

Computer Networks X_400487

Lecture 4

Chapter 4: Medium Access Control



Lecturer: Jesse Donkervliet
Includes slides from Vlad Cursaru

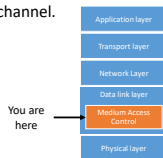


Vrije Universiteit Amsterdam



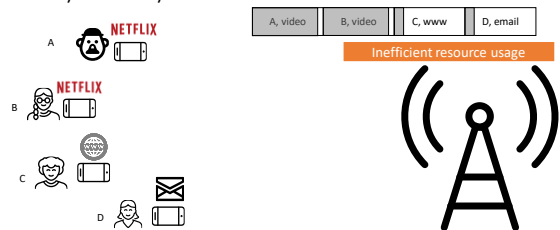
The MAC sublayer Medium Access Control

Lower part of the Data link layer.
Responsible for deciding who can use the communication channel.



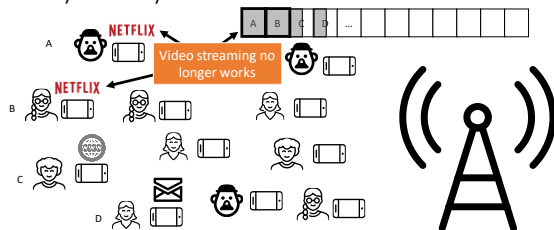
10

Physical-Layer solution is insufficient!



11

Physical-Layer solution is insufficient!



12

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

13

Two Approaches: Contend or Coordinate

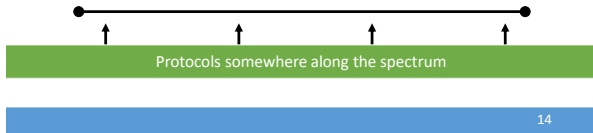
Contend

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

Coordinate

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

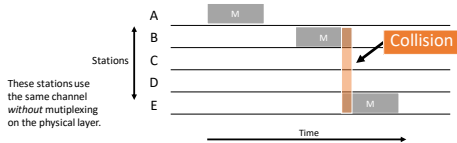
Q: When to apply which strategy?



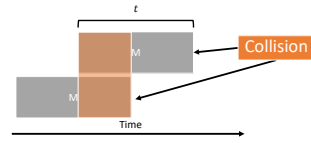
ALOHA

Q: When does ALOHA perform well/badly?

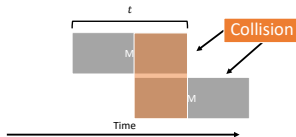
In pure ALOHA, users transmit frames *whenever they have data*; if a collision occurs, *users retry after a random delay*.



Collisions in ALOHA

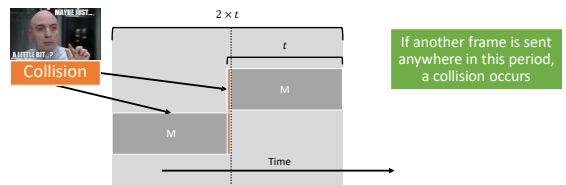


Collisions in ALOHA



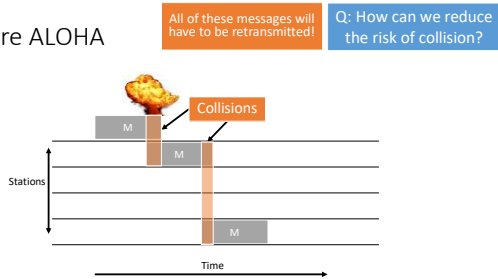
Collisions in ALOHA

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



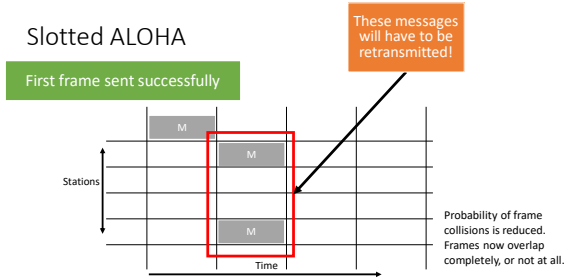
If another frame is sent anywhere in this period, a collision occurs

