Redes de Computadores

Medium Access Control

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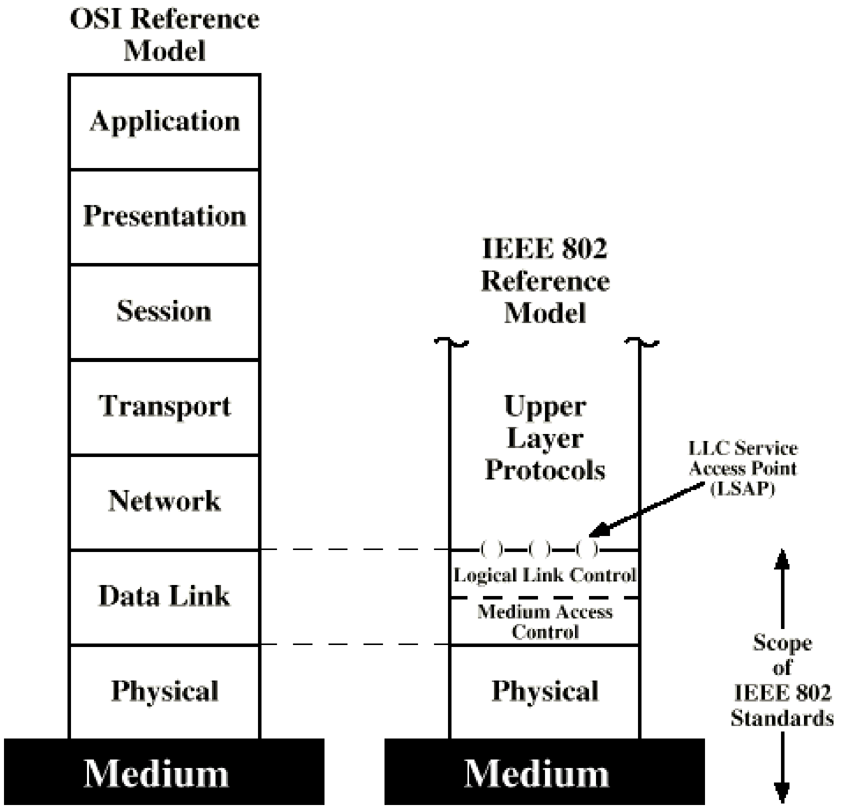
- *How to control the access of computers to a communication medium?*
- *What is the ideal Medium Access Control?*
- *What are the main characteristics of existing MAC protocols ?*
  - *Aloha, Slotted Aloha, CSMA, CSMA/CD, CSMA/CA*

- *What is a MAC address?*
- *What are the Ethernet generations?*
- *What is a Hub? What is Switch?*
- *How does a Switch learn the MAC addresses of the attached stations?*
- *What is a Virtual LAN (VLAN)?*

IEEE 802 Reference Model

- Data Link layer may consist of two sub-layers
  - » LLC (Logical Link Control)
  - » MAC (Medium Access Control)
- LLC
  - » Interface for the network layer
  - » Error and flow control
- MAC
  - » Access control to the shared medium
  - » Frame transmission/reception
  - » Addressing
  - » Error detection

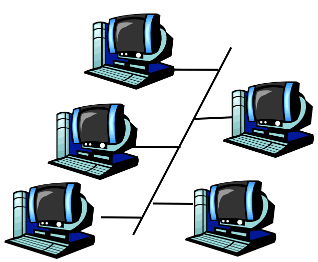


Multiple Access Links

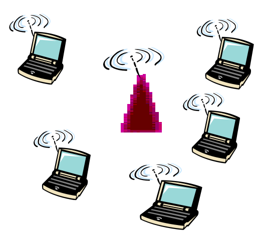
Two types of ***links***

- Point-to-point
  - » PPP for dial-up access
  - » point-to-point link between Ethernet switch and host

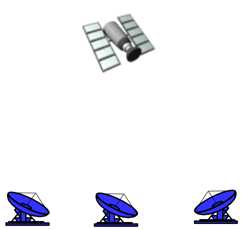
- Broadcast (shared medium, wired or wireless)
  - » old-fashioned cabled Ethernet
  - » 802.11 wireless LAN



shared wire
(e.g., cabled Ethernet)



shared RF
(e.g., 802.11 WiFi)

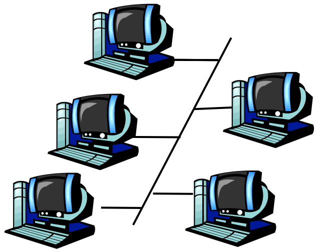


shared RF
(satellite)

Analogy: humans at a cocktail party
(shared air, acoustical)

Multiple Access

- *How to coordinate the stations to use a common broadcast and shared channel ?*



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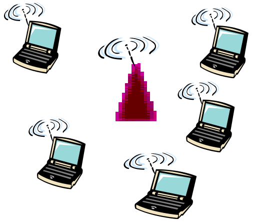


shared RF
(e.g., 802.11 WiFi)

Ideal Multiple Access Protocol

- Problem

  How to coordinate the stations

  to use a common broadcast and shared channel

  of rate **R** bit/s?

- Requirements of the ideal Multiple Access Protocol
  - » one station wants to transmit ➔ it uses the **R** bit/s
  - » **m** stations want to transmit ➔ each station uses an average rate **R/m** bit/s
  - » decentralized: no coordination, no synchronization of clocks
  - » simple

MAC Protocols – Three Classes

Three classes of MAC protocols

- Channel Partitioning
  - *Time Division Multiple Access | Frequency Division Multiple Access*
    - Similar to TDM / FDM but with multiple nodes transmitting instead of a single node transmitting multiple flows
- Random Access
  - channel not partitioned, collisions allowed
- Taking turns
  - stations take turns
  - stations with more data to send can take longer turns

Random Access Protocols

- When station has packet to send
  - » transmits at channel data rate **R** bit/s
  - » no *a priori* coordination among stations
- If two or more stations transmit simultaneously ➜ collision
- Random Access MAC protocol defines
  - » when to send data
  - » how to detect collisions
  - » how to recover from collisions
- Examples of Random Access MAC protocols
  - » ALOHA, CSMA, CSMA/CD, CSMA/CA

MAC Model and Concepts

- Station
  - » Transmits one frame at time
  - » Probability one frame being generated in δ: $p_1(\delta) \approx \lambda\delta$
  - » Poisson arrival

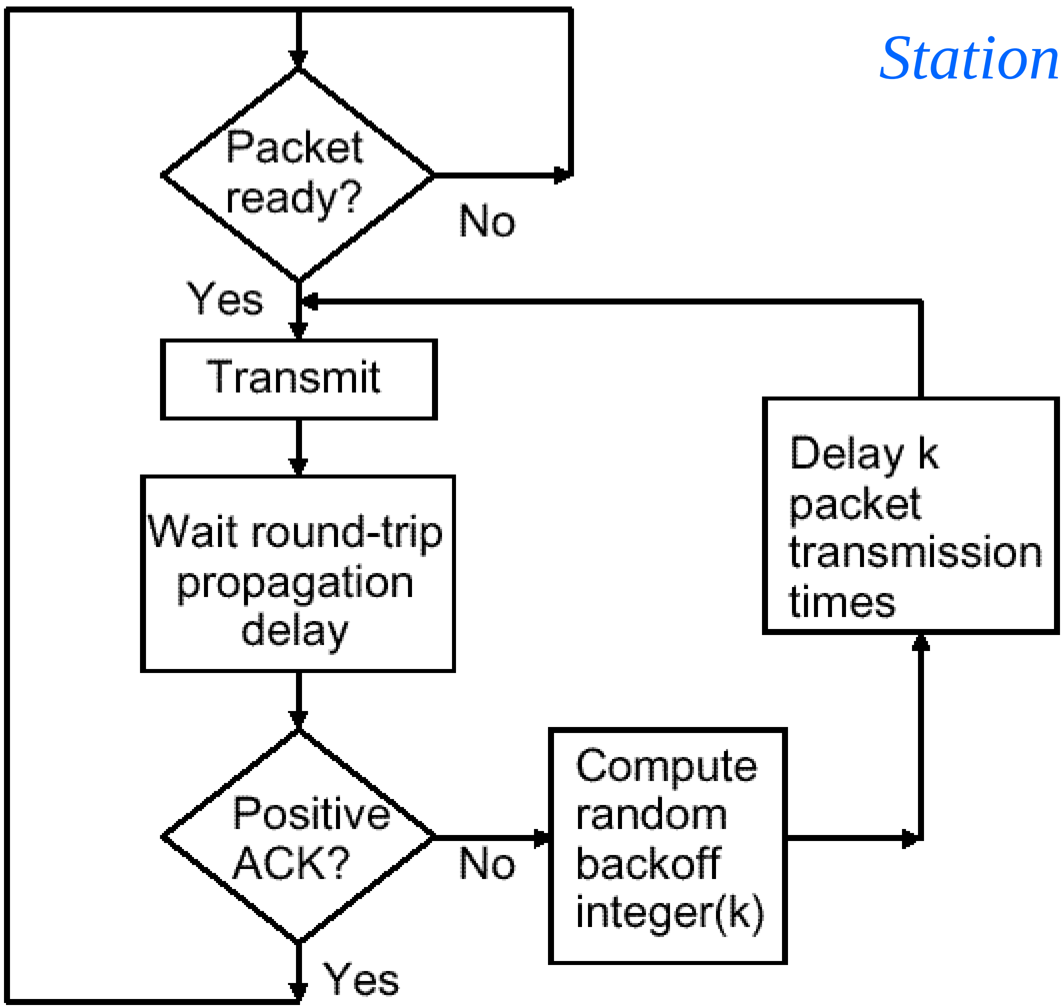
- Collision
  - » If two stations transmit at same time ➔ collision
  - » Frames are retransmitted

- Continuous Time / Slotted Time
  - » Continuous: frame can be transmitted at any time
  - » Slotted: frame can be transmitted only at the beginning of a time slot

- Carrier Sense / No Carrier Sense
  - » Sensing: station can know if medium (channel) is busy before using it
  - » No sensing: station cannot sense channel before using it

ALOHA

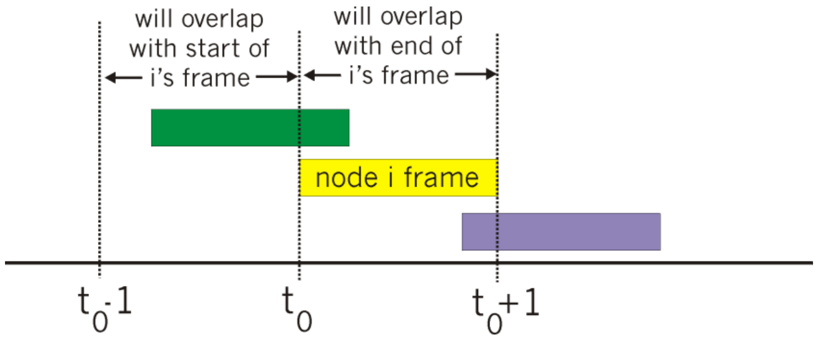
Station behaviour

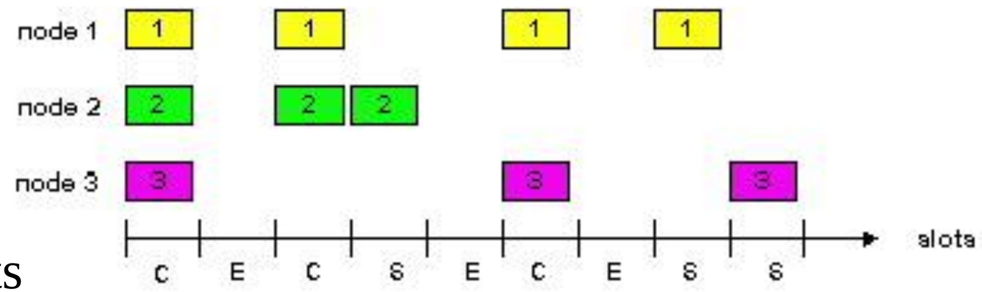


ALOHA – Two versions

- Pure Aloha (unslotted)
  - » No slot concept
  - » Station transmits

    when it has a frame to transmit





- Slotted Aloha
  - » Time divided into time slots
  - » $T_{slot} = T_{frame}$
  - » (Re)transmissions only the beginning of a slot

Slotted Aloha - Efficiency

- Traffic model
  - » Poisson arrival, large number N of stations
  - » Constant frame length, $T_{\text{frame}} = 1$
  - » S – Received traffic

    λ_{rx} – rate of received frames (transmitted with success)

    $S = \lambda_{\text{rx}} * T_{\text{frame}} < 1$; ***S* = efficiency**
  - » G – Generated traffic (new packets and retransmissions)

    λ – rate of generated packets

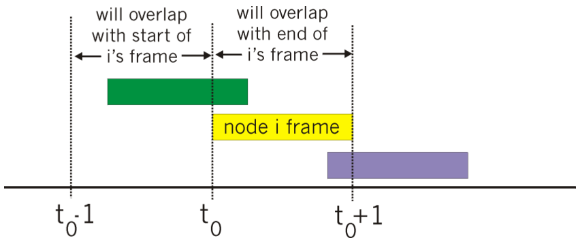
    $G = \lambda * T_{\text{frame}}$
  - » p – probability of **one station** generating a packet (new or retransmission) in T_{frame}

