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*

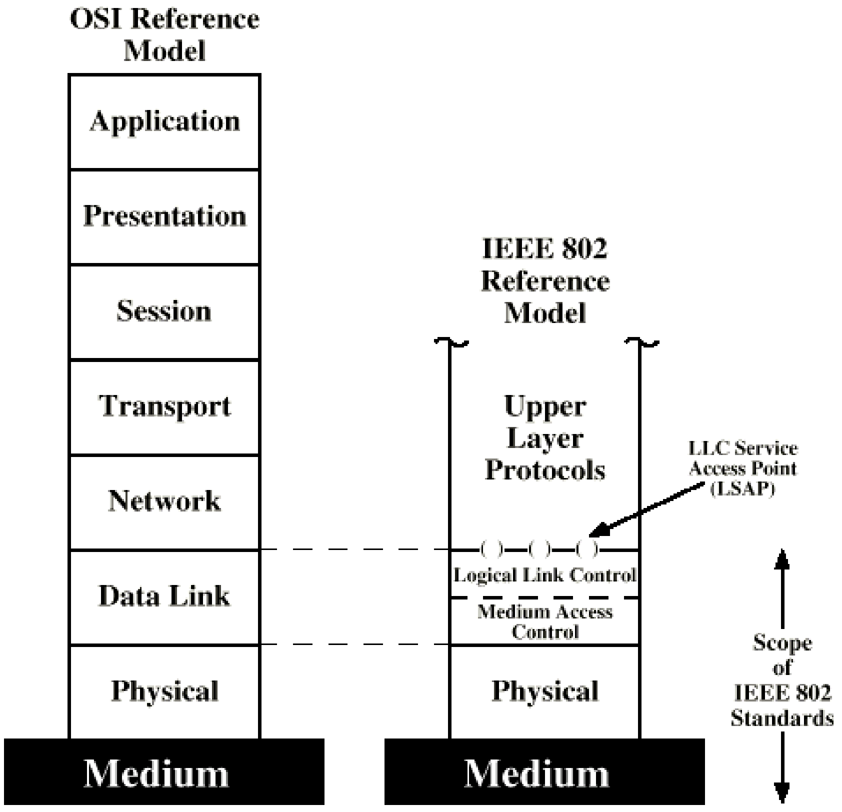
- *What is a MAC address?*
- *What are the Ethernet generations?*
- *What is a Hub? What is Switch?*
- *How does a Switch learn the MAC addresses of the attached stations?*
- *What is a Virtual LAN (VLAN)?*

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 control

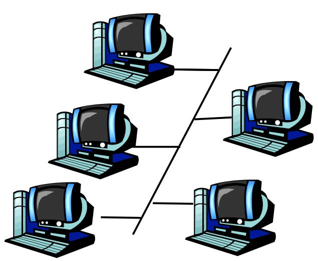


Multiple Access Links

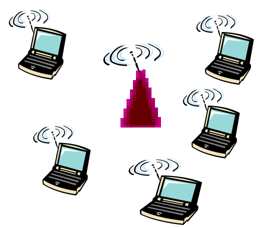
Two types of ***links***

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

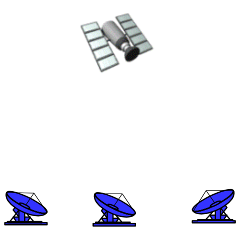
- Broadcast (shared medium, wired or wireless)
  - » old-fashioned cabled Ethernet
  - » 802.11 wireless LAN



shared wire
(e.g., cabled Ethernet)



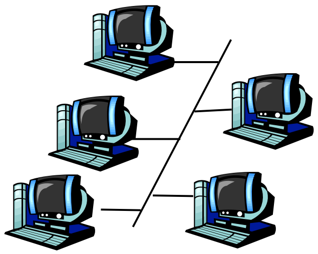
shared RF
(e.g., 802.11 WiFi)



shared RF
(satellite)

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

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



shared wire
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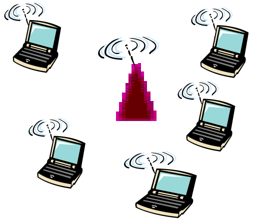


shared RF
(e.g., 802.11 WiFi)

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 Multiplexing | Frequency Division Multiplexing*
- Random Access
  - channel not divided, 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

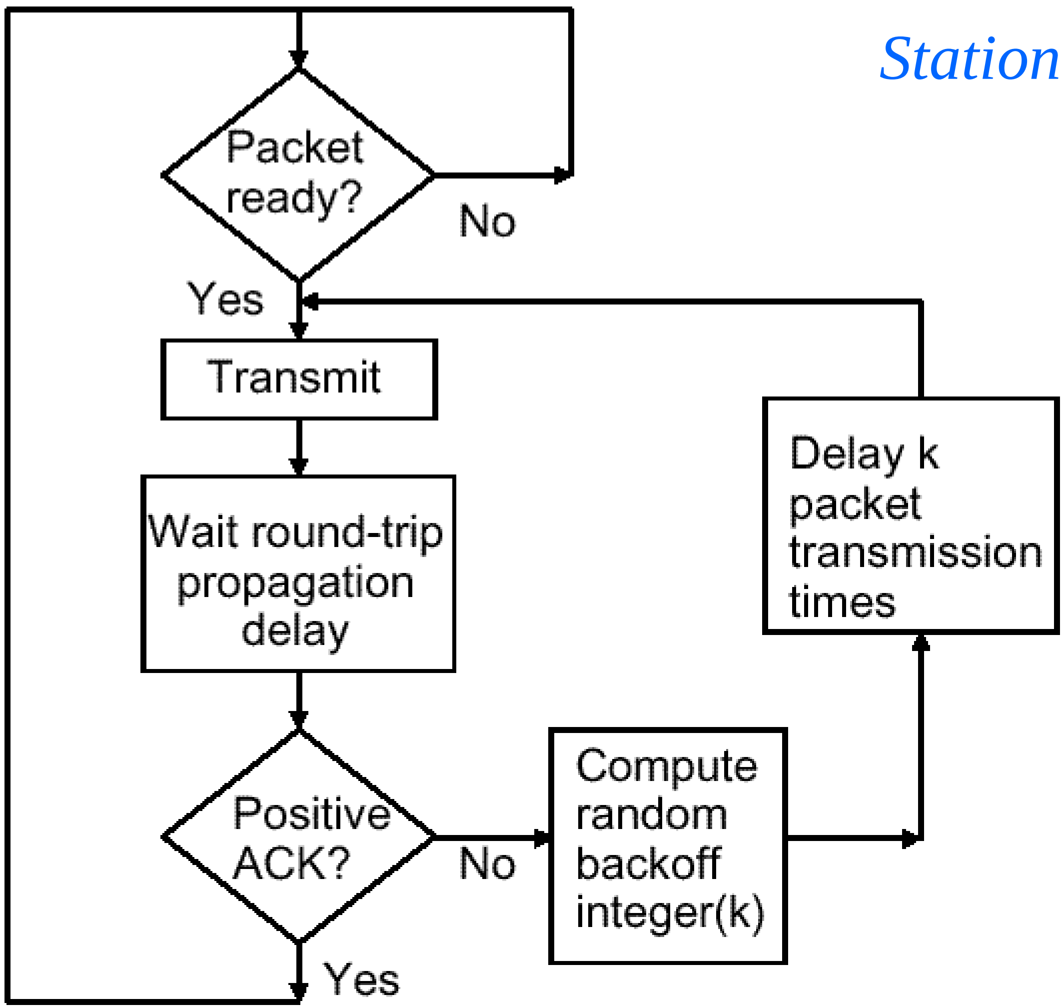
- Station
  - » Transmits one frame at time
  - » Probability one frame being generated in δ: $p_1(\delta) \approx \lambda\delta$
  - » Poisson arrival

- 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

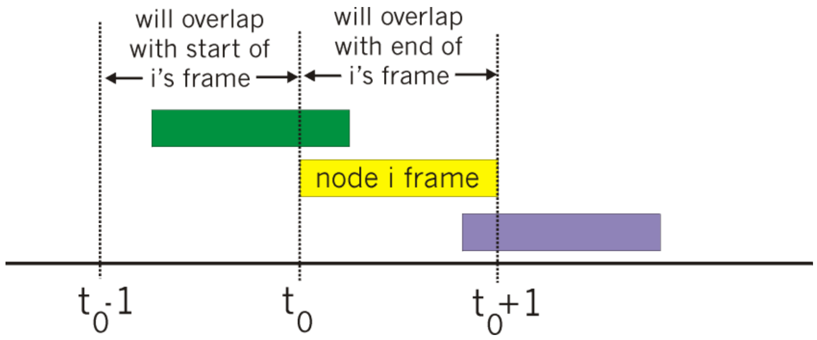
ALOHA

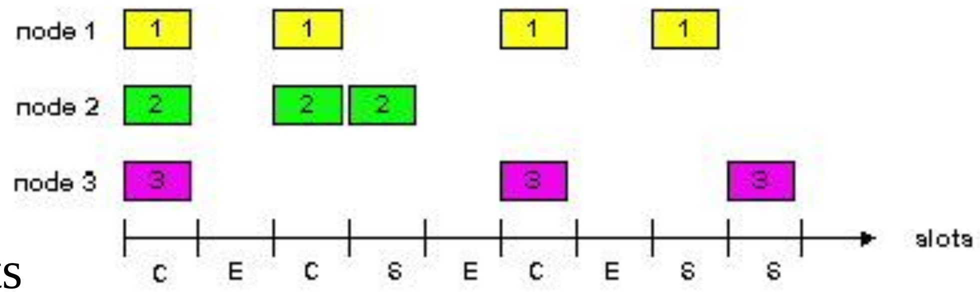


Station behaviour

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, $T_{frame}=1$
  - » S – Received traffic

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

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

    λ – rate of generated packets

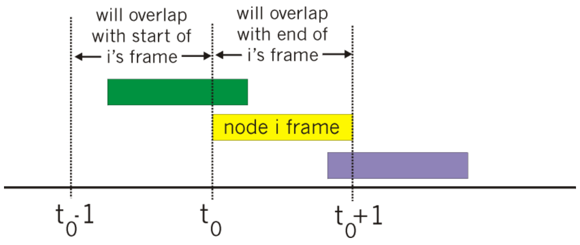
    $G=\lambda * T_{frame}$
  - » p – probability of **one station** generating a packet (new or retransmission) in T_{frame}

