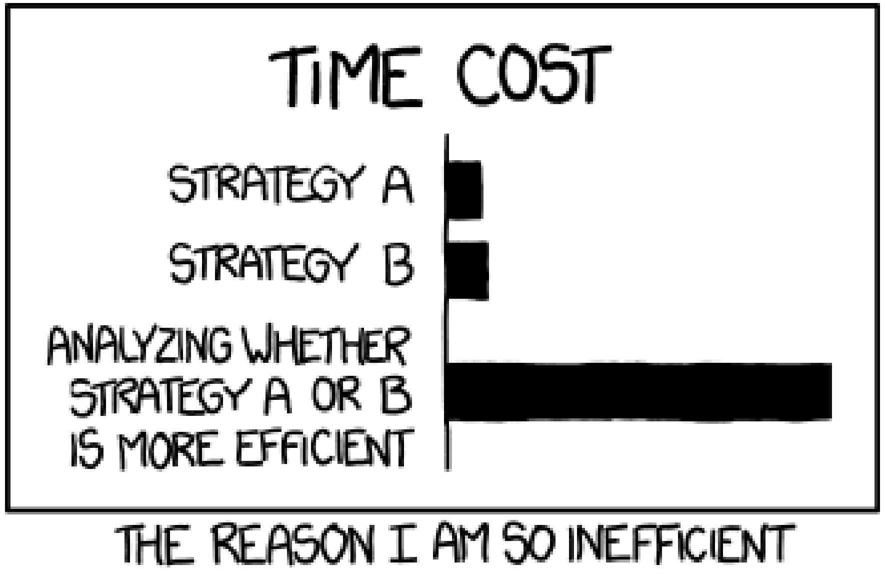
p-persistent CSMA

Applies to *slotted* channels.



Keeps waiting. Sends frame with probability p

Behavior of x-persistent CSMA



Q: What trade-off do these protocols make?

Latency, bandwidth, (protocol) complexity

Early computer networks research evaluated protocol performance theoretically, using assumptions such as packet arrivals following Poisson distributions. Empirical research showed this not to be the case.* We still(!) lack mathematical tools to describe the behavior of these systems, and instead rely on observing the behavior of these systems "in the wild."

*E.g., Paxson and Floyd, 1995; and Leland et al., 1994

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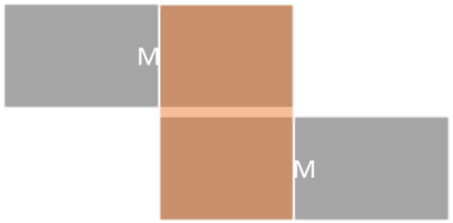
CSMA/CD

Carrier Sense Multiple Access with Collision Detection

CSMA/CD:
CSMA with *Collision Detection*

Remember?



Idea: when collision is detected, do not finish sending.
Stop transmission instead.

Separates **contention periods** from **transmission periods**.

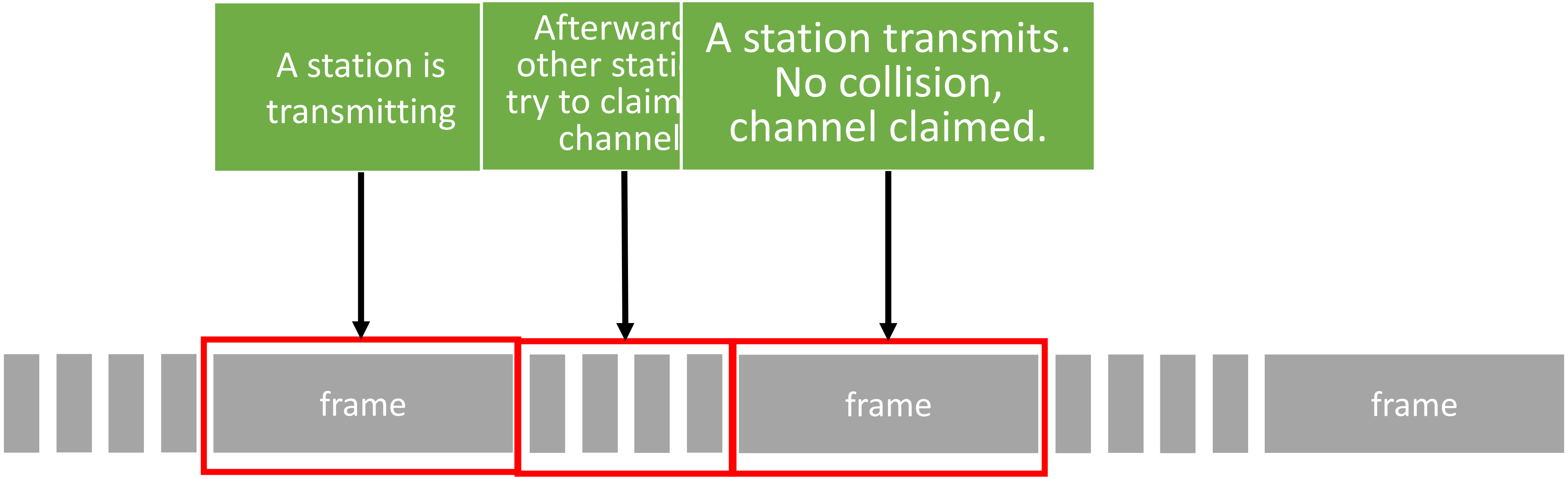
Saves time and bandwidth

Contention period: check if it is safe to send data.

Transmission period: send data.

Collision detection

Abort transmission when collision is detected.



Collision detection

Reduce contention period duration to improve throughput

Abort transmission when collision is detected.

Q: How do longer frames affect throughput? How about latency?

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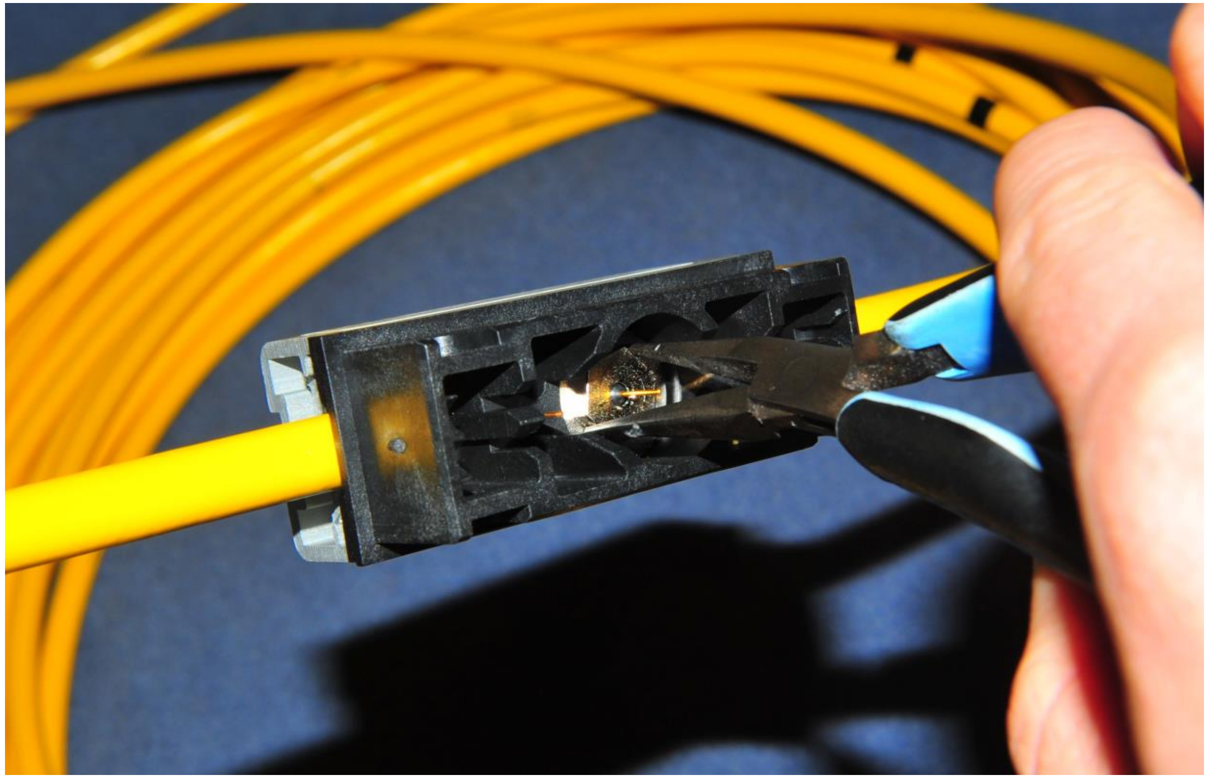
Medium Access Control
Classic Ethernet

Medium Access Control in …
Classic Ethernet

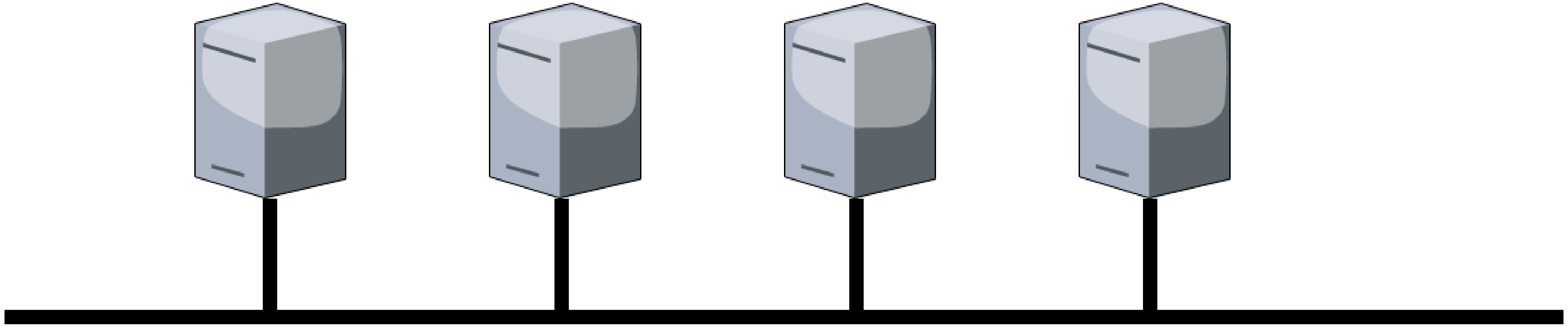
Multiple machines sharing a single Ethernet connection.



Medium Access Control in ... Classic Ethernet

Multiple machines sharing a single Ethernet connection.

Q: Which MAC protocol should we use?



Newer versions of Ethernet (10-gigabit Ethernet and up) only support point-to-point full-duplex operation.

Medium Access Control in … Classic Ethernet

Uses ***1-persistent CSMA/CD.***

Random delay (back-off) after collision is computed with Binary Exponential Back-off.

Station waits w slots, where w between 0 and $2^i - 1$.
i is the number of failed attempts.

Failed Attempts	Maximum Delay	Random Delay Range
0	$2^0 - 1 = 0$	$w \in [0,0]$
1	$2^1 - 1 = 1$	$w \in [0,1]$
2	$2^2 - 1 = 3$	$w \in [0,3]$
3	$2^3 - 1 = 7$	$w \in [0,7]$
4	$2^4 - 1 = 15$	$w \in [0,15]$
…	…	…

```
maxw = 0
collision = True
while collision:
    w = random.randint(0, maxw)
    collision = delayed_send(frame, w)
    if collision:
        maxw = maxw << 1
        maxw = maxw | 1
```

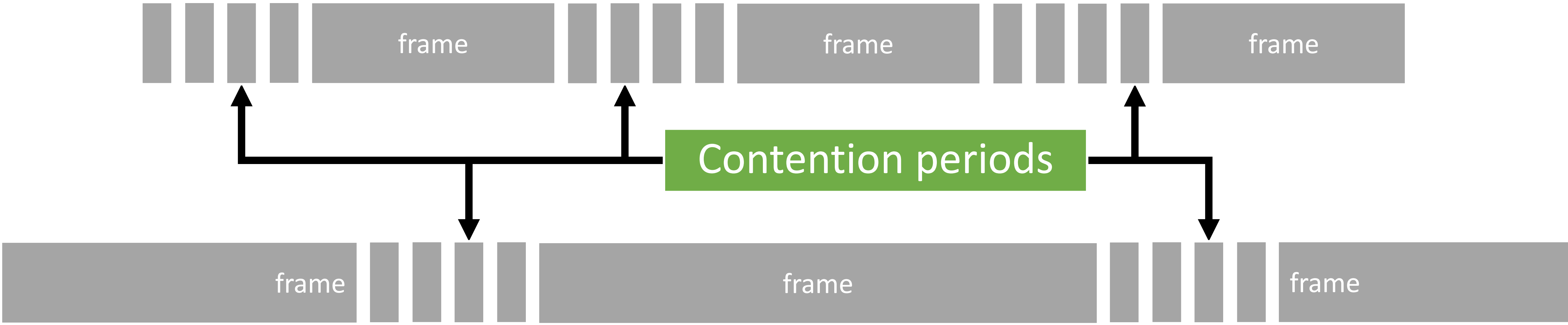
Q: What happens if more than 2 stations are trying to send a frame?

Ethernet performance

Q: What is more bandwidth efficient? Why?

Q: Is there a trade-off here? Why?

Small frames



Large frames

Less time claiming channel → more time sending data

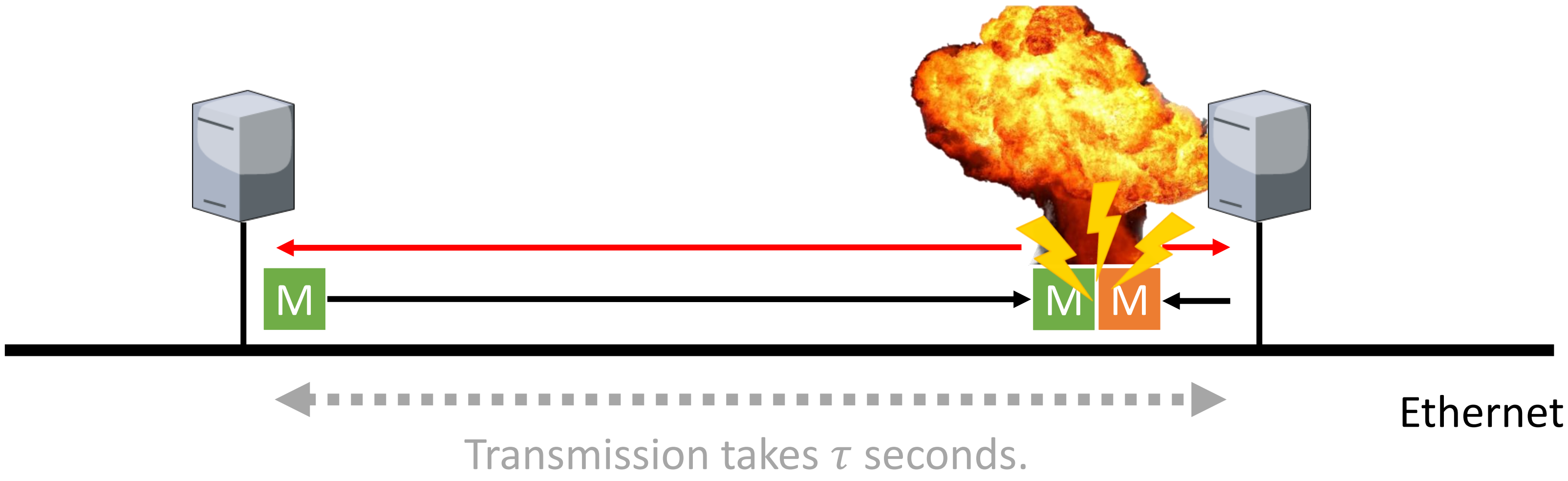
Classic Ethernet
Collision detection

Q: Does the detection latency cause a problem?

Collisions can occur and take as long as 2τ to detect.

τ is the time it takes to propagate over the Ethernet.

Leads to minimum packet size for reliable detection.



Classic Ethernet Collision detection

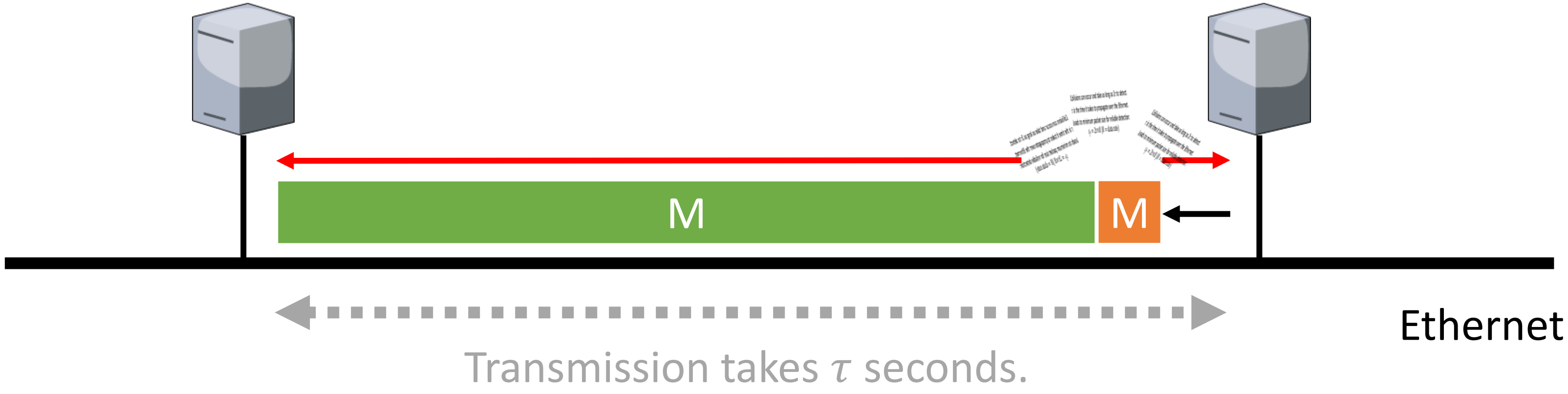
Q: Does the detection latency cause a problem?

Collisions can occur and take as long as 2τ to detect.

τ is the time it takes to propagate over the Ethernet.

Leads to minimum packet size for reliable detection:

$$s_f = 2\tau \times R \ (R = \text{data rate})$$



$\tau = 5\mu s, R = 500\text{Mbps}, S_f = 2 \times 5\mu s \times 500\text{Mbps} = 5000 \text{ bits}$

Ethernet frames

Frame format still used in modern versions of Ethernet.*

	Preamble	Destination address	Source address	T/L	Data	P	CRC
Bytes:	8	6	6	2	0-1500	0-46	4

*VLAN-aware packets from 802.1Q use a slightly modified header.

Ethernet frames

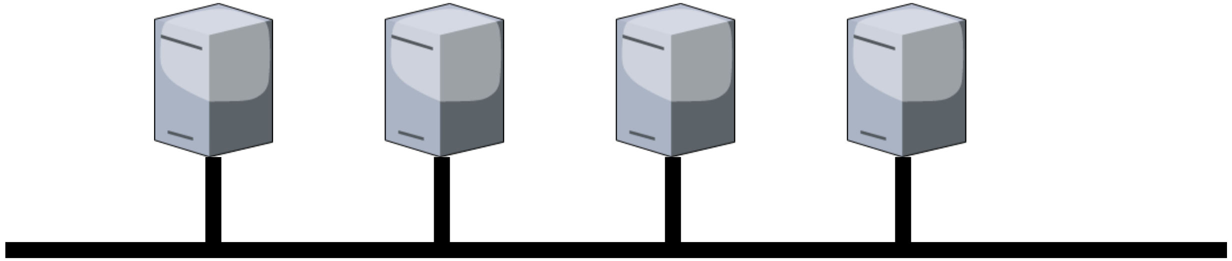
Frame format still used in modern versions of Ethernet.*

	Preamble	Destination address	Source address	T/L	Data	P	CRC
Bytes:	8	6	6	2	0-1500	0-46	4

Bit-sequence used to indicate start of frame.

*VLAN-aware packets from 802.1Q use a slightly modified header.

Ethernet frames



Frame format still used in modern versions of Ethernet.*

	Preamble	Destination address	Source address	T/L	Data	P	CRC
Bytes:	8	6	6	2	0-1500	0-46	4

Source and destination addresses.

Q: Why needed over a single link?

Q: What is the name of this address? What is it assigned to?

*VLAN-aware packets from 802.1Q use a slightly modified header.

Ethernet frames

Frame format still used in modern versions of Ethernet.*

	Preamble	Destination address	Source address	T/L	Data	P	CRC
Bytes:	8	6	6	2	0-1500	0-46	4

Type/length field:

Indicates to which network layer protocol the data should be sent.

Values less than 0x600 (1536) can be interpreted as length.
(IEEE 802.3 only)

*VLAN-aware packets from 802.1Q use a slightly modified header.

Ethernet frames

Frame format still used in modern versions of Ethernet.*

	Preamble	Destination address	Source address	T/L	Data	P	CRC
Bytes:	8	6	6	2	0-1500	0-46	4

Pad field:

Used if data causes frame to be less than the minimum frame length.

*VLAN-aware packets from 802.1Q use a slightly modified header.

Ethernet frames

Q: Reliable delivery?

Frame format still used in modern versions of Ethernet.*

	Preamble	Destination address	Source address	T/L	Data	P	CRC
Bytes:	8	6	6	2	0-1500	0-46	4

No acks!

32-bit Cyclic Redundancy Check used for error detection.

Q: Error detection/correction?

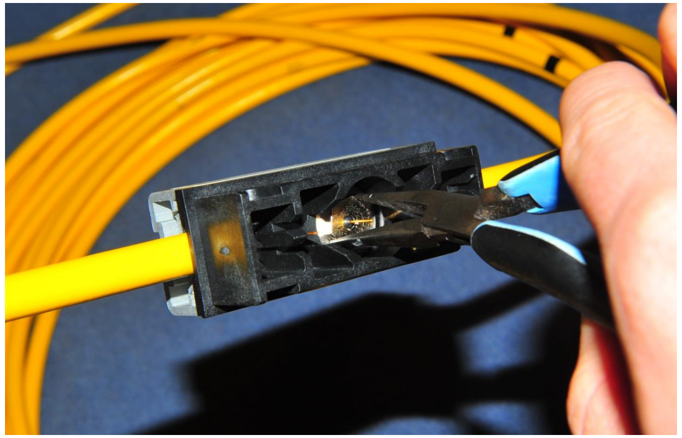
Q: How long is the generator polynomial?