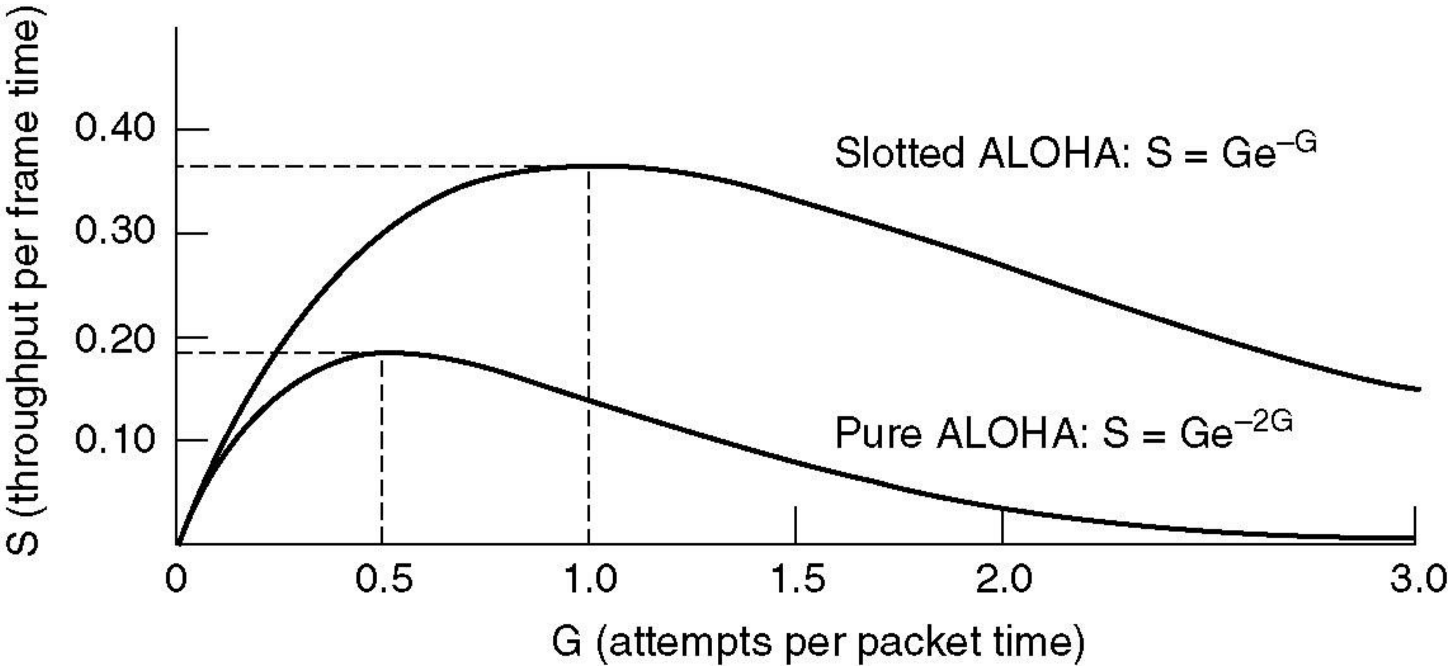
    $N * p = G$

- Slotted Aloha
  - » The probability that a specific station will transmit successfully is $p(1-p)^{N-1}$
  - » $S = P(Success) = N(p(1-p)^{N-1}) \approx Npe^{-p(N-1)} \approx Npe^{-pN} = Ge^{-G} = Gp_0(T_{frame})$
  - » $S_{\max} \Rightarrow \frac{\partial S}{\partial G} = 0 \Leftrightarrow e^{-G} - Ge^{-G} = 0 \Leftrightarrow (1-G)e^{-G} = 0 \Leftrightarrow G = 1$ $\boxed{S_{\max} = \frac{1}{e} \approx 36.8\%}$

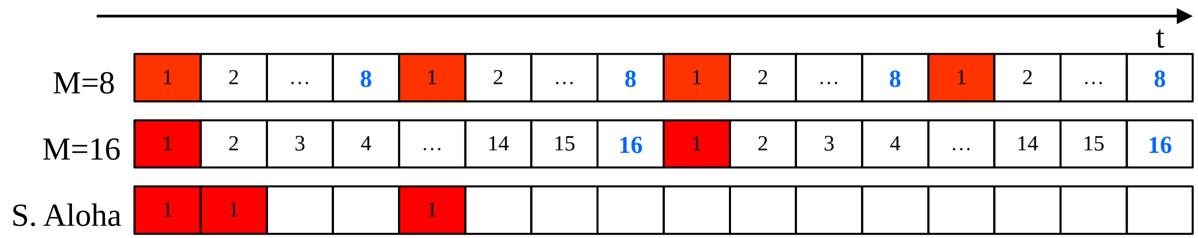
Aloha - Efficiency

- Pure Aloha
  - » $S = Gp_0(2 \times T_{frame}) = Ge^{-2G}$
  - » $S_{\max} \Rightarrow \quad \frac{\partial S}{\partial G} = 0; \quad G = \frac{1}{2}; \quad S_{\max} = \frac{1}{2e} = 18{,}4\%$





Waiting Time – Slotted Aloha vs. Time Division Multiple Access



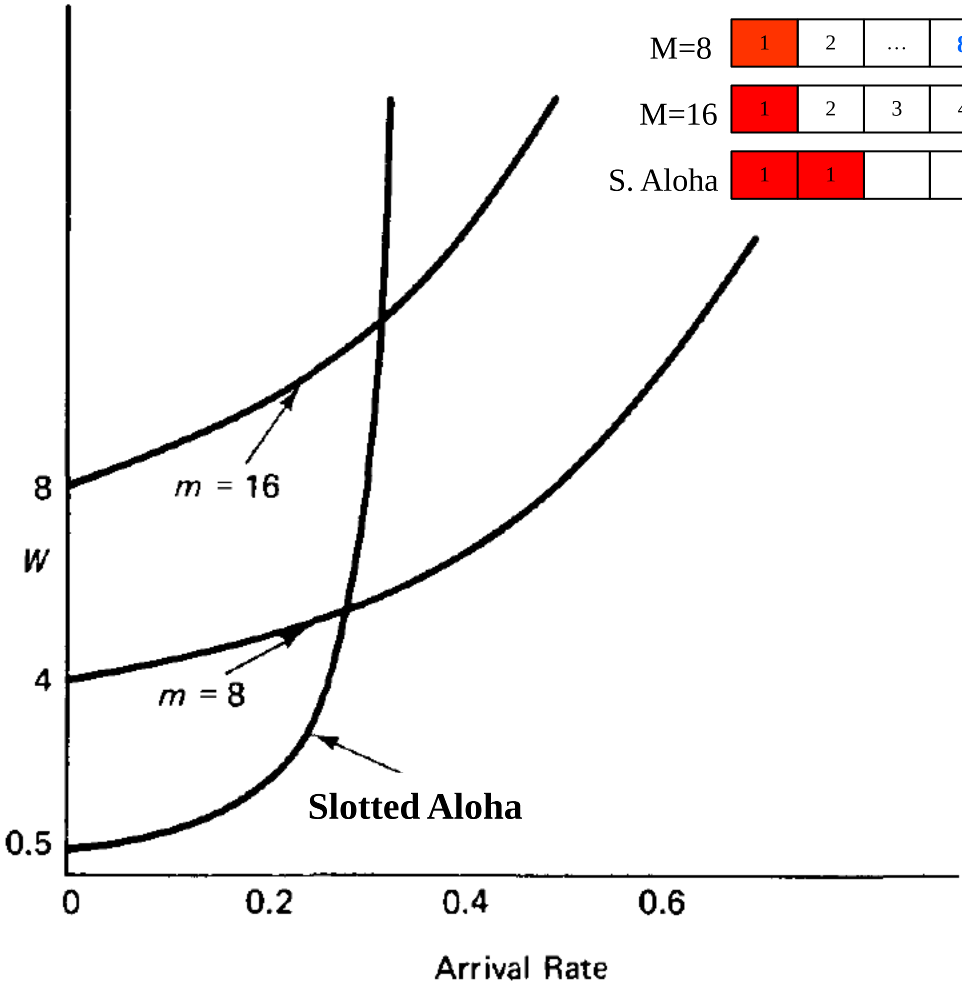


Figure 4.6 Comparison of expected waiting time W in slots, from arrival until beginning of successful transmission, for stabilized Aloha and for TDMA with $m = 8$ and $m = 16$. For small arrival rates, the delay of stabilized Aloha is little more than waiting for the next slot, whereas as the arrival rate approaches $1/e$, the delay becomes unbounded.

CSSMA (Carrier Sense Multiple Access)

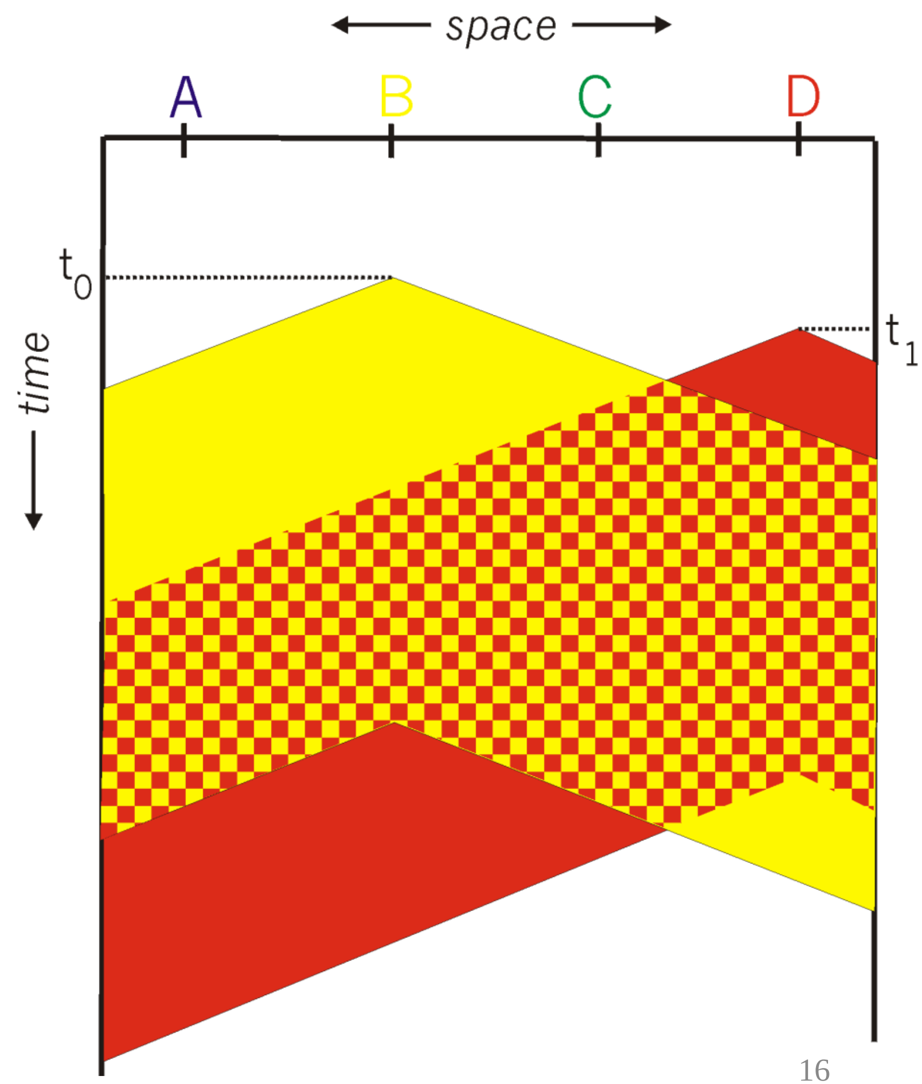
- Human analogy: do not interrupt others
- CSMA → listen before transmit
  - » If channel sensed free → transmit frame
  - » If channel sensed busy → defer transmission

CSMA collisions

- Collisions can still occur
  - » propagation delay
  - » stations may not hear other transmissions

- Collision
  - » entire packet is lost
  - » vulnerability time = T_{prop}

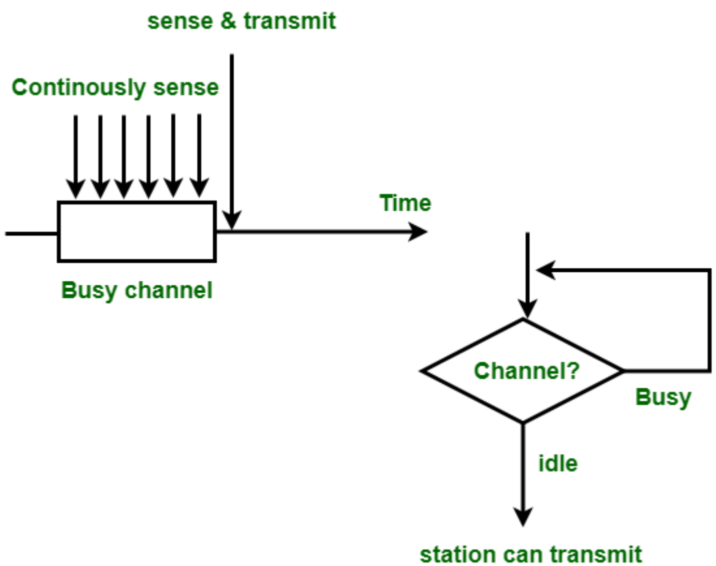
- T_{prop} and T_{frame}
  - » determine collision probability
  - » $\boldsymbol{a = T_{\text{prop}} / T_{\text{frame}} \ll 1}$