Pure ALOHA



20

Slotted ALOHA



21

Carrier Sense Multiple Access



22

Carrier-Sense Multiple Access

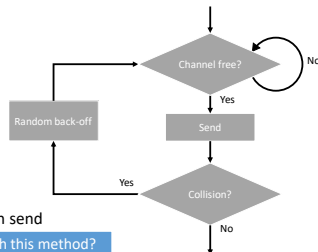
Senders detect ("sense") if the channel is in use

Protocols that apply CSMA:

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

23

1-persistent CSMA

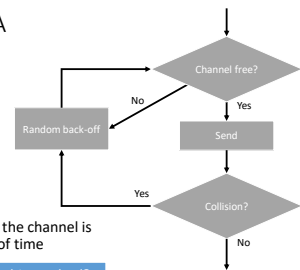


Wait until the channel is idle, then send

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

24

Nonpersistent CSMA



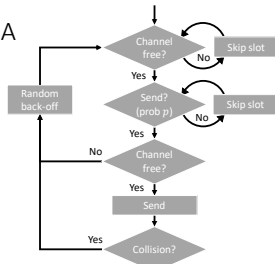
Nonpersistent CSMA is less greedy. If the channel is occupied, it waits a random amount of time

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

25

p-persistent CSMA

Applies to slotted channels.



Keeps waiting. Sends frame with probability p

Behavior of α -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.

MAC Sublayer Outline

ALOHA & Slotted ALOHA

CSMA

1-persistent

nonpersistent

p-persistent

CSMA/CD

802.3 Ethernet

Ethernet Switching

MAC for Wireless

Hidden Terminal

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CSMA/CA

802.11 WiFi

Collision-Free Protocols

Basic Bit-Map

Token Ring

Binary Countdown

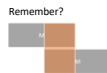
CSMA/CD

Carrier Sense Multiple Access with Collision Detection



CSMA/CD: CSMA with Collision Detection

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



Separates contention periods from transmission periods.

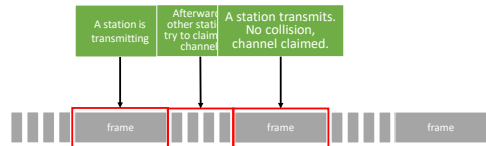
Saves time and bandwidth

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

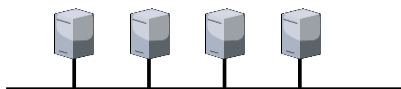
Multiple machines sharing a single Ethernet connection.



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.

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

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	$2^4 - 1 = 15$	$w \in [0,15]$
...