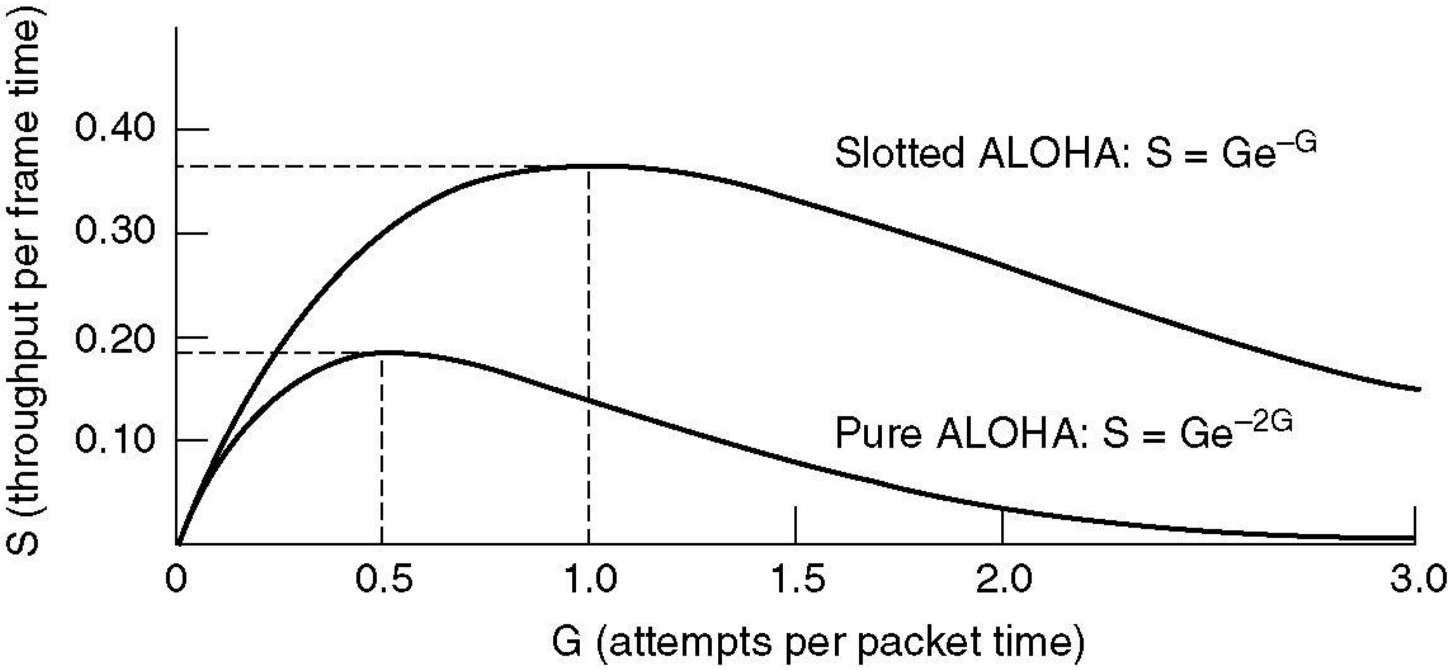
    $N*p=G$

- Slotted Aloha
  - » $S = P(Success) = N\left(p(1-p)^{N-1}\right) \approx Npe^{-p(N-1)} \approx Npe^{-pN} = Ge^{-G} = Gp_0(T_{frame}) = Ge^{-G}$
  - » $S_{\max} \Rightarrow \dfrac{\partial S}{\partial G} = 0; \quad G = 1; \quad S_{\max} = \dfrac{1}{e} = 36{,}8\%$

Aloha - Efficiency

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





Waiting Time –
Aloha versus Time Division Multiplexing

t

M=8	1	2	…	**8**	1	2	…	**8**	1	2	…	**8**	1	2	…	**8**
M=16	1	2	3	4	…	14	15	**16**	1	2	3	4	…	14	15	**16**
Aloha	1	1			1											

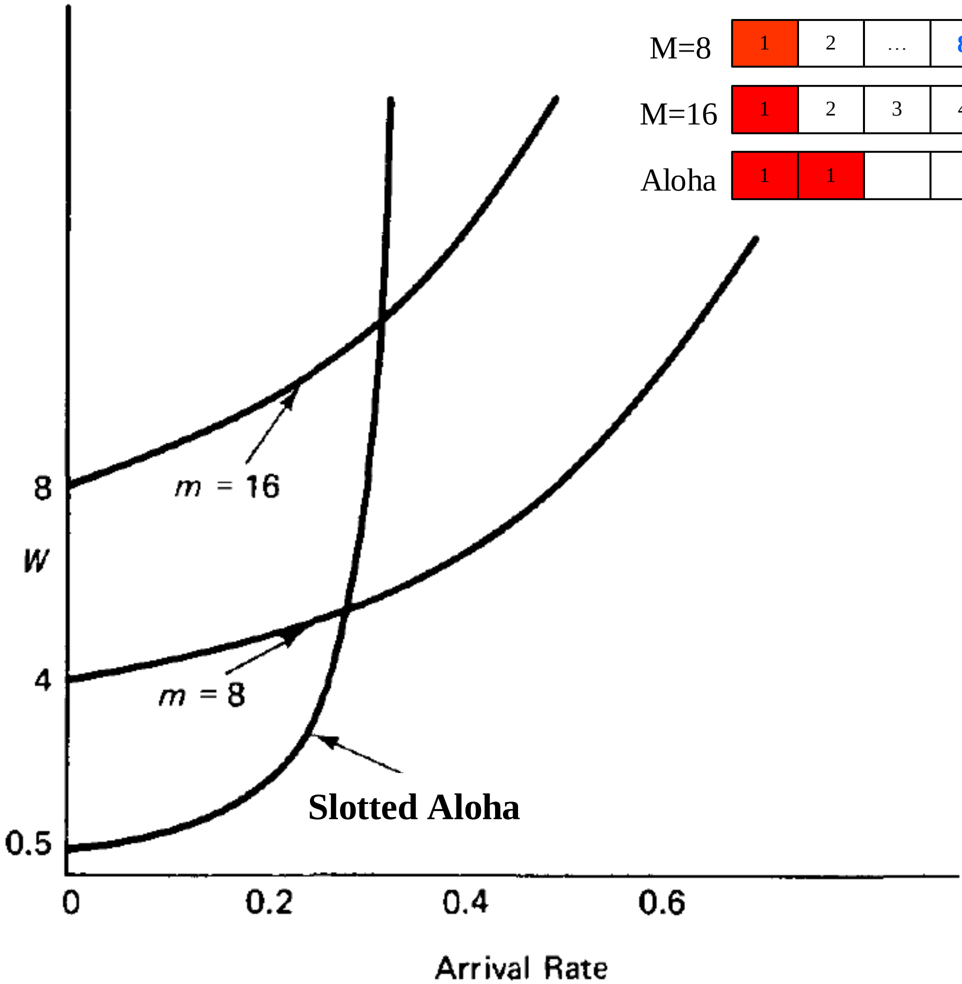


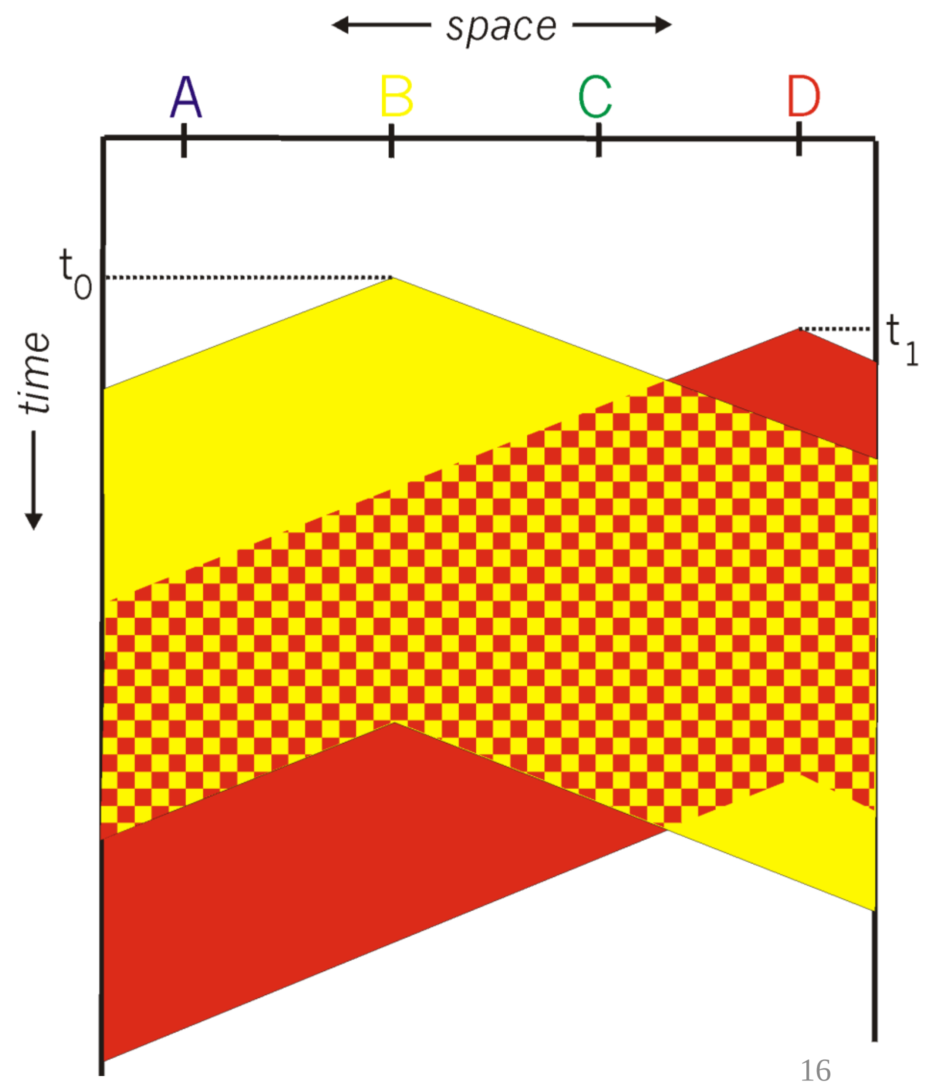
Figure 4.6 Comparison of expected waiting time W in slots, from arrival until beginning of successful transmission, for stabilized Aloha and for TDM with $m = 8$ and $m = 16$. For small arrival rates, the delay of stabilized Aloha is little more than waiting for the next slot, whereas as the arrival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

CSMA (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 = $2*T_{prop}$
- T_{prop} and T_{frame}
  - Determine collision probability
  - **$a = T_{prop}/T_{frame} << 1$**