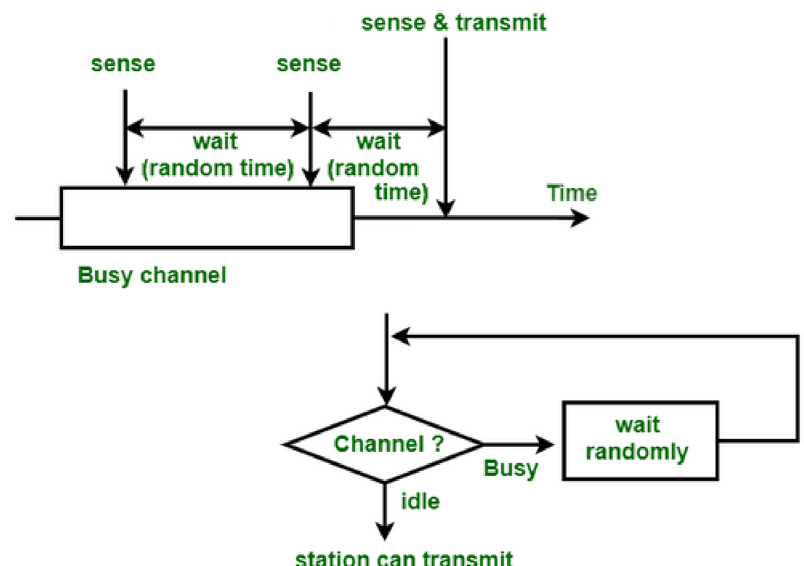
CSMA Variants

- In case of collision ➔ station waits random time and repeats algorithm **(all variants)**
- Persistency - what to do after the medium if found busy

- **Persistent CSMA**
  - » Medium free ➔ station transmits
  - » Medium busy ➔ station waits until medium becomes free, then transmits



- **Non-persistent CSMA**
  - » Medium free ➔ station transmits
  - » Medium busy ➔ station waits a random time, then repeats algorithm

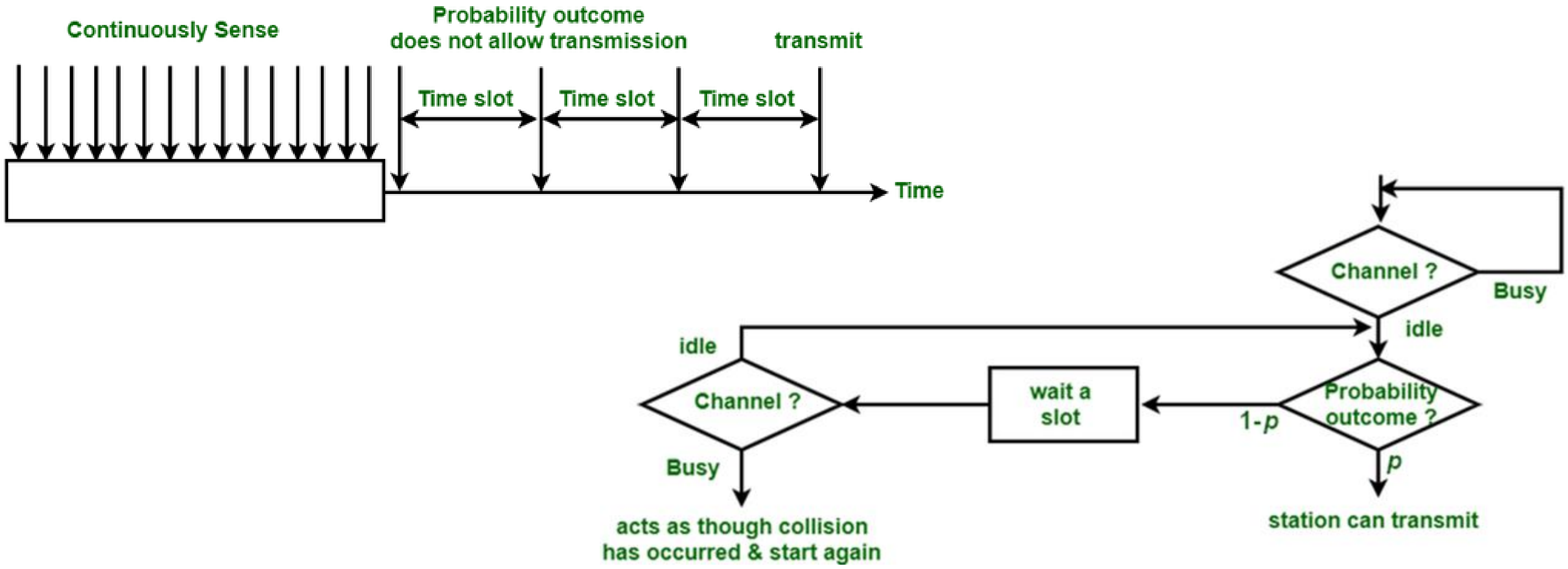


CSMA Variants

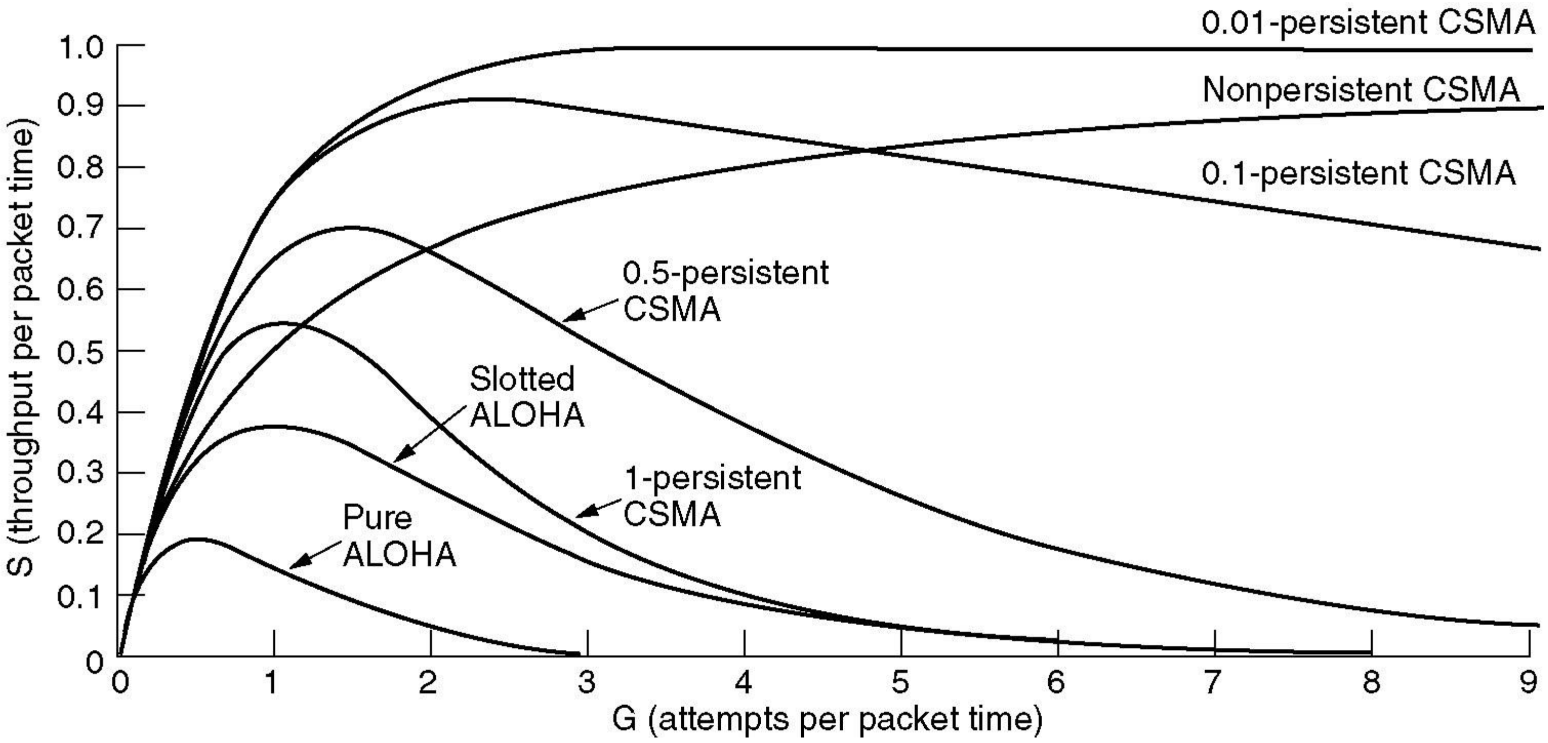
- **p-persistent CSMA**
  - » Slot time = round trip time = $2*T_{prop}$
  - » Medium free ➔ station transmits with probability ***p*** or defers no next slot (1-*p*)
  - » Medium busy ➔

    if transmission deferred from previous time slot ➔ same as collision

    else ➔ station waits until medium becomes free, then repeats algorithm



Efficiencies – x-persistent CSMA

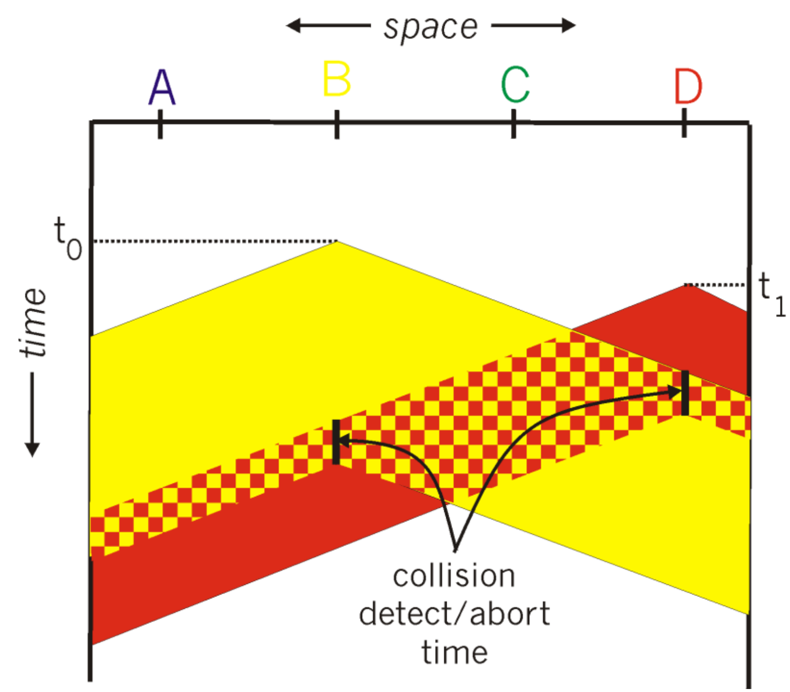


Comparison of the channel utilization versus load for various random access protocols

CSMA/CD –
Carrier Sense Multiple Access / Collision Detection

- **Carrier Sense**
  - » station senses medium before transmitting
    - – if free ➔ station starts transmission
    - – if busy ➔ waits until free and then transmits **persistent**

- **Collision Detection**
  - » station senses medium while transmitting
  - » if collision is detected
    - – transmission is aborted
    - – retransmission delayed using a Binary Exponential Backoff algorithm
  - » **no ACK!**

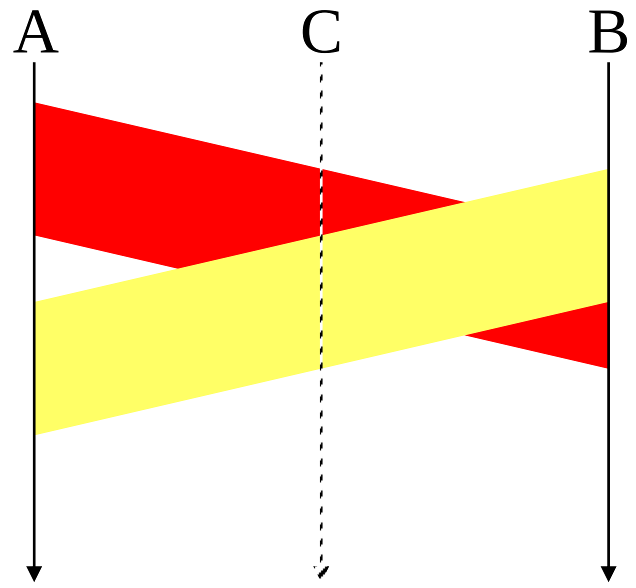


- Binary Exponential Backoff algorithm
  - » time modeled in time slots; $T_{slot} = 2T_{prop.max}$
  - » after the i^{th} consecutive collision ➔
    the station attempts to transmit ,
    after waiting,
    a random number of slots uniformly distributed in $[0, 2^i-1]$

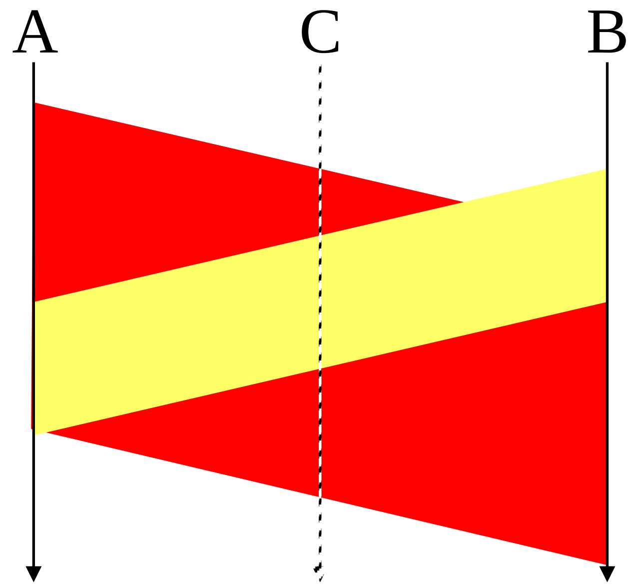
CSMA/CD – Minimum Frame Size is Required

Minimum frame size required for detecting a collision!