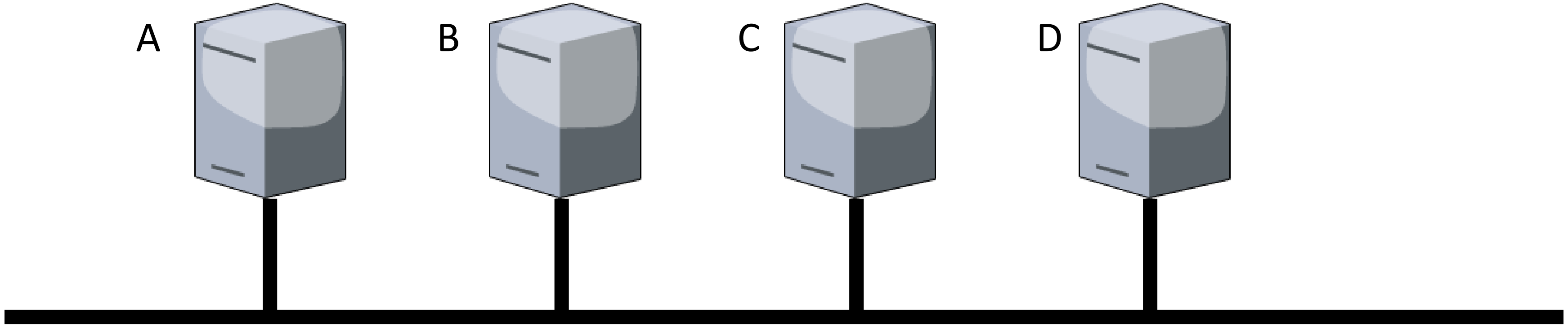
*VLAN-aware packets from 802.1Q use a slightly modified header.

Data Link Layer Switching

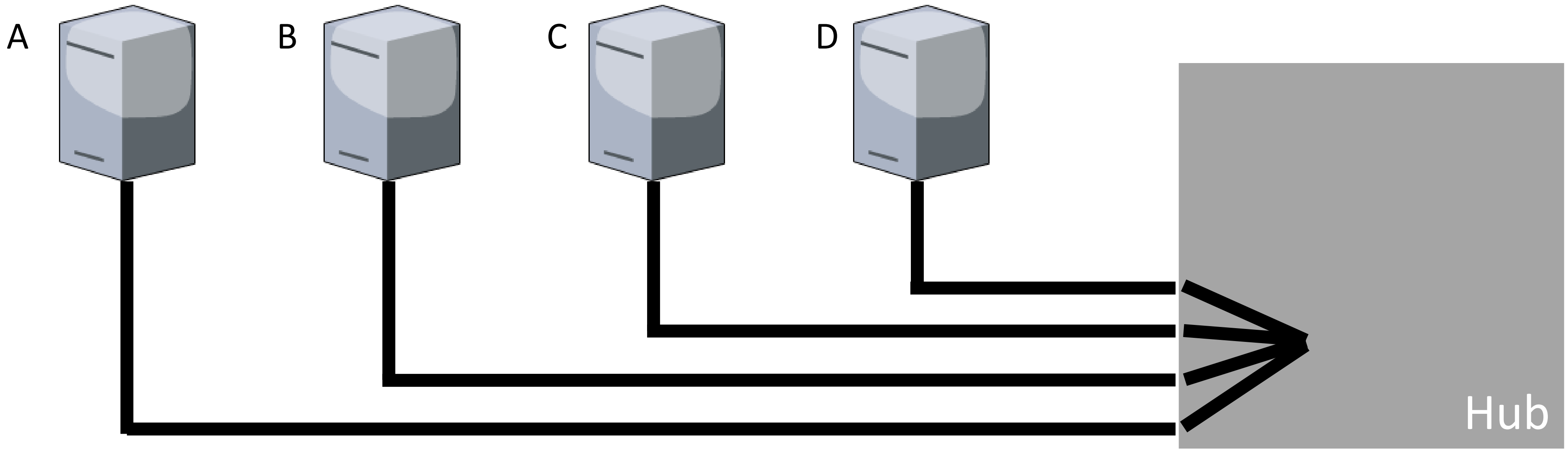
Switching
Classic Ethernet

Remember?





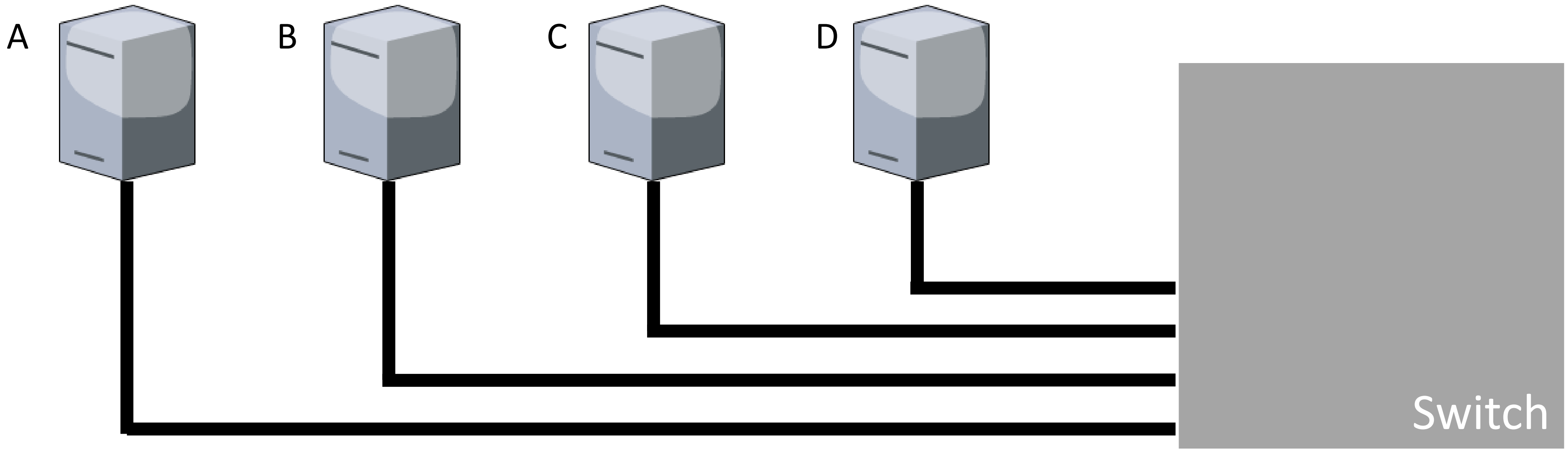
Switching
Classic Ethernet with Hubs



Switching
Classic Ethernet with ✨*Switches*✨

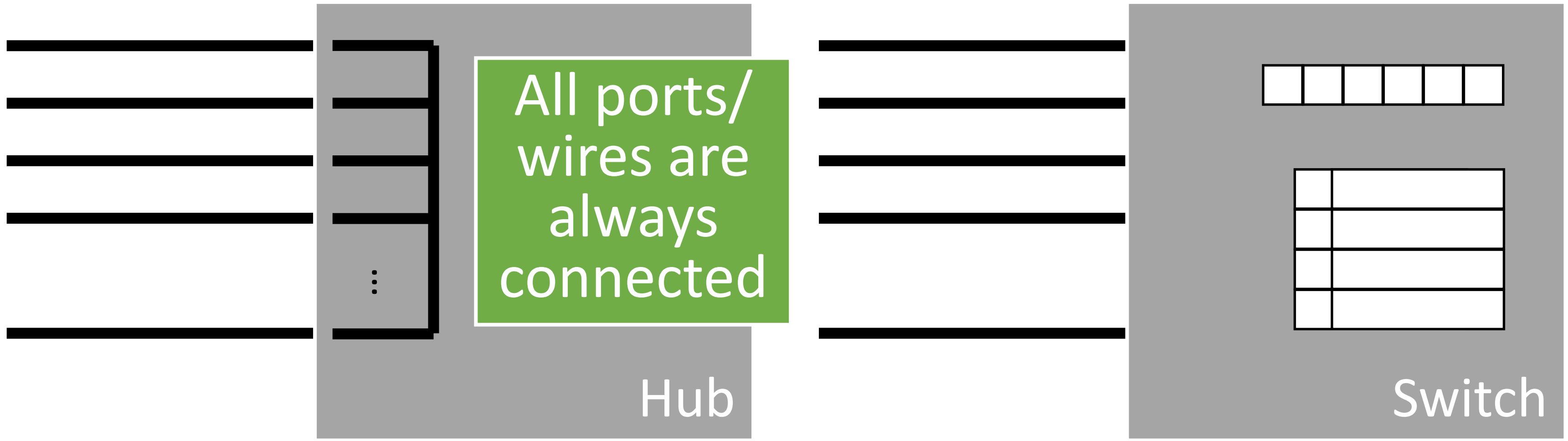
Q: Do we still need MAC?

Same network topology, but MAC protocol no longer needed, if the channel is duplex!



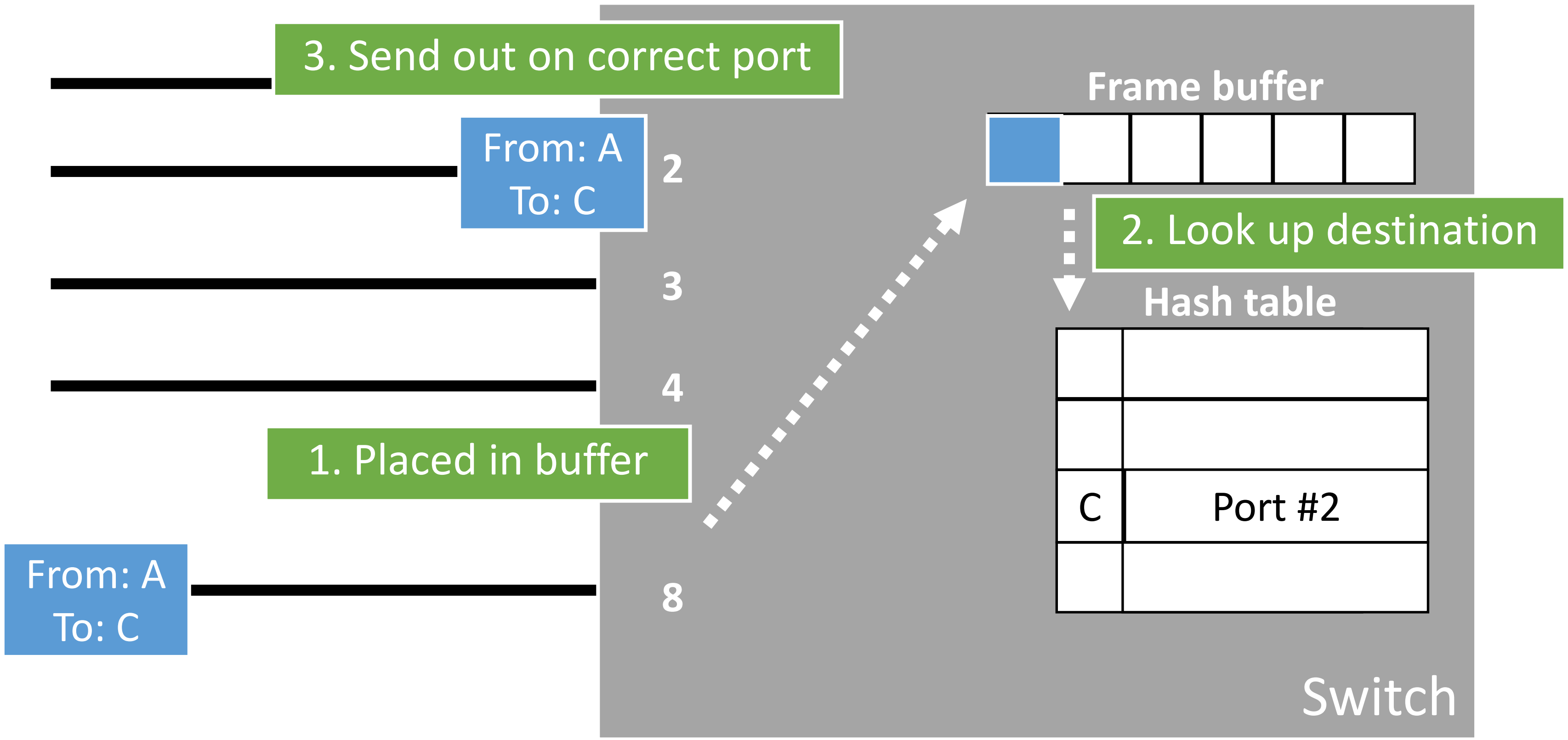
Ethernet evolution
From hubs to switches

1. Classic Ethernet
2. Fast Ethernet
3. Gigabit Ethernet
4. 10-Gigabit Ethernet



Ethernet switch

Q: Advantages of switches?

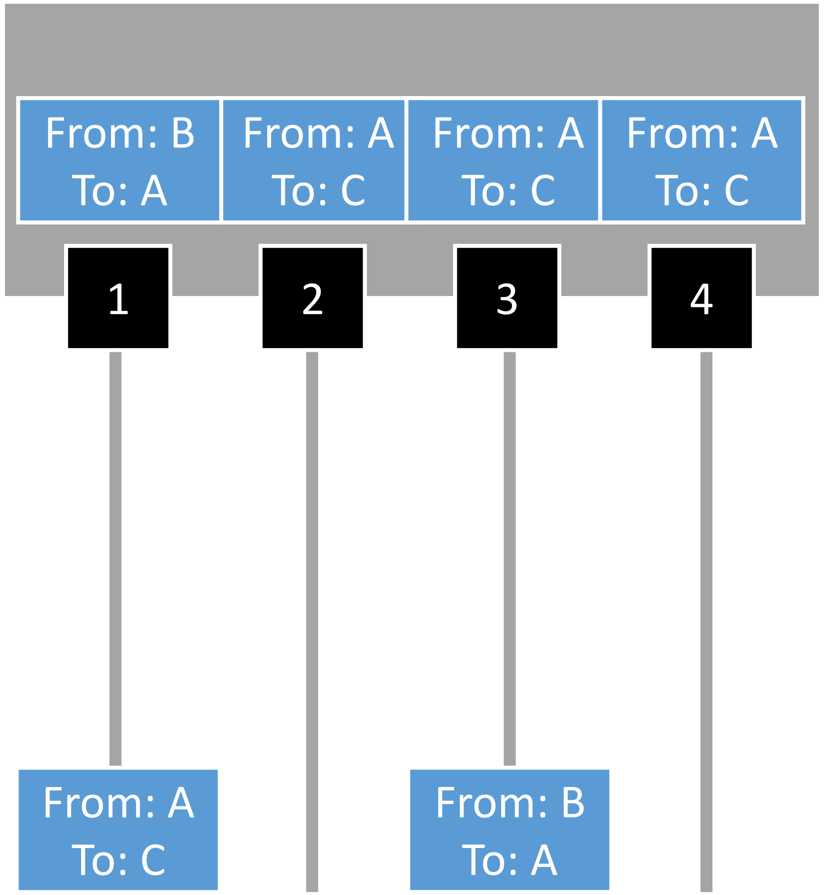


Learning bridges
Backwards learning

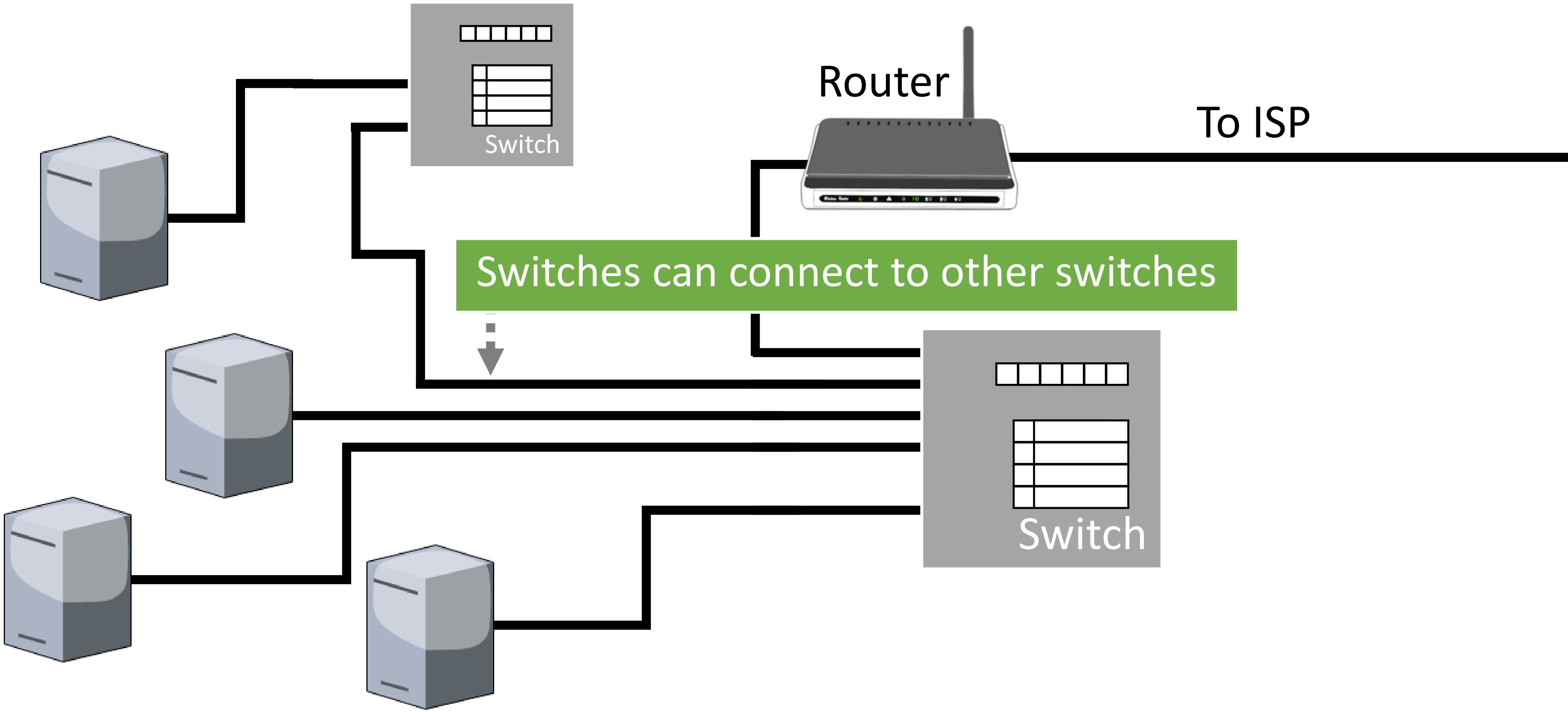
Hash table:

A:1

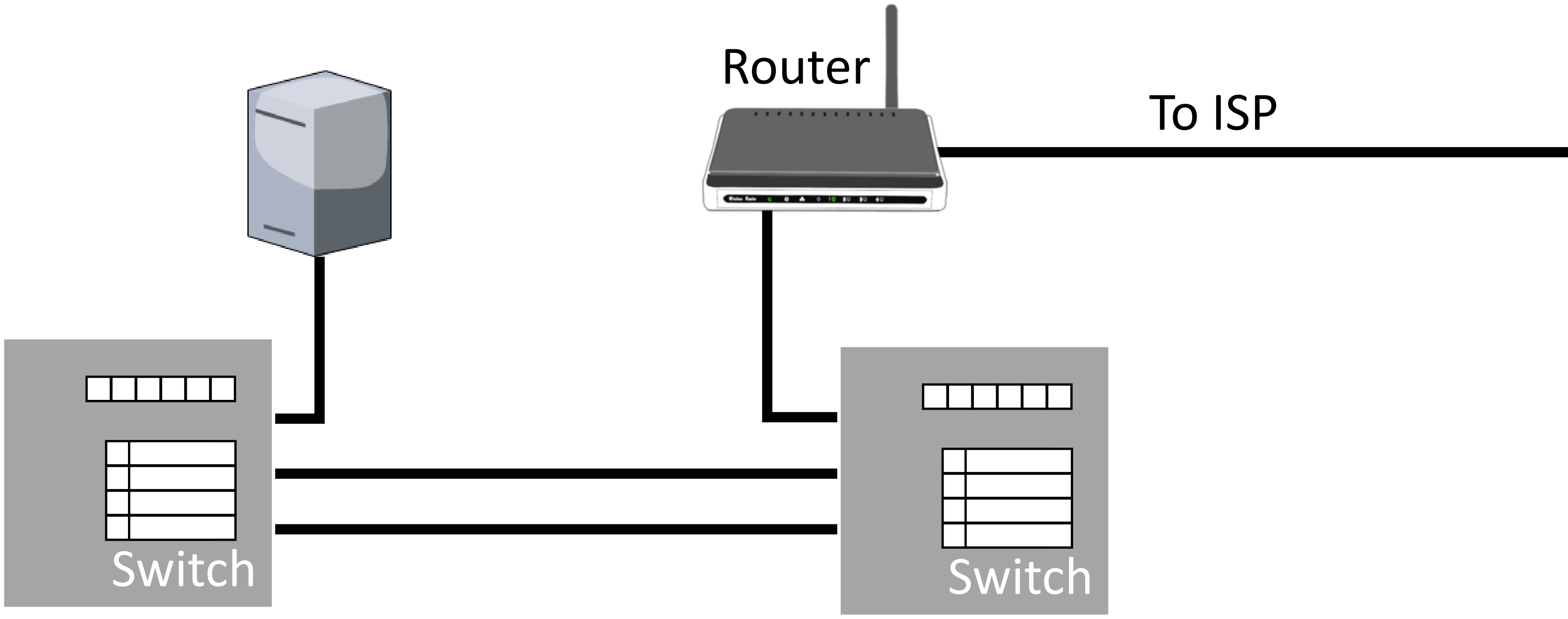
B:3



Ethernet Wiring pattern



Learning bridges
Topology with loops

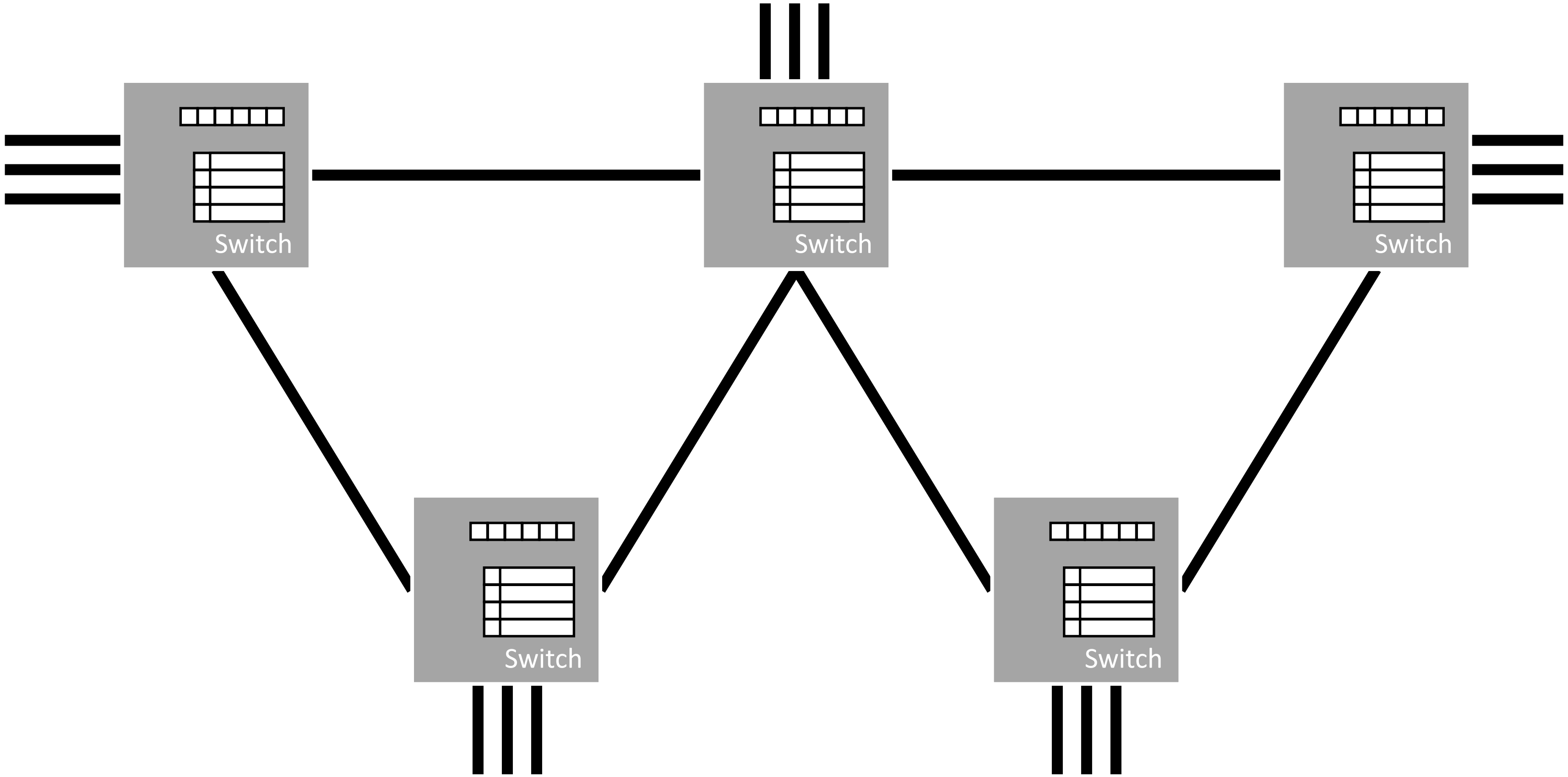


Network contains a loop

Q: What kind of problem can this cause?

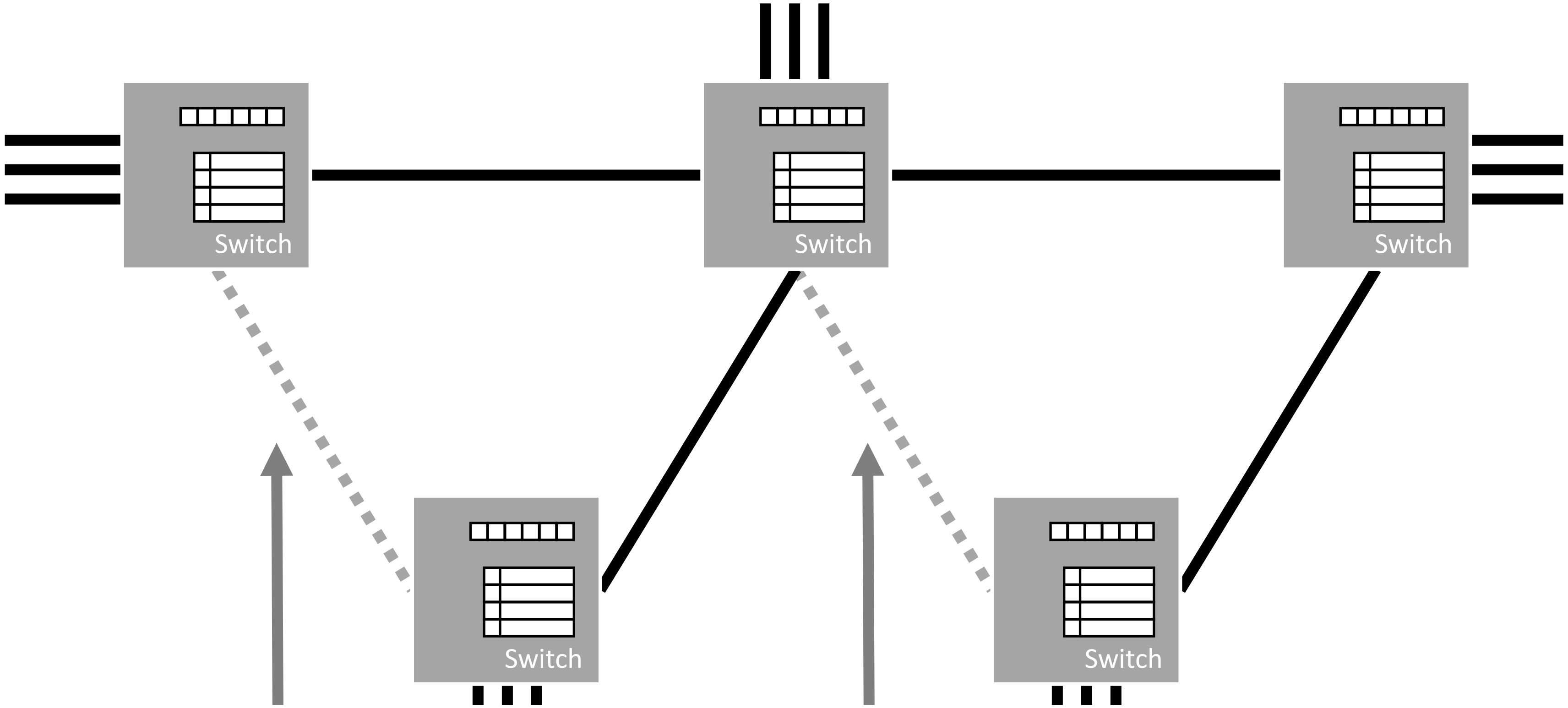
Spanning tree
Example

No direct loops



Spanning tree Example

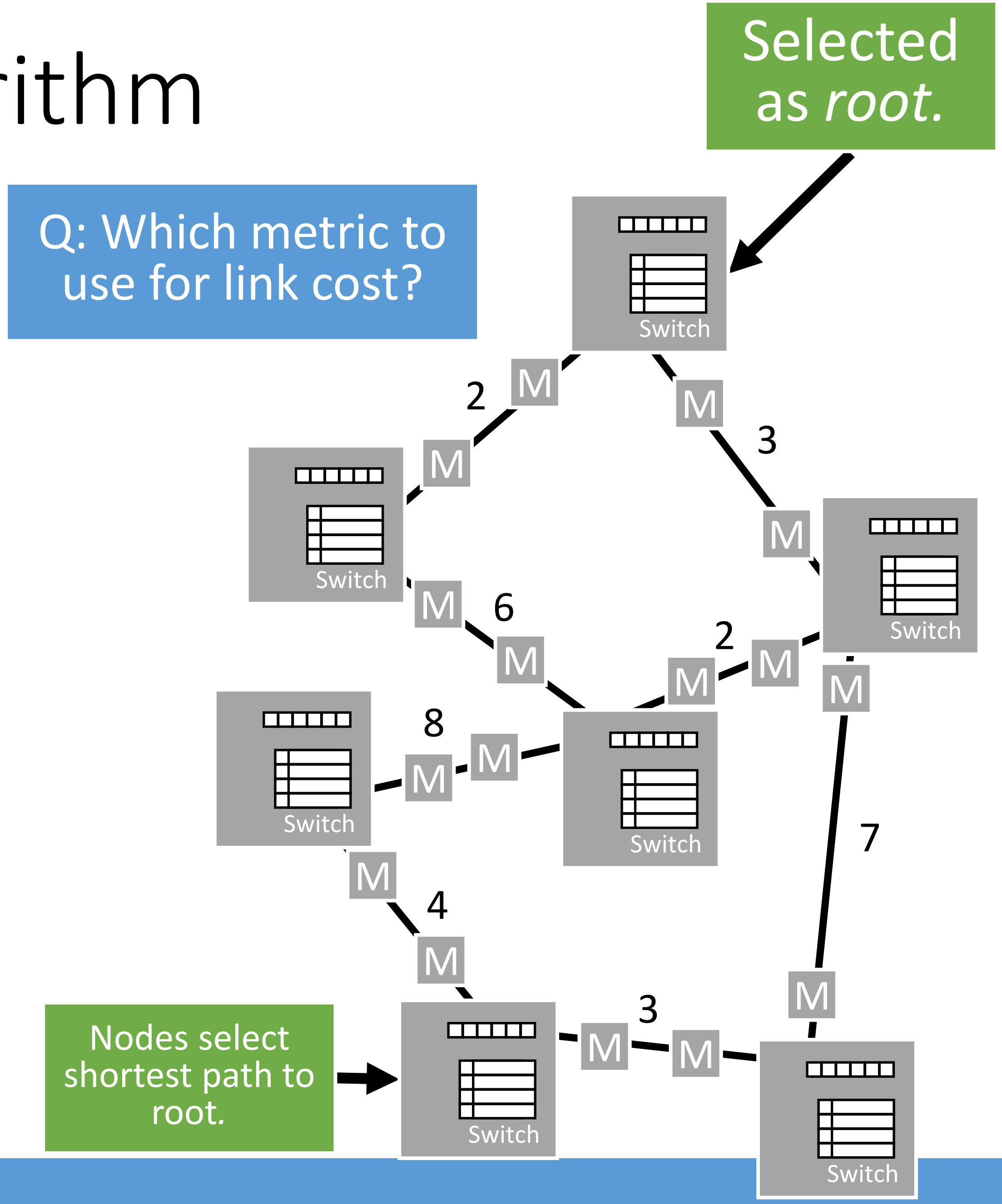
No direct loops



Only links in spanning tree are used. Others ignored

Spanning tree algorithm
As a poem

I think that I shall never see
A graph more lovely than a tree.
A tree whose crucial property
Is loop-free connectivity.
A tree which must be sure to span.
So packets can reach every LAN.
First the Root must be selected
By ID it is elected.
Least cost paths from Root are traced
In the tree these paths are placed.
A mesh is made by folks like me
Then bridges find a spanning tree.
– Radia Perlman, 1985.



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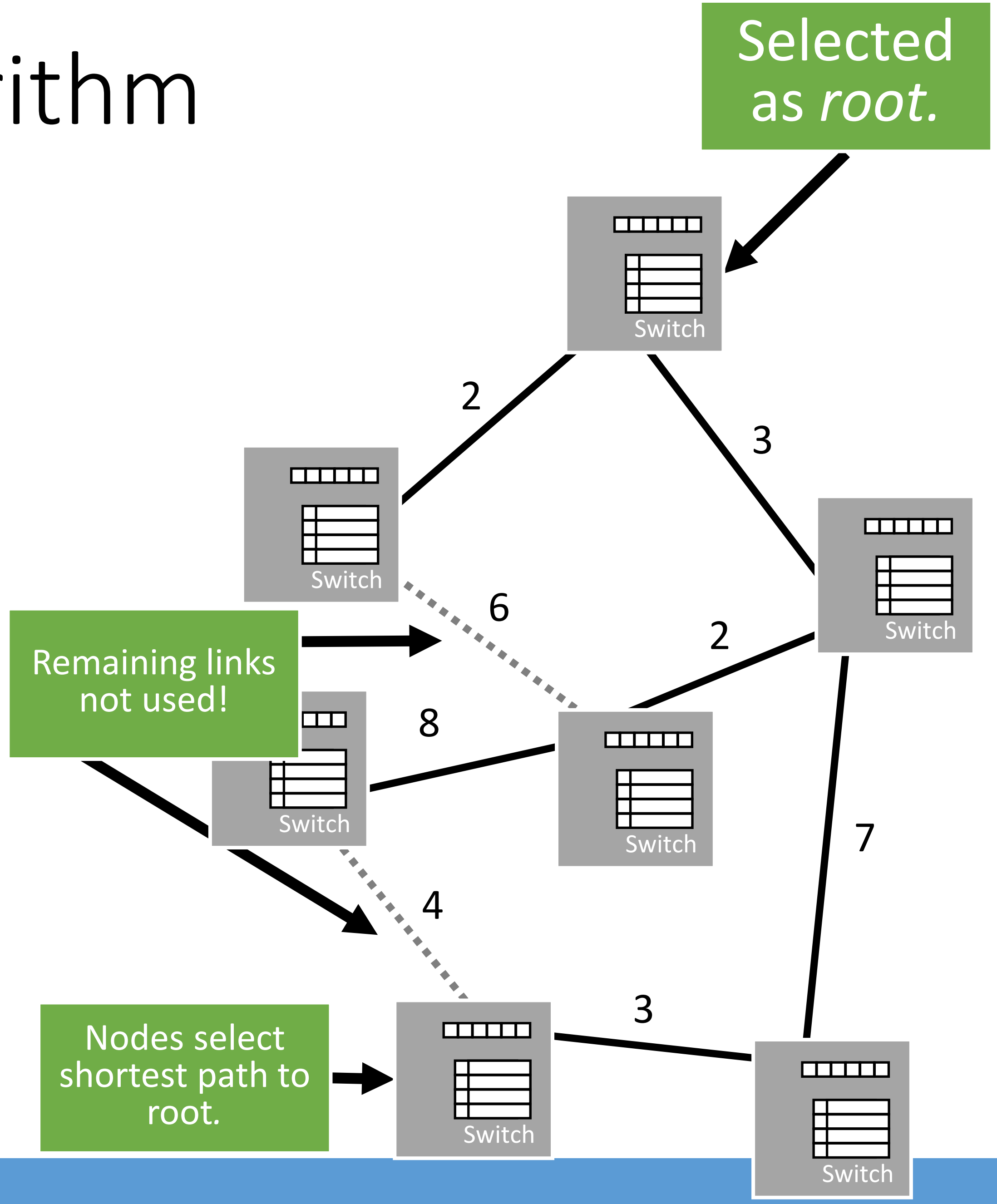

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Medium Access Control for Wireless Channels

Properties of Wireless Channels Affect MAC Protocol Design

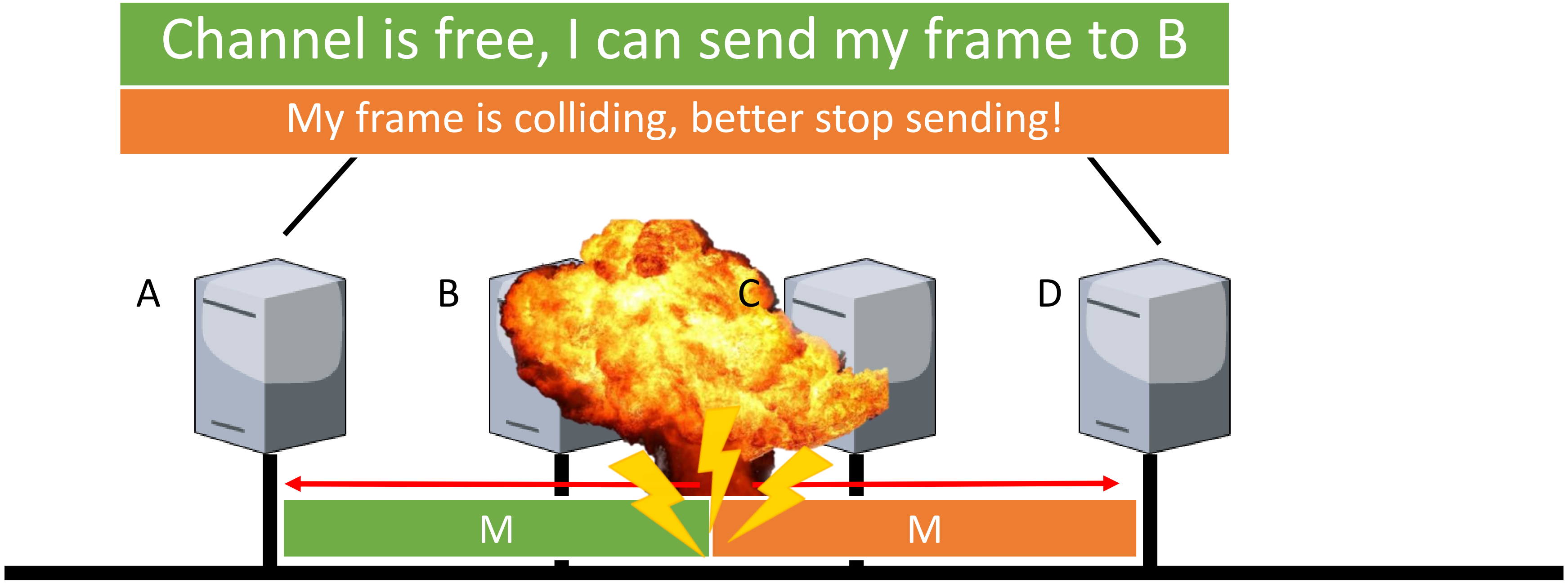
The good news: no more wires.

The bad news:

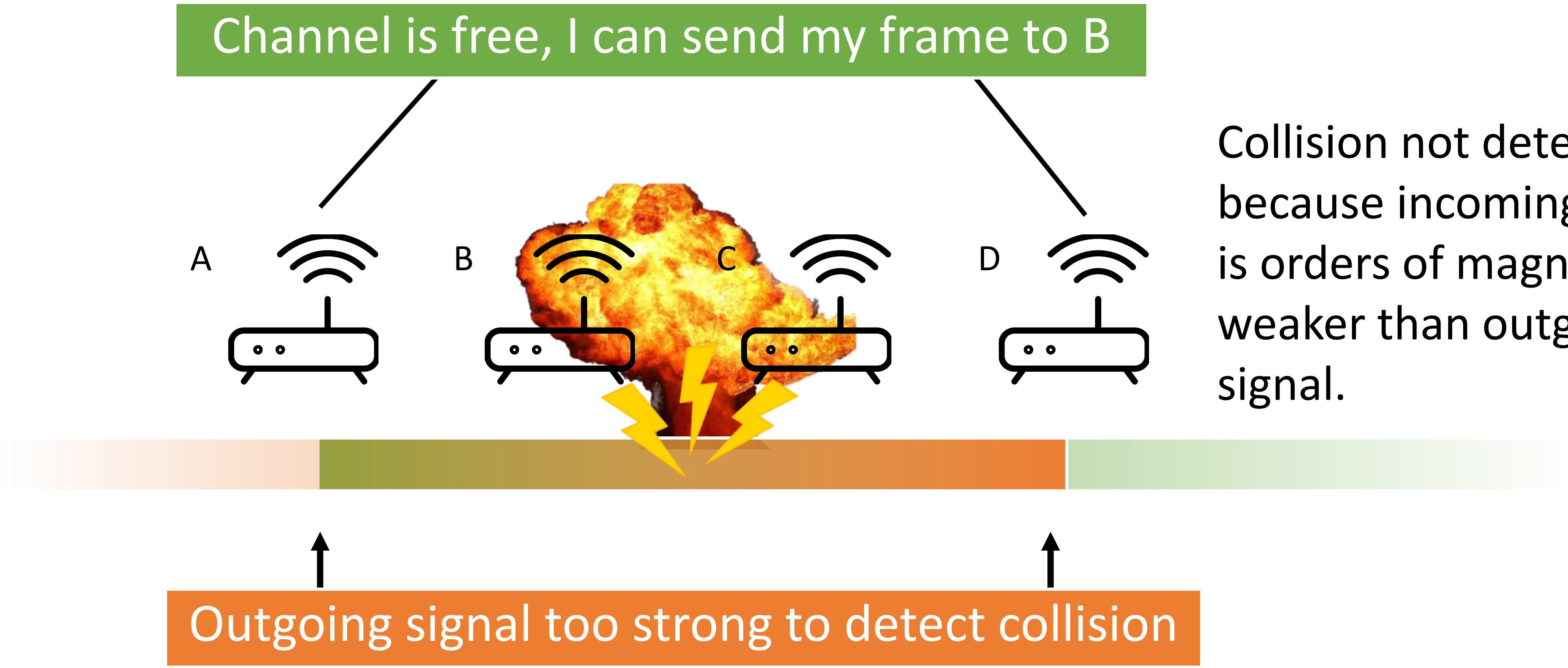
1. Nodes cannot detect collisions while sending. (you cannot talk and listen at the same time!)
2. *Hidden* and *exposed* terminals.

We cannot detect collisions while transmitting!