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

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

persistent

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

non-persistent

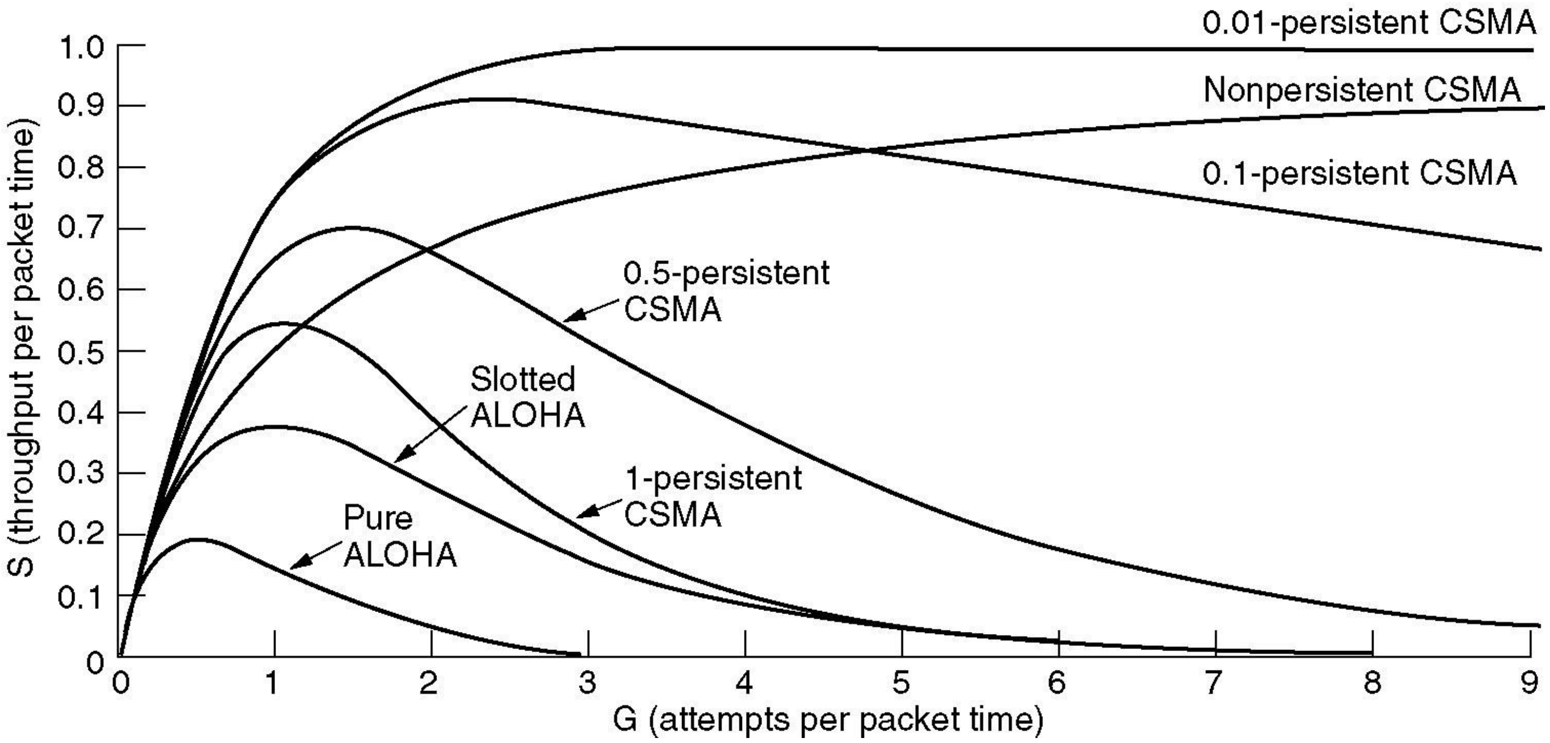
- **CSMA p-persistent**
  - » Slot time = round trip time = 2* T_{prop}
  - » Medium free ➔ station transmits with probability **p** or defers no next slot (1-p)
  - » Medium busy ➔

    if transmission deferred from previous time slot ➔ collision

    else ➔ station waits until medium becomes free and repeats algorithm

p-persistent

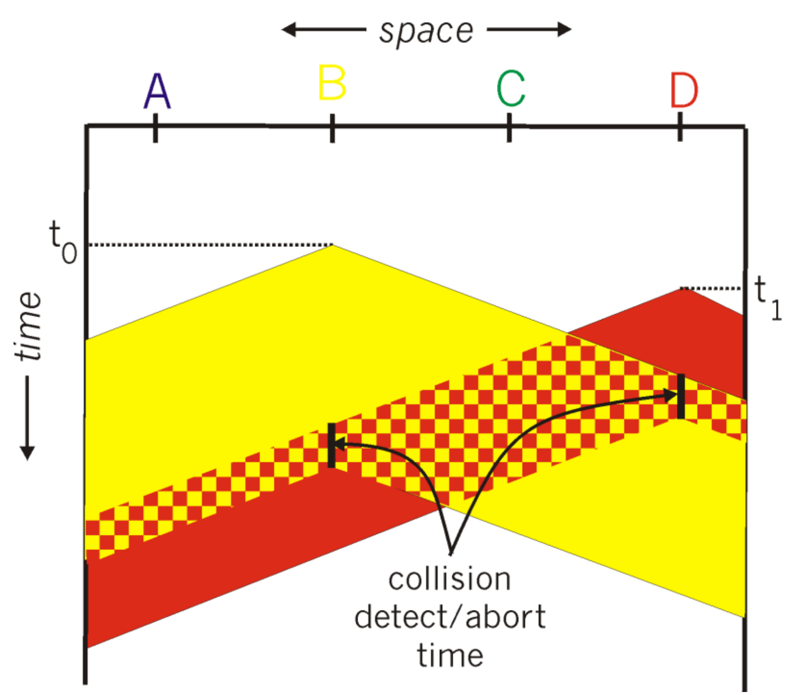
Efficiencies – x-persistent CSMA



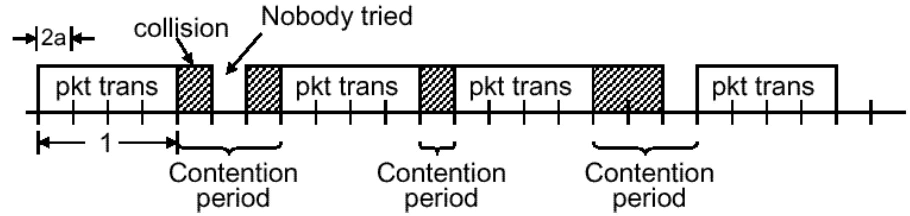
Comparison of the channel utilization versus load for various random access protocols

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 listens medium while transmitting
  - » if collision is detected
    - – transmission is aborted
    - – retransmission delayed using a Binary Exponential Back-off algorithm
  - » **no ACK!**
- Binary Exponential Back-off algorithm
  - » time modeled in time slots; $T_{slot} = 2 * T_{prop}$
  - » 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 - Efficiency



- Let's assume $T_{slot} = 2 \times T_{prop}$, $T_{frame} = 1$
- Number slots $\boldsymbol{n_{tx}}$ required to transmit a frame $n_{tx} = \dfrac{T_{frame}}{T_{slot}} = \dfrac{T_{frame}}{2 \times T_{prop}} = \dfrac{1}{2a}$
- Efficiency $S = \dfrac{n_{tx}}{n_{tx} + E[n_{cont}]}$
- Let's define
  - » p – probability that one station transmits in a slot
  - » A – probability that exactly one station transmits in a slot and gets the medium

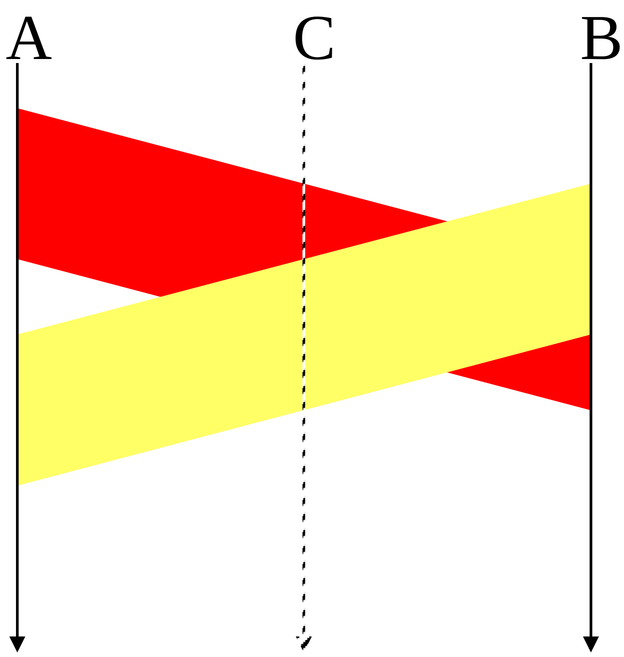
$$A = \binom{N}{1} p^1 (1-p)^{N-1} = Np(1-p)^{N-1}$$

- $E[n_{cont}] = \sum_{i=1}^{+\infty} i(1-A)^i A = \dfrac{1-A}{A} \quad \Rightarrow S = \dfrac{1/2a}{1/2a + (1-A)/A} = \dfrac{1}{1+2a(1-A)/A}$
- p=1/N ➔ $A_{MAX} = \left(1 - \dfrac{1}{N}\right)^{N-1} \quad \lim_{N\to\infty} A_{\max} = \lim_{N\to\infty}\left(1-\dfrac{1}{N}\right)^{N-1} = \dfrac{1}{e} \quad \Rightarrow \lim_{N\to\infty} S = \dfrac{1}{1+3.44a}$

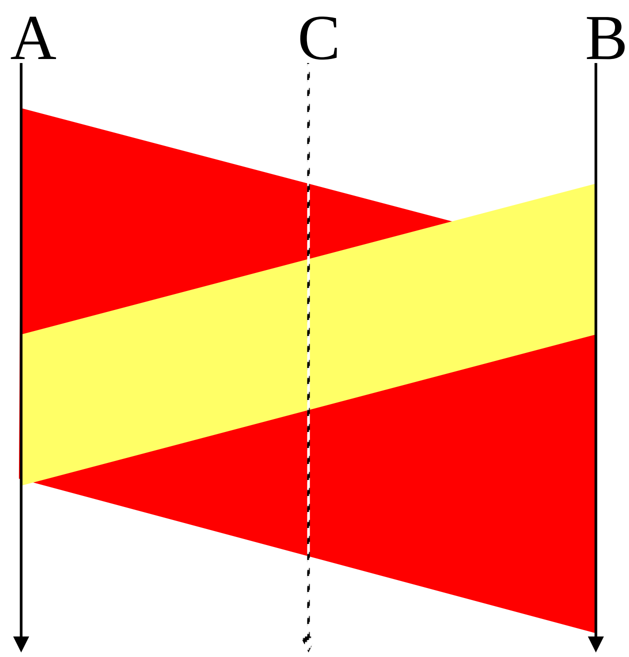
CSMA/CD – Minimum Frame Size is Required