- Frame sent by A is too short
  - » collision is not visible at A
  - » but it exists and is visible at C



- Frame sent by A is large enough
  - » collision is visible at all stations
  - » $T_f > 2T_{prop.max}$ ($a < 0.5$)
    $L > 2CT_{prop.max}$

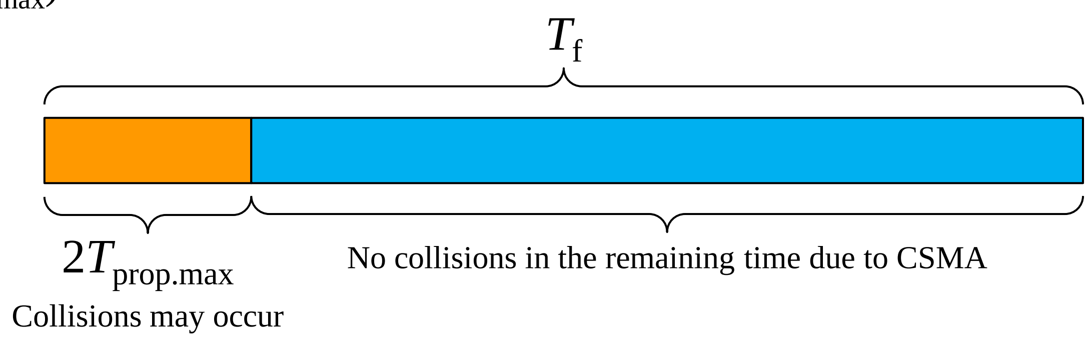


CSMA/CD - Efficiency

- Approximate analysis shows that, for a large number of stations

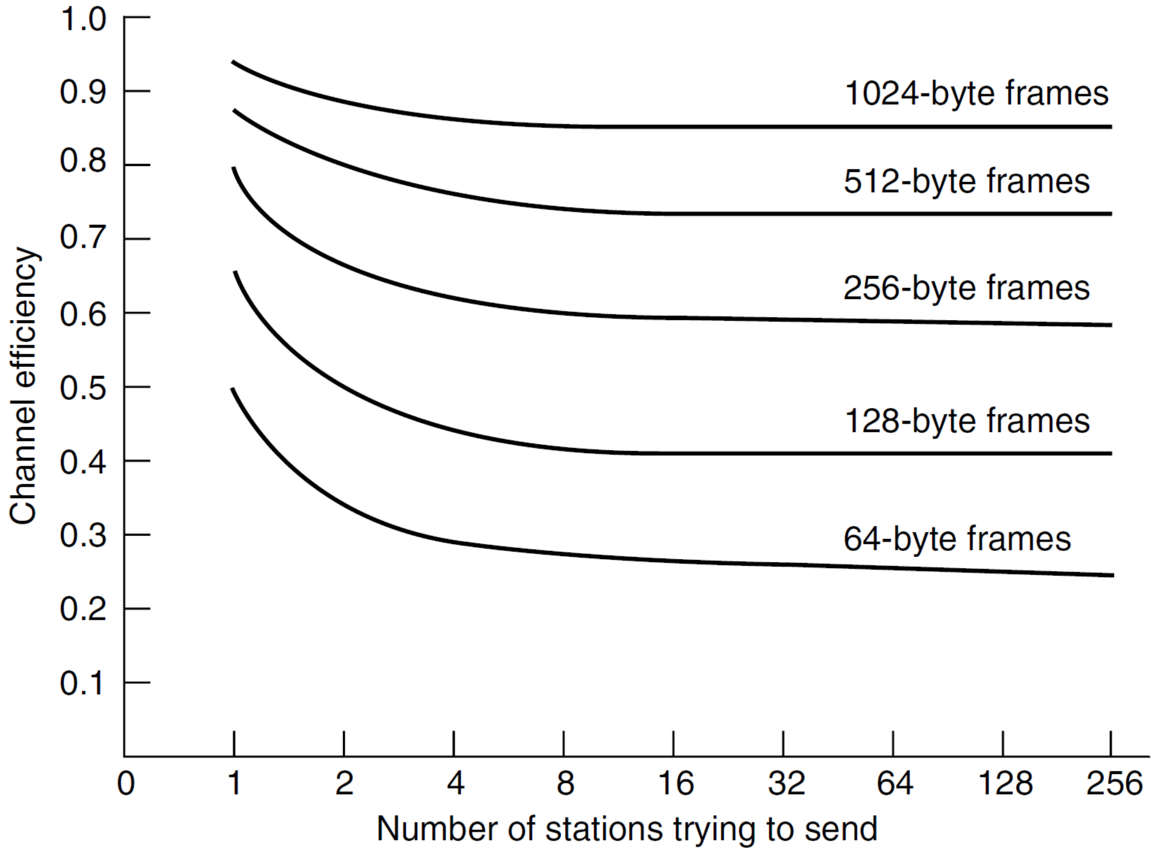
$$S = \frac{1}{1+2ea} \approx \frac{1}{1+5.44a} \qquad \text{with} \quad a = \frac{T_{\mathrm{prop.max}}}{T_{\mathrm{f}}}$$

- S grows towards 1 for
  - » Short cable length (small $T_{\mathrm{prop.max}}$)
  - » Long frames (large T_{f})



- The longer the collision-free portion, the higher the efficiency
- In practice, frames cannot be too large
  - » Large frames have increased FER and lead to longer latencies

CSMA/CD - Efficiency



Efficiency of 10Mb/s Ethernet (CSMA/CD) with $2T_{prop.max} = 51.2\ \mu s$ for different sized frames

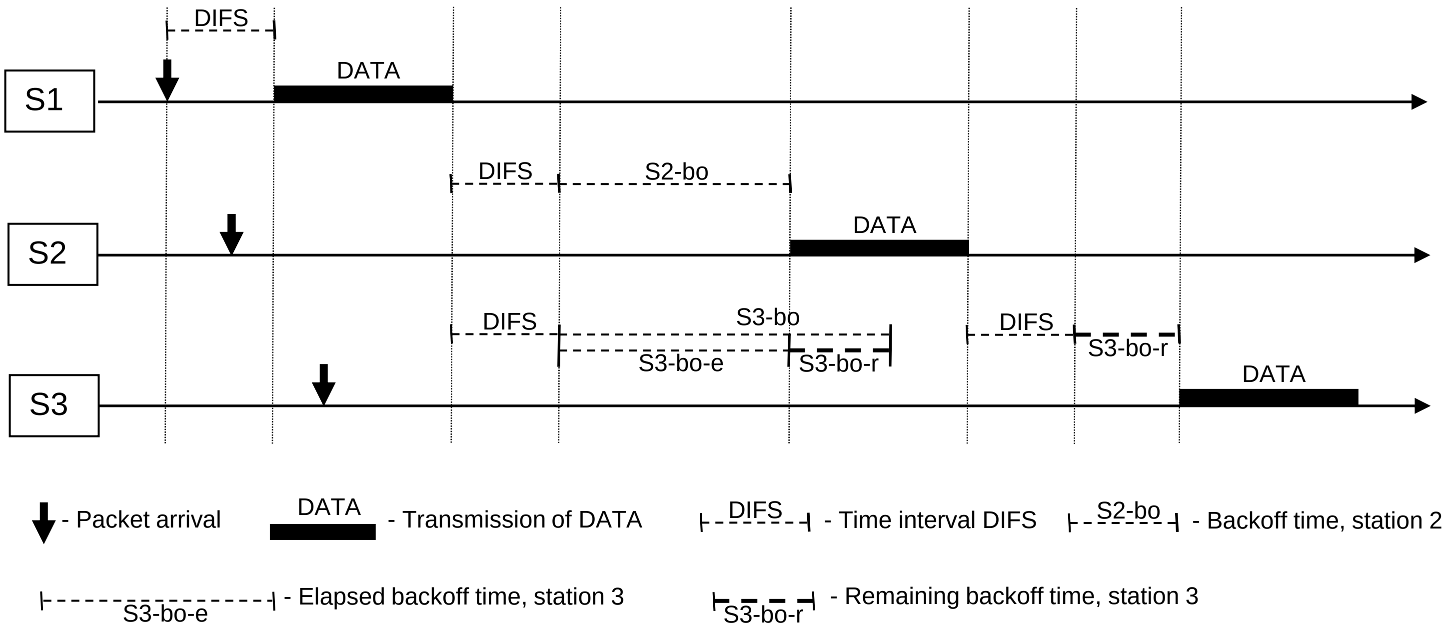
To Think…

- *Why does not CSMA/CD need an ACK frame?*

- *Can we use CSMA/CD in a wireless medium?*

CSMA with Collision Avoidance (CSMA/CA)

- Used when collision detection is infeasible, e.g., wireless



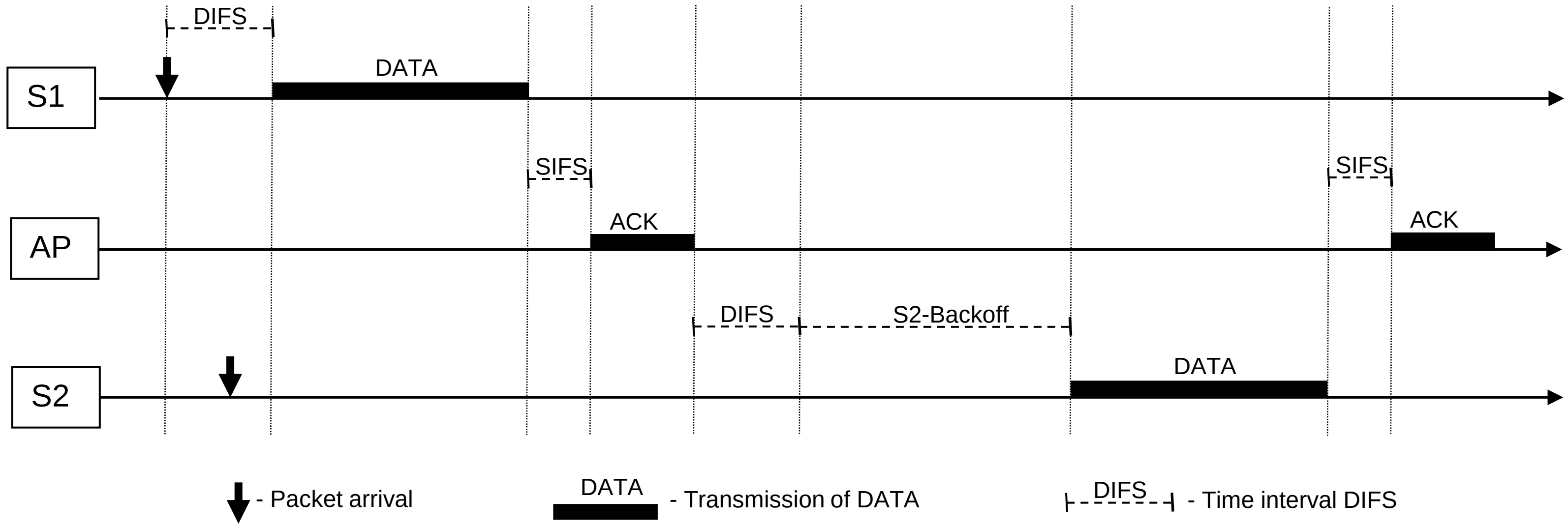
CSMA with Collision Avoidance (CSMA/CA)

- Station with a frame to transmit
  - monitors the channel activity
  - until an idle period equal to a Distributed Inter-Frame Space (DIFS) has been observed
  - if medium free ➔ transmits frame

- If the medium is sensed busy
  - random backoff interval is selected
  - backoff time counter is decremented as long as the channel is sensed idle
  - stopped when a transmission is detected on the channel
  - reactivated when the channel is sensed idle again for more than a DIFS
  - the station transmits when the backoff time reaches 0

- To avoid channel capture
  - station waits random backoff time between two consecutive frame transmissions
  - even if the medium is sensed idle in the DIFS time

