random access protocol & wifi

Computer Networks

Chapter 4: Medium Access Control

The operating system is primarily involved in the higher layers of the OSI model, typically starting from the Transport Layer (Layer 4) and up to the Application Layer (Layer 7). Here's how the OS is engaged in these layers:

Transport Layer: The OS manages the establishment, maintenance, and termination of transport layer connections. It handles the segmentation of data into smaller packets and ensures reliable data delivery using protocols like TCP or UDP.

Network Layer: The OS is responsible for IP address management, routing decisions, and forwarding of packets between different networks. It interacts with the network interface and routing tables to determine the next hop for outgoing packets.

Data Link Layer: The OS interacts with network interface cards (NICs) and device drivers to access the data link layer. It manages the data link layer addressing (MAC addresses) and can control aspects like flow control and error handling.

Physical Layer: The OS is generally not directly involved in the physical layer, as this layer deals with the actual hardware transmission of bits over the network medium.

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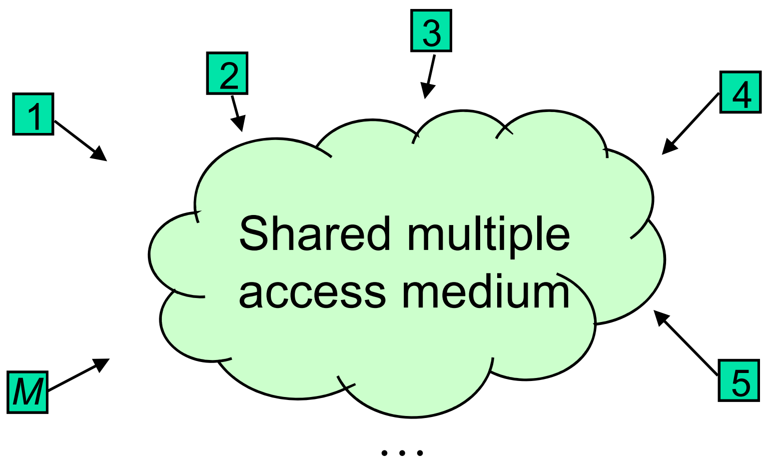
Outline

- 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

multiple access implemented in PHY
MAC in DLC

- Multiplexing
  - 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

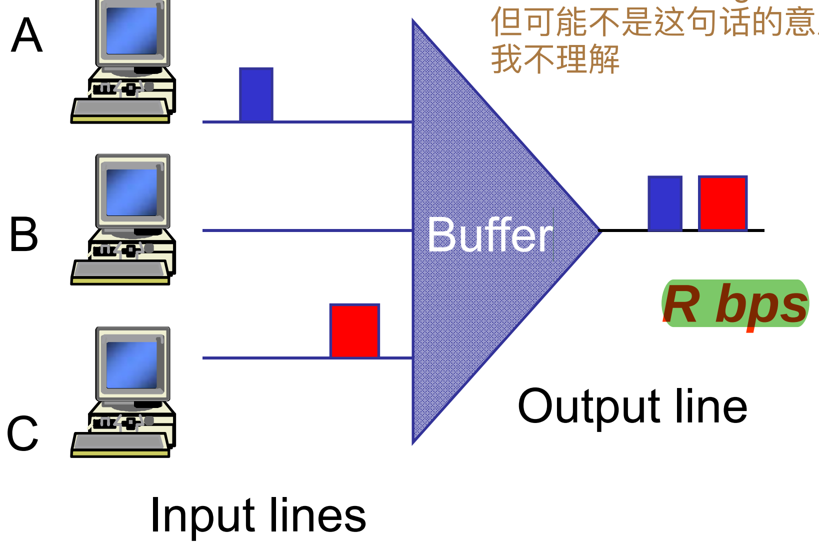
- Medium Access Control
  - Algorithms or schemes controlling the medium access on top of a multiple access mechanism
  - Examples: Slotted Aloha, CSMA/CA, OFDMA MAC, TDMA MAC, CDMA MAC, etc.

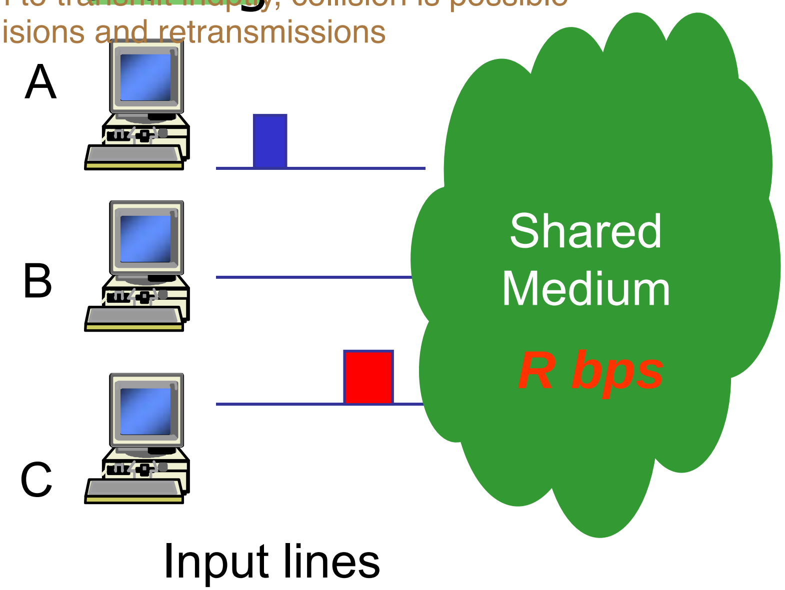
Statistical Multiplexing & Random Access

- 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

since each node decides when to transmit indptly, collision is possible
bandwidth wastage due to collisions and retransmissions
但可能不是这句话的意思
我不理解





Approaches to Media Sharing

Medium sharing techniques

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

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

Static channelization

Dynamic medium access control

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

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

Scheduling

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

phone: needs low-delay transfer
& steady bandwidth
so better scheduling?

Random access

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

web needs large bandwidth and
often bursted, so better to be
dynamic and random access?

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

large BDP, hard to Random access
cuz should be based on feedback
slow

- Bandwidth-delay product (BDP)
- 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)

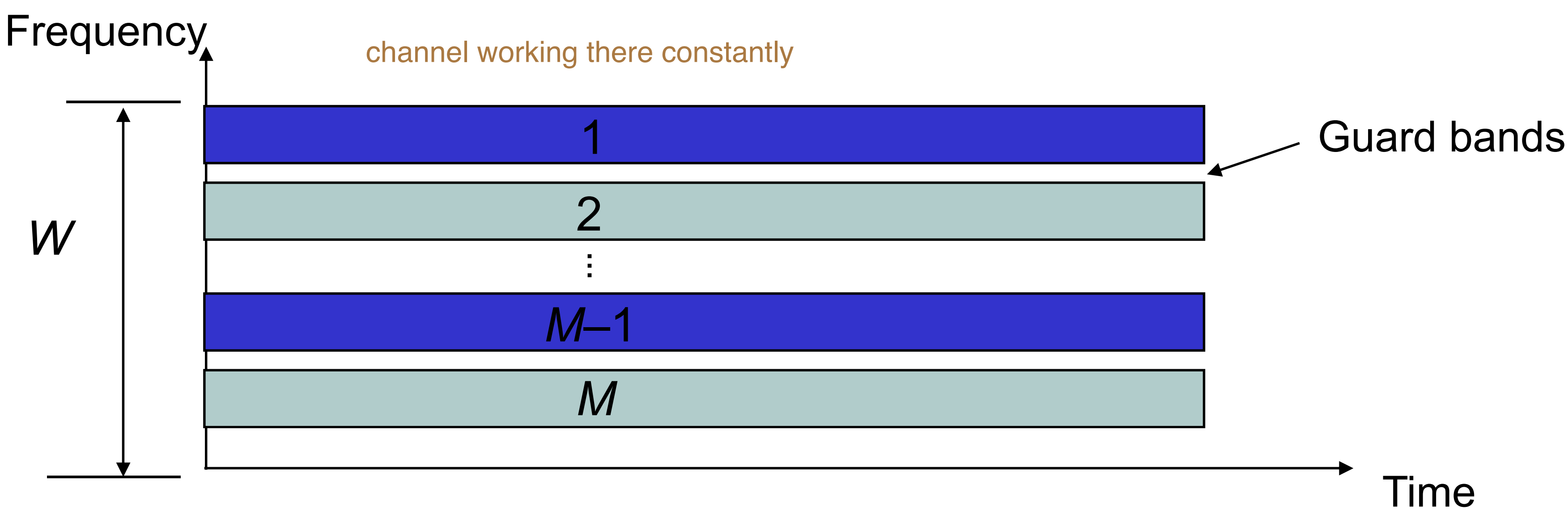
- Channelization
  - Semi-static bandwidth allocation of portion of shared medium to a given user
  - Highly efficient for constant-bit rate traffic
  - Preferred approach in
    - Cellular telephone networks
    - Terrestrial & satellite broadcast radio & TV
- Shortcomings
  - Inflexible in allocation 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

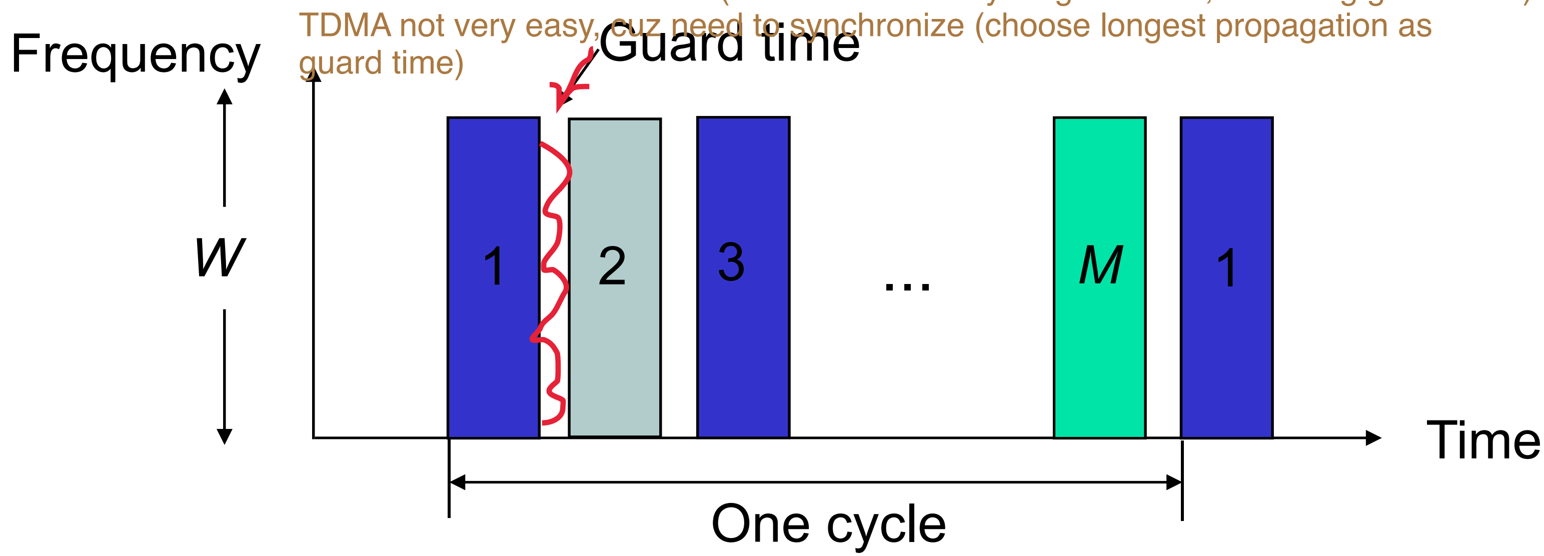
so need guard time to be in the same slot

- 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

w/o guard time, when A is sending in slot 1, C will send in slot 2, then slot 2 will collide

- Inefficient for bursty traffic due to unused dedicated slots

TDMA also cuases overhead(slot small and very long distance, then long guard time)
TDMA not very easy, cuz need to synchronize (choose longest propagation as guard time)



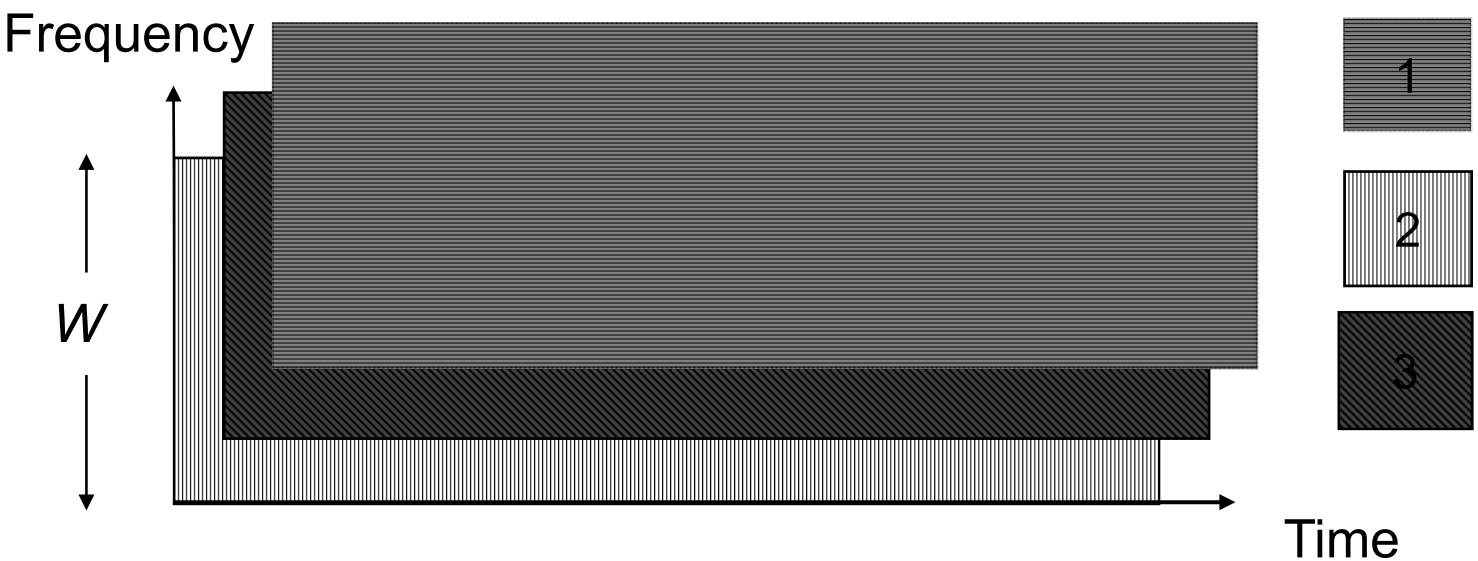
Guardbands

- 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!



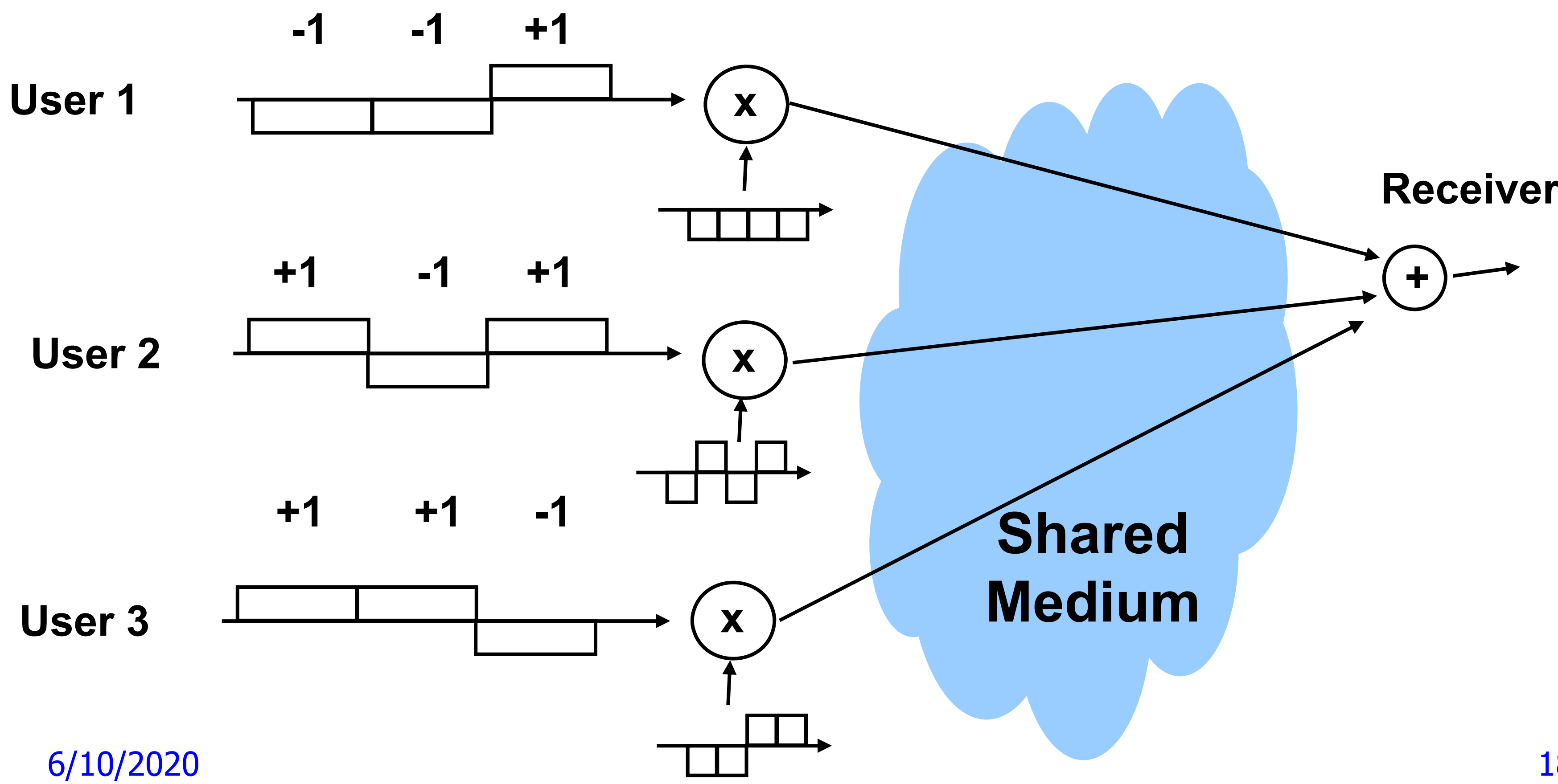
Channelization in Code Space

- 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},

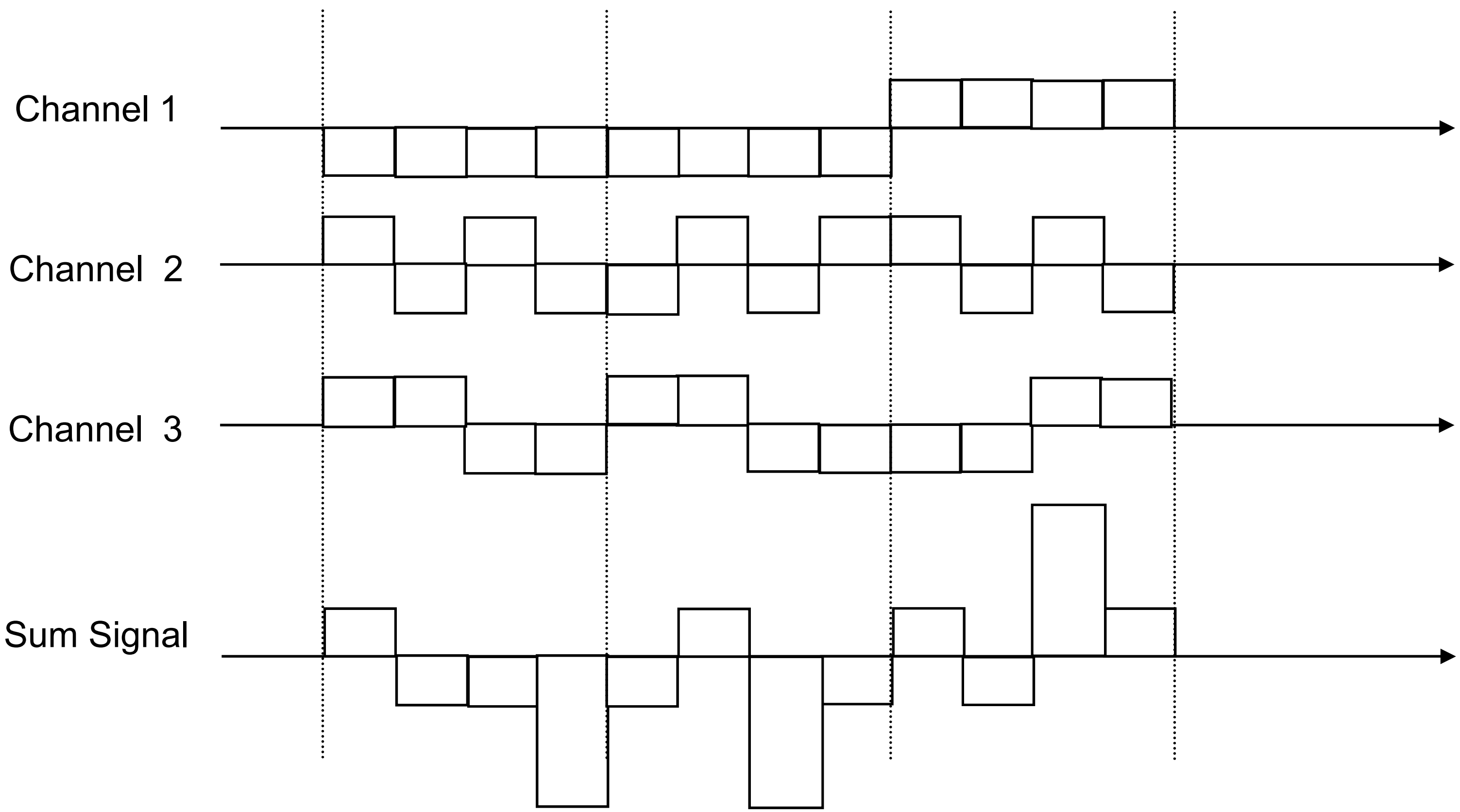
their cross-correlation values satisfy the property of orthogonality



Sum signal is input to receiver

4位code都要乘1 和 1 和0

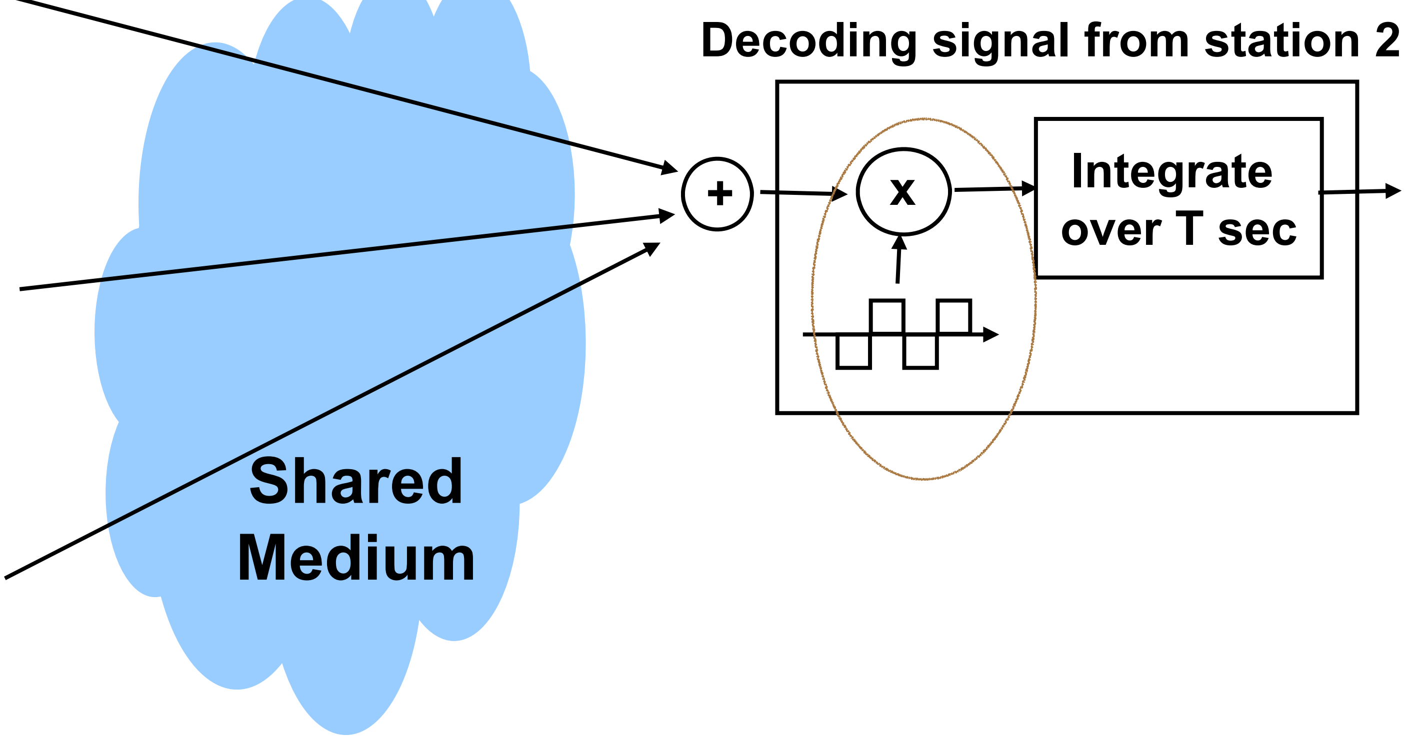
- **Channel 1: 110 -> +1+1-1 -> (-1,-1,-1,-1),(-1,-1,-1,-1),(+1,+1,+1,+1)**
- **Channel 2: 010 -> -1+1-1 -> (+1,-1,+1,-1),(-1,+1,-1,+1),(+1,-1,+1,-1)**
- **Channel 3: 001 -> -1-1+1 -> (+1,+1,-1,-1),(+1,+1,-1,-1),(-1,-1,+1,+1)**
- **Sum Signal: (+1,-1,-1,-3),(-1,+1,-3,-1),(+1,-1,+3,+1)**