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

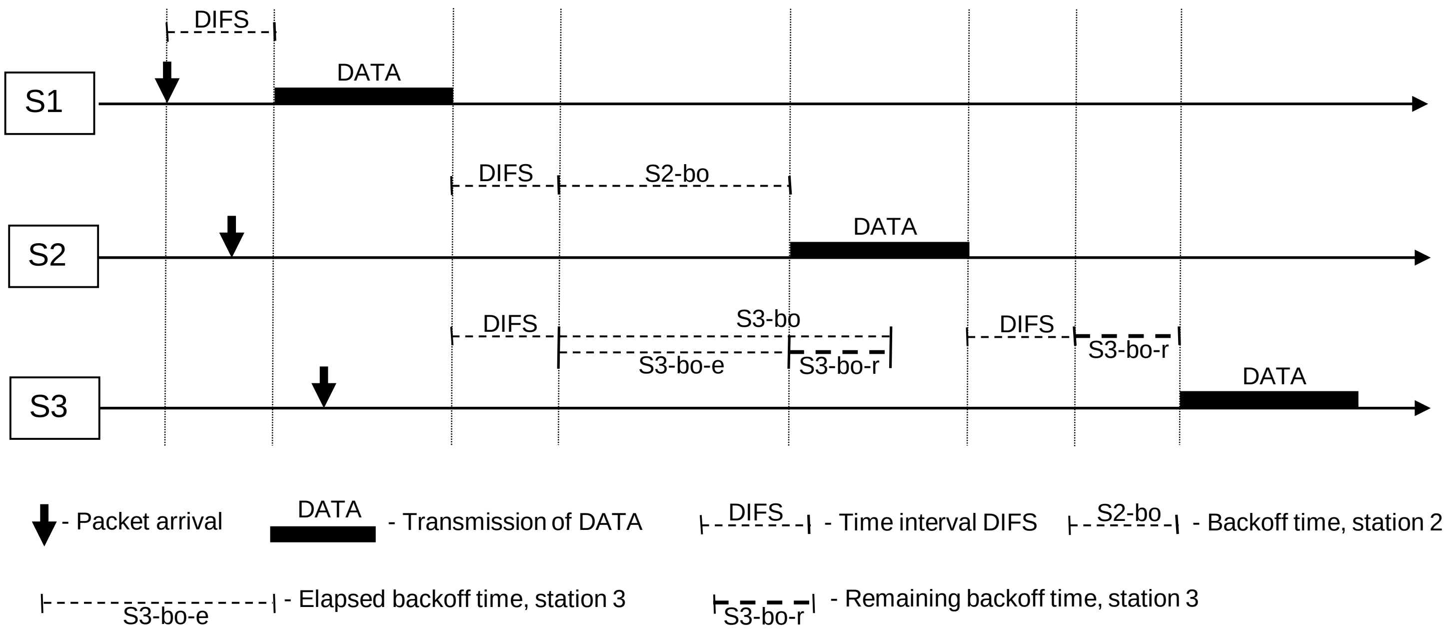


- Frame sent by A is large enough
  - » collision is visible at A



- *Why does not CSMA/CD need an ACK frame?*
- *Can we use CSMA/CD in a wireless medium?*

CSMA with Collision Avoidance (CSMA/CA)



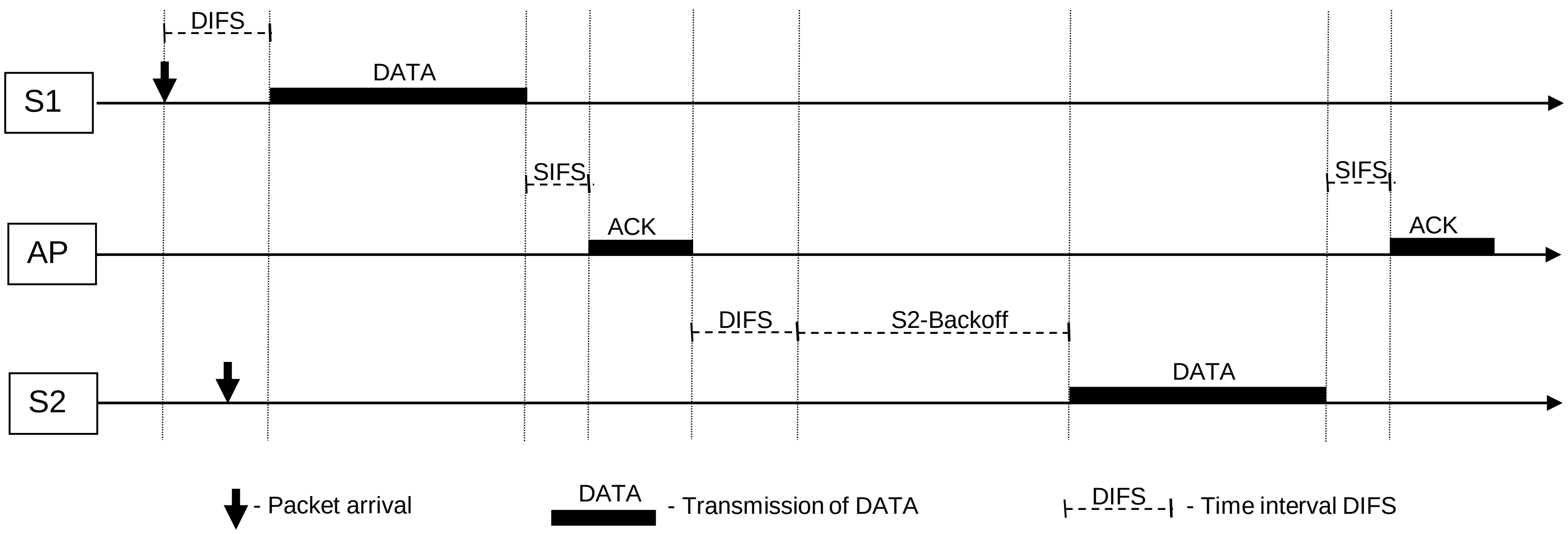
CSMA with Collision Avoidance (CSMA/CA)

- 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 hearing their own transmission
- 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

Taking Turns *MAC protocols*

- Channel partitioning MAC protocols (TDM, FDM)
  - 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!

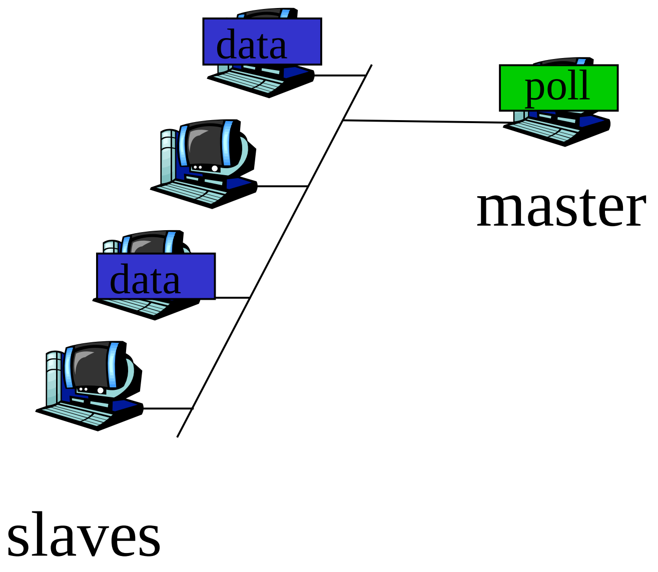
- Random access MAC protocols (Aloha, CSMA, CSMA/CD, CSMA/CA)
  - efficient at low load ➔ single node can fully utilize the channel
  - high load ➔ collisions ➔ inefficiency

- **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)