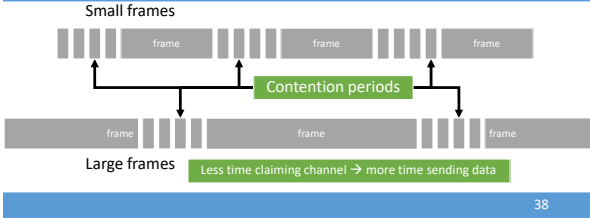
```

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

Ethernet performance

Q: What is more bandwidth efficient? Why?

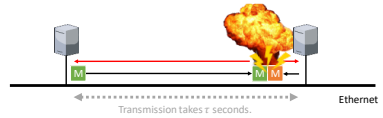
Q: Is there a trade-off here? Why?



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 = 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

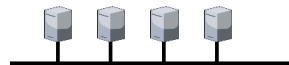
Frame format still used in modern versions of Ethernet.*

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

Q: How is frame length determined?
 Answer in physical layer:
 See 8B/10B encoding in book

Frame format still used in modern versions of Ethernet.*



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.

44

Ethernet frames

Q: How to differentiate data and padding?
 Problem for network layer: IP packet has length field

Frame format still used in modern versions of Ethernet.*



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

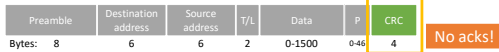
*VLAN-aware packets from 802.1Q use a slightly modified header.

45

Ethernet frames

Q: Reliable delivery?

Frame format still used in modern versions of Ethernet.*



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.

46

Data Link Layer Switching

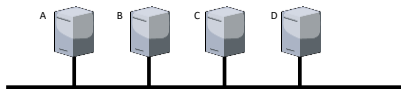


47

Classic Ethernet

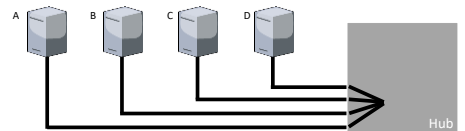
Maximum data rate: 3 to 10 Mbps

Remember?



48

Classic Ethernet with Hubs

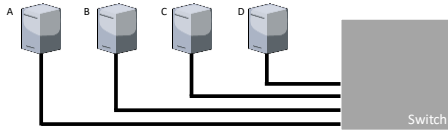


49

Ethernet with Switches

Q: Do we still need MAC?

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

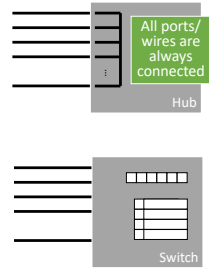


50

Ethernet evolution From hubs to switches

1. Classic Ethernet: 3 to 10 Mbps
2. Fast Ethernet: 100 Mbps
3. Gigabit Ethernet: 1000 Mbps
4. 10-Gigabit Ethernet: 10,000 Mbps
5. 40-Gigabit Ethernet: ...
6. 100-Gigabit Ethernet: ...

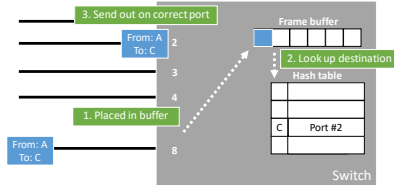
Switched versions of Ethernet



51

Ethernet switch

Q: Advantages of switches?



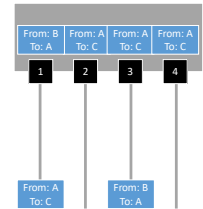
52

Learning bridges Backwards learning

Hash table:

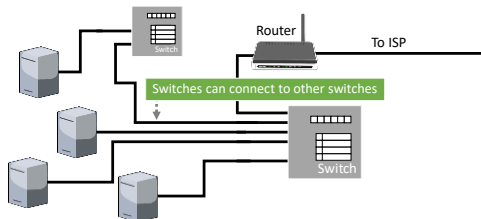
A:1

B:3



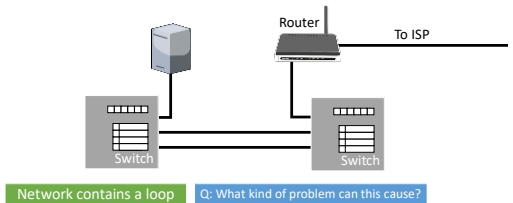
