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*Redes de Computadores*

# **Medium Access Control**

*Manuel P. Ricardo*

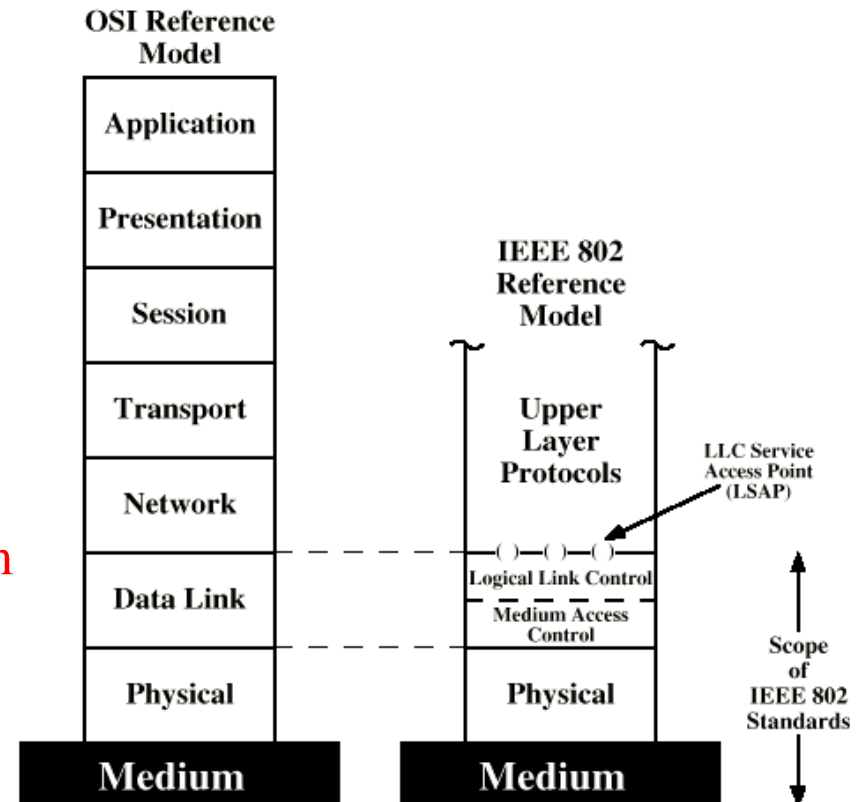
*Faculdade de Engenharia da Universidade do Porto*

- 
- » *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*

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- ◆ 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

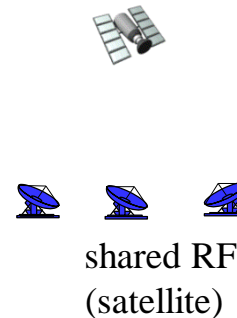
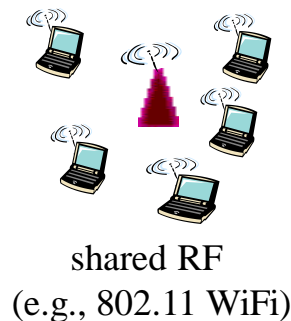
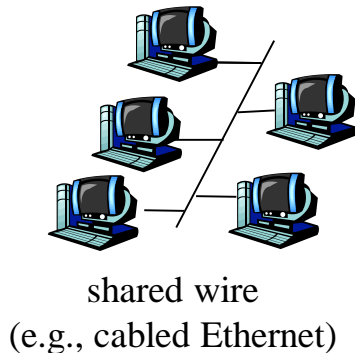


# Multiple Access Links

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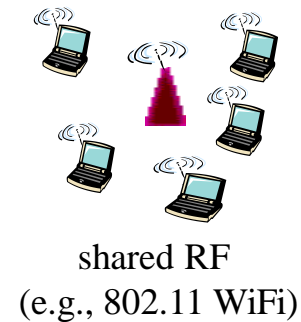
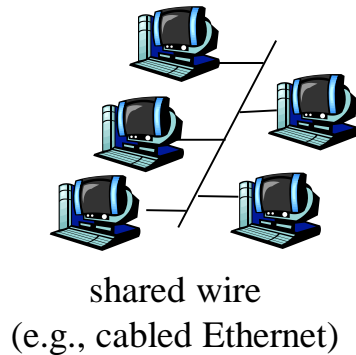
## Two types of *links*

- ◆ 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



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

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



# *Ideal Multiple Access Protocol*

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## ◆ Problem

How to coordinate the stations  
to use a common broadcast and shared channel  
of rate  $\mathbf{R}$  bit/s?



## ◆ Requirements of the **ideal** Multiple Access Protocol

- » one station wants to transmit → it uses the  $\mathbf{R}$  bit/s
- »  $\mathbf{m}$  stations want to transmit → each station uses an average rate  $\mathbf{R/m}$  bit/s
- » decentralized: no coordination, no synchronization of clocks
- » simple

# *MAC Protocols – Three Classes*

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## 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*

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- ◆ 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*

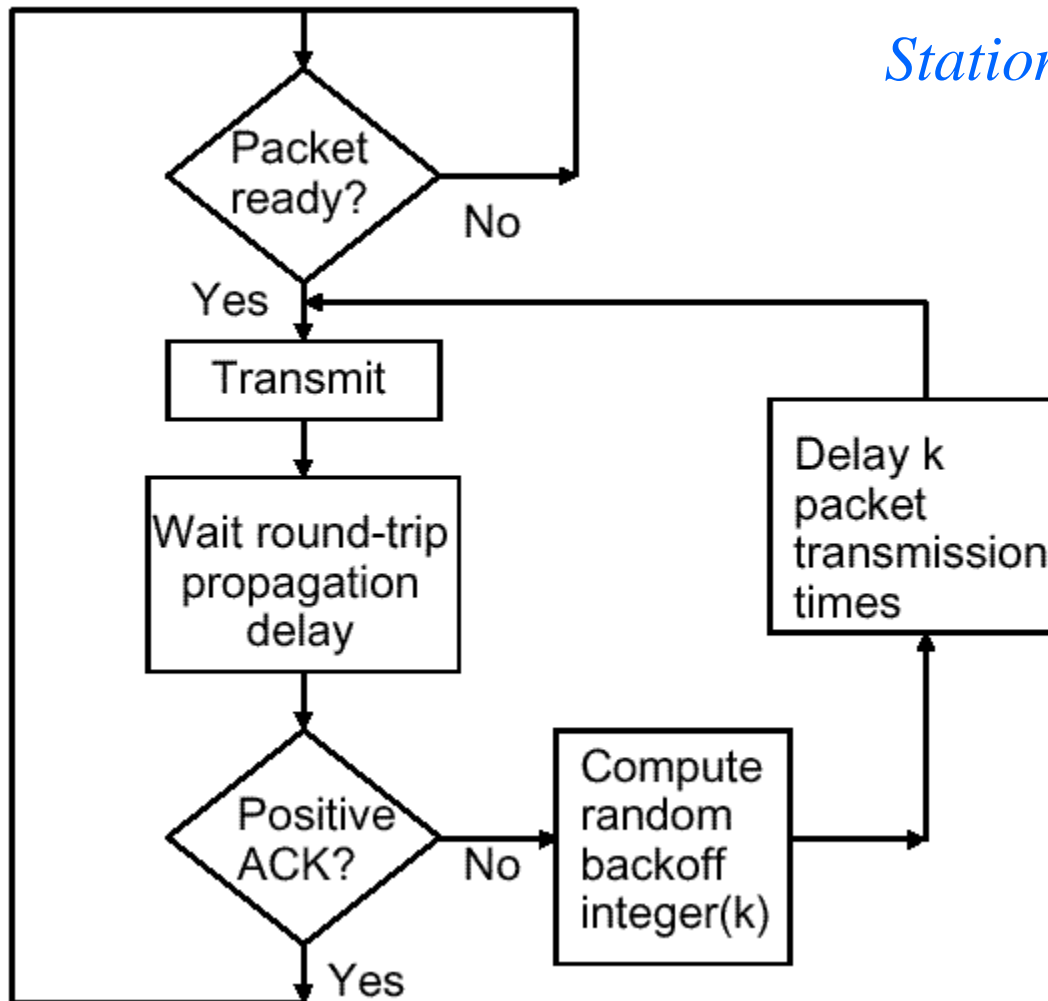
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- ♦ Station
  - » Transmits one frame at time
  - » Probability one frame being generated in  $\delta$ :  $p_1(\delta) \approx \lambda\delta$
  - » Poisson arrival
  
- ♦ Collision
  - » If two stations transmit at same time → collision
  - » Frames 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

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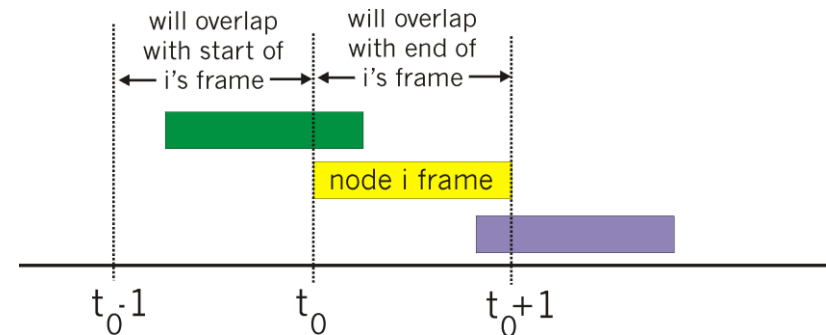
*Station behaviour*



# *ALOHA – Two versions*

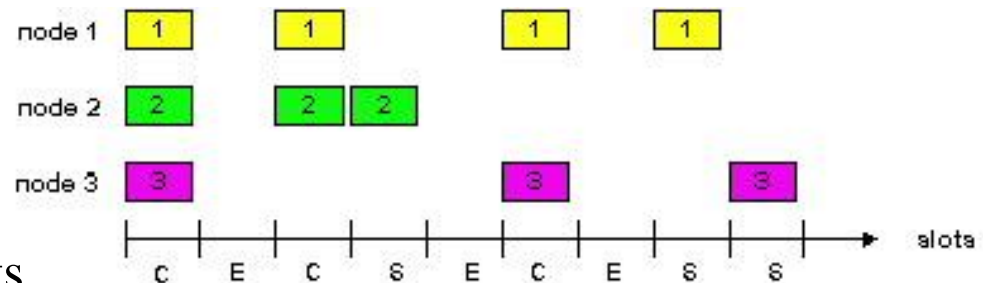
## ♦ Pure Aloha (unslotted)

- » No slot concept
- » Station transmits when it has a frame to transmit



## ♦ Slotted Aloha

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



# Slotted Aloha - Efficiency

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## ♦ Traffic model

- » Poisson arrival, large number  $N$  of stations
- » Constant frame length,  $T_{\text{frame}} = 1$
- »  $S$  – Received traffic
  - $\lambda_{\text{rx}}$  – rate of received frames (transmitted with success)
  - $S = \lambda_{\text{rx}} * T_{\text{frame}} < 1$  ;  **$S$  = efficiency**
- »  $G$  – Generated traffic (new packets and retransmissions)
  - $\lambda$  – rate of generated packets
  - $G = \lambda * T_{\text{frame}}$
- »  $p$  – probability of **one station** generating a packet (new or retransmission) in  $T_{\text{frame}}$ 
  - $N * p = G$

