

# **Computer Networks**

## **Chapter 4: Medium Access Control**

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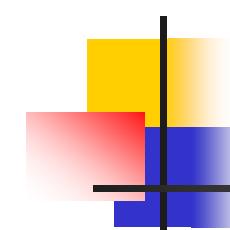
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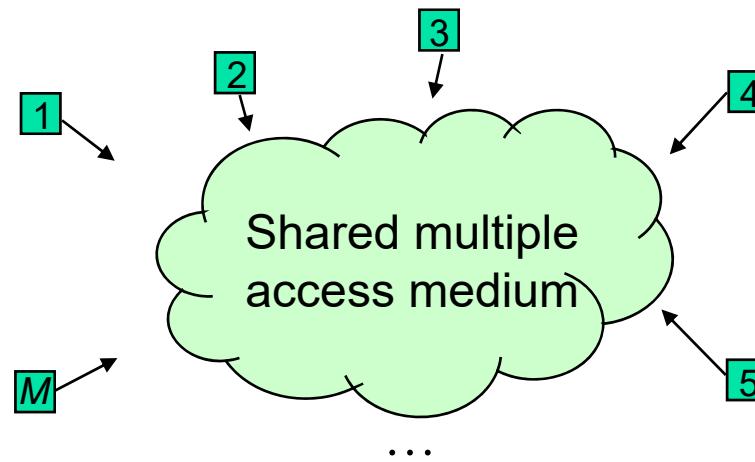
# Outline

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- What is Medium Access Control?
- Medium Access Control Protocols
  - ALOHA
  - Carrier Sense Multiple Access Protocols
  - Collision-Free Protocols
  - Limited-Contention Protocols
  - Wavelength Division Multiple Access Protocols
  - Wireless LAN Protocols
- Medium Access Control in Various Networks
  - Ethernet
  - Wireless LANs (802.11)
  - WiMAX (802.16)
  - Bluetooth
  - Wireless PANs (IEEE 802.15)
- Data Link Switching and Bridging

# Why Need Medium Access Control?

- Share the medium among users in a network with broadcast in nature
  - Networks using shared medium: radio over air; copper or coaxial cable
  - $M$  users communicate by broadcasting into the same medium
- Key issue: How to share the medium?



# Notes on Several Confusing Terms

## ■ Multiplexing

multiple access implemented in PHY  
MAC in DLC

- A node's local function or two nodes' point-to-point function
- Examples: time division multiplexing (TDM), frequency division multiplexing (FDM), code division multiplexing, etc.

## ■ Multiple Access

basic mechanism for users to access the same..  
multiple access in the PHY should match with MAC in DLC

- Function for multiple nodes' PMP/mesh (covers point-to-point case)  
the physical layer should support
- Examples: random access, time division multiple access (TDMA), frequency division multiple access (FDMA), code division multiple access (CDMA), orthogonal frequency division multiple access (OFDMA) etc.  
MAC set slots to node A, B and C

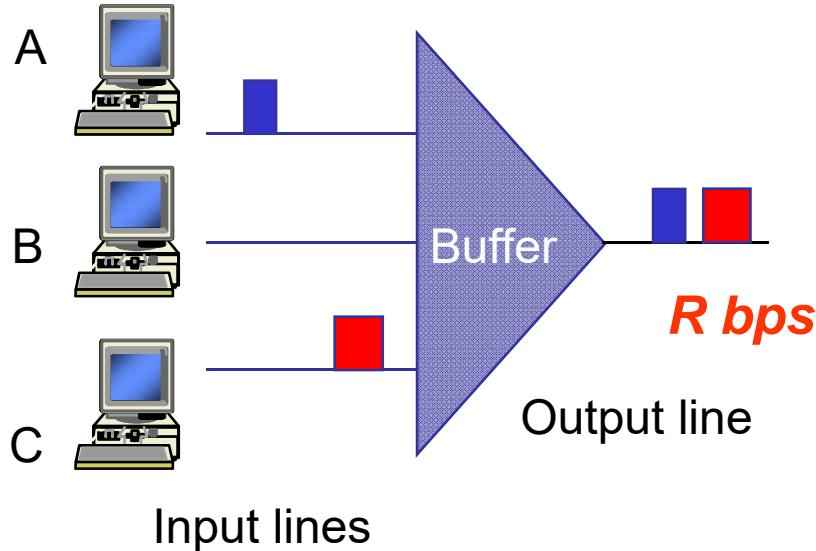
which state/codes -> decided by MAC

## ■ Medium Access Control

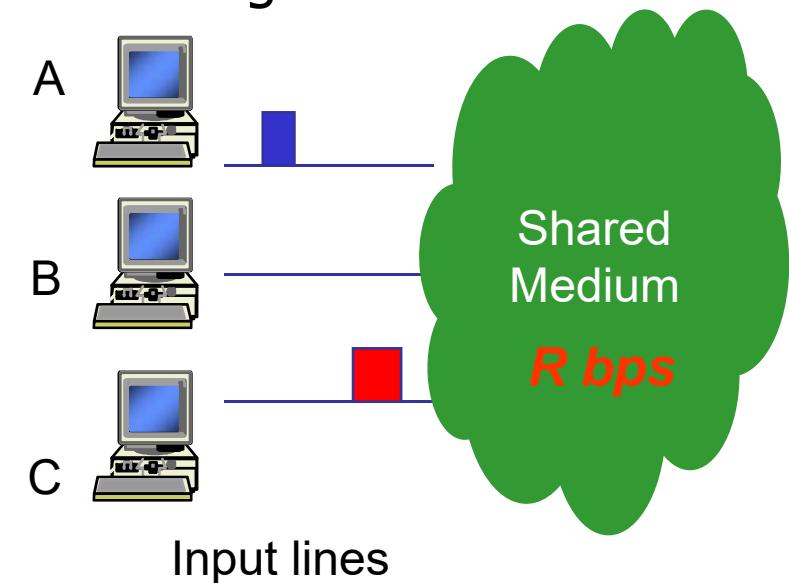
- Algorithms or schemes controlling the medium access on top of a multiple access mechanism
- Examples: Slotted Aloha, CSMA/CA, OFDMA MAC, TDMA MAC, CDMA MAC, etc.

# Statistical Multiplexing & Random Access

- Multiplexing concentrates bursty traffic onto a shared line
- Packets are encapsulated in frames and queued in a buffer prior to transmission
- Central control allows variety of service disciplines



- MAC allows sharing of a broadcast medium
- Packets are encapsulated in frames and queued at station prior to transmission
- Decentralized control “wastes” bandwidth to allow sharing



# Approaches to Media Sharing

## Medium sharing techniques

slots allocated to nodes  
and stay static  
then MAC has no functions

Static  
channelization

MAC determines the change of slots  
if A needs more, allocate more to A  
algo run in the background  
(considering user's dynamic demand)

Dynamic medium  
access control

- Partition medium
- Dedicated allocation to users
- *Early* satellite transmission
- *Early* cellular Telephone

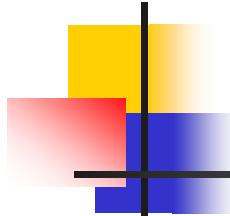
Scheduling

Random access

- Polling: take turns
- Request for slot in transmission schedule
- Token ring
- Cellular, satellite

random access: A B C compete and allocate to the winner (low cost, low efficiency)  
wifi does this  
cell phone based on scheduling  
low efficiency cuz no user may win and rsc loss

- Loose coordination
- Send, wait, retry if necessary
- Aloha
- Ethernet

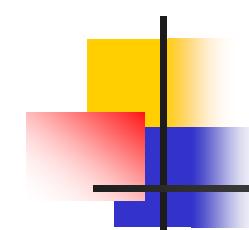


# **Medium Access Control Protocols**



# Selecting a Medium Access Control

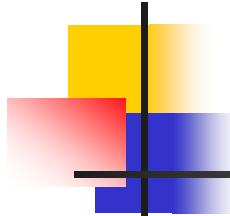
- Applications
  - What type of traffic?
  - Voice streams? Steady traffic, low delay/jitter
  - Data? Short messages? Web page downloads?
  - Enterprise or Consumer market? Reliability, cost
- Scale
  - How much traffic can be carried?
  - How many users can be supported?



# MAC Protocol Features

- Bandwidth-delay product (BDP)  
large BDP, hard to Random access  
cuz should be based on feedback  
slow
- Efficiency scheduling is less sensitive to BDP
- Transfer delay
- Fairness
- Reliability works with ARQ protocols
- Capability to carry different types of traffic
- Quality of service
- Cost

The medium access control – commonly referred to as the MAC protocol – is, effectively, a sublayer or MAC sublayer that controls hardware responsible for the communication with a wired, wireless or optical transmission medium.



# **Channelization**



# Multiple Access and Channelization (1)

- Channelization
  - Semi-static bandwidth allocation of portion of shared medium to a given user
  - Highly efficient for constant-bit rate traffic
  - Preferred approach in
    - Cellular telephone networks
    - Terrestrial & satellite broadcast radio & TV
- Shortcomings
  - Inflexible in allocation of bandwidth to users with different requirements
  - Inefficient for bursty traffic
  - Does not scale well to large numbers of users
    - Average transfer delay increases with number of users  $M$
  - Dynamic MAC much better at handling bursty traffic

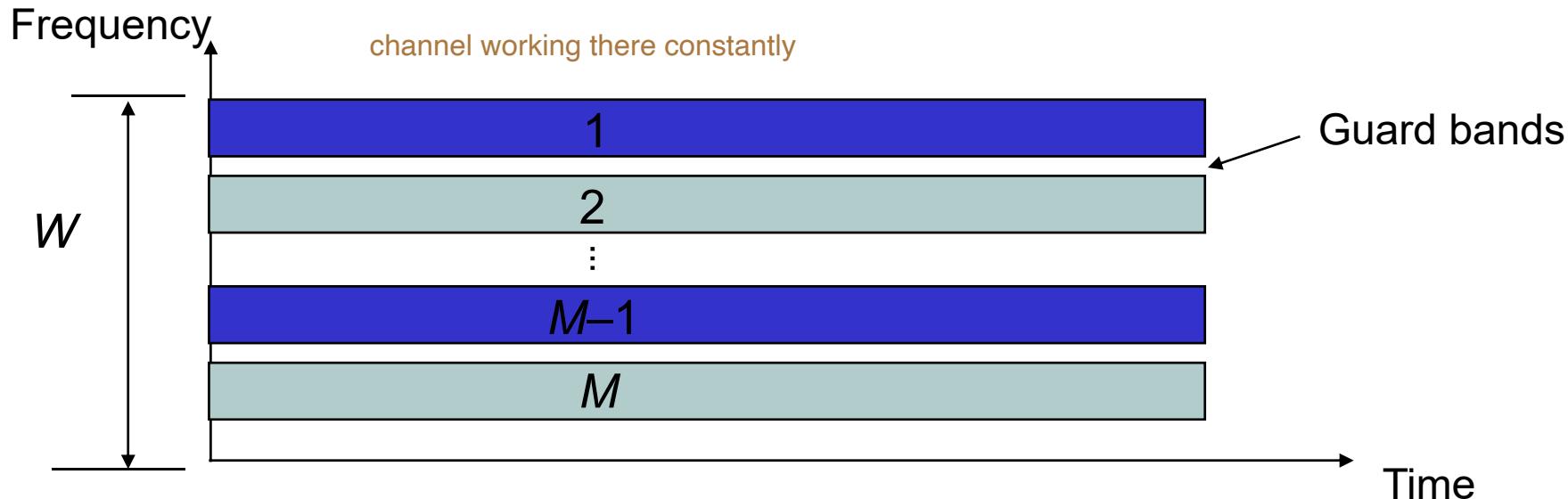


# Multiple Access and Channelization (2)

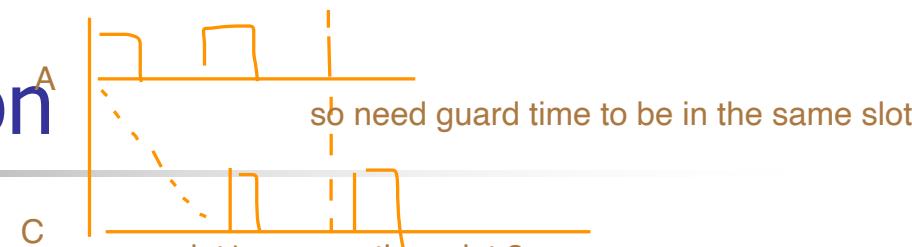
- *Frequency Division Multiple Access (FDMA)*
  - Frequency band allocated to users
  - Broadcast radio & TV, analog cellular phone
- *Time Division Multiple Access (TDMA)*
  - Periodic time slots allocated to users
  - Telephone backbone, GSM digital cellular phone
- *Code Division Multiple Access (CDMA)*
  - Code allocated to users
  - Cellular phones, 3G cellular

# FDMA Channelization

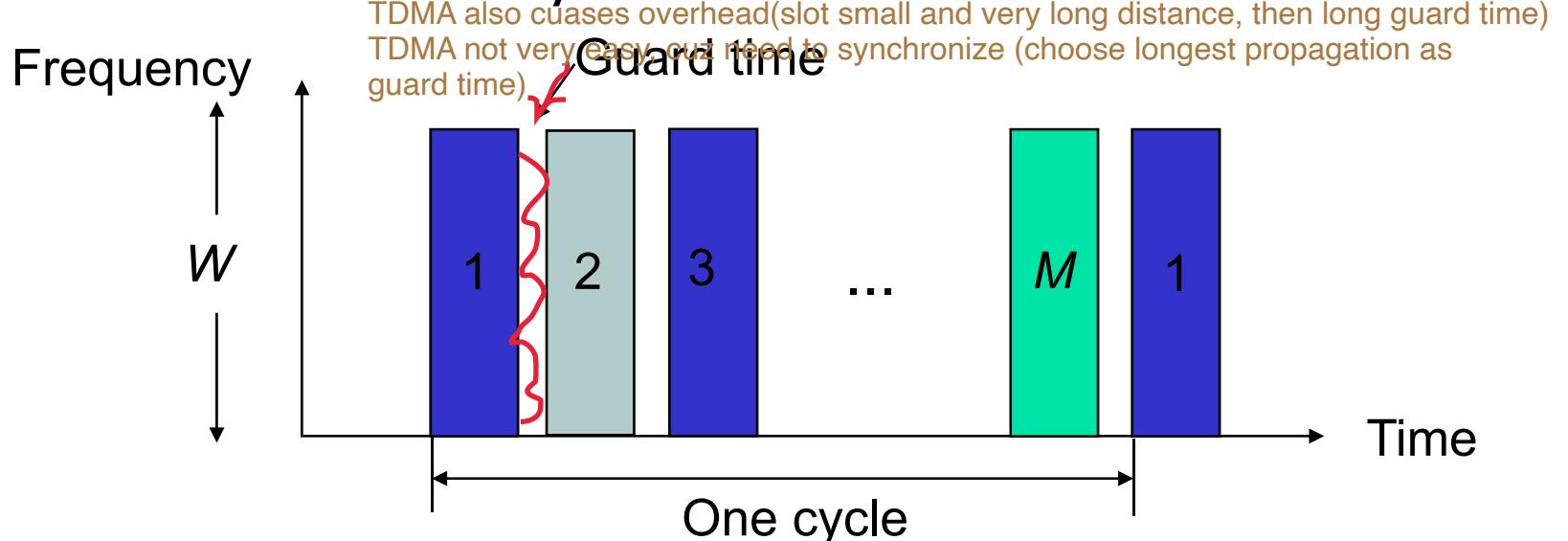
- Divide channel into  $M$  frequency bands
- Each station transmits and listens on assigned bands
- Each station transmits at most  $R/M$  bps
- Good for stream traffic; Used in connection-oriented systems
- Inefficient for bursty traffic

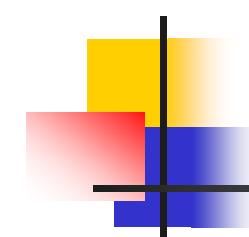


# TDMA Channelization



- Dedicate 1 slot per station in transmission cycles
- Stations transmit data burst at full channel bandwidth
- Each station transmits at  $R$  bps  $1/M$  of the time
- Excellent for stream traffic; Used in connection-oriented systems
- Inefficient for bursty traffic due to unused dedicated slots





# Guardbands

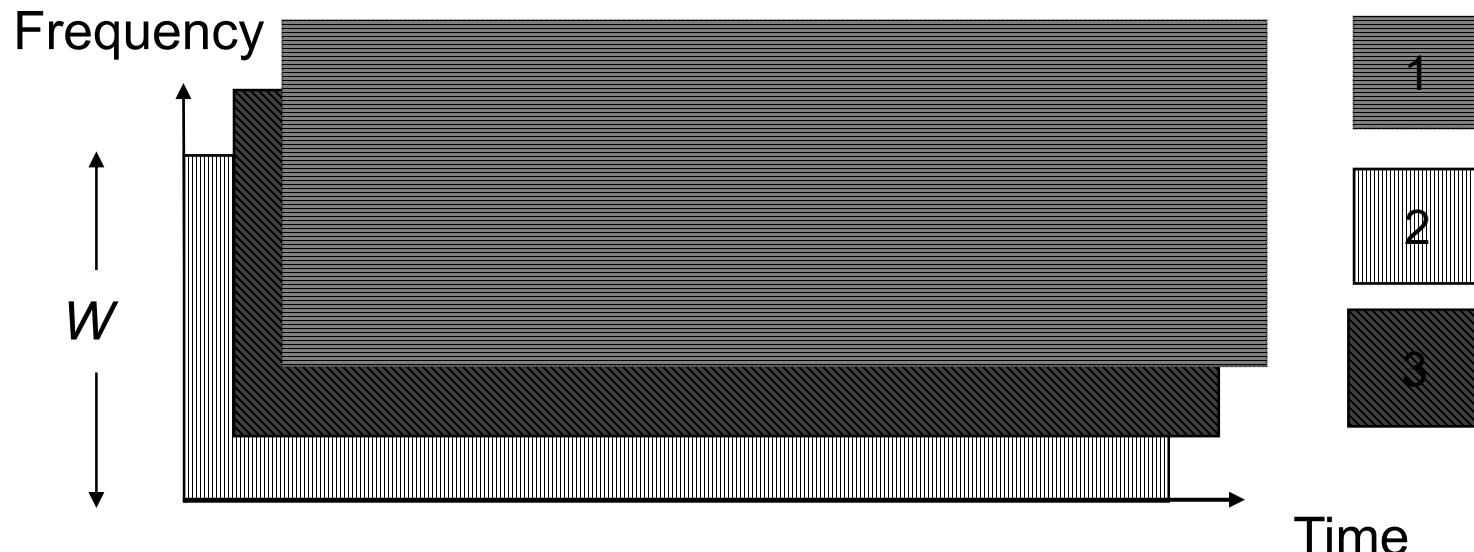
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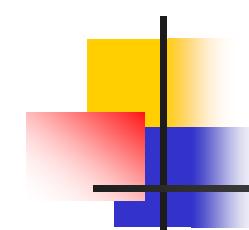
- FDMA
  - Frequency bands must be non-overlapping to prevent interference
  - Guardbands ensure separation; form of overhead
- TDMA
  - Stations must be synchronized to common clock
  - Time gaps between transmission bursts from different stations to prevent collisions; form of overhead
  - Must take into account propagation delays

# CDMA Channelization

maybe we are using different code to talk

- Code Division Multiple Access
  - Channels determined by a code used in modulation and demodulation
- Stations transmit over entire frequency band all of the time!





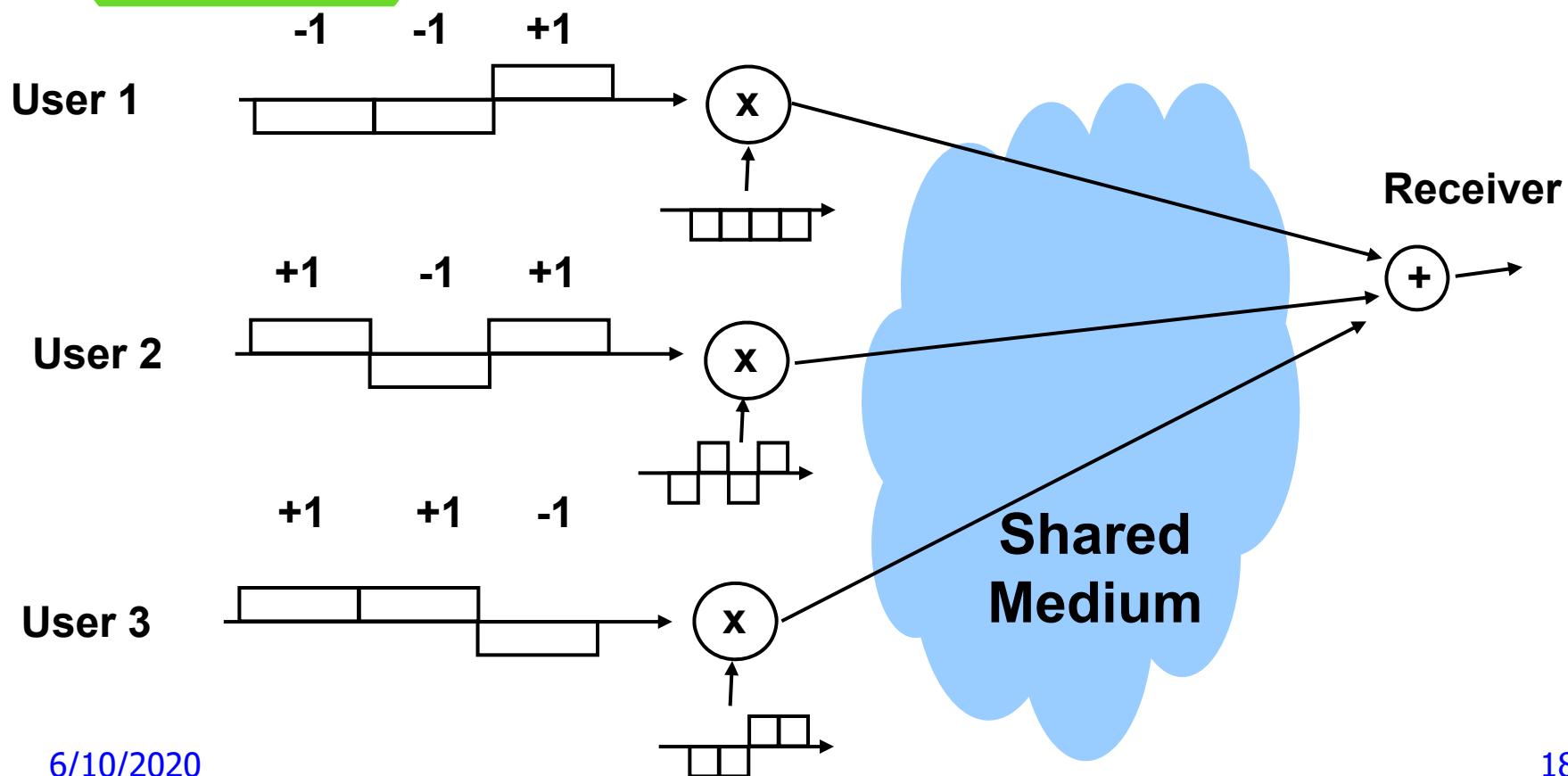
# Channelization in Code Space

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- Each channel uses a different pseudorandom code
- Codes should have low cross-correlation
  - If they differ in approximately half the bits the correlation between codes is close to zero and the effect at the output of each other's receiver is small
- As the number of users increases, effect of other users on a given receiver increases as additive noise
- CDMA has gradual increase in BER due to noise as number of users is increased
- Interference between channels can be eliminated if codes are selected so they are *orthogonal* and if receivers and transmitters are synchronized
  - Shown in next example

# CDMA Example: 3 users

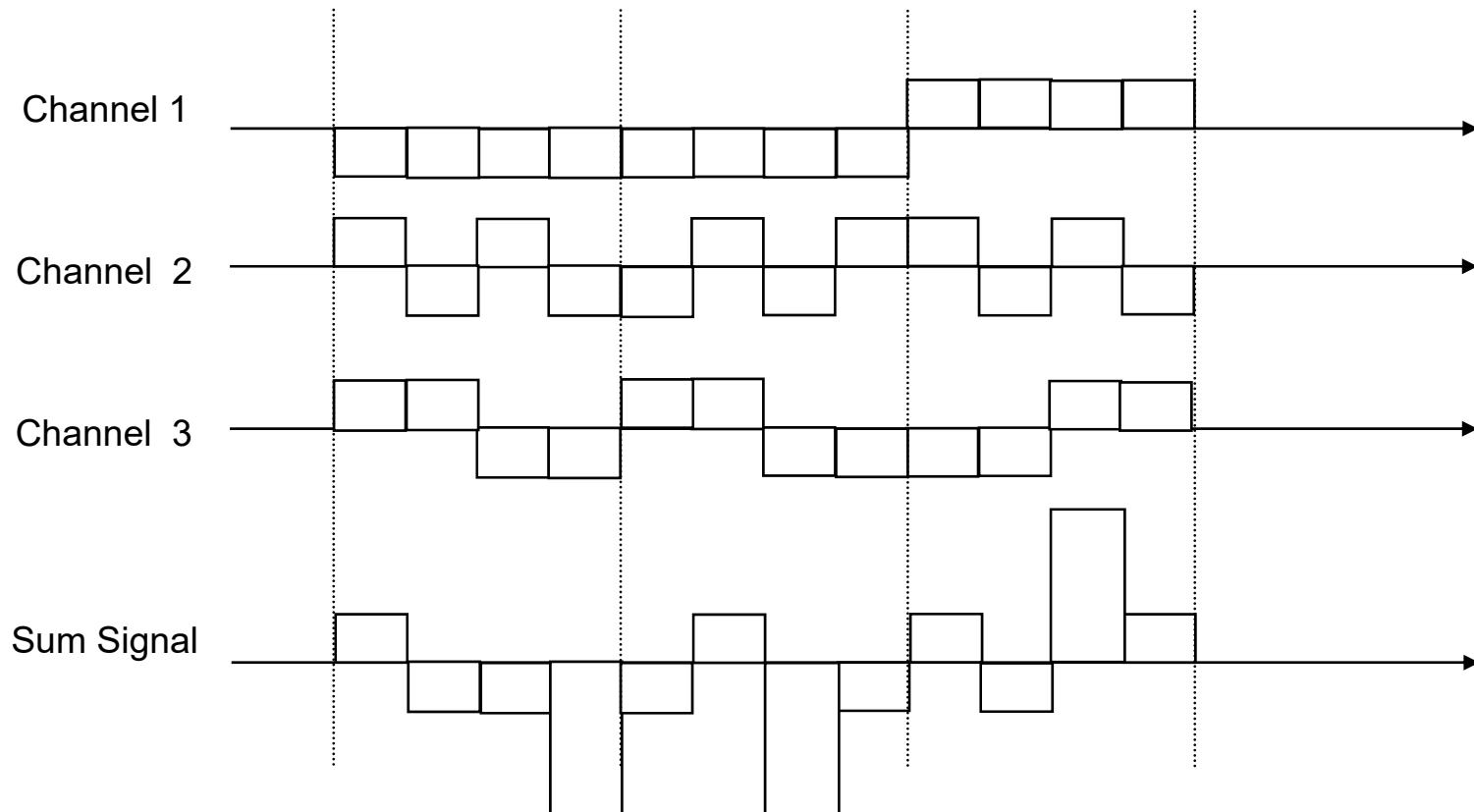
- Assume three users share same medium
- Users are synchronized & use different 4-bit orthogonal codes:  $\{-1, -1, -1, -1\}$ ,  $\{-1, +1, -1, +1\}$ ,  $\{-1, -1, +1, +1\}$ ,  $\{-1, +1, +1, -1\}$ ,



# Sum signal is input to receiver

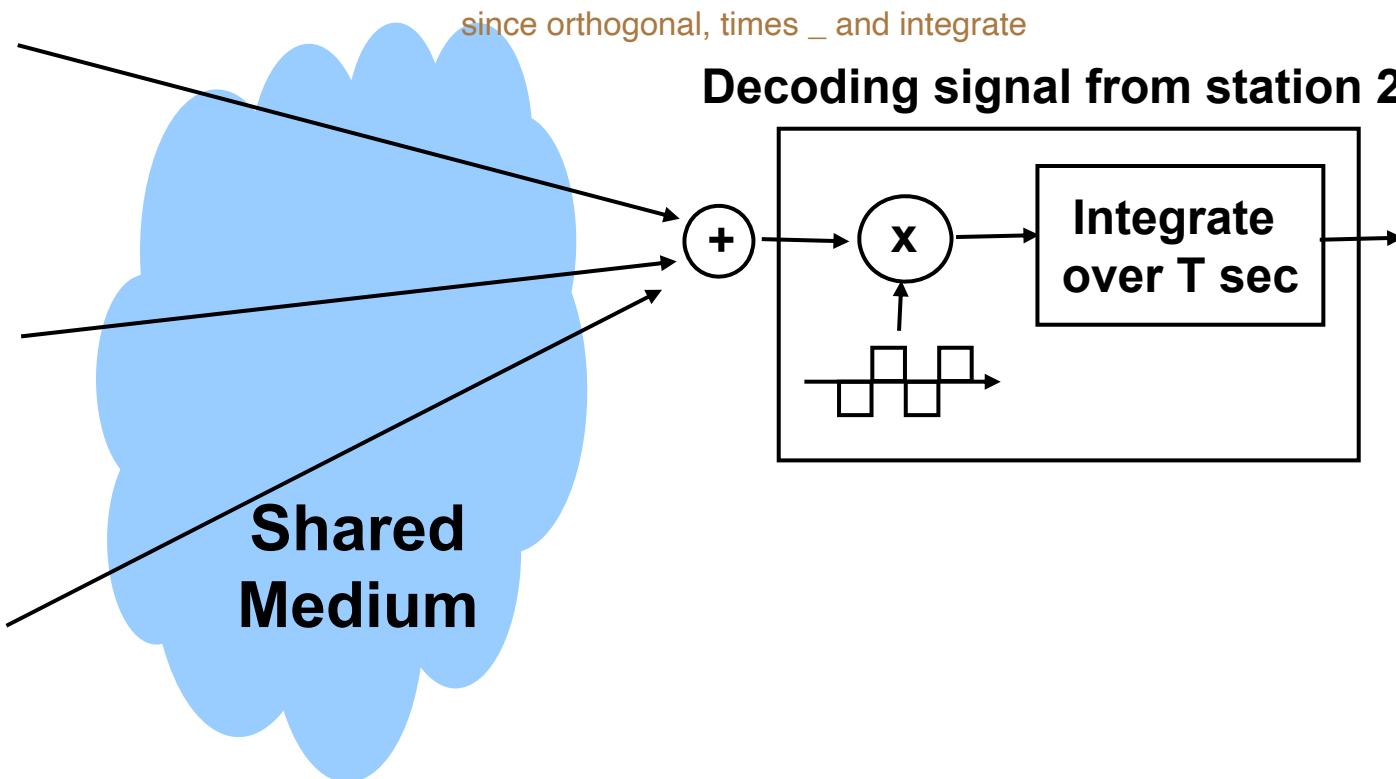
4位code都要乘1 和 1 和0

- Channel 1: 110 -> +1+1-1 -> (-1,-1,-1,-1),(-1,-1,-1,-1),(+1,+1,+1,+1)
- Channel 2: 010 -> -1+1-1 -> (+1,-1,+1,-1),(-1,+1,-1,+1),(+1,-1,+1,-1)
- Channel 3: 001 -> -1-1+1 -> (+1,+1,-1,-1),(+1,+1,-1,-1),(-1,-1,+1,+1)
- Sum Signal: (+1,-1,-1,-3),(-1,+1,-3,-1),(+1,-1,+3,+1)