CSMA/CA – ACK Required



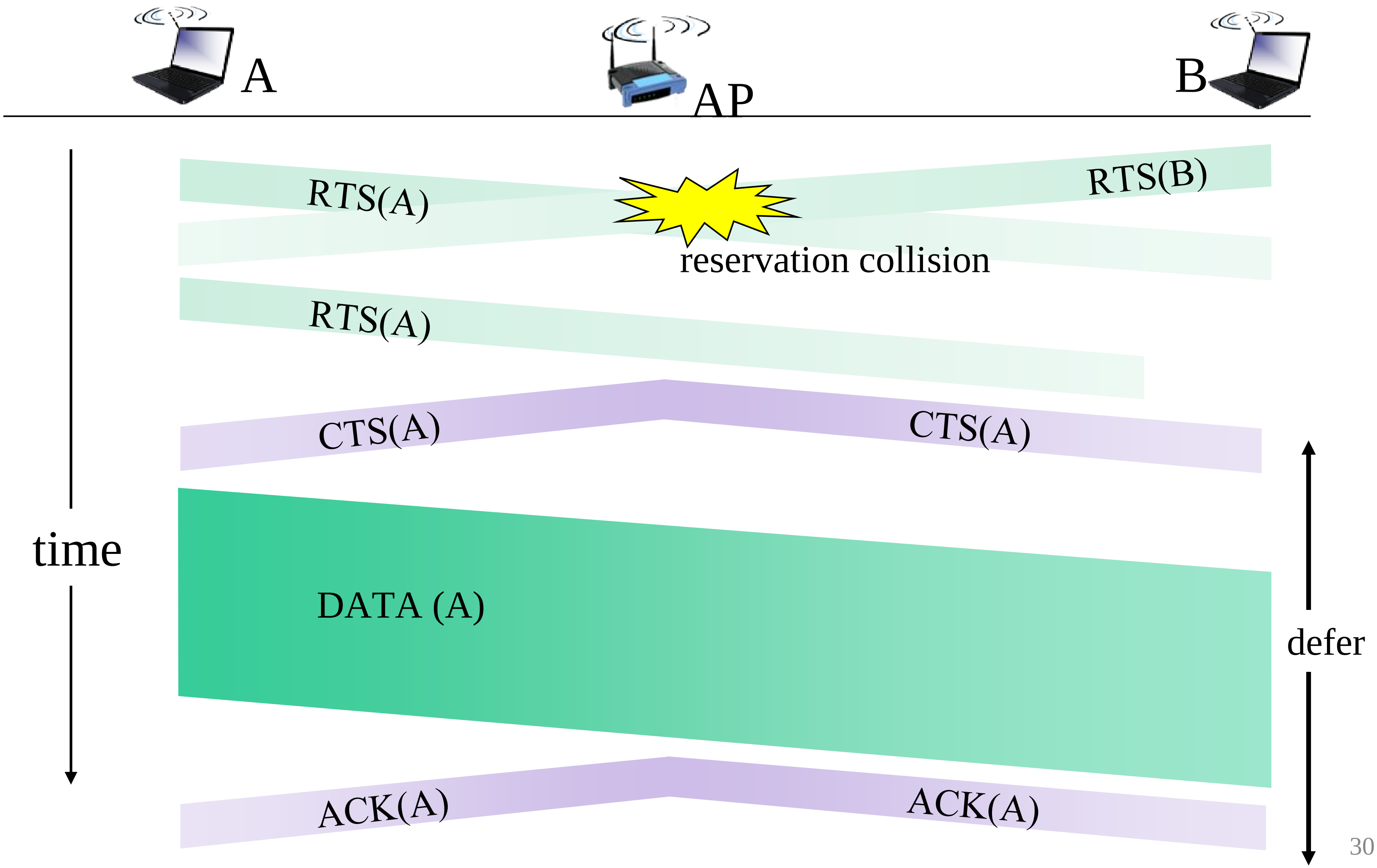
CSMA/CA – ACK Required

- CSMA/CA does not rely on the capability of the stations to detect a collision by sensing the medium while transmitting
- A positive acknowledgement is transmitted by the destination station to signal the successful frame reception
- In order to allow an immediate response, the acknowledgement is transmitted following the received frame, after a Short Inter-Frame Space (SIFS)
- If the transmitting station does not receive the acknowledge within a specified ACK timeout, or it detects the transmission of a different frame on the channel, it reschedules the frame transmission according to the previous backoff rules
- Efficiency of CSMA/CA depends strongly of the number of competing stations. An efficiency of 60% is commonly found

CSMA/CA – Further Improvement: RTS-CTS

- Since collisions cannot be detected (and colliding frames aborted), a collision may waste a lot of time in the medium
- Improvement: avoid collisions in long data frames using short reservation frames
- Transmitter sends Request-to-Send (RTS) to AP
  - RTS may collide, but is short
- In response, AP broadcasts Clear-to-Send (CTS)
- CTS is heard by all stations
  - The data frame can be transmitted without collisions
  - Other stations defer transmissions, even those who cannot “hear” it

CSMA/CA – RTS-CTS



Taking Turns *MAC protocols*

- Channel partitioning MAC protocols (TDMA, FDMA)
  - » share channel efficiently and fairly at high loads
  - » are inefficient at low loads

    delay in channel access; 1/*N* bandwidth allocated even if only 1 active node!

- Random access MAC protocols (Aloha, CSMA, CSMA/CD, CSMA/CA)
  - » efficient at low load ➔ single node can fully utilize the channel
  - » high load ➔ collisions ➔ inefficiency

- **Taking turns** protocols
  - » look for best of both worlds!

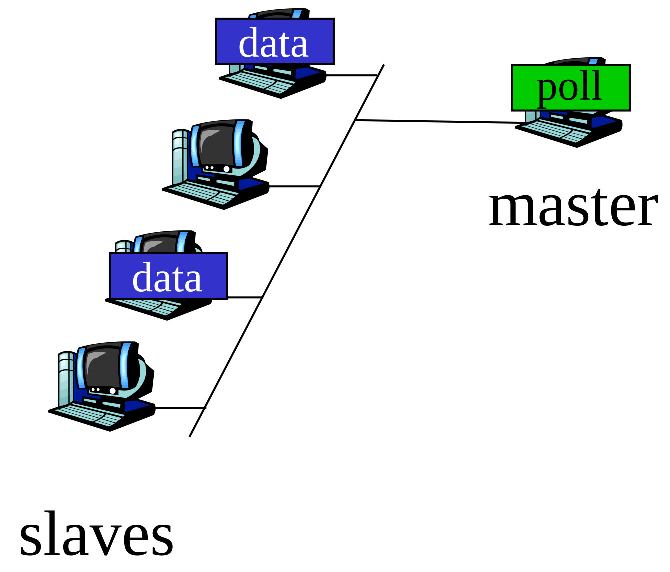
“Taking Turns” MAC protocols

Polling

» master station ***invites*** slave stations to transmit in turn

» concerns

- polling overhead
- latency
- single point of failure (master)

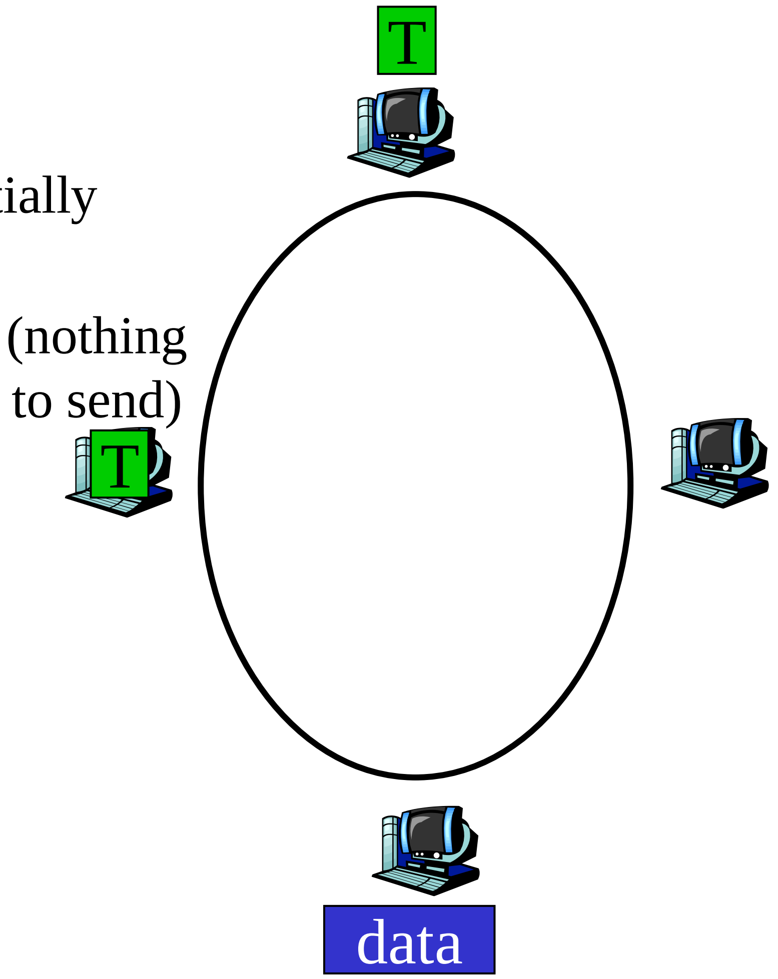


"Taking Turns" MAC protocols

Token passing

- » control token

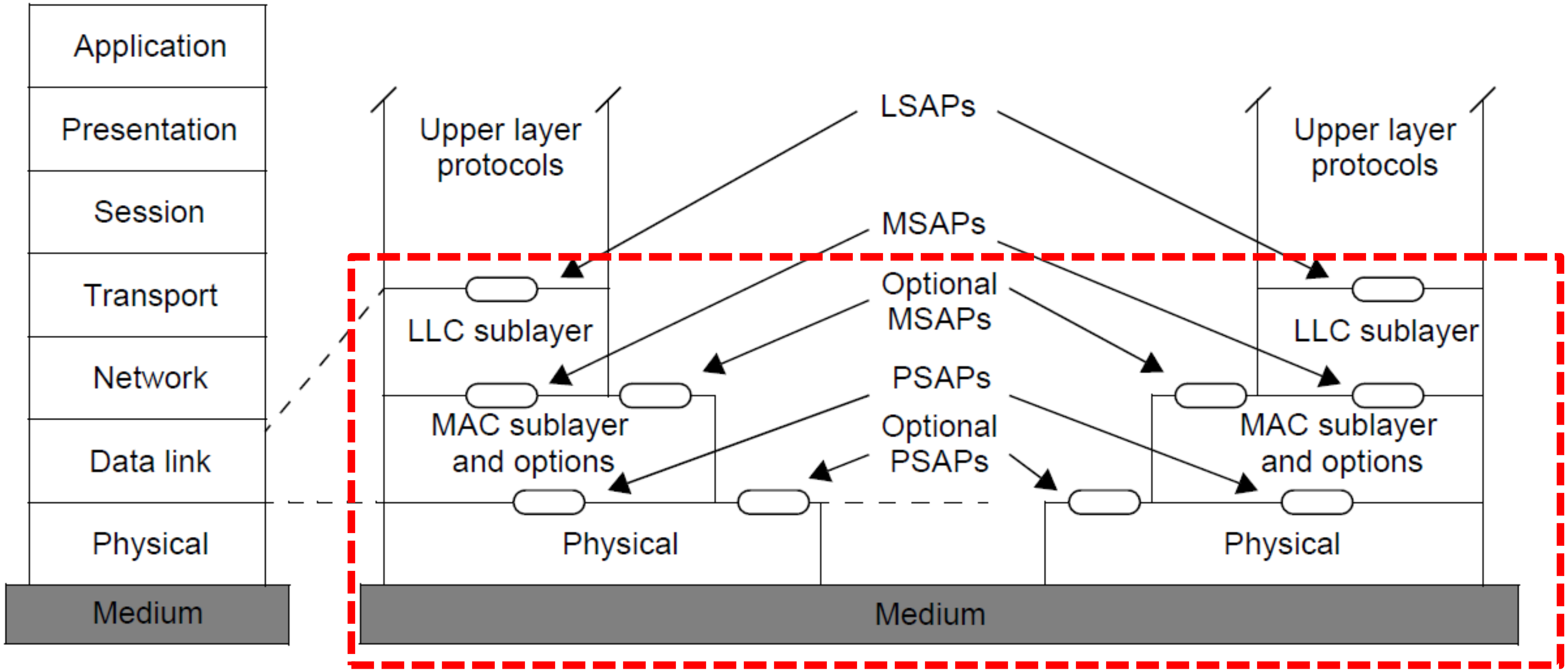
  passed from one station to next sequentially
- » token message
- » concerns
  - token overhead
  - latency
  - single point of failure (token)