## ♦ Slotted Aloha

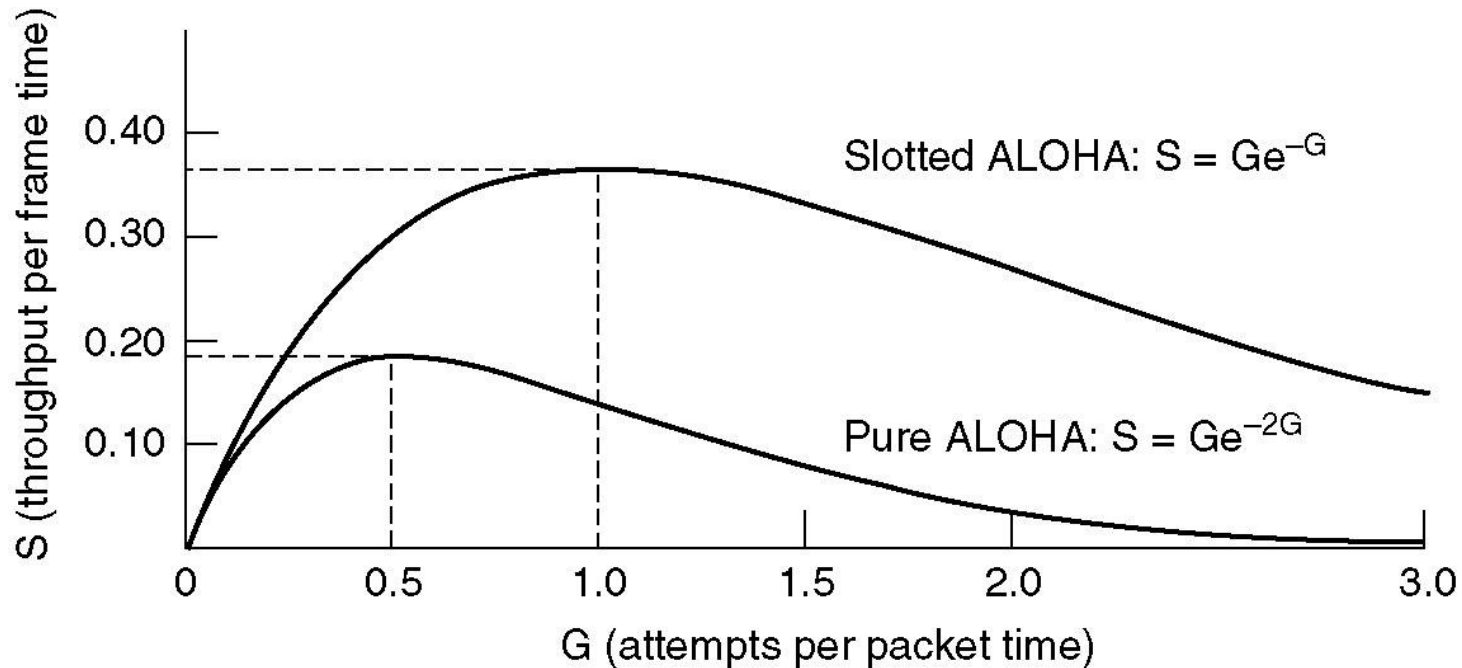
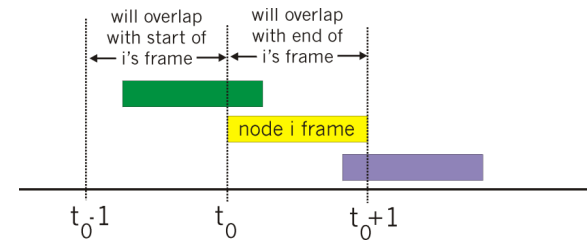
- »  $S = P(\text{Success}) = N(p(1-p)^{N-1}) \approx Npe^{-p(N-1)} \approx Npe^{-pN} = Ge^{-G} = Gp_0(T_{\text{frame}}) = Ge^{-G}$
- »  $S_{\text{max}} \Rightarrow \frac{\partial S}{\partial G} = 0; \quad G = 1; \quad S_{\text{max}} = \frac{1}{e} = 36,8\%$

# Aloha - Efficiency

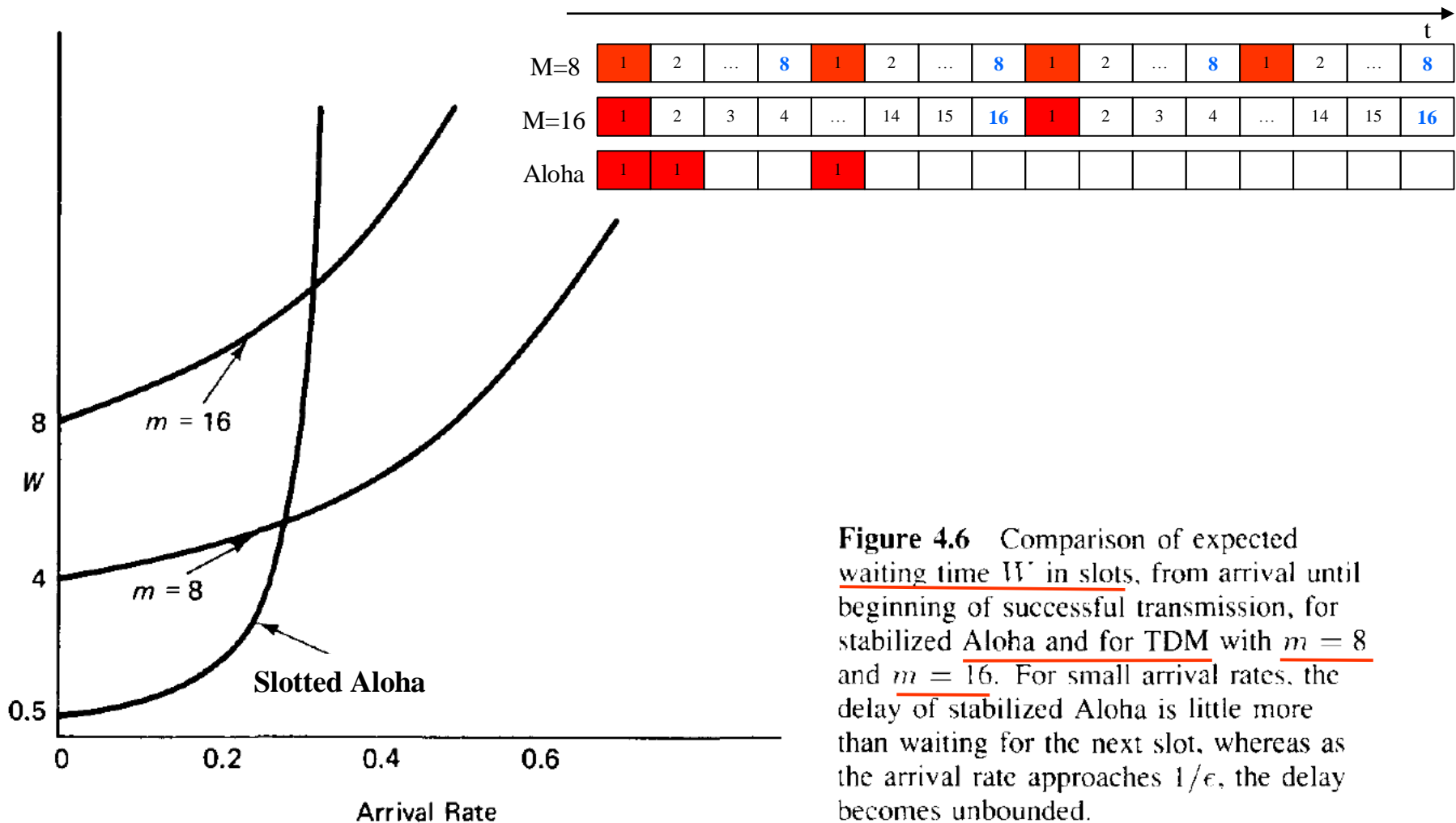
## ◆ Pure Aloha

$$\gg S = Gp_0(2 \times T_{frame}) = Ge^{-2G}$$

$$\gg S_{\max} \Rightarrow \frac{\partial S}{\partial G} = 0; \quad G = \frac{1}{2}; \quad S_{\max} = \frac{1}{2e} = 18,4\%$$



# Waiting Time – Aloha versus Time Division Multiplexing



**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.

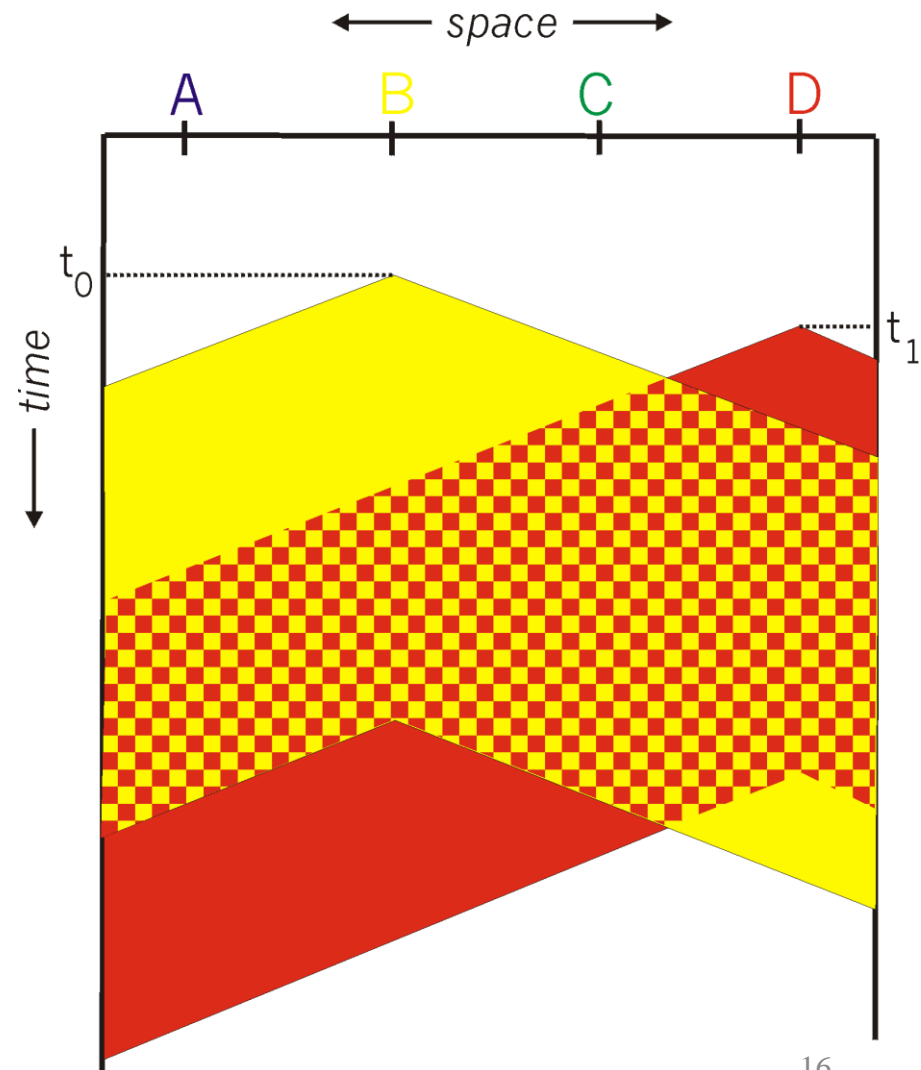
# *CSMA (Carrier Sense Multiple Access)*