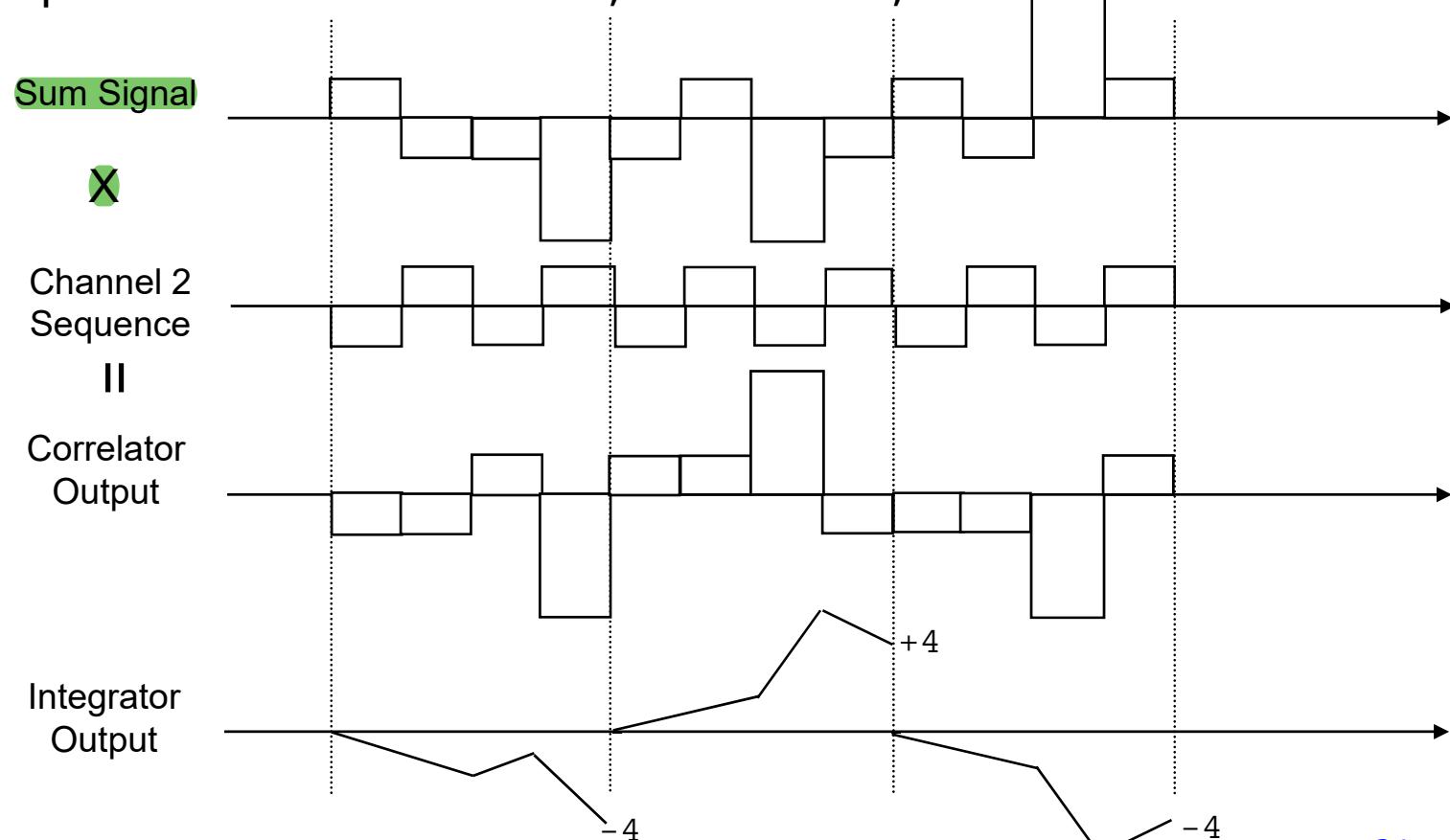
# Receiver for Station 2

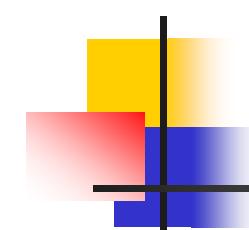
- Each receiver takes sum signal and integrates by code sequence of desired transmitter
- Integrate over T seconds to smooth out noise



# Decoding at Receiver 2

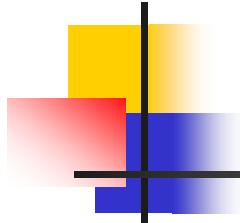
- Sum Signal:  $(+1, -1, -1, -3), (-1, +1, -3, -1), (+1, -1, +3, +1)$
- Channel 2 Sequence:  $(-1, +1, -1, +1), (-1, +1, -1, +1), (-1, +1, -1, +1)$
- Correlator Output:  $(-1, -1, +1, -3), (+1, +1, +3, -1), (-1, -1, -3, +1)$
- Integrated Output:  $-4, +4, -4$
- Binary Output:  $0, 1, 0$





# Channelization Example: Cellular Telephone Networks

- Cellular networks use frequency reuse
  - Band of frequencies reused in other cells that are sufficiently far so that interference is not a problem
  - Cellular networks provide voice connections which is steady stream
- FDMA used in AMPS
- TDMA used in IS-54 and GSM
- CDMA used in IS-95



# **Random Access**

# Random Access: ALOHA

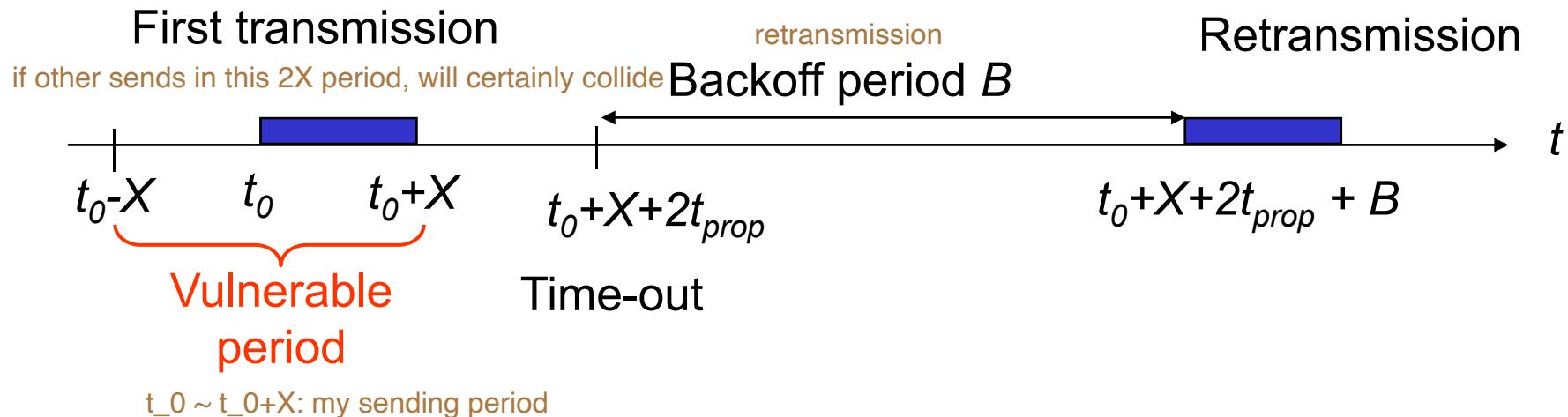
hi in hawaii

random access: collision (A sends to B while C sends to B)

so B sends ACK to A and C

if time-out, retransmit. if retransmitted for many times, find out that failed

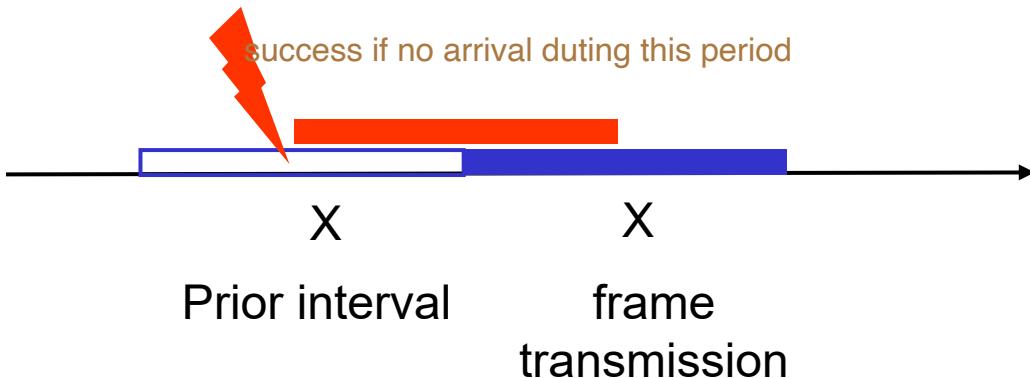
- Wireless link to provide data transfer between main campus & remote campuses of University of Hawaii
- Simplest solution
  - A station transmits whenever it has data to transmit
  - If more than one frames are transmitted, they interfere with each other (collide) and are lost sending while others are sending
  - If ACK not received within timeout, then a station picks random backoff time (to avoid repeated collision)
  - Station retransmits frame after backoff time



# ALOHA Model

- Definitions and assumptions
  - $X$ : frame transmission time (assume constant)
  - $S$ : throughput (average # successful frame transmissions per  $X$  seconds)  
not necessary to be new trans attempts
  - $G$ : load (average # transmission attempts per  $X$  sec.)
  - $P_{success}$ : probability a frame transmission is successful

$$S = GP_{success}$$



- Any transmission that begins during vulnerable period leads to collision
- Success if no arrivals during  $2X$  seconds

# Abramson's Assumption

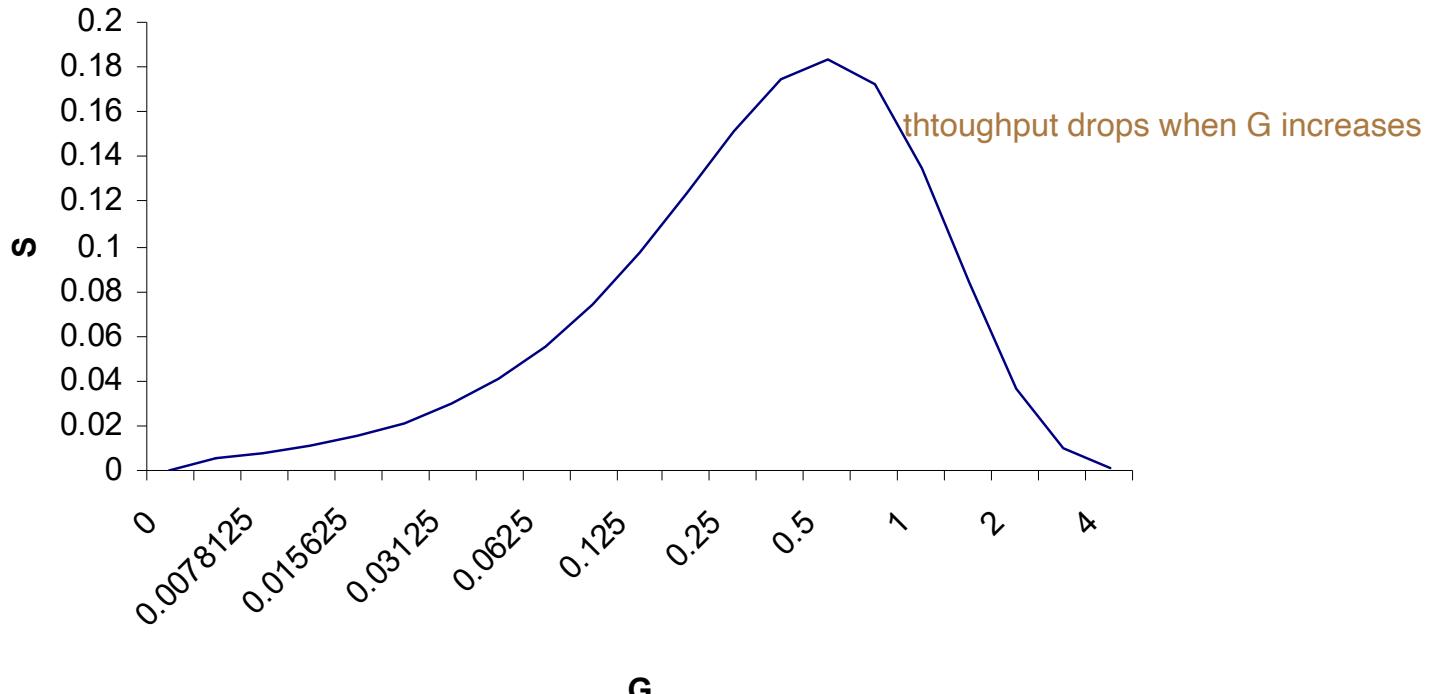
- *What is the probability of no arrivals in vulnerable period?*
- **Abramson assumption:** ***Effect of backoff algorithm (and retransmission) is that frame arrivals are equally likely to occur at any time interval***
- $G$  is avg. # arrivals per  $X$  seconds      arrivals of other packages
- Divide  $X$  into  $n$  intervals of duration  $\Delta = X/n$
- $p$  = probability of arrival in  $\Delta$  interval, then  
$$G = n p \quad \text{since there are } n \text{ intervals in } X \text{ seconds}$$

$$\begin{aligned} P_{\text{success}} &= P[0 \text{ arrivals in } 2X \text{ seconds}] = \\ &= P[0 \text{ arrivals in } 2n \text{ intervals}] \\ &= (1-p)^{2n} = \left(1 - \frac{G}{n}\right)^{2n} \rightarrow e^{-2G} \quad \text{as } n \rightarrow \infty \end{aligned}$$

# Throughput of ALOHA

- Collisions are means for coordinating access
- Max throughput is  $\rho_{\max} = 1/2e (18.4\%)$
- Bimodal behavior:
  - Small G,  $S \approx G$
  - Large G,  $S \rightarrow 0$
- Collisions can snowball and drop throughput to zero

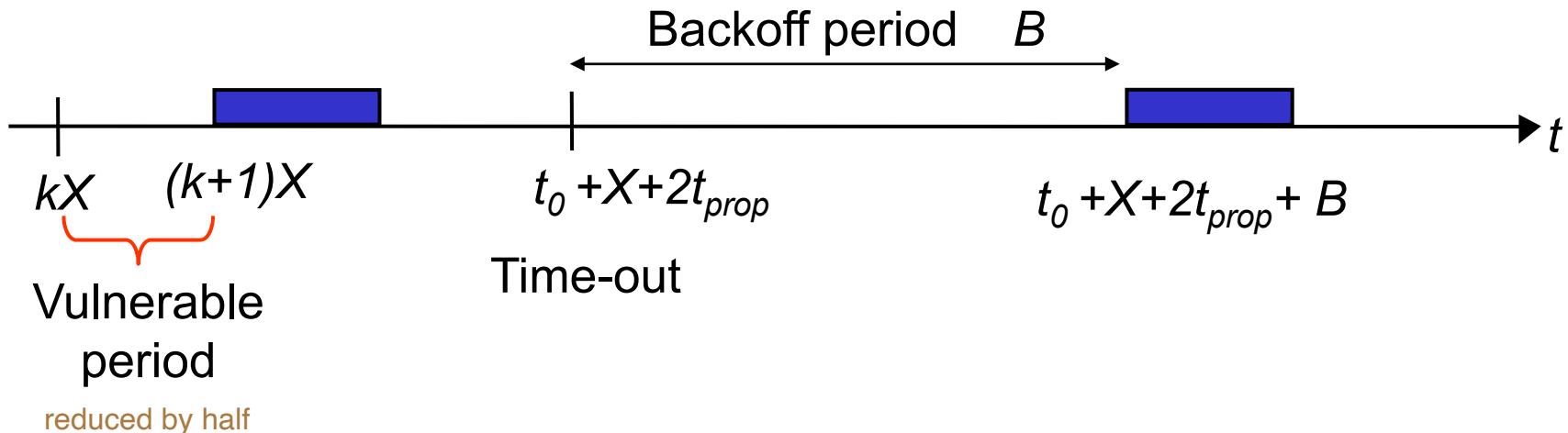
$$S = GP_{\text{success}} = Ge^{-2G}$$



# Slotted ALOHA

each node sends in the edges of slots, cannot send in the middle

- Time is slotted in  $X$  seconds slots
- Stations are **synchronized** to frame times
- Stations transmit frames in first slot after frame arrival
- Backoff intervals in multiple slots



*Only frames that arrive during prior  $X$  seconds collide*

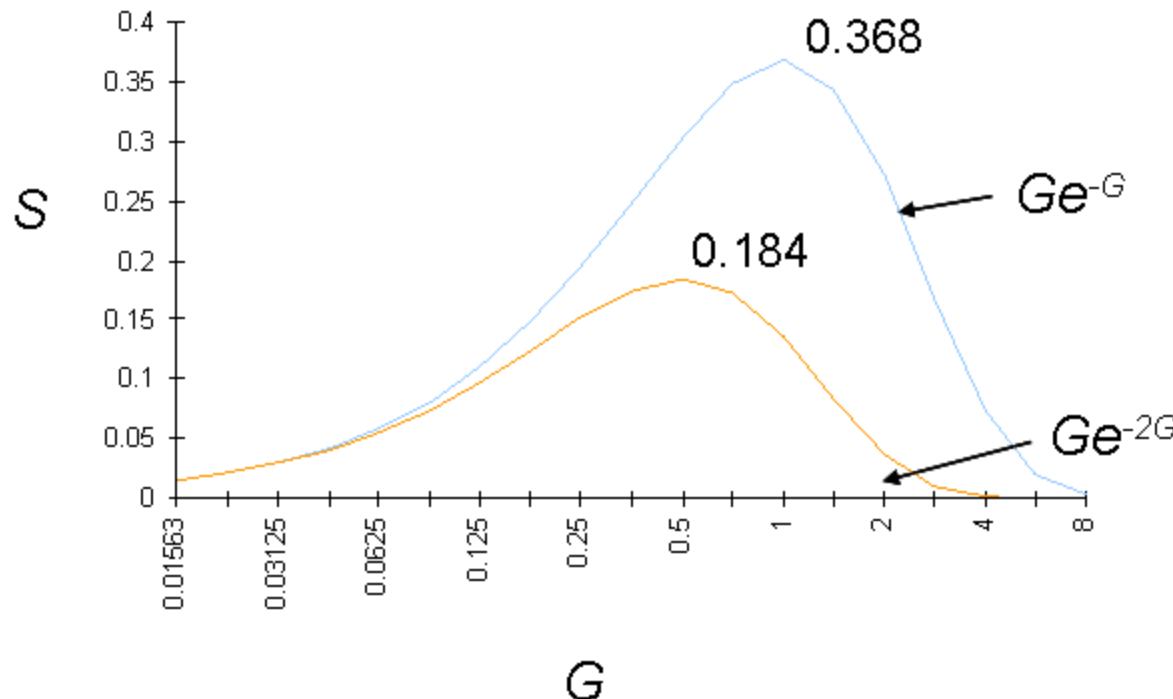
# Throughput of Slotted ALOHA

$$\begin{aligned} S &= GP_{\text{success}} = GP[\text{no arrivals in } X \text{ seconds}] \\ &= GP[\text{no arrivals in } n \text{ intervals}] \end{aligned}$$

why equal likely still holds true?

cuz retransmission

$$= G(1-p)^n = G\left(1 - \frac{G}{n}\right)^n \rightarrow Ge^{-G}$$



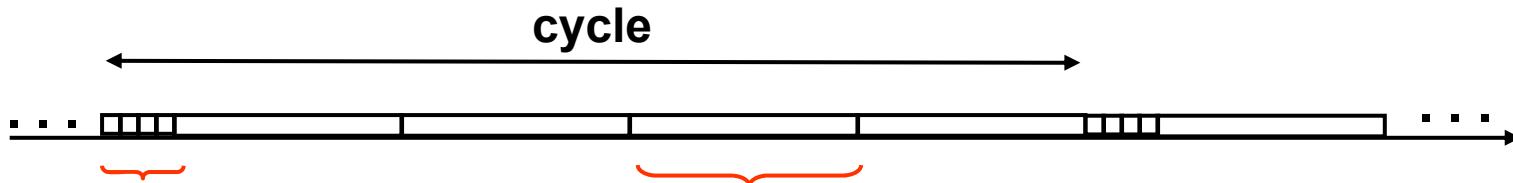
# Application of Slotted Aloha

net protocol

cell phone still uses slotted Aloha (use it to do scheduling)

- Reservation protocol allows a large number of stations with infrequent traffic to reserve slots to transmit their frames in future cycles  
this reservation done by scheduling
- Each cycle has mini-slots allocated for making reservations (i.e. for sending request/response messages)
- Stations use slotted Aloha during mini-slots to request slots

base station reserves 2 slots for user A in a few cycles



## Reservation mini-slots

A wants to get 2 slots, but A does not have slots, so not rscs, cannot send requests  
so use random to solve it

so create a series of mini slots, shared by all users, a user can randomly choose a slot in the mini slots and send (so slotted aloha for users to send requests)

try for several times to request (36% percent of success rate)  
so the first time connection is slow, cuz requesting for rsc allocation

# Carrier Sensing Multiple Access (CSMA)

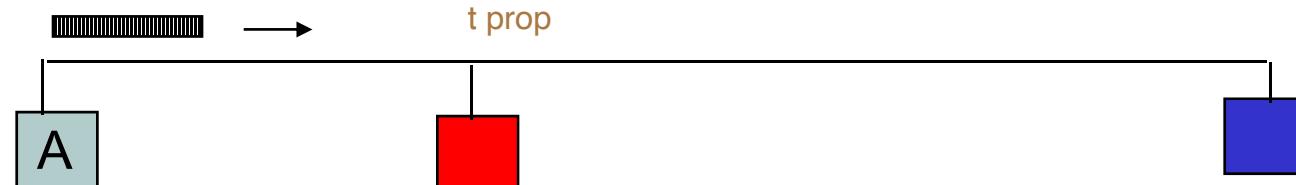
5G use CSMA to improve efficiency

A station senses the channel before it starts transmission

if constantly sensing, power consumption

- If busy, either wait or schedule backoff (different options)
- If idle, start transmission
- Vulnerable period is reduced to  $(t_{prop} \text{ or } 2t_{prop})$  (due to delay in *channel capture* effect)  
test: send a frame need return, so  $2t_{prop}$   
不是這個原因  
是A往B發，B往A發的時候A也vulnerable  
A 和B在一個channel互發
- When collisions occur they involve entire frame transmission times
- If  $t_{prop} > X$  (or if  $a = t_{prop}/X > 1$ ), no gain compared to ALOHA or slotted ALOHA

Station A begins transmission at  $t = 0$



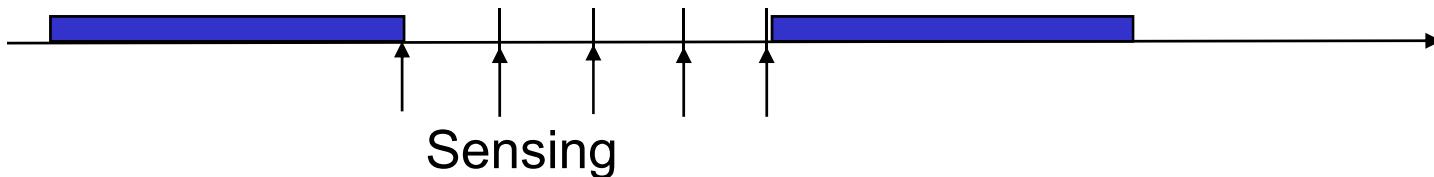
so we want transmission time is much larger than the propagation time,  
so send large packages less frequently

Station A captures channel at  $t = t_{prop}$



# CSMA Options

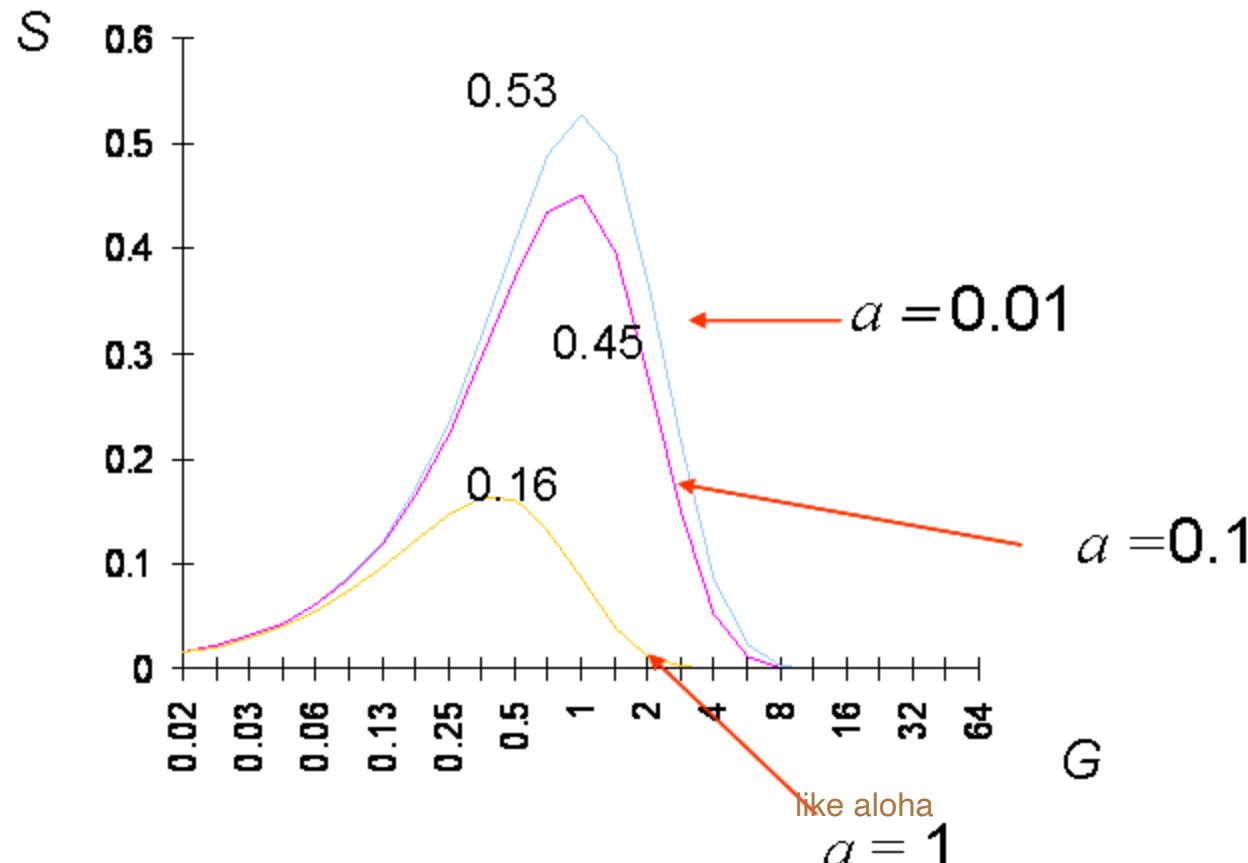
- Transmitter behavior when busy channel is sensed
  - 1-persistent CSMA (most greedy)
    - Start transmission as soon as the channel becomes idle
    - Low delay and low efficiency
  - Non-persistent CSMA (least greedy)
    - Wait a backoff period, then sense carrier again
    - High delay and high efficiency
  - p-persistent CSMA (adjustable greedy)
    - Wait till channel becomes idle, transmit with prob.  $p$ ; or wait one mini-slot time & re-sense (with probability  $1-p$ )
    - Delay and efficiency can be balanced



# 1-Persistent CSMA Throughput

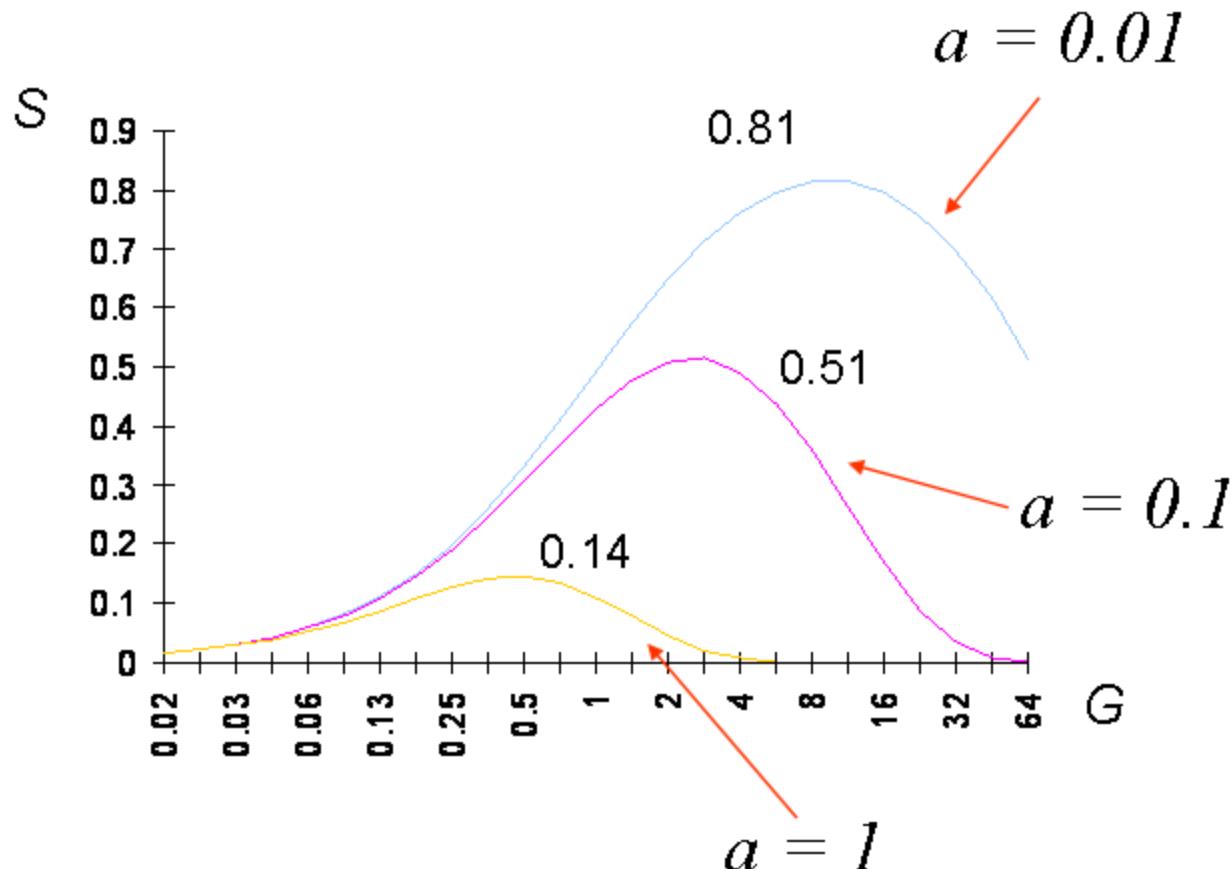
- Better than Aloha & slotted Aloha for small  $\alpha$
- Worse than Aloha for  $\alpha > 1$

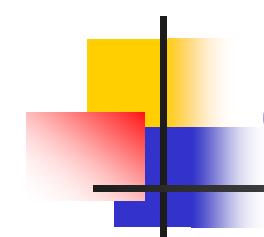
這是啥



# Non-Persistent CSMA Throughput

- Higher maximum throughput than 1-persistent for small  $a$
- Worse than Aloha for  $a > 1$





# CSMA with Collision Detection (CSMA/CD)

stop transmission when collision detected

- Monitor for collisions & abort transmission
  - Stations with frames to send, first do carrier sensing
  - After beginning transmissions, stations continue listening to the medium to detect collisions
  - If collisions detected, all stations involved stop transmission, reschedule random backoff times, and try again at scheduled times *how to detect collisions?*
- In CSMA collisions result in wastage of X seconds spent transmitting an entire frame
- CSMA-CD reduces wastage of time to detect collision and abort transmission