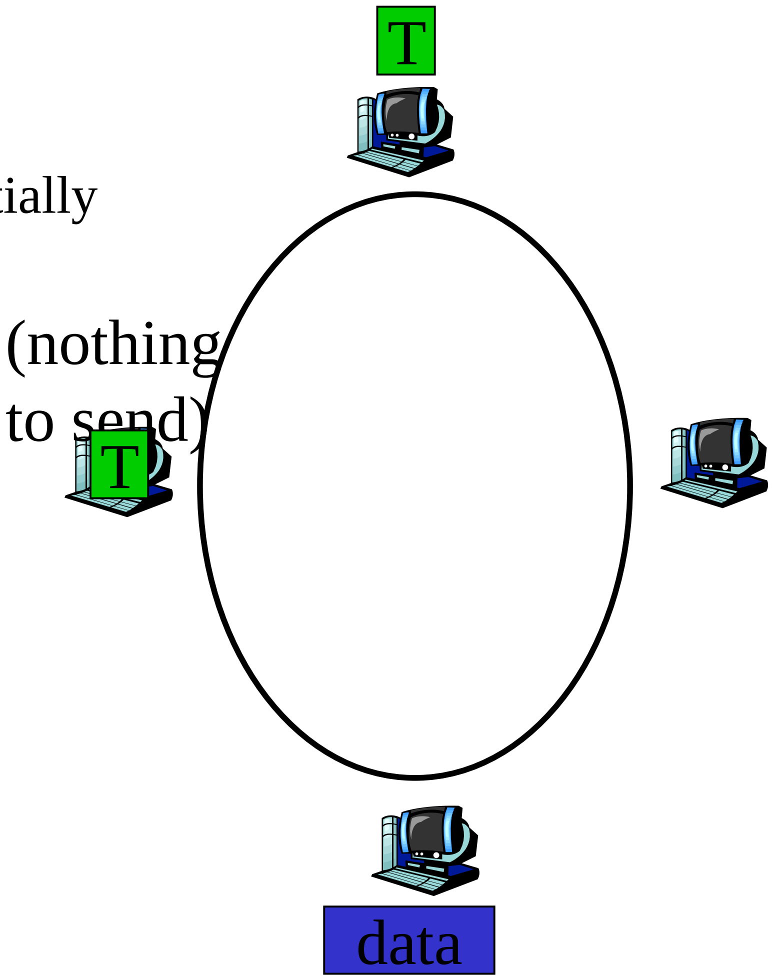


"Taking Turns" MAC protocols

Token passing

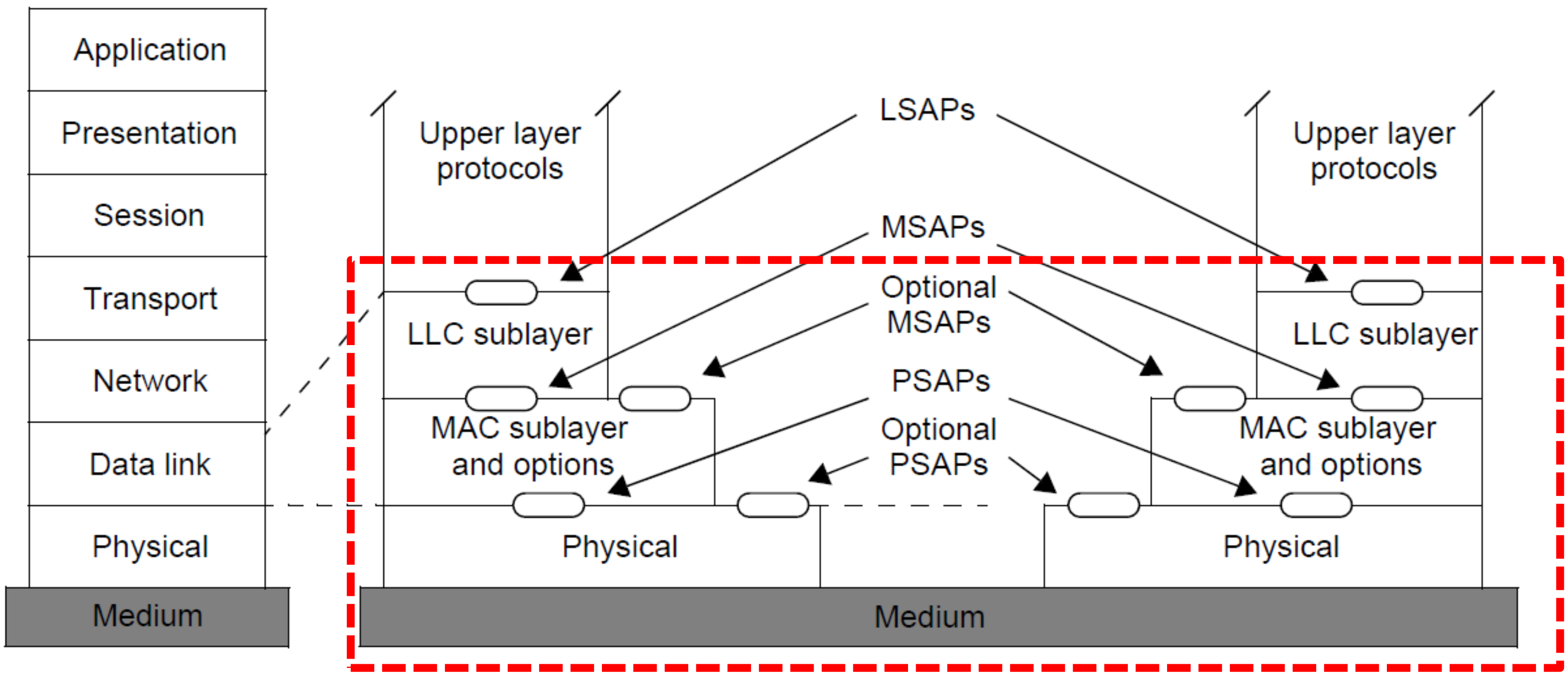
- » control token

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

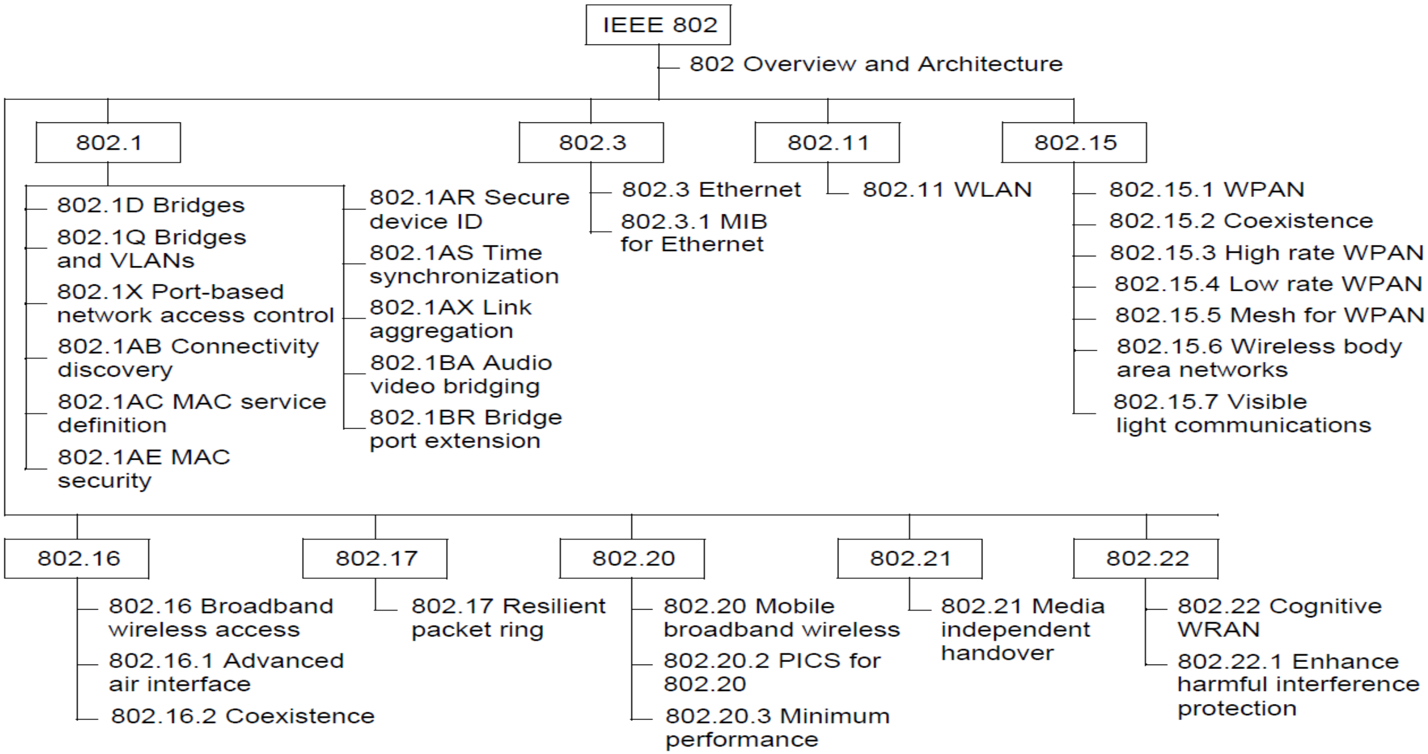


IEEE Standards – Reference Model

MSAP	MAC service access point
LSAP	link service access point
PSAP	PHY service access point



IEEE Standards – Family of IEEE 802 Standards



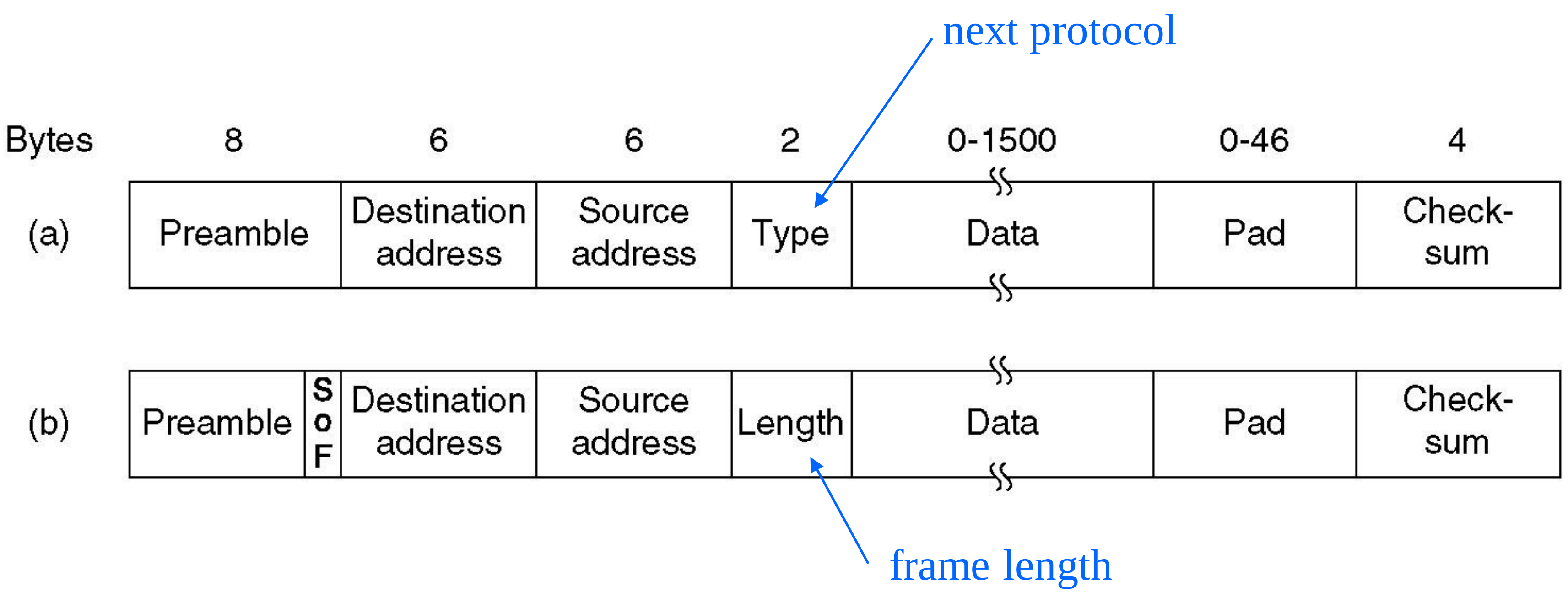
- http://standards.ieee.org/about/get/
- Important standards for RCOM
  - » 802.3 - Ethernet
  - » 802.11 - Wireless LAN (WLAN)

Ethernet MAC Sublayer

Frame formats

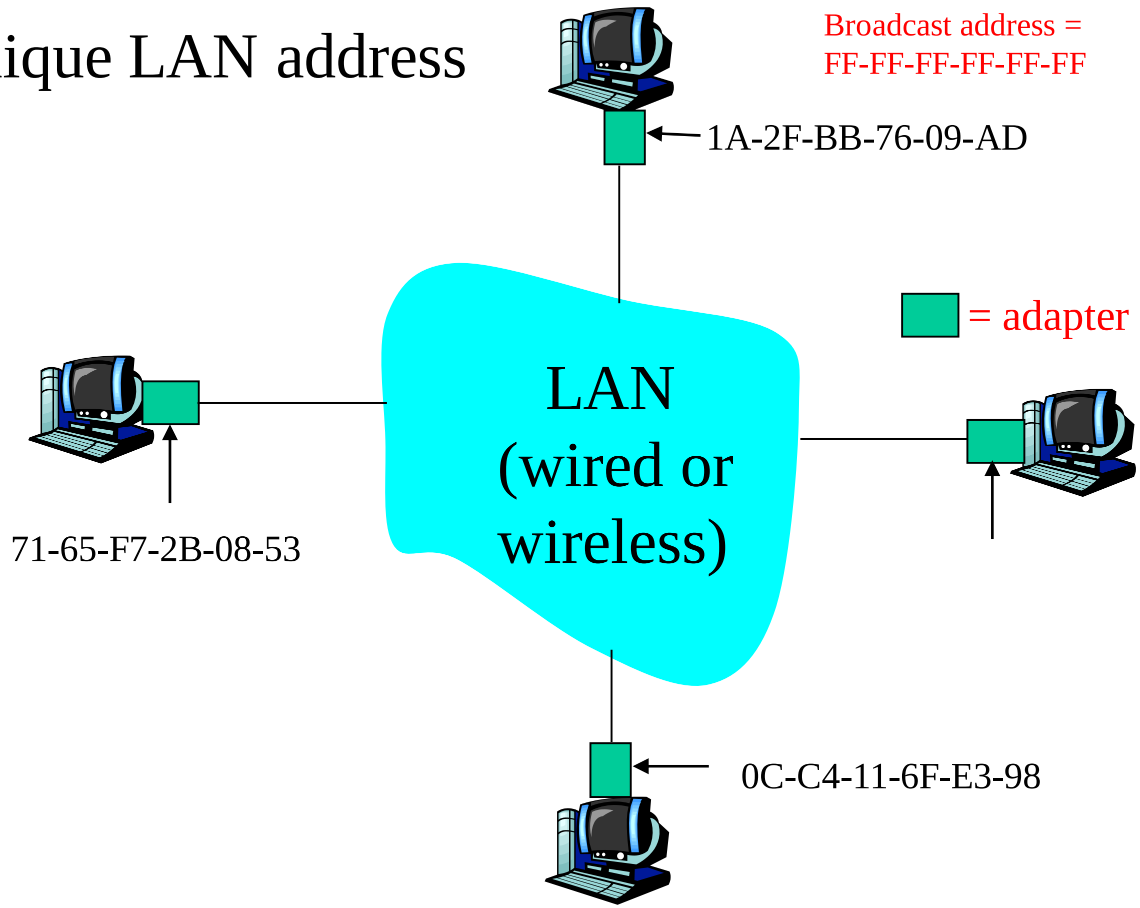
(a) DIX Ethernet ➔ no LLC sublayer, IP over Ethernet