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- ♦ 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 =  $2 * T_{\text{prop}}$
- ◆  $T_{\text{prop}}$  and  $T_{\text{frame}}$ 
  - » Determine collision probability
  - »  $a = T_{\text{prop}} / T_{\text{frame}} \ll 1$





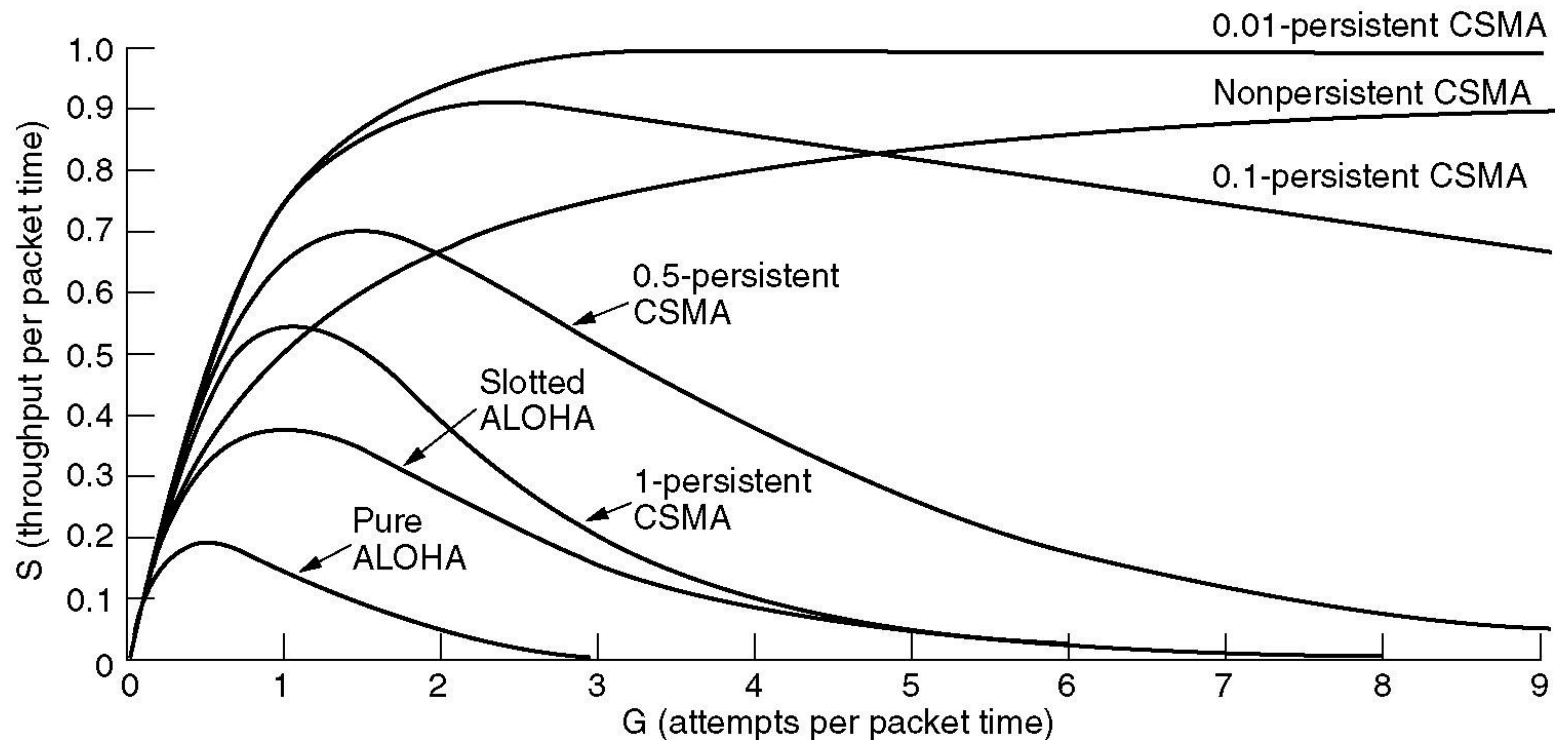
# CSMA Variants

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- ♦ 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 algorithmp-persistent

# *Efficiencies – x-persistent CSMA*

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

# CSMA/CD –

## Carrier Sense Multiple Access / Collision Detection

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### ◆ Carrier Sense

- » station senses medium before transmitting
  - If free → station starts transmission
  - If busy → waits until free and then transmits

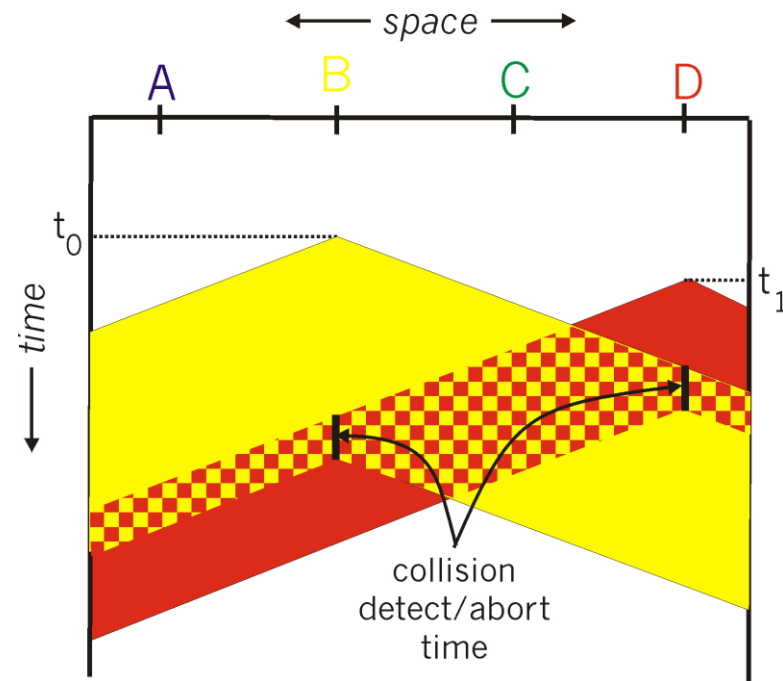
**persistent**

### ◆ Collision Detection

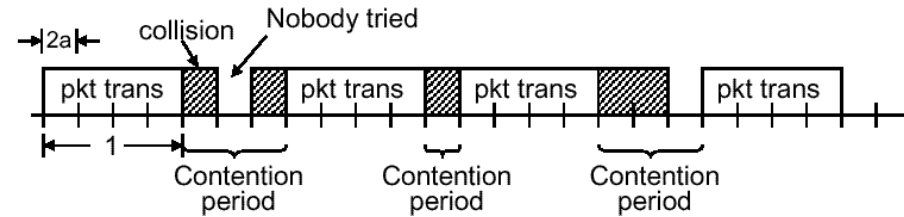
- » station listens medium while transmitting
- » if collision is detected
  - transmission is aborted
  - retransmission delayed using a Binary Exponential Back-off algorithm
- » **no ACK!**

### ◆ Binary Exponential Back-off algorithm

- » time modeled in time slots;  $T_{\text{slot}} = 2 * T_{\text{prop}}$
- » after the  $i^{\text{th}}$  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  $n_{tx}$  required to transmit a frame  $n_{tx} = \frac{T_{frame}}{T_{slot}} = \frac{T_{frame}}{2 \times T_{prop}} = \frac{1}{2a}$

- ◆ Efficiency  $S = \frac{n_{tx}}{n_{tx} + E[n_{cont}]}$

- ◆ 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

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

- ◆  $E[n_{cont}] = \sum_{i=1}^{+\infty} i(1-A)^i A = \frac{1-A}{A} \Rightarrow S = \frac{1/2a}{1/2a + (1-A)/A} = \frac{1}{1 + 2a(1-A)/A}$

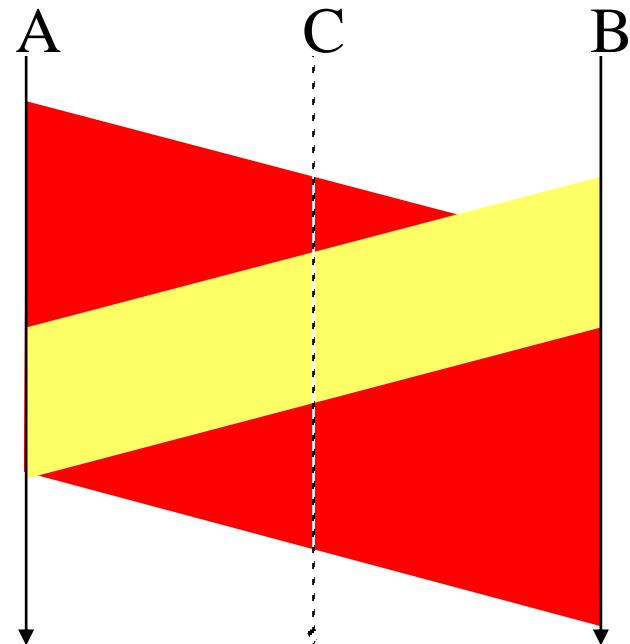
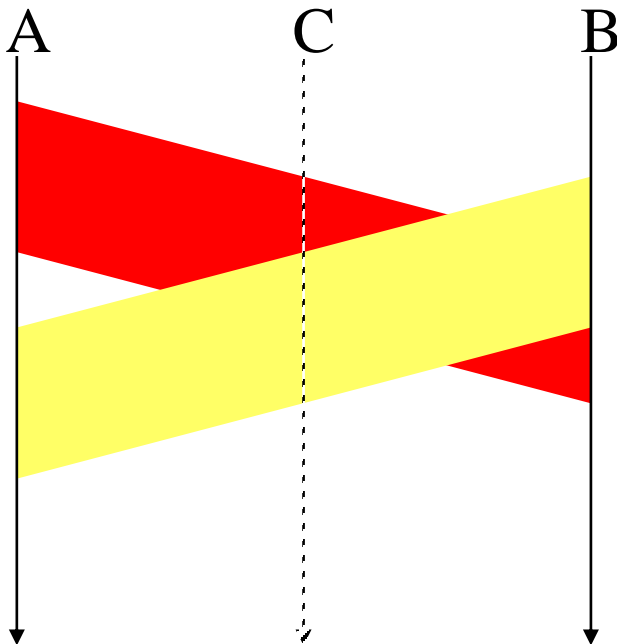
- ◆  $p=1/N \Rightarrow A_{MAX} = \left(1 - \frac{1}{N}\right)^{N-1} \lim_{N \rightarrow \infty} A_{max} = \lim_{N \rightarrow \infty} \left(1 - \frac{1}{N}\right)^{N-1} = \frac{1}{e} \Rightarrow \lim_{N \rightarrow \infty} S = \frac{1}{1 + 3.44a}$