54

Ethernet Wiring pattern



55

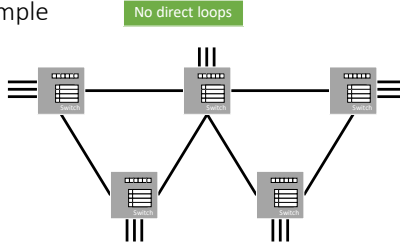
Learning bridges Topology with loops



Network contains a loop Q: What kind of problem can this cause?

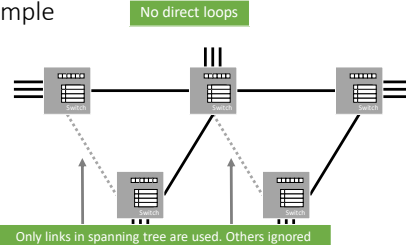
56

Spanning tree Example



57

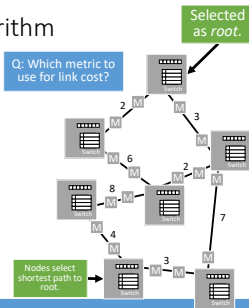
Spanning tree Example



58

Spanning tree algorithm As a poem

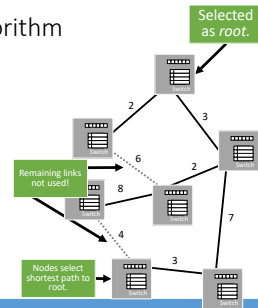
I think that I shall never see
 A graph more lovely than a tree.
 A tree whose crucial property
 Is loop-free connectivity.
 A tree which must be sure to span.
 So packets can reach every LAN.
 First the Root must be selected
 By ID it is elected.
 Least cost paths from Root are traced
 In the tree these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



59

Spanning tree algorithm As a poem

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60

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66

Medium Access Control for Wireless Channels



67

Properties of Wireless Channels Affect MAC Protocol Design

The good news: no more wires.

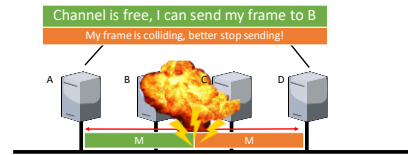
The bad news:

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

We cannot detect collisions while transmitting!

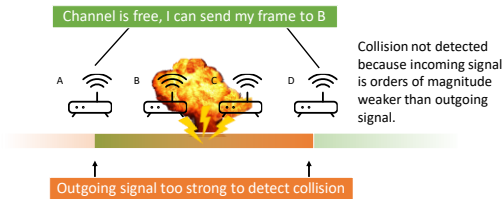


MAC for Wireless Channels: No Collision Detection



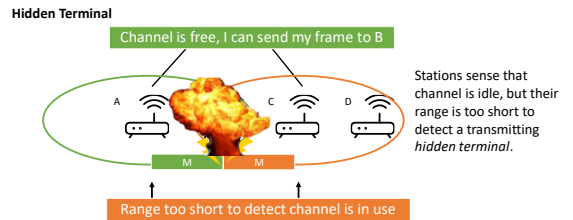
MAC for Wireless Channels: No Collision Detection

Bad news 1/2



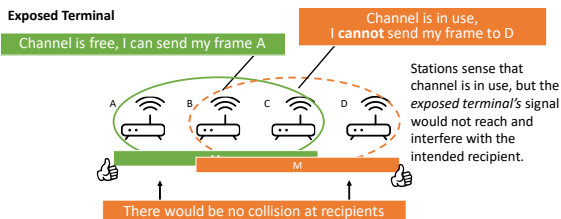
MAC for Wireless Channels: Carrier Sense has Limited Range

Bad news 2/2



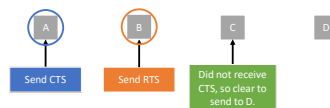
MAC for Wireless Channels: Carrier Sense has Limited Range

Bad news 2/2



Multiple Access with Collision Avoidance (MACA)

An approach to solve the hidden terminal and exposed terminal problem. Example: B wants to send to A.



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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.

CSMA/CA (Collision Avoidance)

Physical channel sensing.

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

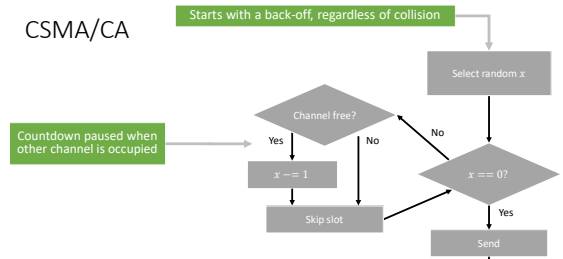
Virtual channel sensing.

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