Receiver for Station 2

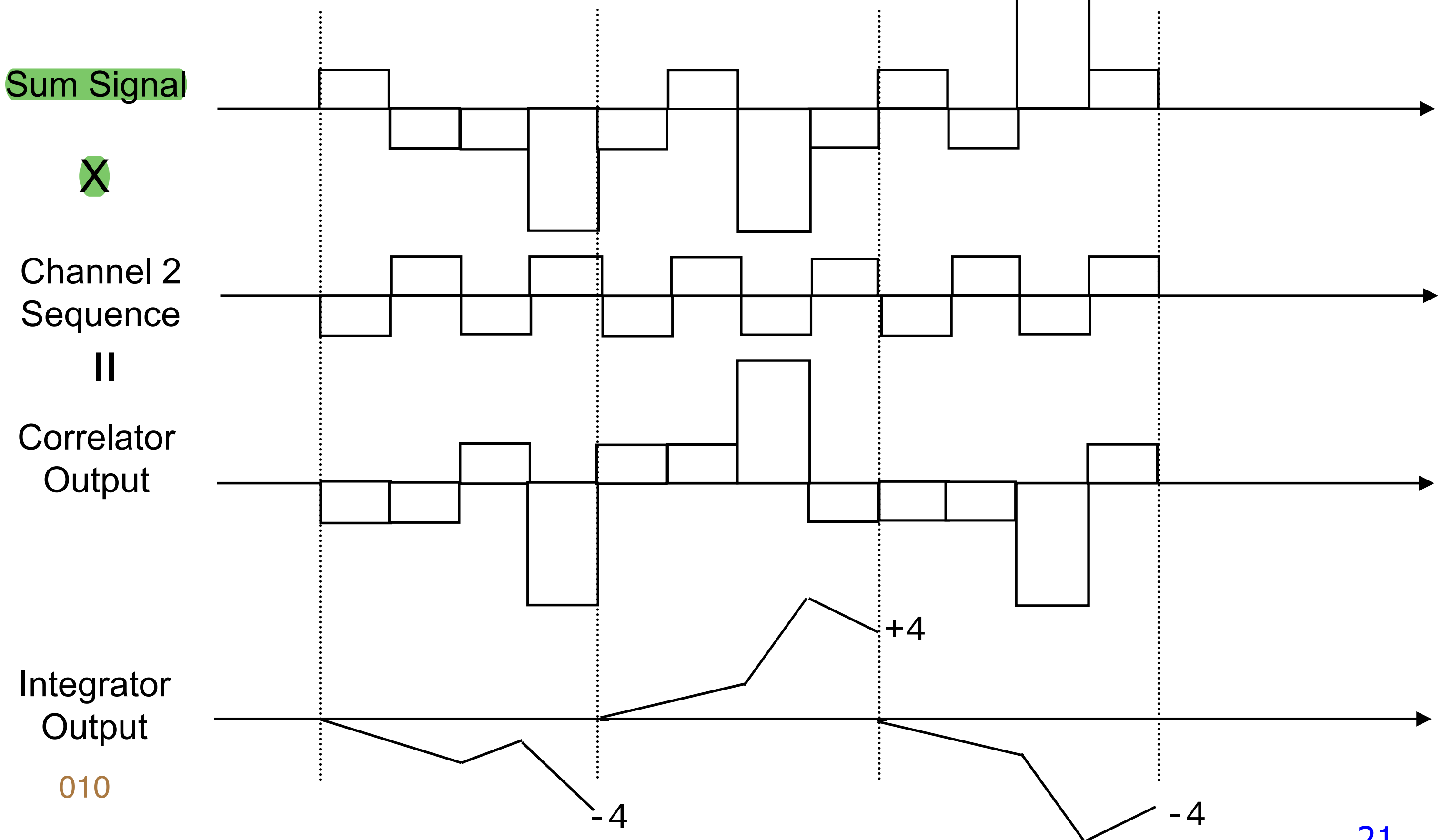
- Each receiver takes sum signal and integrates by code sequence of desired transmitter
- Integrate over T seconds to smooth out noise

since orthogonal, times _ and integrate



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

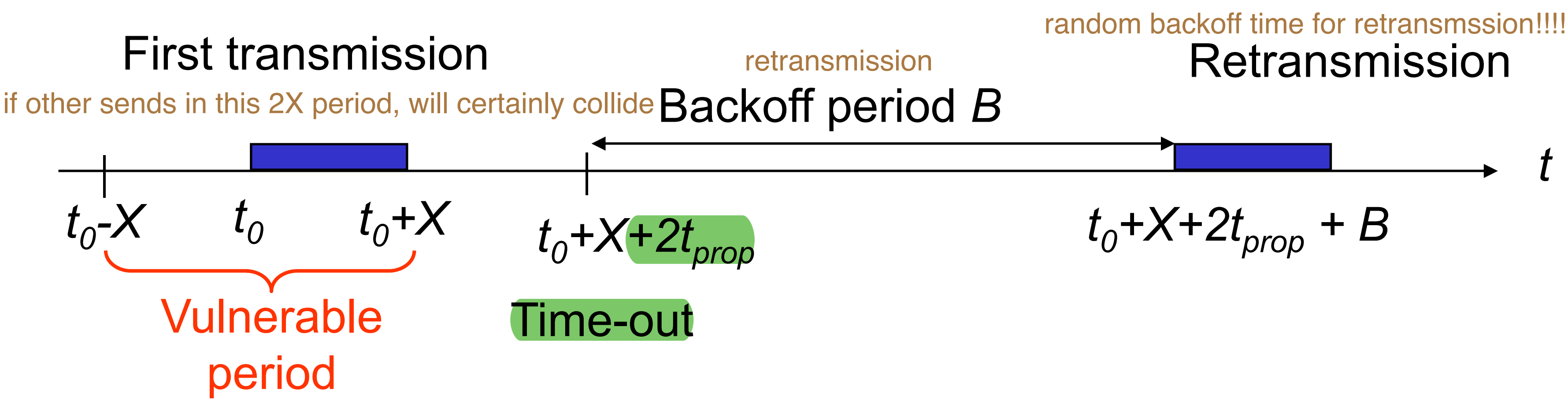
Random Access

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, retransimit. if retransimitted 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



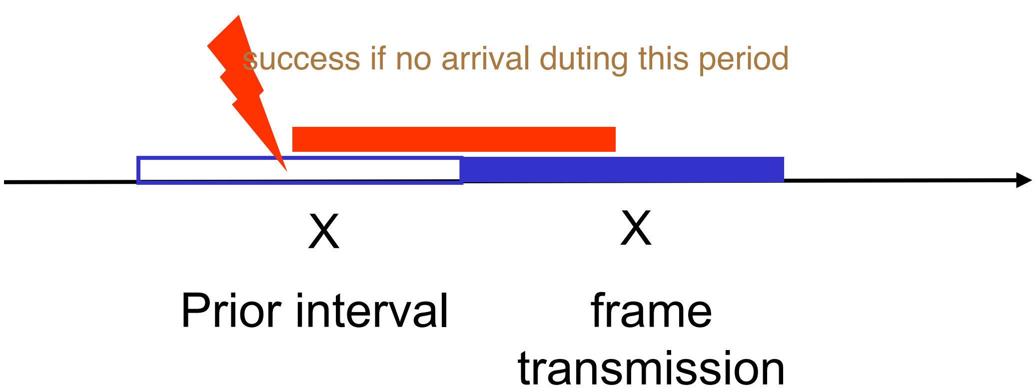
t_0 ~ t_0+X: my sending period

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 Δ interval, then

  G = n p since there are *n* intervals in *X* seconds

zero arrivals of other packages

$$P_{success} = P[0 \text{ arrivals in 2X seconds}] =$$

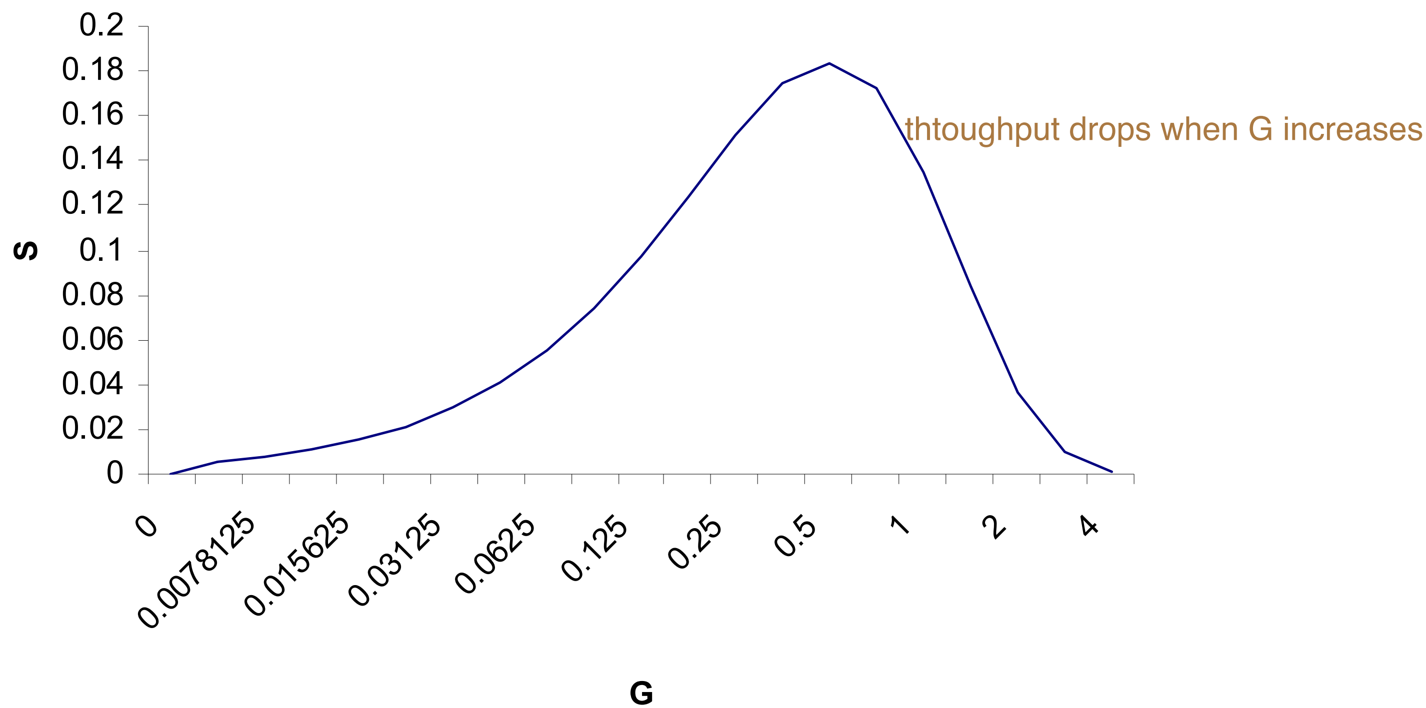
$$= P[0 \text{ arrivals in 2n intervals}]$$

$$= (1 - \text{p})^{2\text{n}} = (1 - \frac{G}{n})^{2n} \rightarrow e^{-2G} \quad \text{as n} \rightarrow \infty$$

Throughput of ALOHA

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

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

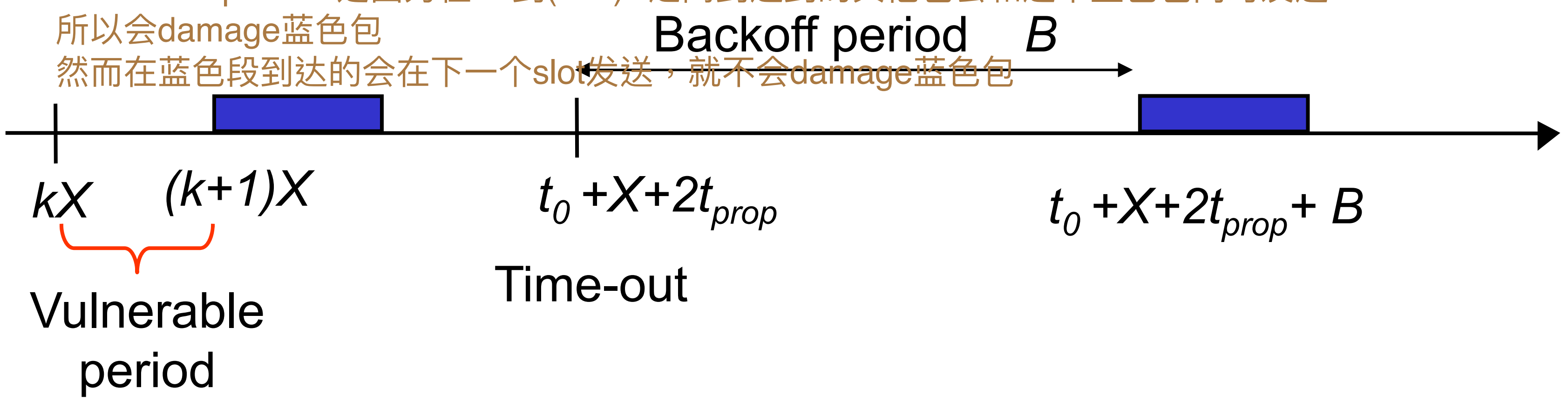


Slotted ALOHA

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

vulnerable period: 是因为在kX到(k+1)X之间到达到的其他包会和这个蓝色包同时发送
所以会damage蓝色包
然而在蓝色段到达的会在下一个slot发送，就不会damage蓝色包



reduced by half

Only frames that arrive during prior X seconds collide

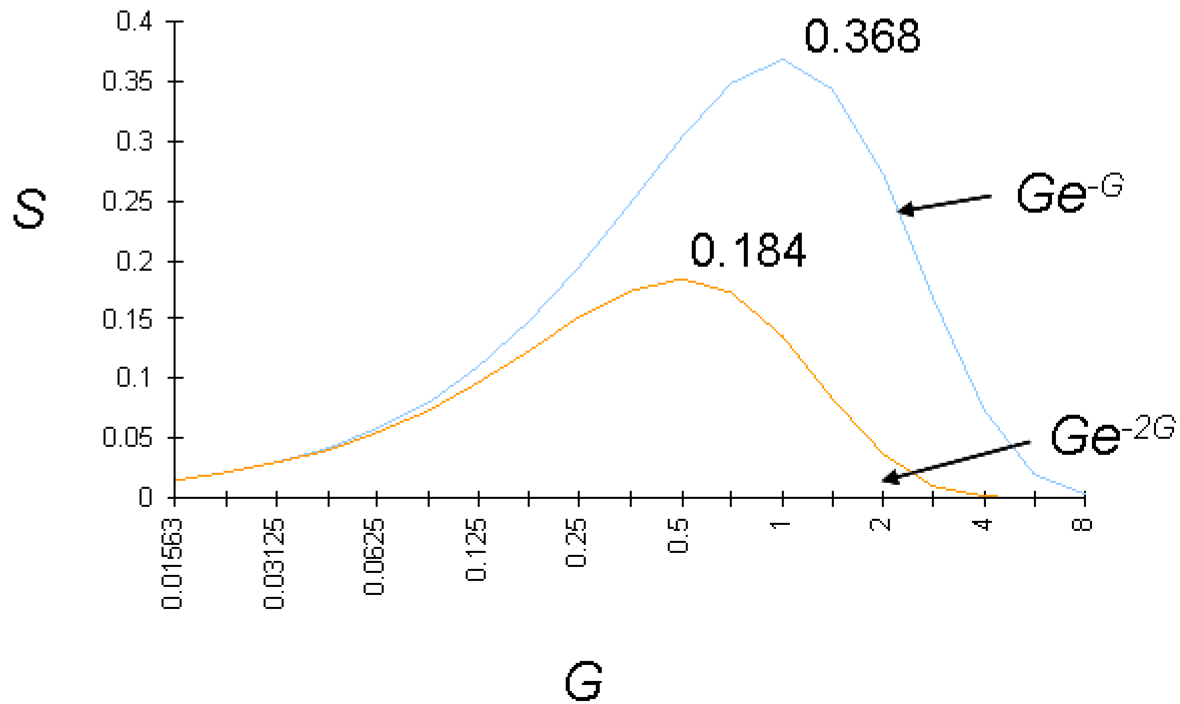
Throughput of Slotted ALOHA

$$S = GP_{success} = GP[\text{no arrivals in X seconds}]$$

$$= GP[\text{no arrivals in n intervals}]$$

why equal likely still holds true?
cuz retransimission

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



Application of Slotted Aloha

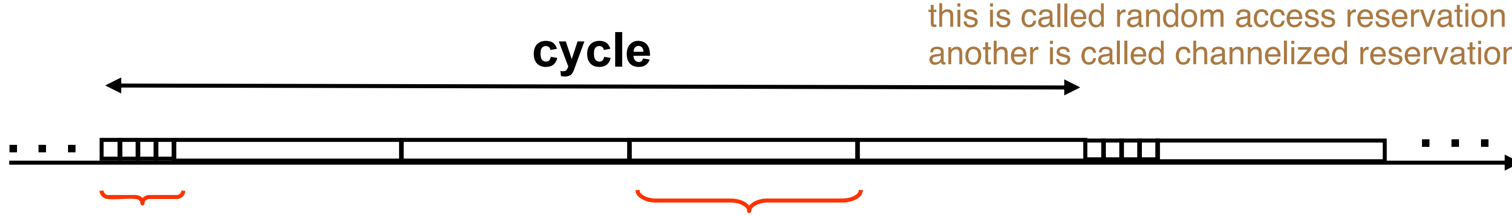
net protocol
cell phone still uses slotted Aloha (use it to do scheduling)

(reservation protocol belongs to scheduling)
this reservation done by scheduling

- Reservation protocol allows a large number of stations with infrequent traffic to reserve slots to transmit their frames in future cycles
- 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

this is called random access reservation protocol
another is called channelized reservation protocol



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

In the context of "Carrier Sensing" in communication systems, the term "carrier" refers to the presence or absence of a carrier signal on the communication channel. A carrier signal is a continuous wave or tone that is modulated with the actual data signal.

Carrier Sensing Multiple Access (CSMA)

5G use CSMA to improve efficiency

- A station senses the channel before it starts transmission

if constantly sensing, power consumpltion

  - If busy, either wait or schedule backoff (different options)
  - If idle, start transmission

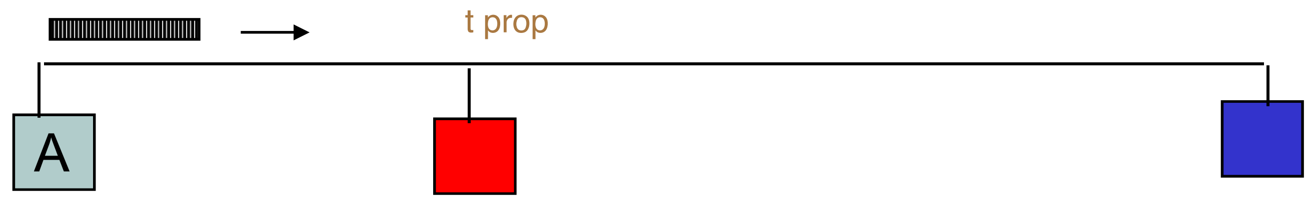
A想往B發， 那t0-t_prop的时候，B发送的包裹Asense不到，所以vulnerable
B往A發的時候，t0+t_prop的时候B察觉不到A发送了，所以A也vulnerable

  - Vulnerable period is reduced to (t_{prop} or $2t_{prop}$?) (due to delay in *channel capture* effect)

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 $t = 0$

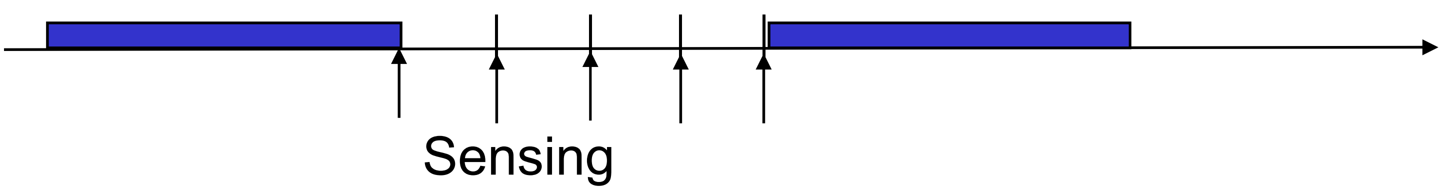


so we want transmission time is much larger than the propagation time,
so send large packages less frequently

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

CSMA Options

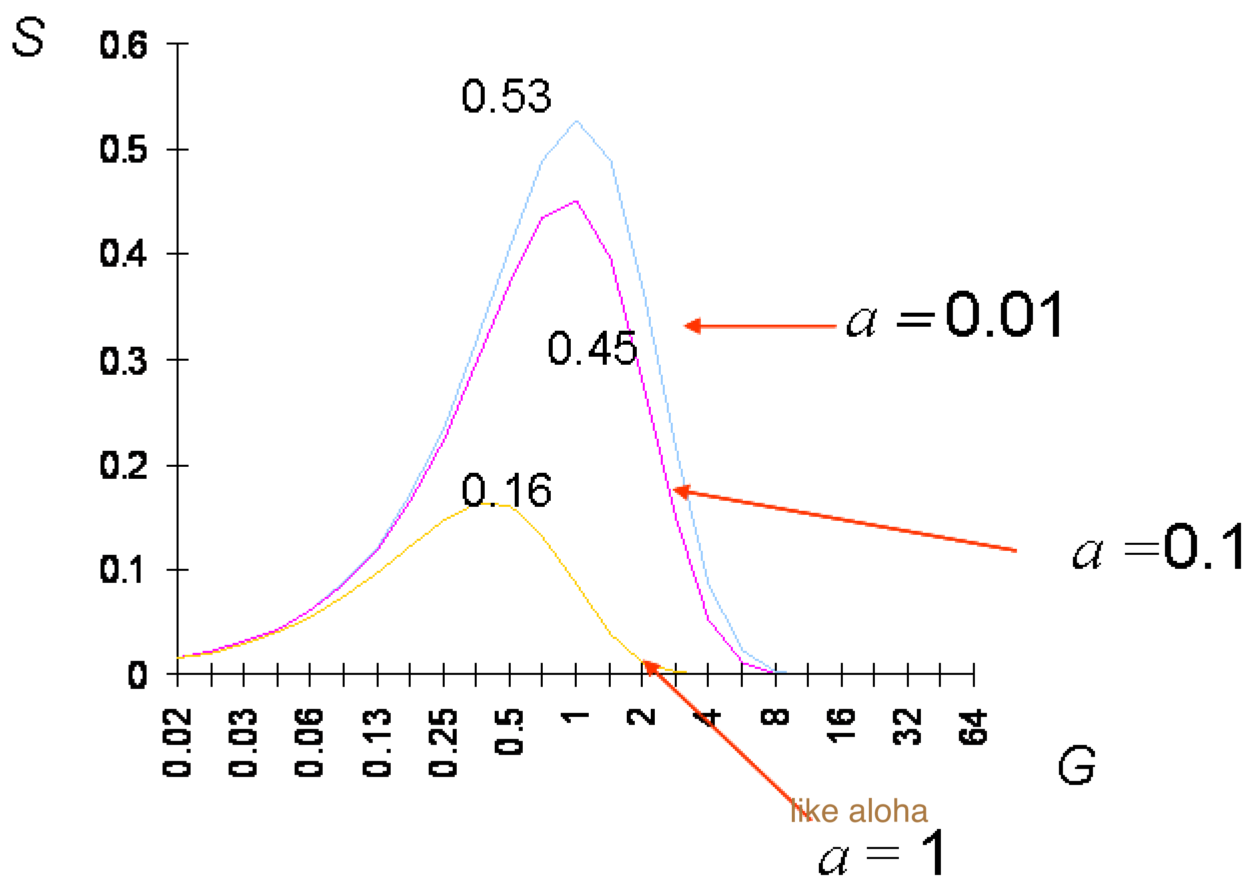
- Transmitter behavior when busy channel is sensed
  - 1-persistent CSMA (most greedy)
    - Start transmission as soon as the channel becomes idle
    - Low delay and low efficiency
  - Non-persistent CSMA (least greedy)
    - Wait a backoff period, then sense carrier again
    - High delay and high 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