# *CSMA/CD – Minimum Frame Size is Required*

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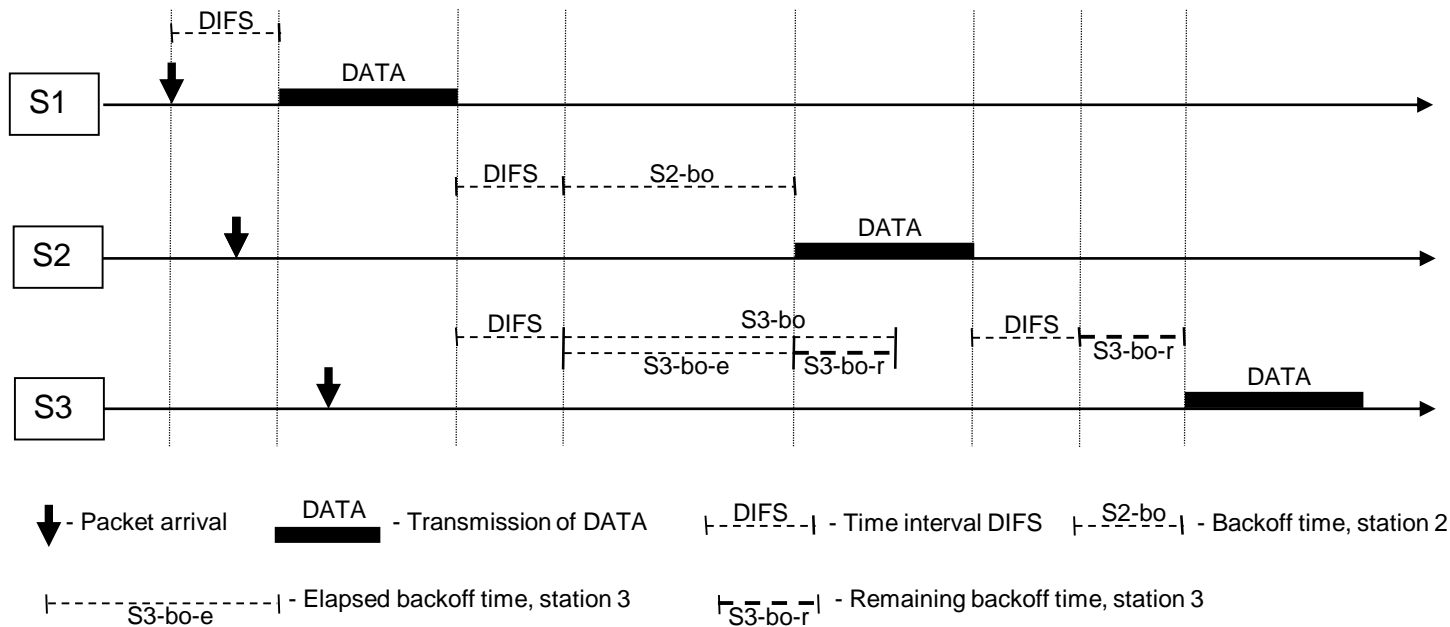
## Minimum frame size required for detecting a collision!

- ◆ 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)*

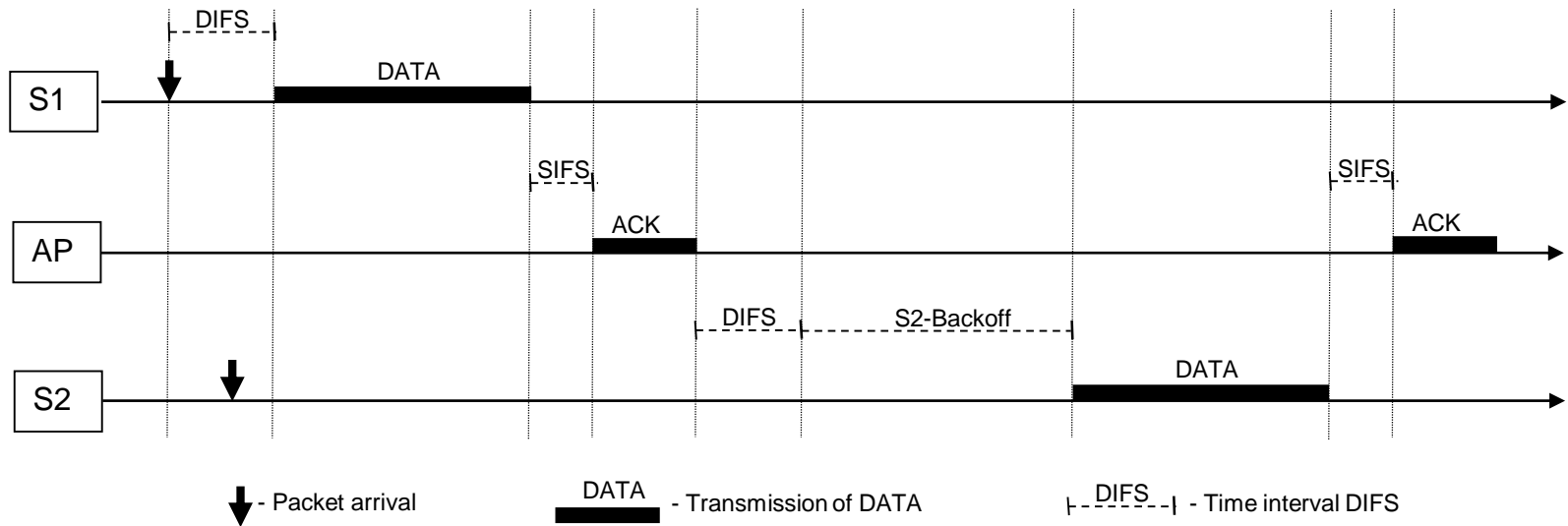
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- ♦ Station with a frame to transmit
  - » monitors the channel activity
  - » until an idle period equal to a Distributed Inter-Frame Space (DIFS) has been observed
  - » if medium free → transmits frame
  
- ♦ If the medium is sensed busy
  - » random 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

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## *CSMA/CA – ACK Required*

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- ♦ 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***

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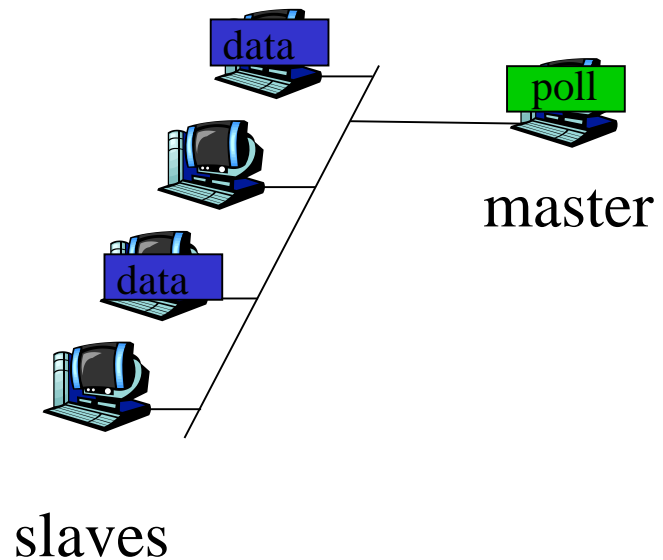
- ♦ Channel partitioning MAC protocols (TDM, FDM)
  - » share channel efficiently and fairly at high loads
  - » are inefficient at low loads
    - delay in channel access;  $1/N$  bandwidth allocated even if only 1 active node!
  
- ♦ Random access MAC protocols (Aloha, CSMA, CSMA/CD, CSMA/CA)
  - » 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

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## Polling

- » master station *invites* slave stations to transmit in turn
- » concerns
  - polling overhead
  - latency
  - single point of failure (master)