Data + Ack

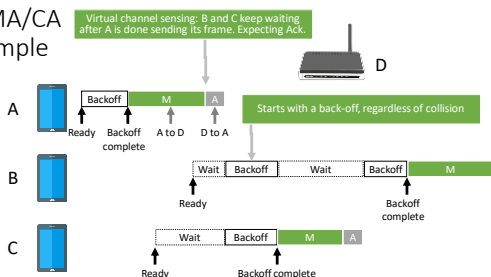
Wait for end of exchange.

CSMA/CA

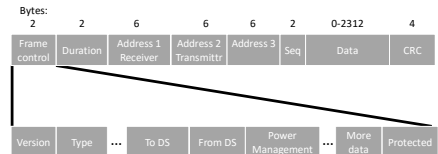


Backoff by selecting and counting down x.

CSMA/CA Example



802.11 frames



802.11 frames



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

80

802.11 frames

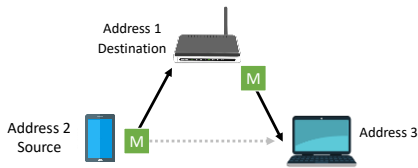


Q: Why a third address?

Third address is destination (Address 2 is access point)

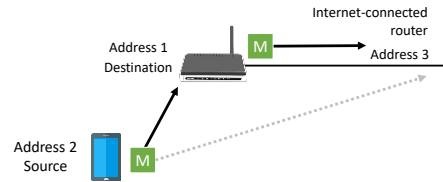
81

Access point forwards frame to recipient



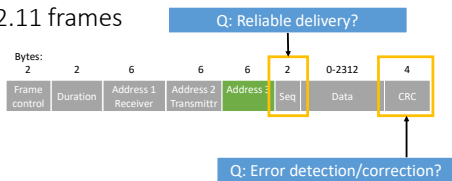
82

Access point forwards frame to recipient



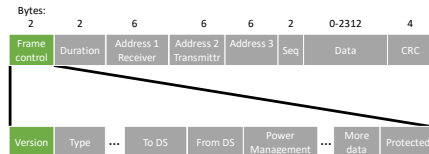
83

802.11 frames



84

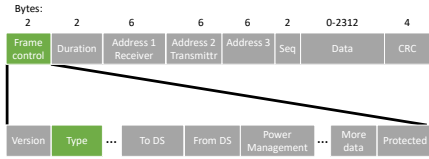
802.11 frames



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

85

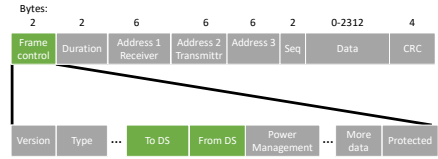
802.11 frames



Indicates a control, management, or data frame.

86

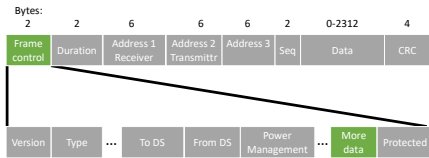
802.11 frames



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

87

802.11 frames



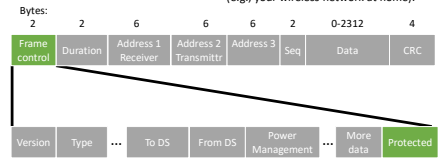
Indicates that the sender has more frames for the receiver.

88

802.11 frames

WPA2 uses encryptions based on AES (Advanced Encryption Standard)

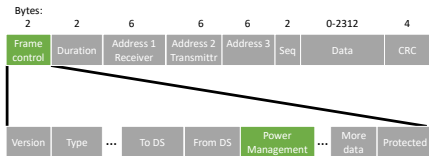
Authentication uses username+password (e.g., Eduroam), or only a password (e.g., your wireless network at home).



Indicates that the data is encrypted.

89

802.11 frames



Indicates that the sender will enter power save mode.

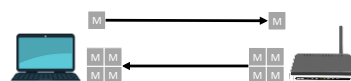
90

Power saving in 802.11

Multiple methods possible

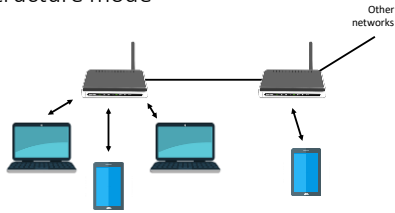
- Beacon frames
- Automatic Power Save Delivery (APSD)
- ...

APSD example:



91

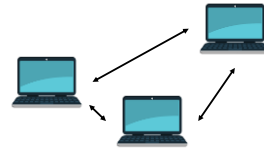
802.11 Infrastructure mode



92

802.11 Ad-hoc networks

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



93

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

94

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

95

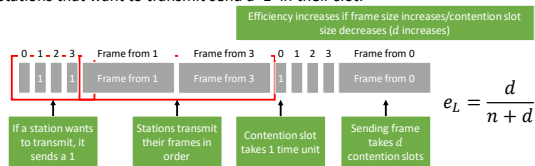
The Basic Bit-Map Protocol

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,

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