# CSMA/CD reaction time

A begins to transmit at  $t = 0$

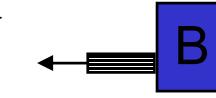


prop time 到底是哪段

why  
A detects collision at  $t = 2 t_{prop} - \delta$



why  
B begins to transmit at  $t = t_{prop} - \delta$ ;  
B detects collision at  $t = t_{prop}$



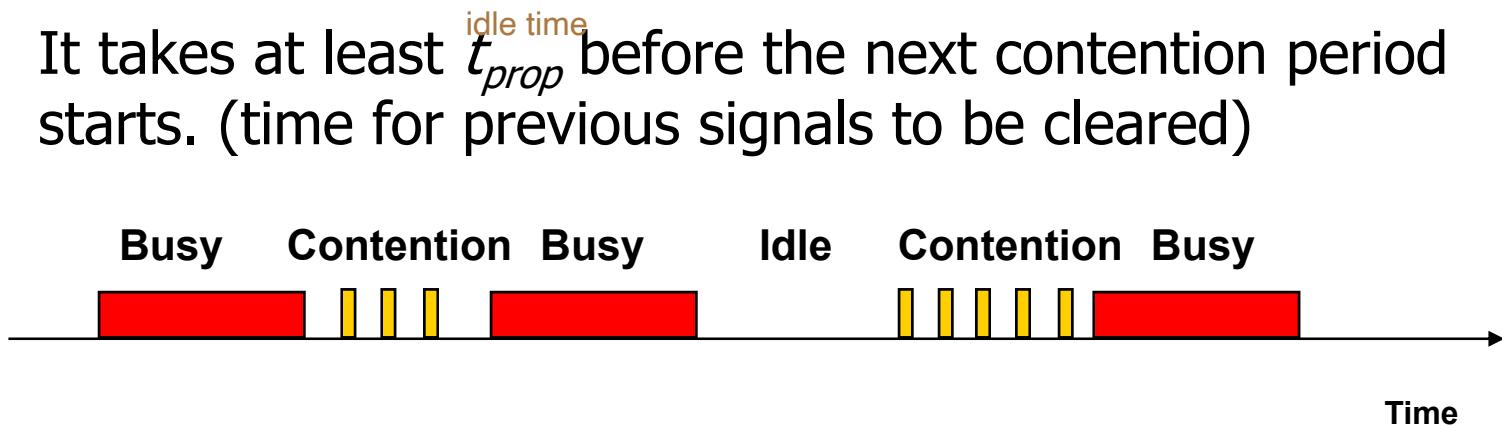
worse case for A

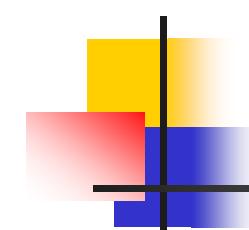
*It takes  $2 t_{prop}$  to find out if channel has been captured*

# CSMA-CD Model

## ■ Assumptions

- Collisions can be detected in  $2t_{prop}$
- Time slotted in interval of  $2t_{prop}$  during contention periods
- Assume  $n$  busy stations, and each may transmit with probability  $p$  in each contention time slot
- Once the contention period is over (a station successfully occupies the channel), it takes  $X$  seconds for a frame to be transmitted
- It takes at least  $t_{prop}$  before the next contention period starts. (time for previous signals to be cleared)





# Contention Resolution

- How long does it take to resolve contention?
- Contention is resolved ("success") if exactly 1 station transmits in a slot:

$$P_{\text{success}} = np(1 - p)^{n-1}$$

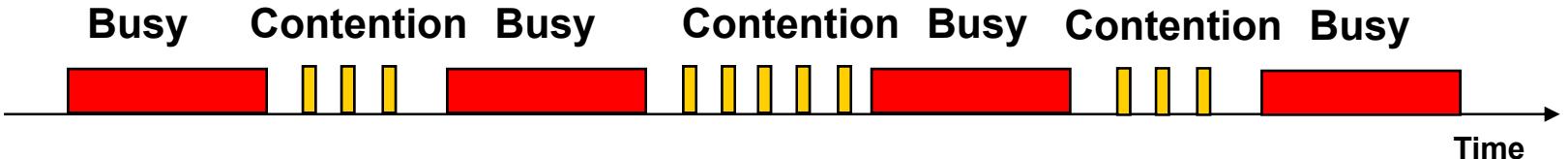
- By taking derivative of  $P_{\text{success}}$  we find max occurs at  $p=1/n$

$$P_{\text{success}}^{\max} = n \frac{1}{n} \left(1 - \frac{1}{n}\right)^{n-1} = \left(1 - \frac{1}{n}\right)^{n-1} \rightarrow \frac{1}{e}$$

- On average,  $1/P^{\max} = e = 2.718$  time slots to resolve contention

*Average Contention Period =  $2t_{\text{prop}}e$  seconds*

# CSMA/CD Throughput



- At maximum throughput, system alternates between contention periods and frame transmission times

long cable, performance really low

$$\rho_{\max} = \frac{X}{X + t_{prop} + 2et_{prop}} = \frac{\text{看看 } 1}{1 + (2e + 1)a} = \frac{1}{1 + (2e + 1)Rd / v L}$$

- where:

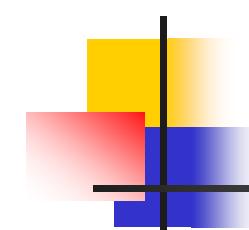
$R$  bits/sec,  $L$  bits/frame,  $X=L/R$  seconds/frame

$$a = t_{prop}/X$$

$v$  meters/sec. speed of light in medium

$d$  meters is diameter of system

$$2e+1 = 6.44$$



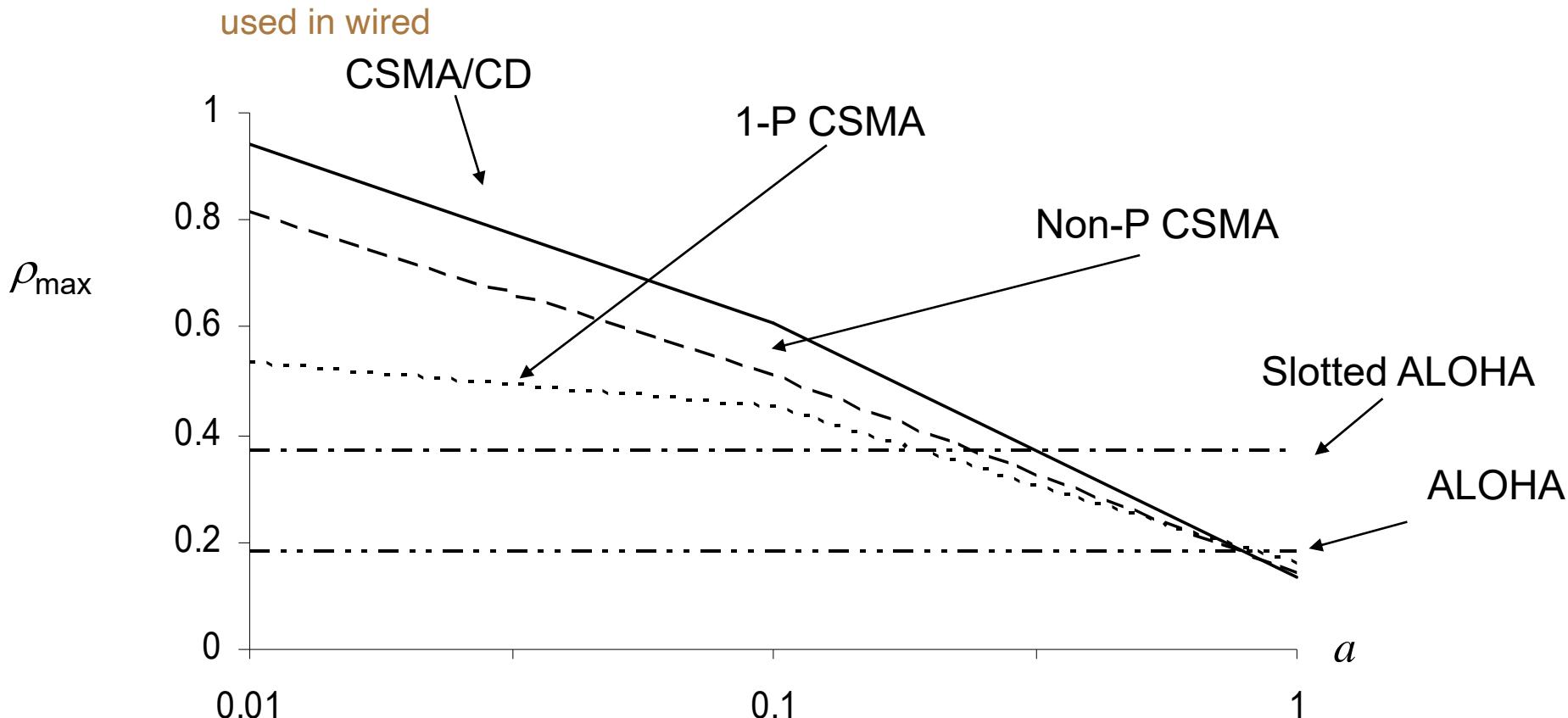
# CSMA-CD Application: Ethernet

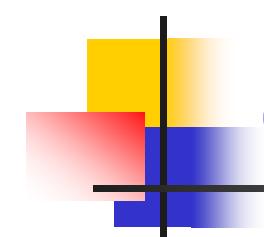
- First Ethernet LAN standard used CSMA-CD
  - 1-persistent Carrier Sensing
  - $R = 10 \text{ Mbps}$
  - $t_{\text{prop}} = ?$ 
    - 512 bits = 64 byte slot = 2  $t_{\text{prop}}$
    - $t_{\text{prop}} = 51.2/2 = 25.6 \text{ microsec}$
    - Distance:  $25.6 \text{ microsec} \times 2000 \text{ km/s} = 5.12 \text{ km}$
    - accommodates 5 km + 4 repeaters
  - Truncated Binary Exponential Backoff
    - After nth collision, select backoff from  $\{0, 1, \dots, 2^k - 1\}$ , where  $k = \min(n, 10)$

# Throughput for Random Access MACs

used in ethernet  
short cable

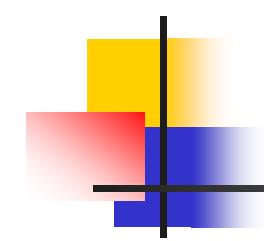
- For small  $a$ : CSMA-CD has best throughput
- For larger  $a$ : Aloha & slotted Aloha better throughput





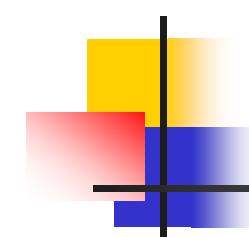
# Carrier Sensing and Priority Transmission

- Certain applications require faster response than others, e.g. ACK messages
- Impose different **interframe times** for different users  
interval between sending two msg
  - High priority traffic sense channel for time  $\tau_1$  probability of getting a channel higher (cuz shorter sensing time)
  - Low priority traffic sense channel for time  $\tau_2 > \tau_1$
  - High priority traffic, if present, seizes channel first
- This priority mechanism is used in IEEE 802.11 wireless LAN



之前講的都是random access

# Scheduling



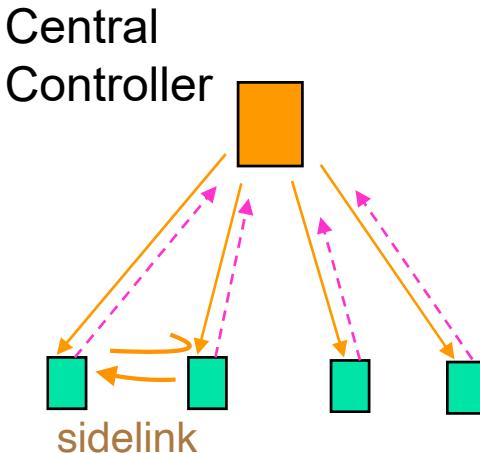
# Scheduling

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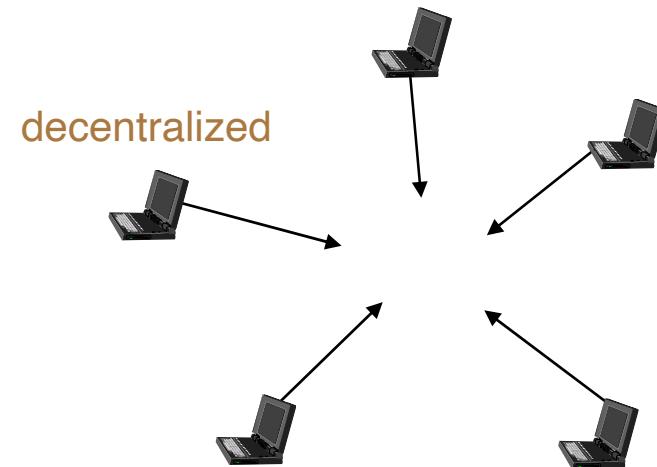
- Schedule frame transmissions to avoid collision in shared medium
  - ✓ More efficient channel utilization
  - ✓ Less variability in delays
  - ✓ Can provide fairness to stations
  - ✗ Increased computational or procedural complexity
- Two main approaches
  - Reservation
  - Polling

# Reservations Systems

- ***Centralized systems***: A central controller accepts requests from stations and issues grants to transmit
  - Frequency Division Duplex (FDD): Separate frequency bands for uplink & downlink
  - Time-Division Duplex (TDD): Uplink & downlink time-share the same channel  
sidelink: can be in dtb sys or handled by base station
- ***Distributed systems***: Stations implement a decentralized algorithm to determine transmission order

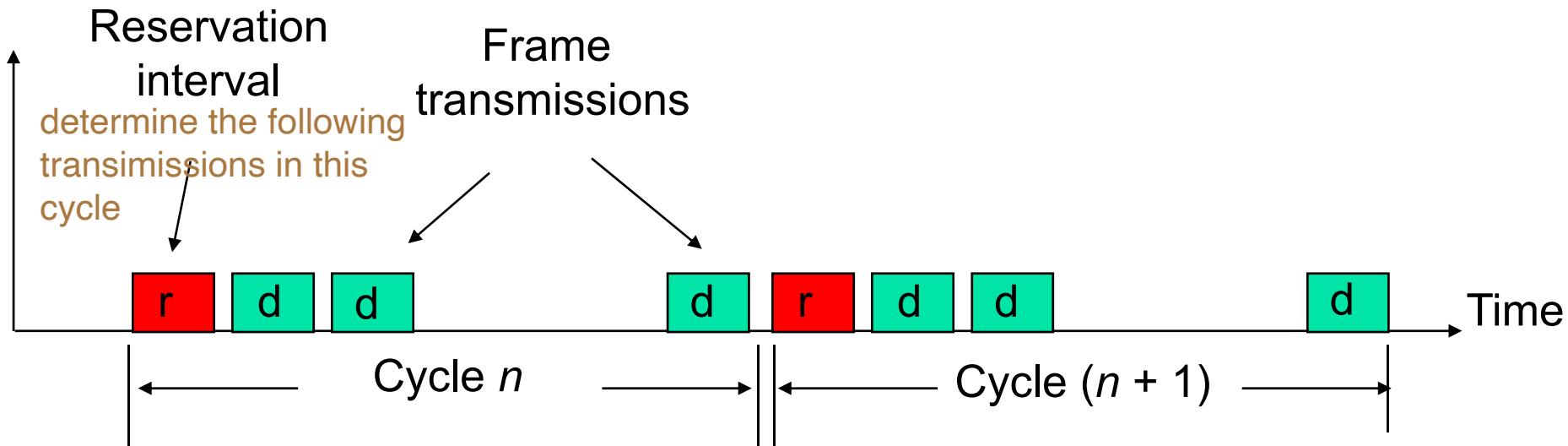


6/10/2020 (begin to be impt in 5g)



# Reservation Systems

- Transmissions organized into cycles
- Cycle: reservation interval + frame transmissions
- Reservation interval has a minislot for **each** station to request reservations for frame transmissions



cut the r into mini slots, used by multiple stations

normally  $n \gg M$



mini slots reserved for requests from stations

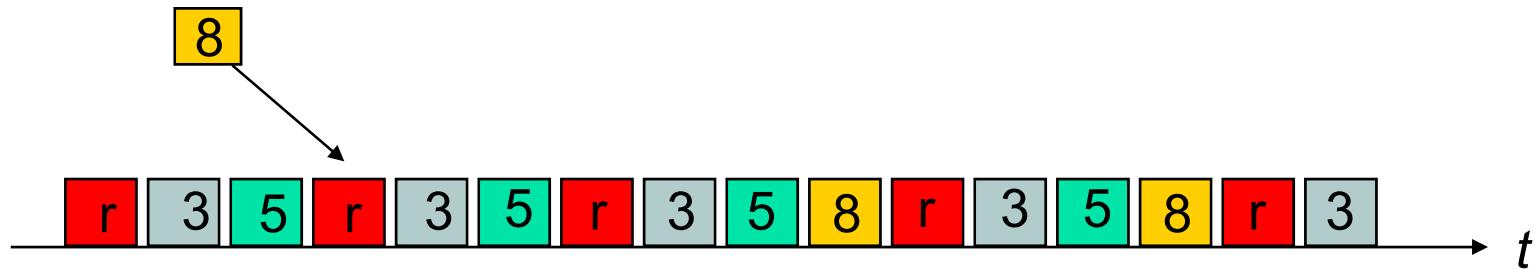
6/10/2020  
used random access (for stations competing) in this to send requests

# Reservation System Options

- Centralized or distributed system
  - *Centralized systems*: A central controller listens to reservation information, decides order of transmission, issues grants
  - *Distributed systems*: Each station determines its slot for transmission from the reservation information
- Single or Multiple Frames
  - *Single frame reservation*: Only one frame transmission can be reserved within a reservation cycle
  - *Multiple frame reservation*: More than one frame transmission can be reserved within a reservation cycle
- Channelized or Random Access Reservations
  - $n \leq M$  ■ *Channelized (typically TDMA) reservation*: Reservation messages from different stations are multiplexed without any risk of collision
  - $n > M$  ■ *Random access reservation*: Each station transmits its reservation message randomly until the message goes through      **normal case**

# Example

- Initially stations 3 & 5 have reservations to transmit frames
- Station 8 becomes active and makes reservation
- Cycle now also includes frame transmissions from station 8



# Efficiency of Reservation Systems

what is v what is X

- Assume minislot duration = vX  $v \ll 1$
- TDMA single frame reservation scheme
  - If propagation delay is negligible, a single frame transmission requires  $(1+v)X$  seconds  $X+vX$
  - Link is fully loaded when all stations transmit, maximum efficiency is:

$$\rho_{\max} = \frac{MX}{MvX + MX} = \frac{1}{1 + v}$$

- TDMA  $k$  frame reservation scheme
  - If  $k$  frame transmissions can be reserved with a reservation message and if there are  $M$  stations, as many as  $Mk$  frames can be transmitted in  $XM(k+v)$  seconds
  - Maximum efficiency is:

$$\rho_{\max} = \frac{MkX}{MvX + MkX} = \frac{1}{1 + \frac{v}{k}}$$

# Random Access Reservation Systems

- *Large number of light traffic stations*
  - Dedicating a minislot to each station is inefficient
- **Slotted ALOHA reservation scheme** for mini slot allocation
  - Stations use slotted Aloha in reservation minislots
  - On average, each reservation takes at least  $e$  minislot attempts
  - Effective time required for the reservation is  $2.71vX$

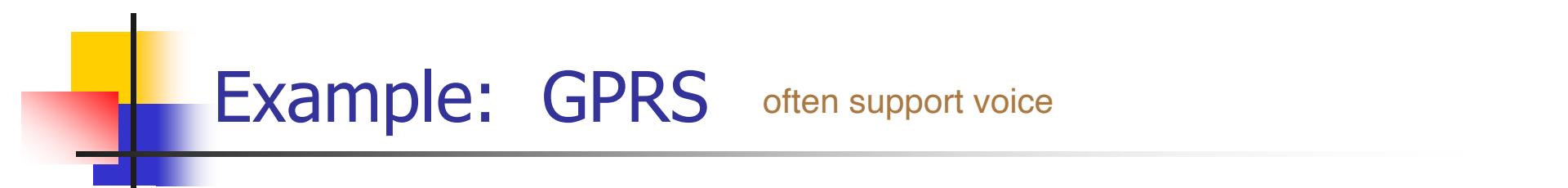
$e$  number of \mu (mini slot length)

effi not low with small v

$$\rho_{\max} = \frac{X}{X(1+ev)} = \frac{1}{1 + 2.71v}$$

overhead

Text



# Example: GPRS

often support voice

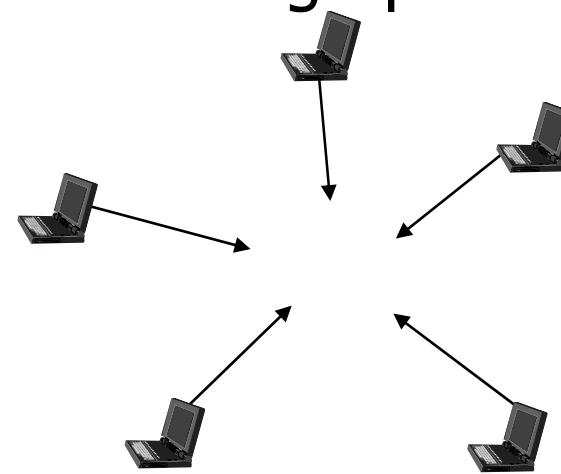
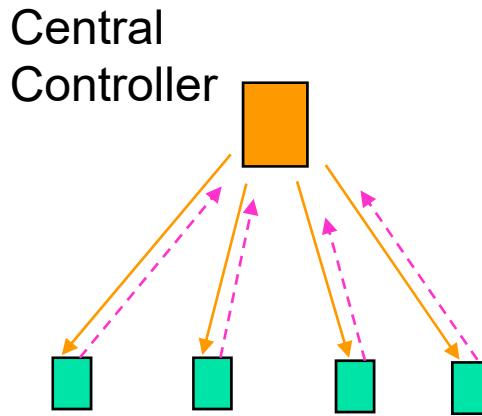
- General Packet Radio Service
  - Packet data service in GSM cellular radio
  - GPRS devices, e.g. cellphones or laptops, send packet data over radio and then to Internet
  - Slotted Aloha MAC used for reservations
  - Single & multi-slot reservations supported

# Reservation Systems and Quality of Service

- Different applications; different requirements
    - Immediate transfer for ACK frames
    - Low-delay transfer & steady bandwidth for voice
    - High-bandwidth for Web transfers
  - Reservation provide direct means for QoS
    - Stations make requests per frame
    - Stations can request for persistent transmission access
    - Centralized controller issues grants
      - Preferred approach
    - Decentralized protocol allows stations to determine grants
      - Protocol must deal with error conditions when requests or grants are lost
- Algorithm: given required QoS and sys constraint rsc,  
if rsc enough, set  
otherwise, reject requests

# Polling Systems

- *Centralized polling systems*: A central controller transmits polling messages to stations according to a certain order
- *Distributed polling systems*: A permit for frame transmission is passed from station to station according to a certain order
- A signaling procedure exists for setting up order



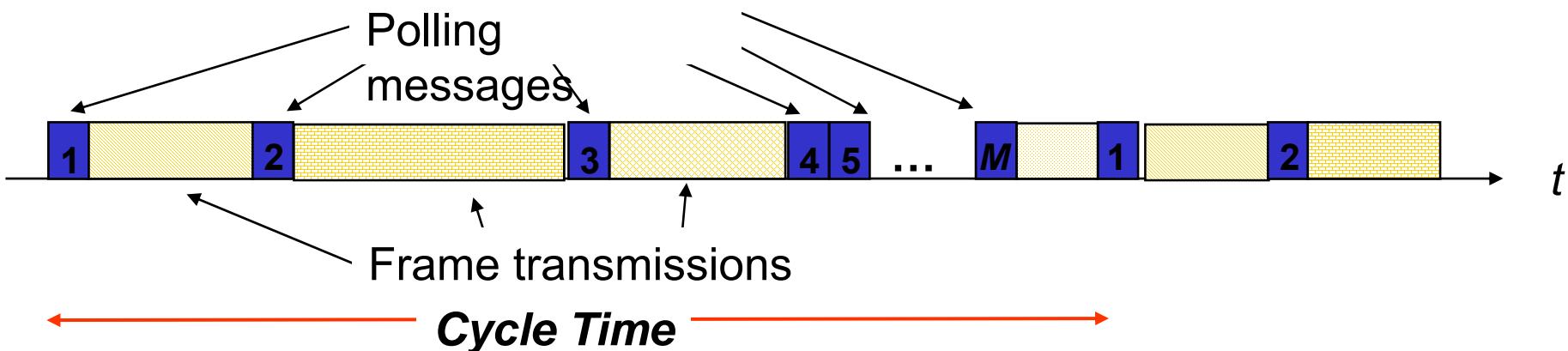


# Polling System Options

- Service Limits: How much is a station allowed to transmit per poll?
  - *Exhaustive*: until station's data buffer is empty (including new frame arrivals)
  - *Gated*: all data in buffer when poll arrives
  - *Frame-Limited*: one frame per poll
  - *Time-Limited*: up to some maximum time
- Priority mechanisms
  - More bandwidth & lower delay for stations that appear multiple times in the polling list

# Walk Time & Cycle Time

- Assume polling order is round robin
- Time is “wasted” in polling stations
  - Time to prepare & send polling message
  - Time for station to respond
- *Walk time*: from when a station completes transmission to when next station begins transmission
- *Cycle time* is between consecutive polls of a station
- Overhead/cycle = total walk time/cycle time



# Average Cycle Time

- Assume walk times all equal to  $t'$
- Exhaustive Service: stations empty their buffers
- Cycle time =  $Mt' +$  time to empty M station buffers
- $\lambda$  be frame arrival rate at the system
- $N_c$  average number of frames transmitted from a station
- Time to empty one station buffer:

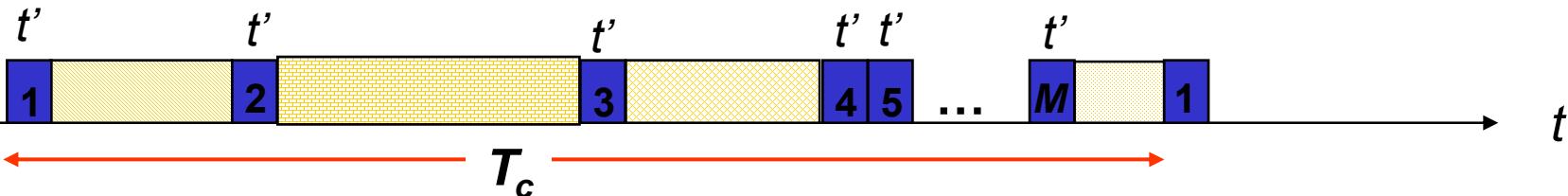
$$T_{station} = N_c X = \left(\frac{\lambda}{M} T_c\right) X = \frac{\rho T_c}{M} \quad \rho = \lambda X$$

1/X是output rate

- Average Cycle Time:

$$T_c = Mt' + MT_{station} = Mt' + \rho T_c \Rightarrow T_c = \frac{Mt'}{1 - \rho}$$

walk time  
divided by 1-rou



# Efficiency of Polling Systems

## ■ Exhaustive Service

- Cycle time increases as traffic increases, so delays become very large
- Walk time per cycle becomes negligible compared to cycle time:

$$\text{Efficiency} = \frac{T_c - Mt'}{T_c} = \rho$$

*Can approach  
100%*

## ■ Limited Service

- Many applications cannot tolerate extremely long delays
- Time or transmissions per station are limited
- This limits the cycle time and hence delay
- Efficiency of 100% is not possible

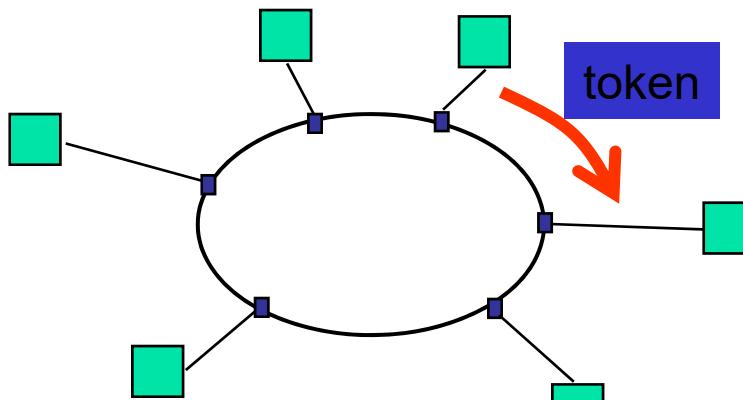
MX: transimmission

Mt': walk time

$$\text{Efficiency} = \frac{MX}{MX + Mt'} = \frac{1}{1 + t'/X}$$

*Single frame  
per poll*

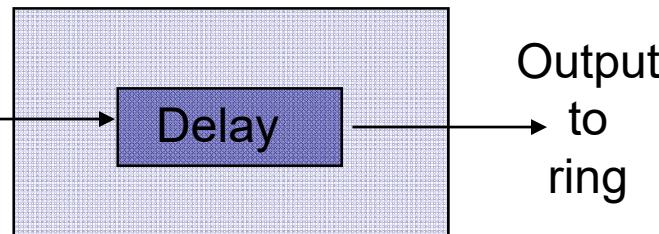
# Application: Token-Passing Rings



if station is not sending, then it is in the listening mode  
just checking the token(not modifying it)  
if a station wants to transmit, it finds out a free token and flip it to a busy token  
after sending, insert a free token

Listen mode

Input from ring



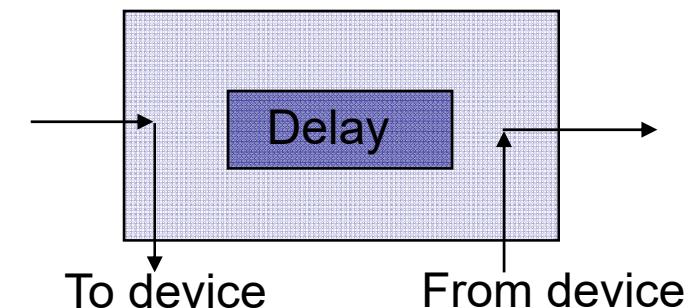
Ready station looks for free token

**Free Token = Poll**

Frame Delimiter is Token

Free = 0111110  
Busy = 0111111 flip

Transmit mode

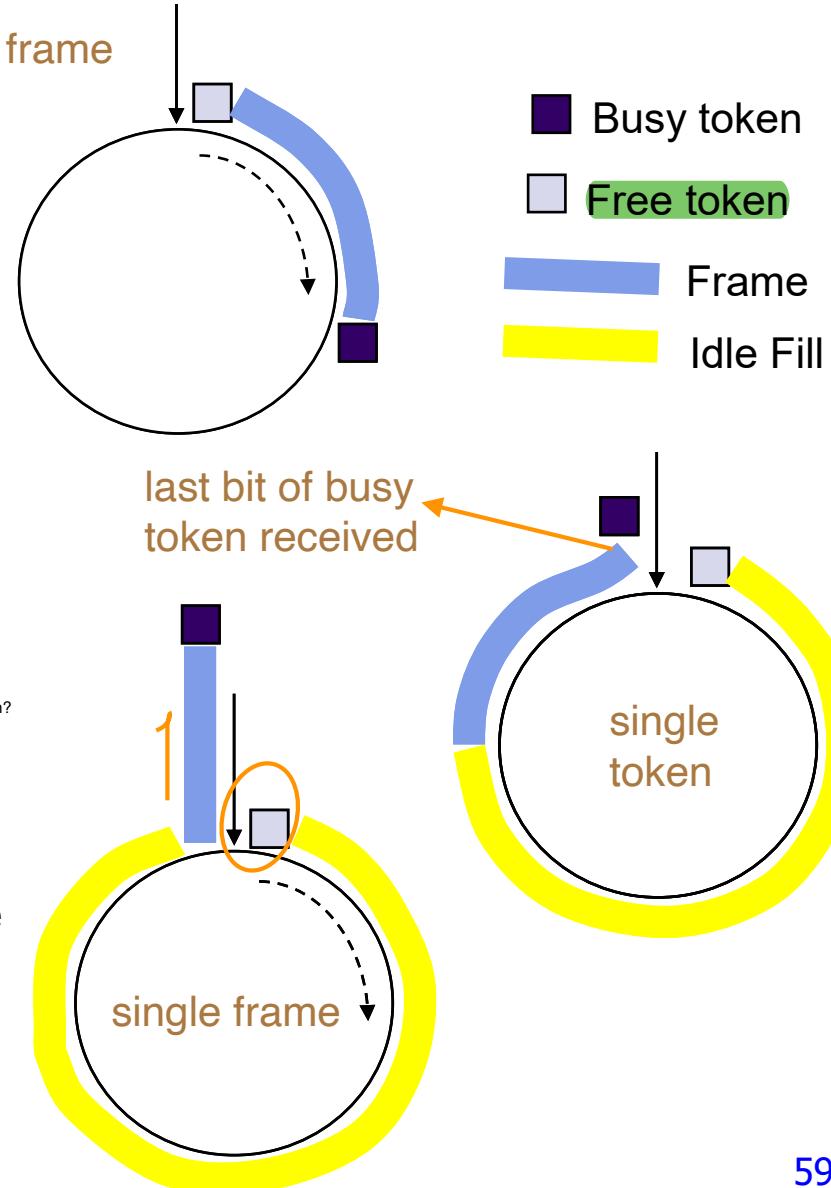


Flips bit to change free token to busy  
Ready station inserts its frames  
Reinserts free token when done