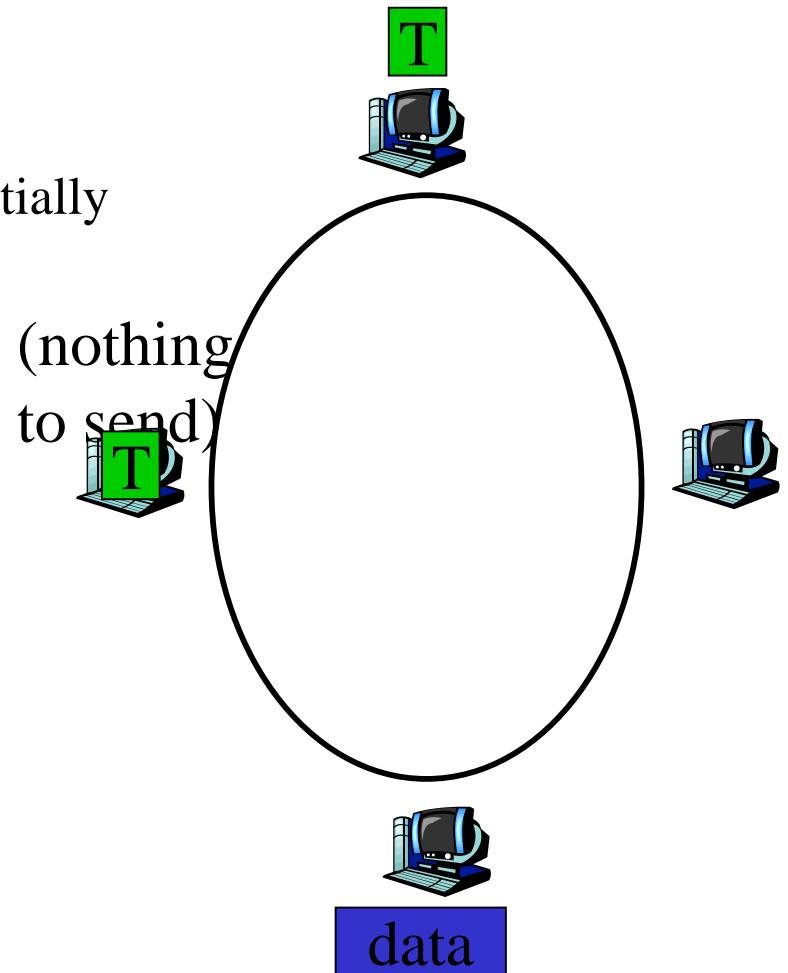


# *“Taking Turns” MAC protocols*

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## Token passing

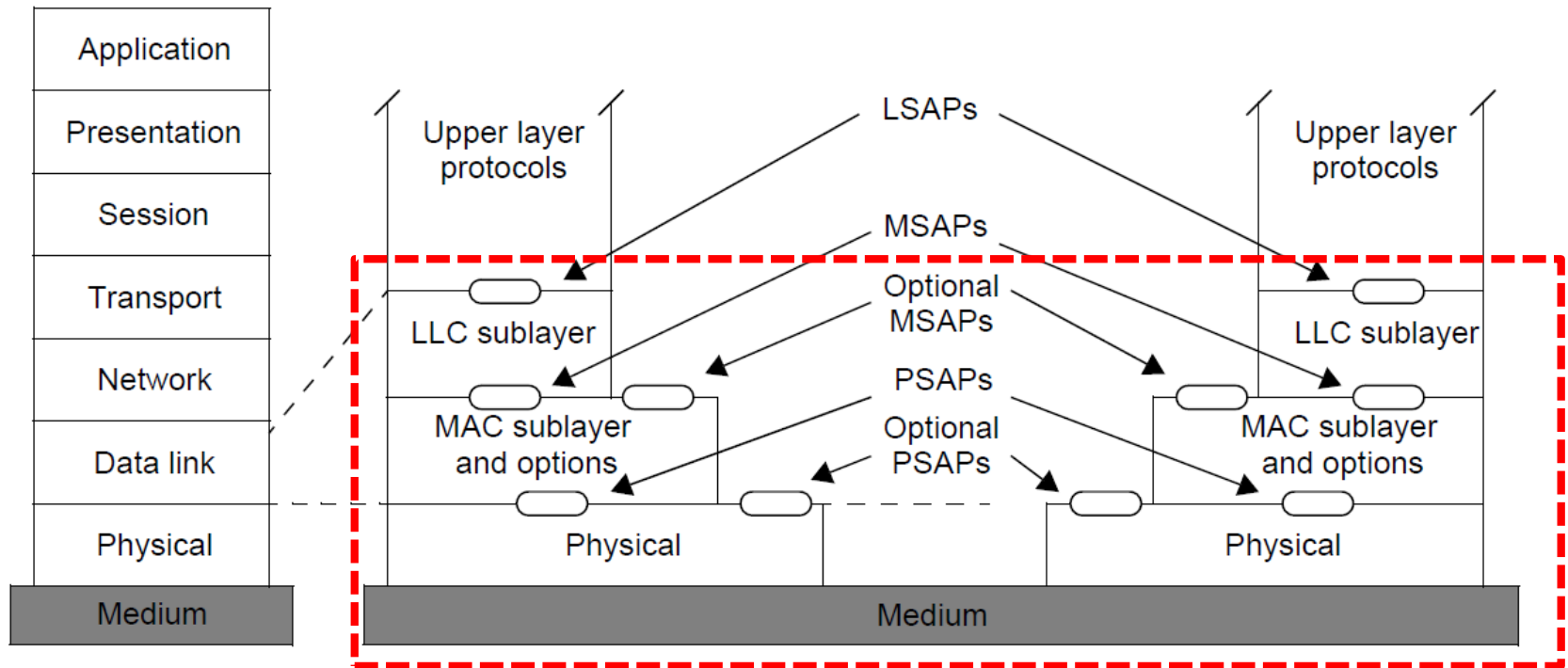
- » control token
  - passed from one station to next sequentially
- » token message
- » concerns
  - token overhead
  - latency
  - single point of failure (token)



# *IEEE Standards – Reference Model*

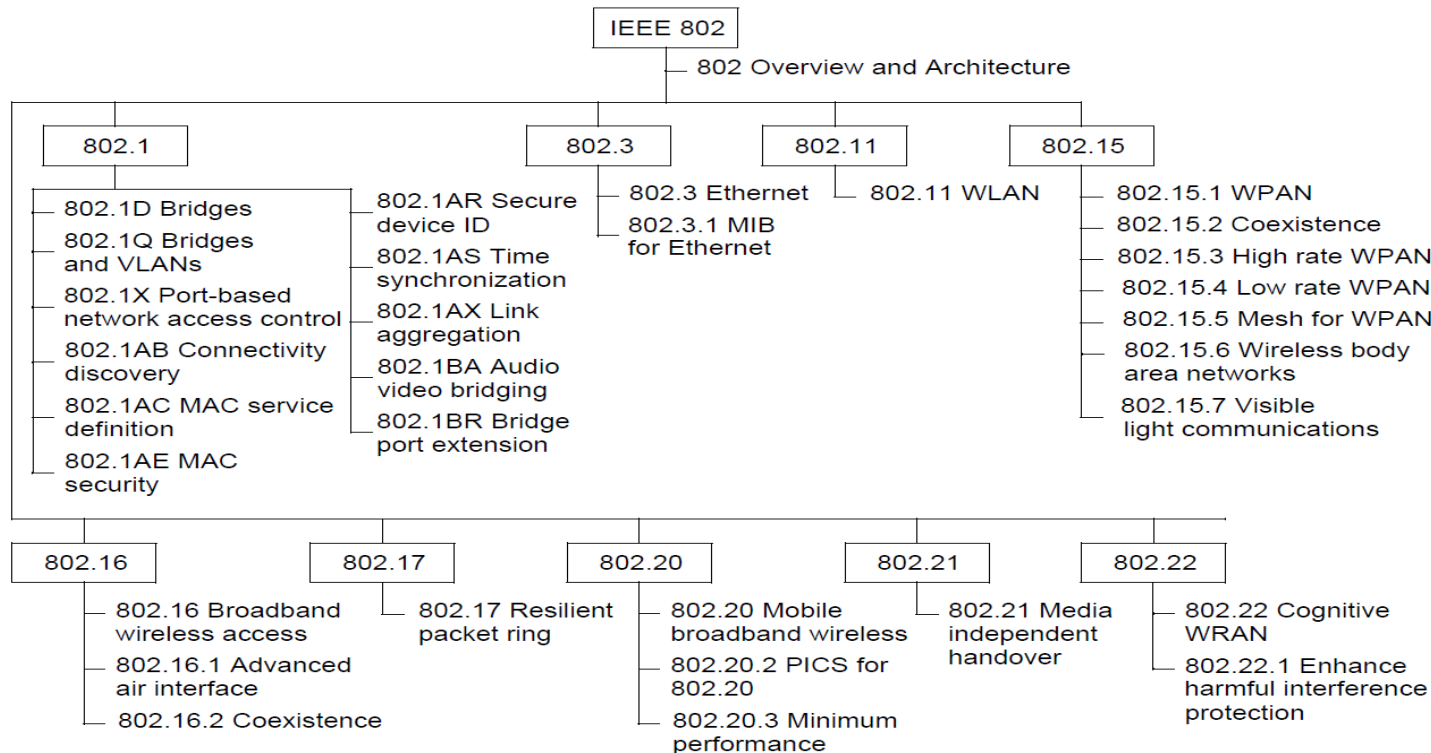
MSAP    MAC service access point  
LSAP    link service access point