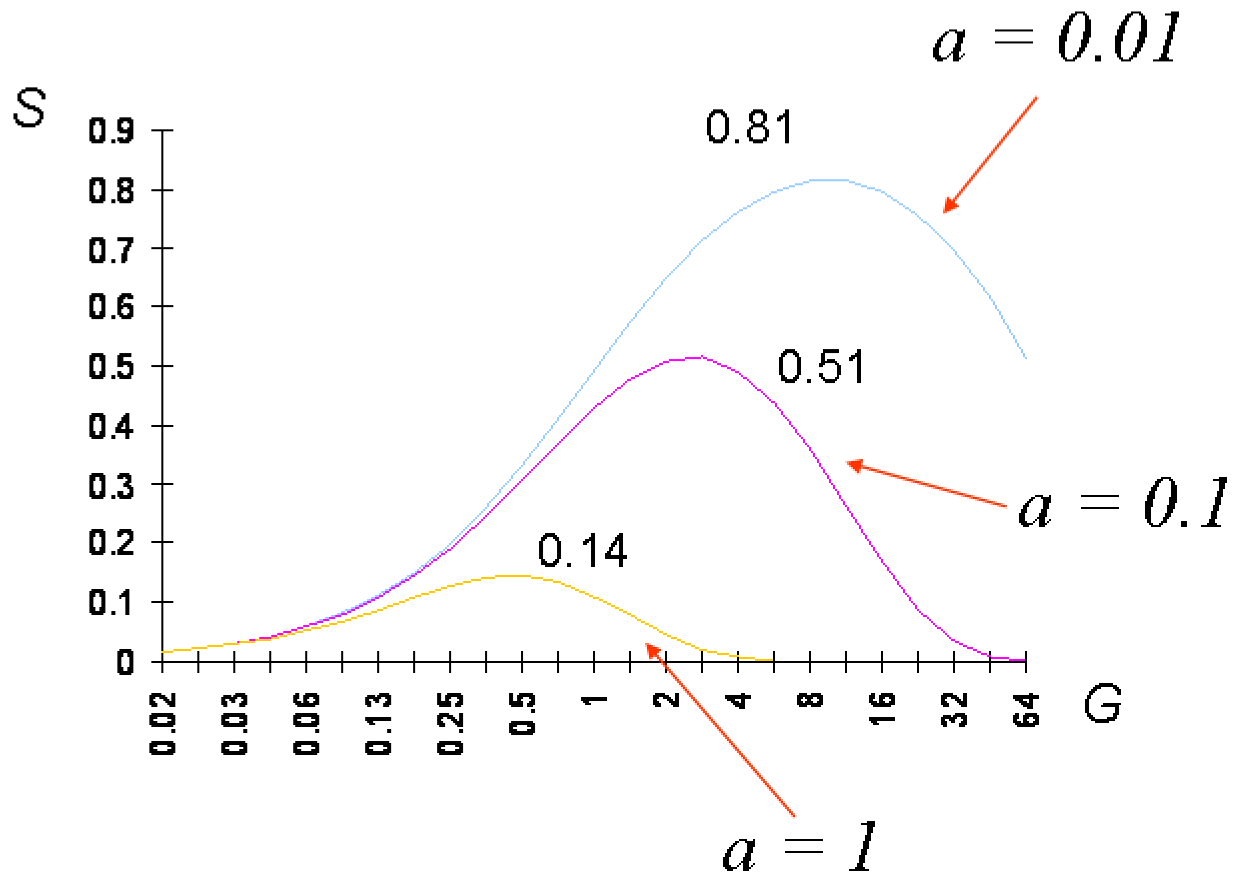
- Better than Aloha & slotted Aloha for small a
- Worse than Aloha for $a > 1$

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

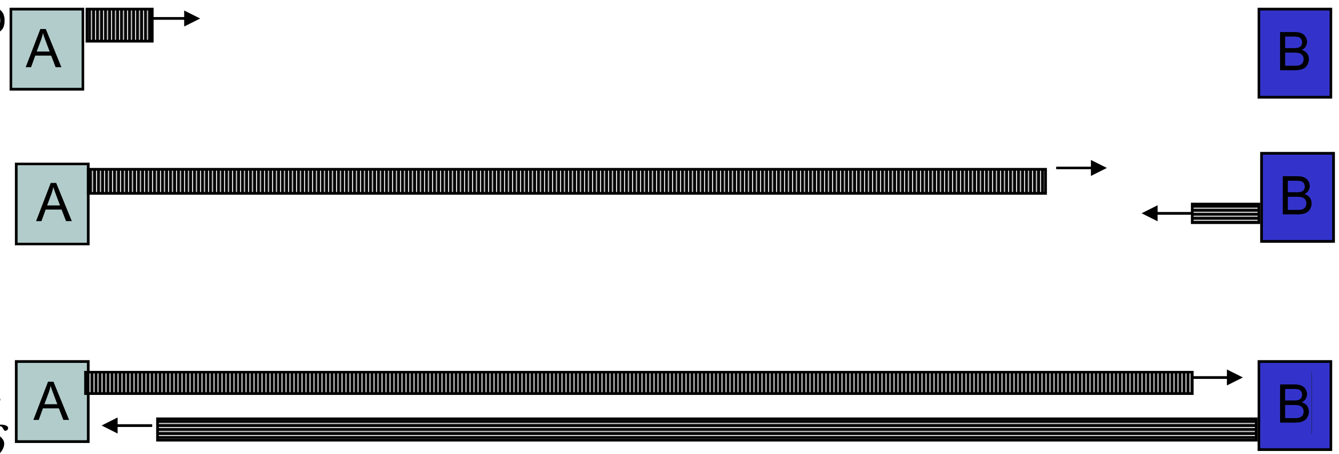
how to detect collisions?
can be though of detected instantly?

- 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

carrier sensing是检测我的接收端有没有信号！！
所以要A到达B的时间，刚好在B的vulnerable period内，B才知道A和Bcollide了
B自己不会返回

A begins to transmit at $t = 0$



just assumptions

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

B detects collision at $t = t_{prop}$

why

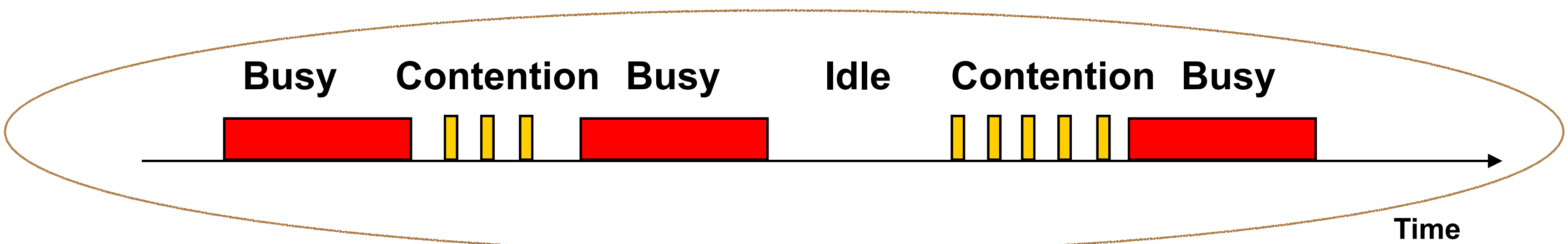
A detects collision at $t = 2\, t_{prop} - \delta$

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 $2t_{prop}$ 每个slot的长度是2t_prop吧
  - 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} idle time 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:

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

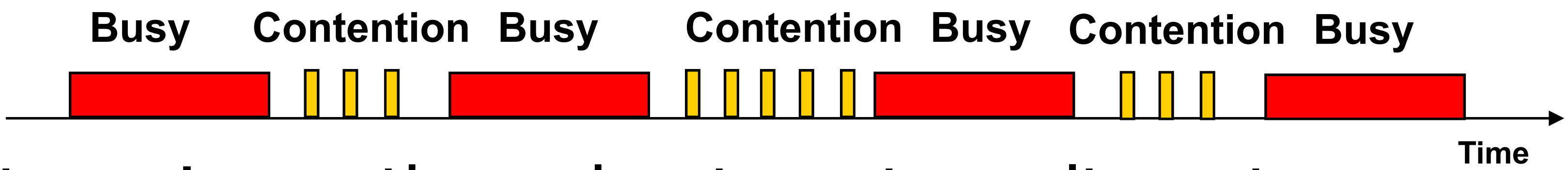
- By taking derivative of $P_{success}$ we find max occurs at p=1/n

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

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

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

CSMA/CD Throughput



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

long cable, performance really low

看看

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

- 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

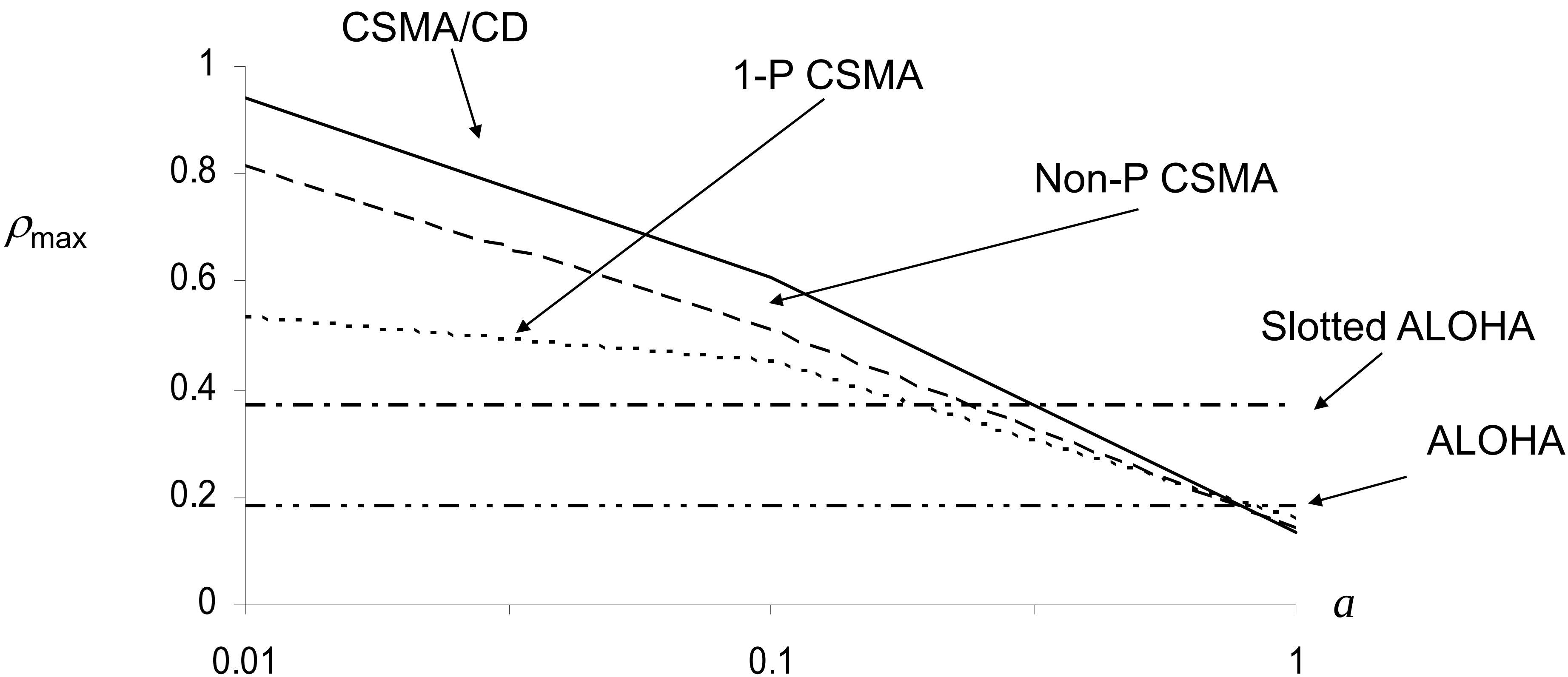
- First Ethernet LAN standard used CSMA-CD
  - 1-persistent Carrier Sensing
  - R = 10 Mbps
  - t_{prop} = ?
    - 512 bits = 64 byte slot = 2 t_{prop}
    - t_{prop} = 51.2/2 = 25.6 microsec
    - Distance: 25.6 microsec x 2000 km/s = 5.12 km
    - accommodates 5 km + 4 repeaters
  - Truncated Binary Exponential Backoff
    - After nth collision, select backoff from {0, 1,…, 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

used in wired



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 τ_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

- 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

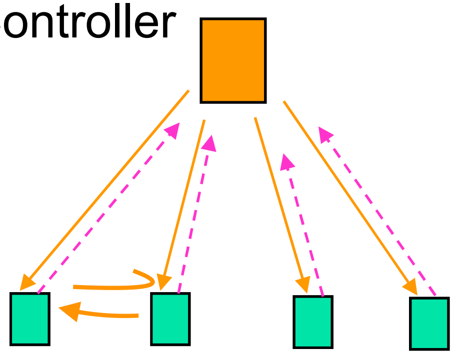
Reservations Systems

- *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

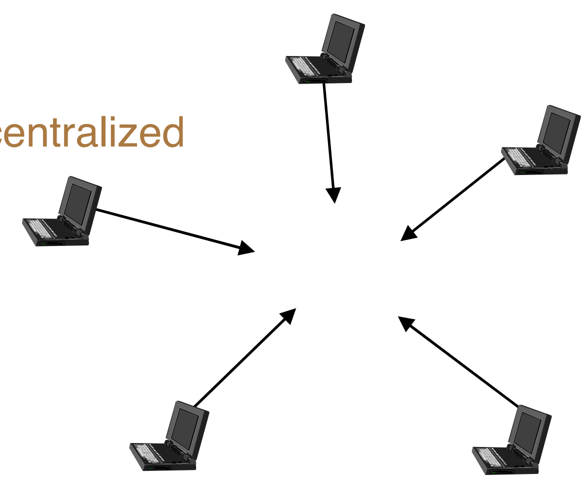
- *Distributed systems*: Stations implement a decentralized algorithm to determine transmission order

Central Controller



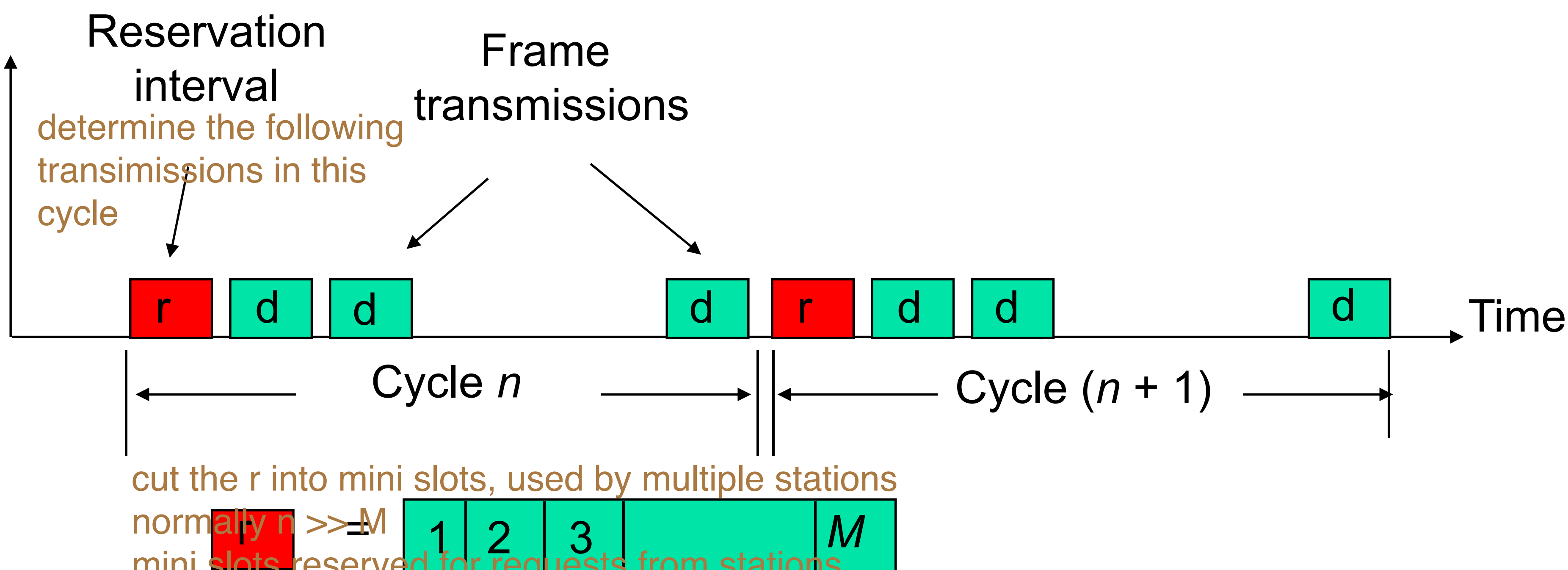
sidelink
(begin to be impt in 5g)

decentralized



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



determine the following transimissions in this cycle

cut the r into mini slots, used by multiple stations

normally n >> M

mini slots reserved for requests from stations

used random access (for stations competing)in this to send requests

Reservation System Options

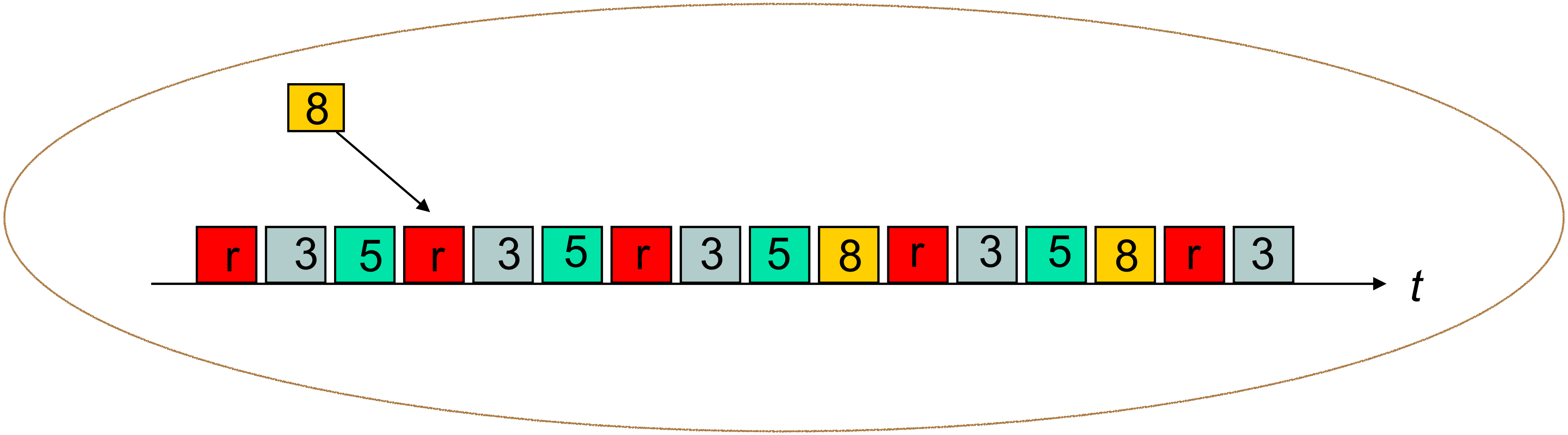
- Centralized or distributed system
  - *Centralized systems*: A central controller listens to reservation information, decides order of transmission, issues grants
  - *Distributed systems*: Each station determines its slot for transmission from the reservation information
- Single or Multiple Frames
  - *Single frame reservation*: Only one frame transmission can be reserved within a reservation cycle but many stations can transmit within a cycle
  - *Multiple frame reservation*: More than one frame transmission can be reserved within a reservation cycle
- Channelized or Random Access Reservations

what is n

  - n<=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



single frame的意思是每个station一次只能reserve一个frame，而不是只有一个station能reserve一个frame

Efficiency of Reservation Systems

what is v what is X

- Assume one minislot duration = vX v<<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

这个是channelized reservation

- 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 2.71 vX

effi not low with small v

e number of \mu (mini slot length)

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

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

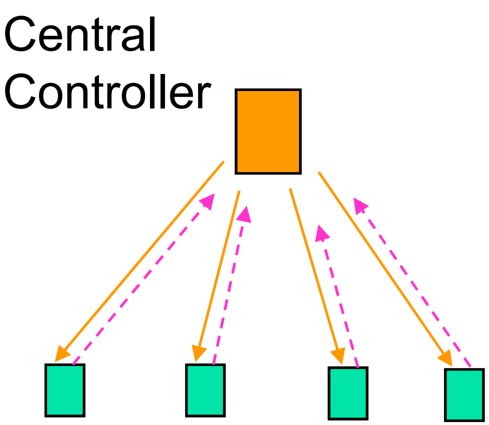
Reservation Systems and Quality of Service

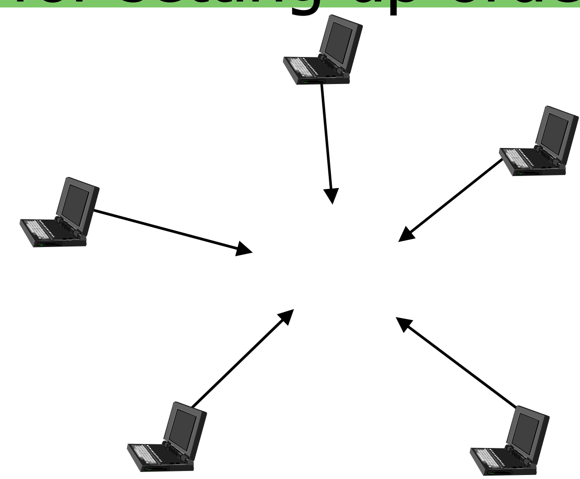
- Different applications; different requirements
  - Immediate transfer for ACK frames
  - Low-delay transfer & steady bandwidth for voice   so better scheduling..?
  - High-bandwidth for Web transfers
- Reservation provide direct means for QoS
  - Stations make requests per frame
  - Stations can request 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

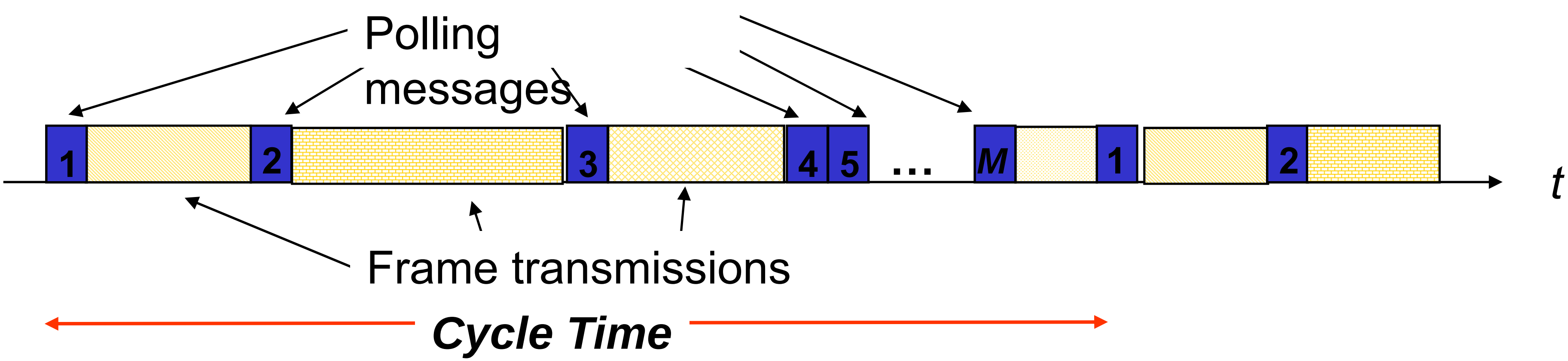
- Service Limits: How much is a station allowed to transmit per poll?
  - *Exhaustive*: until station's data buffer is empty (including new frame arrivals)
  - *Gated*: all data in buffer when poll arrives
  - *Frame-Limited*: one frame per poll
  - *Time-Limited*: up to some maximum time
- Priority 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

blue frames

- *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
- λ be frame arrival rate at the system
- N_C average number of frames transmitted from a station
- Time to empty one station buffer:

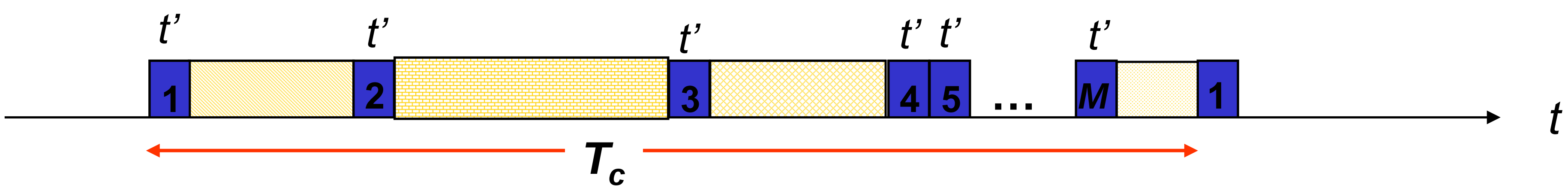
$$T_{station} = N_c X = \left(\frac{\lambda}{M} T_c\right) X = \frac{\rho T_c}{M} \qquad \rho = \lambda X$$

1/X是output rate

- Average Cycle Time:

walk time
divided by 1-rou

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



Efficiency of Polling Systems

- Exhaustive Service

  pos: high efficiency
  cons: high delay

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

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

Can approach 100%

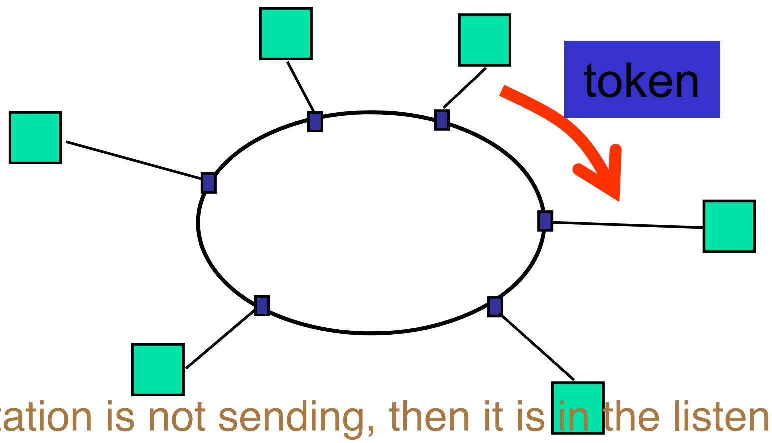
- Limited Service
  - Many applications cannot tolerate extremely long delays
  - Time or transmissions per station are limited
  - This limits the cycle time and hence delay
  - Efficiency of 100% is not possible