MAC for Wireless Channels: No Collision Detection



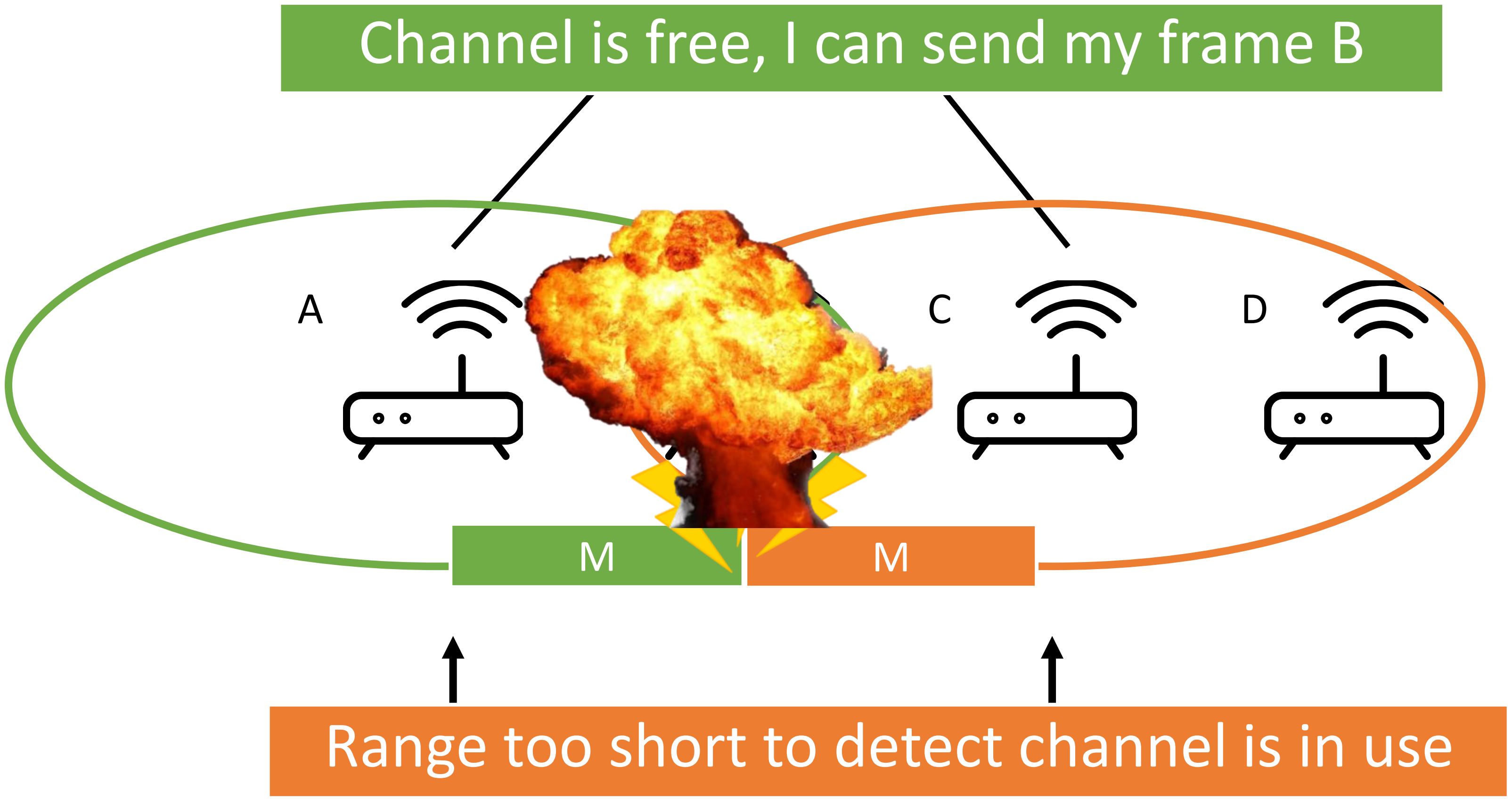
MAC for Wireless Channels: No Collision Detection



Collision not detected because incoming signal is orders of magnitude weaker than outgoing signal.

MAC for Wireless Channels: Carrier Sense has Limited Range

Hidden Terminal



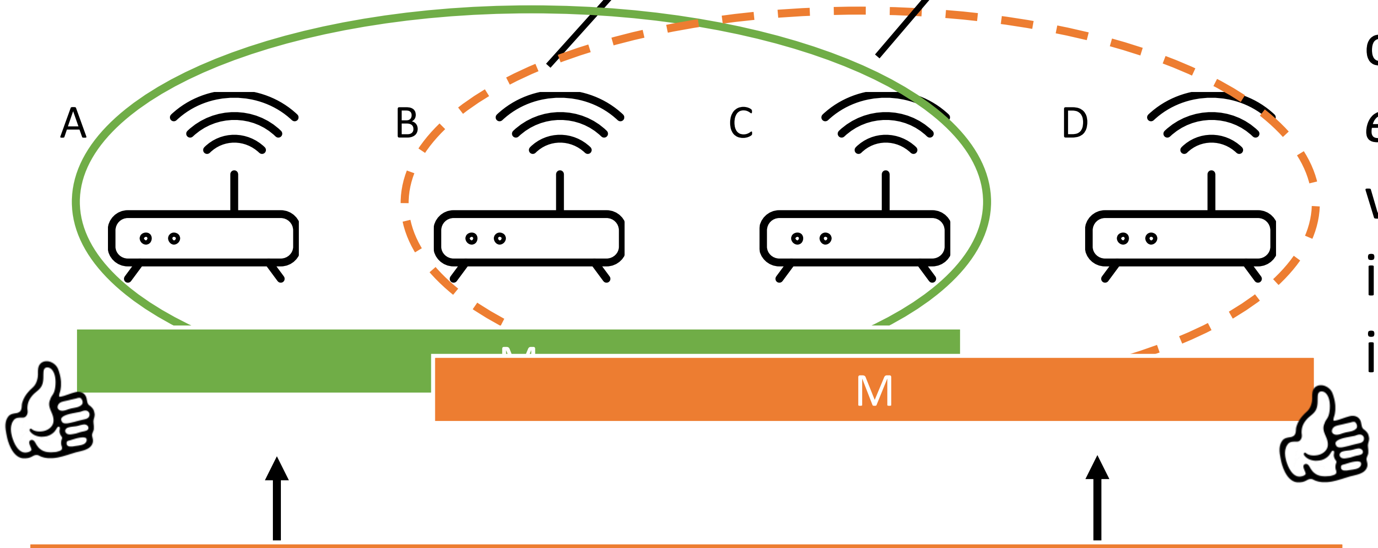
Stations sense that channel is idle, but their range is too short to detect a transmitting *hidden terminal*.

MAC for Wireless Channels: Carrier Sense has Limited Range

Exposed Terminal

Channel is free, I can send my frame A

Channel is in use,
I **cannot** send my frame to D



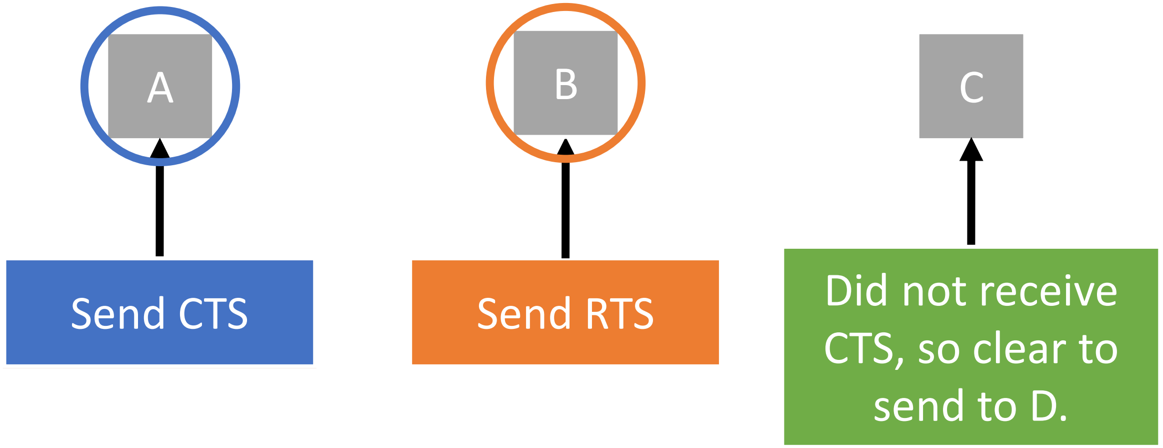
Stations sense that channel is in use, but the *exposed terminal's* signal would not reach and interfere with the intended recipient.

There would be no collision at recipients

Multiple Access with Collision Avoidance (MACA)

An approach to solve the hidden terminal and exposed terminal problem.

Example: B wants to send to A.



CSMA/CA (Collision Avoidance)

Physical channel sensing.

Sense if the channel is in use. Wait for channel to become idle.

Virtual channel sensing.

Frames carry a Network Allocation Vector (NAV) that indicates the length of the exchange.

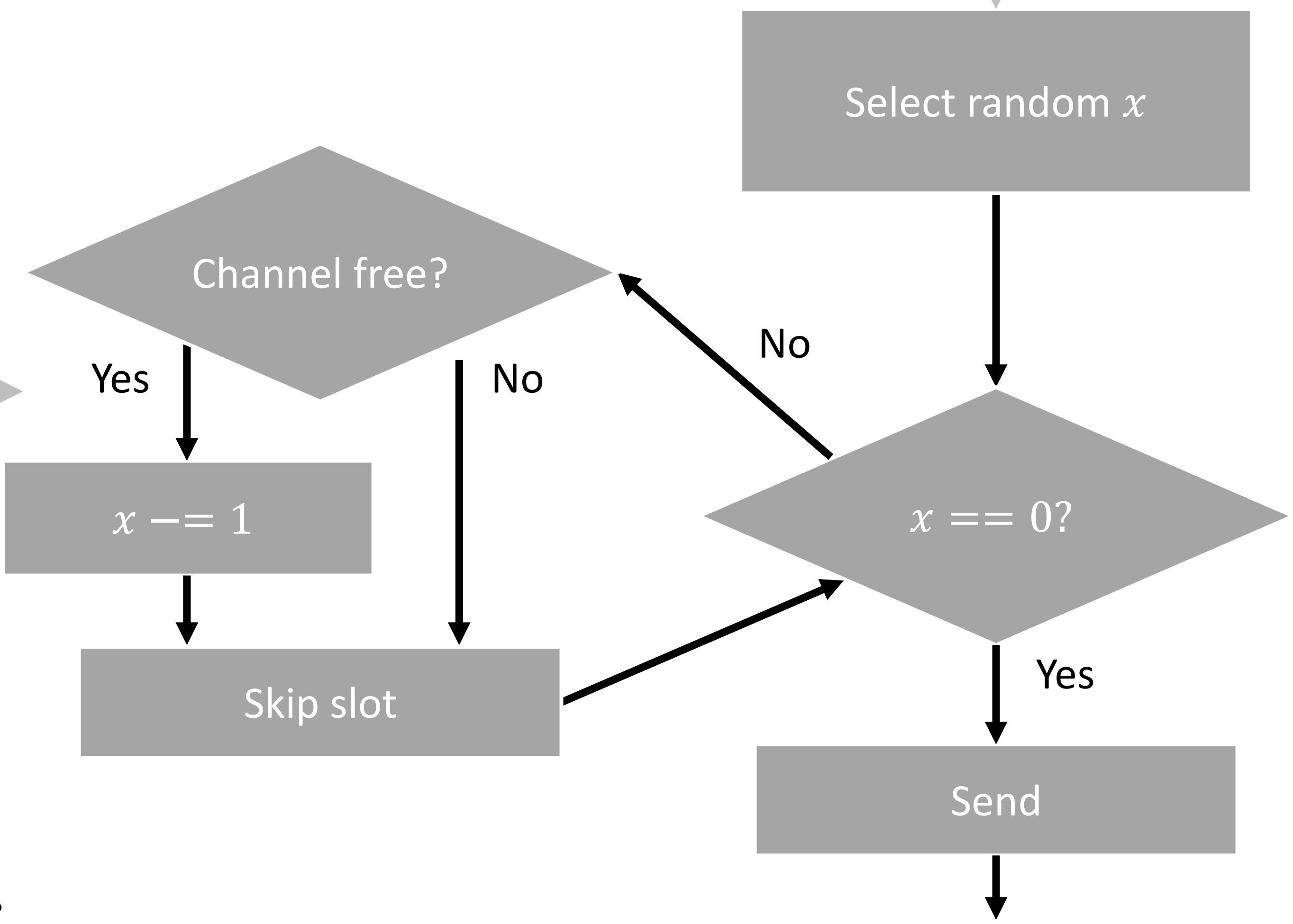
Data + Ack

Wait for end of exchange.

CSMA/CA

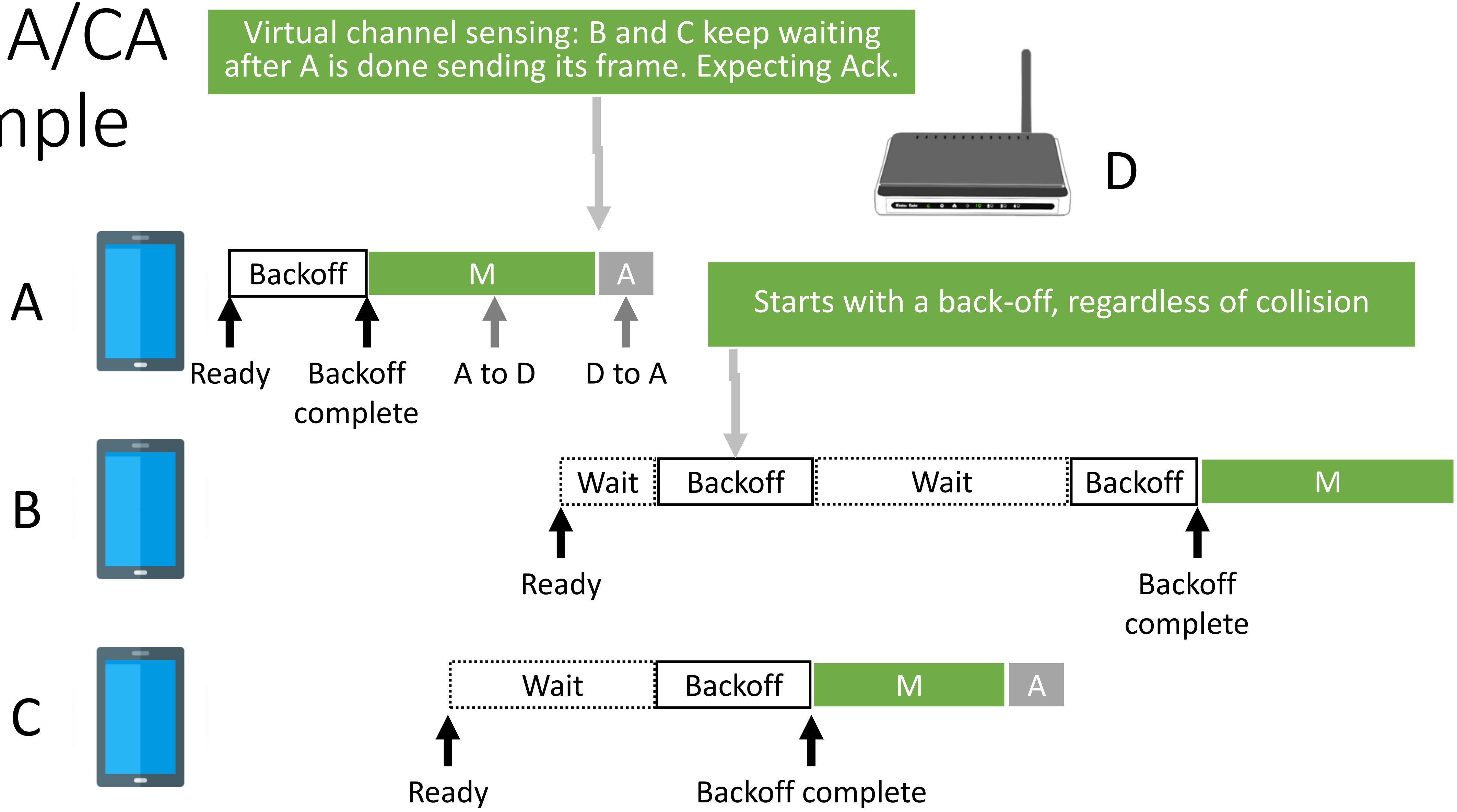
Starts with a back-off, regardless of collision

Countdown paused when other channel is occupied



Backoff by selecting and counting down x.

CSMA/CA Example



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Medium Access Control in … 802.11

Stations cannot detect collisions while they occur.

Relies on ACKs to determine if collision occurred.

If ACK is lost, sender assumes frame was lost; retransmits frame

Can use RTS/CTS, but usually does not.

Instead uses a protocol called **CSMA/CA**.
CA: Collision Avoidance.

Core elements of CSMA/CA

Physical channel sensing.

Sense if the channel. Wait for channel to become idle.

Virtual channel sensing.

Frames carry a Network Allocation Vector (NAV)
that indicates the length of the exchange.

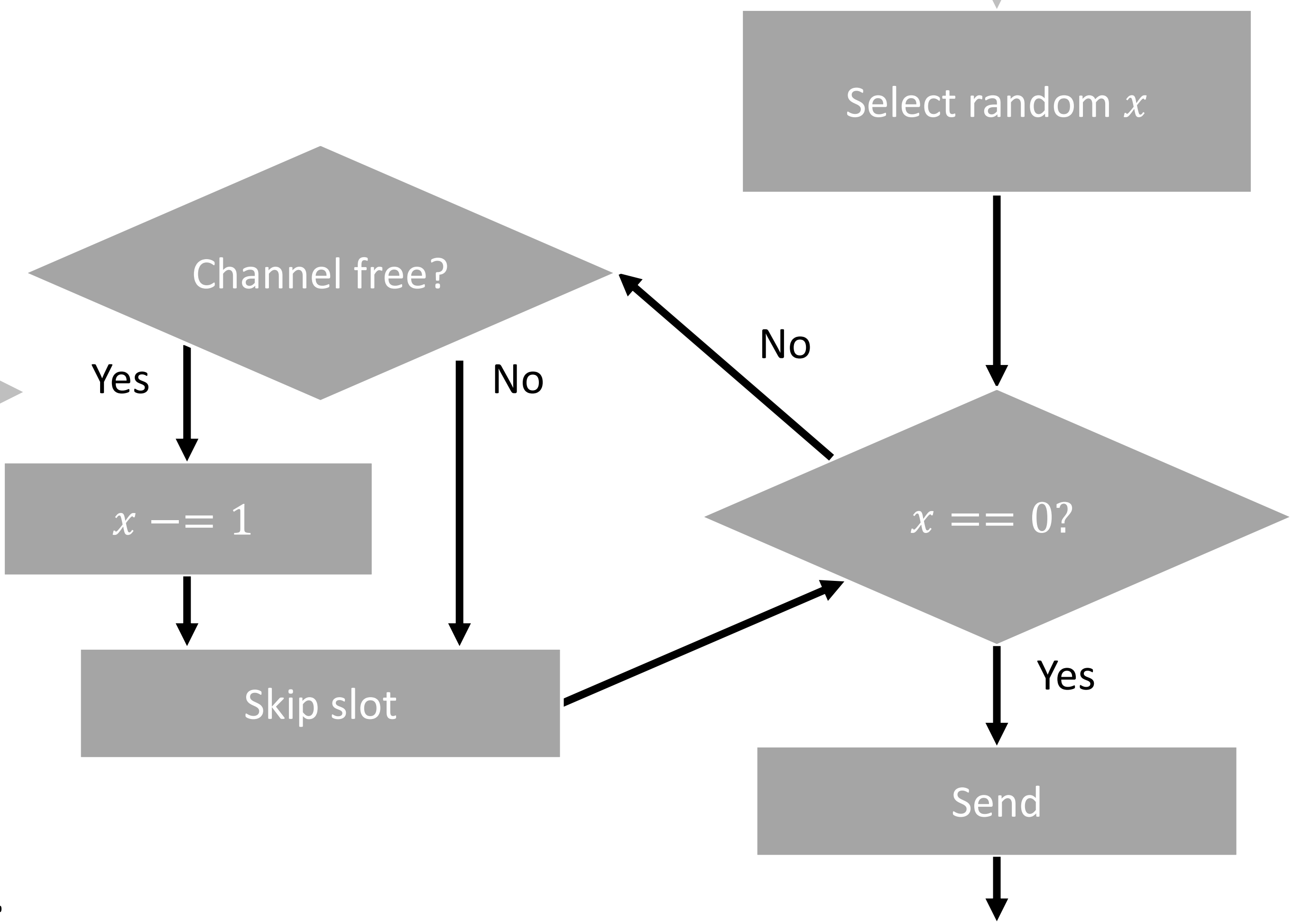
Data + Ack

Wait for end of exchange.