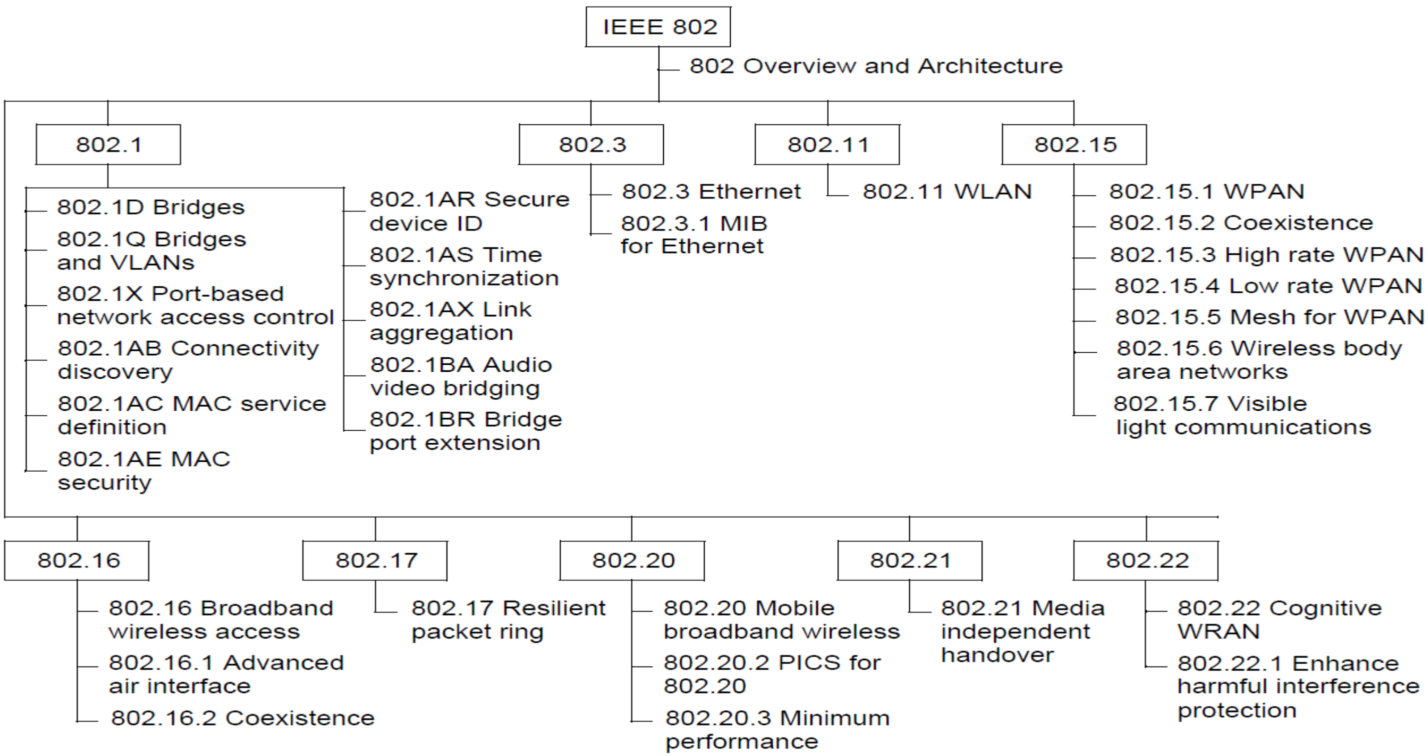
IEEE Standards – Reference Model

MSAP MAC service access point
LSAP link service access point

PSAP PHY service access point



IEEE Standards – Family of IEEE 802 Standards



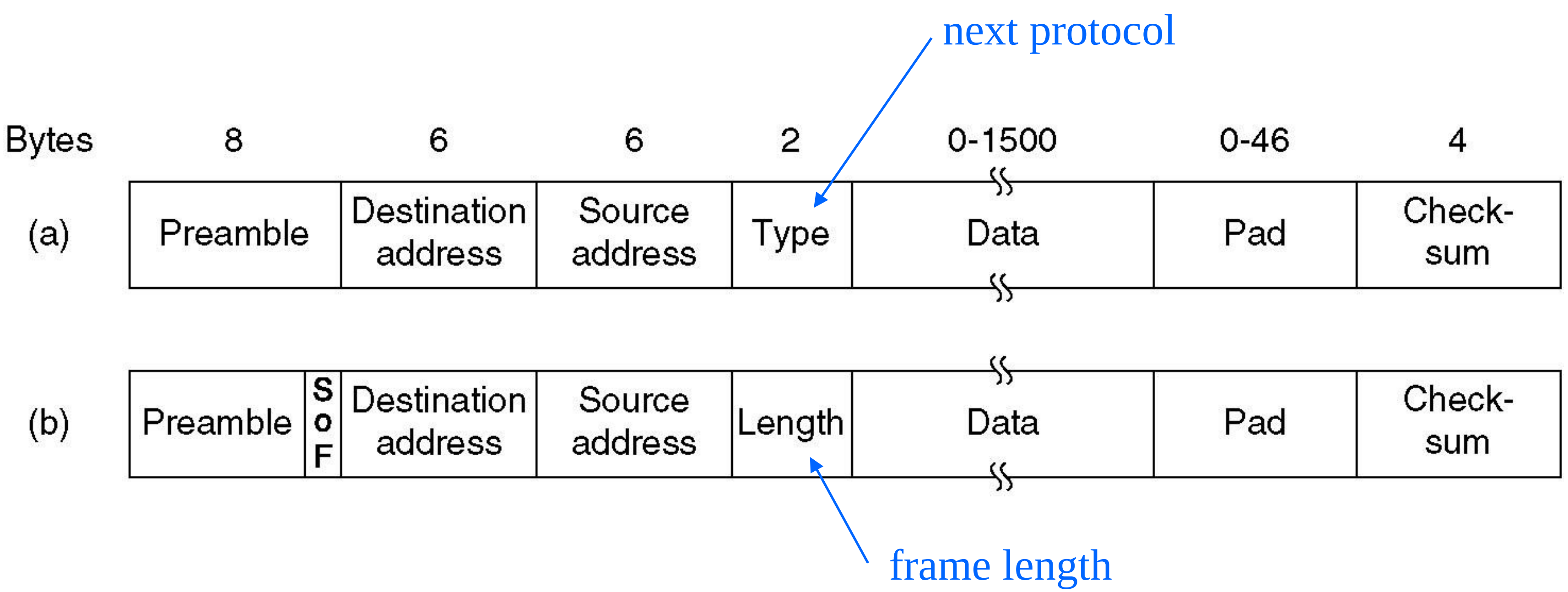
- http://standards.ieee.org/about/get/
- Important standards for RCOM
  - » 802.3 - Ethernet
  - » 802.11 - Wireless LAN (WLAN)

Ethernet MAC Sublayer

Frame formats

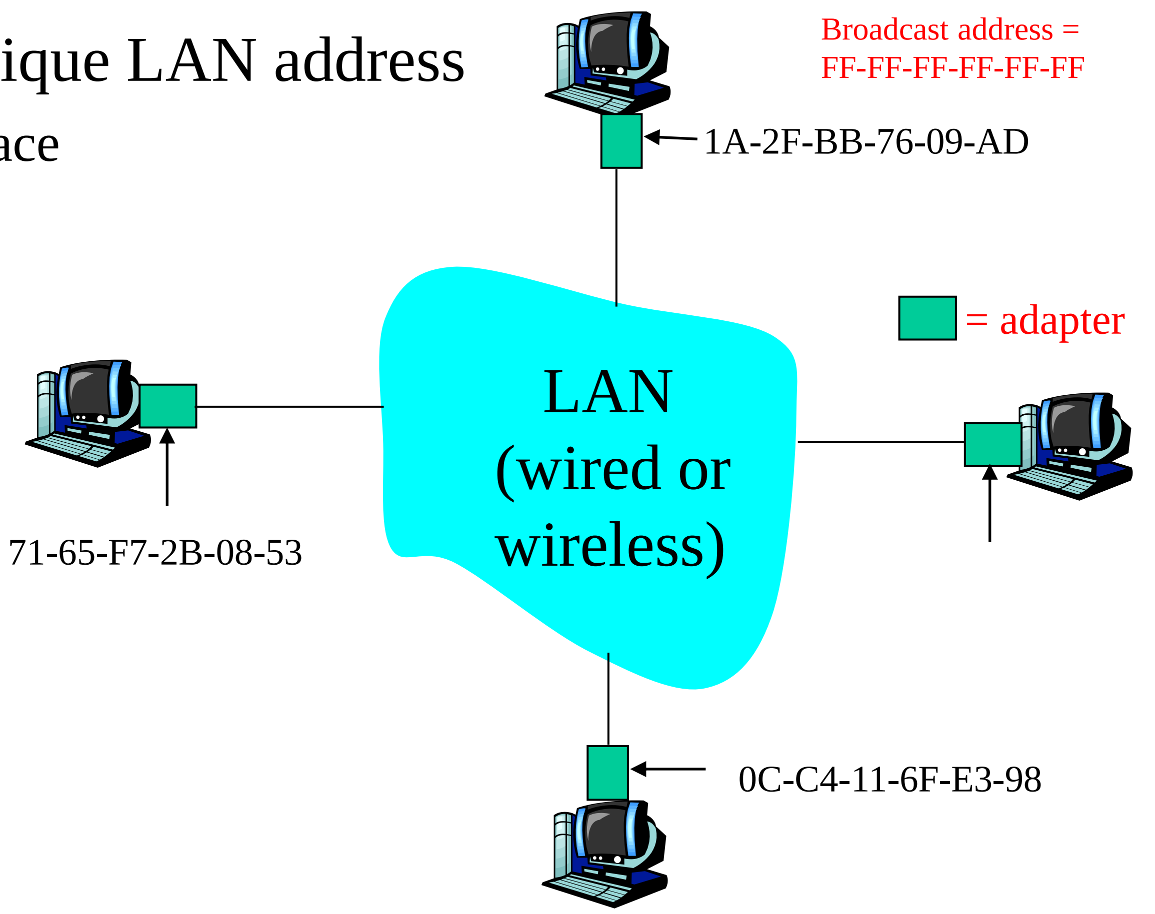
(a) DIX Ethernet → no LLC sublayer, IP over Ethernet

(b) IEEE 802.3



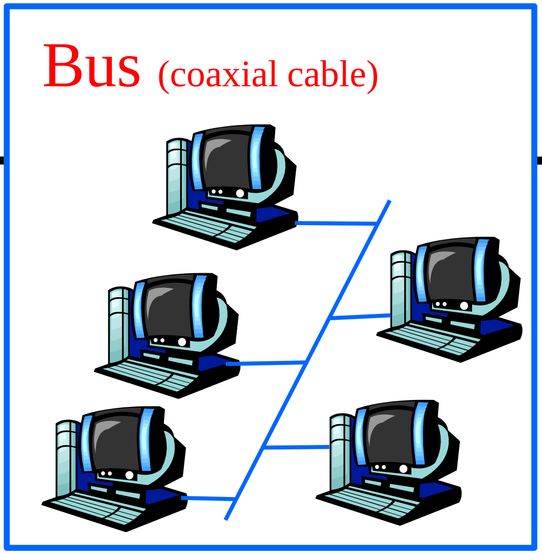
MAC Address

- 48 bit MAC address (for most LANs)
- Each adapter has unique LAN address
  - » Hardcoded in interface



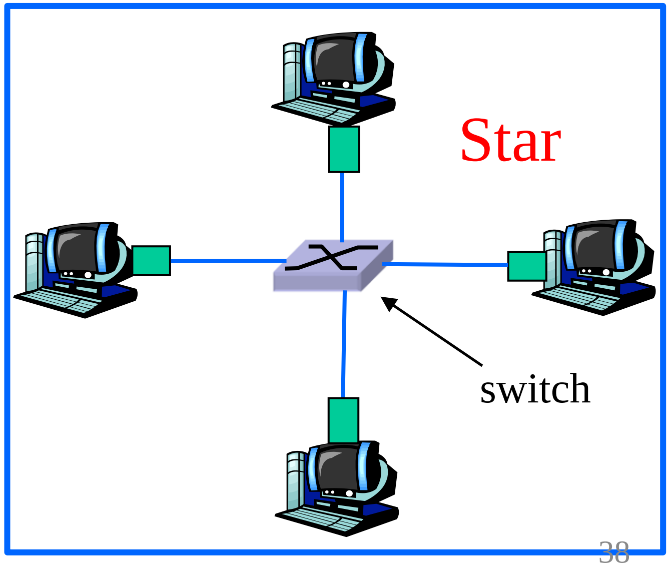
Ethernet Topology

- Medium Access Control Protocol
  ➔ CSMA/CD



- Bus topology
  » popular in mid 90s
  » stations in same collision domain

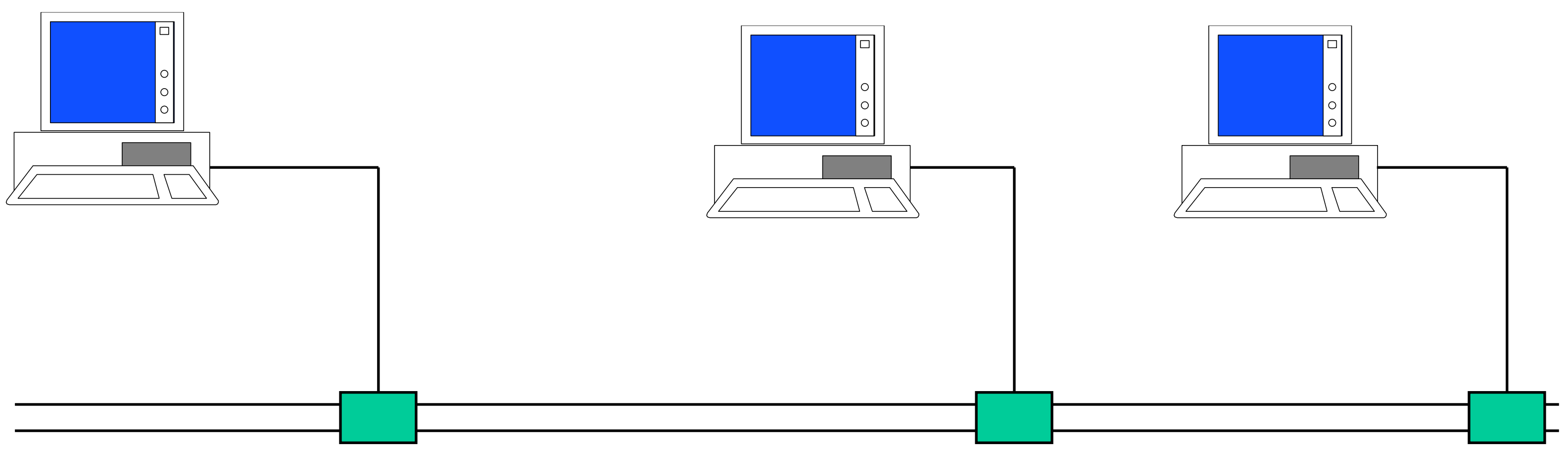
- Star topology
  » current topology
  » active switch in center
  » each station runs
  individual Ethernet protocol
  » stations do not collide with each other