(b) IEEE 802.3



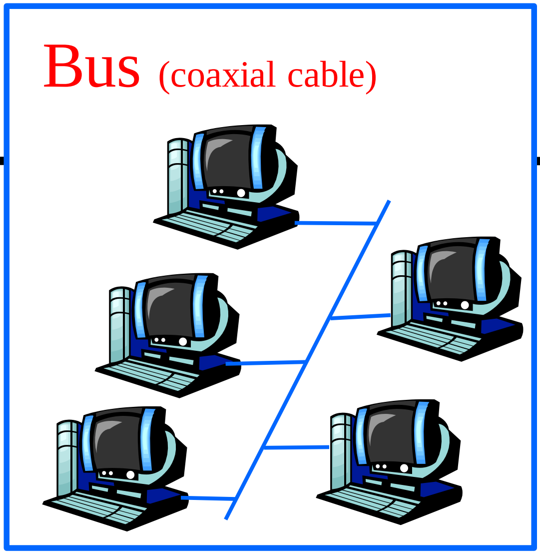
MAC Address

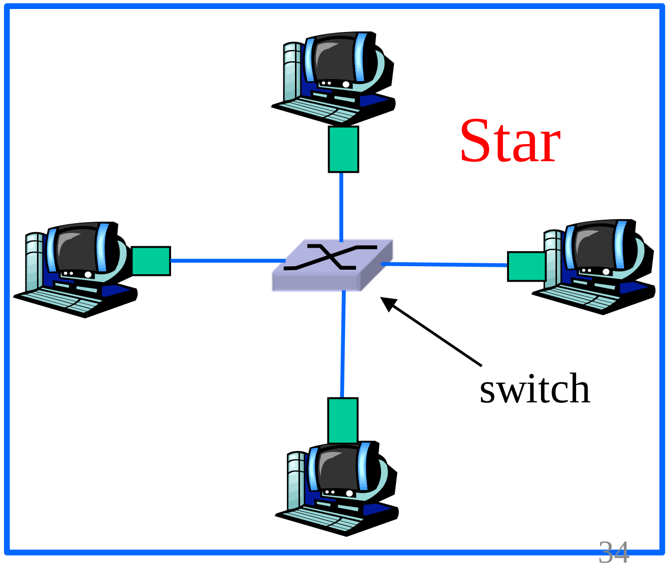
- 48 bit MAC address (for most LANs)
- Each adapter has unique LAN address