CSMA/CA

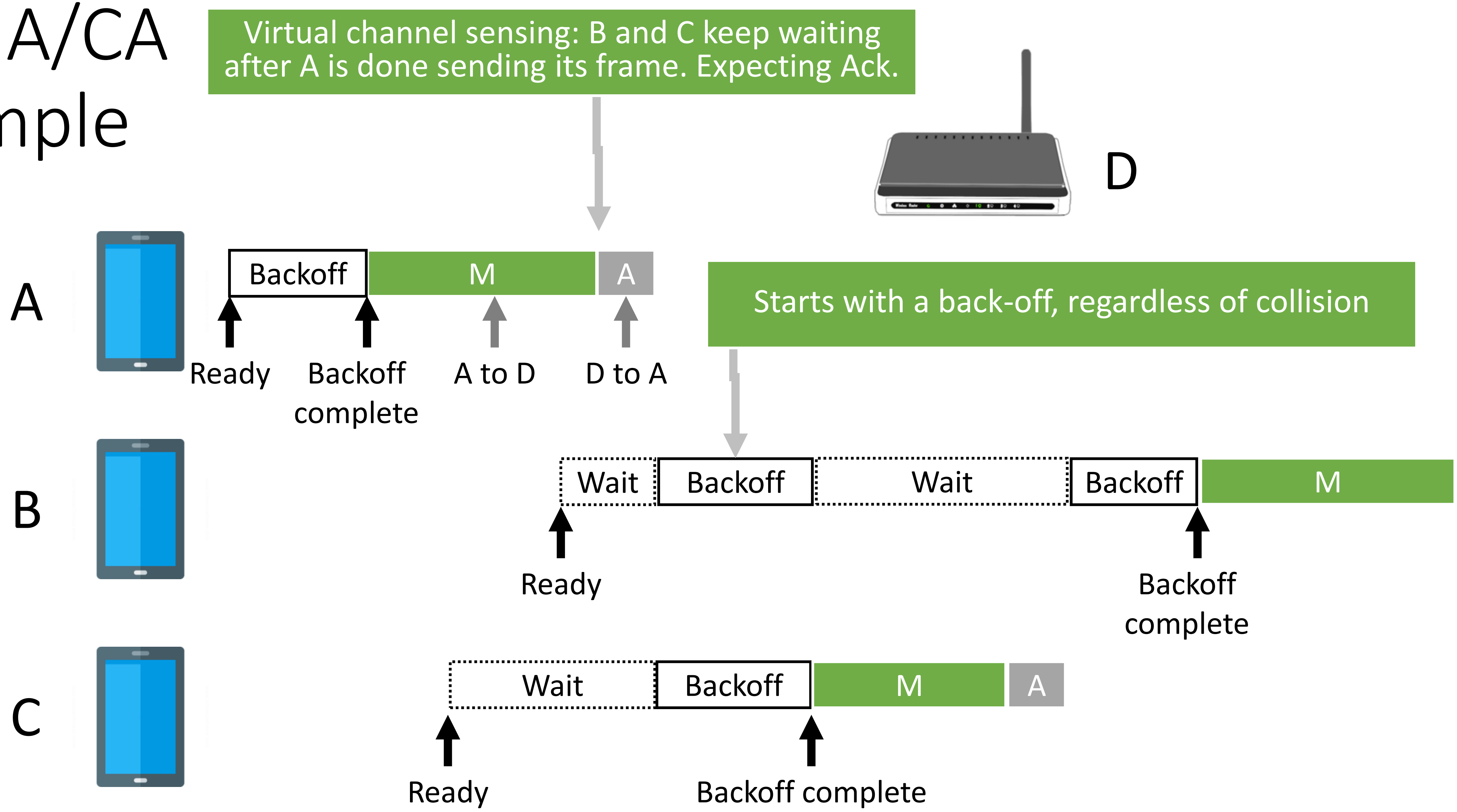
Starts with a back-off, regardless of collision

Countdown paused when other channel is occupied



Backoff by selecting and counting down x.

CSMA/CA Example

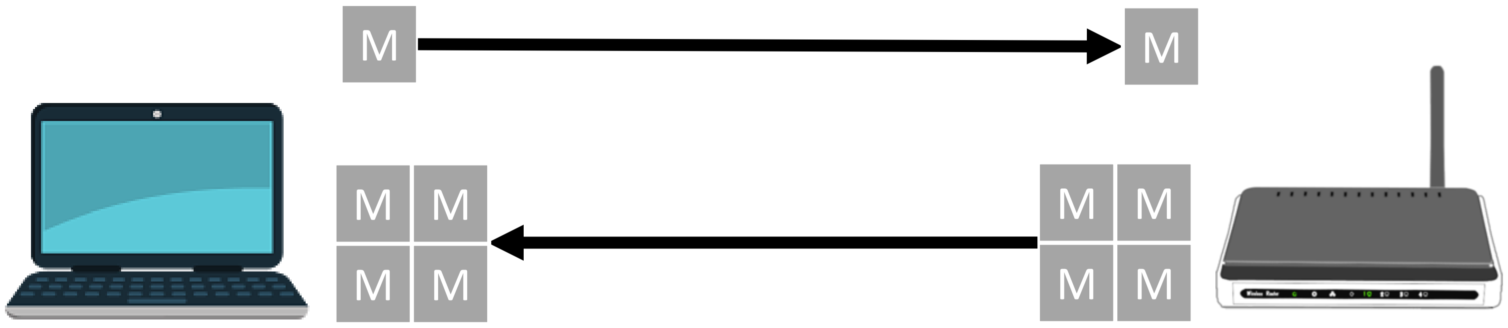


Power saving in 802.11

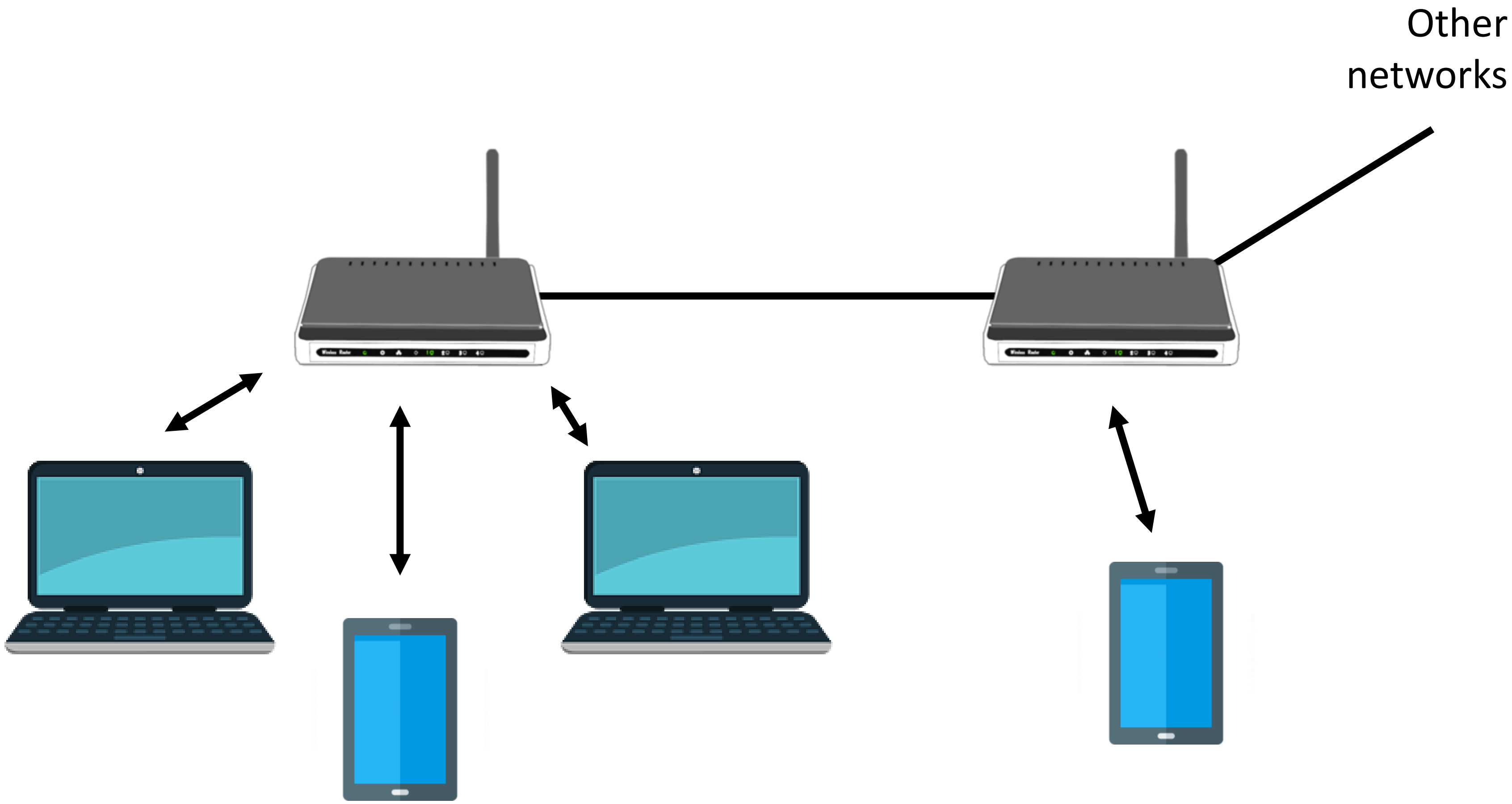
Multiple methods possible

- Beacon frames
- Automatic Power Save Delivery (APSD)
- …

APSD example:

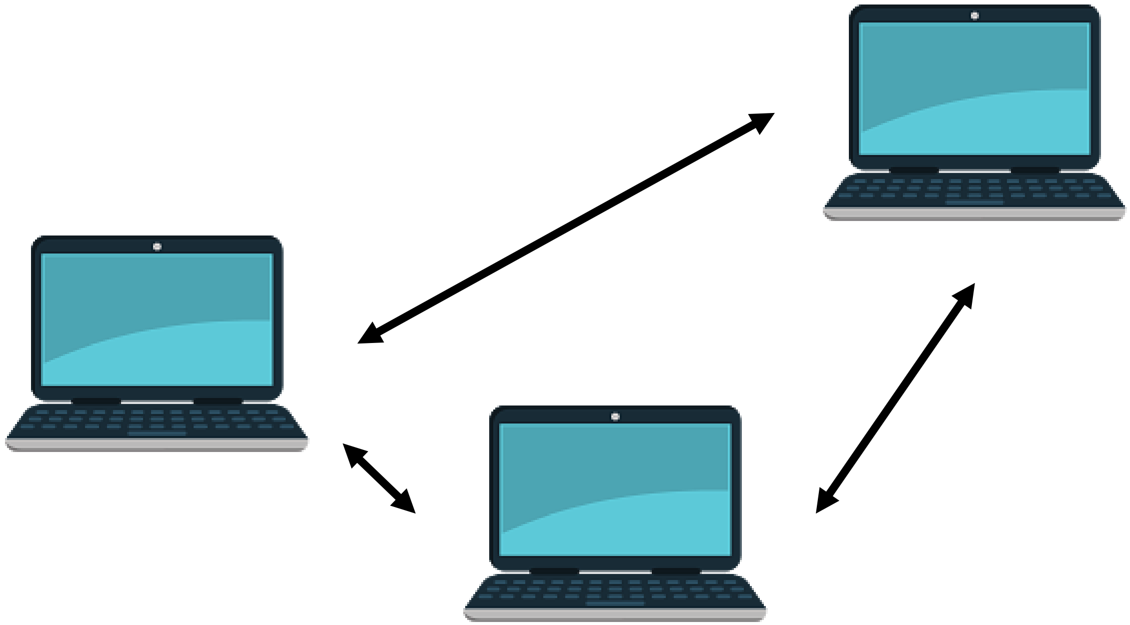


802.11
Infrastructure mode

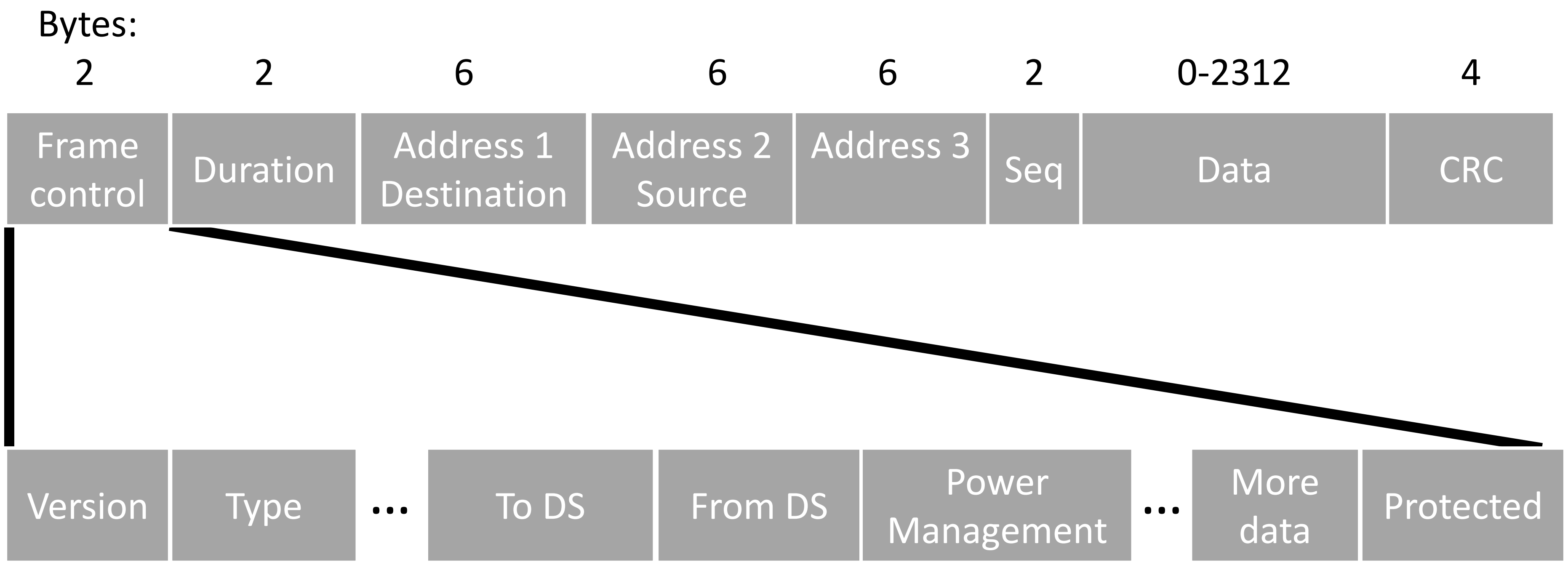


802.11
Ad-hoc networks

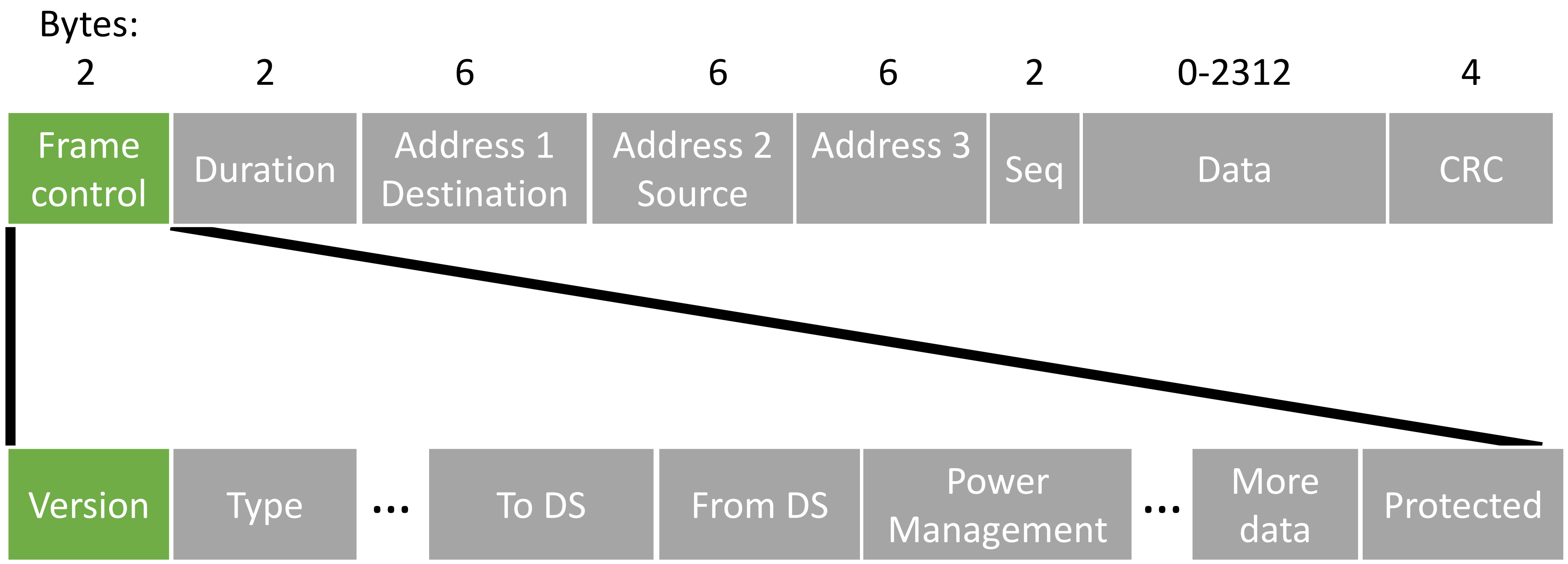
Q: Can you think of a (dis)advantage?



802.11 frames

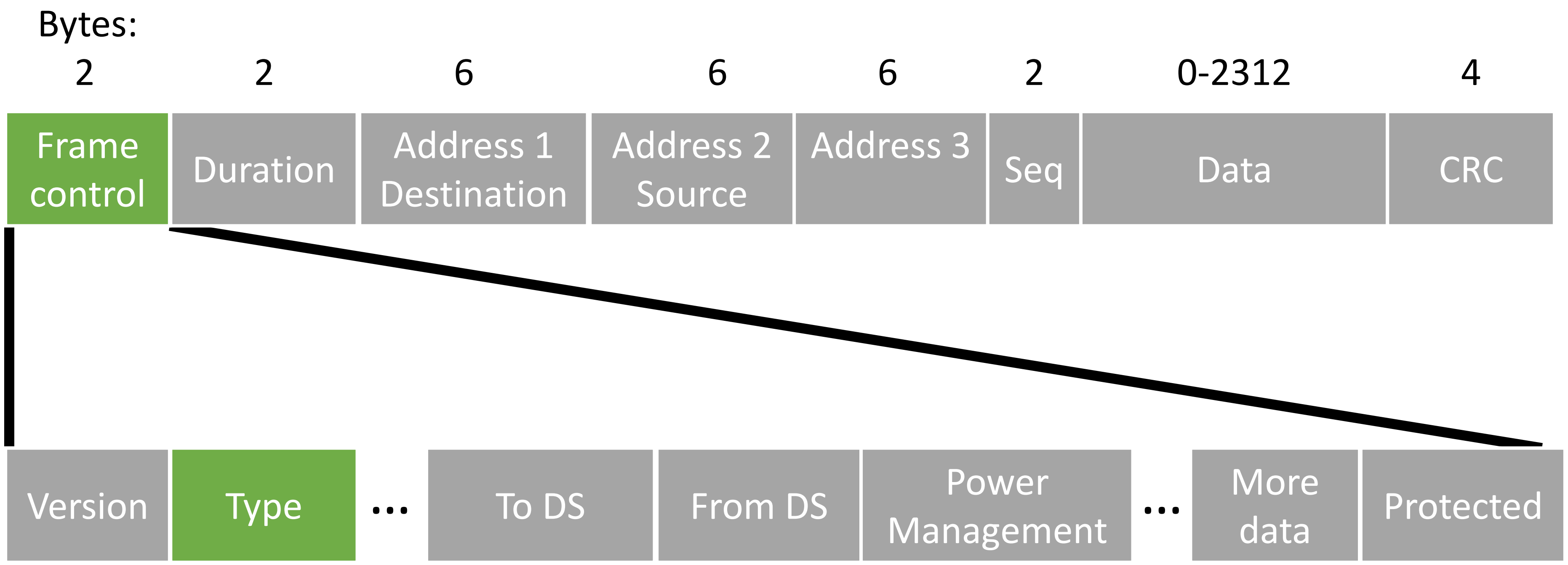


802.11 frames



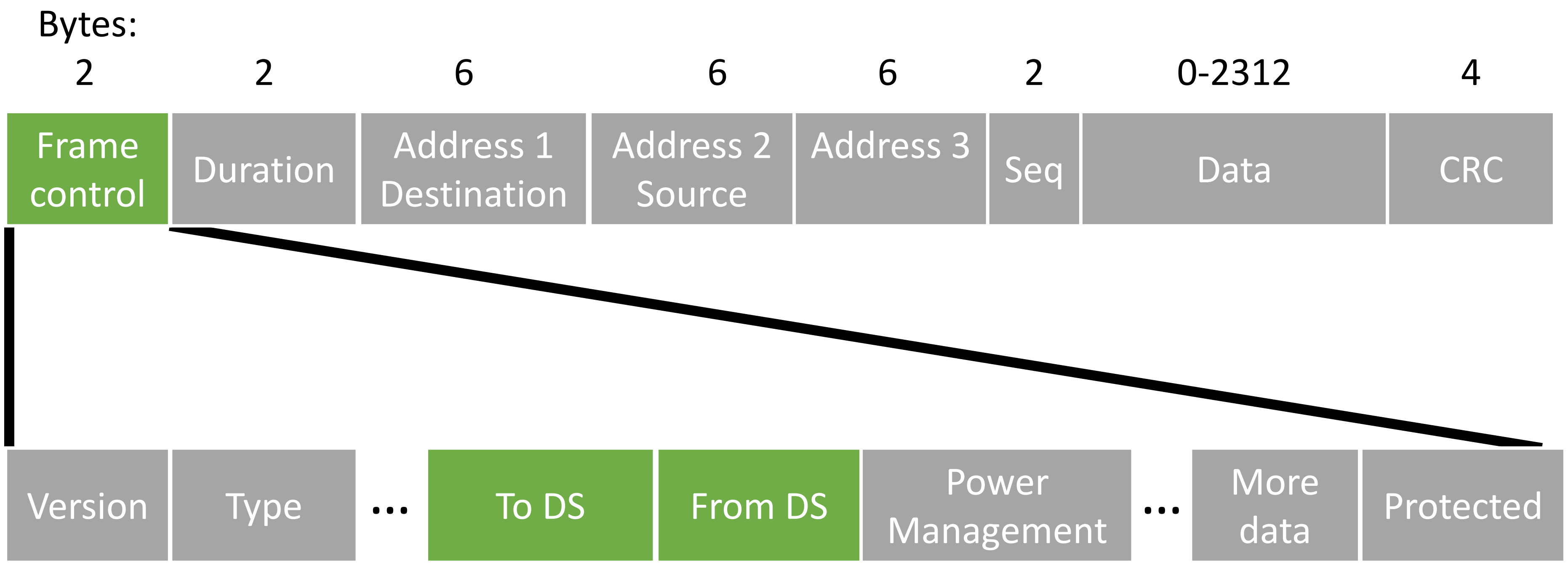
Available for other types of frames in future versions of the protocol.