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

96

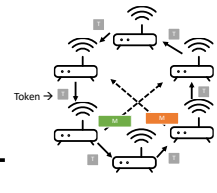
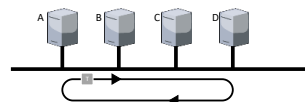
Token Ring

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



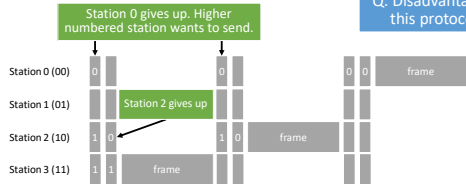
97

Binary countdown

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

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

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



Q: Disadvantage of this protocol?

MAC Layer Summary

- Multiplexing on the link layer**
 - Contention and coordination
 - Properties: bandwidth efficiency, latency, complexity.
- Protocols and mechanisms**
 - Carrier Sense
 - Collision Detection, 1-persistent, non-persistent, p-persistent
 - Collision Avoidance, MACA, CSMA/CA
 - Collision-free protocols, Basic bitmap, Token ring, Binary countdown
- Wireless Channels**
 - Limited Radio Range
 - Hidden terminals and Exposed terminals
- Routing on the link layer**
 - No MAC protocol needed when used on full-duplex wired channels

Q: Why not used on wireless channels?

Q: How to know where to send frames?

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

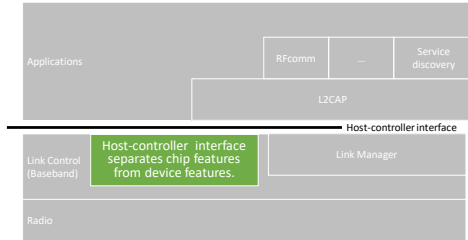


Bluetooth Protocol Stack

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

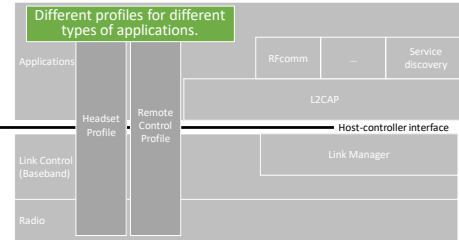
25 profiles, including headset, intercom, streaming audio, remote control, personal area network, and others.

Bluetooth Protocol Stack



114

Bluetooth Protocol Stack



115

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.

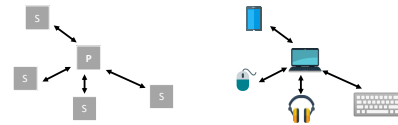
Links undergo pairing (user confirms passkey/PIN) to authorize them before use.

116

Medium Access Control in ... Bluetooth

A Bluetooth network is called a *piconet*.

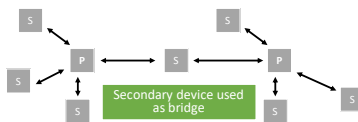
Secondaries may be asleep (*parked*) to save power.



117

Bluetooth piconet

Two piconets can be bridged into a *scatternet*.



118

Bluetooth frames

Uses multiple types of frames, similar to 802.16.



119

Bluetooth frames

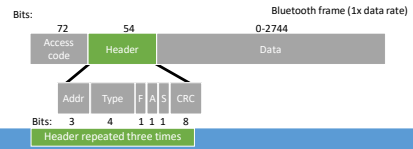
Uses multiple types of frames, similar to 802.16.



120

Bluetooth frames