MX: transimmission
Mt’: walk time

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

Single frame per poll

Application: Token-Passing Rings



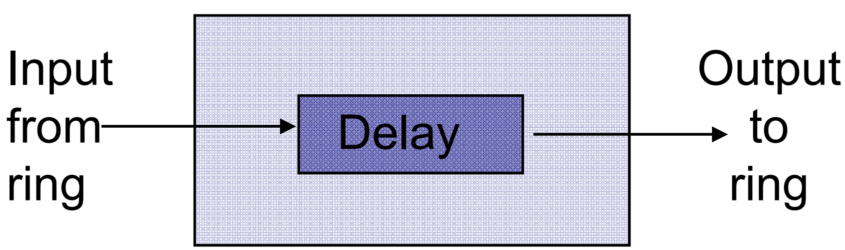
Free Token = Poll

Frame Delimiter is Token
Free = 01111110
Busy = 01111111

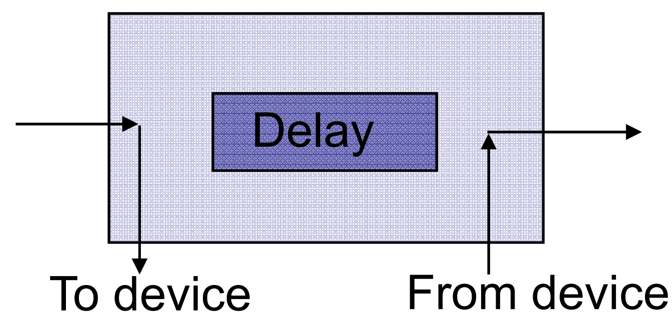
flip

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

Listen mode



Transmit mode



这俩图啥意思

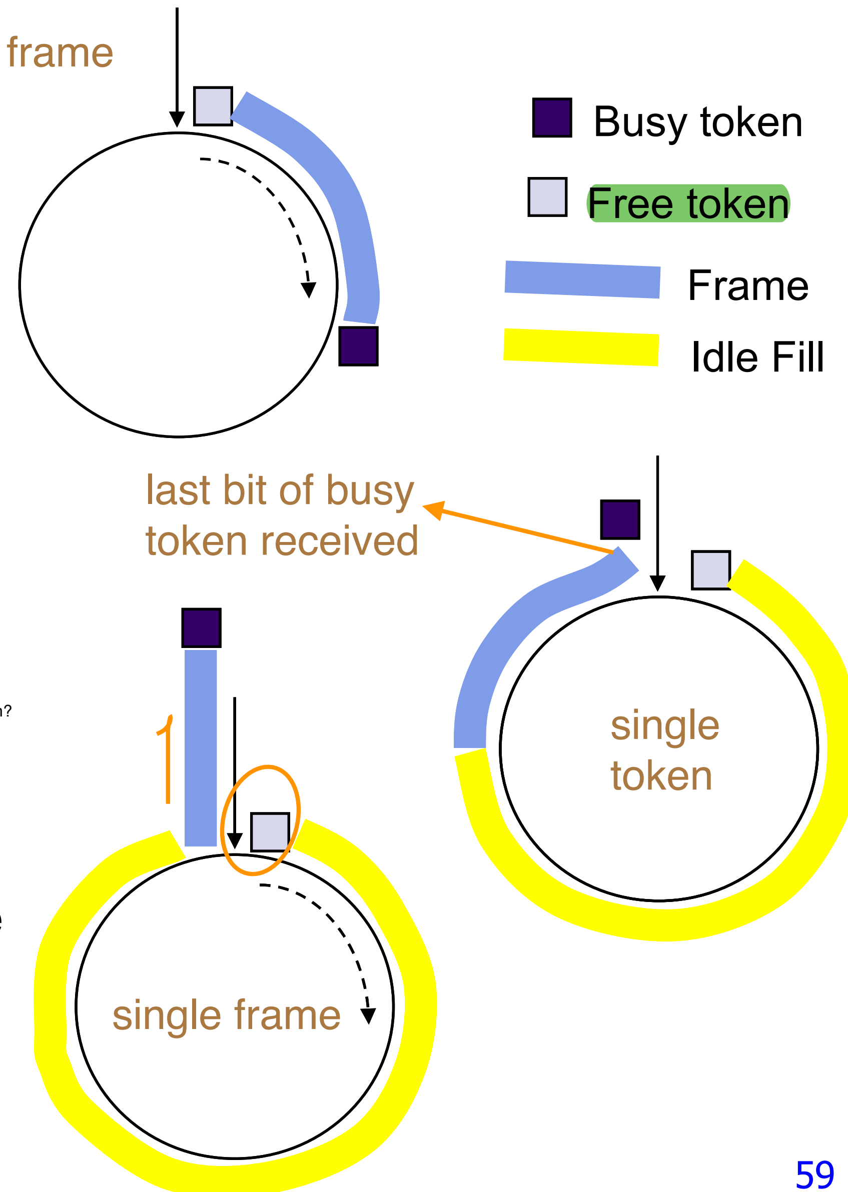
Ready station looks for free token

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   collision?
- 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

為什麼加tau '
what

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

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

Token Ring Throughput

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

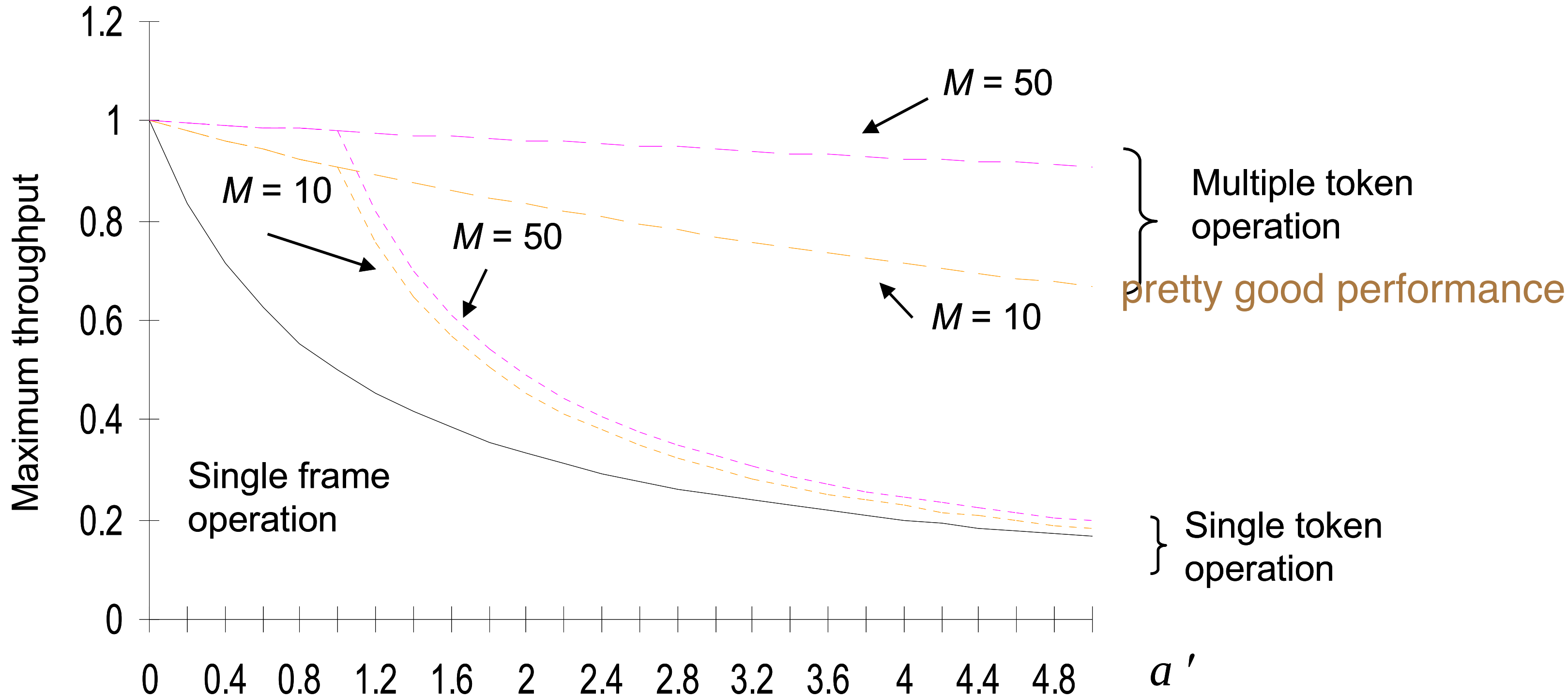
$$\rho_{max} = \frac{MX}{\tau' + M \max\{(X, \tau'\}} = \frac{1}{\max\{1, a'\} + a'/M}$$

if tau ' > transimission time
wait for it to come back

- *Single-frame operation*
  - Effective frame transmission time is X+ τ',therefore

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

Token Reinsertion Efficiency Comparison



- a <<1, any token reinsertion strategy acceptable
- a ≈1, single token reinsertion strategy acceptable
- a >1, multitoken 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

- 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

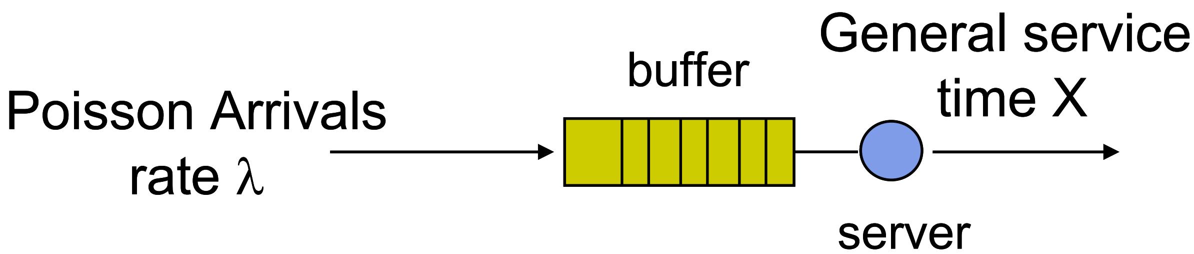
Comparison of MAC approaches

- 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

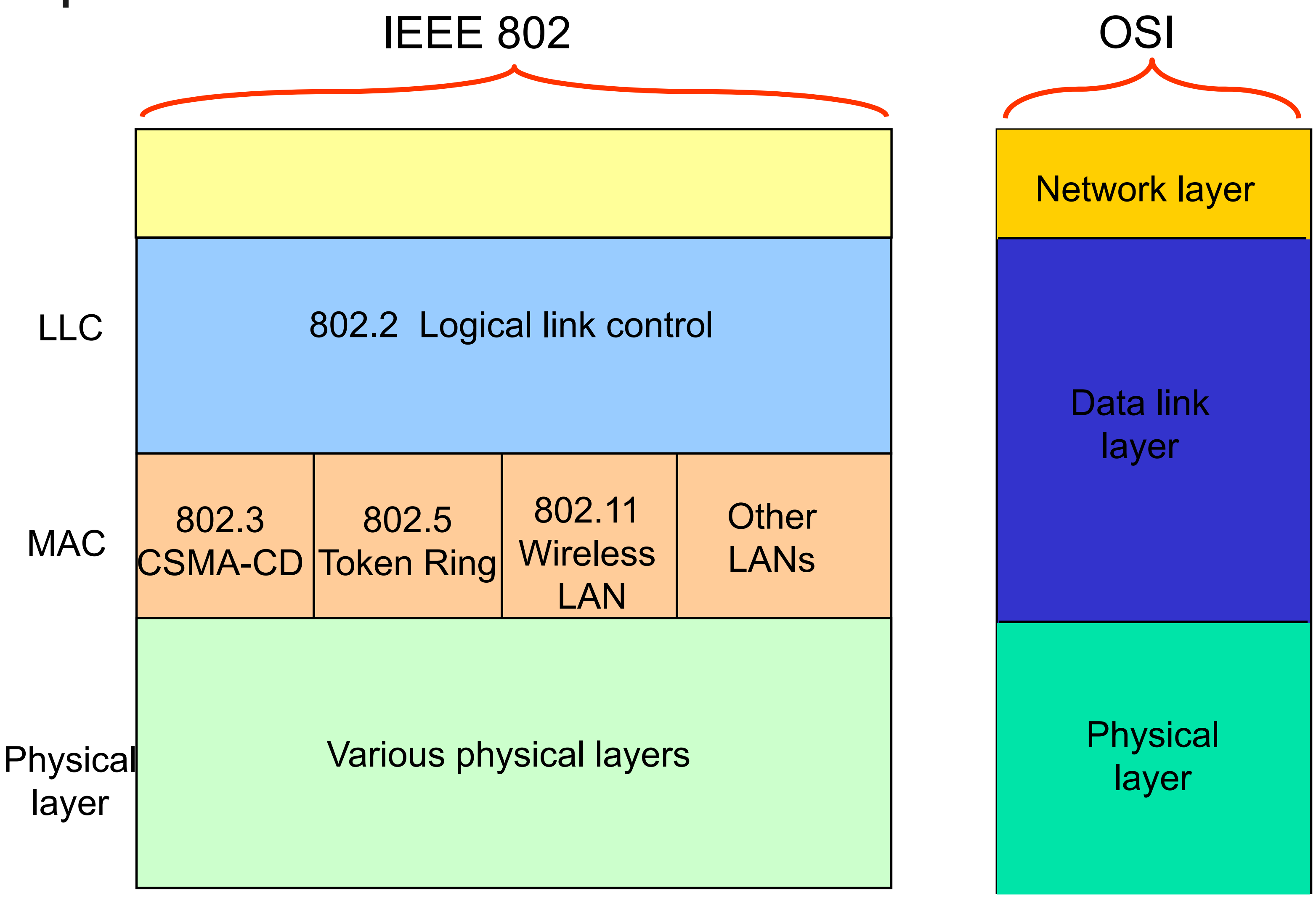
- In M/G/1 model, a frame arriving to an empty multiplexer begins transmission immediately
- In many MACs, there is a delay before transmission can begin Text
- *M/G/1 Vacation Model*: when system empties, server goes away on vacation for random time V

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

Extra delay term

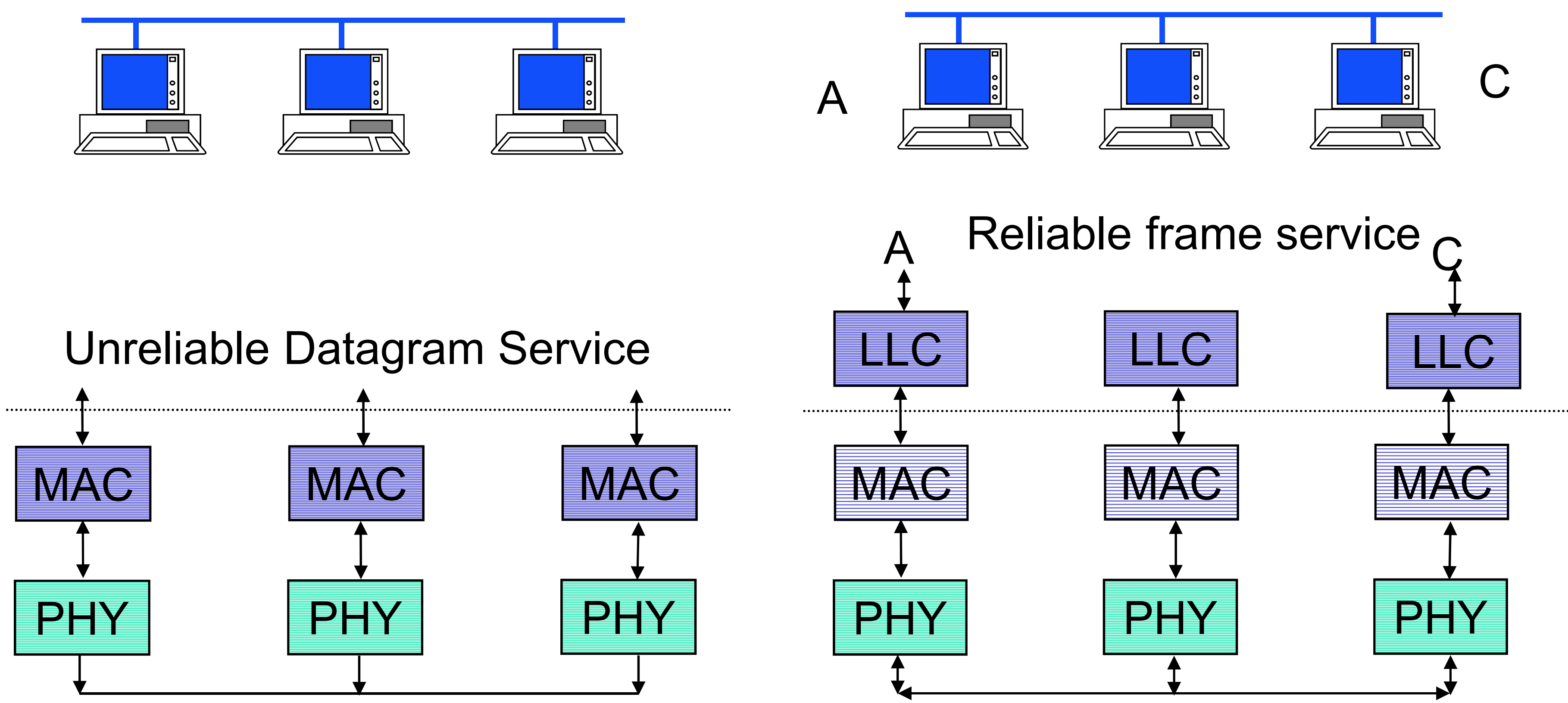
MAC in Different Networks

IEEE 802 Networks



Logical Link Control Layer

- IEEE 802.2: LLC enhances service provided by MAC

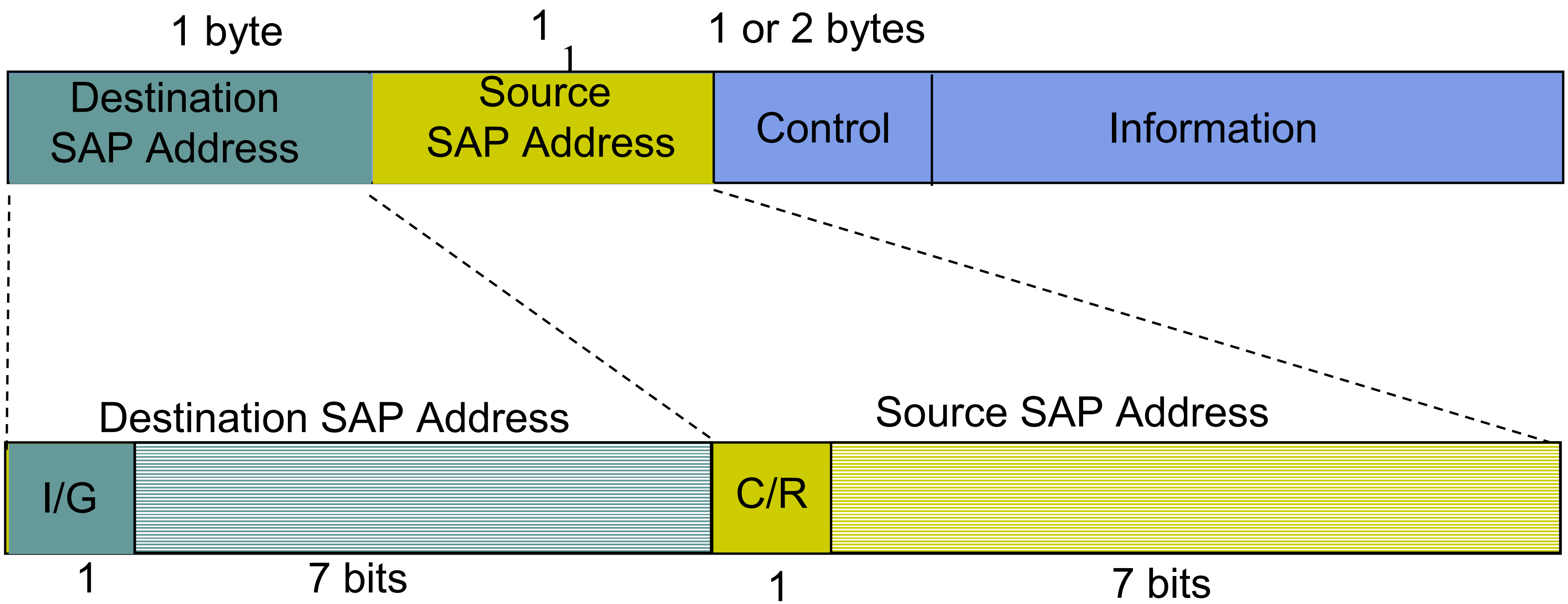


Logical Link Control Services

- 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).

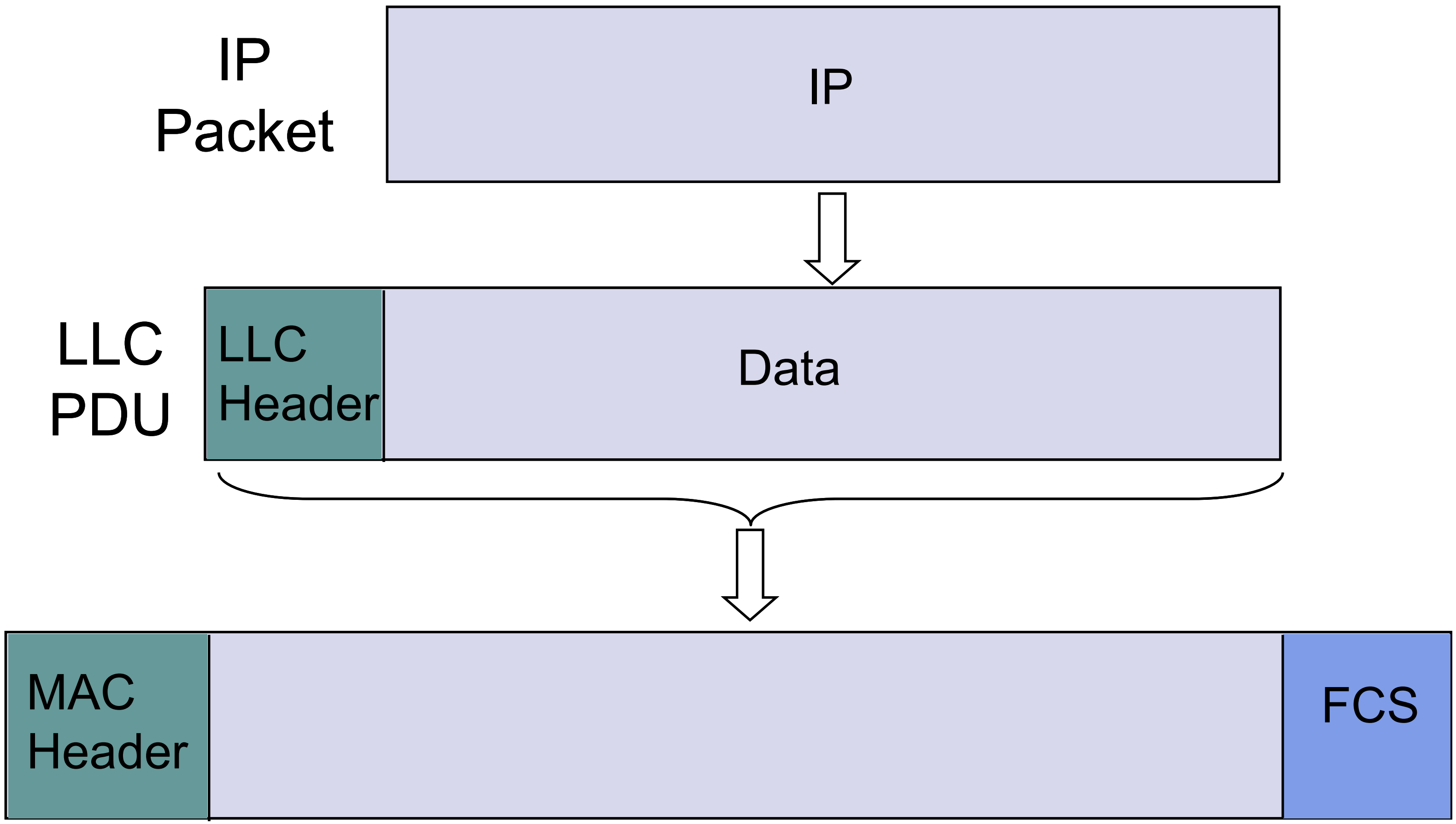
LLC PDU Structure



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{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

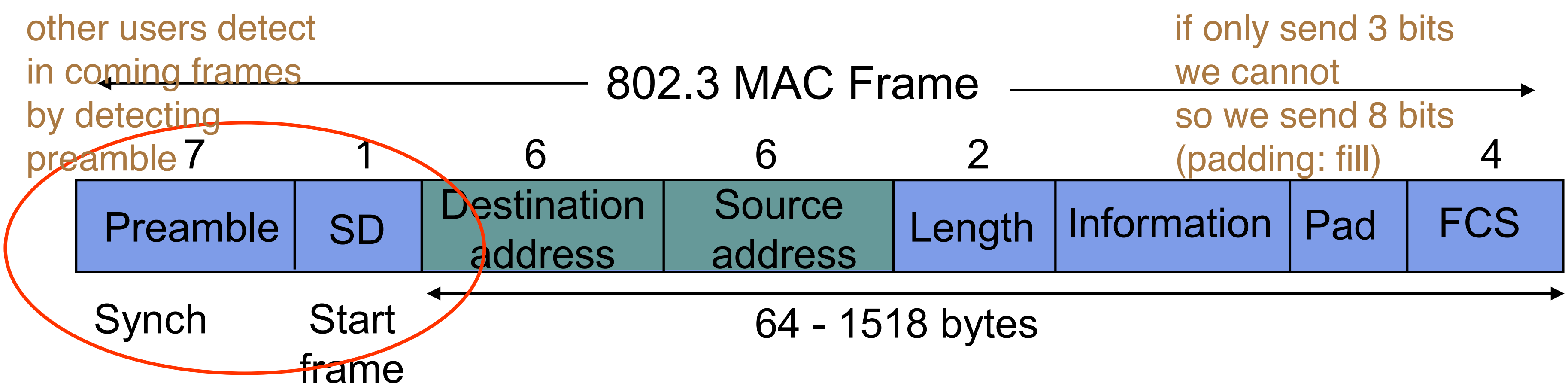
IEEE 802.3 Original Parameters

- Transmission Rate: 10 Mbps
- Min Frame: 512 bits = 64 bytes
- Slot time: 512 bits/10 Mbps = 51.2 μsec
  - 51.2 μsec x 2×10^5 km/sec =10.24 km, 1 way
  - 5.12 km round trip distance
- Max Length: 2500 meters + 4 repeaters