# Methods of Token Reinsertion

normally efficiency multi>single token>single frame

- **Ring latency:** number of bits that can be simultaneously in transit on ring
- **Multi-token operation** on one ring
  - Free token transmitted immediately after last bit of data frame
- **Single-token operation**
  - Free token inserted after last bit of the busy token is received back
  - Transmission time at least ring latency
  - If frame is longer than ring latency, equivalent to multi-token operation
- **Single-Frame operation**
  - Free token inserted after transmitting station has received last bit of its frame
  - Equivalent to attaching trailer equal to ring latency



# Token Ring Throughput

## ■ Definition

- $\tau'$ : ring latency (time required for bit to circulate ring)
- $X$ : maximum frame transmission time allowed per station

為什麼加tau  
what

## ■ *Multi-token operation*

- Assume network is fully loaded, and all  $M$  stations transmit for  $X$  seconds upon the reception of a free token
- This is a polling system with limited service time:

$$\rho_{\max} = \frac{MX}{\tau' + MX} = \frac{1}{1 + \tau' / MX} = \frac{1}{1 + a' / M}$$

consider fully loaded

$M$  token? all the frames(token?) can send  $X$  seconds

$a' = \frac{\tau'}{X}$  is the normalized ring latency

# Token Ring Throughput

- *Single-token operation*
  - Effective frame transmission time is maximum of X and  $\tau'$ , therefore

$$\rho_{\max} = \frac{MX}{\tau' + M \max\{X, \tau'\}} = \frac{1}{\max\{1, a'\} + a'/M}$$

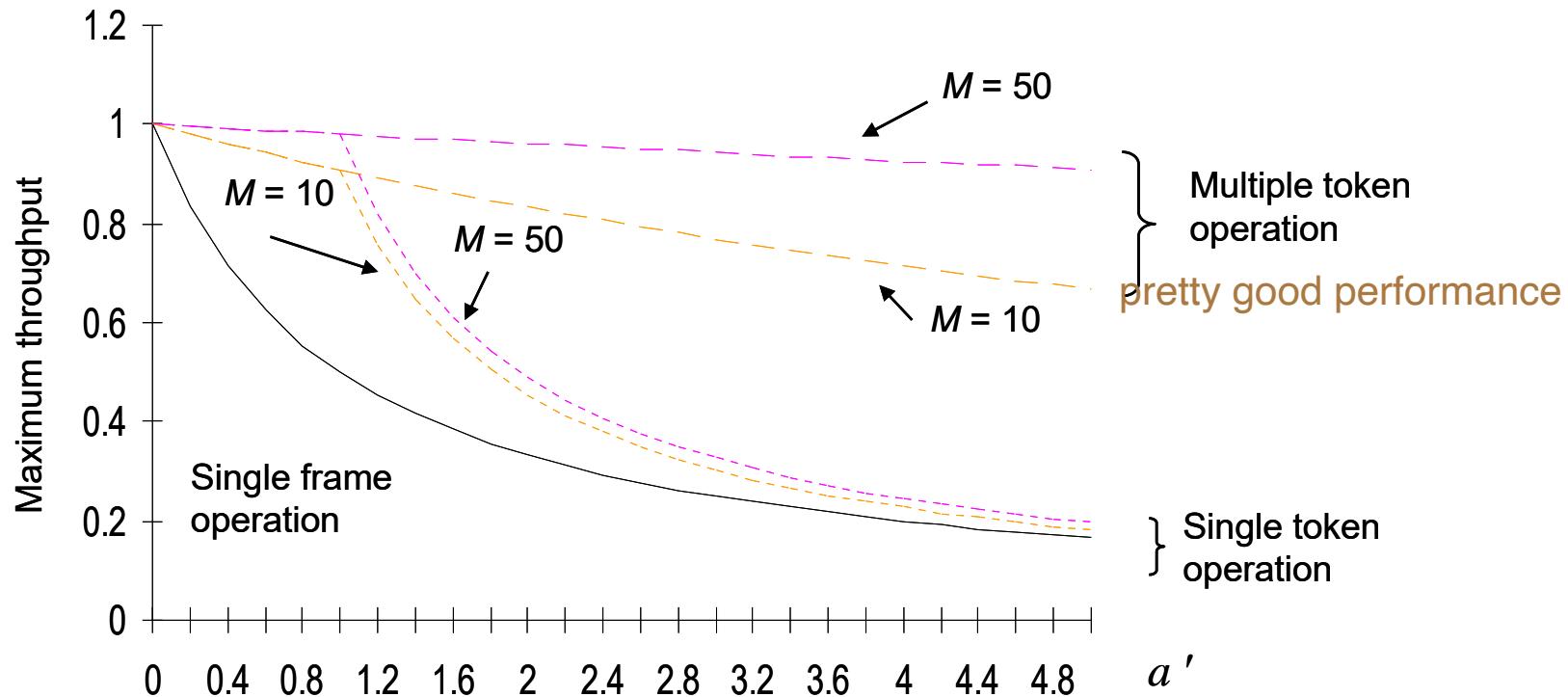
if tau ' > transmission time

wait for it to come back

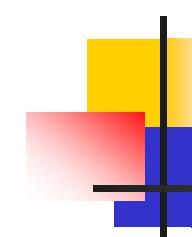
- *Single-frame operation*
  - Effective frame transmission time is  $X + \tau'$ , therefore

$$\rho_{\max} = \frac{MX}{\tau' + M(X + \tau')} = \frac{1}{1 + a'(1 + 1/M)}$$

# Token Reinsertion Efficiency Comparison



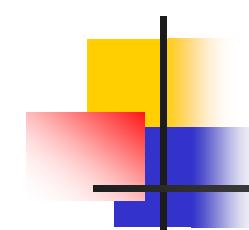
- $a \ll 1$ , any token reinsertion strategy acceptable
- $a \approx 1$ , single token reinsertion strategy acceptable
- $a > 1$ , multitone reinsertion strategy necessary



# Application Examples

---

- Single-frame reinsertion
  - IEEE 802.5 Token Ring LAN @ 4 Mbps
- Single token reinsertion
  - IBM Token Ring @ 4 Mbps
- Multi-token reinsertion
  - IEEE 802.5 and IBM Ring LANs @ 16 Mbps
  - FDDI Ring @ 50 Mbps
- All of these LANs incorporate token priority mechanisms



# Comparison of MAC approaches

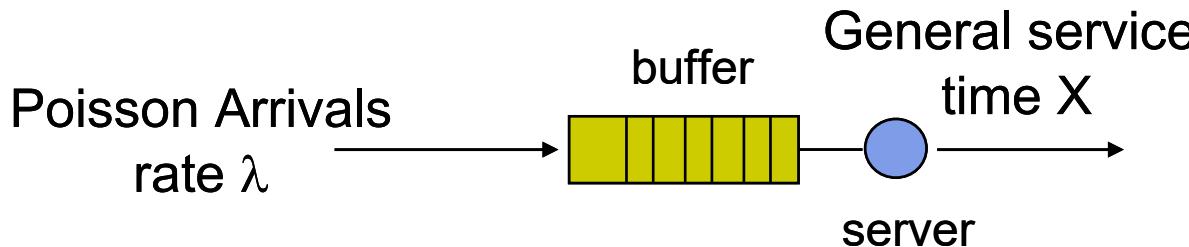
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- Aloha & Slotted Aloha
  - Simple & quick transfer at very low load
  - Accommodates large number of low-traffic bursty users
  - Highly variable delay at moderate loads
  - Efficiency does not depend on  $a = t_{prop}/X$
- CSMA-CD
  - Quick transfer and high efficiency for low delay-bandwidth product
  - Can accommodate a large number of bursty users
  - Variable and unpredictable delay

# Comparison of MAC approaches

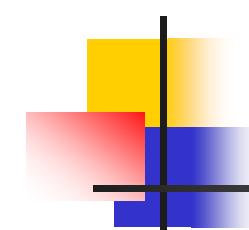
- **Reservation**      if user has steady traffic to send,  
                          then prefer reservation and polling  
                          more efficient
  - On-demand transmission of bursty or steady streams
  - Accommodates large number of low-traffic users with slotted Aloha reservations
  - Can incorporate QoS
  - Handles large delay-bandwidth product via delayed grants
- **Polling**
  - Generalization of time-division multiple access
  - Provides fairness through regular access opportunities
  - Can provide bounds on access delay
  - Performance deteriorates with large delay-bandwidth product

# Delay Performance and Queuing



- Arrival Model
  - Independent frame interarrival times:
  - Average  $1/\lambda$
  - Exponential distribution
  - “Poisson Arrivals”
- Infinite Buffer
  - No Blocking
- Frame Length Model
  - Independent frame transmission times  $X$
  - Average  $E[X] = 1/\mu$
  - General distribution
  - Constant, exponential,...
- Load  $\rho = \lambda/\mu$
- Stability Condition:  $\rho < 1$

*M/G/1 model can be used as baseline for MAC performance*



# M/G/1 Performance Results

Total Delay = Waiting Time + Service Time

Average Waiting Time:

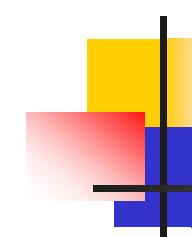
$$E[W] = \frac{\rho}{2(1-\rho)} \left(1 + \frac{\sigma_X^2}{E[X]^2}\right) E[X]$$

Average Total Delay:

$$E[T] = E[W] + E[X]$$

Example: M/D/1

$$E[W] = \frac{\rho}{2(1-\rho)} E[X]$$

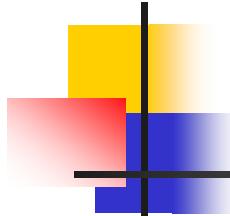


# M/G/1 Vacation Model

- In M/G/1 model, a frame arriving to an empty multiplexer begins transmission immediately
- In many MACs, there is a delay before transmission can begin
- *M/G/1 Vacation Model*: when system empties, server goes away on vacation for random time  $V$

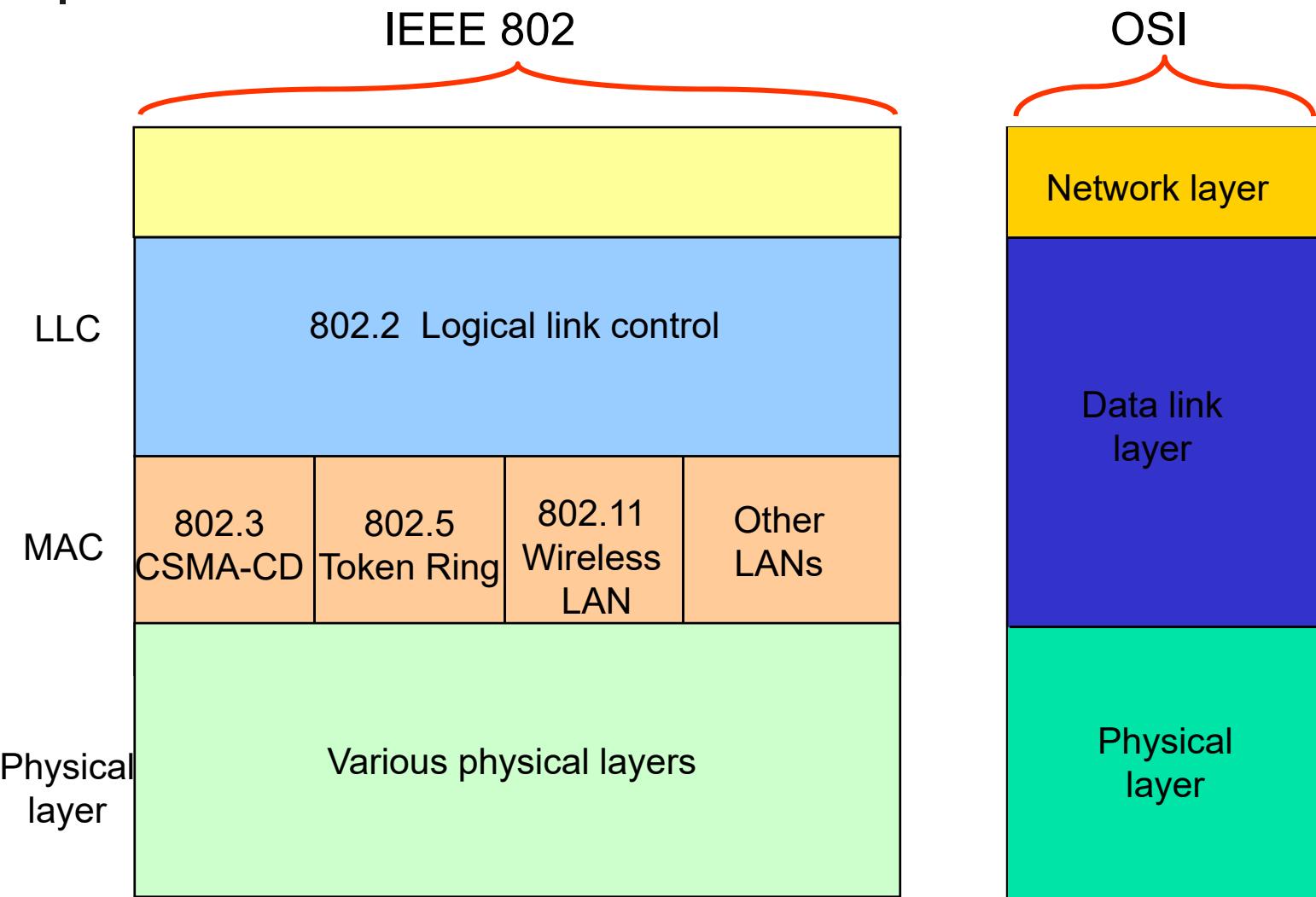
$$E[W] = \frac{\rho}{2(1-\rho)} \left( 1 + \frac{\sigma_X^2}{E[X]^2} \right) E[X] + \frac{E[V^2]}{2E[V]}$$

Extra delay term



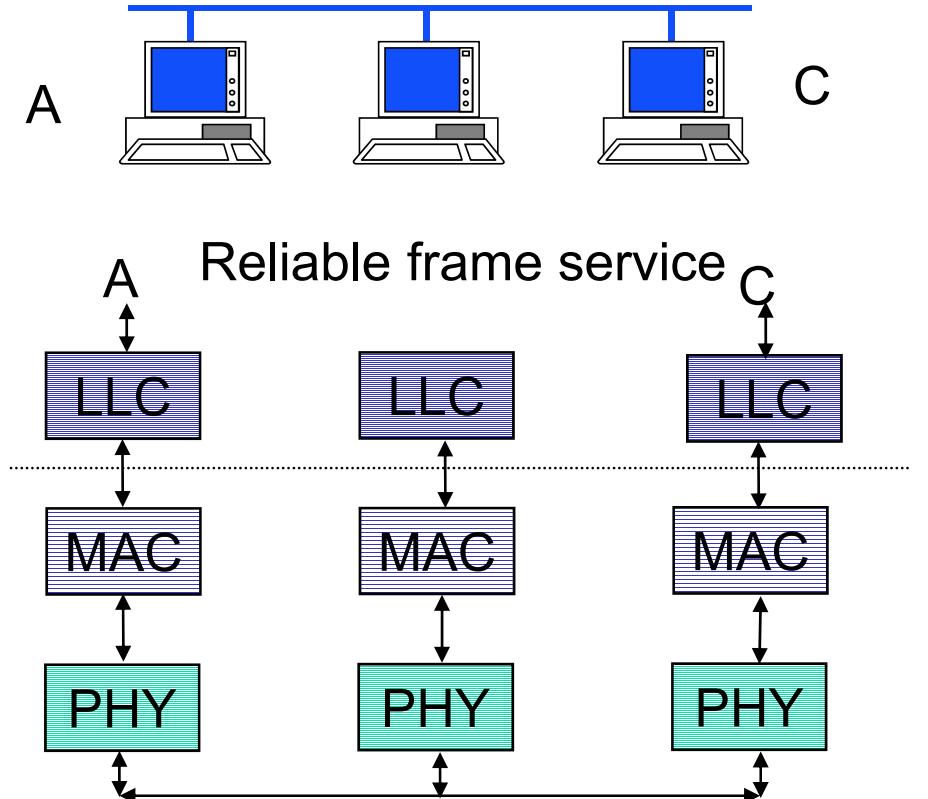
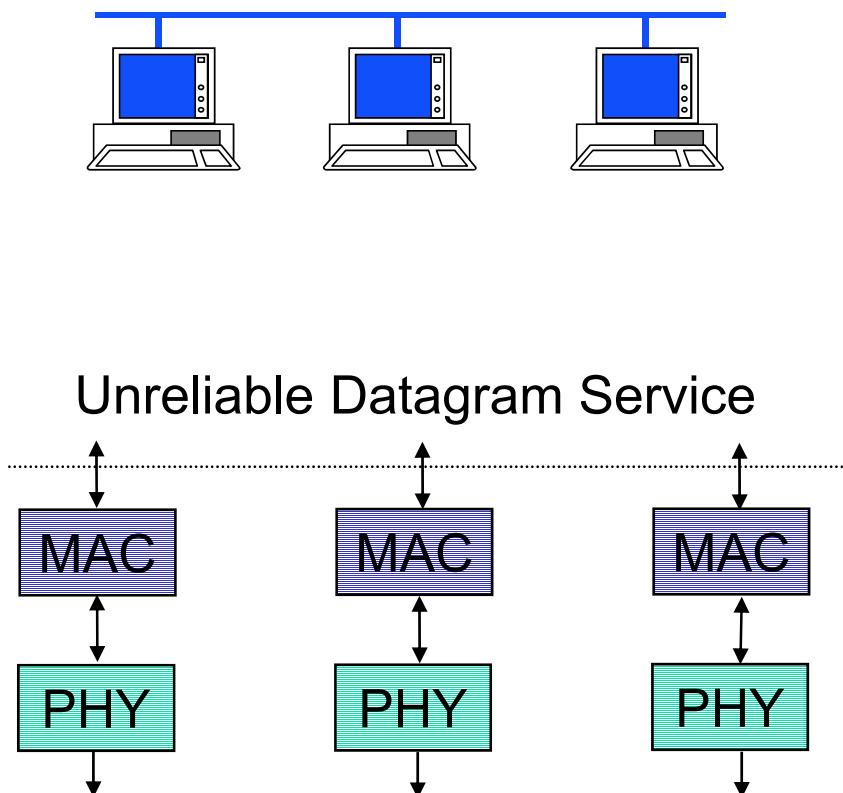
# **MAC in Different Networks**

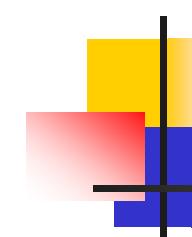
# IEEE 802 Networks



# Logical Link Control Layer

- IEEE 802.2: LLC enhances service provided by MAC



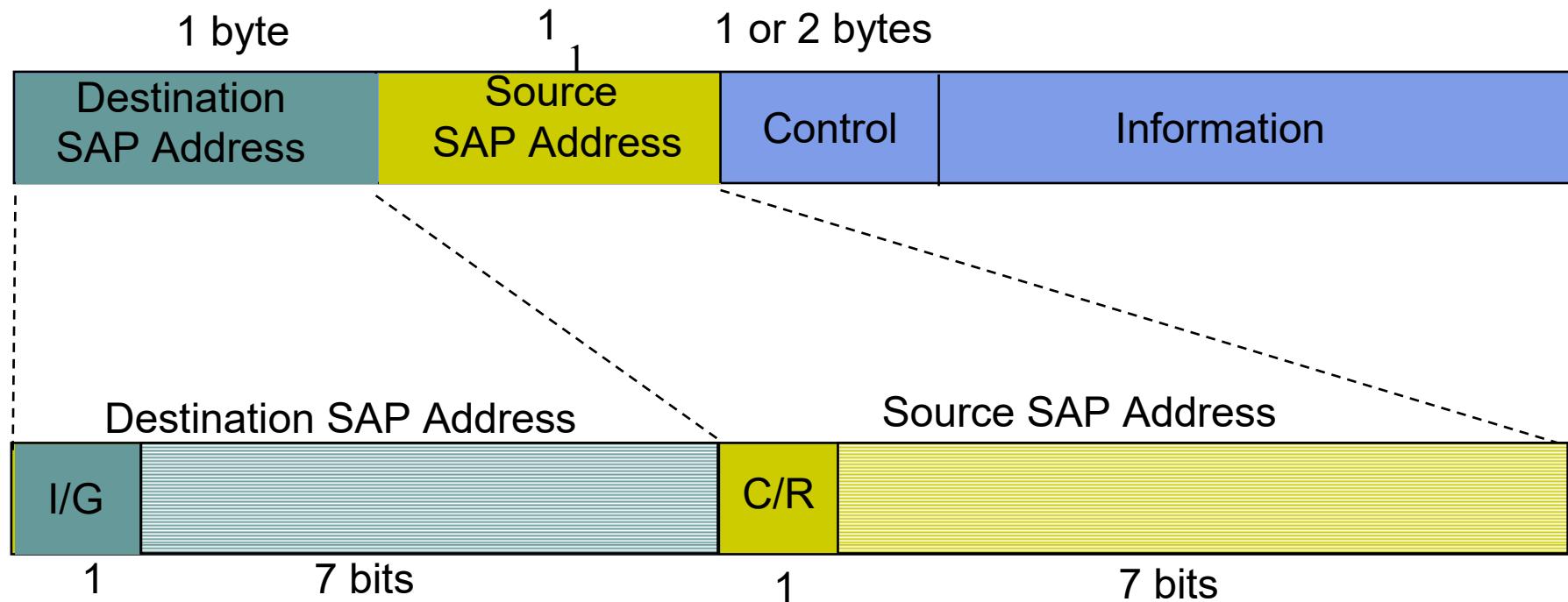


# Logical Link Control Services

---

- Type 1: Unacknowledged connectionless service
  - Unnumbered frame mode of HDLC
- Type 2: Reliable connection-oriented service
  - Asynchronous balanced mode of HDLC
- Type 3: Acknowledged connectionless service
- Additional addressing
  - A workstation has a single MAC physical address
  - Can handle several logical connections, distinguished by their SAP (service access points).

# LLC PDU Structure



I/G = Individual or group address

C/R = Command or response frame

Examples of SAP Addresses:

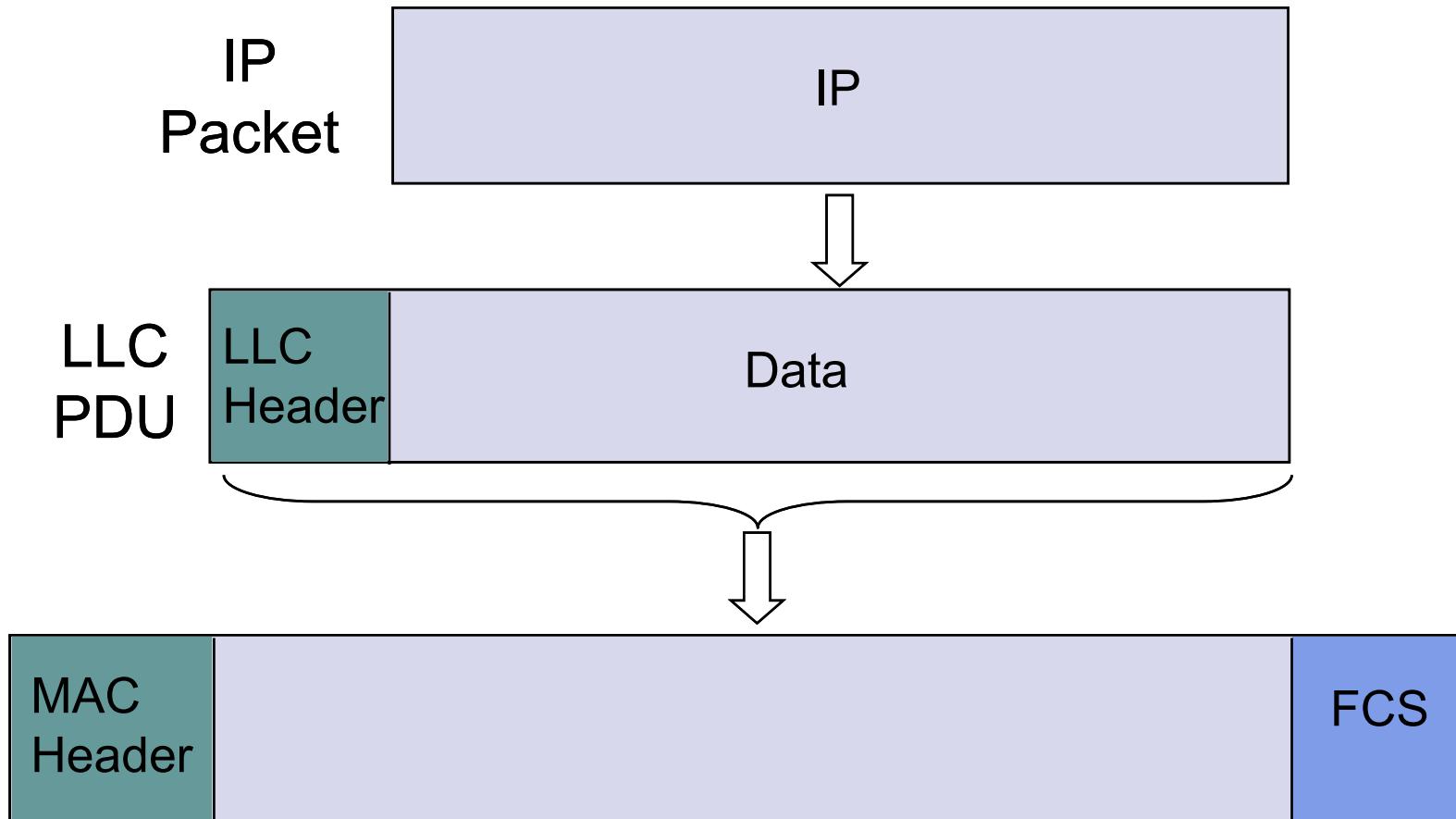
06 IP packet

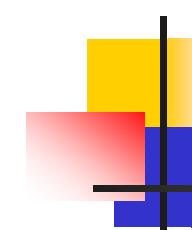
E0 Novell IPX

FE OSI packet

AA SubNetwork Access protocol (SNAP)

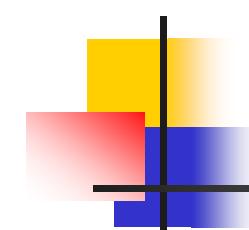
# Encapsulation of MAC frames





# IEEE 802.3 MAC: Ethernet

- CSMA/CD
- *Slot Time* is the critical system parameter
  - upper bound on time to detect collision
  - upper bound on time to acquire channel
  - upper bound on length of frame segment generated by collision
  - quantum for retransmission scheduling
  - $\max\{\text{round-trip propagation, MAC jam time}\}$
- Truncated binary exponential backoff
  - for retransmission  $n$ :  $0 < r < 2^k$ , where  $k = \min(n, 10)$
  - Give up after 16 retransmissions

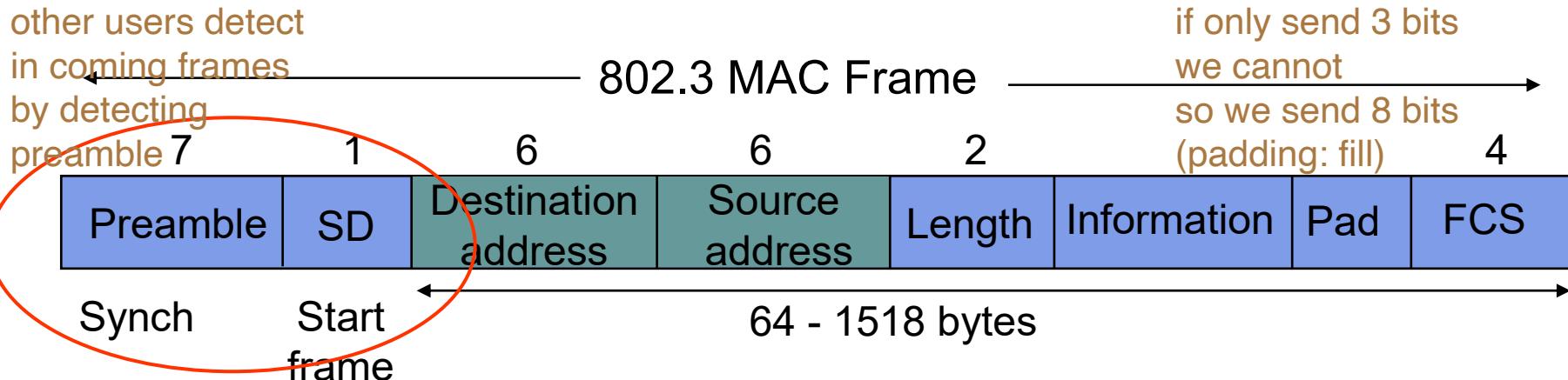


# IEEE 802.3 Original Parameters

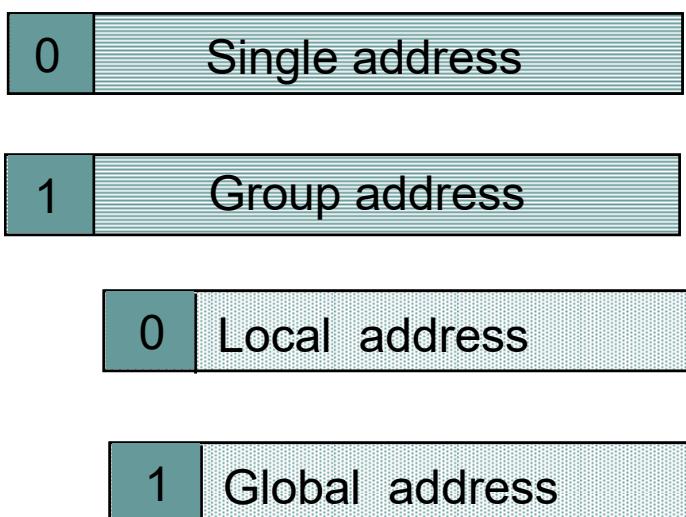
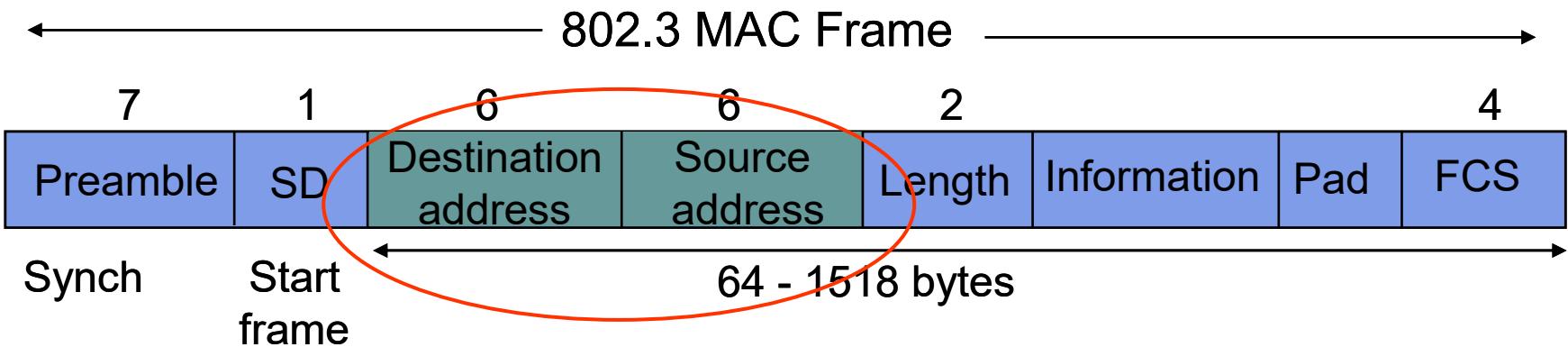
- Transmission Rate: 10 Mbps
- Min Frame: 512 bits = 64 bytes
- Slot time: 512 bits/10 Mbps = 51.2  $\mu$ sec
  - $51.2 \mu\text{sec} \times 2 \times 10^5 \text{ km/sec} = 10.24 \text{ km, 1 way}$
  - 5.12 km round trip distance
- Max Length: 2500 meters + 4 repeaters
- *Each x10 increase in bit rate, must be accompanied by x10 decrease in distance*