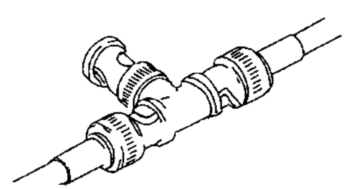


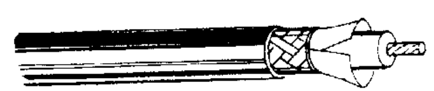
Ethernet Evolution – Coaxial Cable

First Ethernet was on coaxial cable

- Allows multiple transmitters and receivers

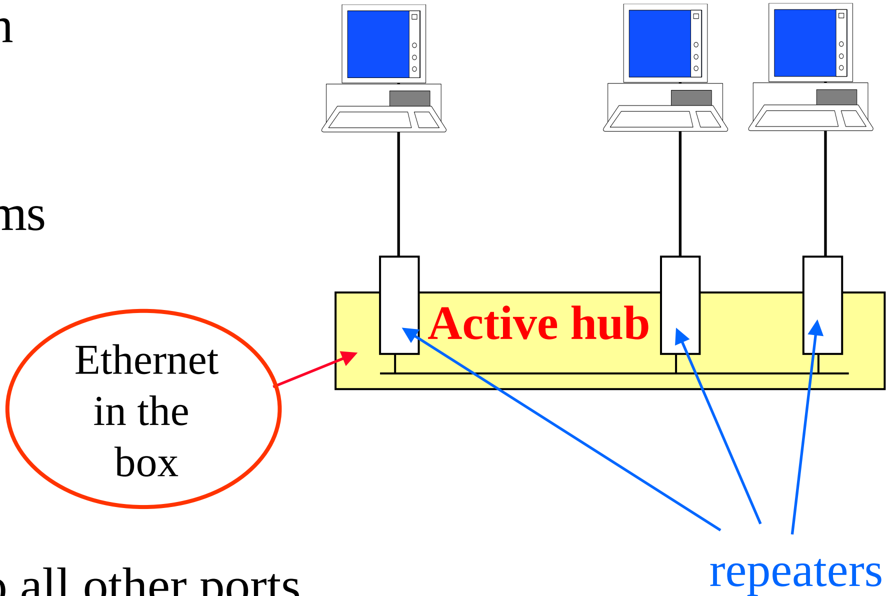






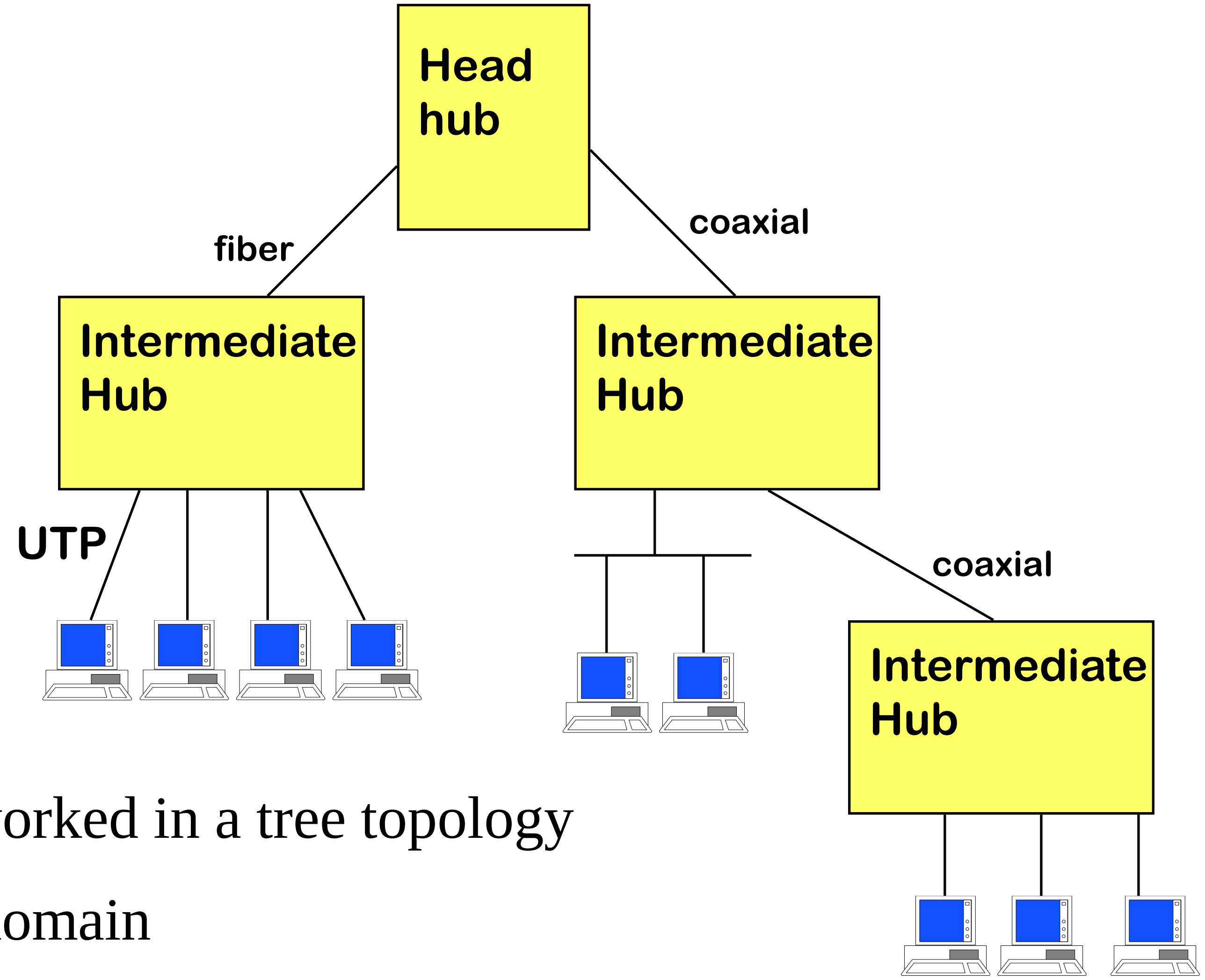
Ethernet Evolution - Active Hub

- Original shared medium Ethernet ➔ difficult to manage
  - » cable faults were hard to detect
  - » faults brought entire network down
- Active Hub
  - » solution to overcome cable problems
  - » point to point cables
  - » repeaters
  - » works on physical layer



- Repeaters
  - » repeats bits received on one port to all other ports
  - » performs physical layer functions only
  - » if collision detected on one port ➔ repeats random bits on other port
- One network with repeaters ➔ one collision domain

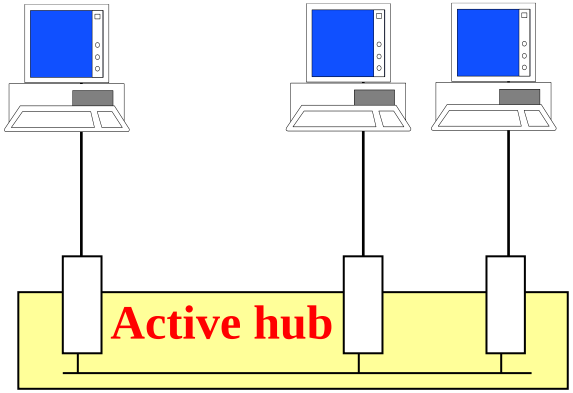
Ethernet Evolution – Networks of Hubs



- Active hubs networked in a tree topology
- Single collision domain

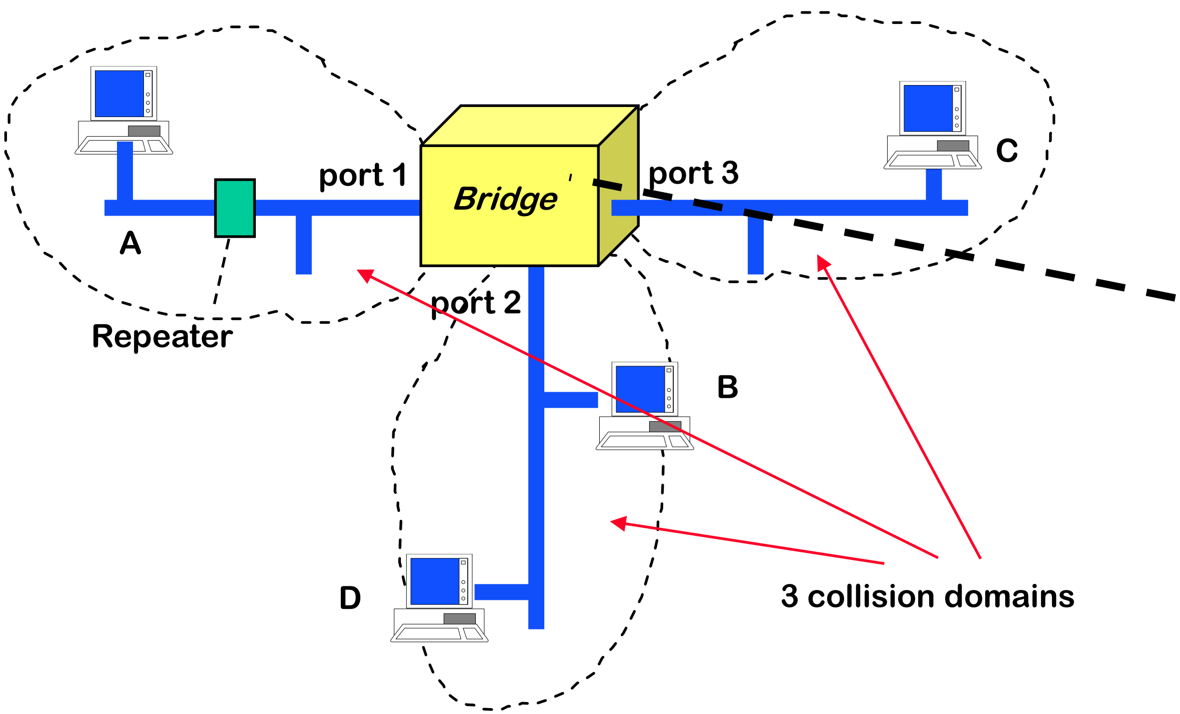
To Think…

- *How to improve the efficiency of a Hub?*



Ethernet Evolution - Bridge

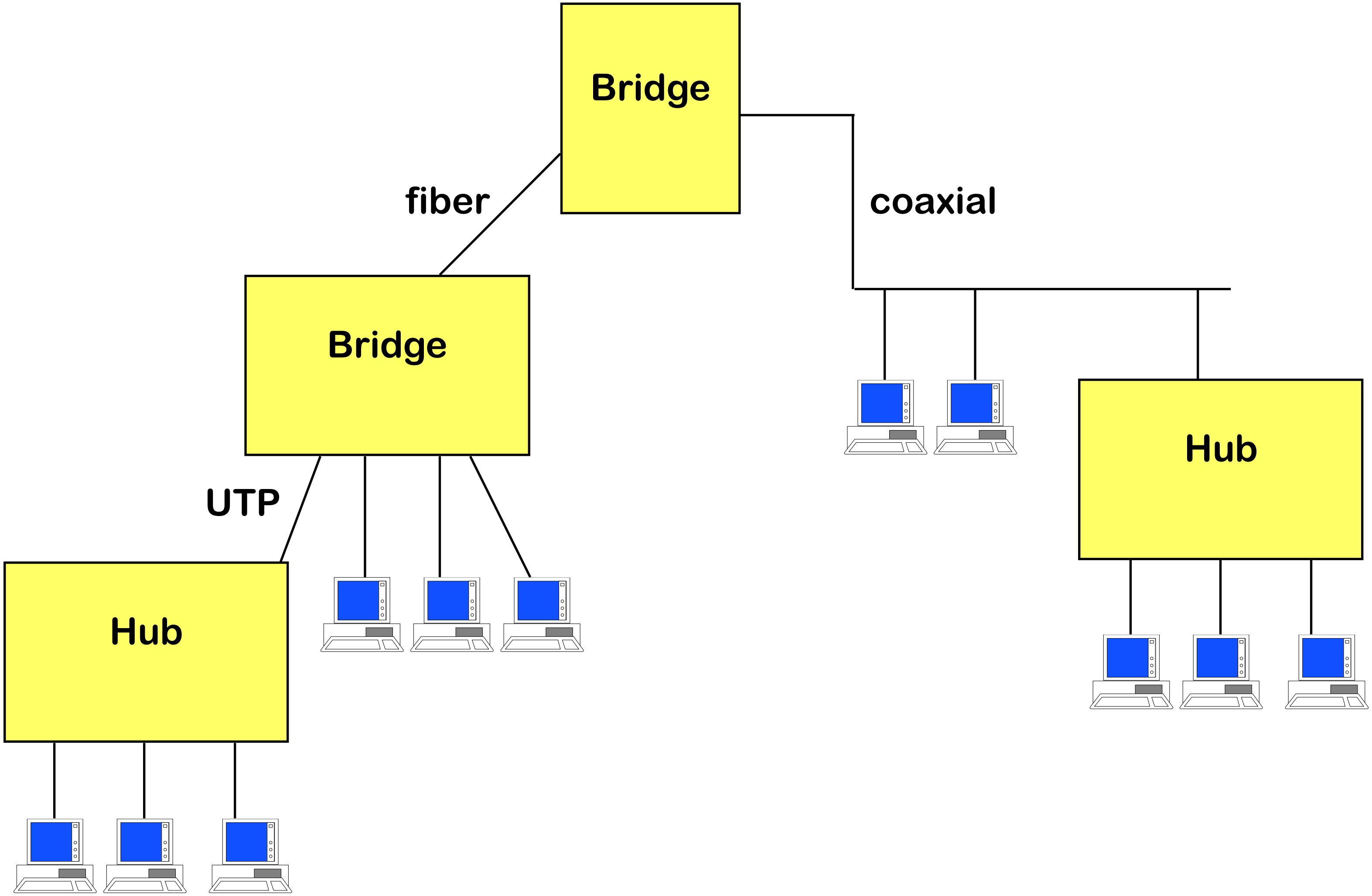
- Bridge
  - » forwards MAC frames to destinations based on MAC addresses ➔ works on MAC layer
  - » packet received on one port ➔ analyzed by bridge ➔ re-sent on some other port
- Bridge separates **collision** domains
  - » a bridged LAN maybe larger than a repeated LAN
  - » several frames may be transmitted simultaneously



Forwarding Table

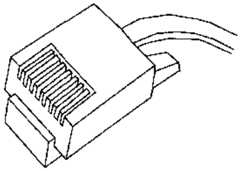
Dest MAC addr	Port Nb
A	1
B	2
C	3
D	2

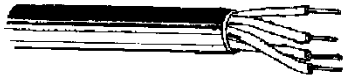
Ethernet Evolution – Bridges and Repeaters Combined



Ethernet Evolution – The Point-to-Point Only Cable

- Point-to-point cables can be used in Hubs and Bridges
- Unshielded Twisted Pair (UTP)
  - » cheaper and easier to install (can be bent) than coaxial cable
  - » does not support well many multiple transmitters or receivers
- UTP started to be used in Ethernet