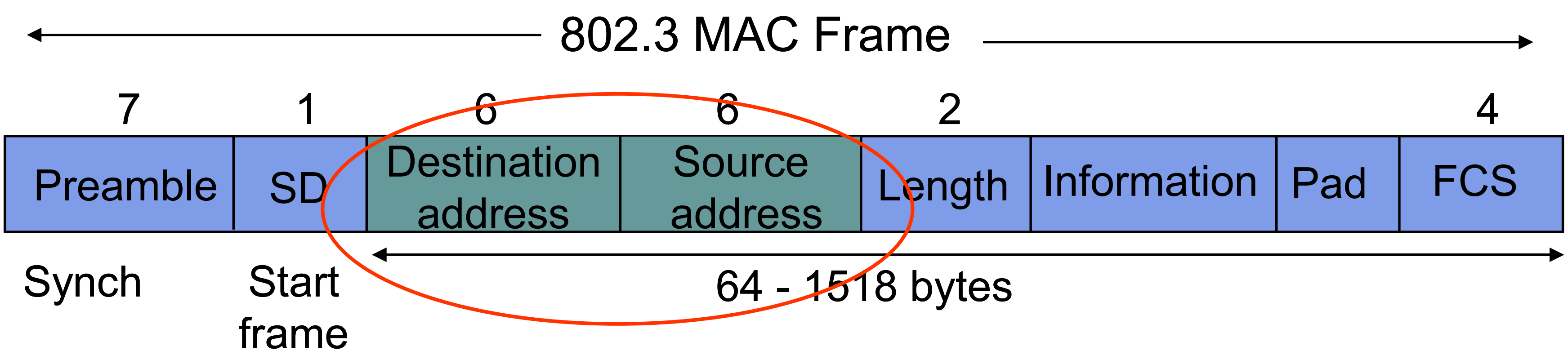
- *Each x10 increase in bit rate, must be accompanied by x10 decrease in distance*

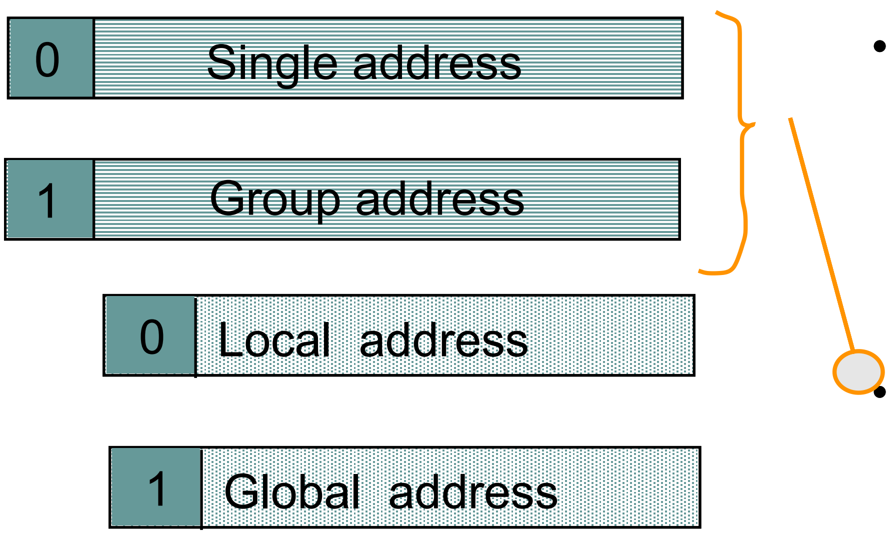
IEEE 802.3 MAC Frame

- 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

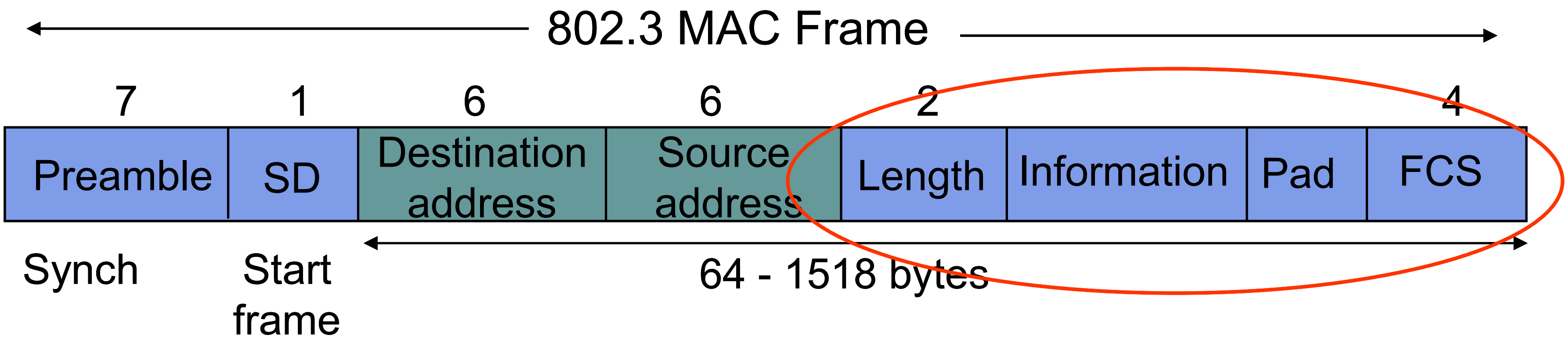




- Destination address
  - single address
  - group address
  - broadcast = 111...111

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

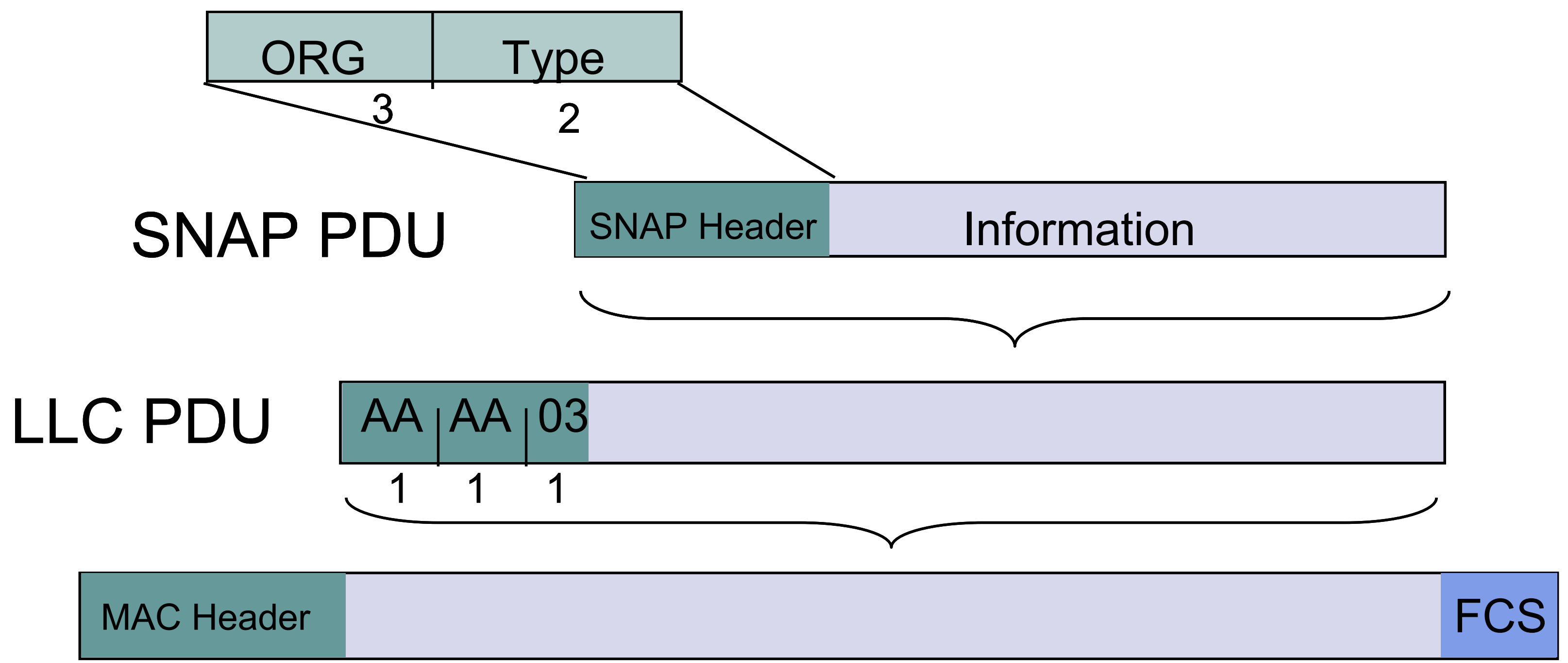
IEEE 802.3 MAC Frame



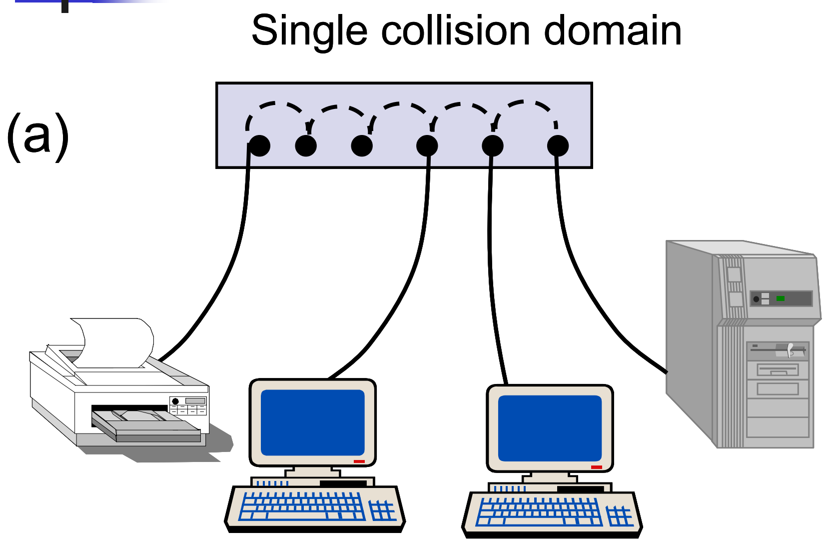
- Length: # bytes in information field
  - Max frame 1518 bytes, excluding preamble & SD
  - Max information 1500 bytes: 05DC
- Pad: ensures min frame of 64 bytes
- FCS: CCITT-32 CRC, covers addresses, length, information, pad fields
  - NIC discards frames with improper lengths or failed CRC

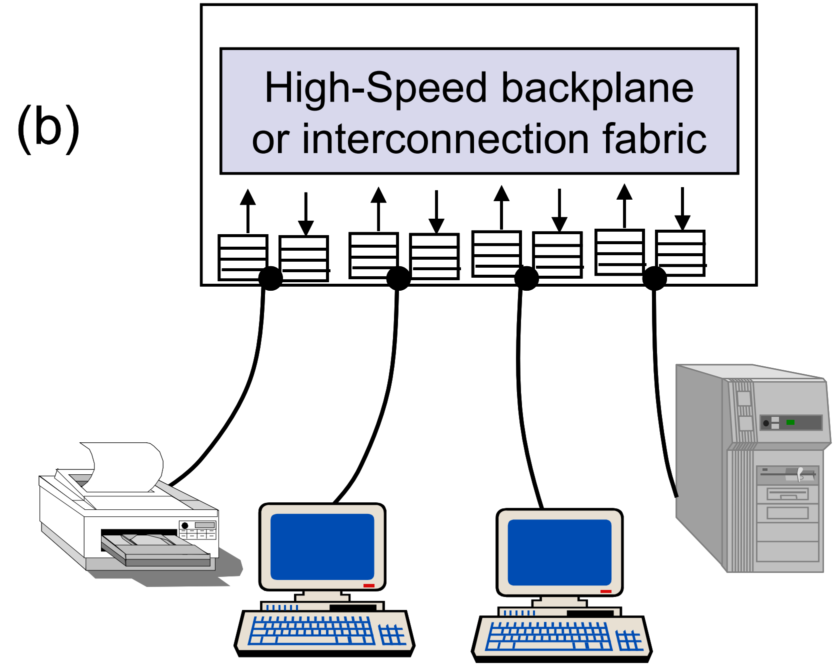
SubNetwork Access Protocol (SNAP)

- 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



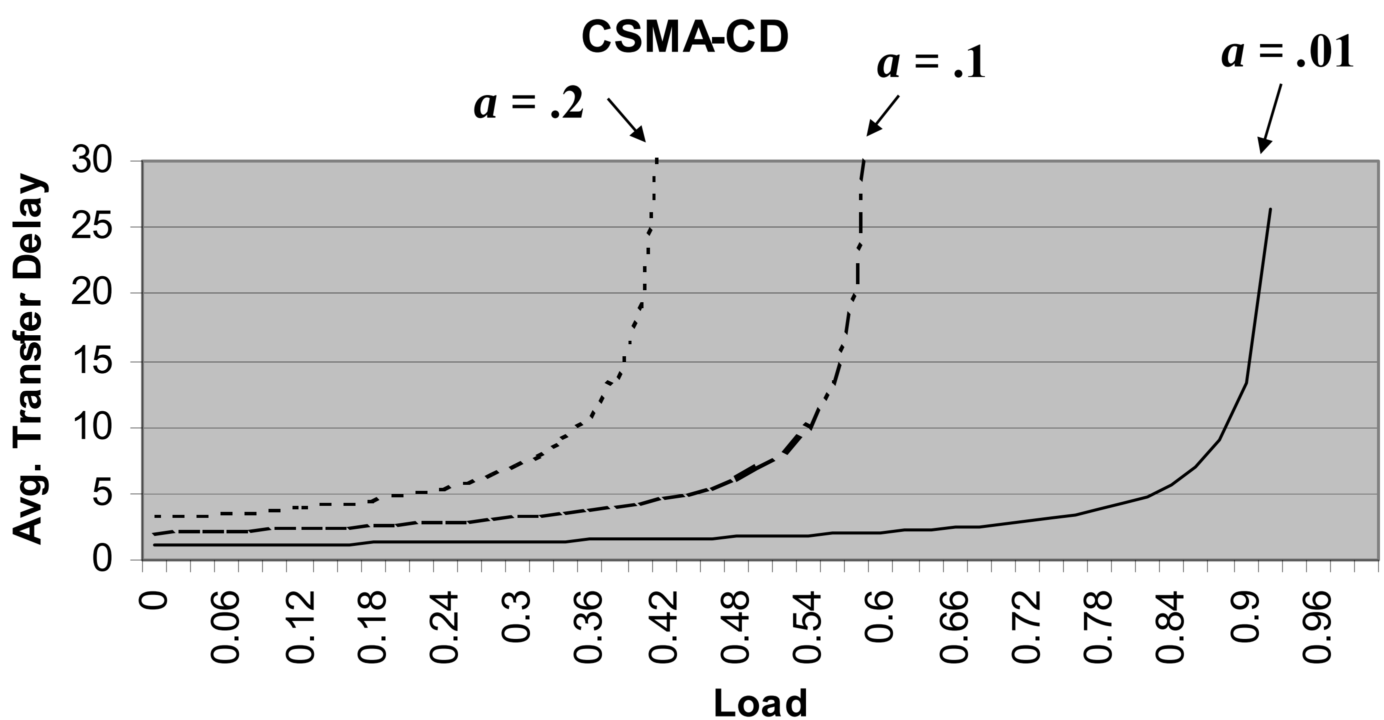


Twisted Pair Cheap
Easy to work with
Reliable
Star-topology CSMA-CD

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

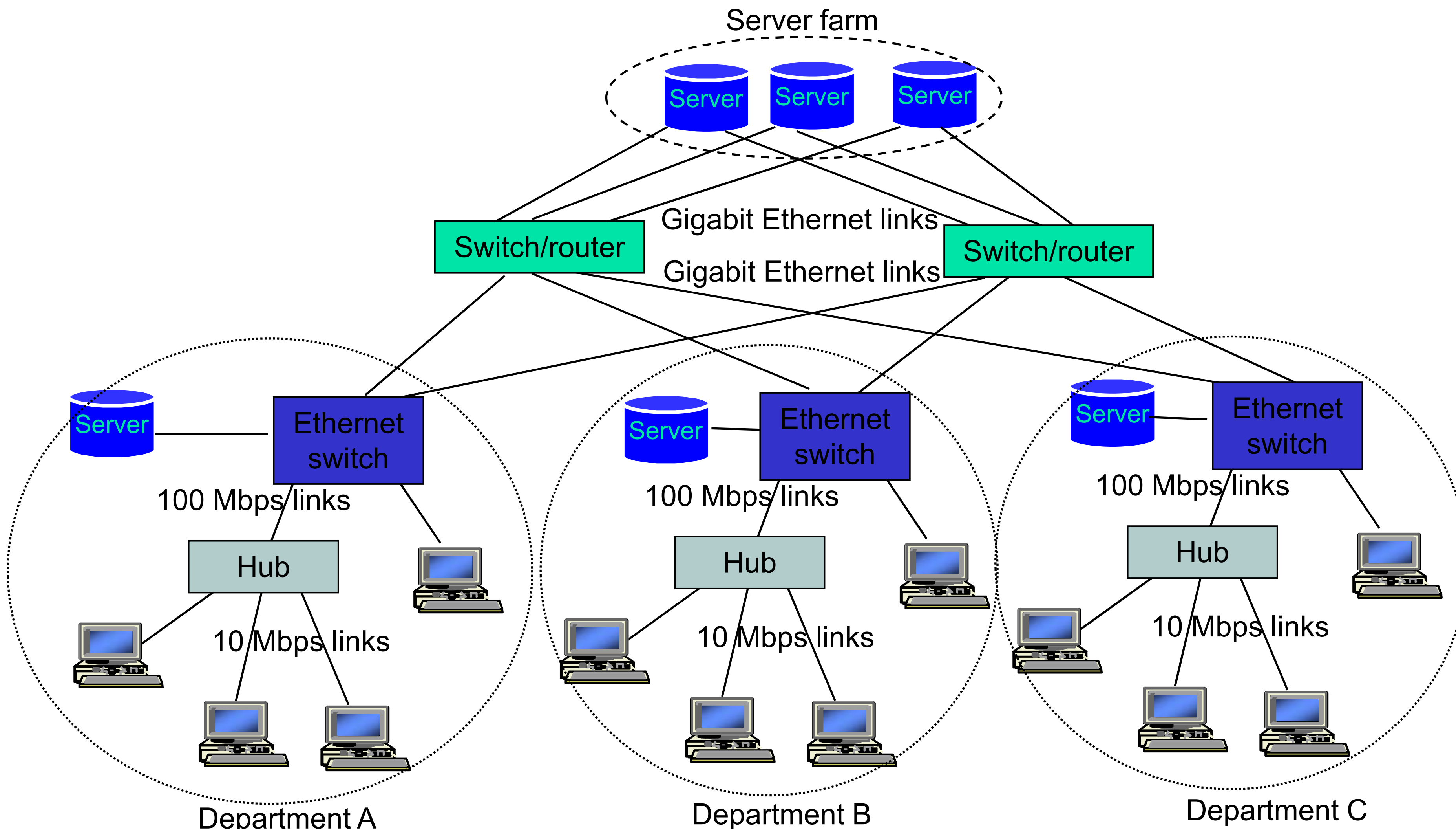
	100baseT4	**100baseT**	**100baseFX**
Medium	Twisted pair category 3 UTP 4 pairs	Twisted pair category 5 UTP two pairs	Optical fiber multimode Two strands
Max. Segment Length	100 m	100 m	2 km
Topology	Star	Star	Star

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

	1000baseSX	**1000baseLX**	**1000baseCX**	**1000baseT**
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

in final exam

ieee .11 standard group as a building block for wifi

- 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

    recently we have 6 GHz opening up for wifi use
- Targeted wireless LANs @ 20 Mbps
- MAC for high speed wireless LAN

  wifi certify on your device
  (not legal to sell non-certified)
- Ad Hoc & Infrastructure networks
- Variety of physical layers

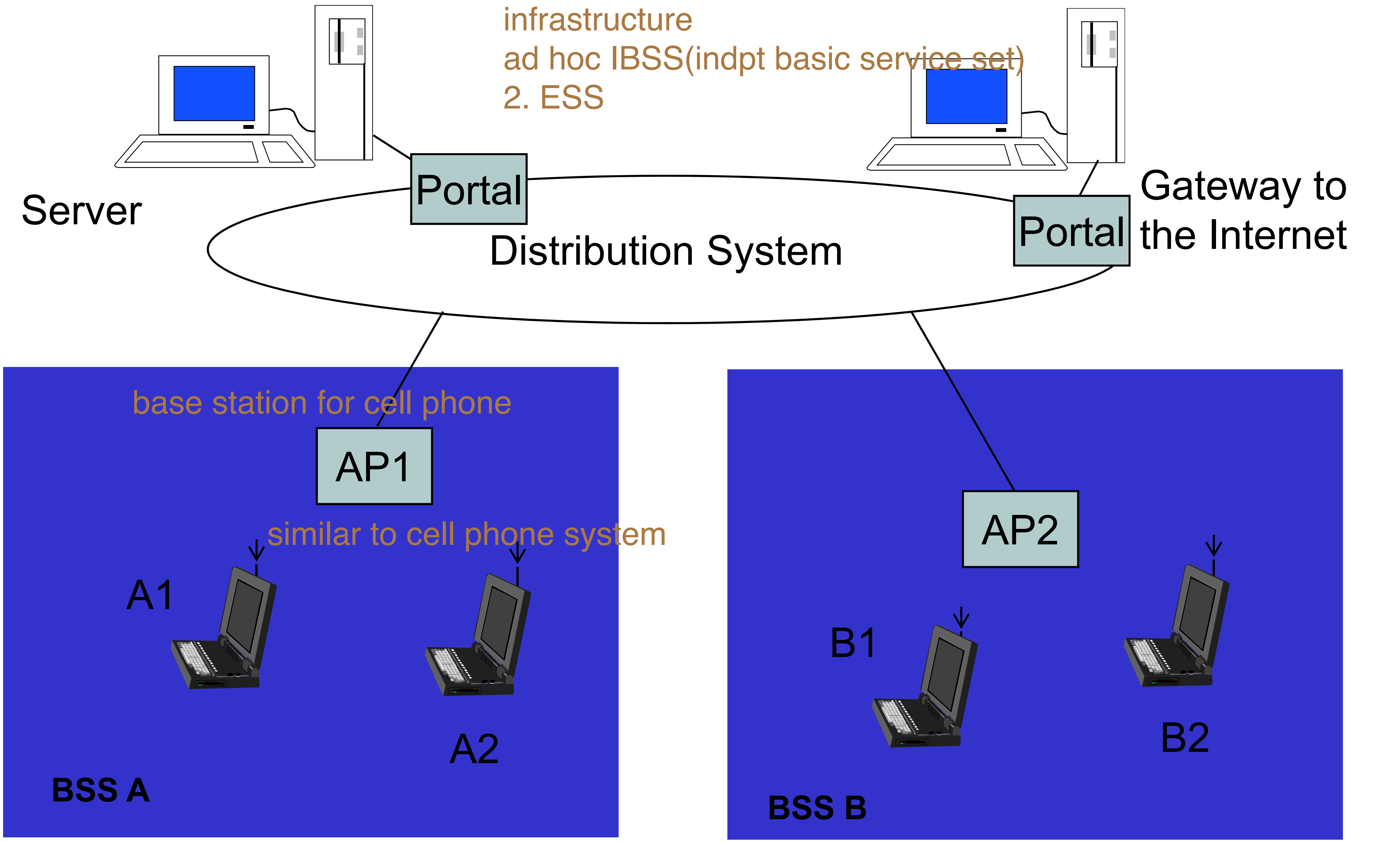
ISM no subscription, unlicensed, no need to buy for wifi, unlike 5g

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

2 modes for wifi:
1. BSS
infrastructure
ad hoc IBSS(indpt basic service set)
2. ESS

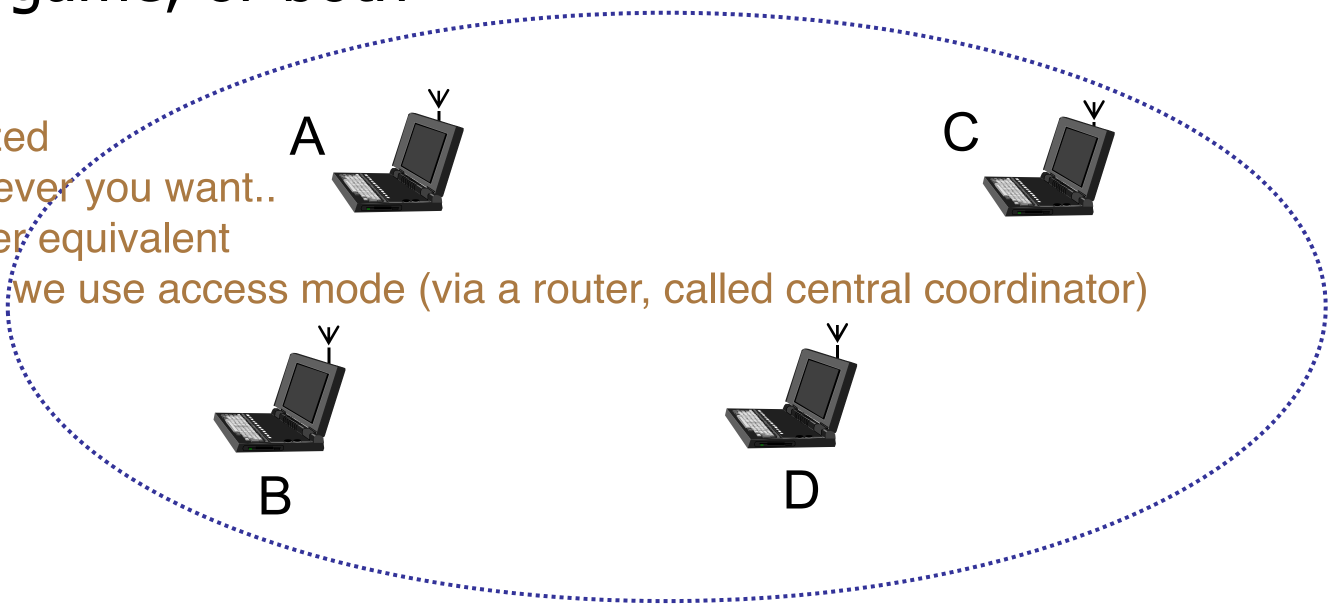


Ad Hoc Communications

set wifi at ad hoc mode to share among computers
if no internet available?