# IEEE 802.3 MAC Frame

- Every frame transmission begins “from scratch”
- Preamble helps receivers synchronize their clocks to transmitter clock
- 7 bytes of 10101010 generate a square wave
- Start frame byte changes to 1010101**1**
- Receivers look for change in 10 pattern

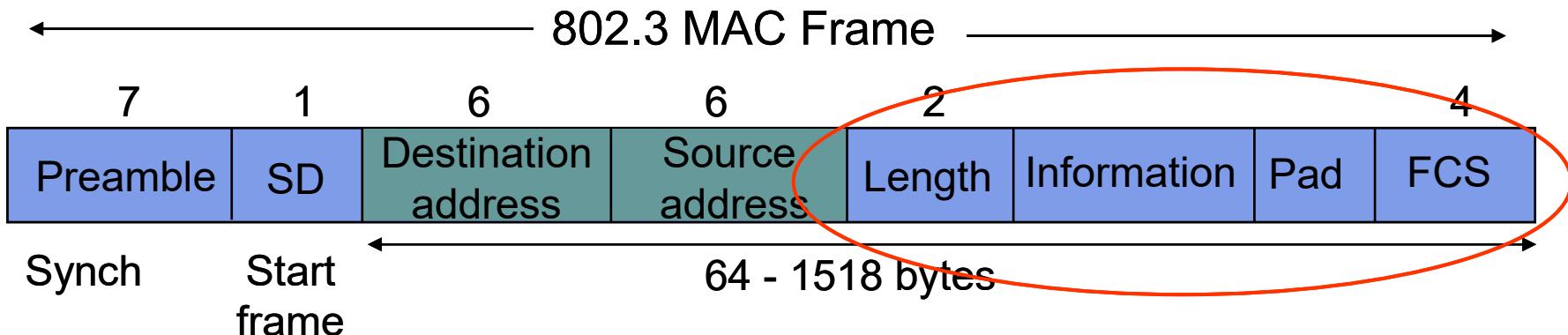


# IEEE 802.3 MAC Frame



- Destination address
  - single address
  - group address
  - broadcast = 111...111
- Addresses
  - local or global
- Global addresses
  - first 24 bits assigned to manufacturer;
  - next 24 bits assigned by manufacturer
  - Cisco 00-00-0C
  - 3COM 02-60-8C

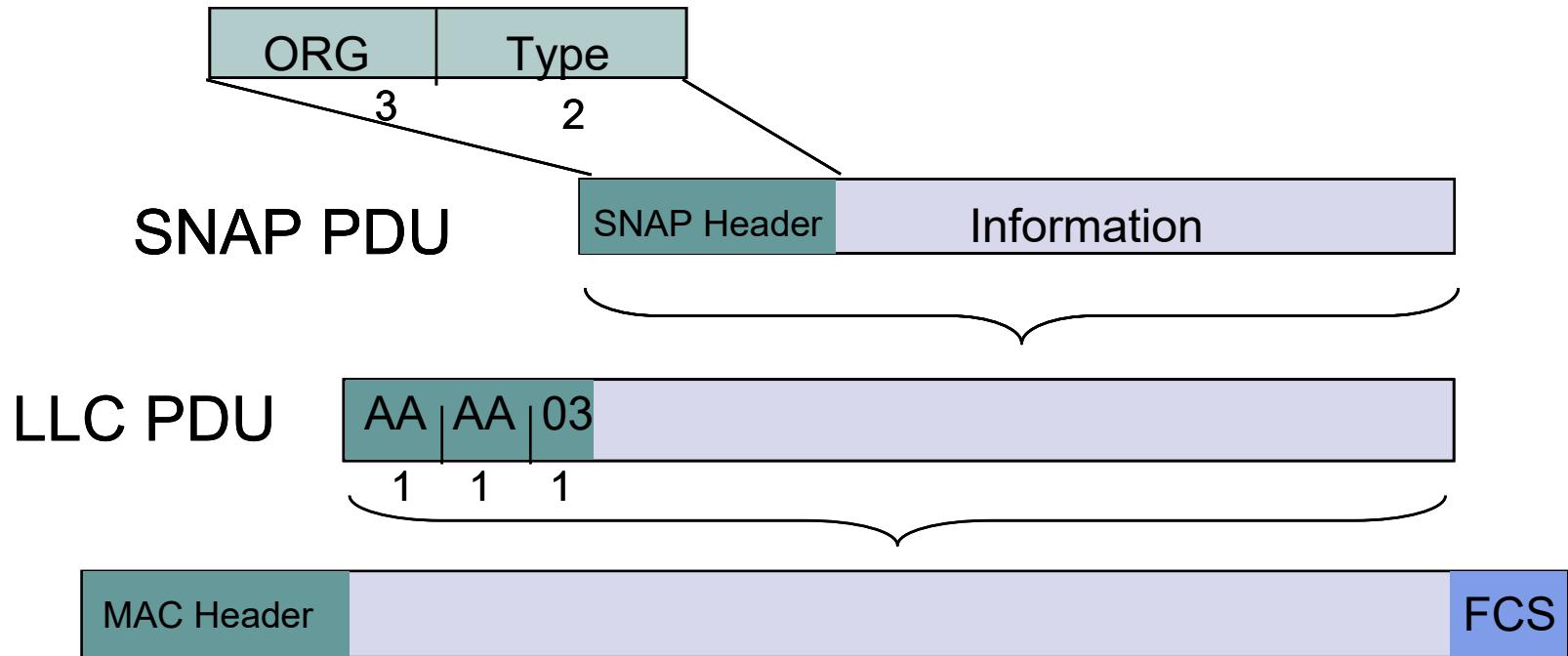
# IEEE 802.3 MAC Frame



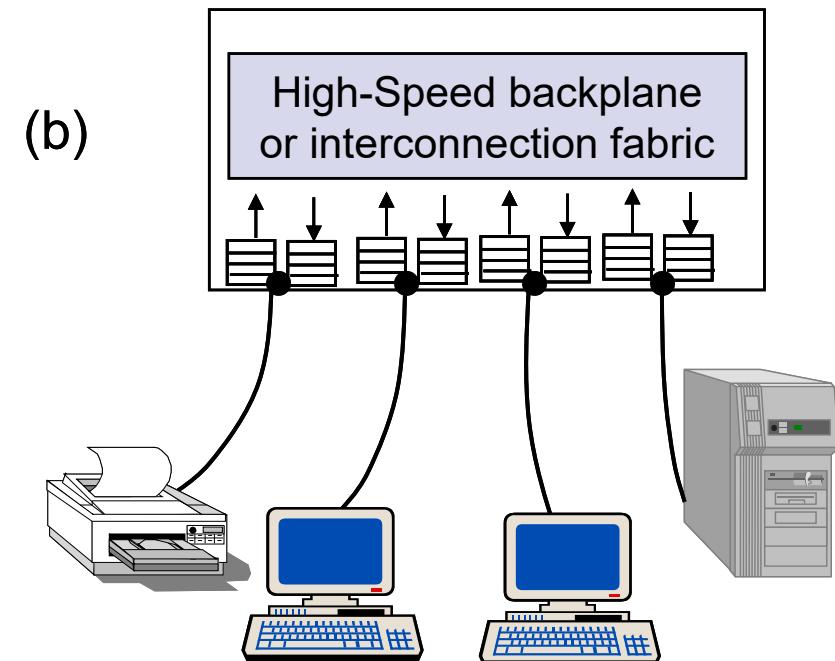
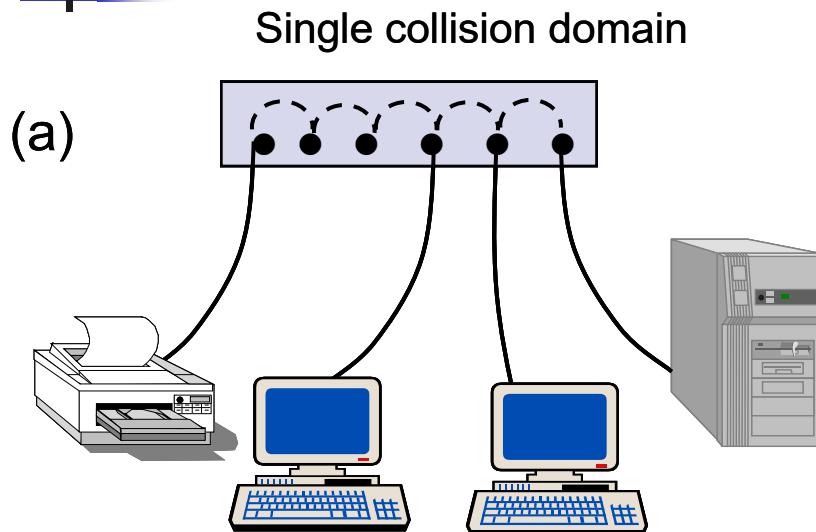
- Length: # bytes in information field
  - Max frame 1518 bytes, excluding preamble & SD
  - Max information 1500 bytes: 05DC
- Pad: ensures min frame of 64 bytes
- FCS: CCITT-32 CRC, covers addresses, length, information, pad fields
  - NIC discards frames with improper lengths or failed CRC

# SubNetwork Access Protocol (SNAP)

- IEEE standards assume LLC always used
- Higher layer protocols developed for DIX expect *type* field
- DSAP, SSAP = AA, AA indicate SNAP PDU;
- 03 = Type 1 (connectionless) service
- SNAP used to encapsulate Ethernet frames



# Ethernet Hubs & Switches

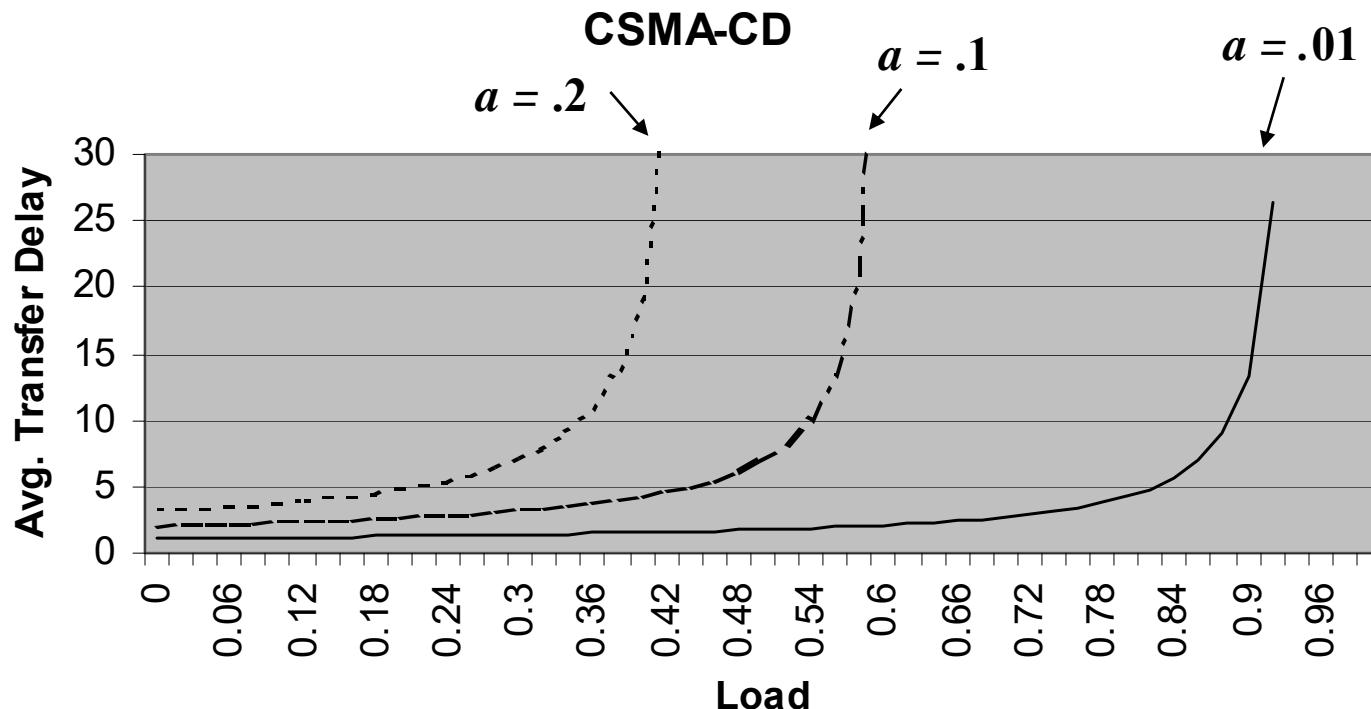


Twisted Pair Cheap  
Easy to work with  
Reliable  
Star-topology CSMA-CD

Twisted Pair Cheap  
Bridging increases scalability  
Separate collision domains  
Full duplex operation

# Ethernet Scalability

- CSMA-CD maximum throughput depends on normalized delay-bandwidth product  $a = t_{prop}/X$
- x10 increase in bit rate = x10 decrease in X
- To keep  $a$  constant need to either: decrease  $t_{prop}$  (*distance*) by x10; or increase frame length x10



# Fast Ethernet

To preserve compatibility with 10 Mbps Ethernet:

- Same frame format, same interfaces, same protocols
- Hub topology only with twisted pair & fiber
- Bus topology & coaxial cable abandoned
- Category 3 twisted pair (ordinary telephone grade) requires 4 pairs
- Category 5 twisted pair requires 2 pairs (most popular)
- Most prevalent LAN today

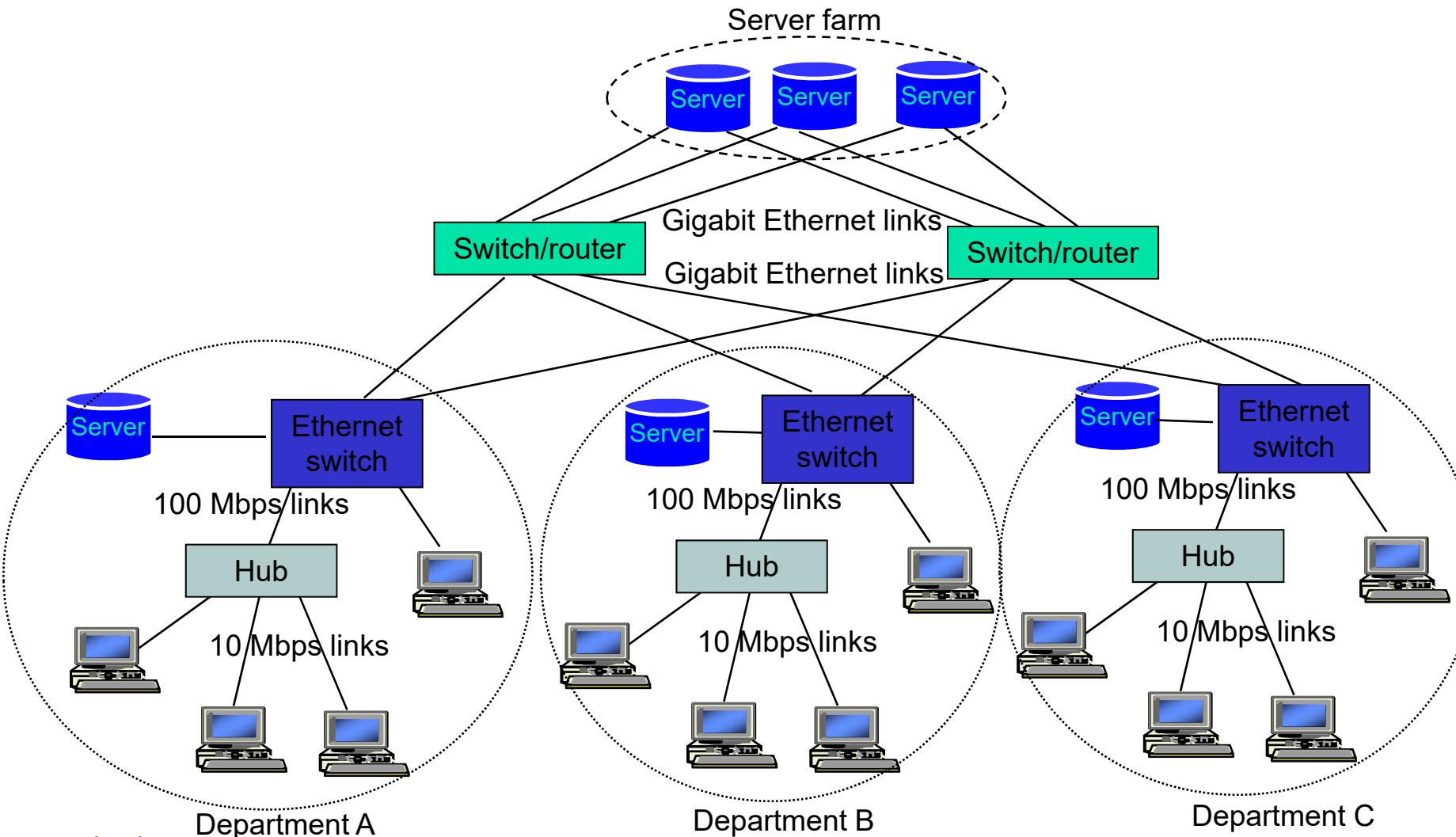
	<b>100baseT4</b>	<b>100baseT</b>	<b>100baseFX</b>
Medium	Twisted pair category 3 UTP 4 pairs	Twisted pair category 5 UTP two pairs	Optical fiber multimode Two strands
Max. Segment Length	100 m	100 m	2 km
Topology	Star	Star	Star

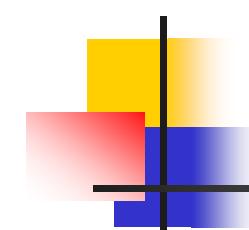
# Gigabit Ethernet

- Slot time increased to *512 bytes*
- Small frames need to be extended to 512 B
- Frame bursting to allow stations to transmit burst of short frames
- Frame structure preserved but CSMA-CD essentially abandoned
- Extensive deployment in backbone of enterprise data networks and in server farms

	<b>1000baseSX</b>	<b>1000baseLX</b>	<b>1000baseCX</b>	<b>1000baseT</b>
Medium	Optical fiber multimode Two strands	Optical fiber single mode Two strands	Shielded copper cable	Twisted pair category 5 UTP
Max. Segment Length	550 m	5 km	25 m	100 m
Topology	Star	Star	Star	Star

# Typical Ethernet Deployment





# IEEE 802.11 Wireless LAN

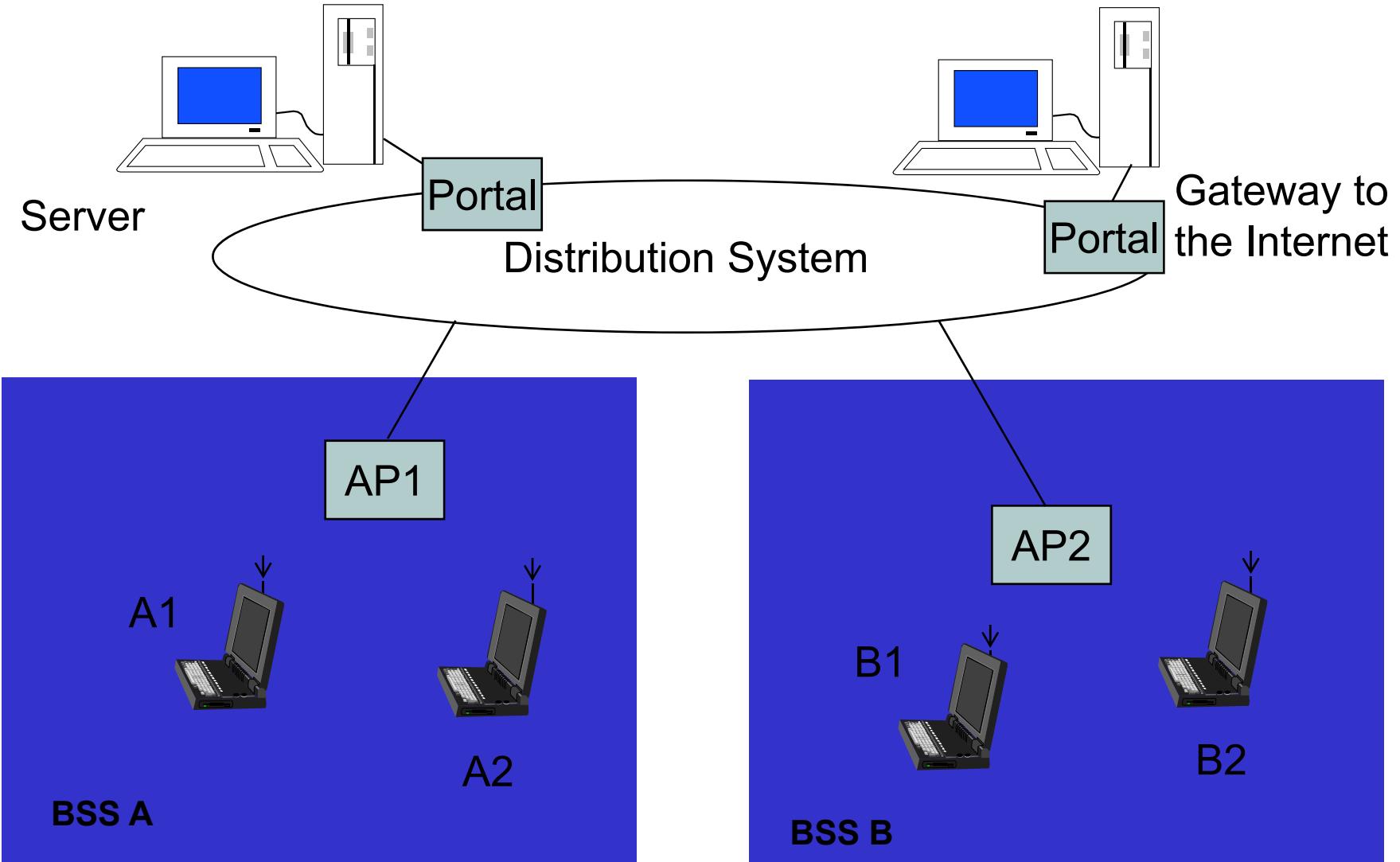
- Stimulated by availability of *unlicensed spectrum*
  - U.S. Industrial, Scientific, Medical (ISM) bands
  - 902-928 MHz, 2.400-2.4835 GHz, 5.725-5.850 GHz
- Targeted wireless LANs @ 20 Mbps
- MAC for high speed wireless LAN
- Ad Hoc & Infrastructure networks
- Variety of physical layers



# 802.11 Definitions

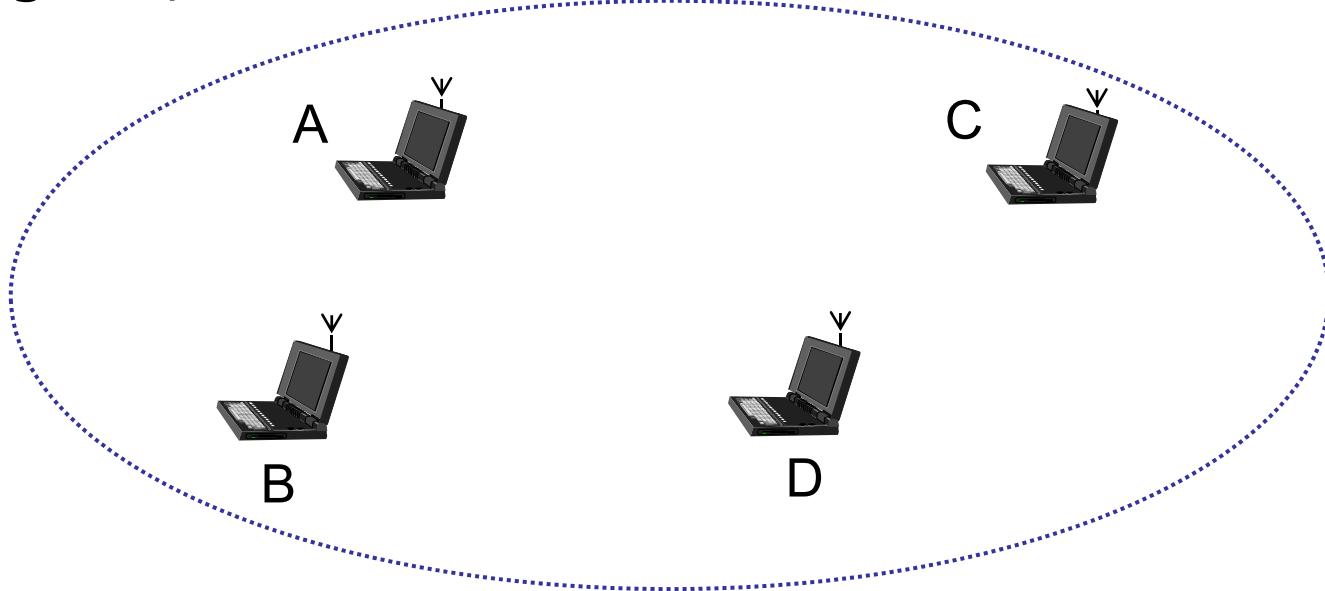
- *Basic Service Set (BSS)*
  - Group of stations that *coordinate their access* using a given instance of MAC
  - Located in a *Basic Service Area (BSA)*
  - Stations in BSS can communicate with each other
  - Distinct collocated BSS's can coexist
- *Extended Service Set (ESS)*
  - Multiple BSSs interconnected by *Distribution System (DS)*
  - Each BSS is like a cell and stations in BSS communicate with an *Access Point (AP)*
  - *Portals* attached to DS provide access to Internet

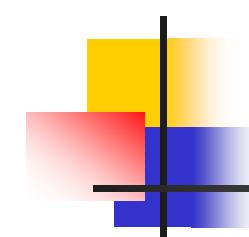
# Infrastructure Network



# Ad Hoc Communications

- Temporary association of group of stations
  - Within range of each other
  - Need to exchange information
  - E.g. Presentation in meeting, or distributed computer game, or both

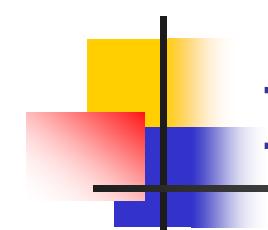




# Distribution Services

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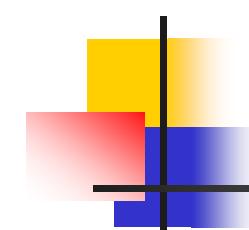
- Stations within BSS can communicate directly with each other
- DS provides *distribution services*:
  - Transfer MAC SDUs between APs in ESS
  - Transfer MSDUs between portals & BSSs in ESS
  - Transfer MSDUs between stations in same BSS
    - Multicast, broadcast, or stations's preference
- ESS looks like single BSS to LLC layer



# Infrastructure Services

---

- Select AP and establish *association* with AP
  - Then can send/receive frames via AP & DS
- *Reassociation service* to move from one AP to another AP
- *Dissociation service* to terminate association
- *Authentication service* to establish identity of other stations
- *Privacy service* to keep contents secret



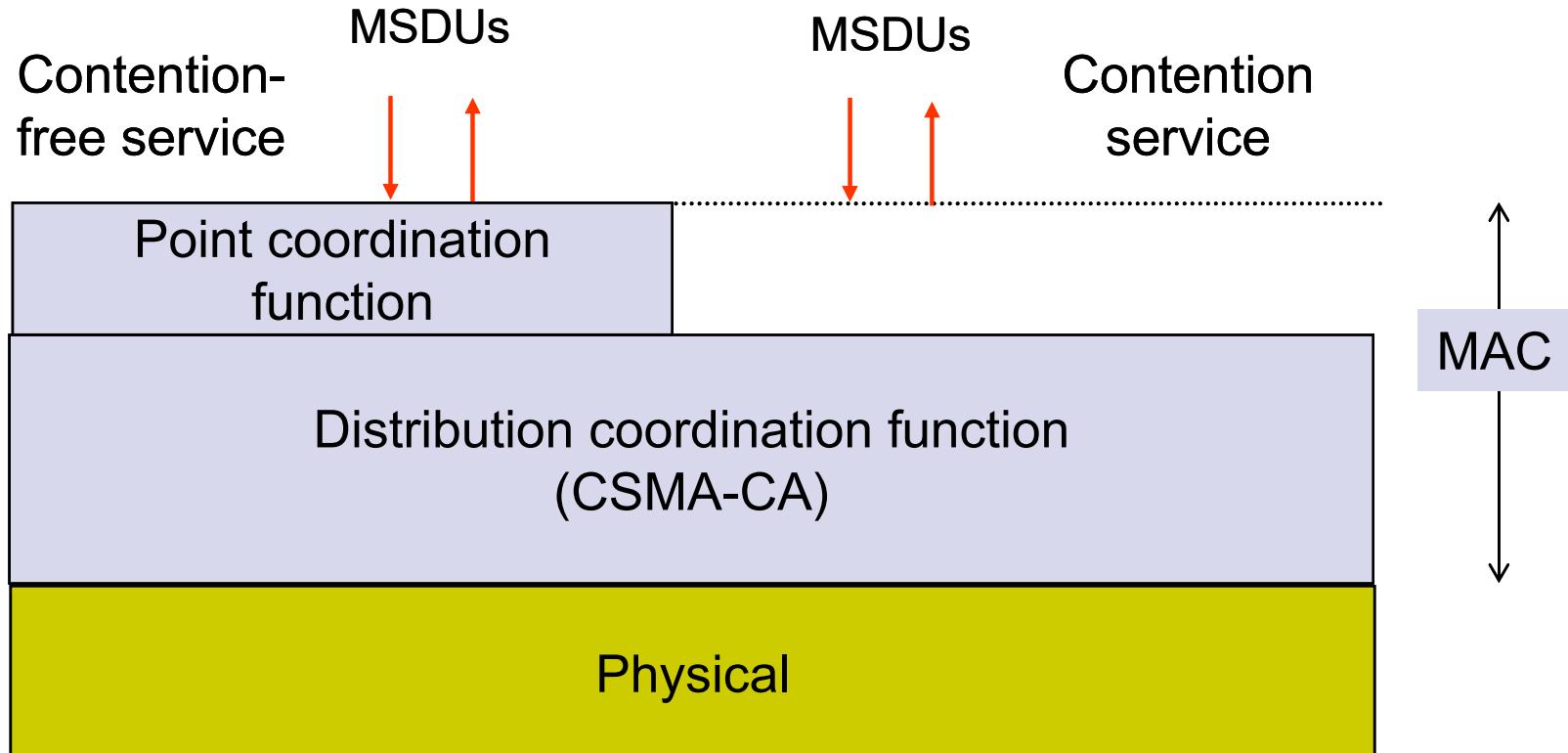
# IEEE 802.11 MAC

---

- MAC sublayer responsibilities
  - Channel access
  - PDU addressing, formatting, error checking
  - Fragmentation & reassembly of MAC SDUs
- MAC security service options
  - Authentication & privacy
- MAC management services
  - Roaming within ESS
  - Power management