802.11 frames



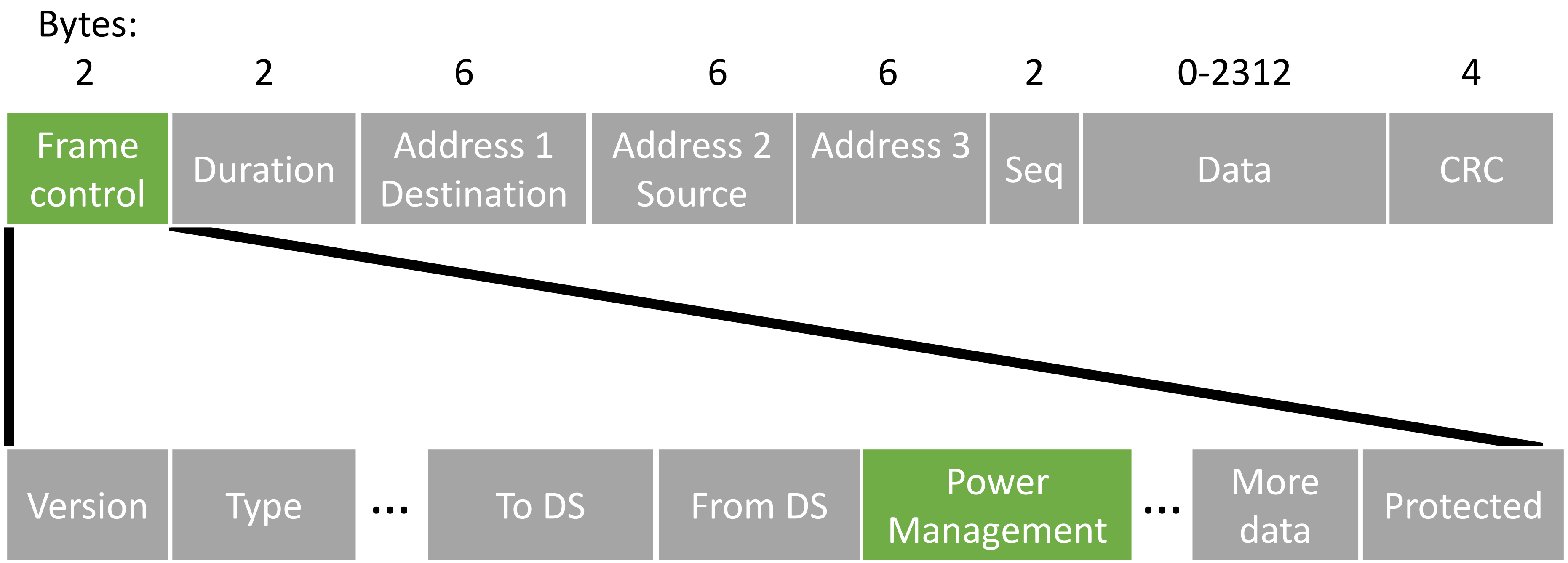
Indicates a control, management, or data frame.

802.11 frames



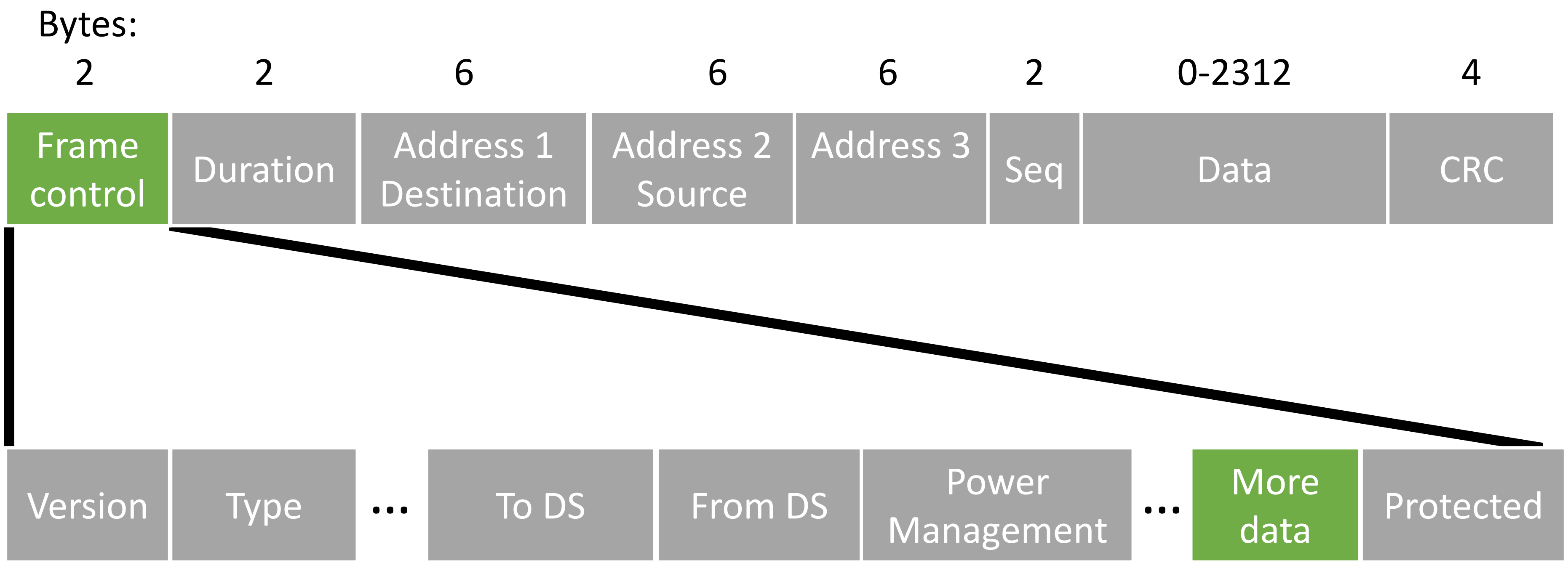
Indicates frames to and from the access points (distribution system) respectively.

802.11 frames



Indicates that the sender will enter power save mode.

802.11 frames

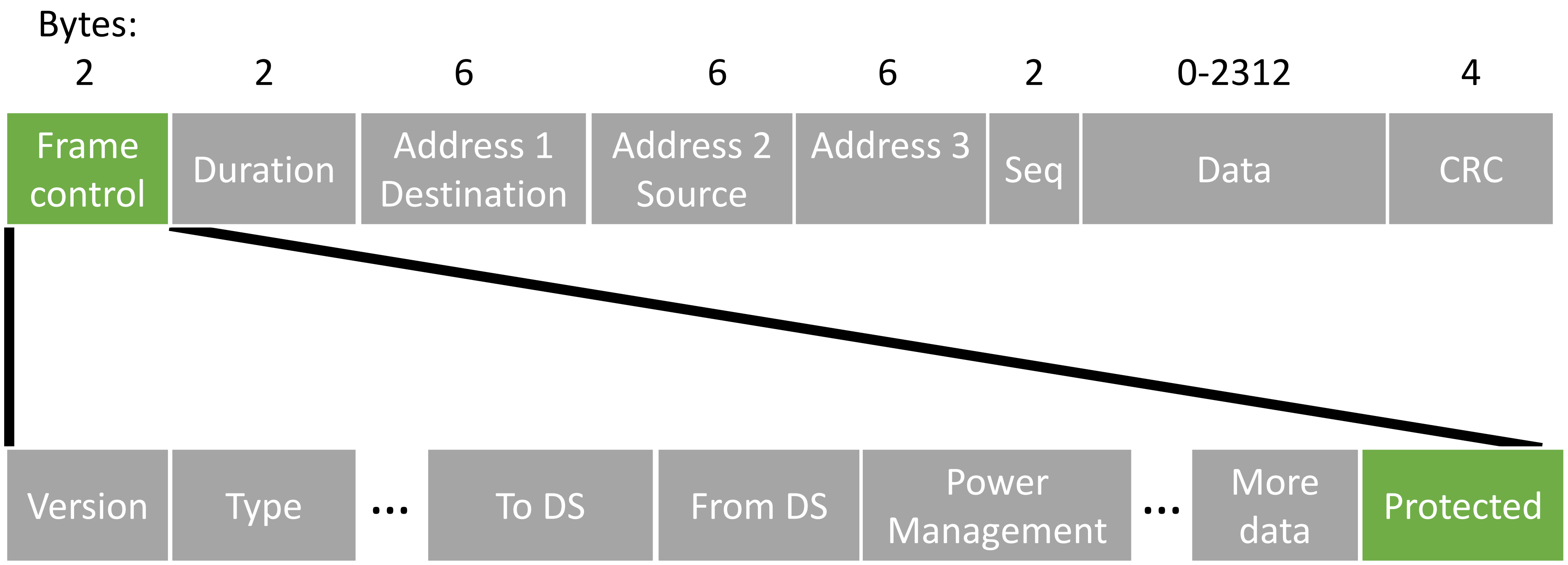


Indicates that the sender has more frames for the receiver.

WPA2 uses encryptions based on AES (Advanced Encryption Standard)

802.11 frames

Authentication uses username+password (e.g., Eduroam), or only a password (e.g., your wireless network at home).



Indicates that the data is encrypted.

802.11 frames

Bytes:

2	2	6	6	6	2	0-2312	4
Frame control	Duration	Address 1 Destination	Address 2 Source	Address 3	Seq	Data	CRC

Stations use the duration to update their Network Allocation Vector (NAV).

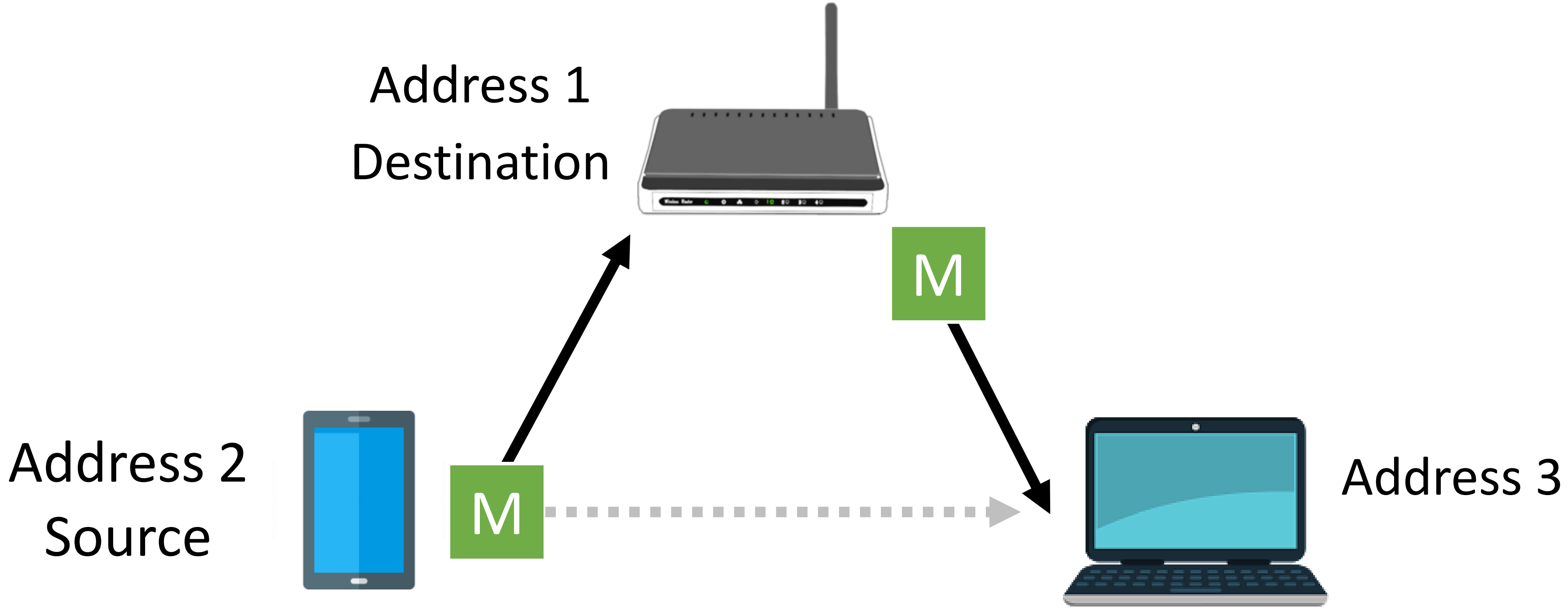
802.11 frames

Bytes:

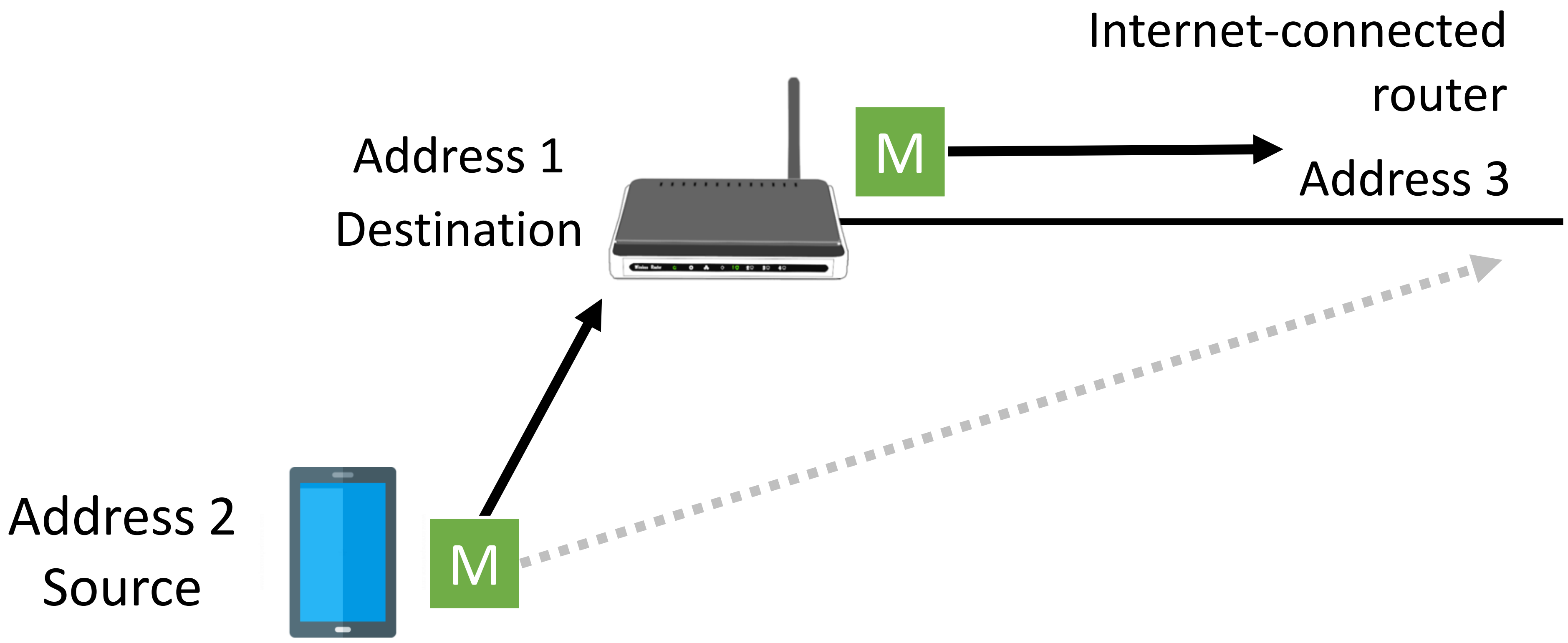
2	2	6	6	6	2	0-2312	4
Frame control	Duration	Address 1 Destination	Address 2 Source	Address 3	Seq	Data	CRC

Q: Why a third address?

Access point forwards frame to recipient

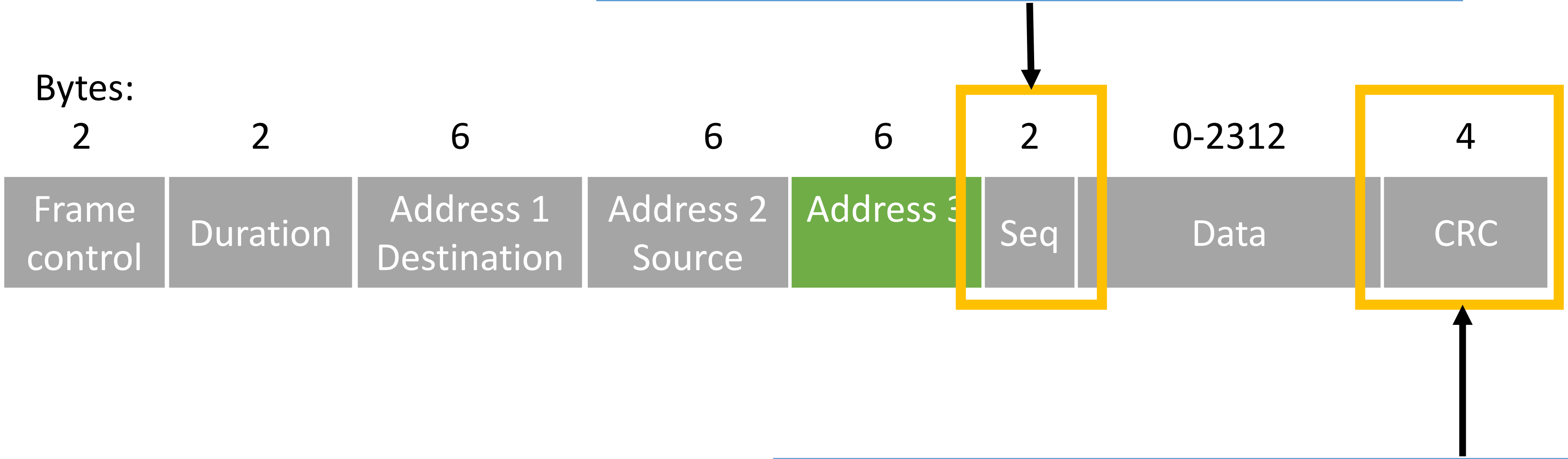


Access point forwards frame to recipient



802.11 frames

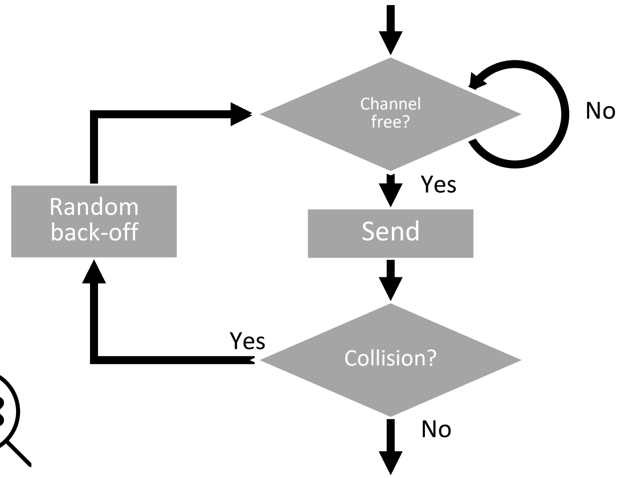
Q: Reliable delivery?



Q: Error detection/correction?

Q: Why a third address?

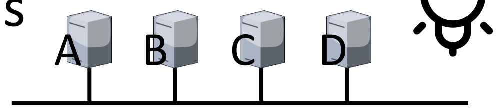
MAC Layer Summary



Multiplexing on the link layer **Q: Why useful?**

- Contention and coordination **Q: Which is better?**
- Centralized and decentralized protocols
- Properties: bandwidth efficiency, latency, complexity.

Protocols and mechanisms



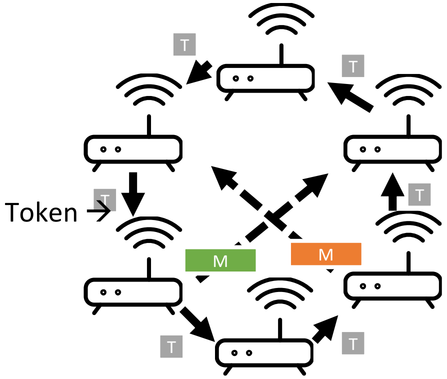
- Carrier Sense
- Collision Detection, 1-persistent, nonpersistent, p-persistent **Q: Why not used on wireless channels?**
- Collision Avoidance, MACA, CSMA/CA
- Collision-free protocols, Basic bitmap, Token ring, Binary countdown

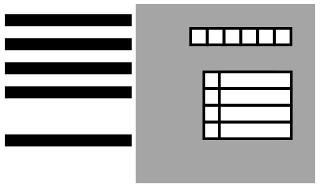
Wireless Channels

- Limited Radio Range
- Hidden terminals and Exposed terminals

Switching **Q: How to know where to send frames?**

- Routing on the link layer
- No MAC protocol needed when used on full-duplex wired channels





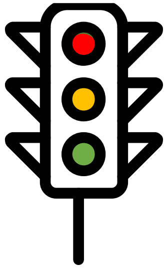
MAC Sublayer Outline

- ALOHA & Slotted ALOHA
- CSMA
  - 1-persistent
  - nonpersistent
  - p-persistent
- CSMA/CD
- **802.3 Ethernet**
- Ethernet Switching
- MAC for Wireless
  - Hidden Terminal
  - Exposed Terminal
- CSMA/CA
- **802.11 WiFi**
- Collision-Free Protocols
  - Basic Bit-Map
  - Token Ring
  - Binary Countdown

Collision-Free Protocols

Replacing *contention* with *coordination*

Instead of detecting collisions, why not prevent collisions?



Protocol examples:

1. Basic Bit-Map Protocol
2. Token Ring
3. Binary Countdown

The Basic Bit-Map Protocol

Q: What is the efficiency of this protocol?

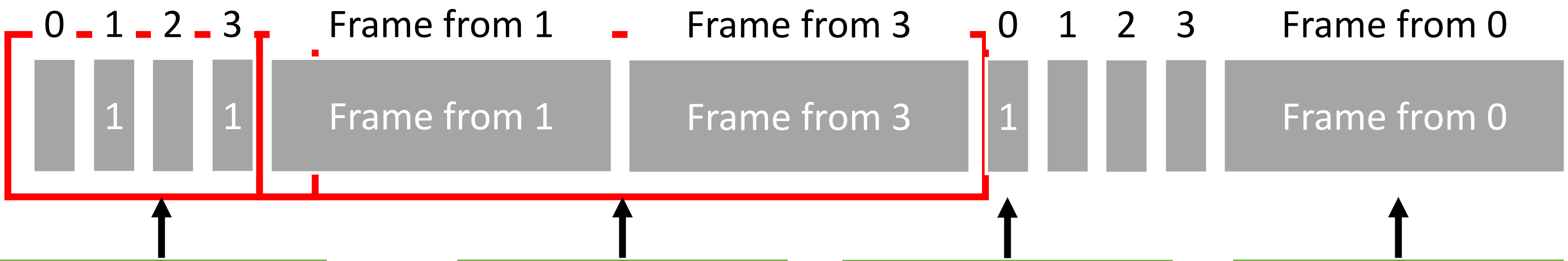
An example of a *collision-free* protocol.