- 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

uncentralized
do it whenever you want..
peer to peer equivalent
but usually we use access mode (via a router, called central coordinator)



Distribution Services

- 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 and connect to one wifi through desktop

- 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

shift wifi network

- *Dissociation service* to terminate association
- *Authentication service* to establish identity of other stations

enter pw

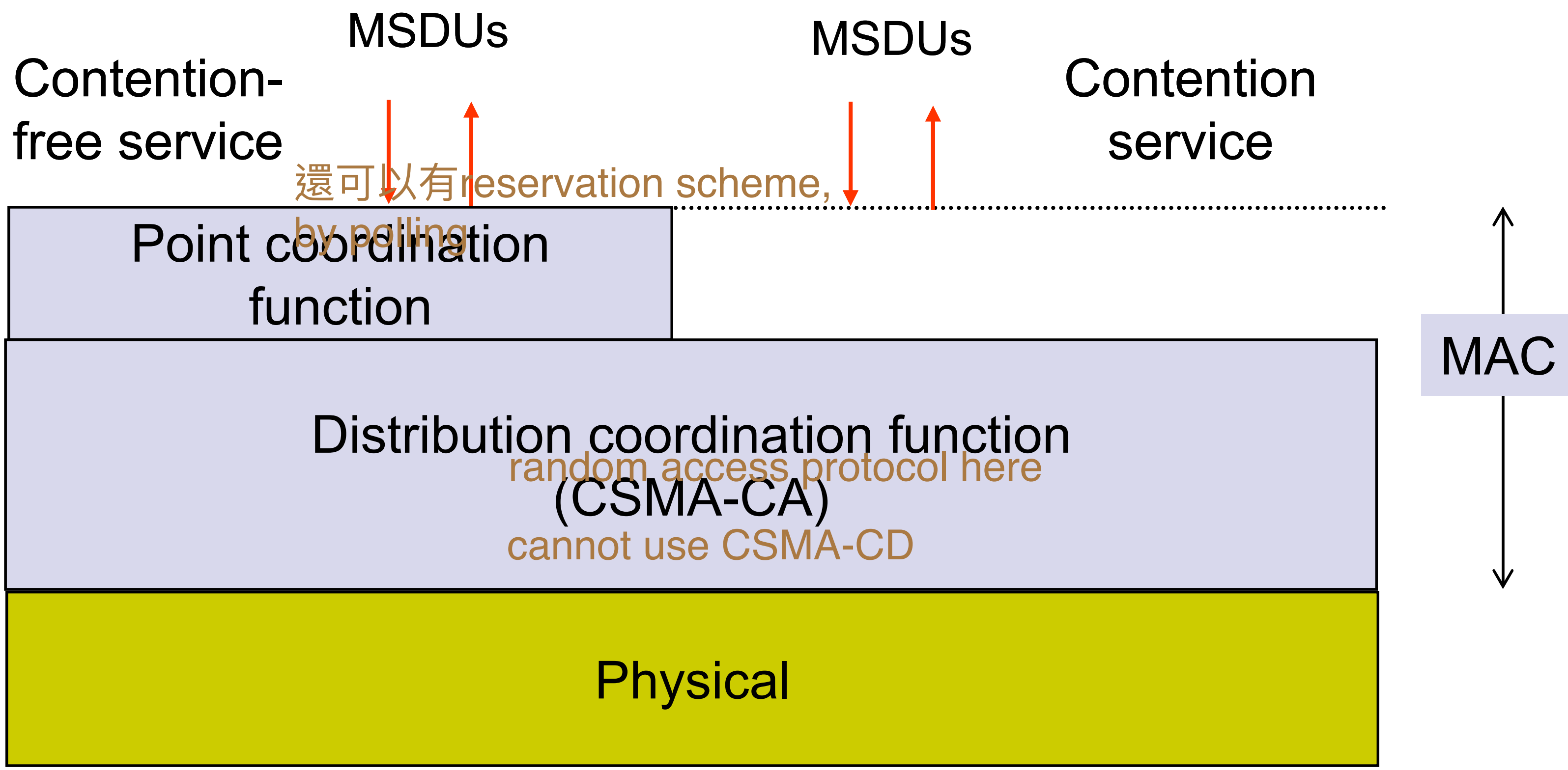
- *Privacy service* to keep contents secret

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

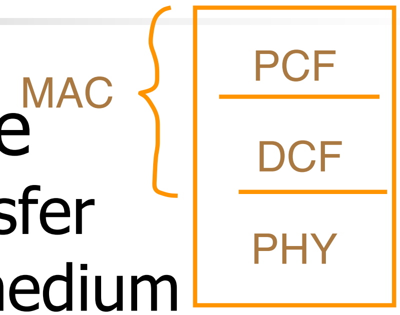
MAC Services

- 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)

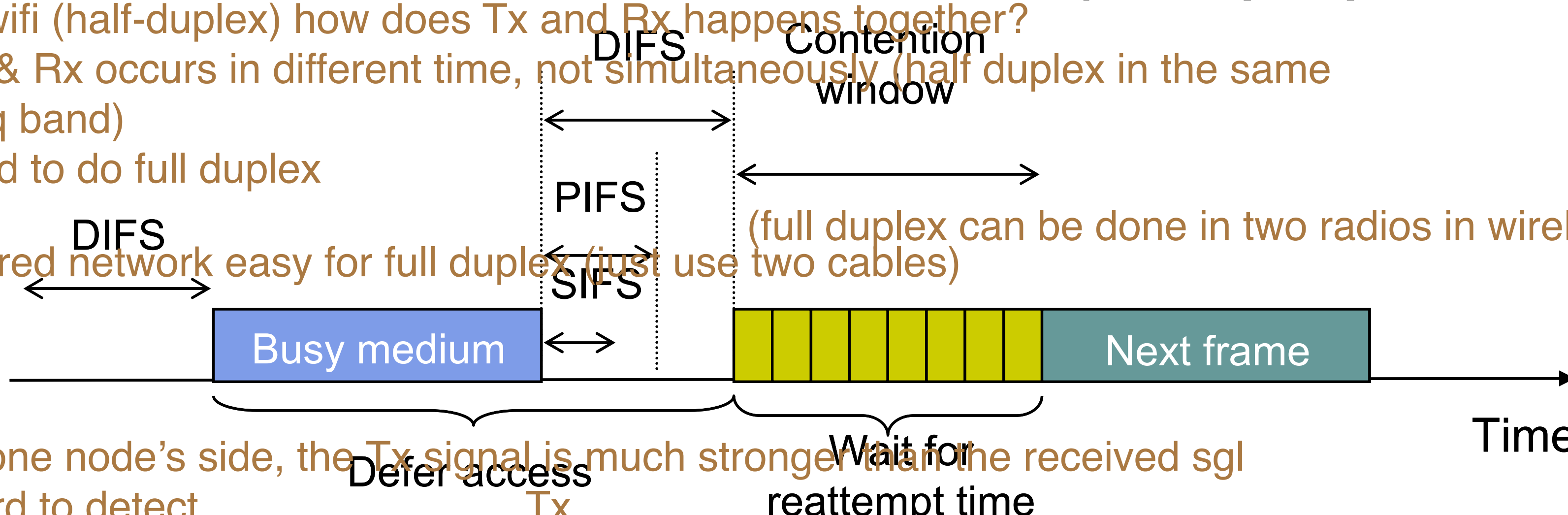
in MAC, we have
PCF (polling, built over DCF, which built over CSMA-CA)
and
DCF (CSMA-CA)



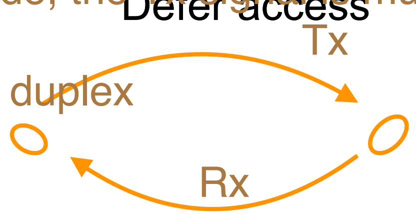
- DCF provides basic access service
  - Asynchronous best-effort data transfer
  - All stations contend for access to medium
- CSMA/CA
  - Ready stations wait for completion of transmission
  - All stations must wait *Interframe Space (IFS)*

duplex:
how does transmission and receiving comes together
in wifi (half-duplex) how does Tx and Rx happens together?
Tx & Rx occurs in different time, not simultaneously (half duplex in the same freq band)
hard to do full duplex

(full duplex can be done in two radios in wireless)
wired network easy for full duplex (just use two cables)



from one node's side, the Tx signal is much stronger than the received sgl
so hard to detect
so hard to impl full duplex



A station that is ready to send frames chooses a random number of slots as wait time.

Carrier Sensing in 802.11

2 tech needed for full duplex
1. self-interference cacellation (cancel the sgl that I send) hard to commercialize
2. high resolution ADC, too expensive
the Tx sgl is too strong and ADC has a limit resolution so hard to detect low power Rx (seemed to be ignored if Rx)

- *Physical Carrier Sensing*

physical carrier sensing especially in wired communication?

  - Analyze all detected frames

normally we cannot achieve full duplex

  - Monitor relative signal strength from other sources
- *Virtual Carrier Sensing* at MAC sublayer
  - Source stations informs other stations of transmission time (in μsec) 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

in half duplex, we cannot do detection (CD not possible in wireless)
cuz we cannot do hearing while sending

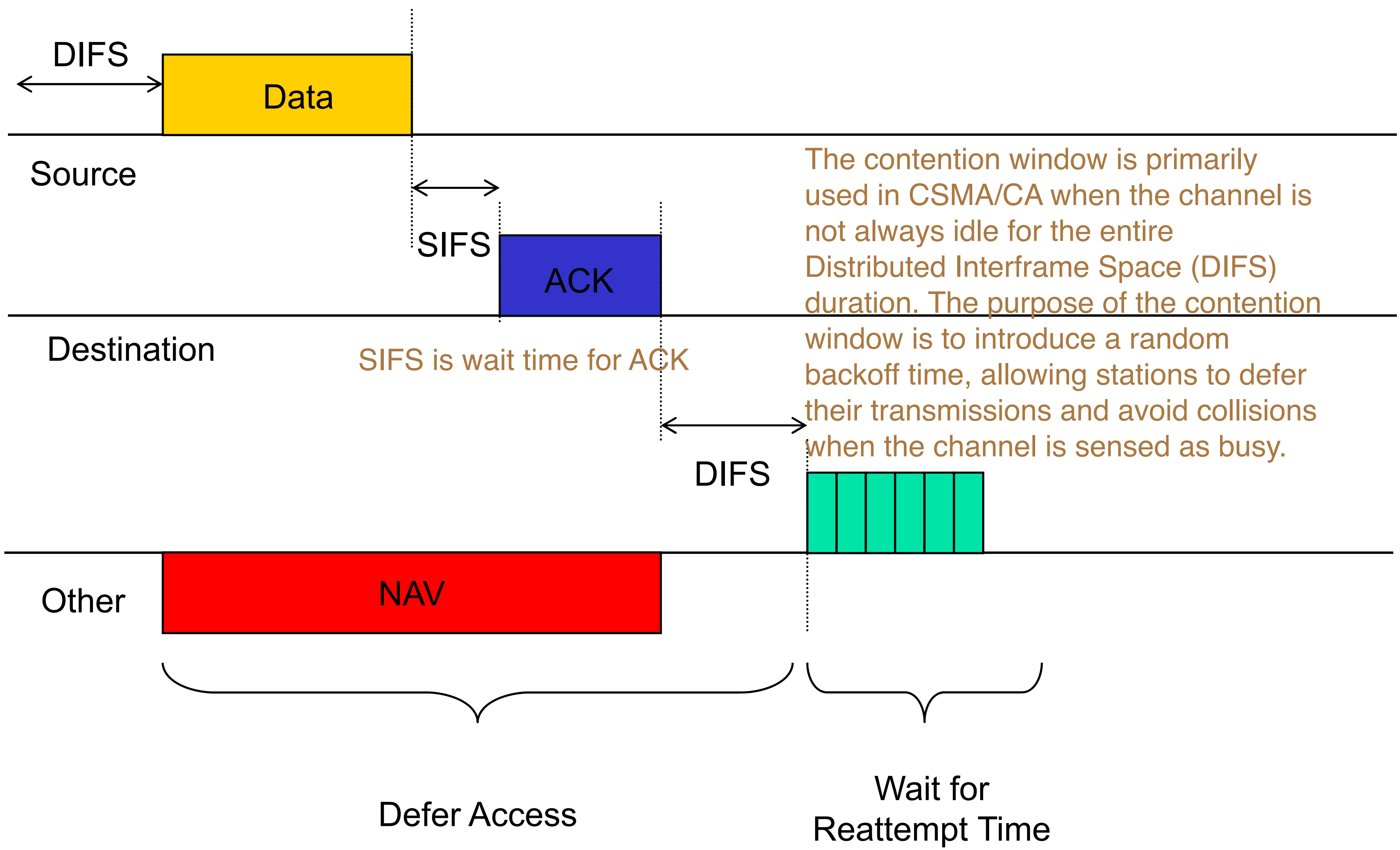
in wired network, we can do CD (hearing for collision while transimission)

Contention & Backoff Behavior

- If channel is still idle after DIFS period, ready station can transmit an *initial* MPDU MAC protocol data unit
- 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

Initially, when a station needs to transmit and senses the medium as idle during the Distributed Interframe Space (DIFS), it selects a random backoff time from within the contention window. If the medium remains idle for the entire backoff period, the station transmits its data. However, if the medium becomes busy again during the backoff time, the station freezes the backoff timer until the medium is idle once more. This process continues until the backoff timer expires and the station can transmit.

Transmission of MPDU without RTS/CTS

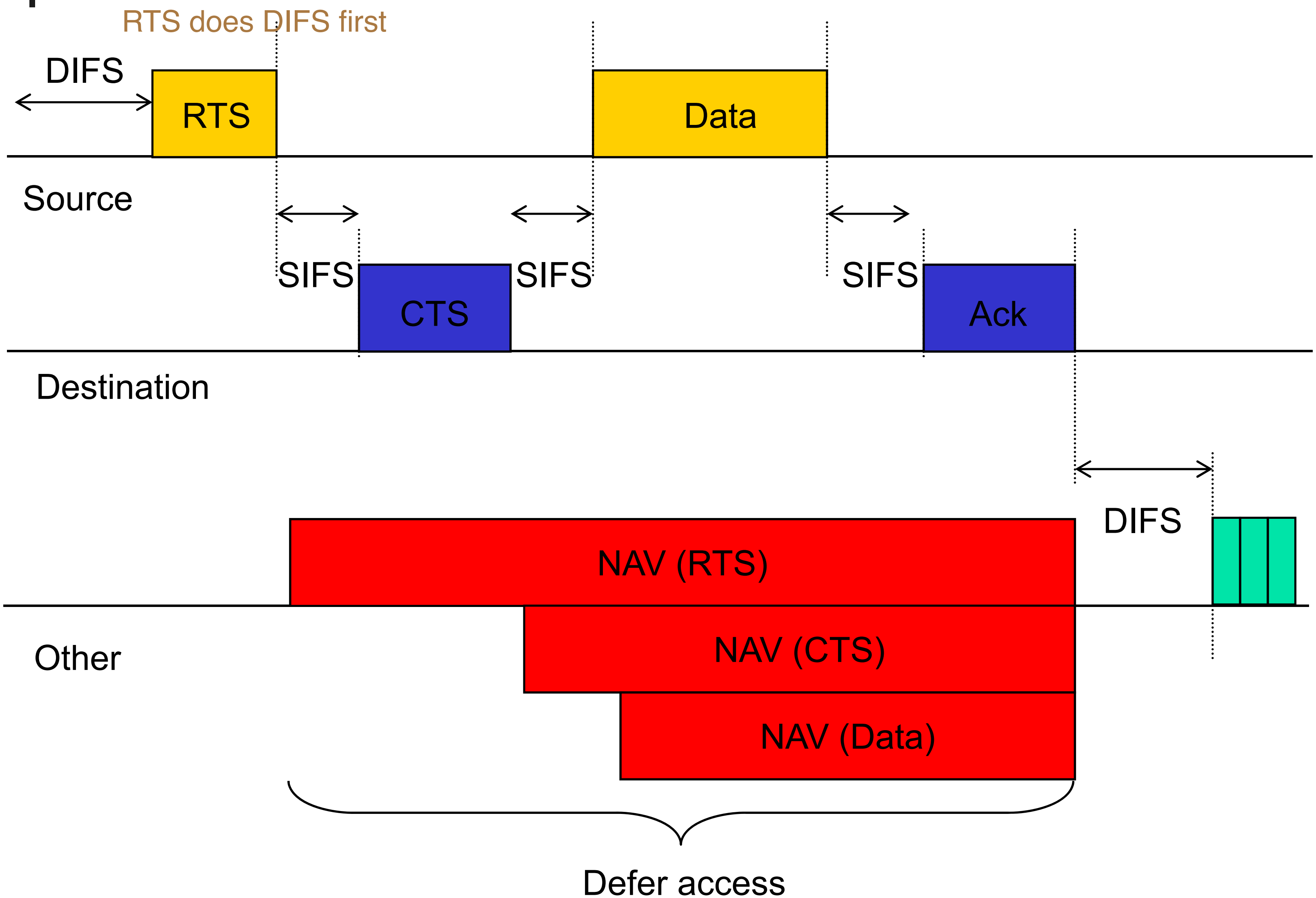


SIFS is wait time for ACK

The contention window is primarily used in CSMA/CA when the channel is not always idle for the entire Distributed Interframe Space (DIFS) duration. The purpose of the contention window is to introduce a random backoff time, allowing stations to defer their transmissions and avoid collisions when the channel is sensed as busy.

backoff time before reattempt to transmit

Transmission of MPDU with RTS/CTS

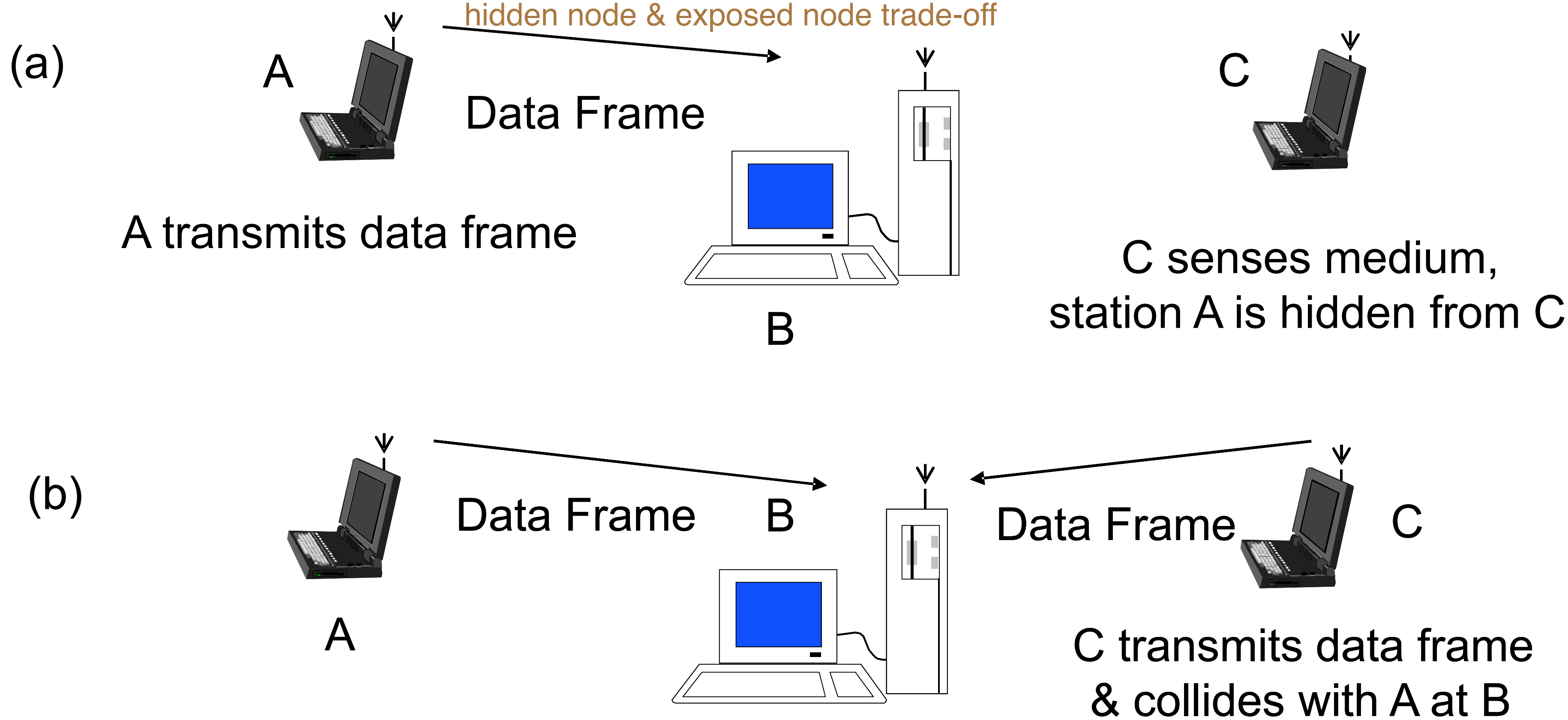


Collisions, Losses & Errors

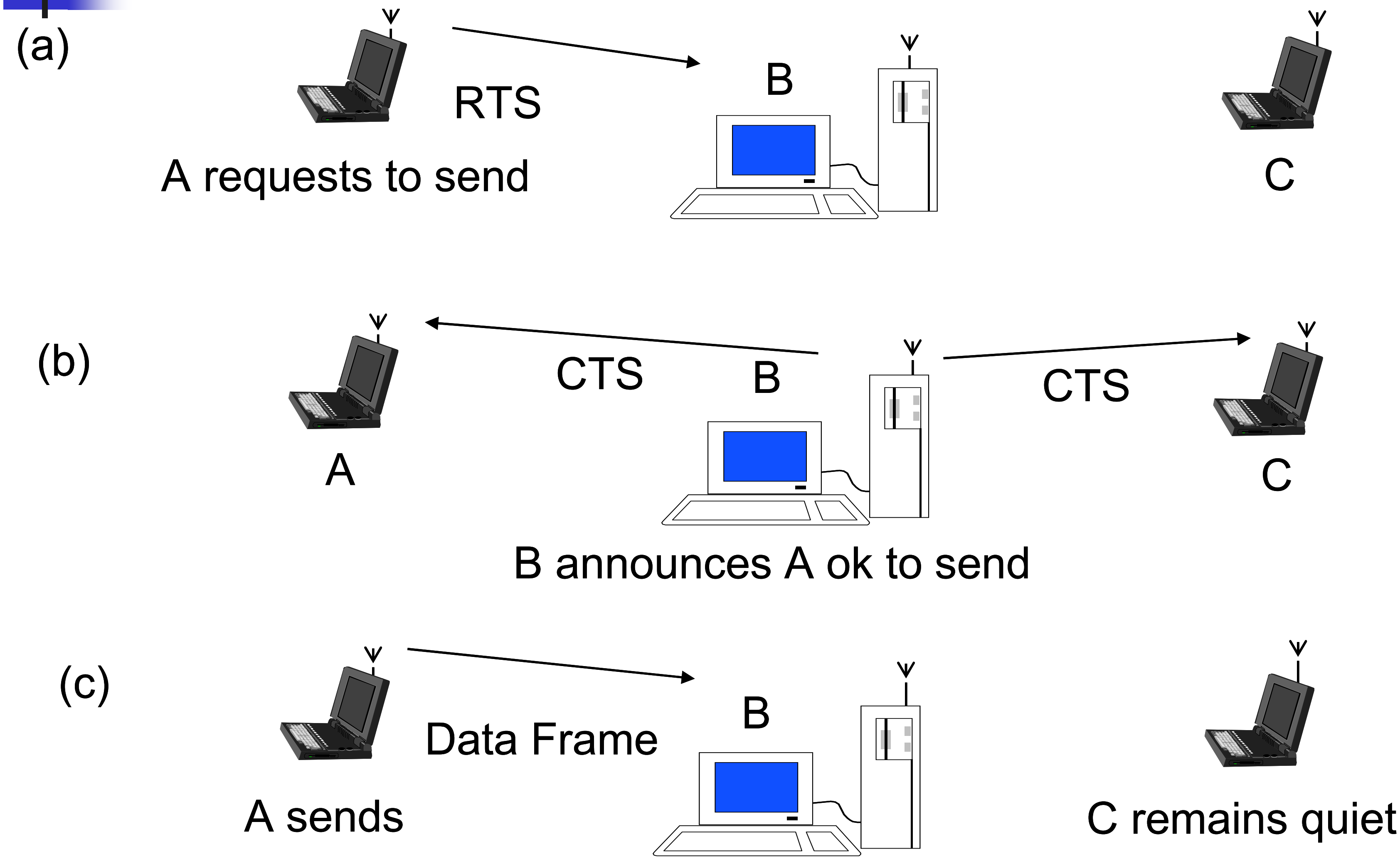
- Collision Avoidance
  - When station senses channel busy, it waits until channel becomes idle for DIFS period & then begins random backoff time (in units of idle slots)
  - Station transmits frame when backoff timer expires
  - If collision occurs, recompute backoff over interval that is twice as long
  - *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