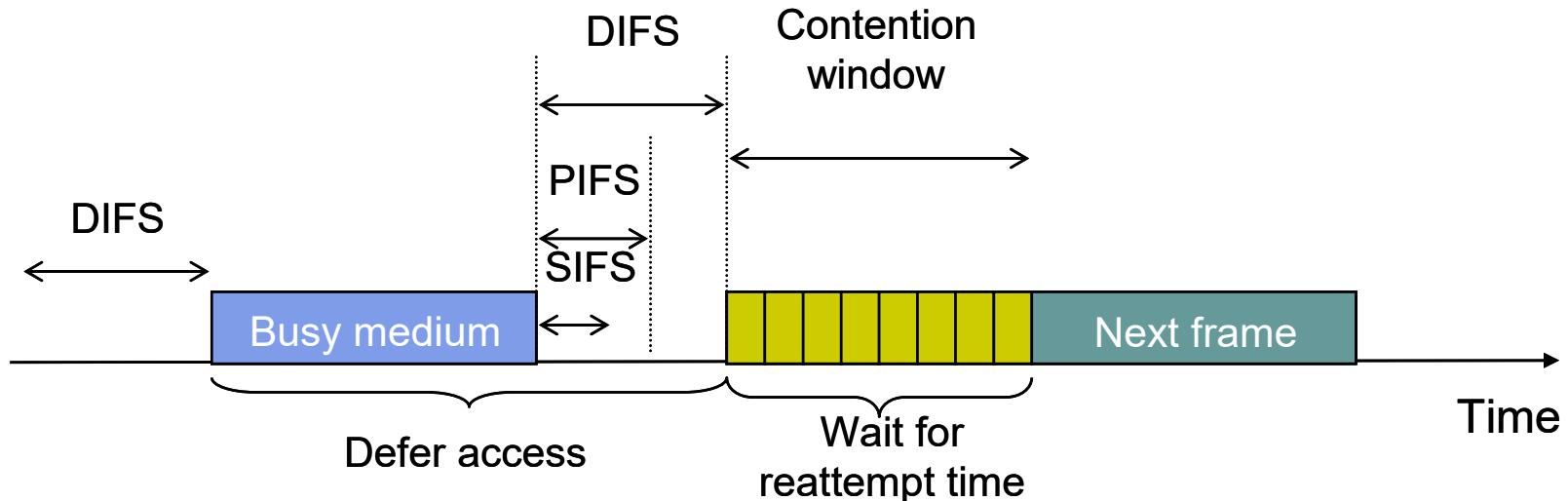
# MAC Services

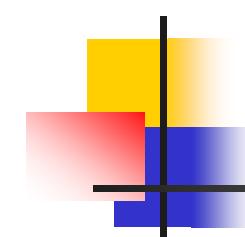
- Contention Service: Best effort
- Contention-Free Service: time-bounded transfer
- MAC can alternate between Contention Periods (CPs) & Contention-Free Periods (CFPs)



# Distributed Coordination Function (DCF)

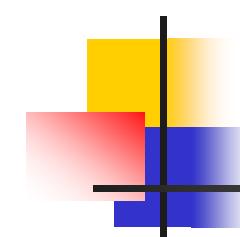
- DCF provides basic access service
  - Asynchronous best-effort data transfer
  - All stations contend for access to medium
- CSMA/CA
  - Ready stations wait for completion of transmission
  - All stations must wait *Interframe Space (IFS)*





# Carrier Sensing in 802.11

- *Physical Carrier Sensing*
  - Analyze all detected frames
  - Monitor relative signal strength from other sources
- *Virtual Carrier Sensing* at MAC sublayer
  - Source stations informs other stations of transmission time (in  $\mu$ sec) for an MPDU
  - Carried in *Duration* field of RTS & CTS
  - Stations adjust *Network Allocation Vector* to indicate when channel will become idle
- Channel busy if either sensing is busy

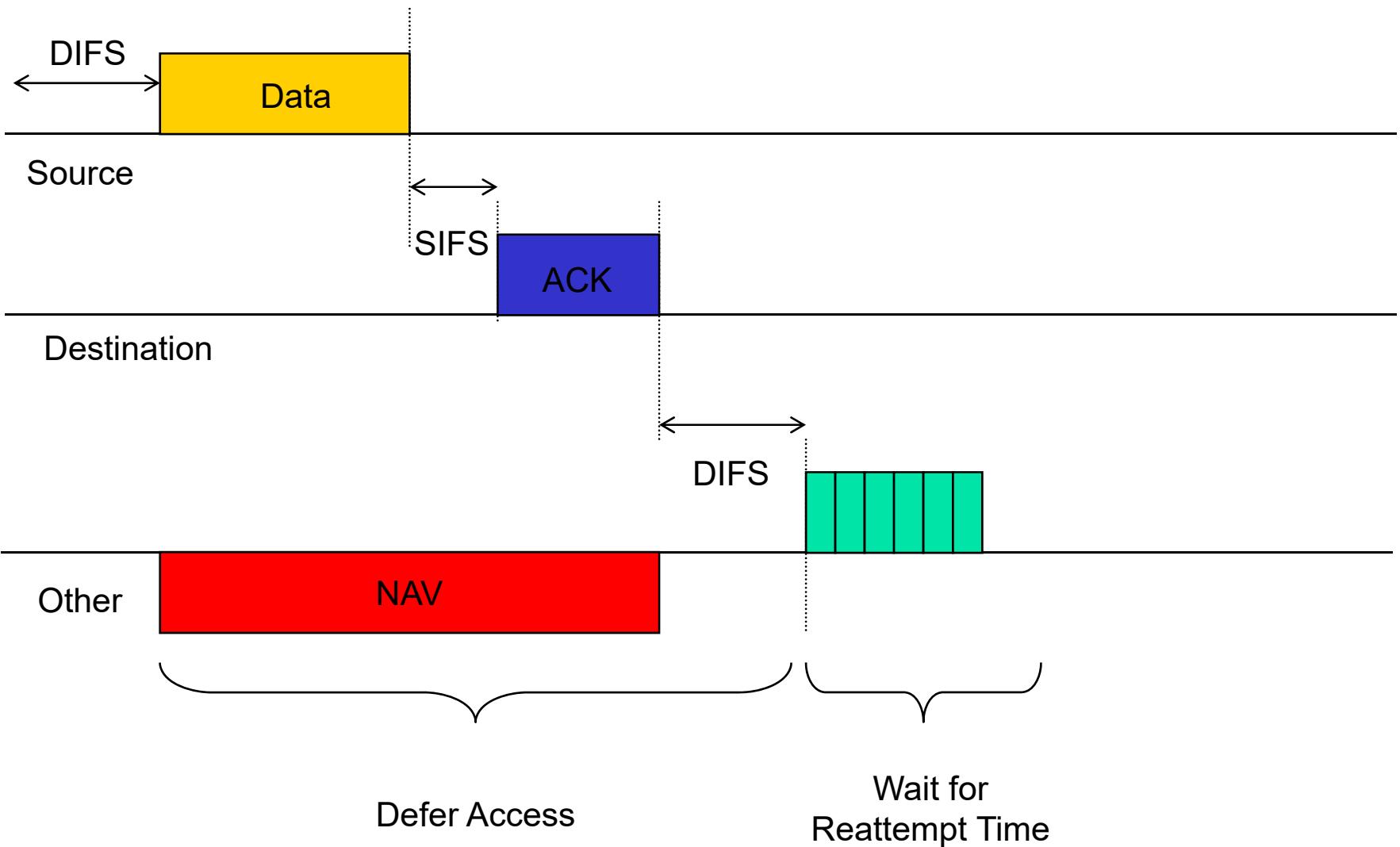


# Contention & Backoff Behavior

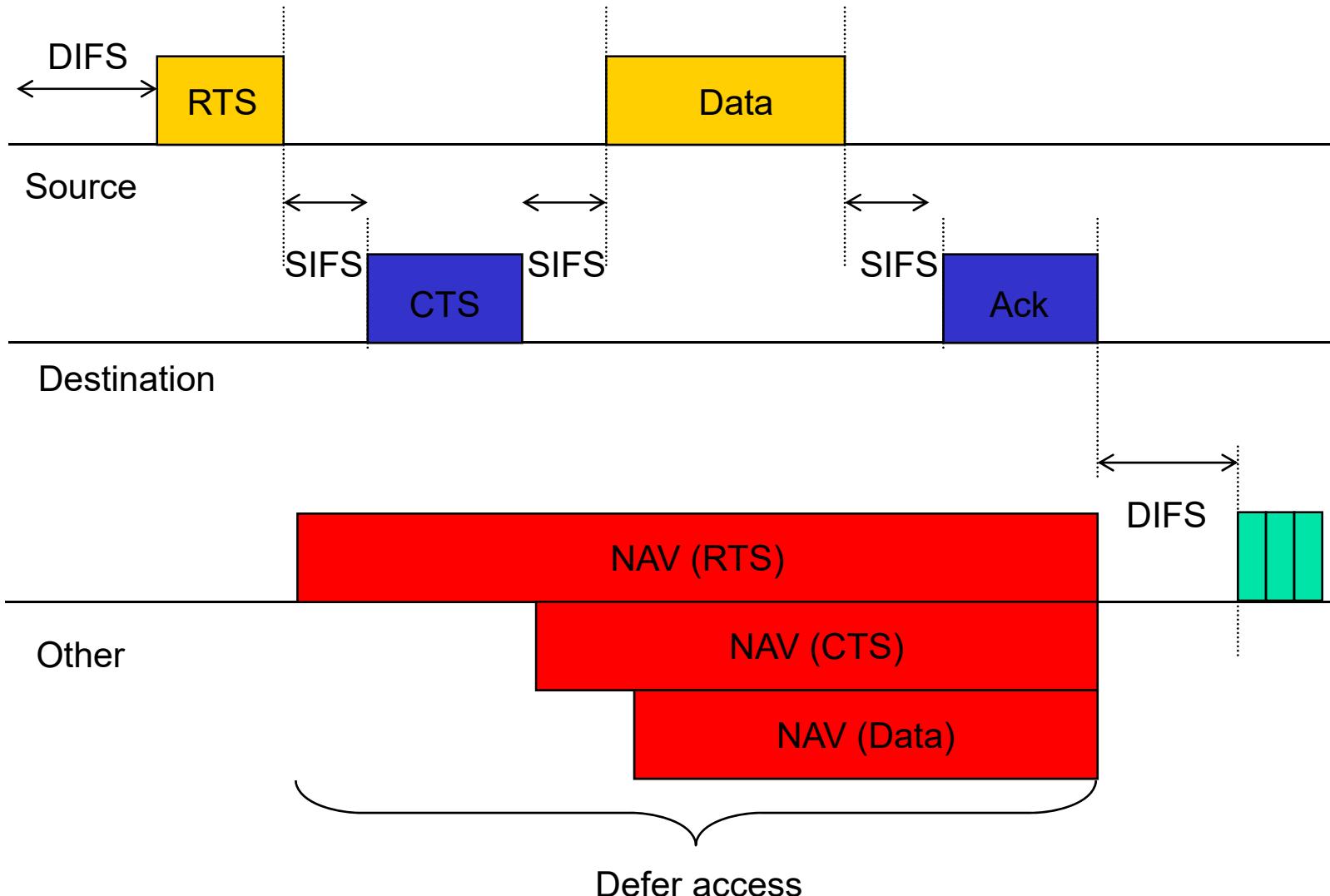
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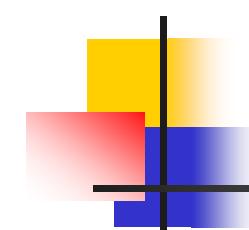
- If channel is still idle after DIFS period, ready station can transmit an *initial* MPDU
- If channel becomes busy before DIFS, then station must schedule *backoff time* for reattempt
  - Backoff period is integer # of *idle contention time slots*
  - Waiting station monitors medium & decrements backoff timer each time an idle contention slot expires
  - Station can contend when backoff timer expires
- A station that completes a frame transmission is not allowed to transmit immediately
  - Must first perform a backoff procedure

# Transmission of MPDU without RTS/CTS



# Transmission of MPDU with RTS/CTS



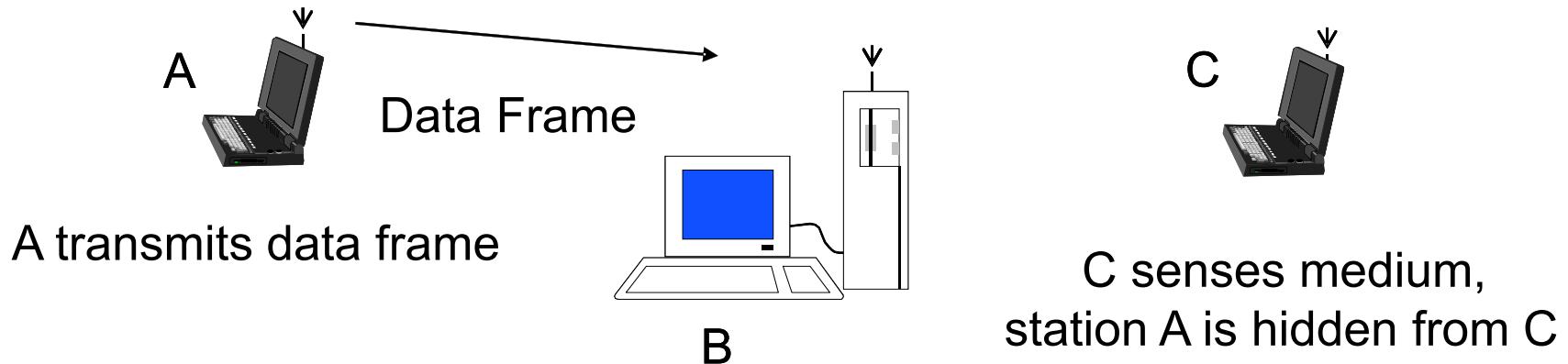


# Collisions, Losses & Errors

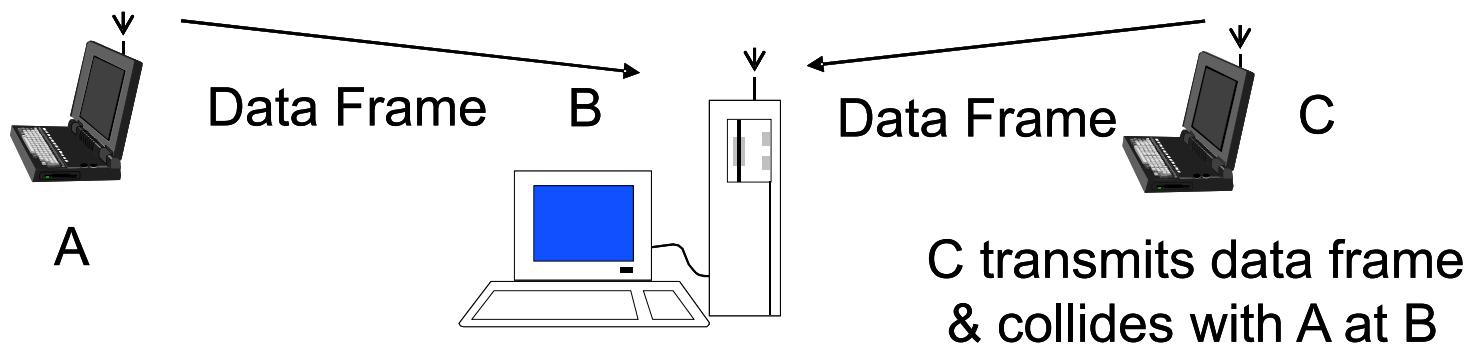
- Collision Avoidance
  - When station senses channel busy, it waits until channel becomes idle for DIFS period & then begins random backoff time (in units of idle slots)
  - Station transmits frame when backoff timer expires
  - If collision occurs, recompute backoff over interval that is twice as long
  - *Use Ack and timeout to find out collision*
- Receiving stations of error-free frames send ACK
  - Sending station interprets non-arrival of ACK as loss
  - Executes backoff and then retransmits
  - Receiving stations use sequence numbers to identify duplicate frames

# Hidden Terminal Problem

(a)

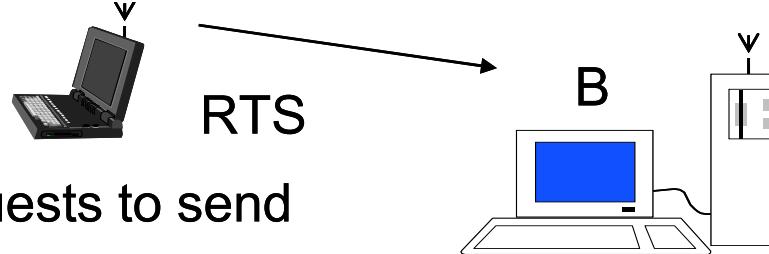


(b)



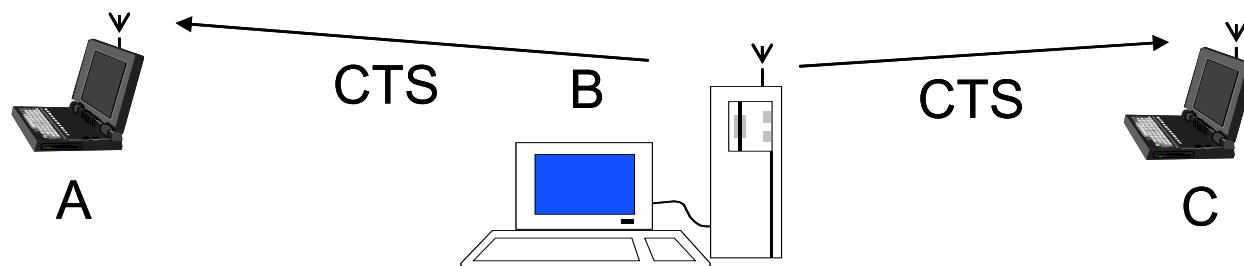
# Collision avoidance and virtual carrier sensing

(a)



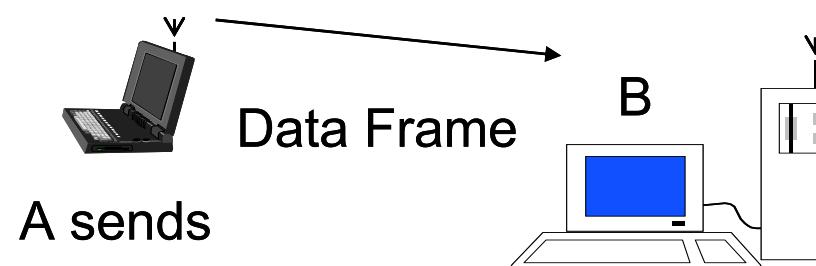
A requests to send

(b)



B announces A ok to send

(c)



A sends

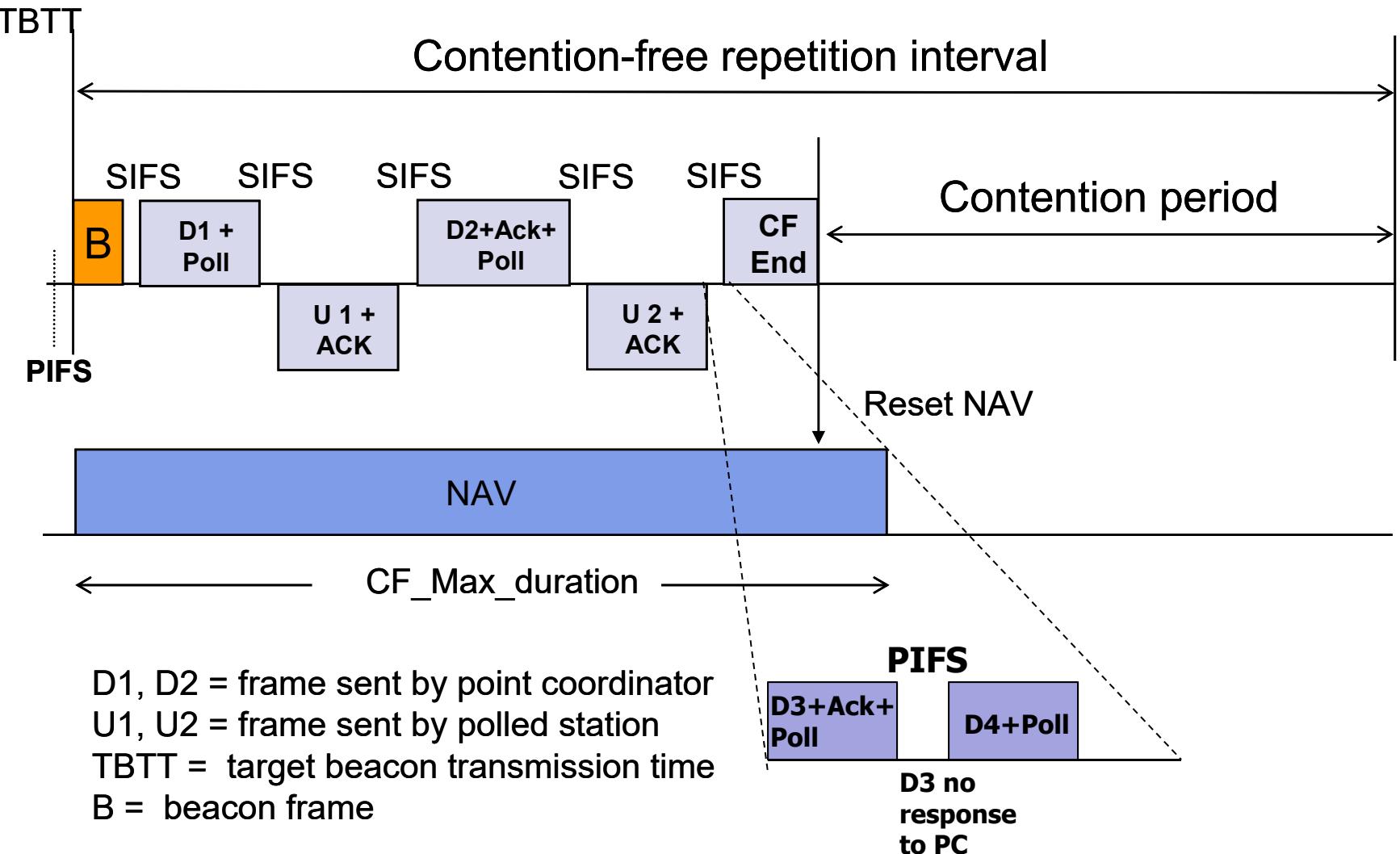
C remains quiet

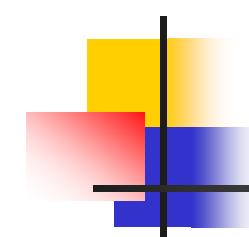


# Point Coordination Function

- PCF provides connection-oriented, contention-free service through *polling*
- *Point coordinator (PC)* in AP performs PCF
- Polling table up to implementor
- CFP repetition interval
  - Determines frequency with which CFP occurs
  - Initiated by *beacon frame* transmitted by PC in AP
  - Contains CFP and CP
  - During CFP stations may only transmit to respond to a poll from PC or to send ACK

# PCF Frame Transfer





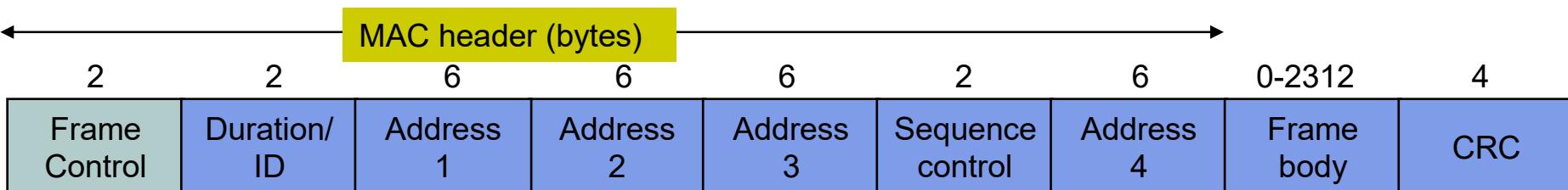
# Frame Types

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- Management frames
  - Station association & disassociation with AP
  - Timing & synchronization
  - Authentication & deauthentication
- Control frames
  - Handshaking
  - ACKs during data transfer
- Data frames
  - Data transfer

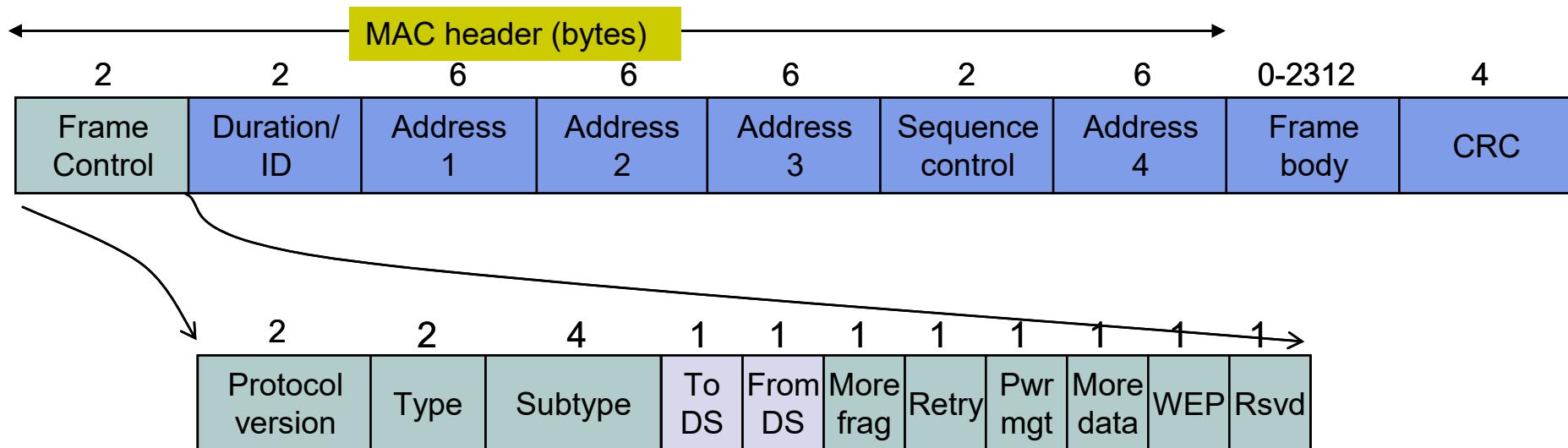
# Frame Structure

- MAC Header: 30 bytes
- Frame Body: 0-2312 bytes
- CRC: CCITT-32 4 bytes CRC over MAC header & frame body

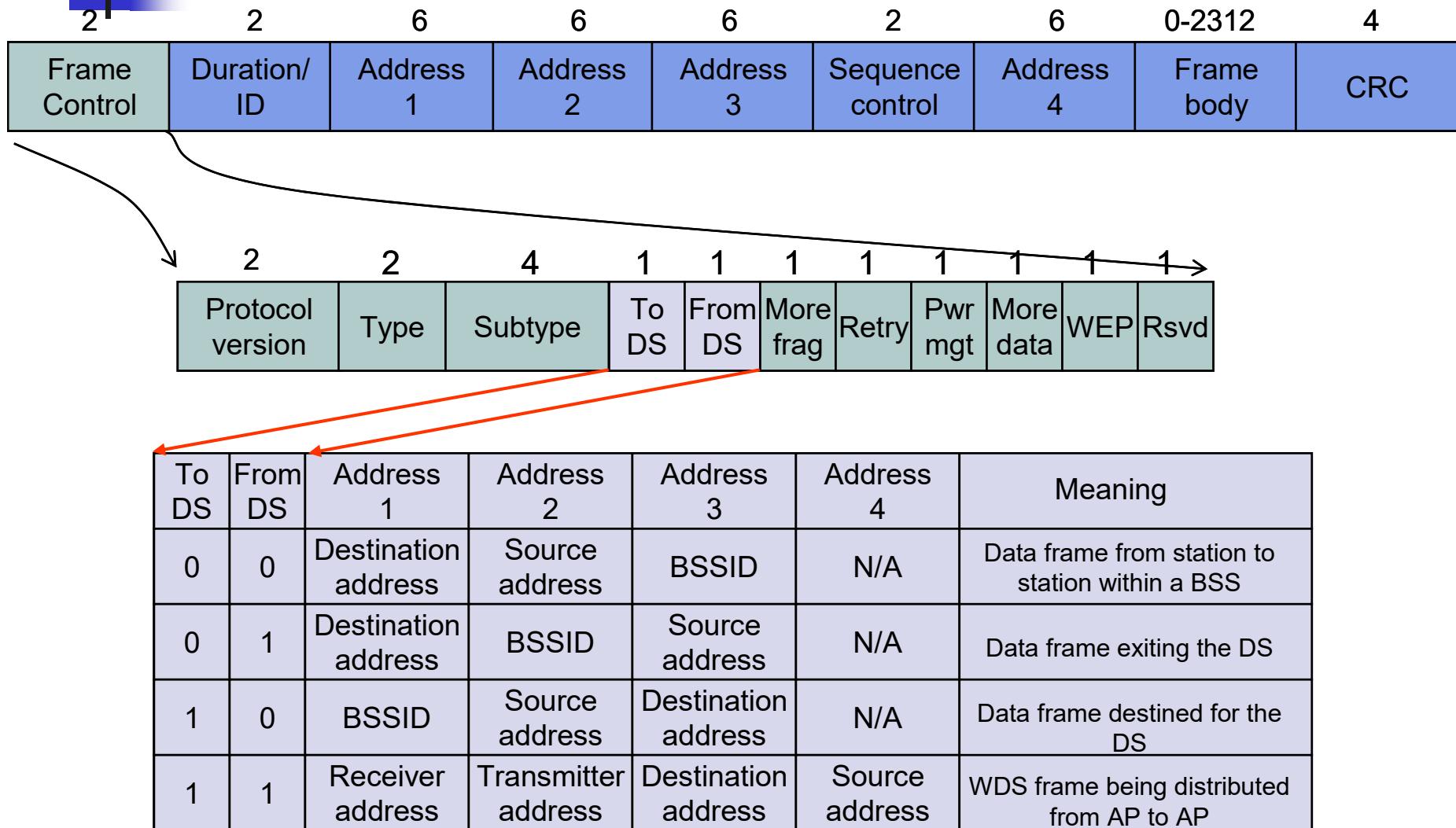


# Frame Control (1)

- Protocol version = 0
- Type: Management (00), Control (01), Data (10)
- Subtype within frame type
- Type=00, subtype=association; Type=01, subtype=ACK
- MoreFrag=1 if another fragment of MSDU to follow