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

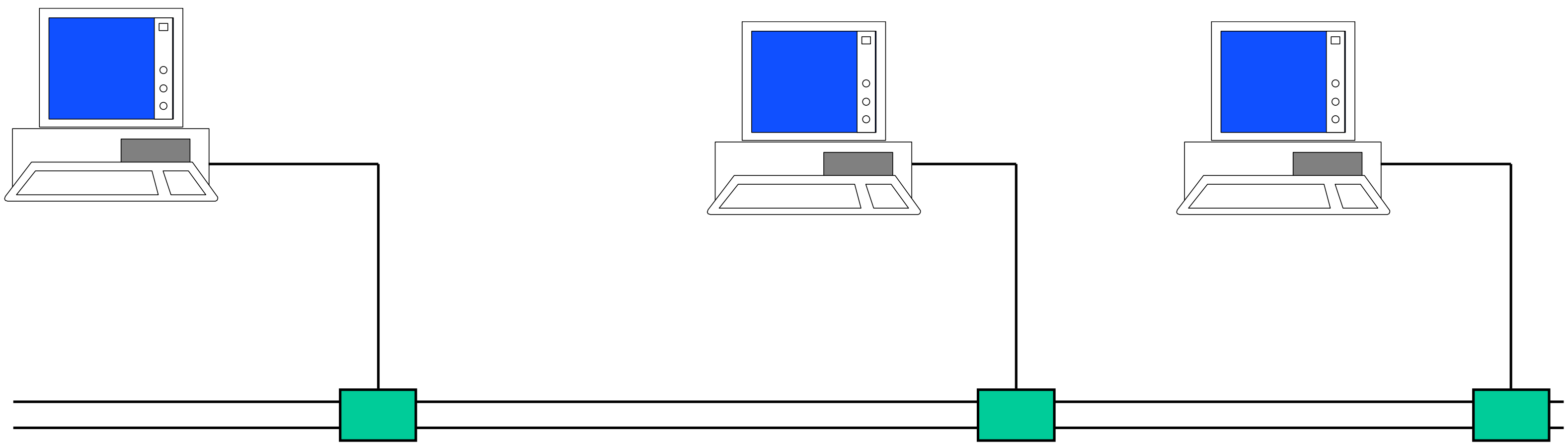


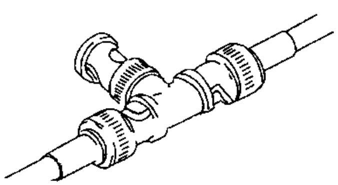


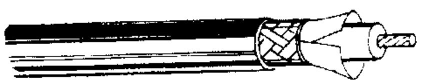
Ethernet Evolution – Coaxial Cable

First Ethernet was on coaxial cable

- Allows multiple transmitters and receivers

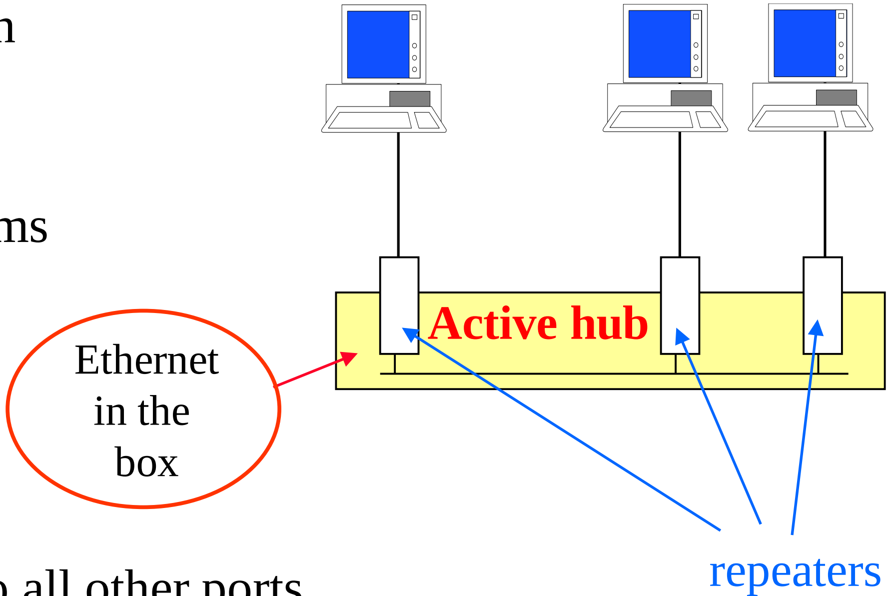






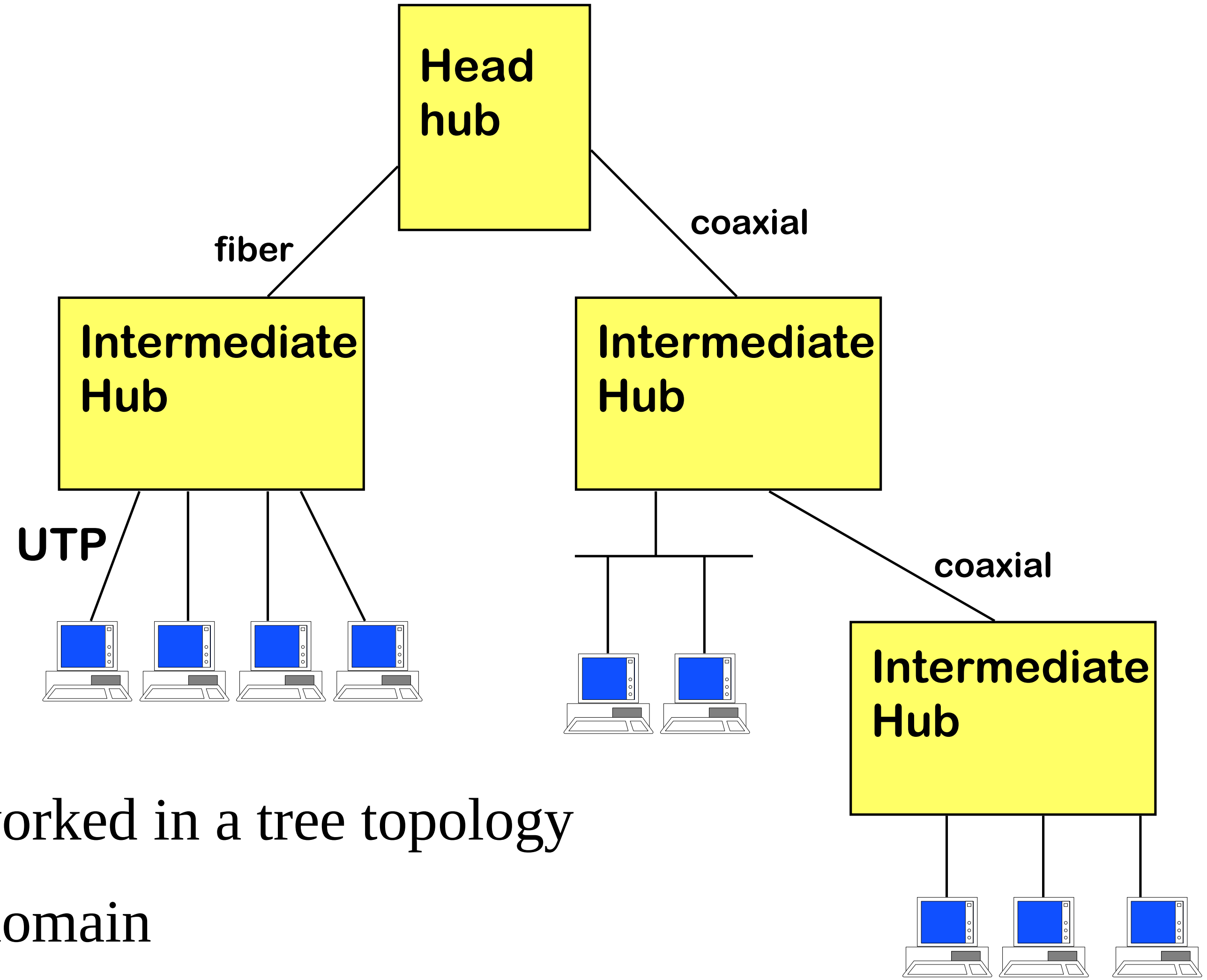
Ethernet Evolution - Active Hub

- 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



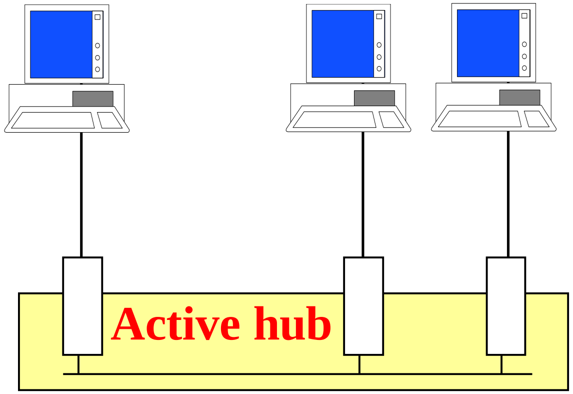
- Repeaters
  - » repeats bits received on one port to all other ports
  - » performs physical layer functions only
  - » if collision detected on one port ➔ repeats random bits on other port
- One network with repeaters ➔ one collision domain

Ethernet Evolution – Networks of Hubs



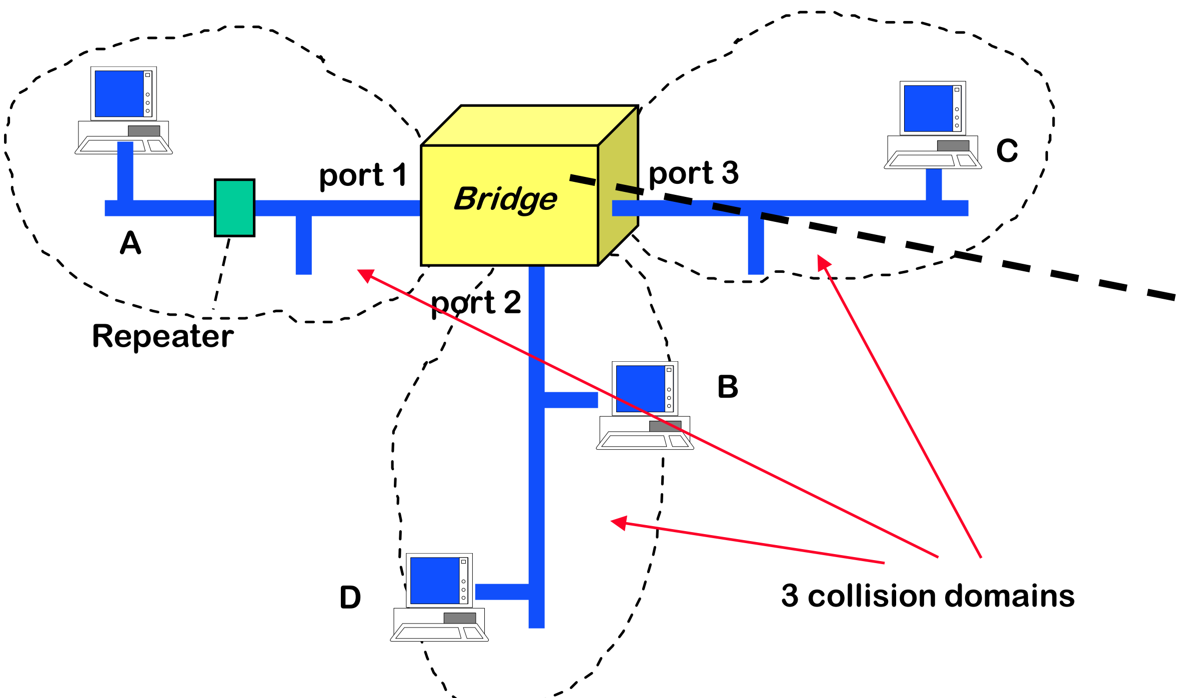
- Active hubs networked in a tree topology
- Single collision domain

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



Ethernet Evolution - Bridge

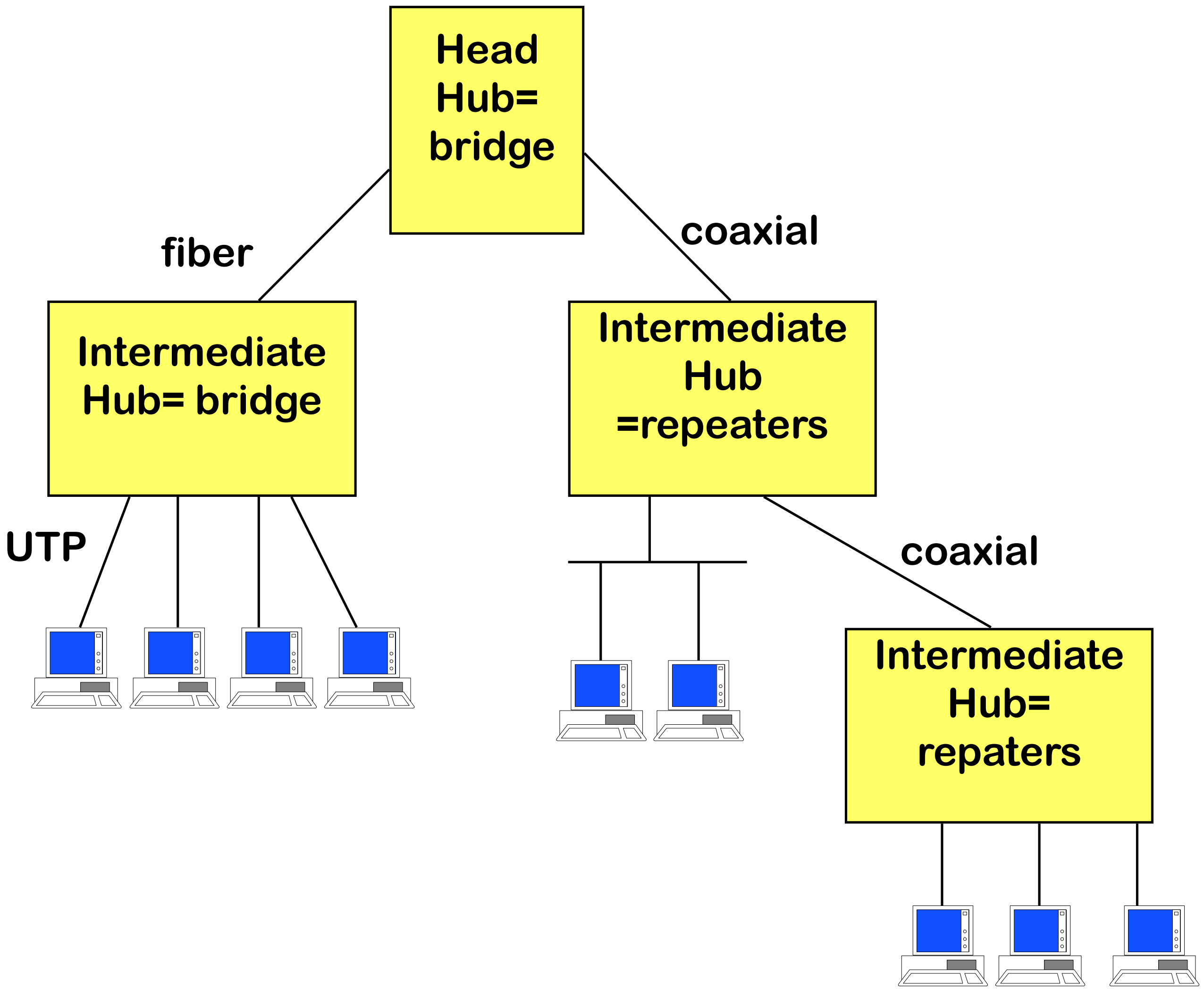
- Bridge
  - » forwards MAC frames to destinations based on MAC addresses
  - » Packet received on one port ➔ analyzed by bridge ➔ re-sent on some other port
- Bridge separates **collision** domains
  - » a bridged LAN maybe larger than a repeated LAN
  - » several frames may be transmitted simultaneously



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

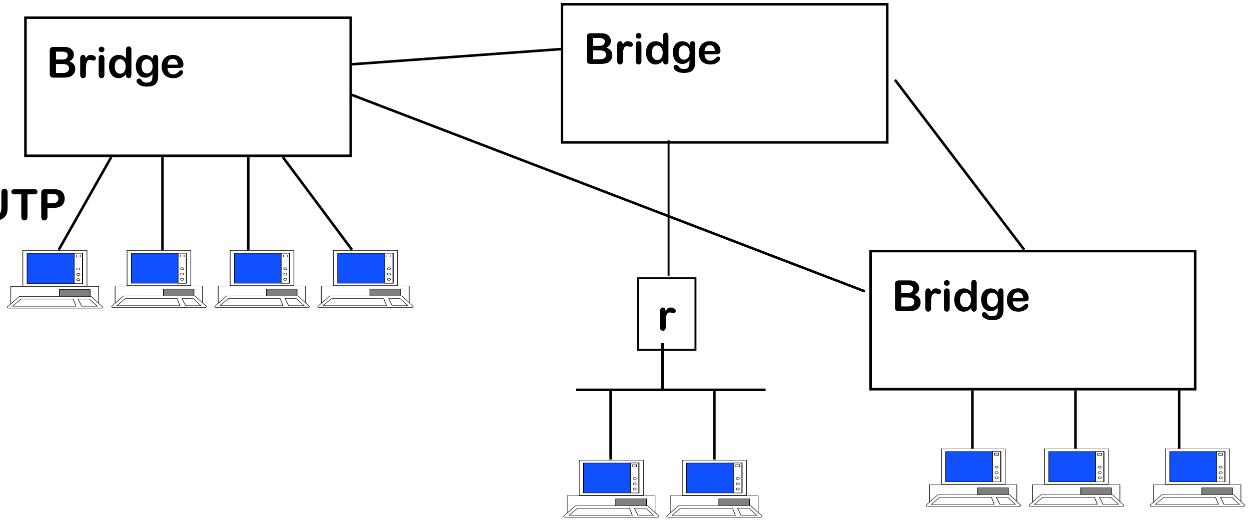
- UTP cables have multiple pairs of cables
  - » Two pairs started to be used to support communications in both directions simultaneously