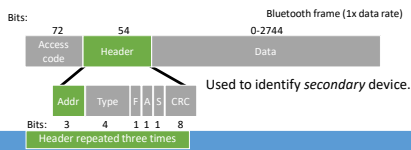
Uses multiple types of frames, similar to 802.16.



121

Bluetooth frames

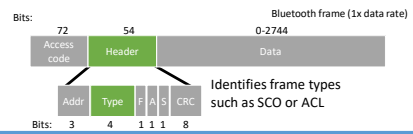
Uses multiple types of frames, similar to 802.16.



122

Bluetooth frames

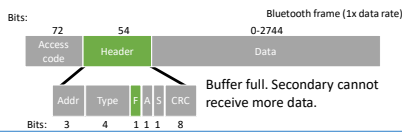
Uses multiple types of frames, similar to 802.16.



123

Bluetooth frames

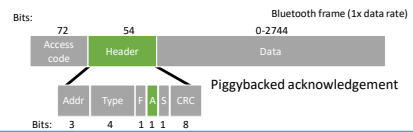
Uses multiple types of frames, similar to 802.16.



124

Bluetooth frames

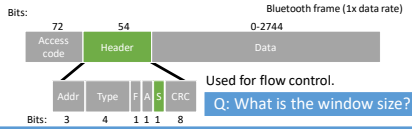
Uses multiple types of frames, similar to 802.16.



125

Bluetooth frames

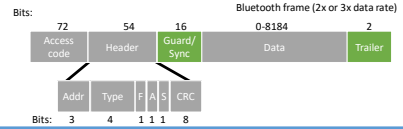
Uses multiple types of frames, similar to 802.16.



126

Bluetooth frames

Enhanced data rates send faster but for the same time.



127

Medium Access Control RFID



128

RFID Readers



129

Medium Access Control in ... RFID

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



130

Medium Access Control in ... RFID

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



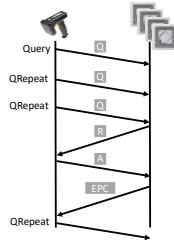
131

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

RFID communication example

Generation 2 Tag identification.

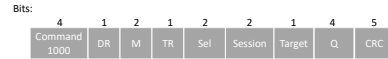
1. Reader sends query and sets slot structure.
2. Tags reply (RN16) in a random slot; may collide.
3. Reader asks one tag for its identifier. (ACK)
4. Process continues until no tags are left.



132

RFID request frame

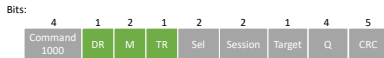
RFID uses multiple types of frames.
Example of a request-frame:



133

RFID request frame

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

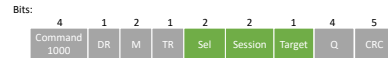


Used to configure physical layer properties (e.g., data rate).

134

RFID request frame

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

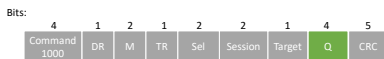


Used to keep track of which tag is identified by which reader.
Allows tags to reply to multiple readers in the same area.

135

RFID request frame

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



Limits random backoff values available to the tags.

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

136