Stations that want to transmit send a ‘1’ in their slot.

With n stations,

$$e_H = \frac{nd}{n+nd} = \frac{d}{1+d}$$

Efficiency increases if frame size increases/contention slot size decreases (d increases)



If a station wants to transmit, it sends a 1

Stations transmit their frames in order

Contention slot takes 1 time unit

Sending frame takes d contention slots

$$e_L = \frac{d}{n+d}$$

Token Ring

Station with token is allowed to send frame, pass on token

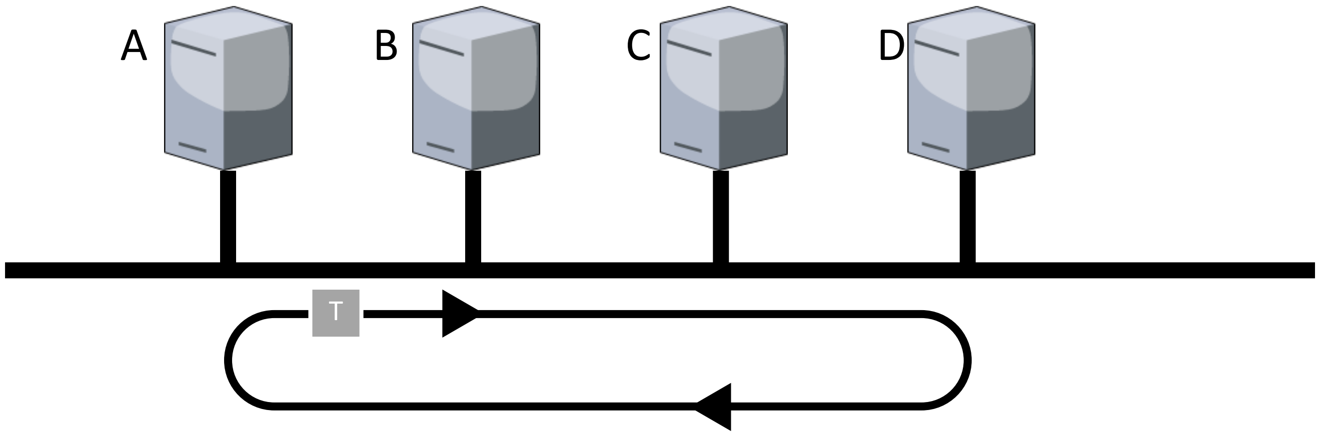
Q: What is the efficiency of this protocol?

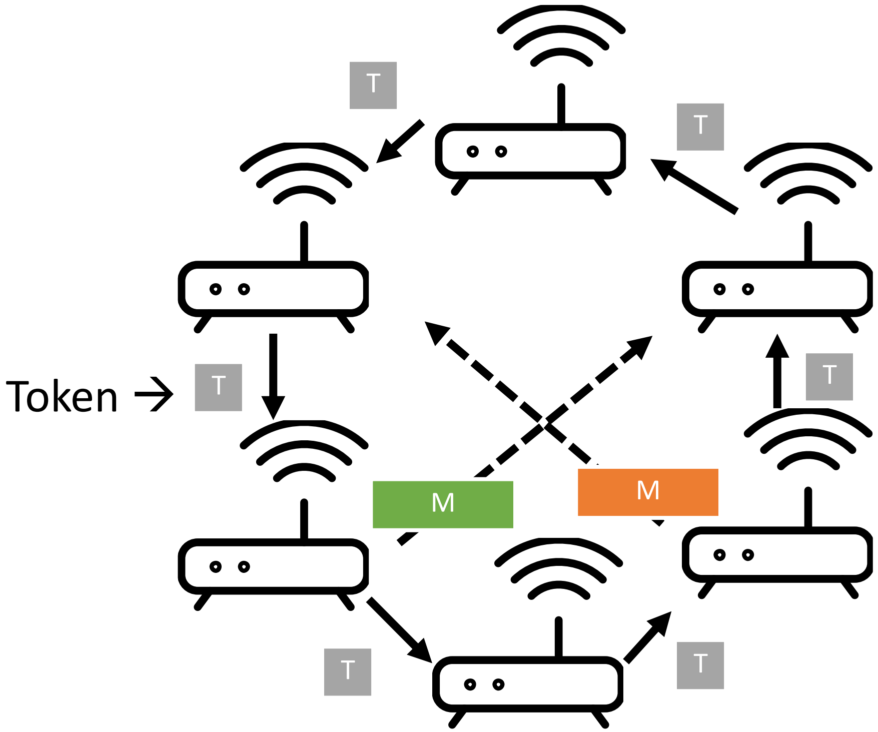
A *collision-free* protocol.

Similar to the basic bit-map protocol.

All stations send in a predefined order.

Physical network layout need not be a ring





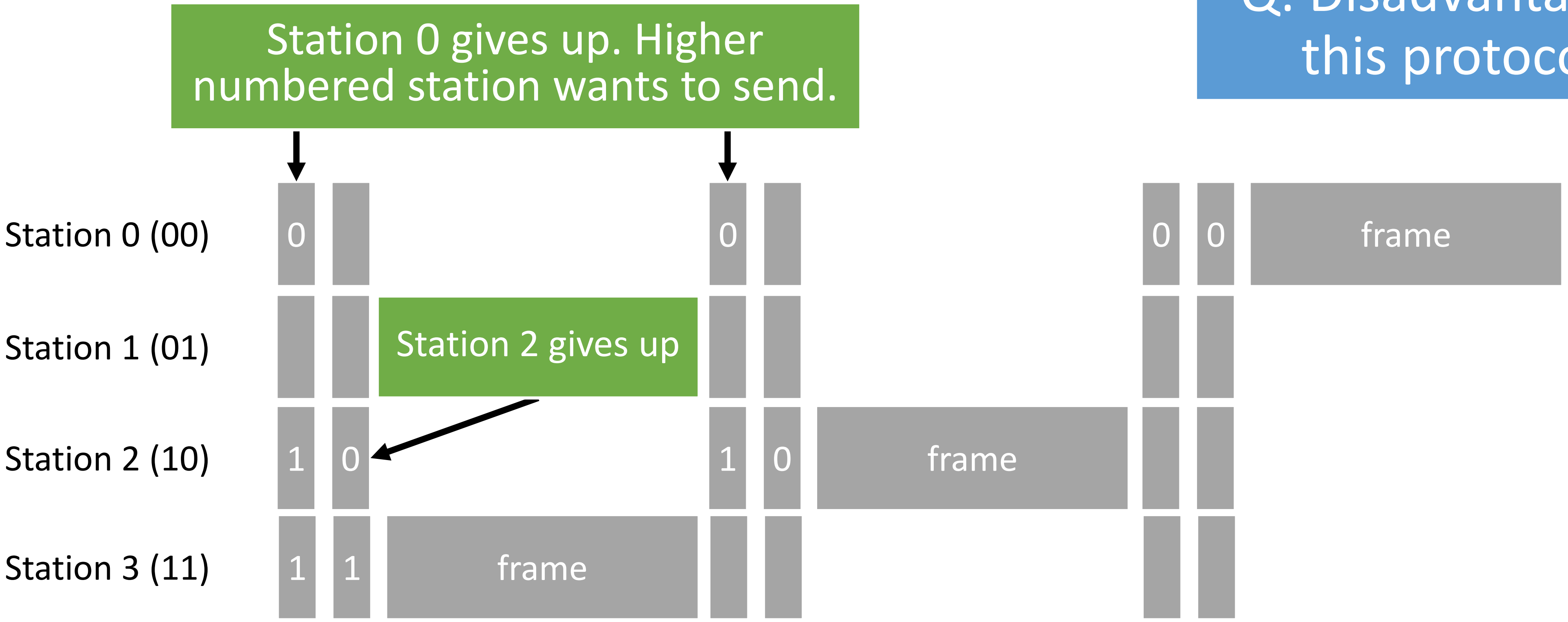
Binary countdown

Q: What is the trade-off these protocols make?

$\log_2(n)$ overhead, $e = \dfrac{d}{d + \log_2 n}$

Example: Stations 0, 2, and 3 want to send a frame

Q: Disadvantage of this protocol?



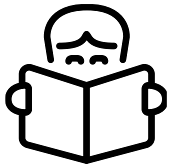
Computer Networks X_400487

Lecture 5

Chapter 4: Medium Access Control

Lecturer: Jesse Donkervliet

Includes slides from Vlad Cursaru

Extra Slides 

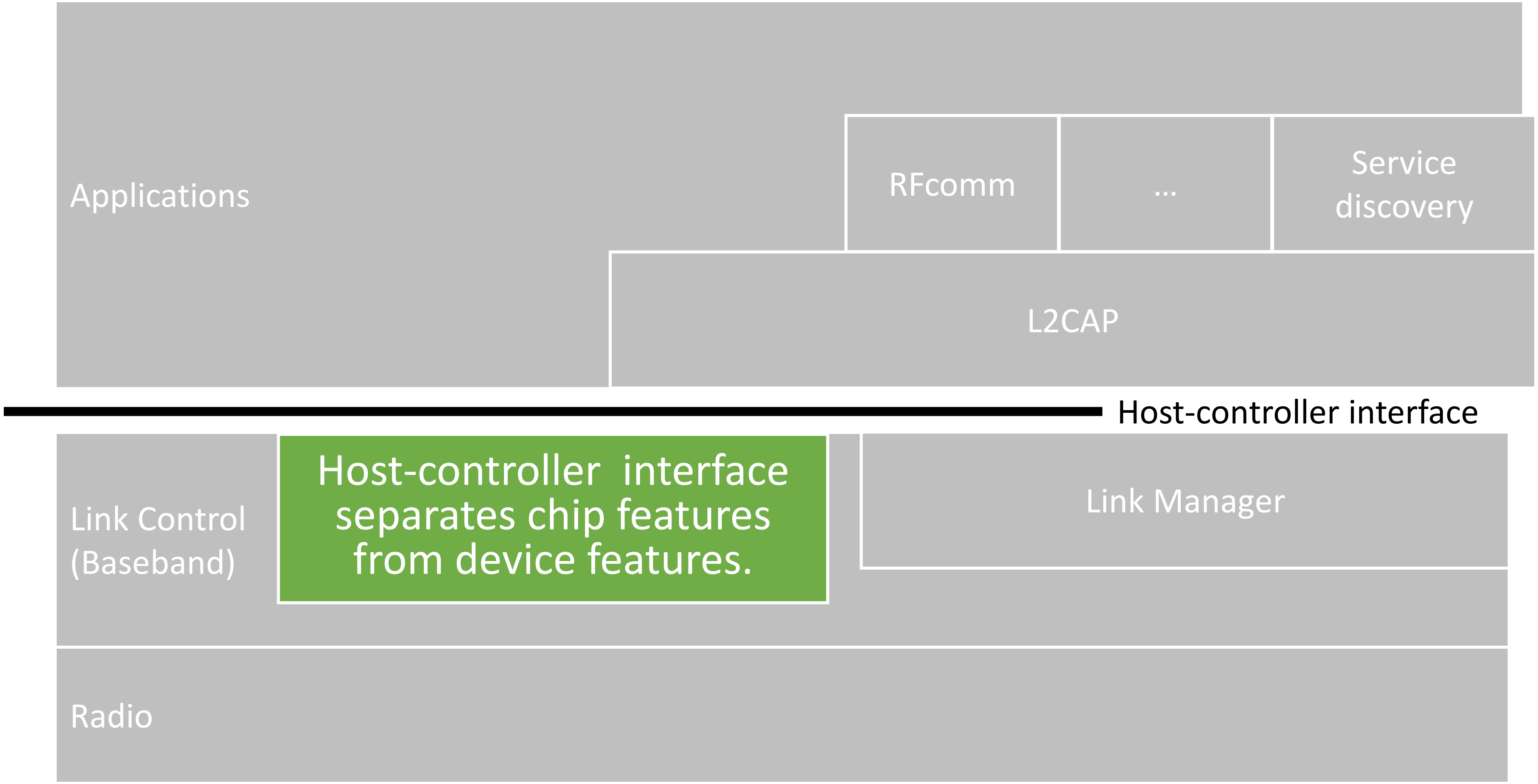
Medium Access Control Bluetooth

Bluetooth Protocol Stack

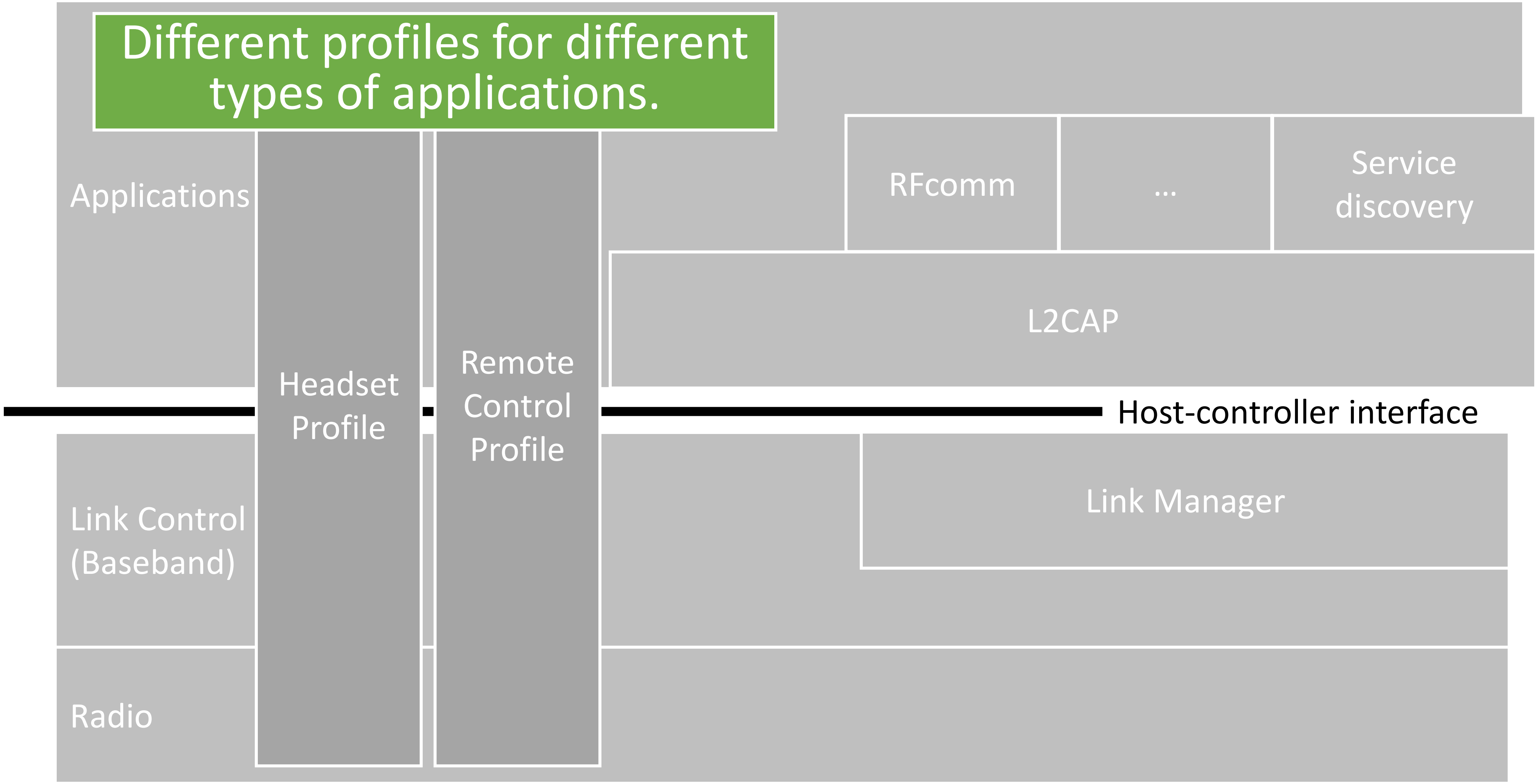
No fixed set of protocols. Instead, **profiles** define the set of protocols for a given application.

25 profiles, including headset, intercom, streaming audio, remote control, personal area network, and others.

Bluetooth Protocol Stack



Bluetooth Protocol Stack



Medium Access Control in … Bluetooth

Radio layer

Q: How to prevent interference with 802.11?

Uses adaptive frequency hopping in 2.4GHz band.

Link layer

Connectionless or connection-oriented depending on the application.

TDM with timeslots for master and slaves.

Synchronous CO for periodic slots in each direction.

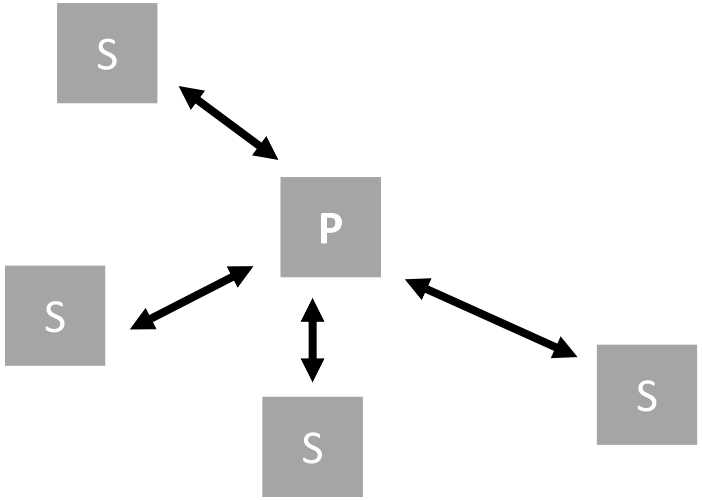
Asynchronous CL for packet-switched data.

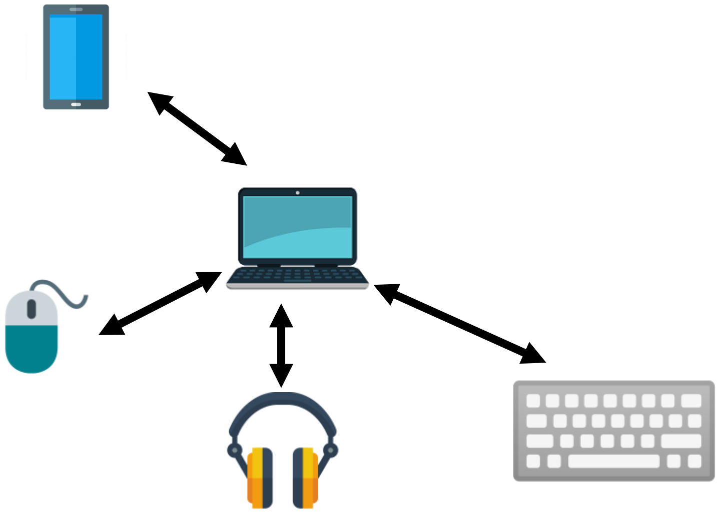
Links undergo pairing (user confirms passkey/PIN) to authorize them before use.

Medium Access Control in ... Bluetooth

A Bluetooth network is called a *piconet*.

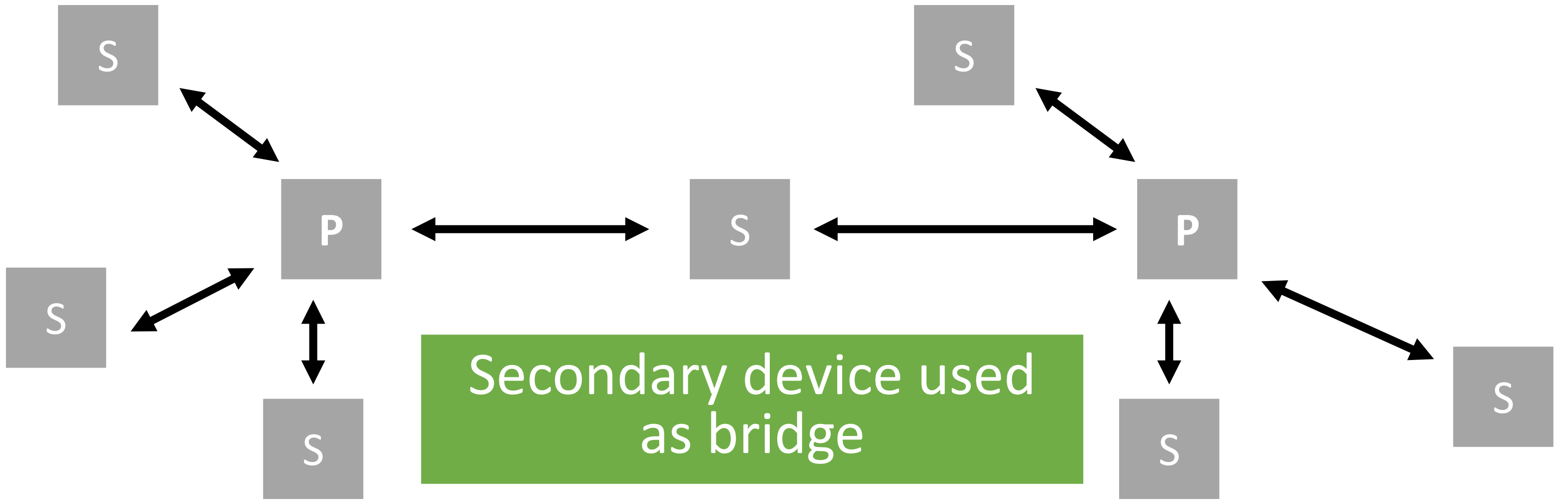
Secondaries may be asleep (parked) to save power.





Bluetooth piconet

Two piconets can be bridged into a *scatternet*.



Bluetooth frames

Uses multiple types of frames, similar to 802.16.