- 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

- 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
  - Active hubs are primarily *bridges*

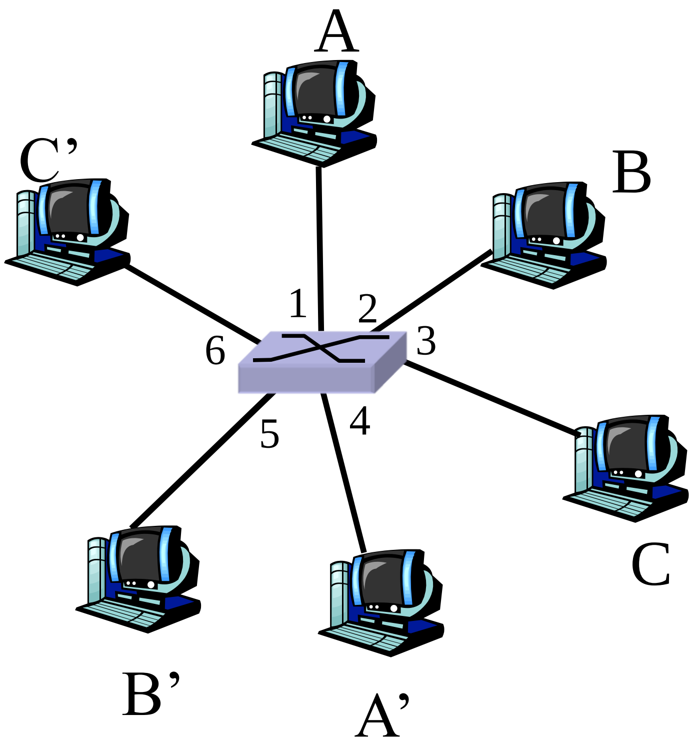


Switch

- Link-layer device
- Forwards Ethernet frames
- Transparent to hosts

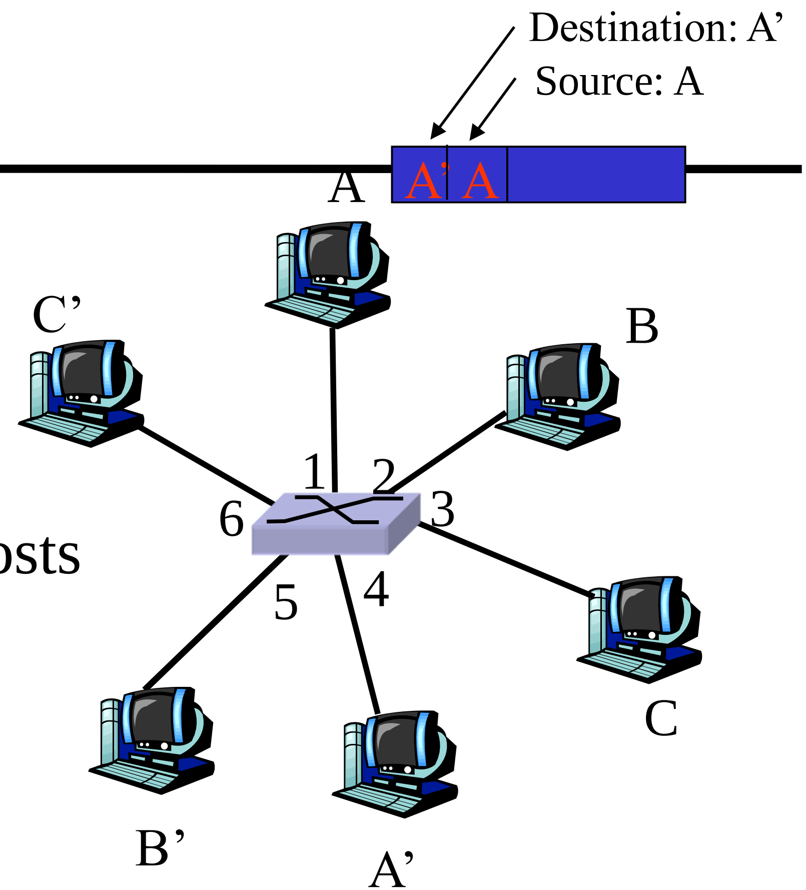
  hosts are unaware of its presence
- Plug-and-play, self-learning

  Does not need to be configured
- Has forwarding table



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 link 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

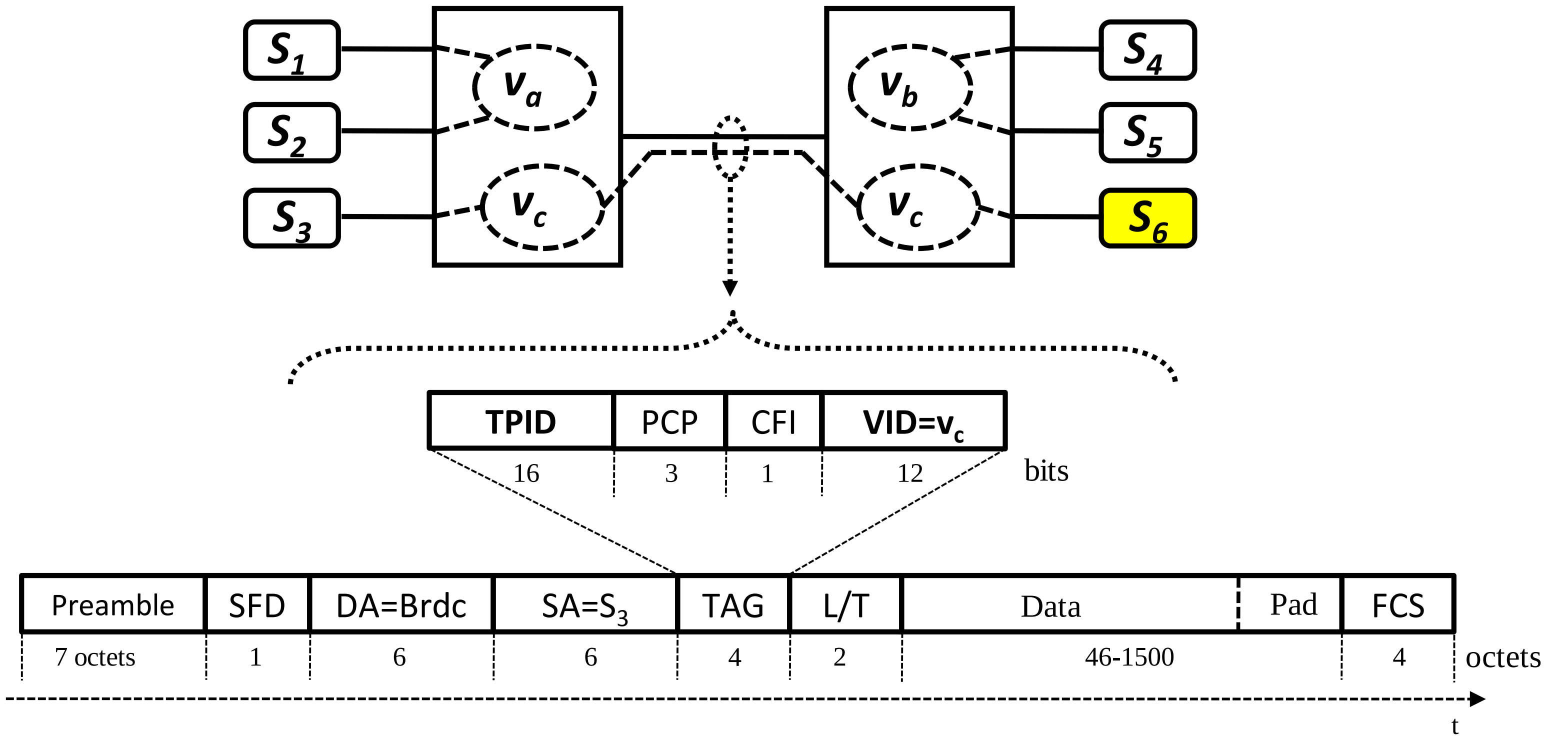
}

else flood

forward on all but the interface
on which the frame arrived

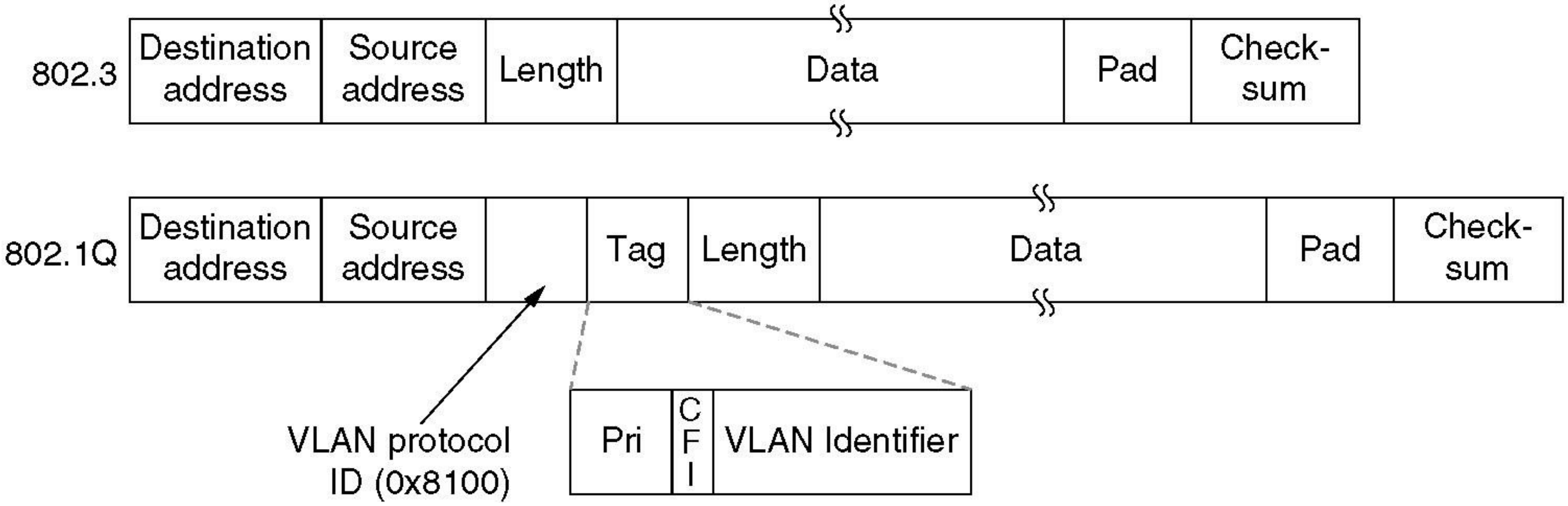
Virtual LANs

- One bridge/switch simulates multiple LANs / broadcast domains
- One LAN may be extended to other bridges



The IEEE 802.1Q Standard (2)

The 802.3 (legacy) and 802.1Q Ethernet frame formats



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