PSAP    PHY service access point



# *IEEE Standards – Family of IEEE 802 Standards*

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

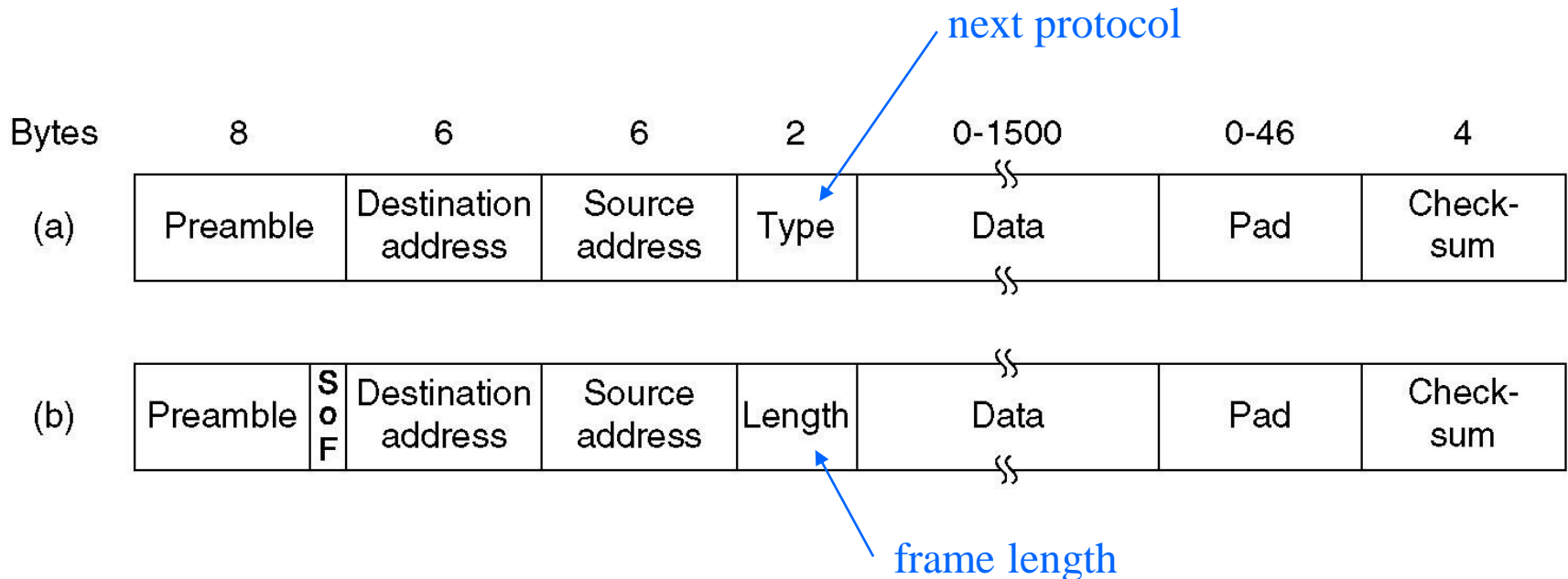
# Ethernet MAC Sublayer

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## Frame formats

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

**(b) IEEE 802.3**

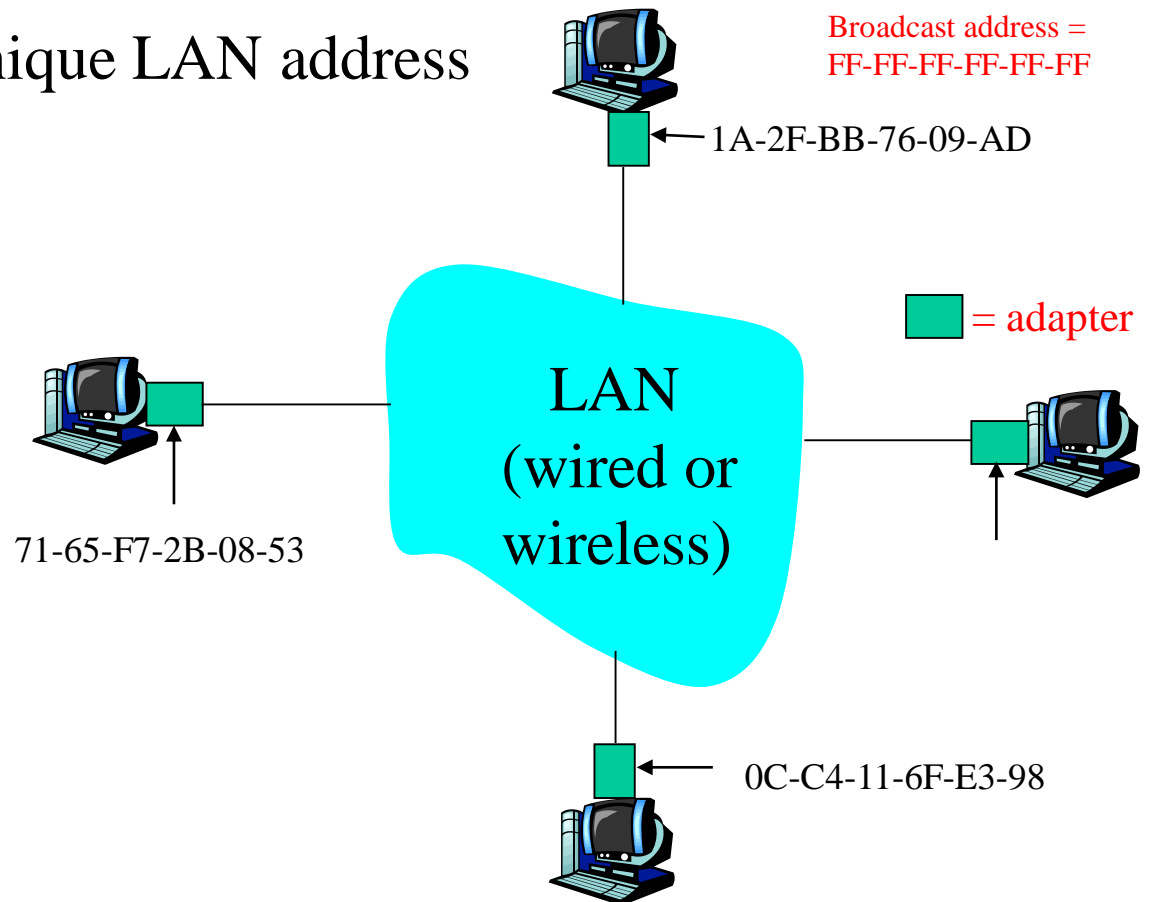




# MAC Address

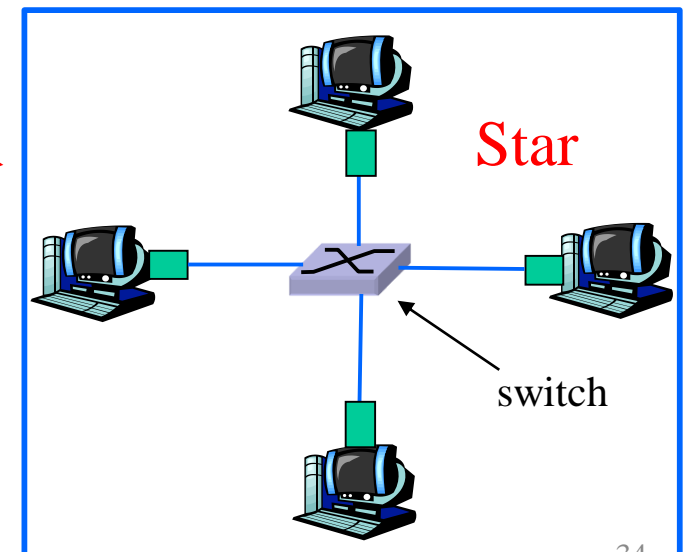
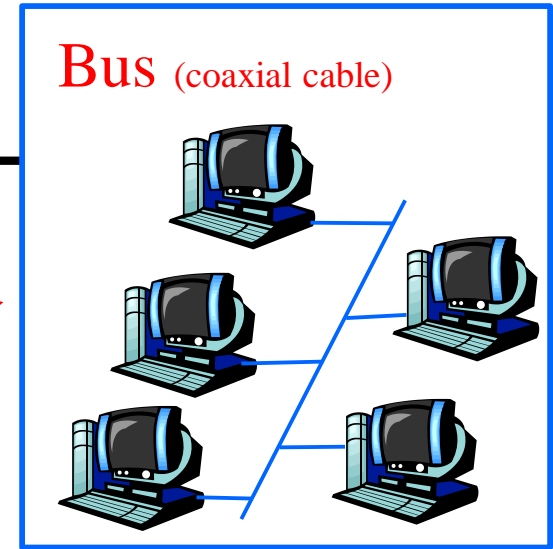
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- ◆ 48 bit MAC address (for most LANs)
- ◆ Each adapter has unique LAN address



# *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

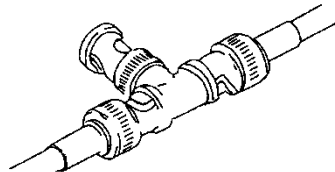
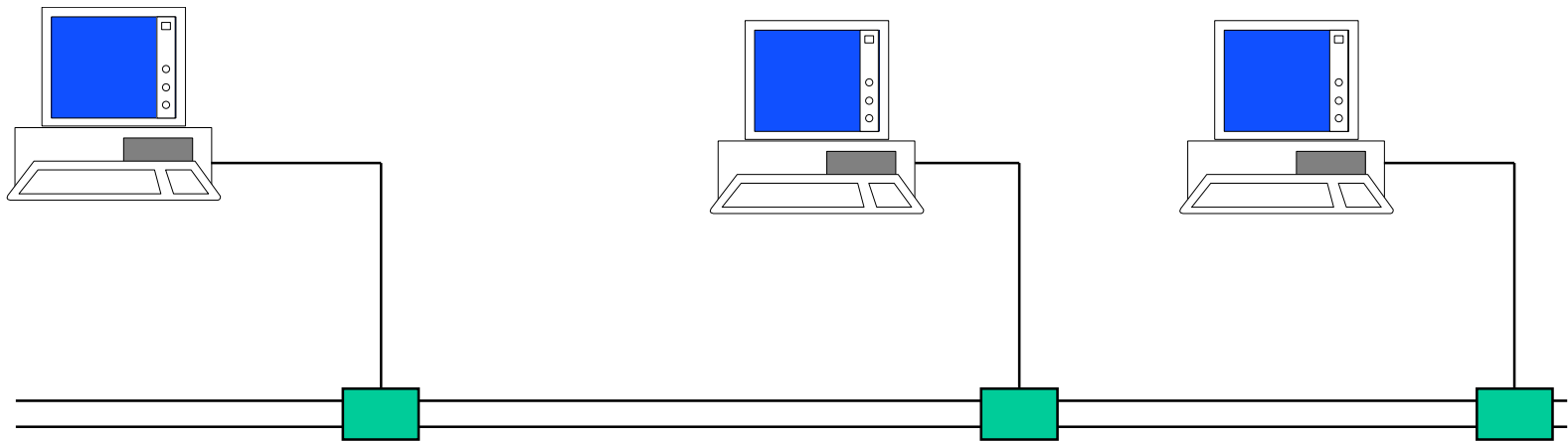


# *Ethernet Evolution – Coaxial Cable*

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First Ethernet was on coaxial cable

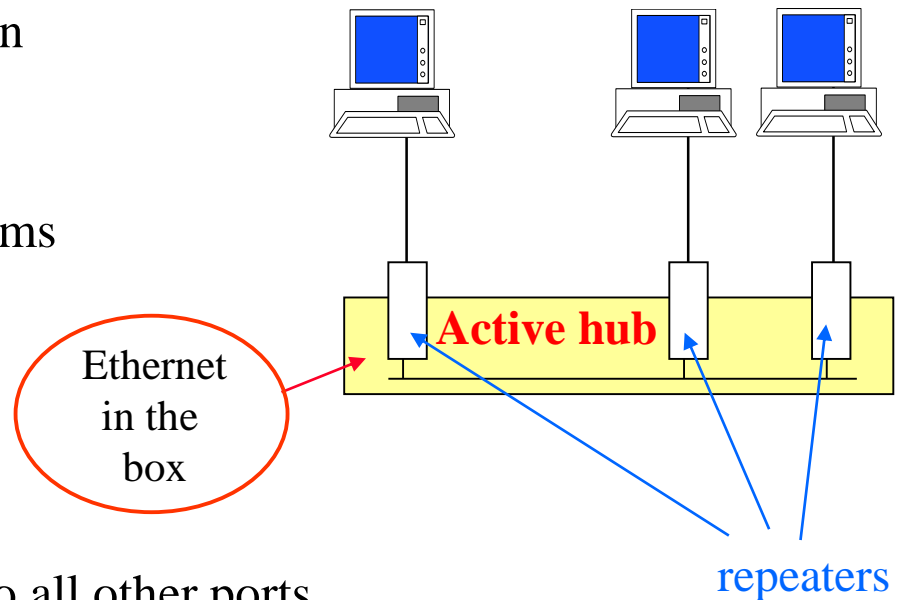
Allows multiple transmitters and receivers



# *Ethernet Evolution - Active Hub*

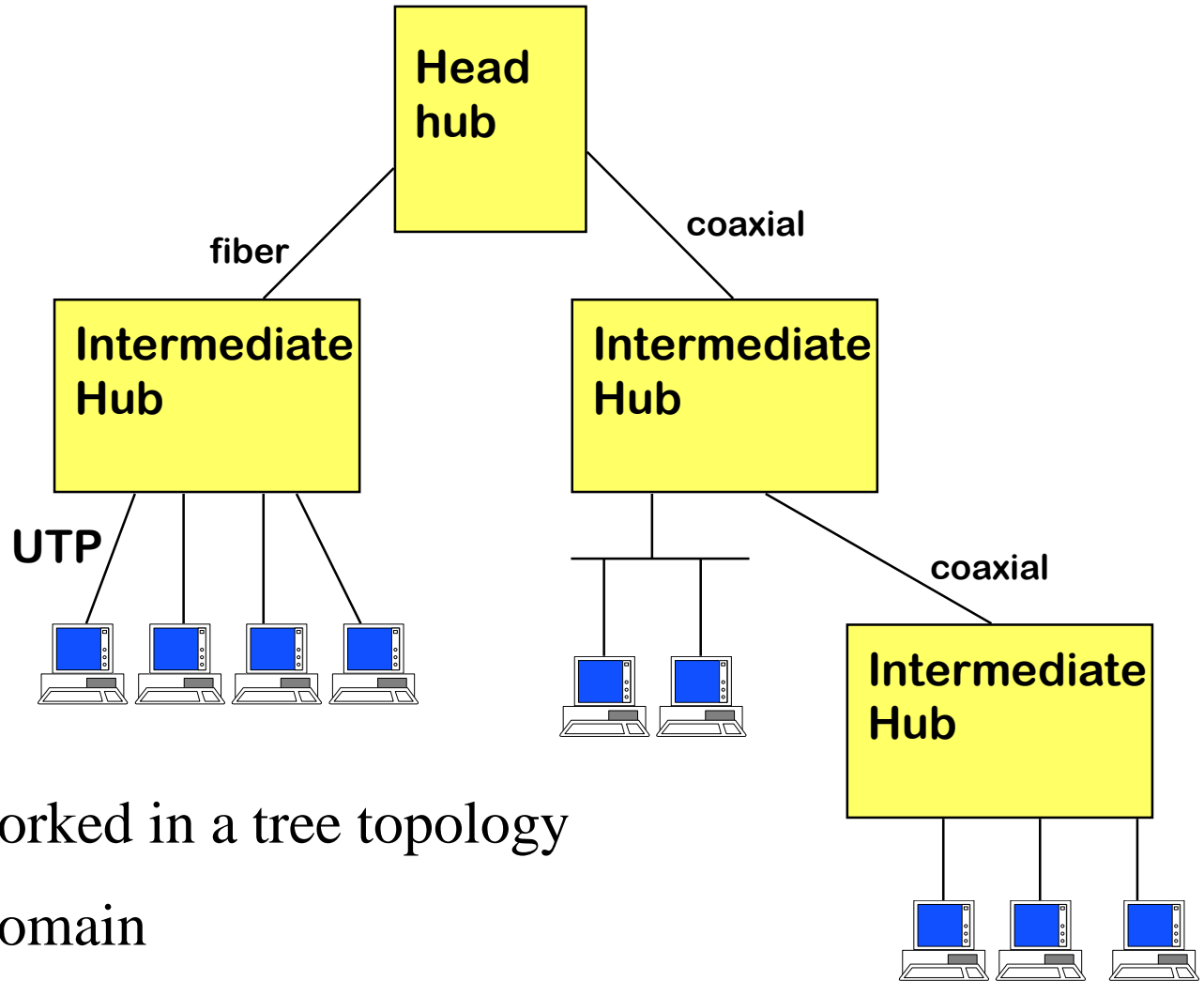
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- ◆ Original shared medium Ethernet → difficult to manage
  - » cable faults were hard to detect
  - » faults brought entire network down
- ◆ Active Hub
  - » solution to overcome cable problems
  - » point to point cables
  - » repeaters
- ◆ Repeaters
  - » 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