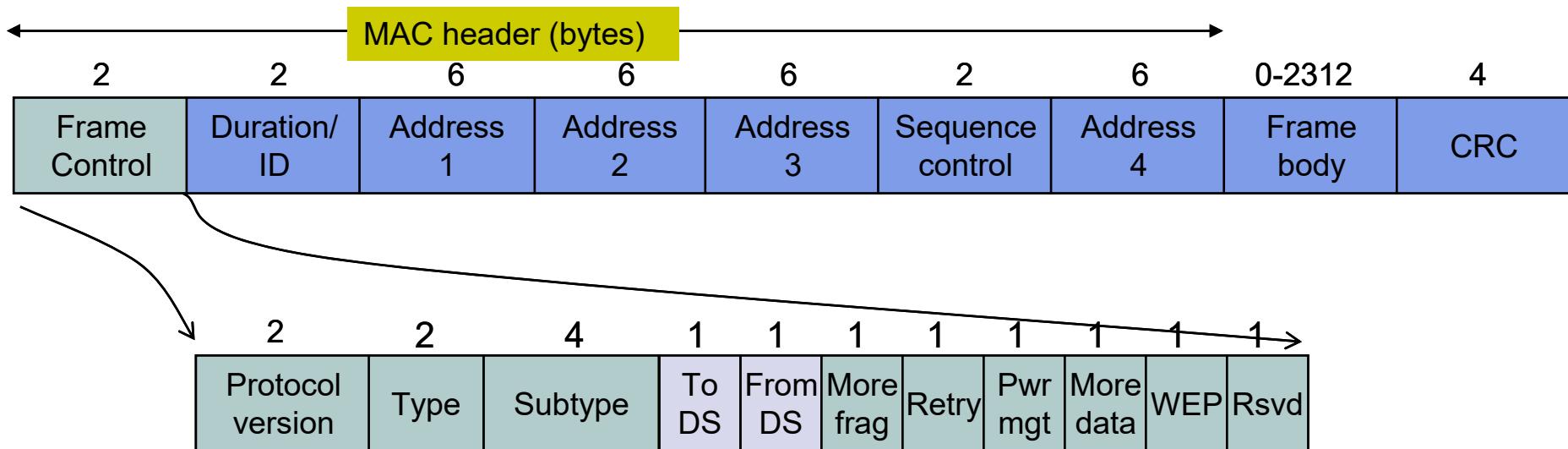
# Frame Control (2)



6/10/2020 To DS = 1 if frame goes to DS; From DS = 1 if frame exiting DS

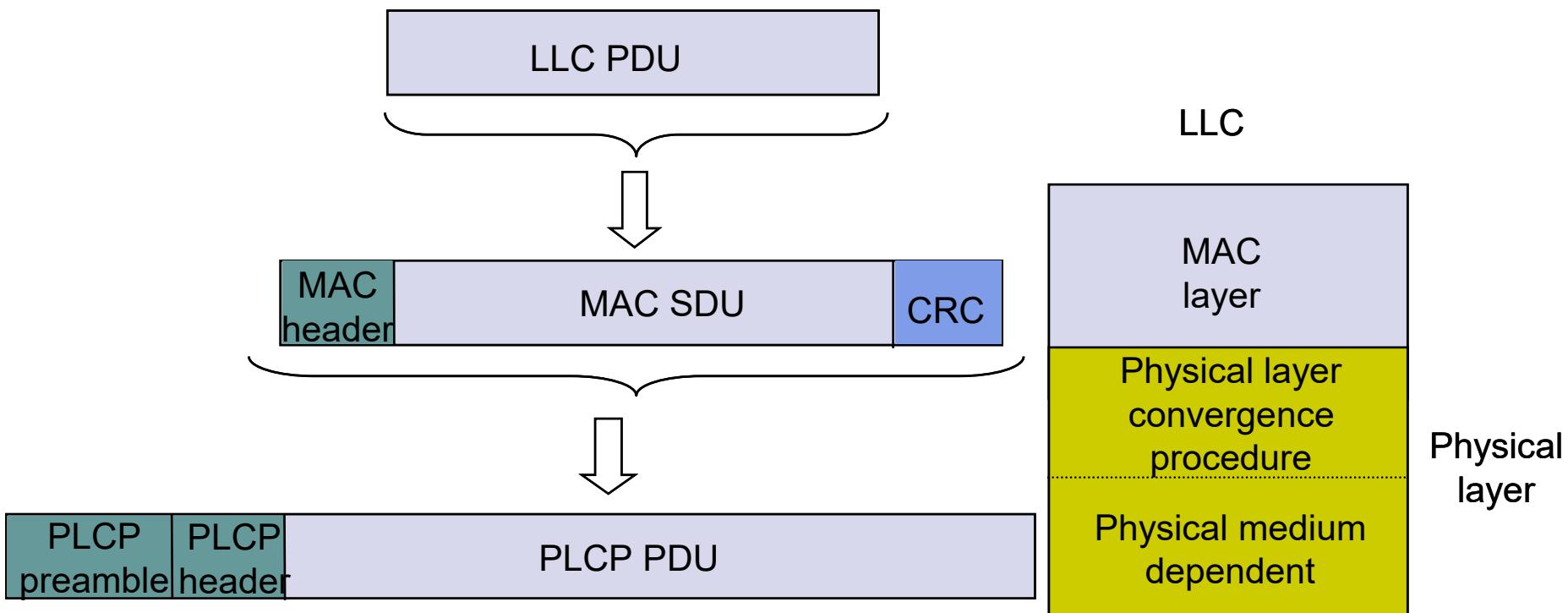
# Frame Control (3)

- Retry=1 if a data/management frame is a retransmission
- Power Management used to put station in/out of sleep mode
- More Data =1 to tell station in power-save mode more data buffered for it at AP
- WEP=1 if frame body encrypted



# 802.11 protocol layers

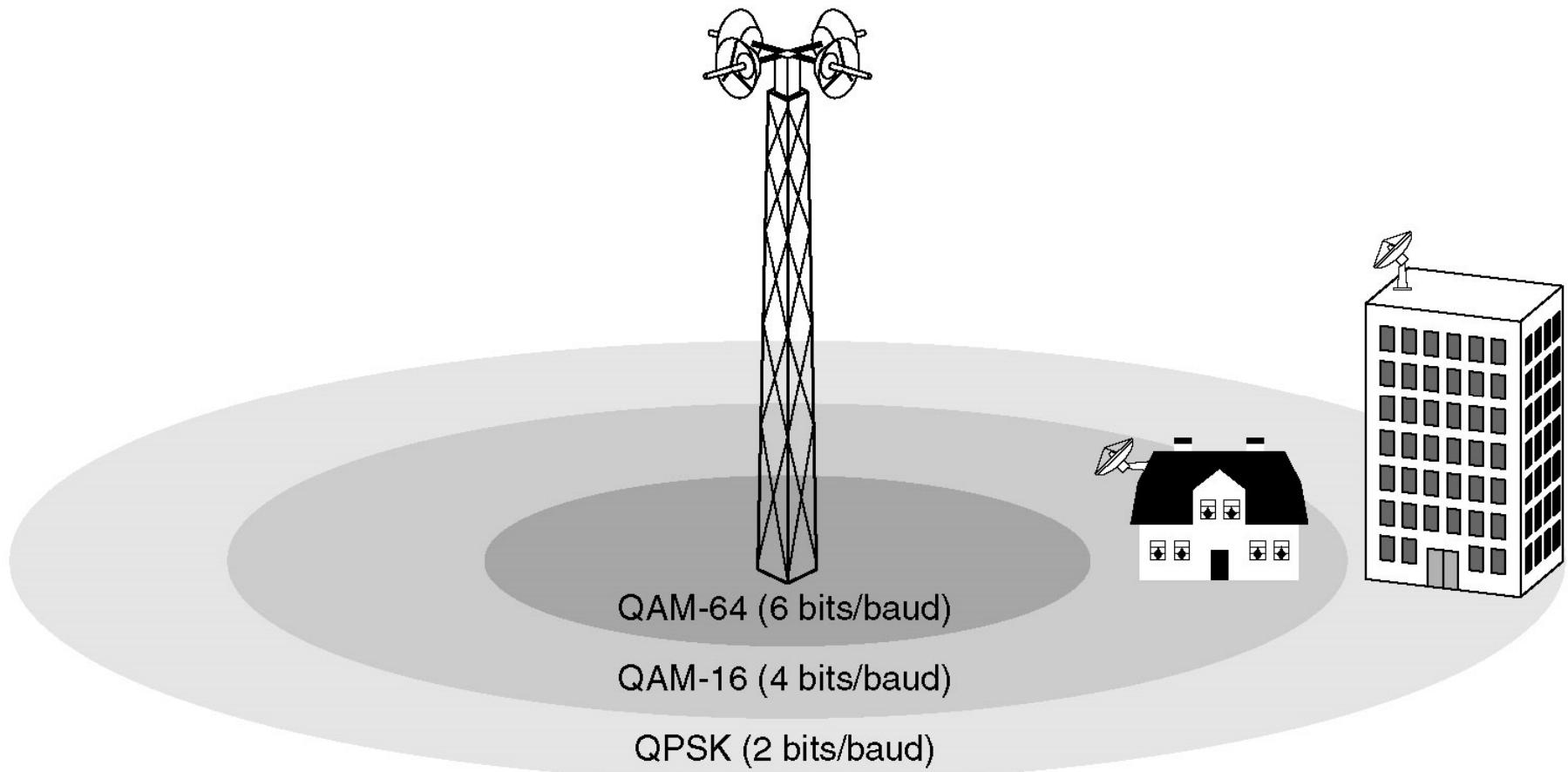
- 802.11 designed to
  - Support LLC
  - Operate over many physical layers



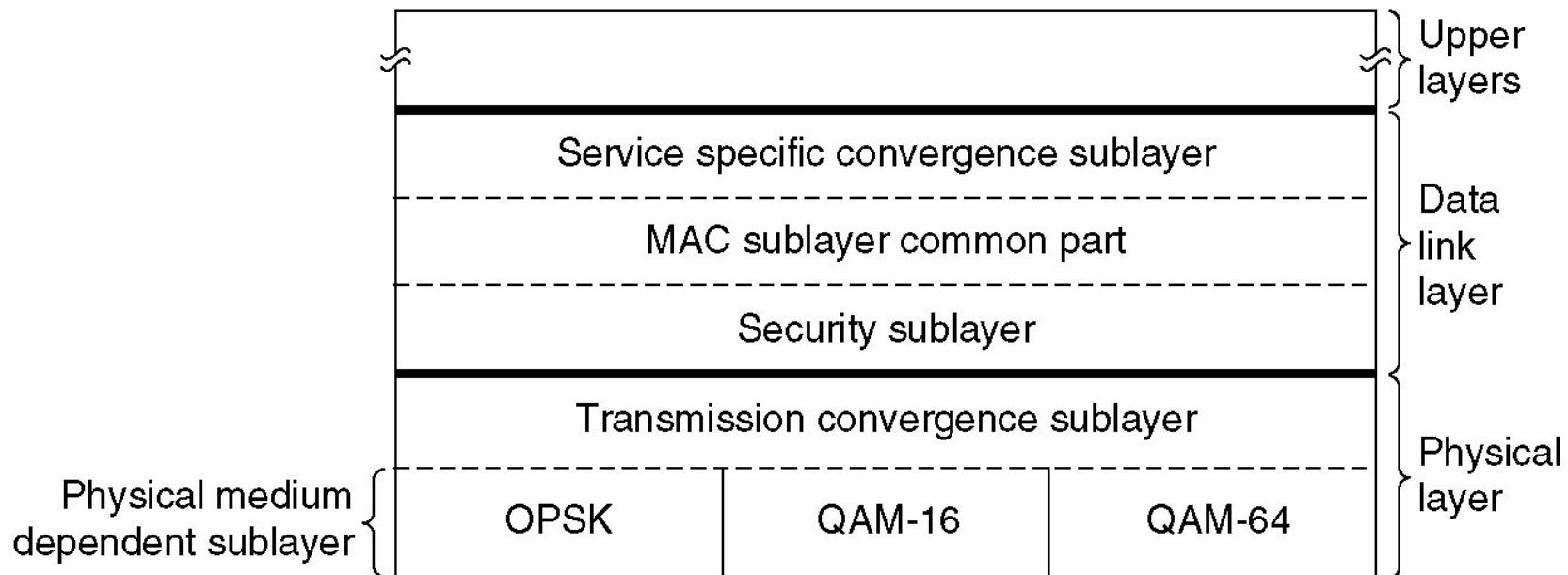
# 802.11 Phy options

	Frequency Band	Bit Rate	Modulation Scheme
802.11	2.4 GHz	1-2 Mbps	Frequency-Hopping Spread Spectrum, Direct Sequence Spread Spectrum
802.11b	2.4 GHz	11 Mbps	Complementary Code Keying & QPSK
802.11g	2.4 GHz	54 Mbps	Orthogonal Frequency Division Multiplexing & CCK for backward compatibility with 802.11b
802.11a	5-6 GHz	54 Mbps	Orthogonal Frequency Division Multiplexing

# 802.16 and WiMAX



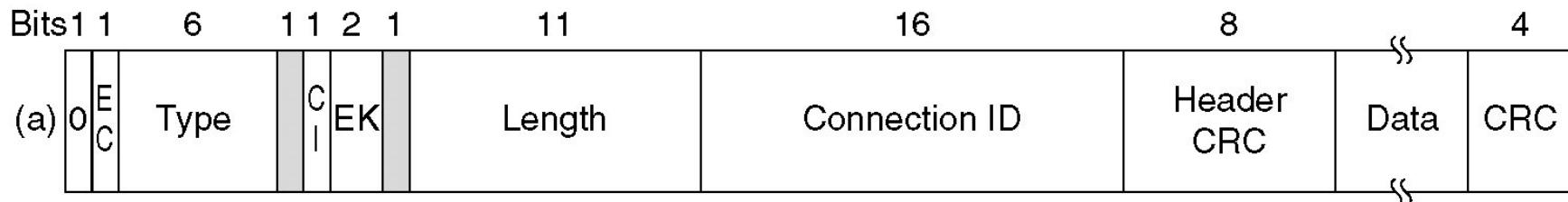
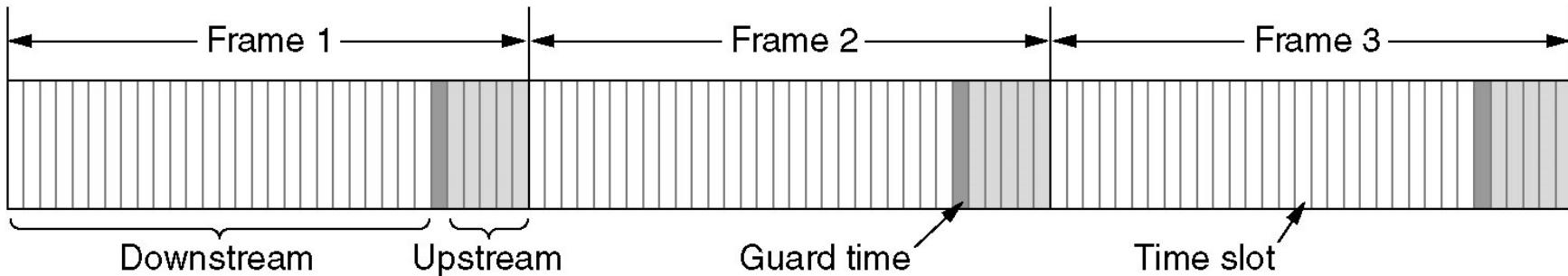
# 802.16 Protocol Stack



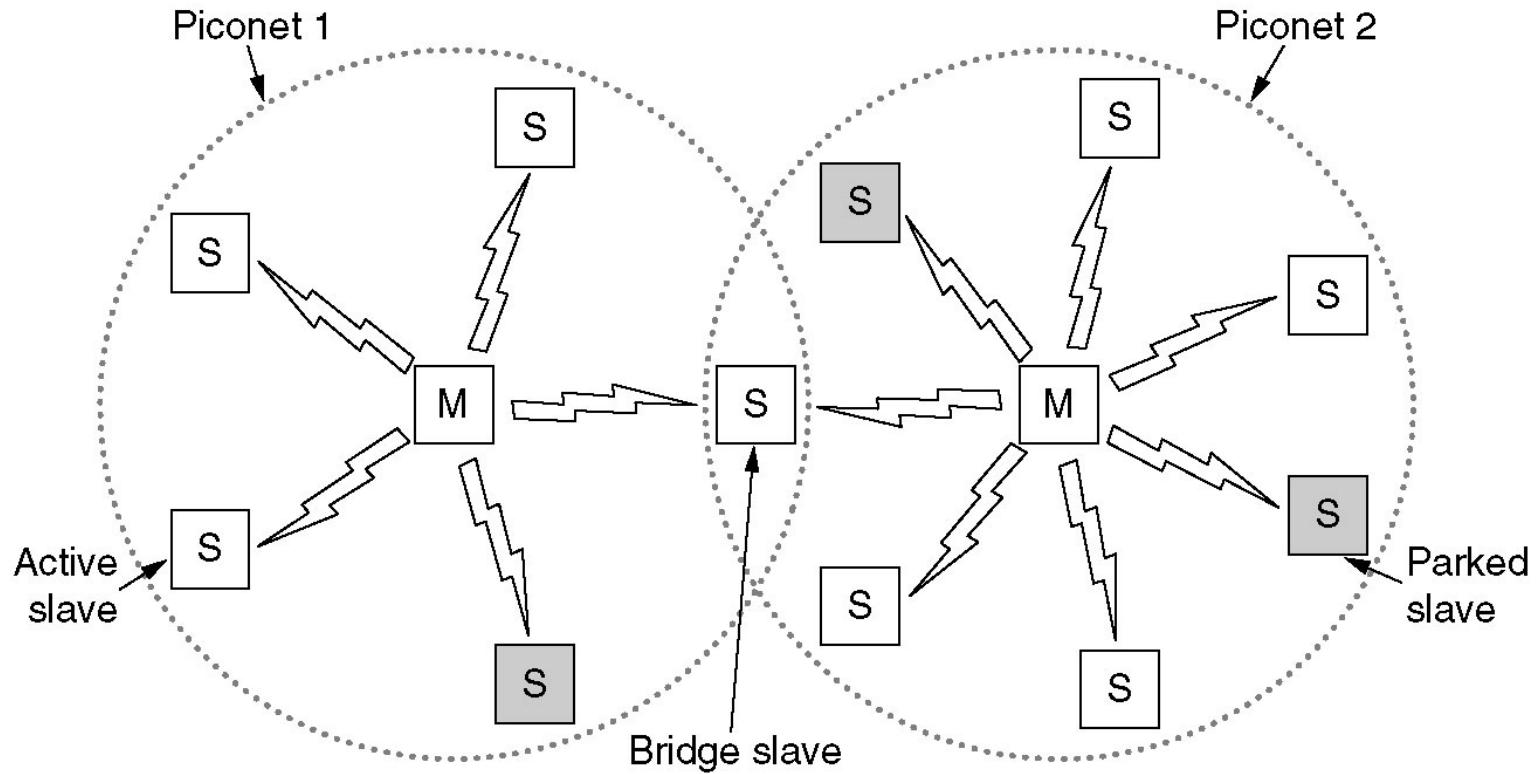
# Services and Frame Structure

## Constant bit rate service

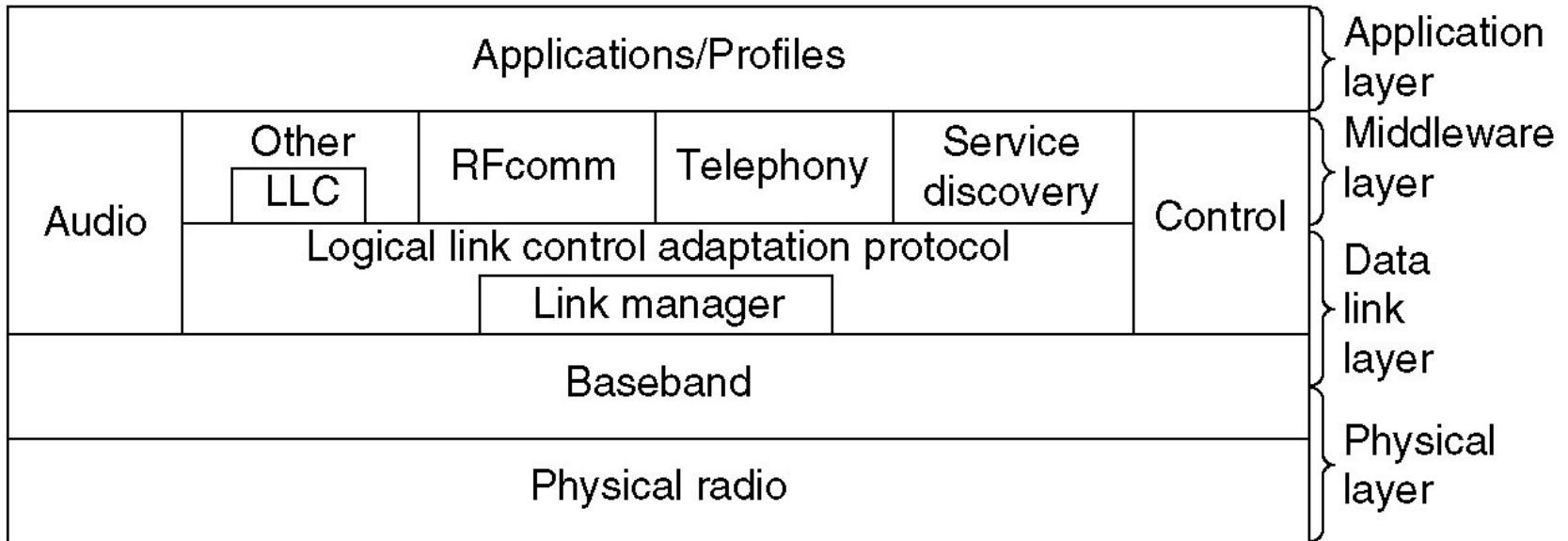
- Real-time variable bit rate service
- Non-real-time variable bit rate service
- Best efforts service



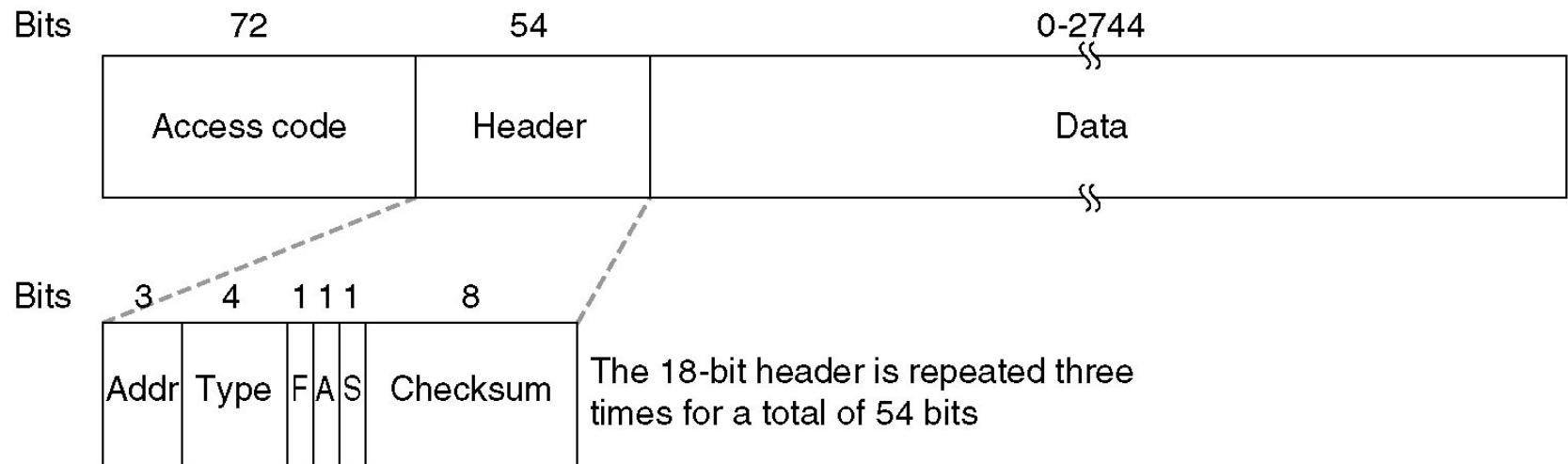
# Bluetooth



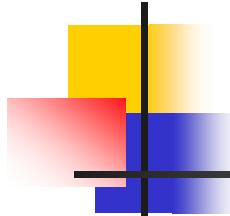
# Bluetooth Protocol Stack



# Bluetooth Frame Structure



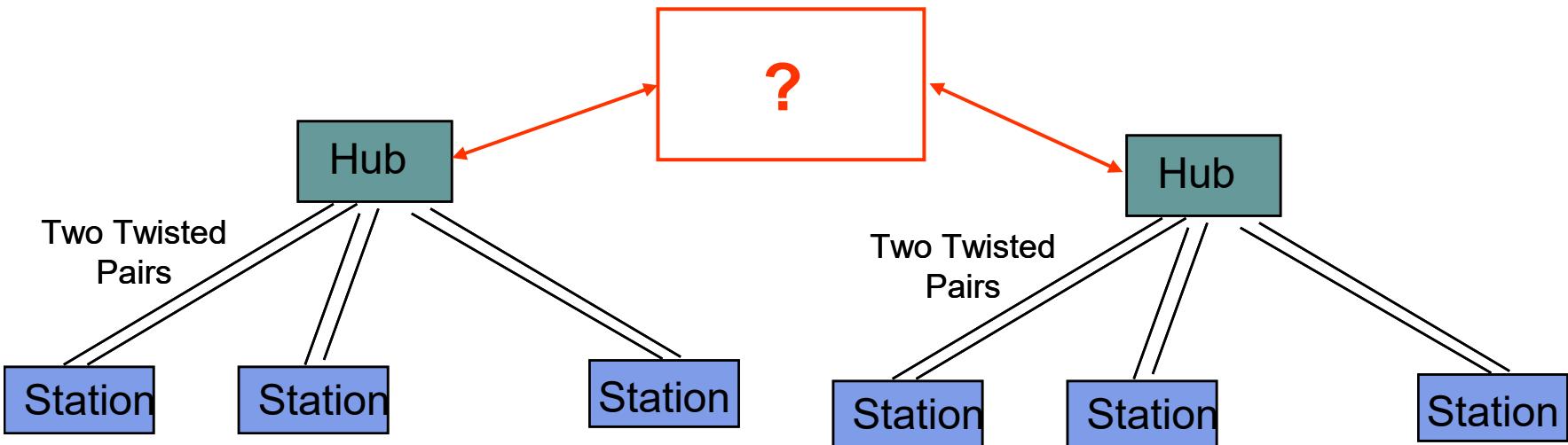




# **Bridging and Switching**

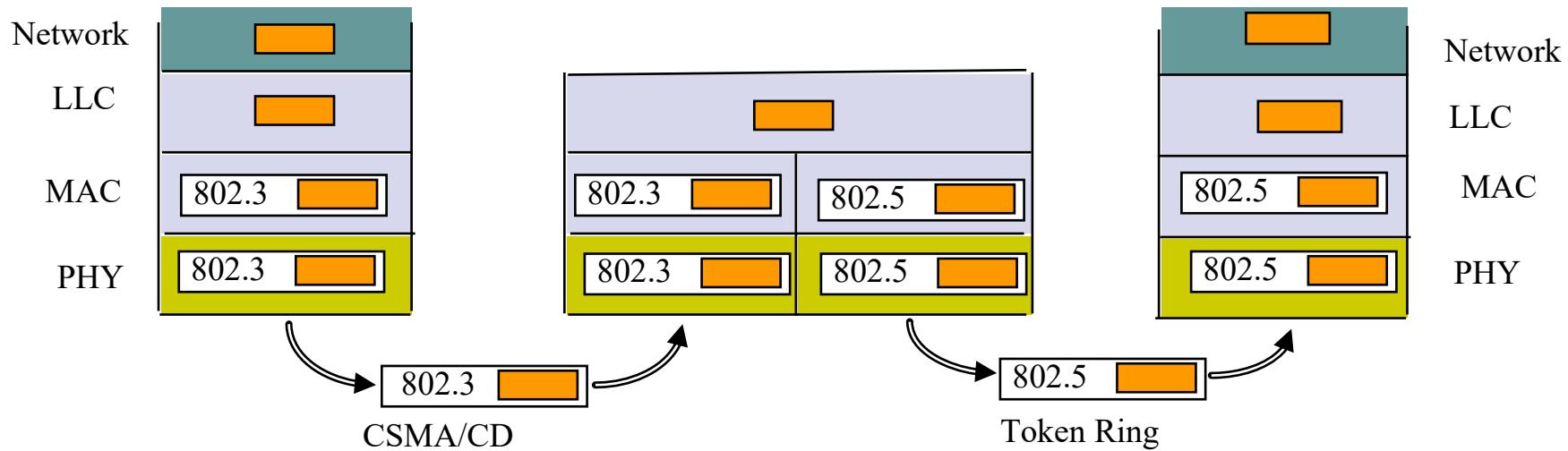
# Hubs, Bridges & Routers

- Interconnecting Hubs
  - Repeater: Signal regeneration
    - Physical layer interconnection; all traffic appears in both LANs
  - Bridge: MAC address filtering
    - MAC/link layer interconnection; local traffic stays in own LAN
  - Routers: Internet routing
    - Network layer interconnection; traffic crosses different networks
  - Gateway: router with additional functions
    - Backhaul access, protocol conversion, security (firewall) functions



# General Bridge Issues

- Operation at data link level implies capability to work with multiple network layers
- However, must deal with
  - Difference in MAC formats
  - Difference in data rates; buffering; timers
  - Difference in maximum frame length





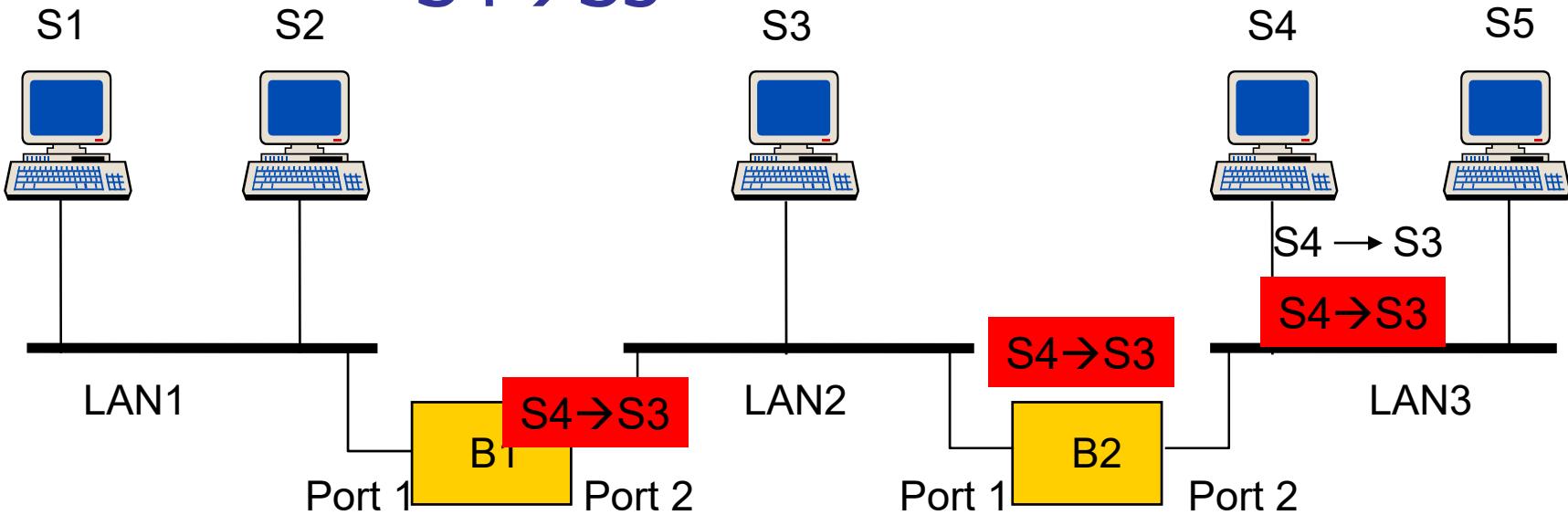
# Transparent Bridges

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- Interconnection of IEEE LANs with complete transparency
- Use table lookup, and
  - discard frame, if source & destination in same LAN
  - forward frame, if source & destination in different LAN
  - use flooding, if destination unknown
- Use backward learning to build table
  - observe source address of arriving LANs
  - handle topology changes by removing old entries