应该是A和C太远了,
不是A被B挡住了
hidden node & exposed node trade-off



Collision avoidance and virtual carrier sensing

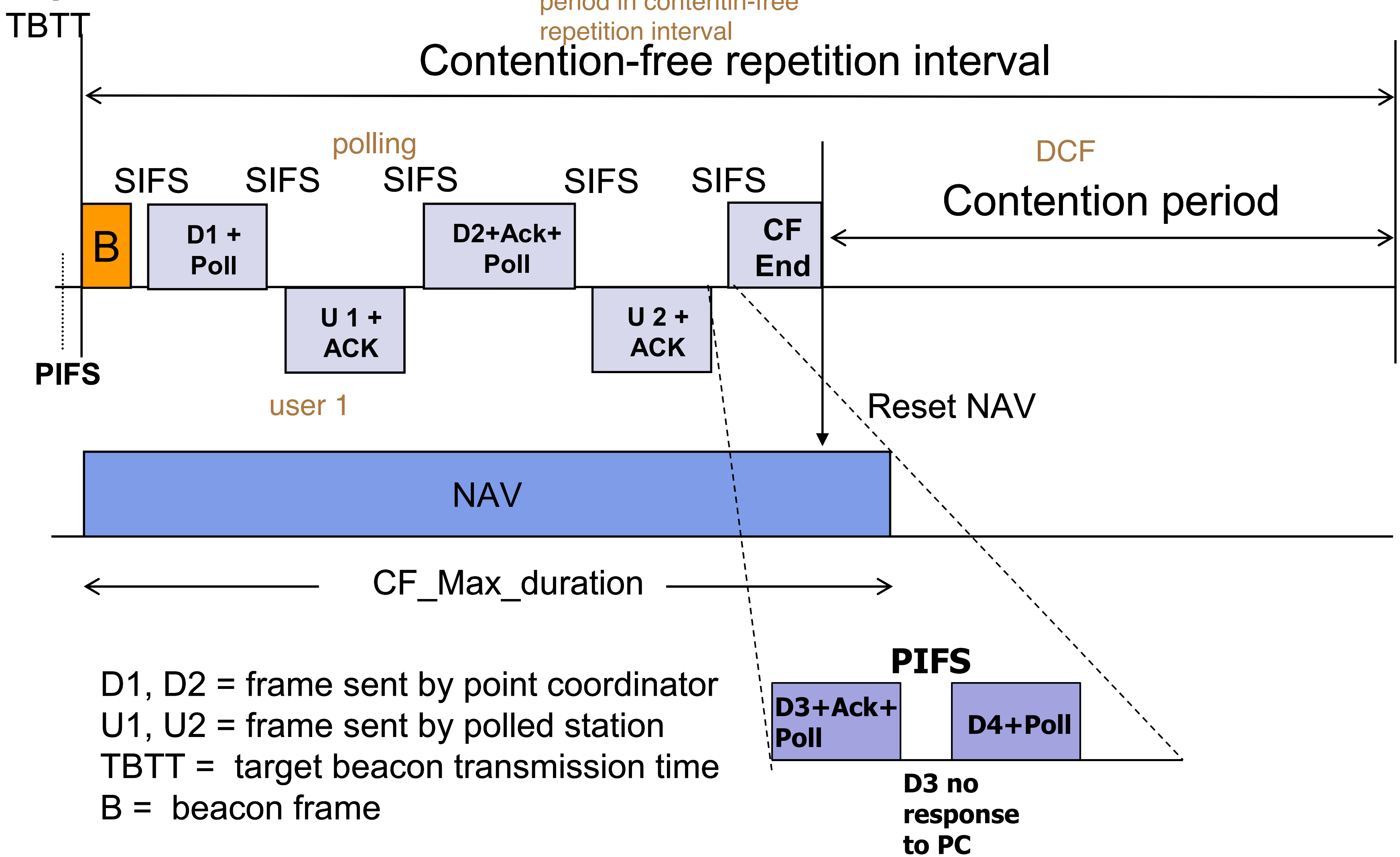


Point Coordination Function

- 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

why there's contention
period in contentin-free
repetition interval



D1, D2 = frame sent by point coordinator
U1, U2 = frame sent by polled station
TBTT = target beacon transmission time
B = beacon frame

going for many users

Frame Types

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

Frame Structure

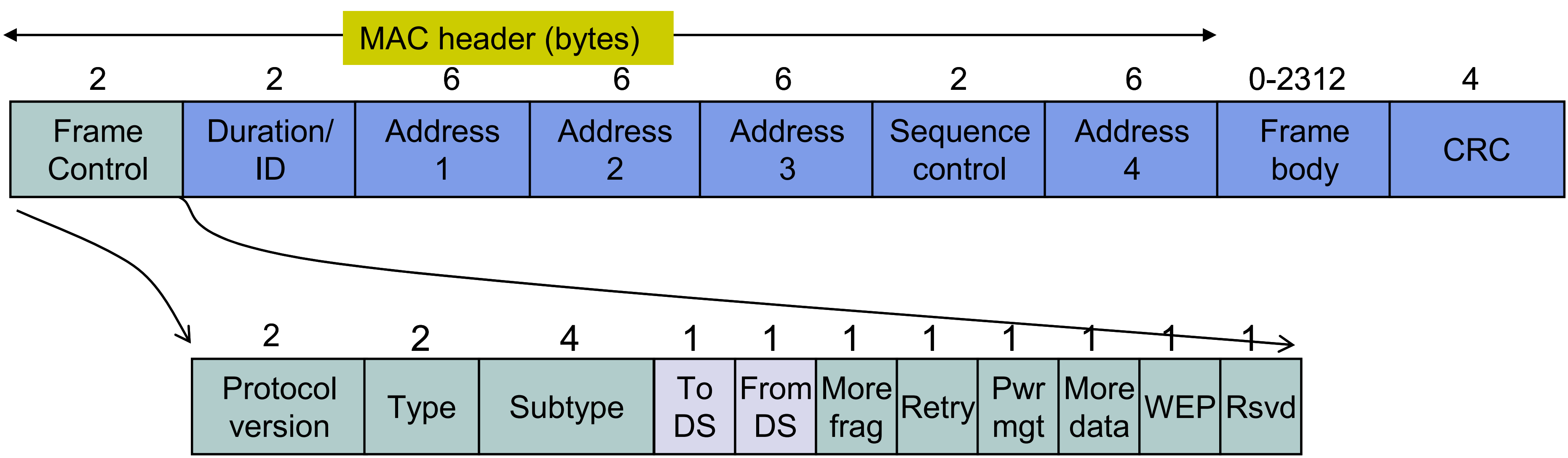
- MAC Header: 30 bytes
- Frame Body: 0-2312 bytes
- CRC: CCITT-32 4 bytes CRC over MAC header & frame body

MAC header (bytes)

2	2	6	6	6	2	6	0-2312	4
Frame Control	Duration/ ID	Address 1	Address 2	Address 3	Sequence control	Address 4	Frame body	CRC

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)

Frame Control	Duration/ ID	Address 1	Address 2	Address 3	Sequence control	Address 4	Frame body	CRC
2	2	6	6	6	2	6	0-2312	4

Protocol version	Type	Subtype	To DS	From DS	More frag	Retry	Pwr mgt	More data	WEP	Rsvd
2	2	4	1	1	1	1	1	1	1	1

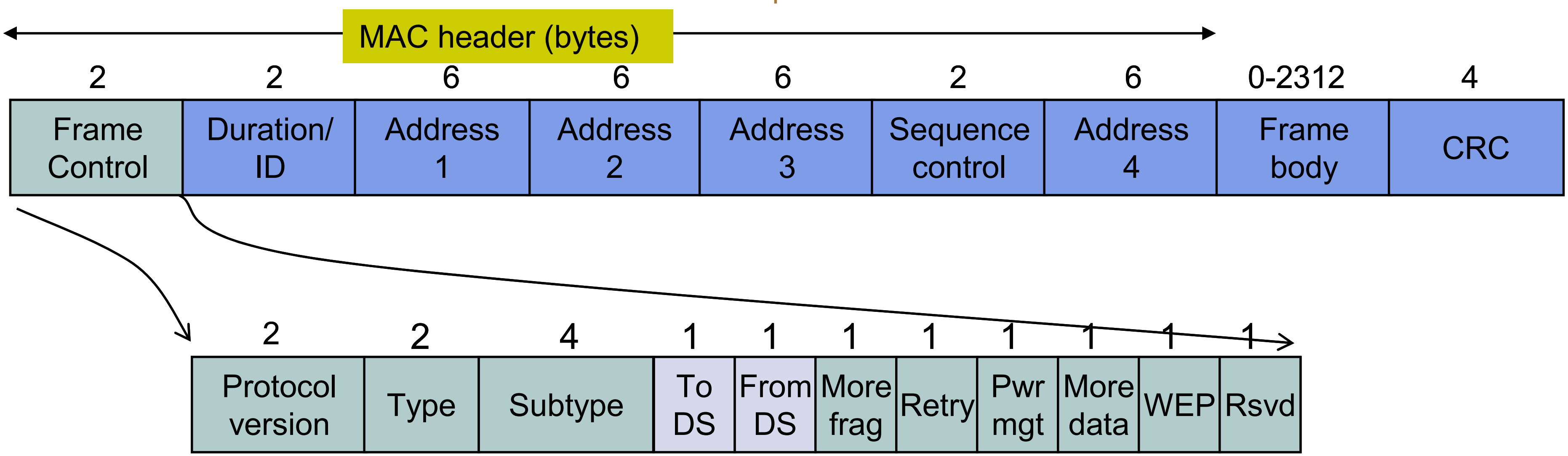
To DS	From DS	Address 1	Address 2	Address 3	Address 4	Meaning
0	0	Destination address	Source address	BSSID	N/A	Data frame from station to station within a BSS
0	1	Destination address	BSSID	Source address	N/A	Data frame exiting the DS
1	0	BSSID	Source address	Destination address	N/A	Data frame destined for the DS
1	1	Receiver address	Transmitter address	Destination address	Source address	WDS frame being distributed from AP to AP

To DS = 1 if frame goes to DS; From DS = 1 if frame exiting DS

Frame Control (3)

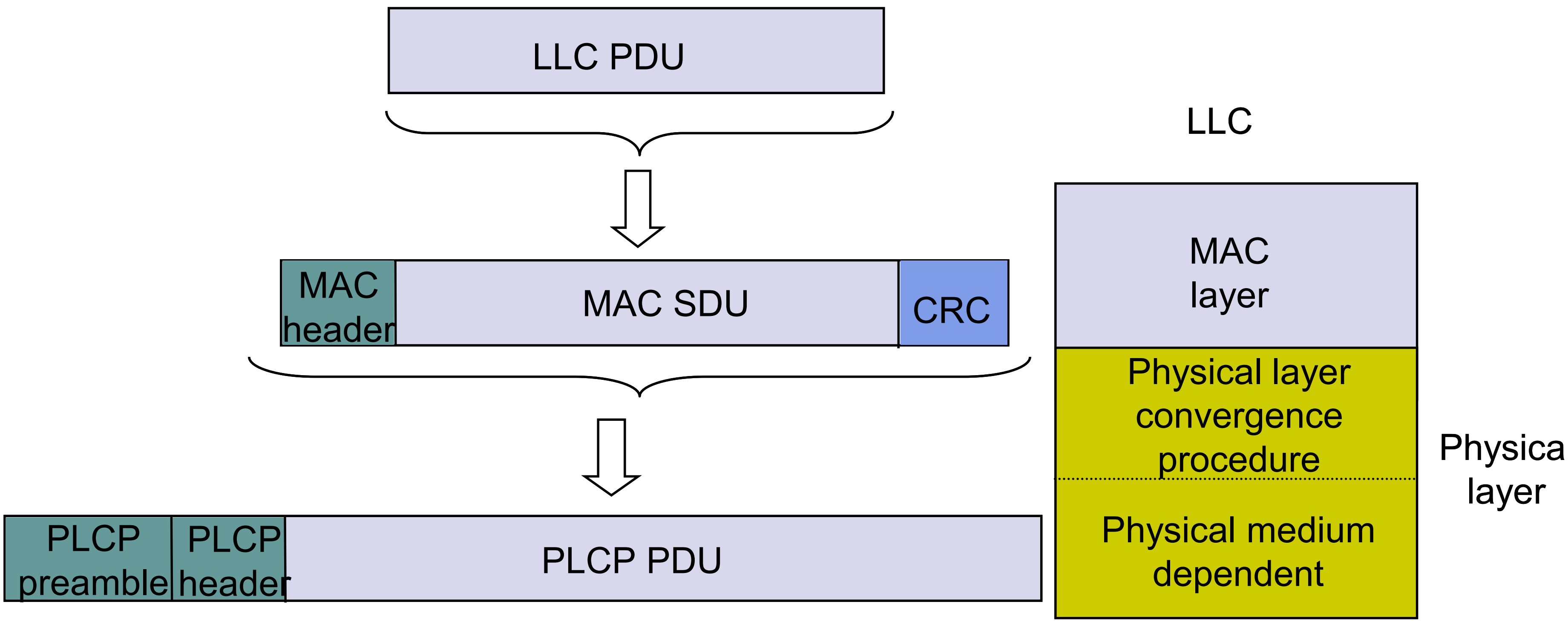
- Retry=1 if a data/management frame is a retransmission
- Power Management used to put station in/out of sleep mode
- More Data =1 to tell station in power-save mode more data buffered for it at AP
- WEP=1 if frame body encrypted

slotted aloha
csma-cd ca
bridging
2 questions for the exam
impt



802.11 protocol layers

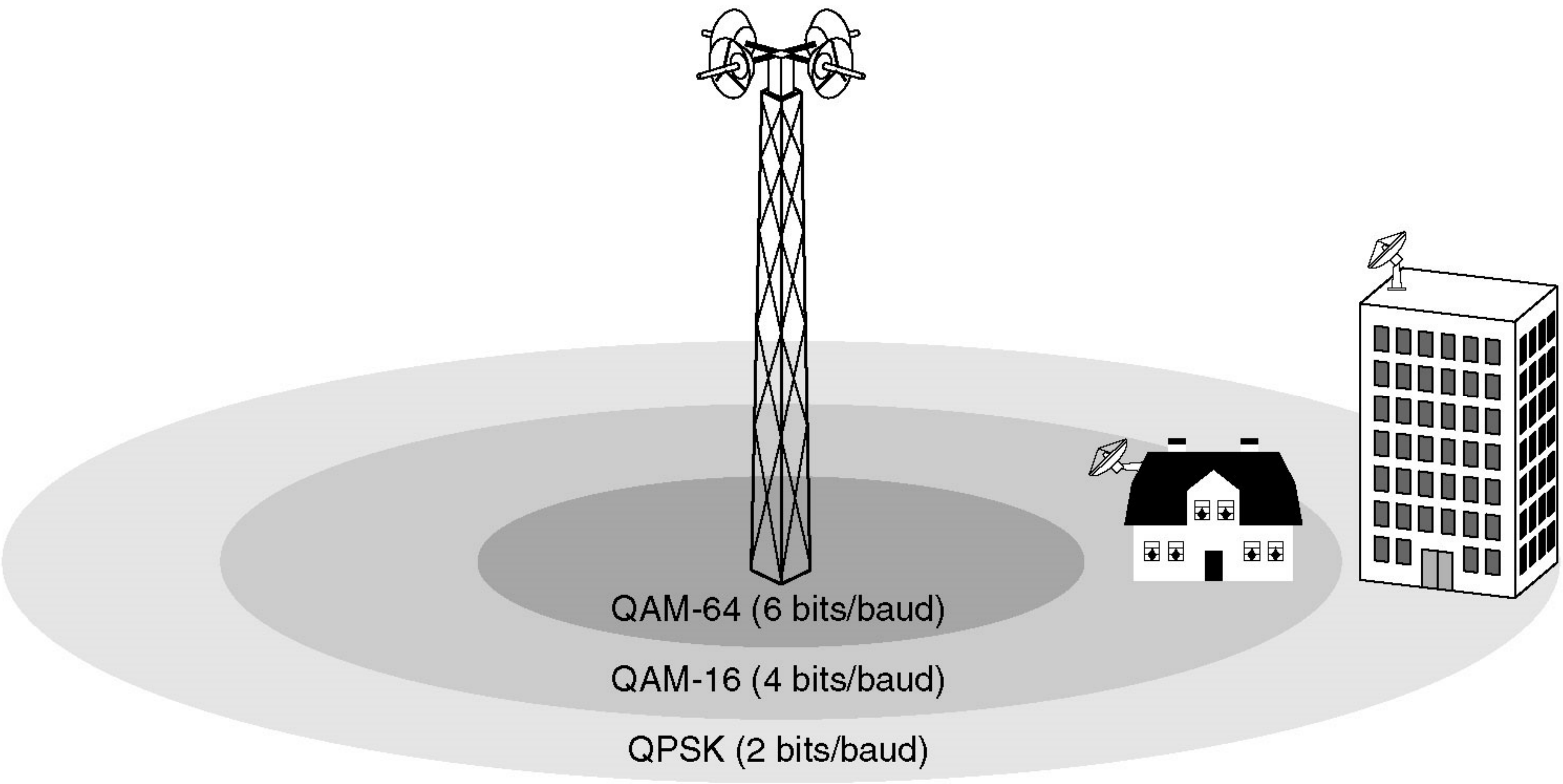
- 802.11 designed to
  - Support LLC
  - Operate over many physical layers



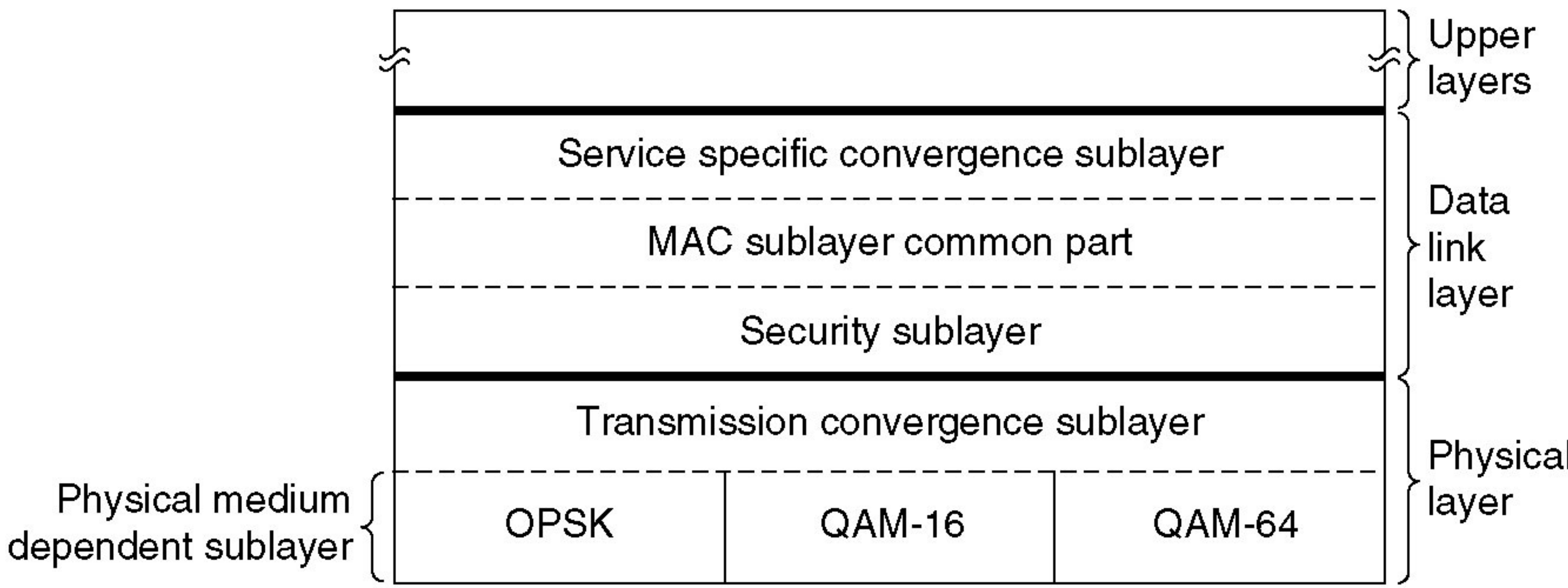
802.11 Phy options

	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

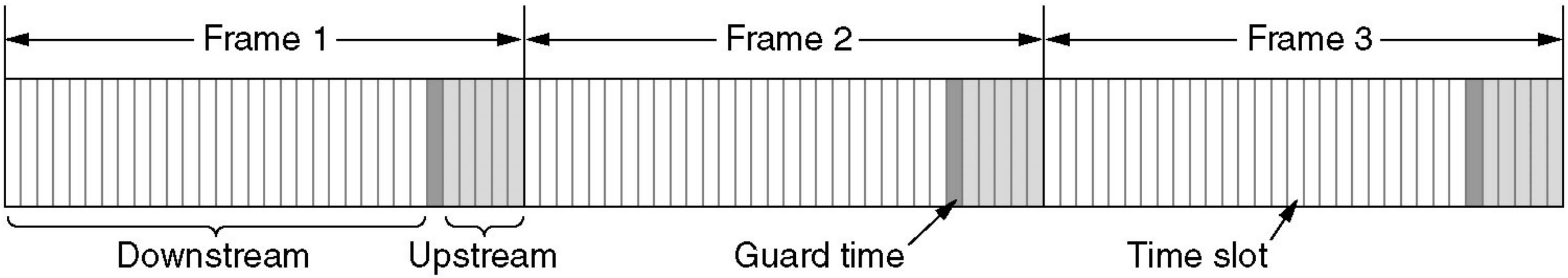


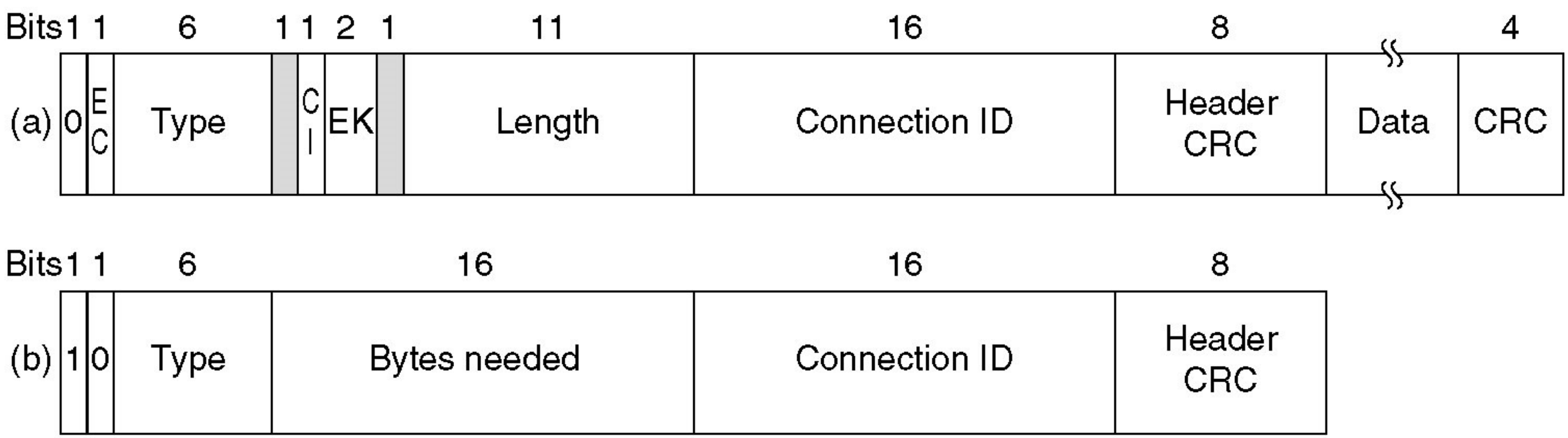
802.16 Protocol Stack



Services and Frame Structure

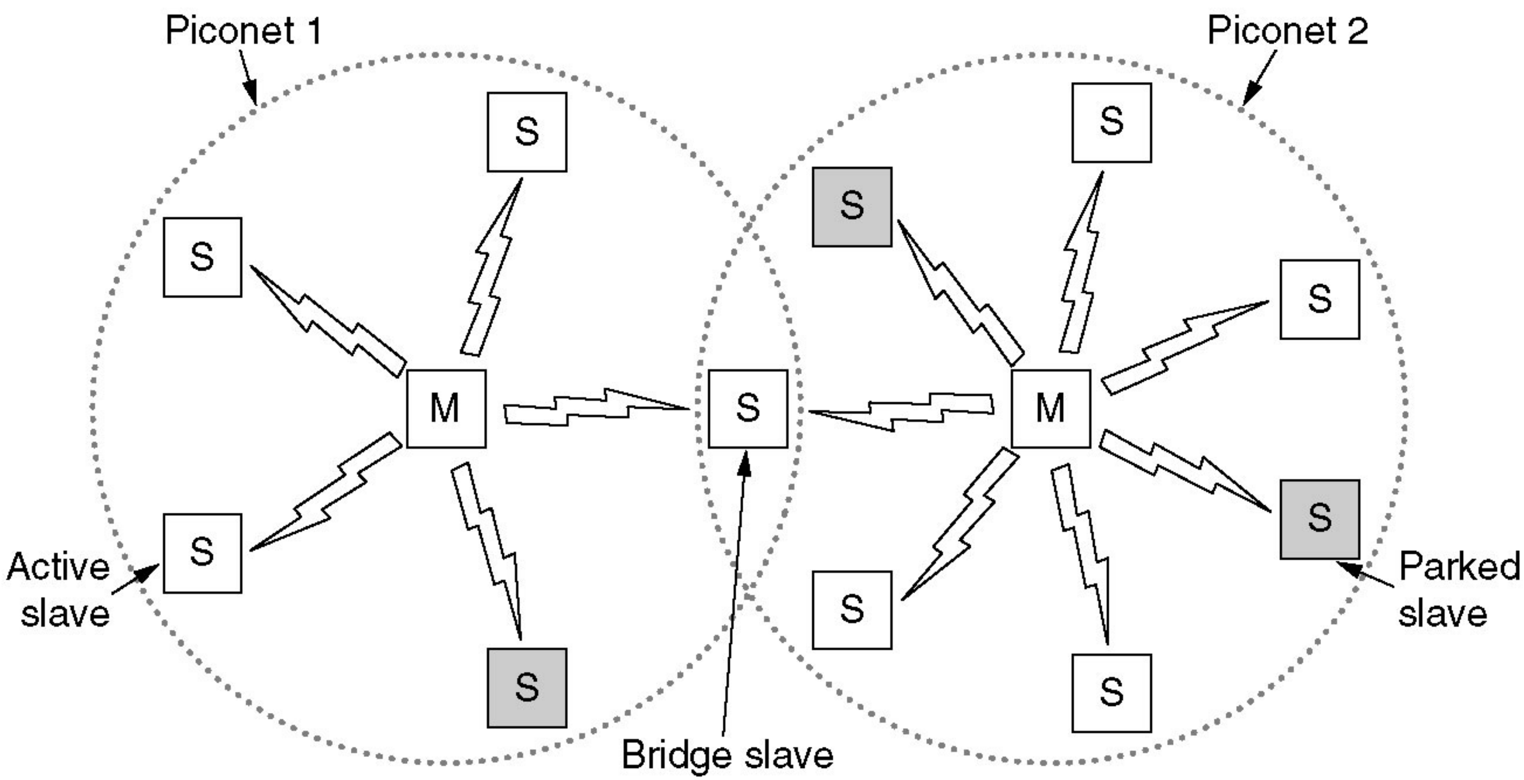
- Constant bit rate service
- Real-time variable bit rate service
- Non-real-time variable bit rate service
- Best efforts service