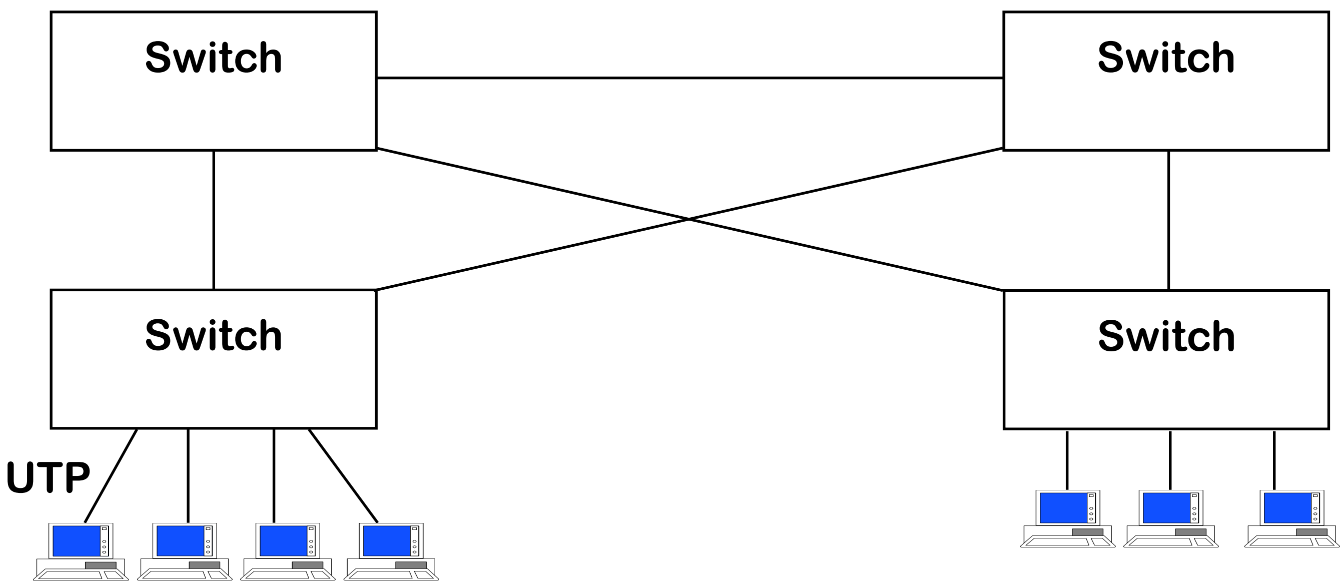


Ethernet Evolution –Full Duplex Ethernet

- UTP cables have multiple pairs of wires
  - » Two pairs started to be used to support communications in both directions simultaneously
- Emergence of the **Full Duplex Ethernet**
  - » CSMA/CD in practice is not used → no collisions
  - » From the original Ethernet we retain only
    the frame format and the MAC addresses

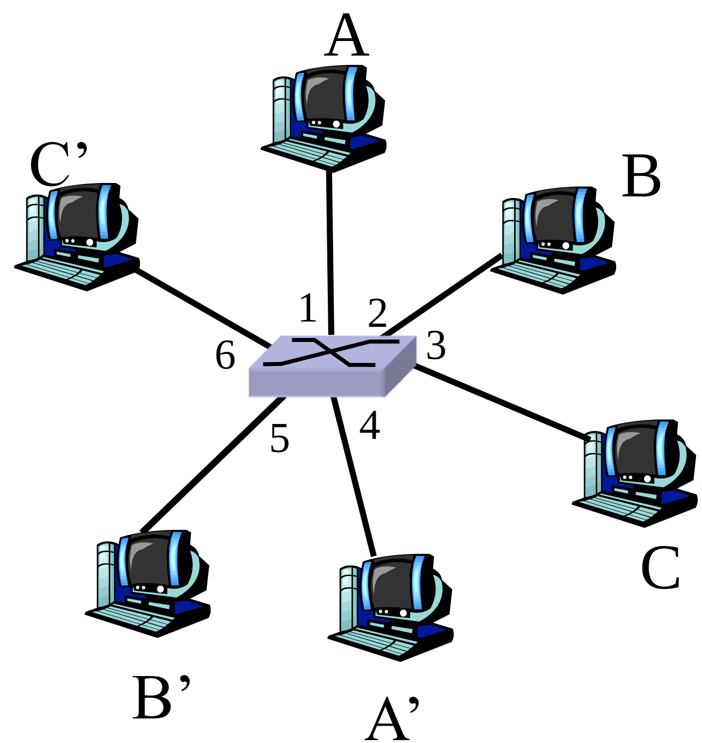
Current Ethernet

- Switched Ethernet used for local interconnection
  of a limited number of systems (up to a few 100s in practice)
- Uses primarily point-to-point cables
  - » UTP for short distances, optical fiber for long links
- May support redundant links for fault tolerance



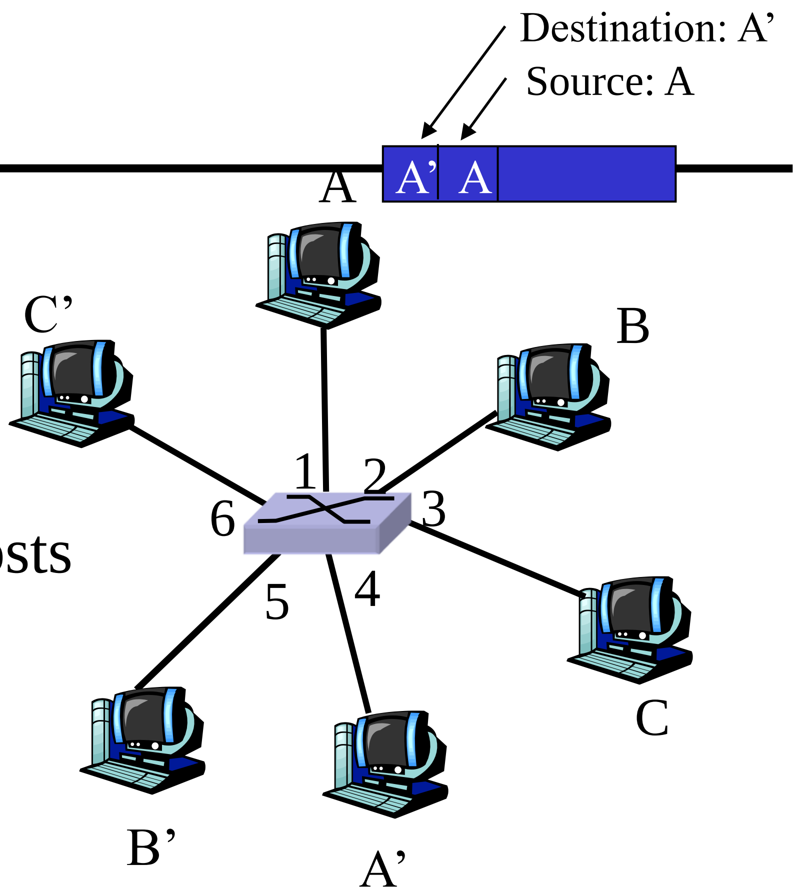
Ethernet Switches

- Link layer devices
  - » Similar to *bridges*
- Forward Ethernet frames
- Transparent to hosts
  - Hosts are unaware of its presence
- Plug-and-play, self-learning
  - Does not need to be configured
- Have forwarding tables



switch with six interfaces (1,2,3,4,5,6)

Switch: Self-learning



Switch learns addresses of attached hosts

- » looks at source address of frames
- » adds entry to forwarding table

MAC addr	interface	TTL
A	1	60

Forwarding table (initially empty)

Switch - Frame forwarding/flooding

When Switch receives a frame:

1. record interface associated with sending host

2. index forwarding table using MAC destination address

3. if (entry found in table) **{**

  if (destination is on segment from which frame arrived)

    drop the frame

    else forward the frame on interface indicated

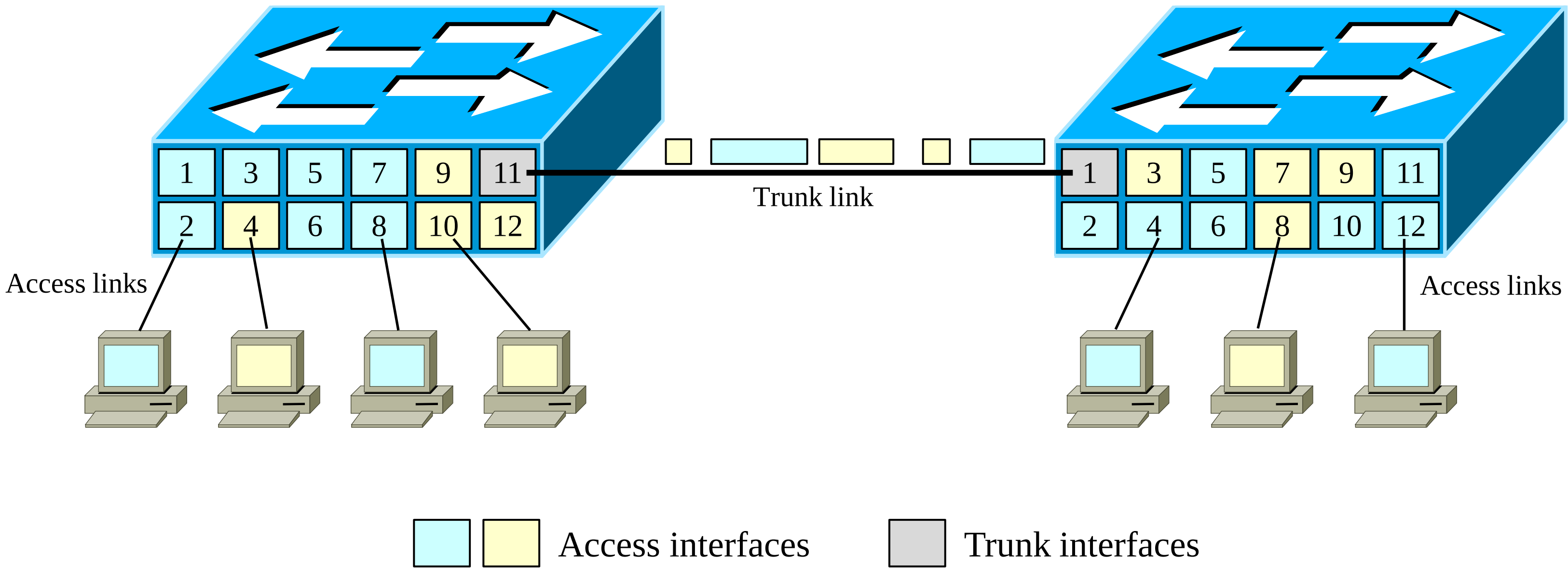
  }

  else flood

forward on all but the interface
on which the frame arrived

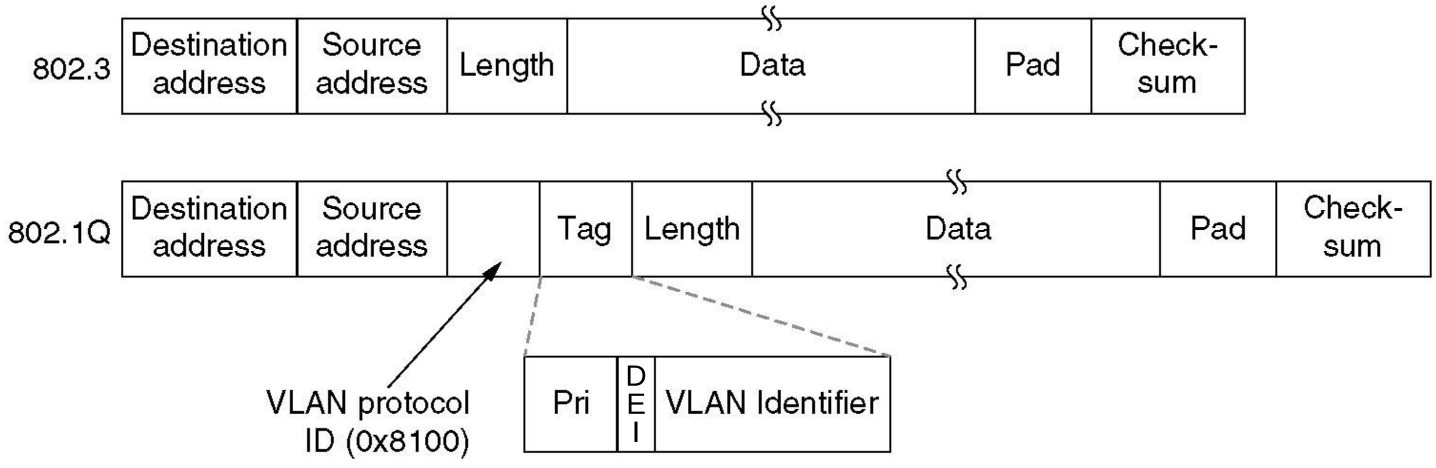
Virtual LANs

- One bridge / switch simulates multiple LANs / broadcast domains
  - Several logical bridges, isolated from each other
    ➔ Multiple broadcast domains (one per VLAN)
- VLANs may be extended to other switches through trunk interfaces
  - Frames sent in trunk interfaces need an ID of the VLAN they belong to



The IEEE 802.1Q Standard

The 802.3 (legacy) and 802.1Q Ethernet frame formats



- Legacy frames used in access links
  - » All frames belong to the same VLAN
- 802.1Q frames used in trunk links
  - » VLAN ID used by receiving switch to assign each frame to the correct VLAN

Homework

1. Review slides
2. Read from Tanenbaum
   - » Sec. 4.1, 4.2, 4.3, 4.4, 4.8, 4.9
3. Read from Bertsekas&Gallager
   - » Sec. 4.2, Sec. 4.4
4. Answer questions at moodle