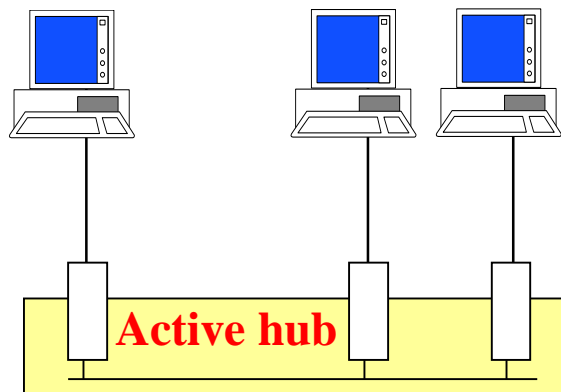
# *Ethernet Evolution – Networks of Hubs*

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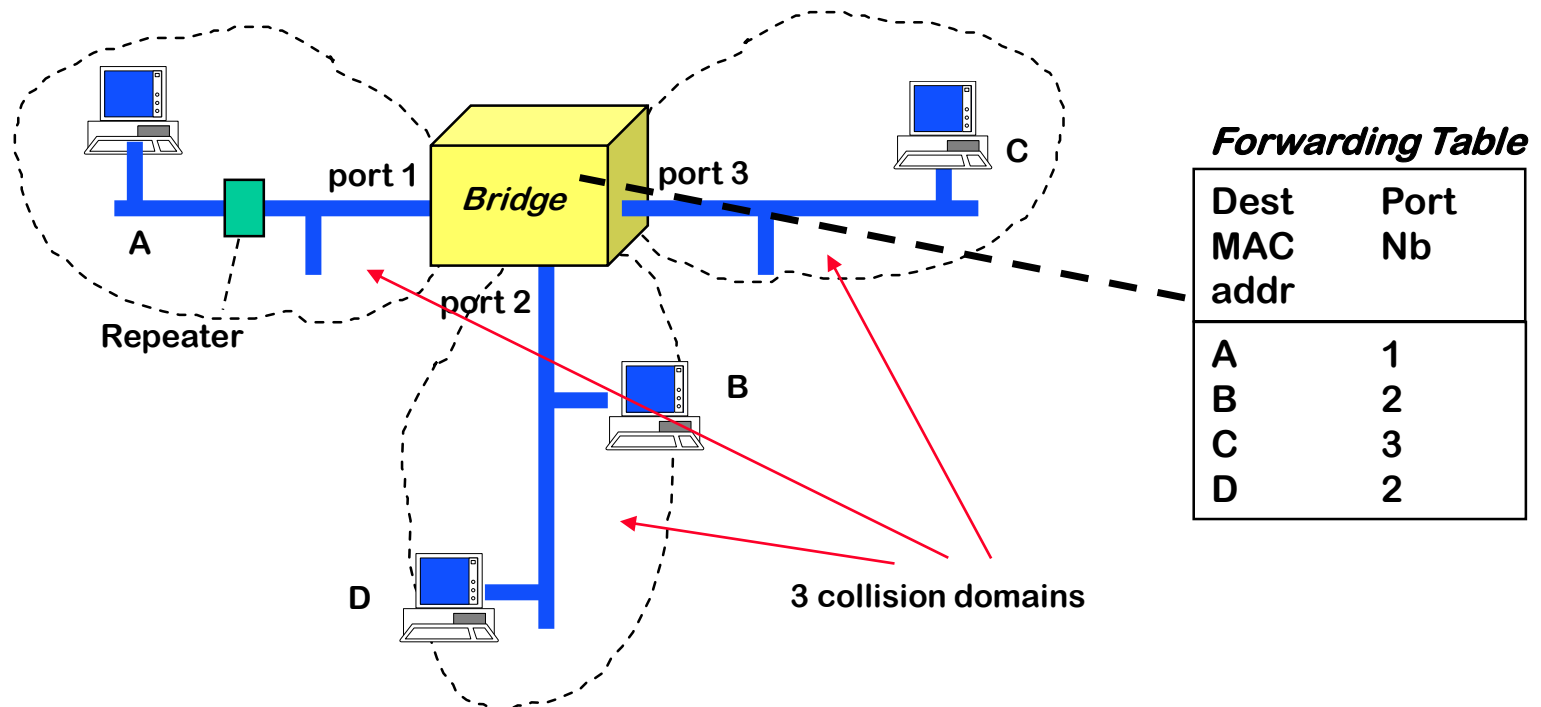
- ◆ Active hubs networked in a tree topology
- ◆ Single collision domain

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



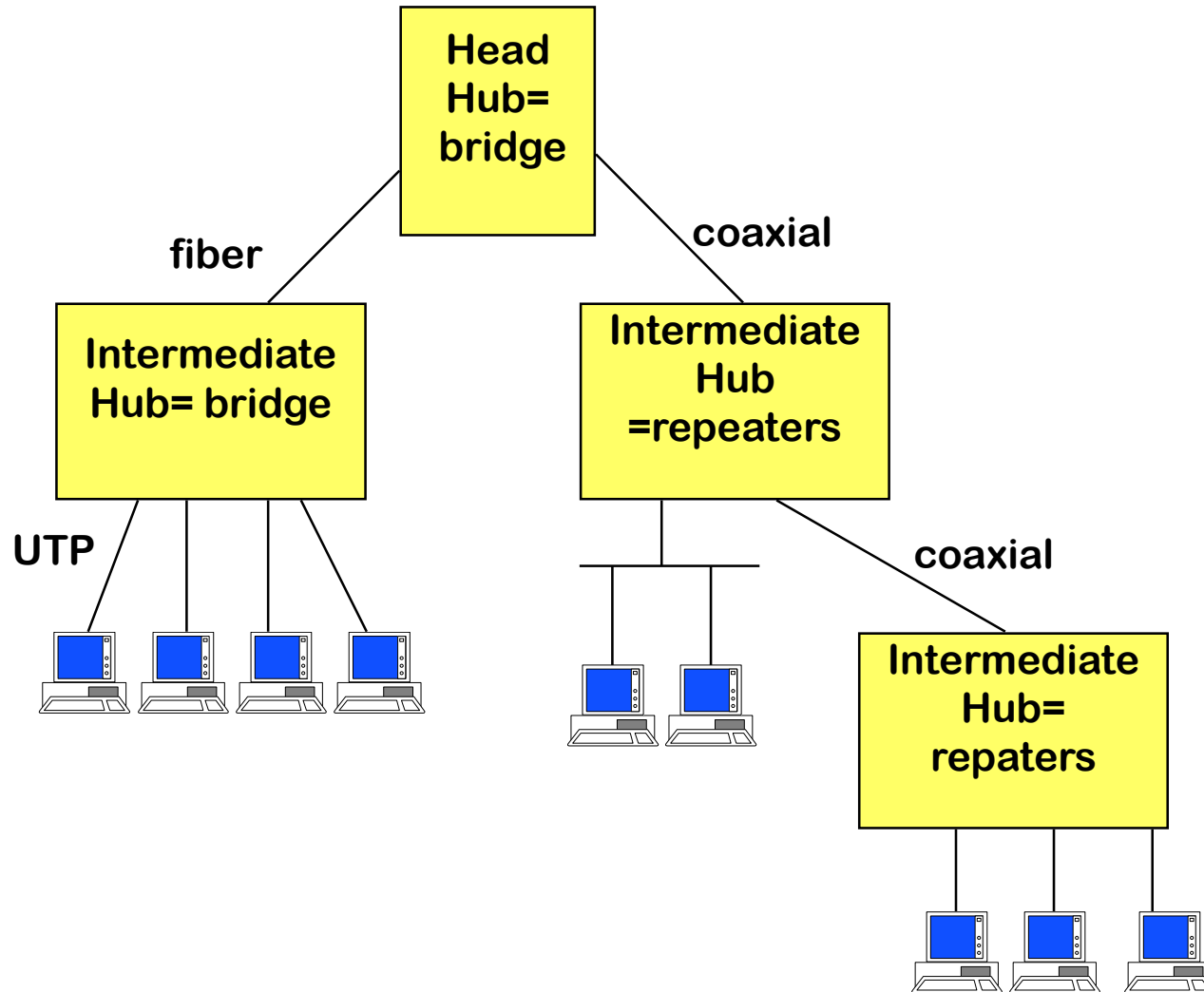
# Ethernet Evolution - Bridge

- ◆ 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



# *Ethernet Evolution – Bridges and Repeaters Combined*

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# *Ethernet Evolution – The Point to Point Only Cable*

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- ◆ 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*

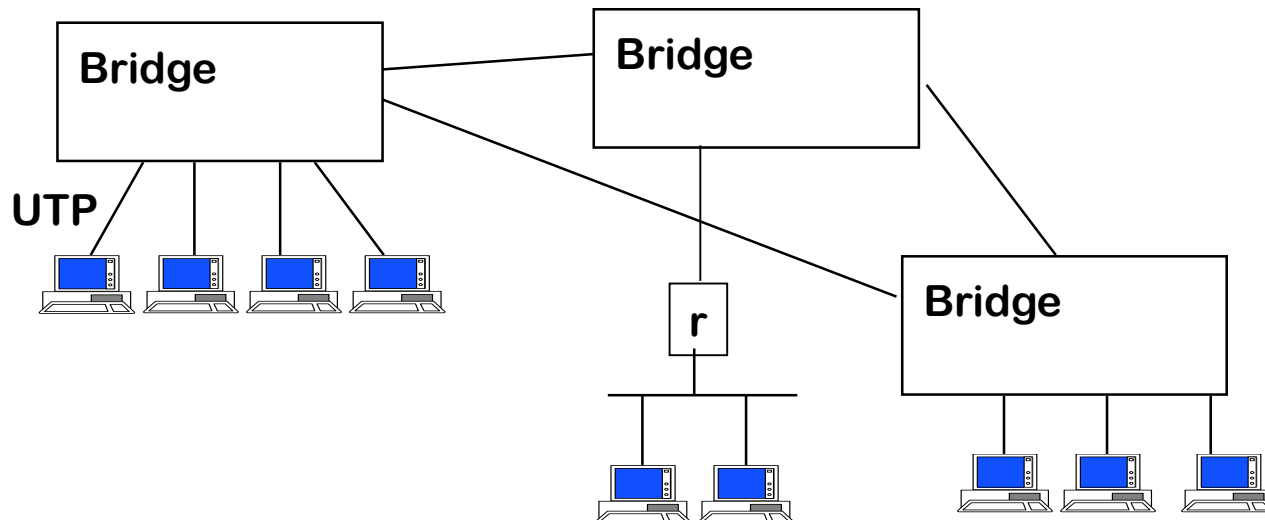
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- ♦ UTP cables have multiple pairs of cables
  - » Two pairs started to be used to support communications in both directions simultaneously
- ♦ Emergence of the **Full Duplex Ethernet**
  - » CSMA/CD in practice is not used → no collisions
  - » From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