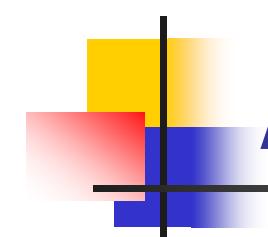
# Example: Basic learning procedures

$S4 \rightarrow S3$



Address	Port
S1	1
S3	2
S4	2

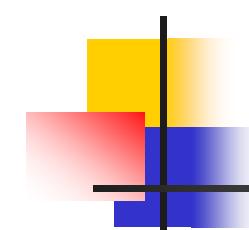
Address	Port
S1	1
S3	1
S4	2



# Adaptive Learning

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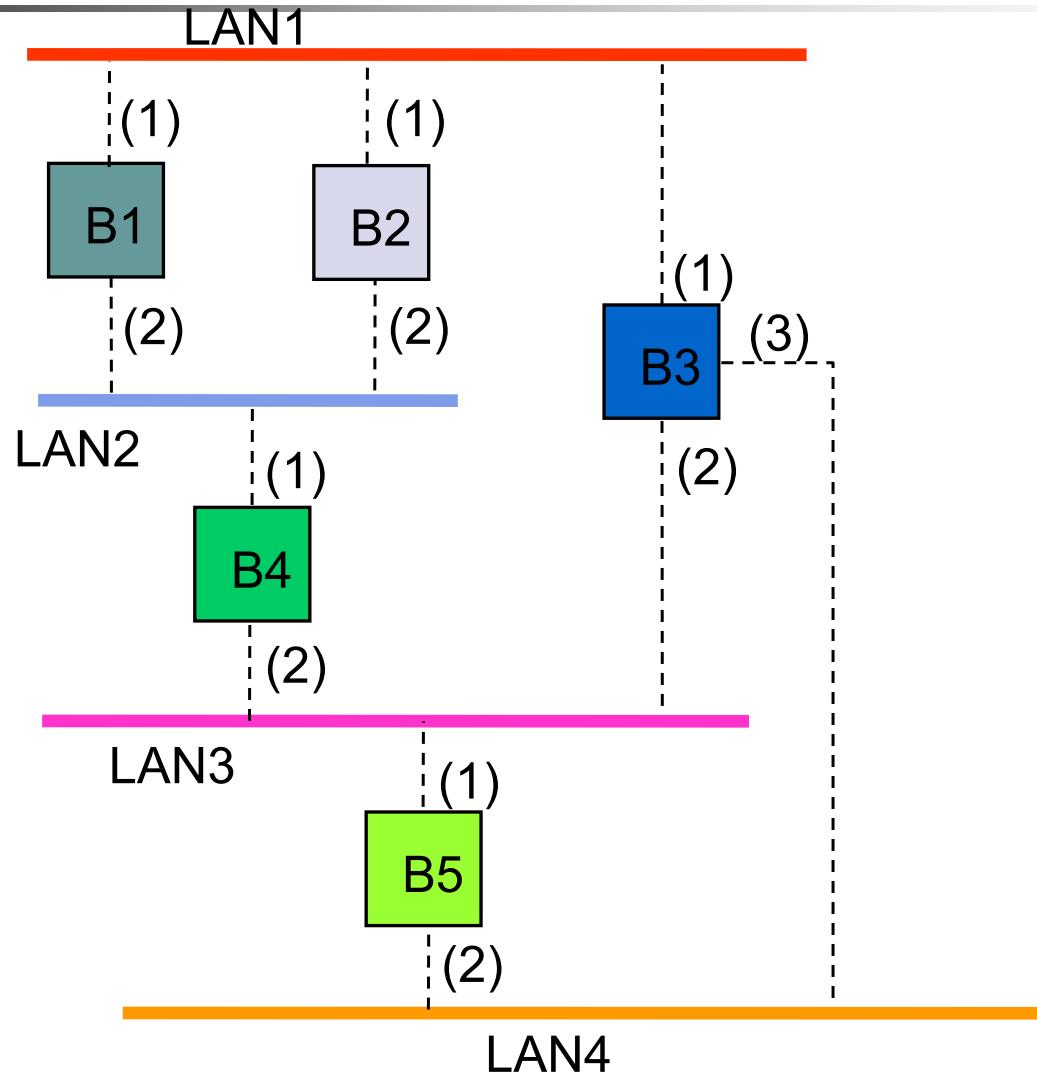
- In a static network, tables eventually store all addresses & learning stops
- In practice, stations are added & moved all the time
  - Introduce timer (minutes) to age each entry & force it to be relearned periodically
  - If a frame arrives on port that differs from frame address & port in table, update the table immediately



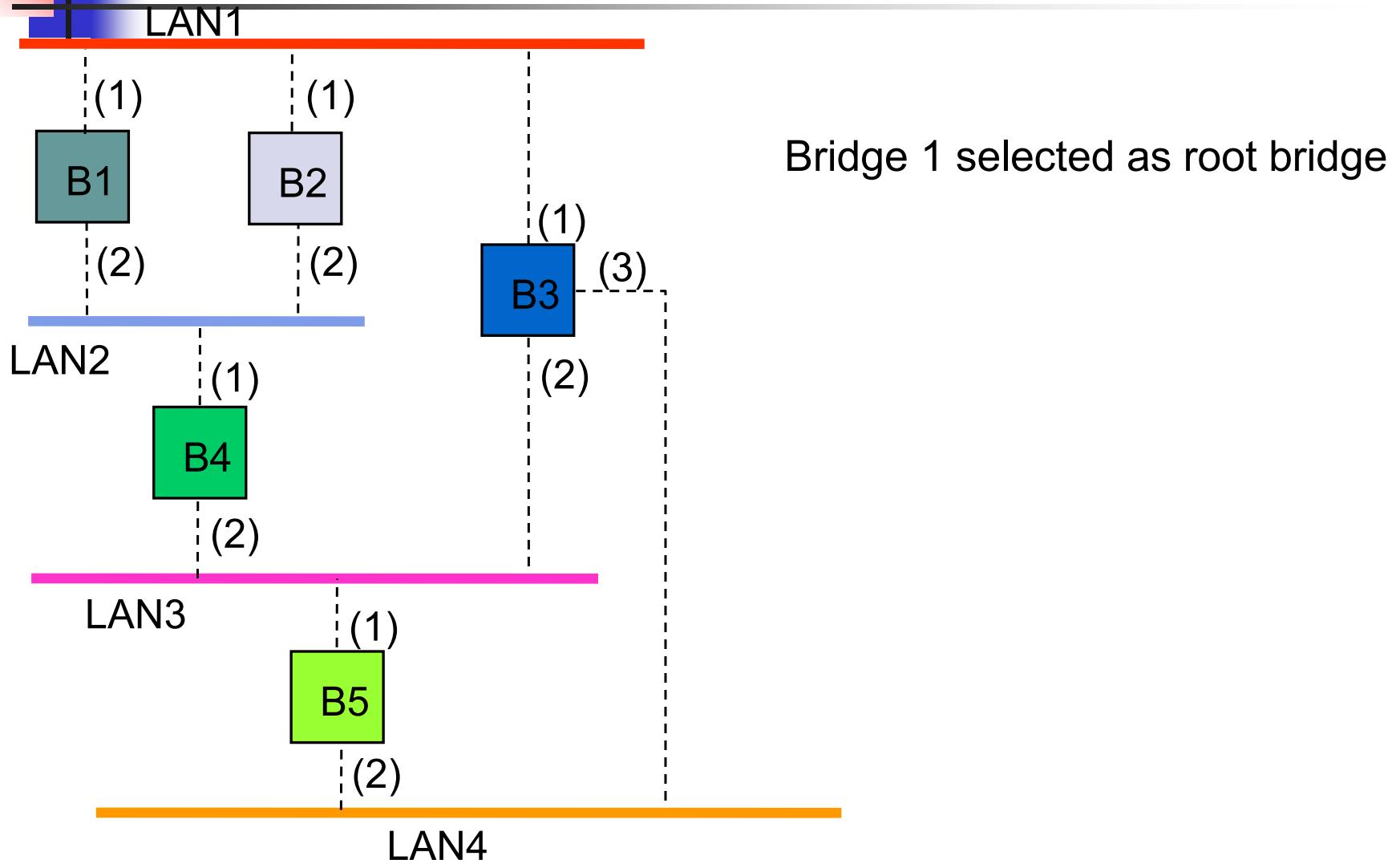
# Spanning Tree Algorithm

1. Select a *root bridge* among all the bridges.
  - root bridge = the lowest bridge ID.
2. Determine the *root port* for each bridge except the root bridge
  - root port = port with the least-cost path to the root bridge
3. Select a *designated bridge* for each LAN
  - designated bridge = bridge has least-cost path from the LAN to the root bridge.
  - *designated port* connects the LAN and the designated bridge
4. All root ports and all designated ports are placed into a “forwarding” state. These are the only ports that are allowed to forward frames. The other ports are placed into a “blocking” state.

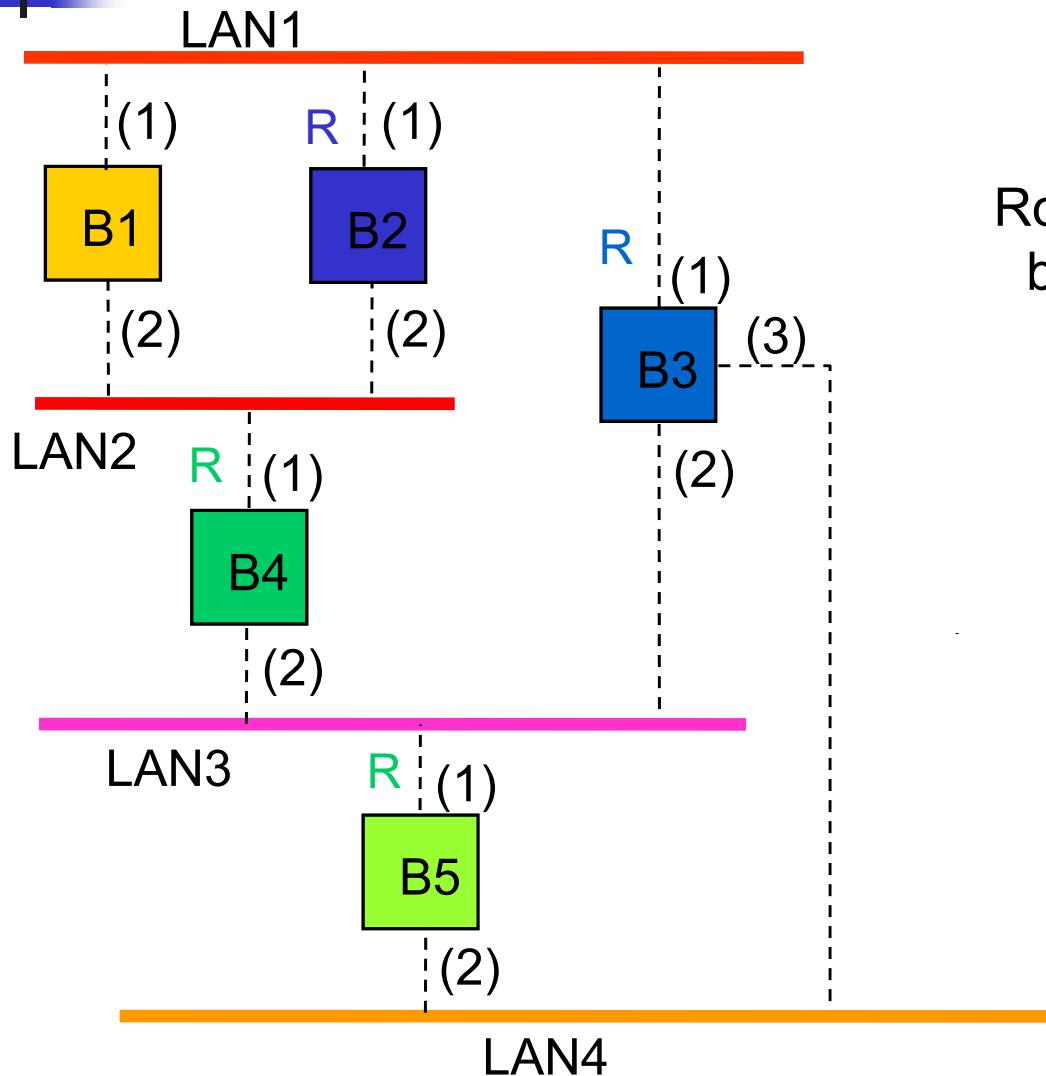
# Example (1)



# Example (2)

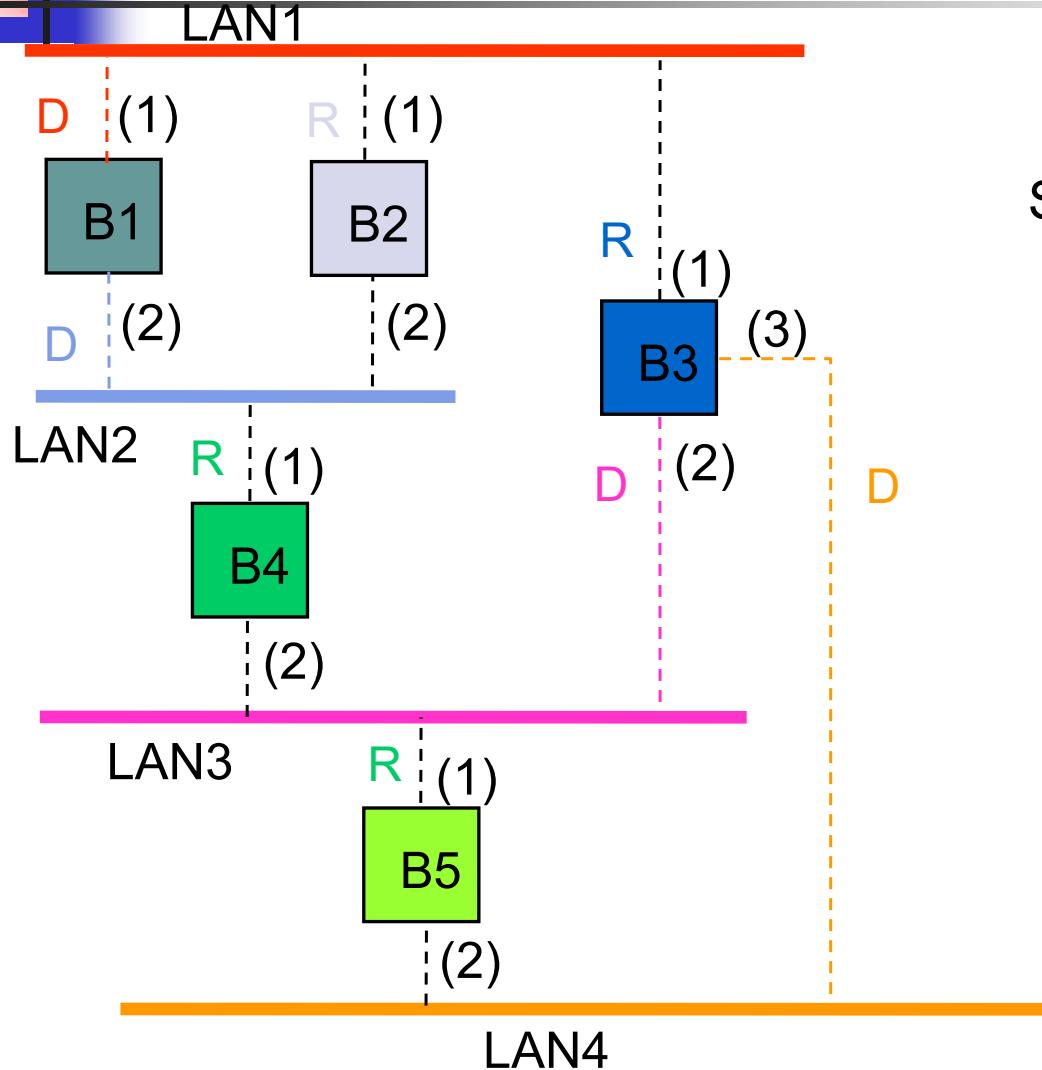


# Example (3)



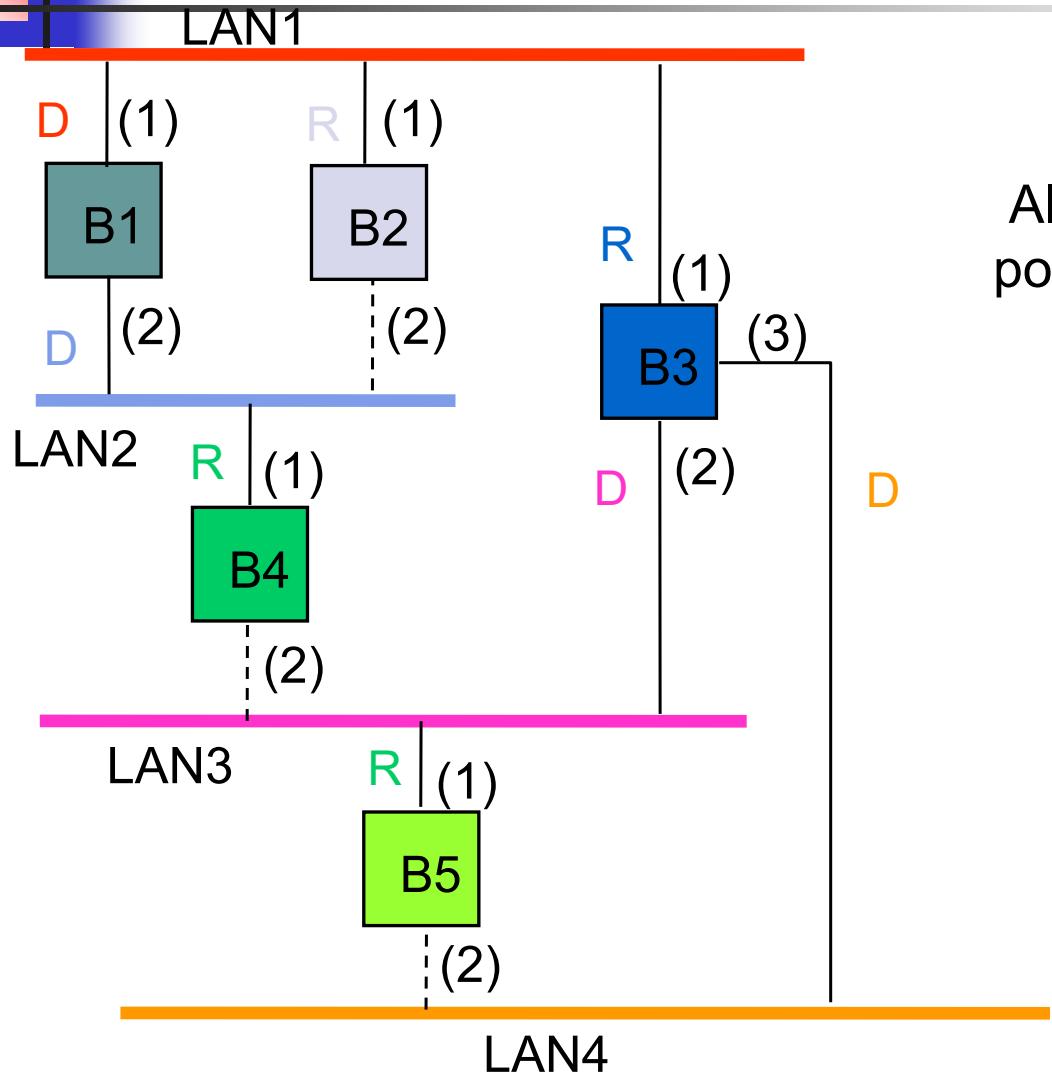
Root port selected for every bridge except root bridge

# Example (4)



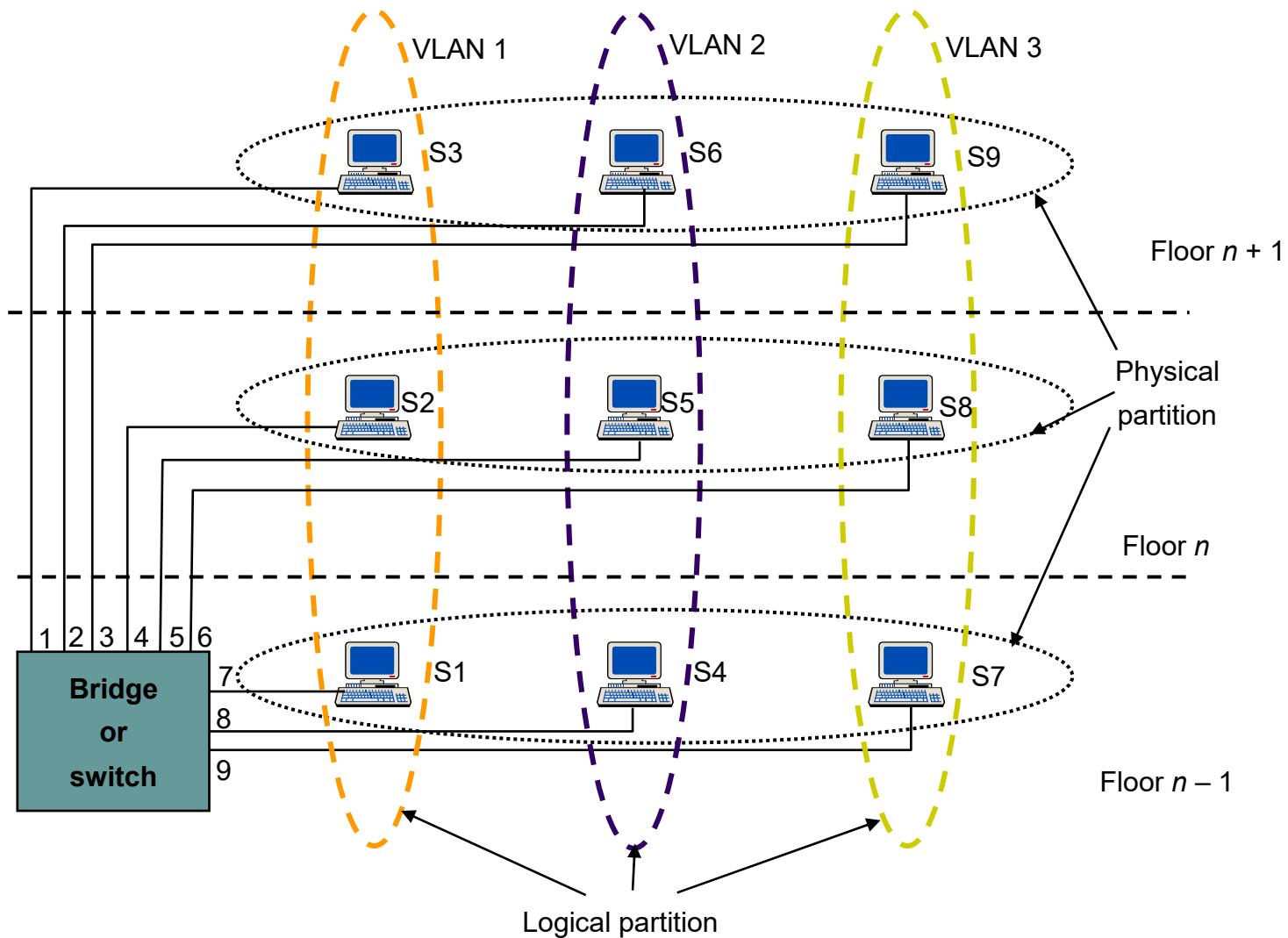
Select designated bridge  
for each LAN

# Example (5)

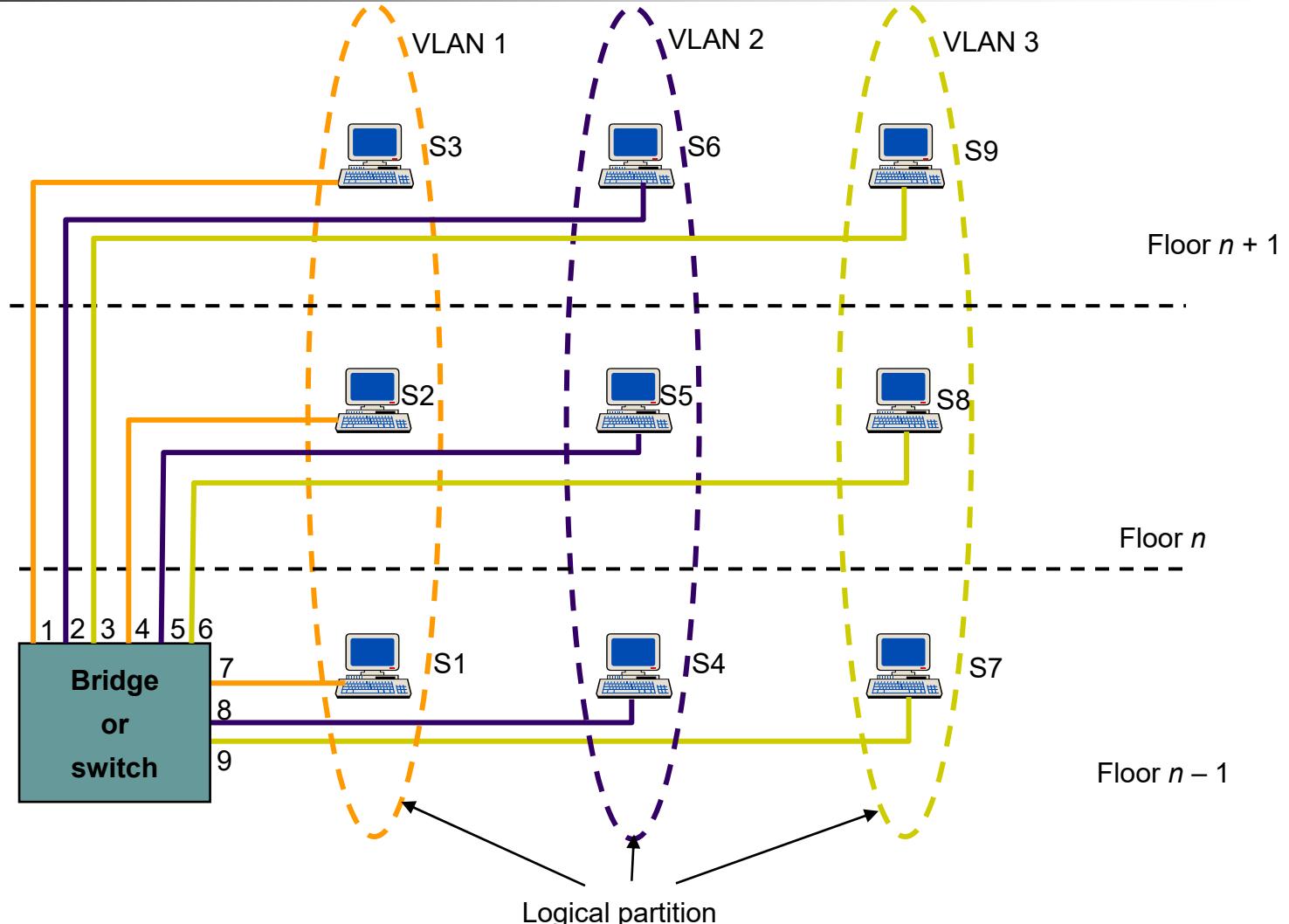


All root ports & designated ports put in forwarding state

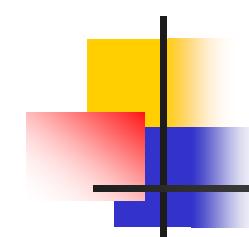
# Virtual LAN



# Per-Port VLANs



**The bridge only forwards frames to outgoing ports associated with the same VLAN of the incoming port.**

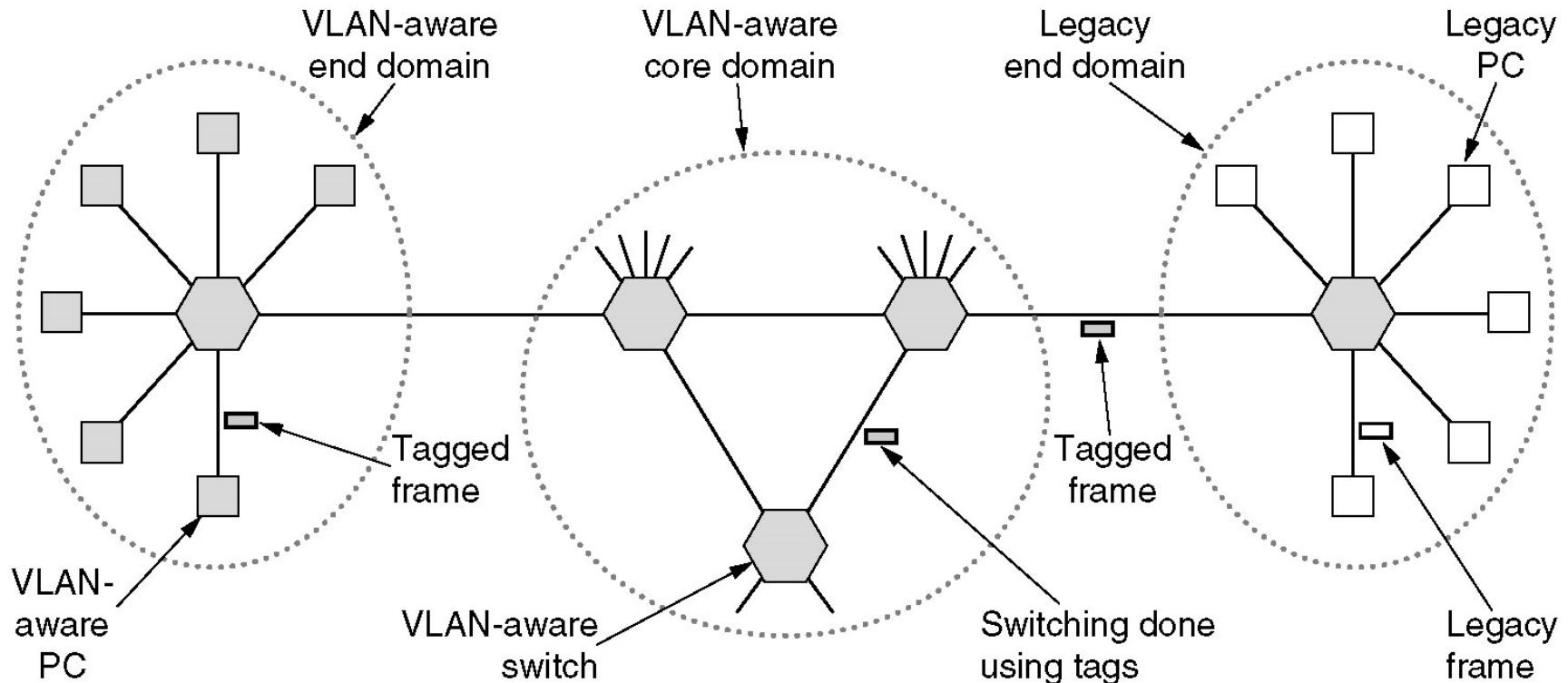


# Tagged VLANs

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- More flexible than Port-based VLANs
- Insert VLAN tag after source MAC address in each frame
  - VLAN protocol ID + tag
- VLAN-aware bridge forwards frames to outgoing ports according to VLAN ID
- VLAN ID can be associated with a port statically through configuration or dynamically through bridge learning
- IEEE 802.1q

# The IEEE 802.1Q Standard



# 802.1Q frame