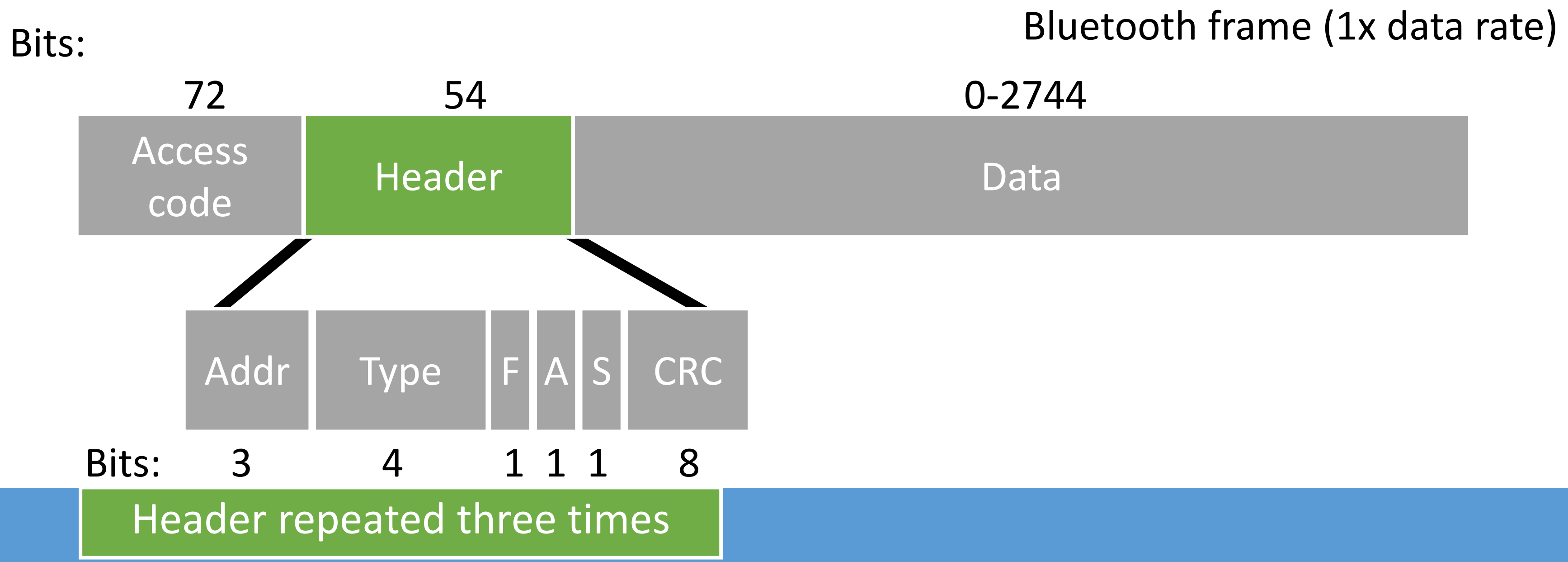
Bluetooth frames

Uses multiple types of frames, similar to 802.16.

Used to identify *primary* device.

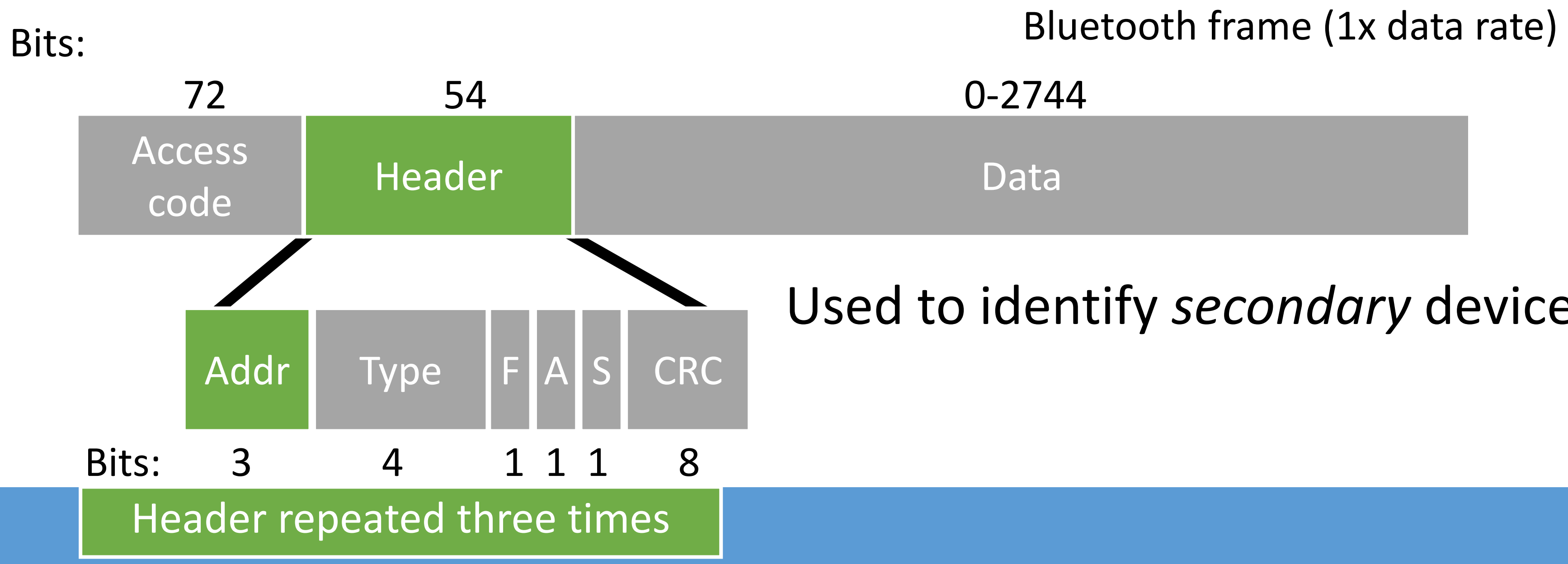
Bluetooth frames

Uses multiple types of frames, similar to 802.16.



Bluetooth frames

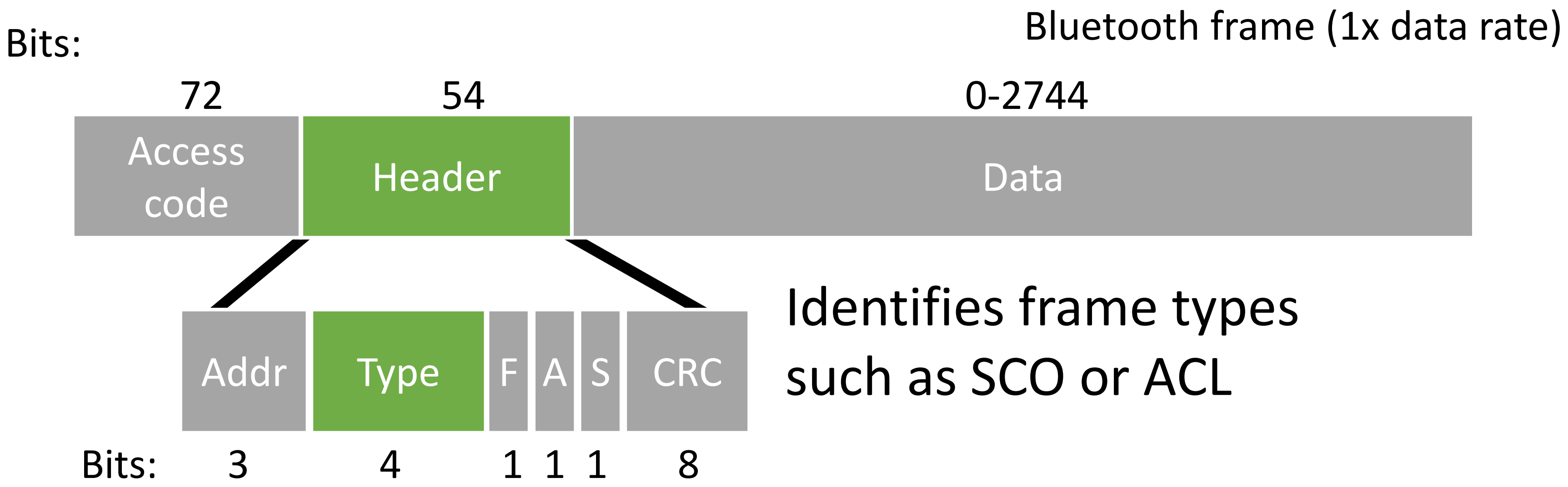
Uses multiple types of frames, similar to 802.16.



Used to identify *secondary* device.

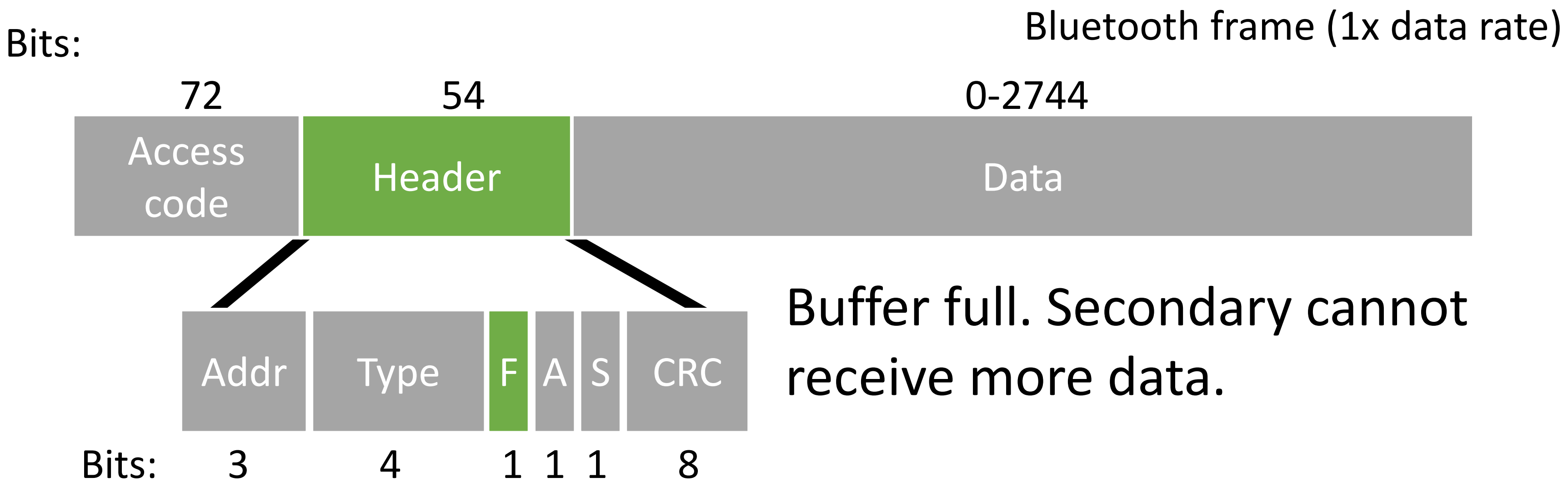
Bluetooth frames

Uses multiple types of frames, similar to 802.16.



Bluetooth frames

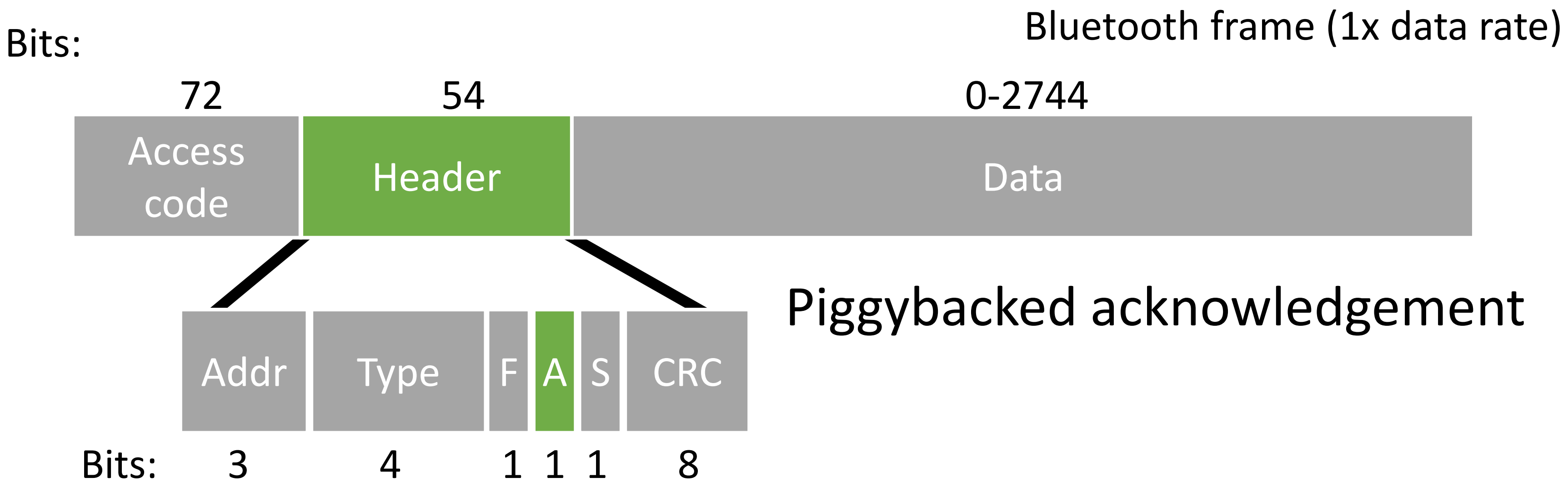
Uses multiple types of frames, similar to 802.16.



Buffer full. Secondary cannot receive more data.

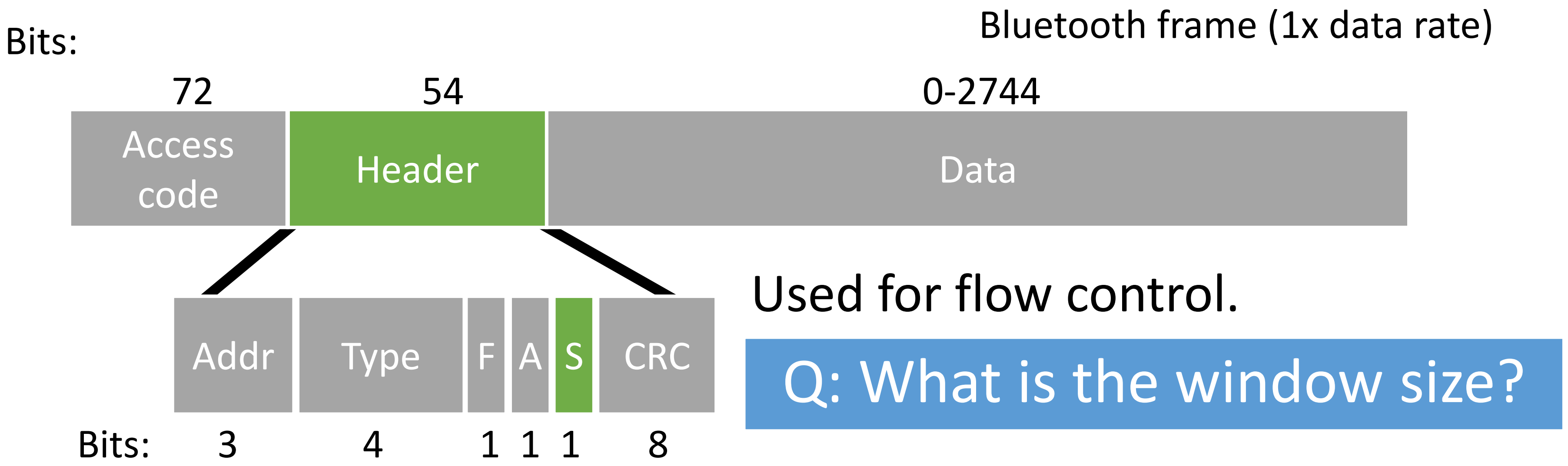
Bluetooth frames

Uses multiple types of frames, similar to 802.16.



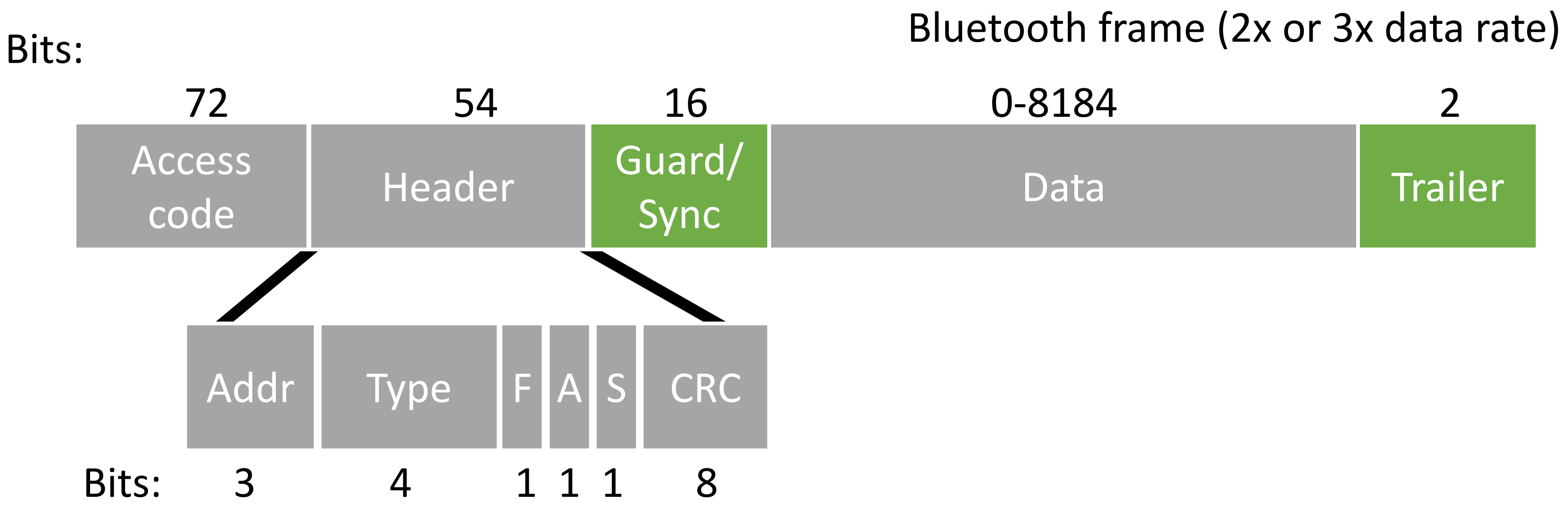
Bluetooth frames

Uses multiple types of frames, similar to 802.16.



Bluetooth frames

Enhanced data rates send faster but for the same time.



Medium Access Control
RFID

RFID Readers

Stationary reader

Mobile reader

Medium Access Control in …
RFID

RFID uses **readers** and **tags**. Reader in charge of medium access control. Tags reply to requests.

Tags have no battery.
Use reader signal to power reply

Medium Access Control in …
RFID

RFID uses **readers** and **tags**. Reader in charge of medium access control. Tags reply to requests.

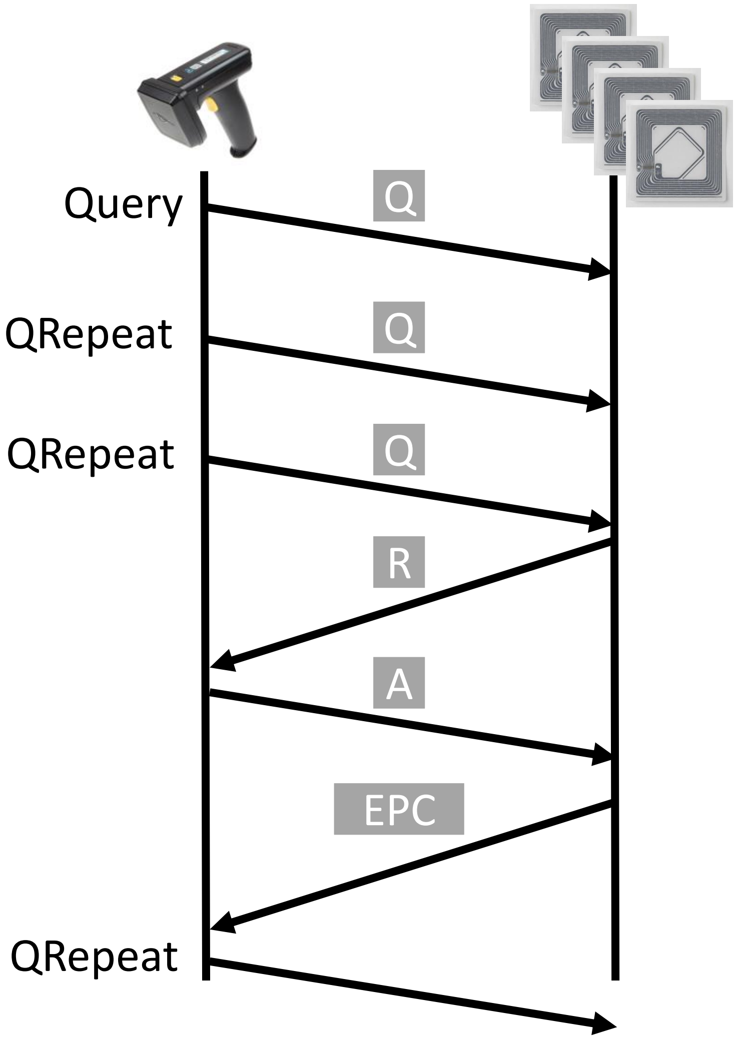
Tags have no battery.
Use reader signal to power reply

Q: Similar to a method we have seen last lecture?

RFID communication example

Generation 2 Tag identification.

1. Reader sends query and sets slot structure.
2. Tags reply (RN16) in a random slot; may collide.
3. Reader asks one tag for its identifier. (ACK)
4. Process continues until no tags are left.



RFID request frame

RFID uses multiple types of frames.
Example of a request-frame:

Bits:

4	1	2	1	2	2	1	4	5
Command 1000	DR	M	TR	Sel	Session	Target	Q	CRC

RFID request frame

RFID uses multiple types of frames.
Example of a request-frame:

Bits:

4	1	2	1	2	2	1	4	5
Command 1000	DR	M	TR	Sel	Session	Target	Q	CRC

Used to configure physical layer properties (e.g., data rate).

RFID request frame

RFID uses multiple types of frames.
Example of a request-frame:

Bits:

4	1	2	1	2	2	1	4	5
Command 1000	DR	M	TR	Sel	Session	Target	Q	CRC

Used to keep track of which tag is identified by which reader.
Allows tags to reply to multiple readers is the same area.

RFID request frame

RFID uses multiple types of frames.
Example of a request-frame:

Bits:

4	1	2	1	2	2	1	4	5
Command 1000	DR	M	TR	Sel	Session	Target	Q	CRC

Limits random backoff values available to the tags.

Tag responds in a slot between 0 and $2^Q - 1$