# Current Ethernet

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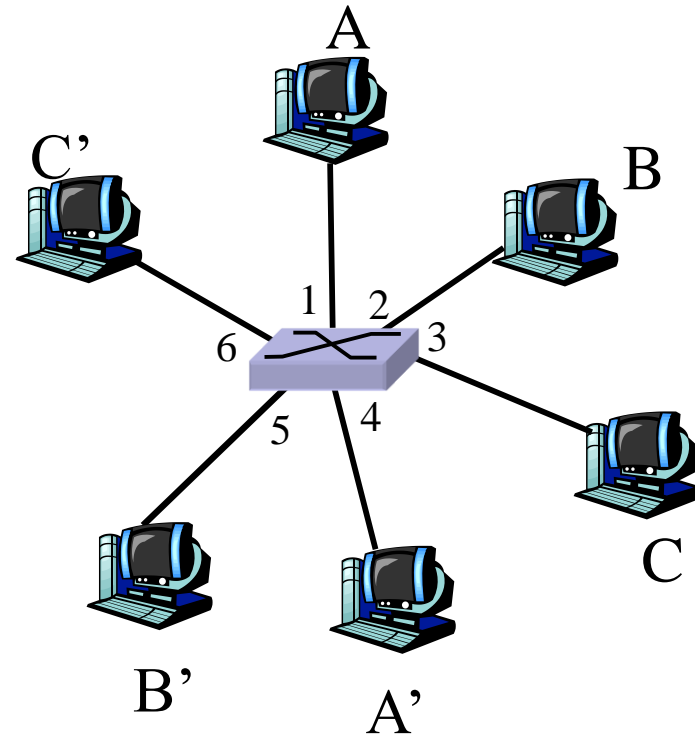
- ♦ Ethernet used for local interconnection of a limited number of systems (up to a few 100s in practice)
- ♦ Uses primarily point to point cables
  - » UTP for short distances, optical fiber for long links
  - » Active hubs are primarily *bridges*



# Switch

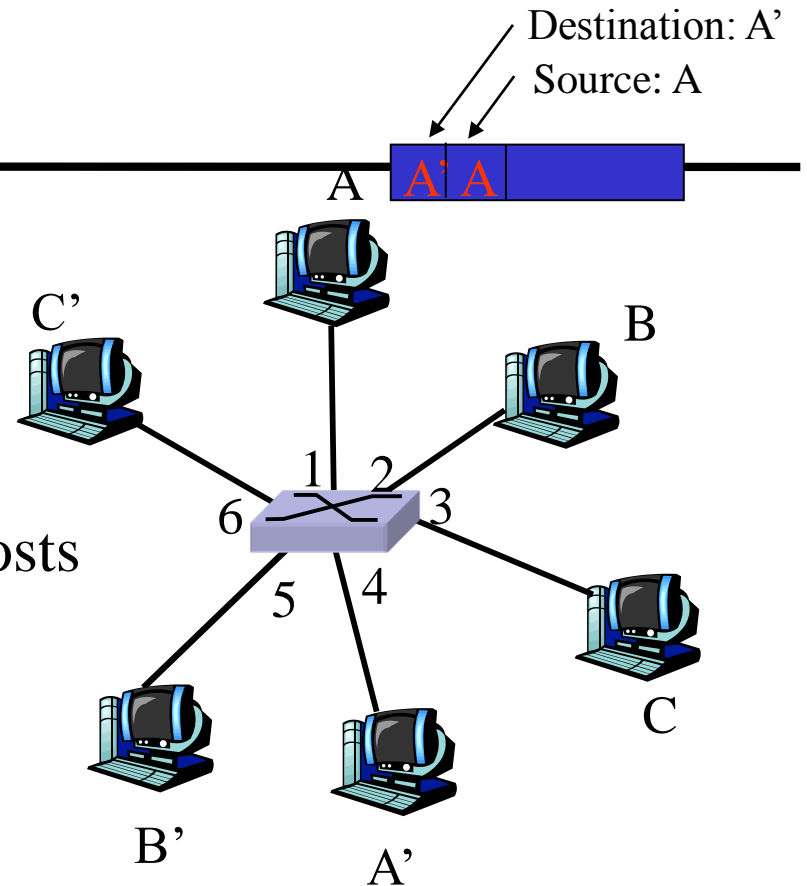
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- ◆ Link-layer device
- ◆ Forwards Ethernet frames
- ◆ Transparent to hosts
  - hosts are unaware of its presence
- ◆ Plug-and-play, self-learning
  - Does not need to be configured
- ◆ Has forwarding table



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*

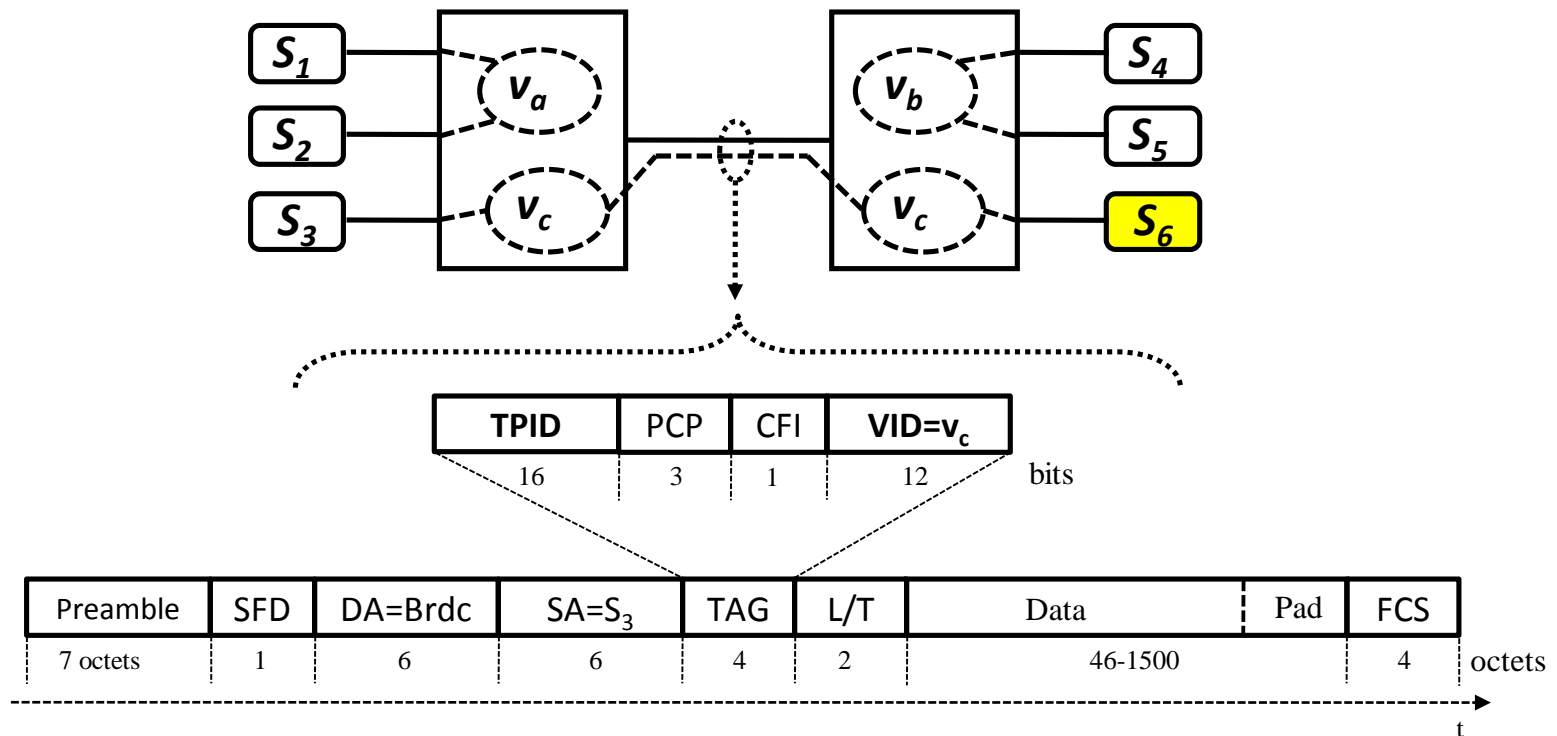
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## When Switch receives a frame:

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
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# Virtual LANs

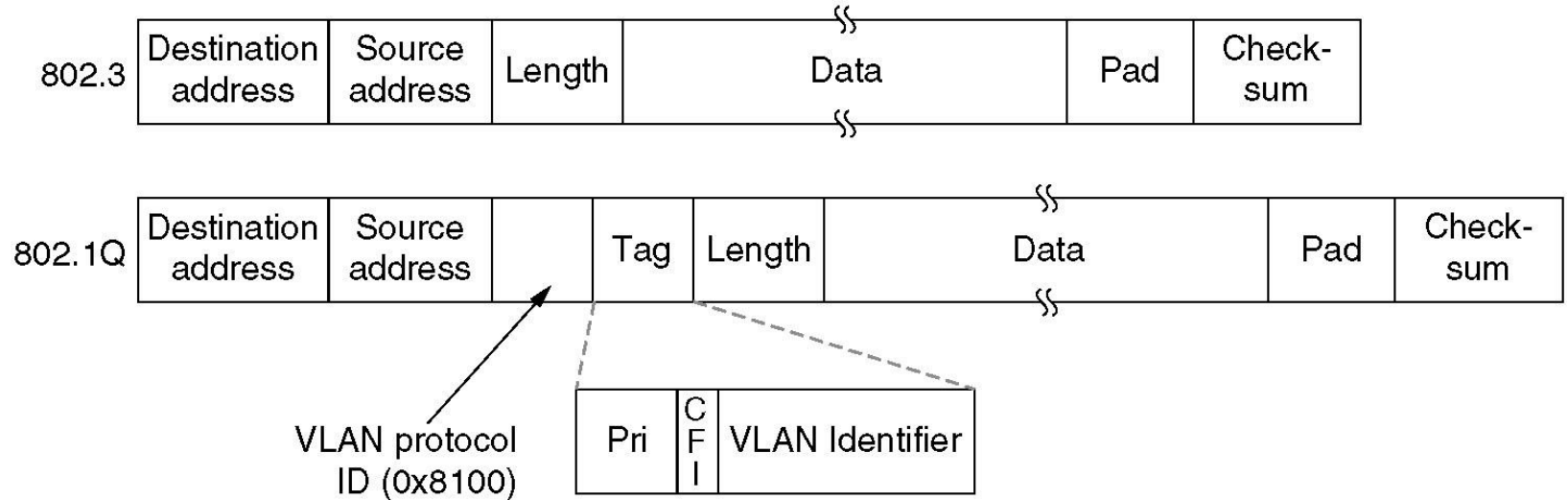
- ◆ One bridge/switch simulates multiple LANs / broadcast domains
- ◆ One LAN may be extended to other bridges



# *The IEEE 802.1Q Standard (2)*

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The 802.3 (legacy) and 802.1Q Ethernet frame formats





# *Homework*

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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