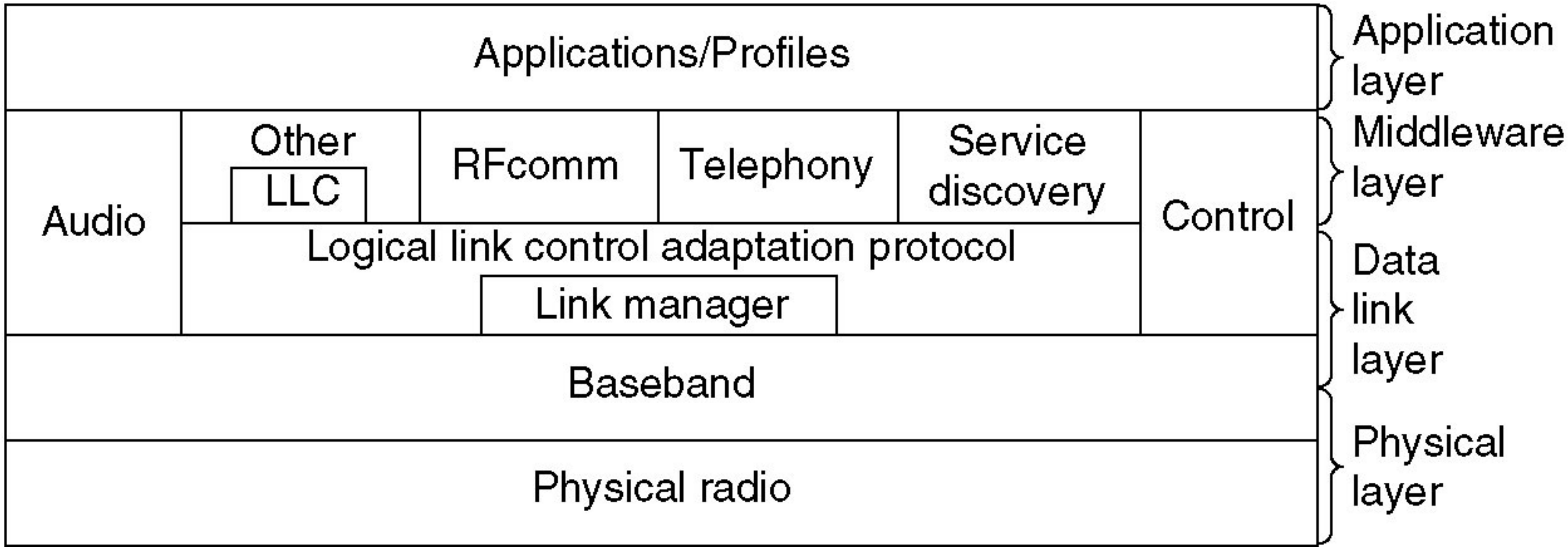


(a) A generic frame. (b) A bandwidth request frame.

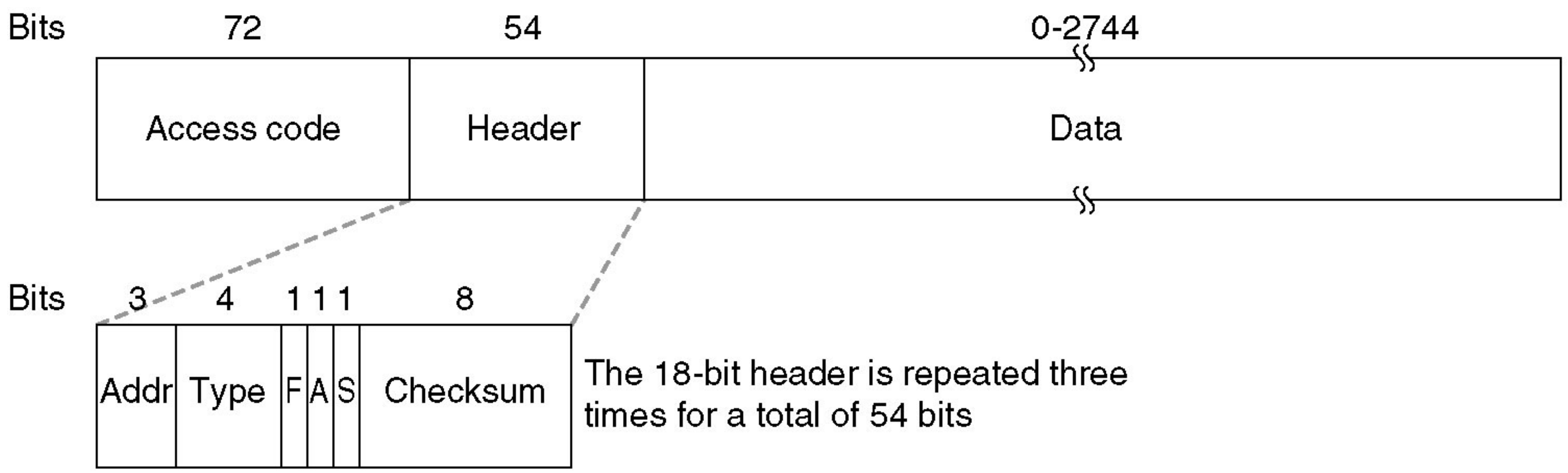
Bluetooth


Piconet 1
Piconet 2
S
S
S
M
S
M
S
S
S
S
S
S
S
S
Active
slave
Parked
slave
Bridge slave

Bluetooth Protocol Stack



Bluetooth Frame Structure



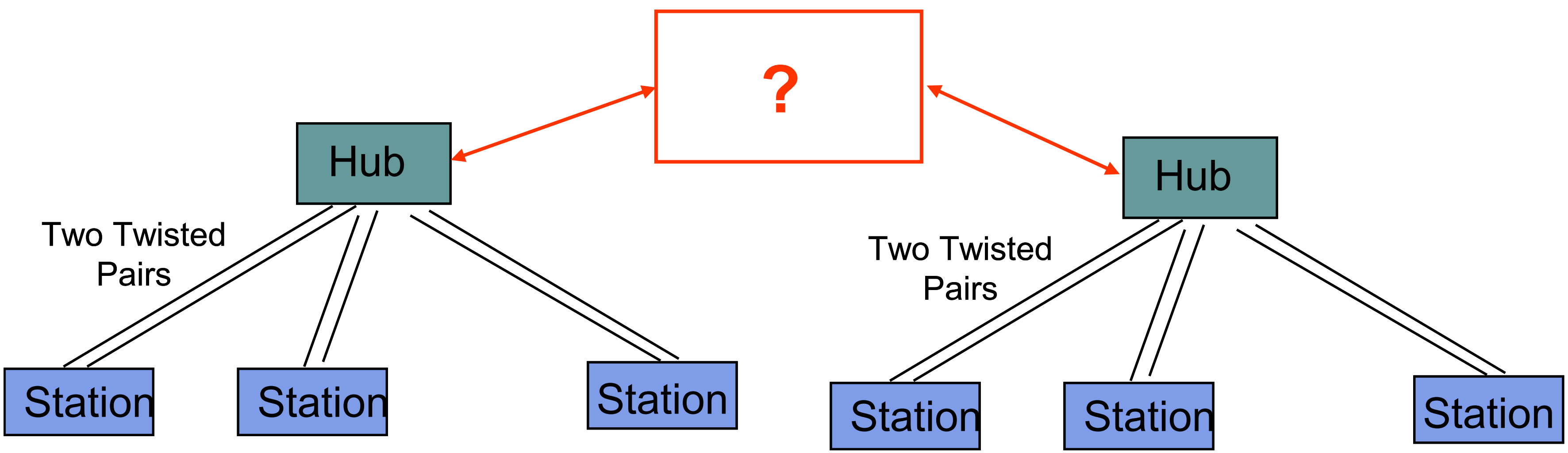
BSS, ESS are all WLAN, which are within one LAN
so bridges, switches and hubs can be used in one LAN

Bridging and Switching

Hubs, Bridges & Routers

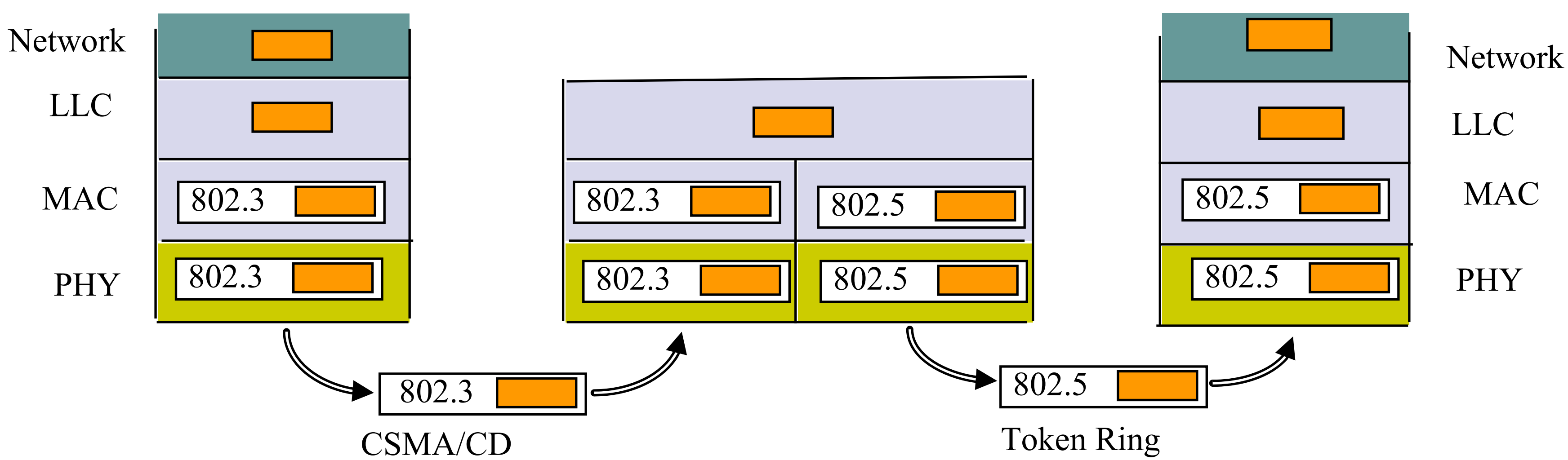
hubs simply broadcast packets to all connected devices, switches intelligently forward packets based on MAC addresses, and bridges connect different network segments. Switches are the most commonly used devices today due to their advanced features and better network performance.

- 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

- 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

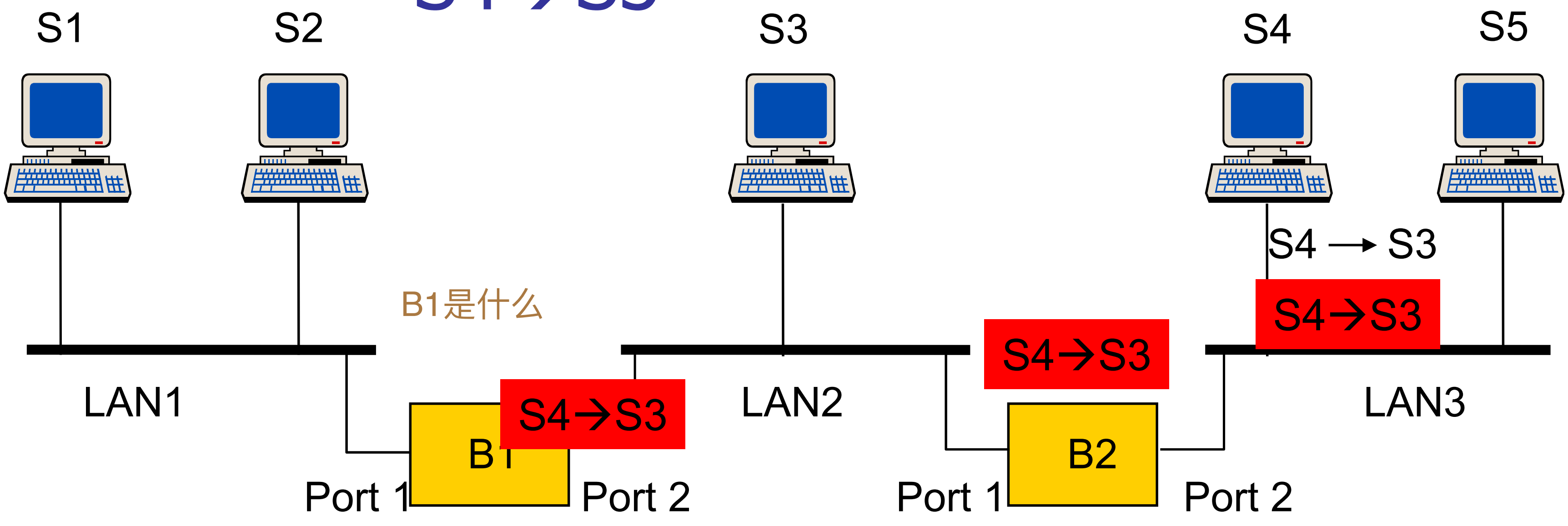
In reality, bridges are primarily used within a single LAN or network segment to connect devices together. They extend the reach of a LAN by interconnecting different network segments, allowing devices within those segments to communicate with each other.

Bridging refers to the process of forwarding data packets between two or more network segments or LANs at the data link layer (Layer 2) of the network protocol stack. A bridge is a networking device that connects these segments together, allowing them to operate as a single logical network. Bridges operate based on MAC addresses.

Bridges can be used to connect different LANs and make them appear as a single logical LAN. This is achieved through a technique called bridging, which allows

Example: Basic learning procedures

S4→S3



Address	Port
S1	1
S3	2
S4	2

Address	Port
S1	1
S3	1
S4	2

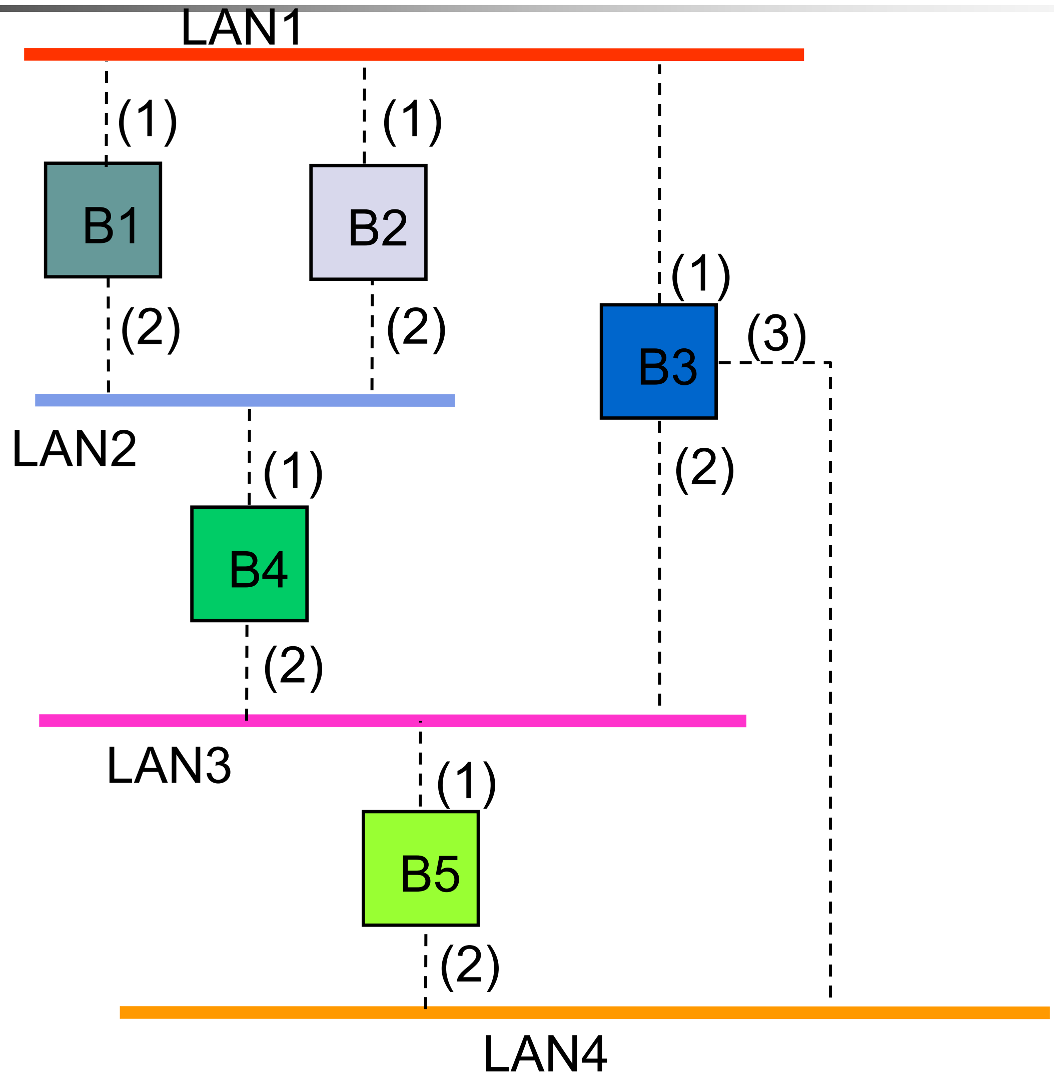
Adaptive Learning

- 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

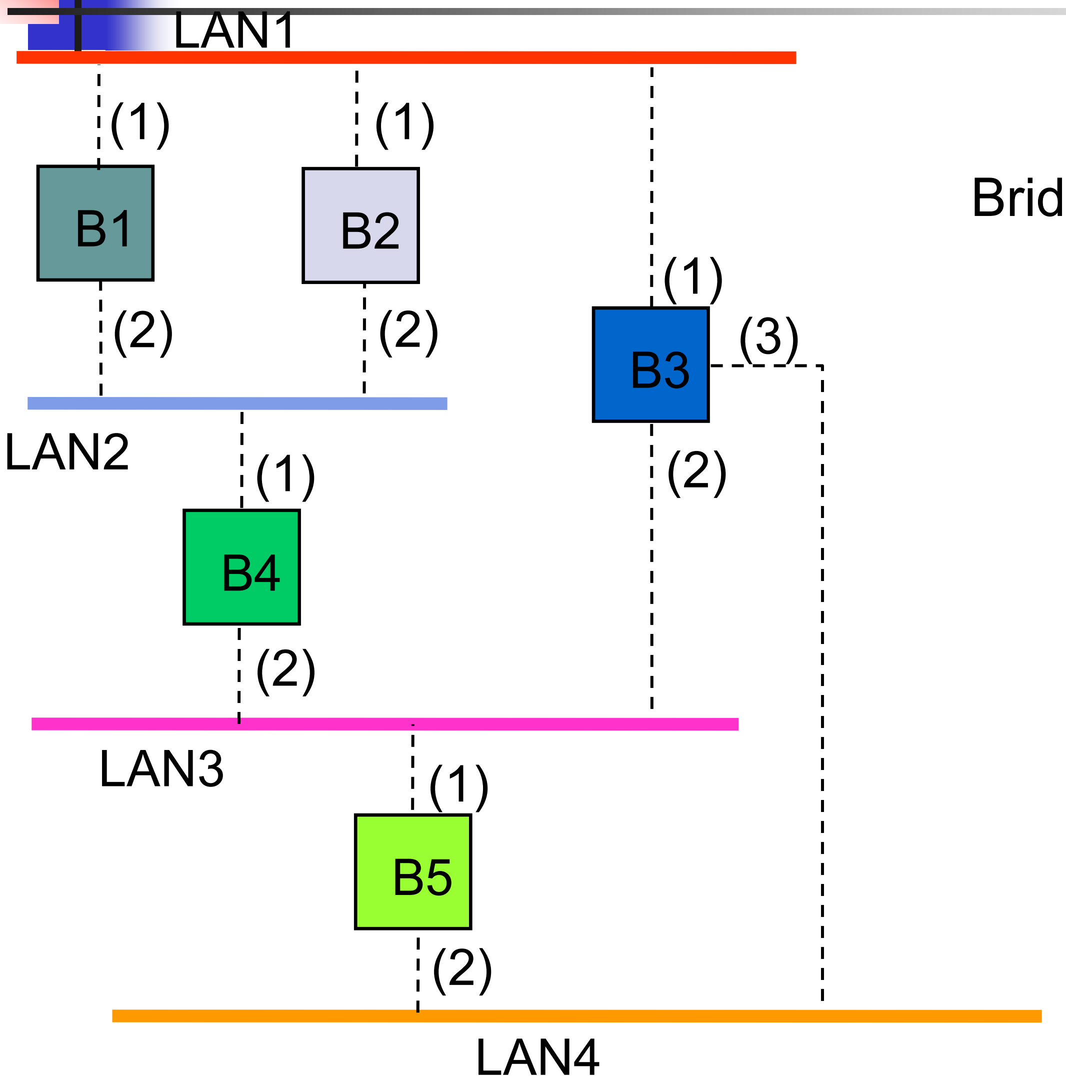
Spanning Tree Algorithm

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)

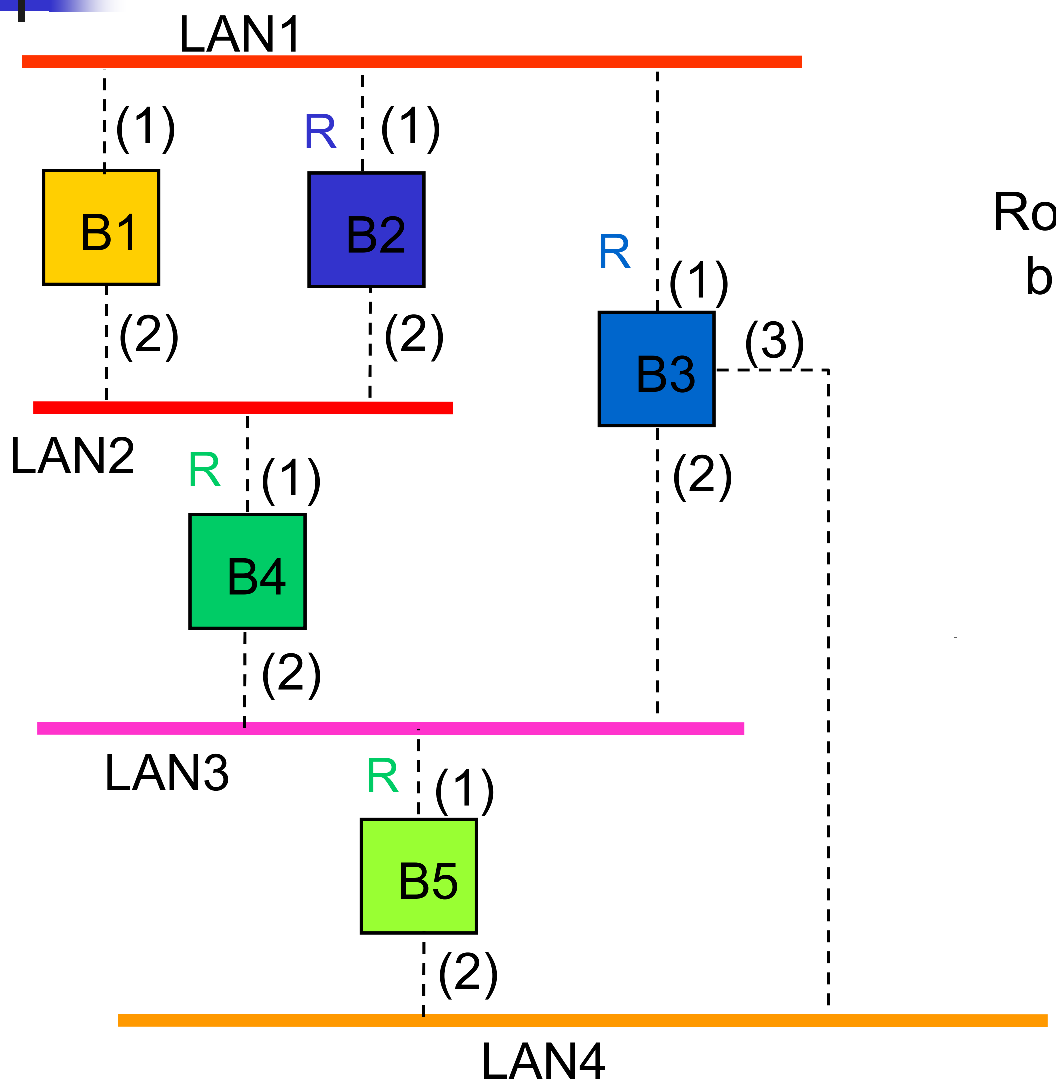


Example (2)



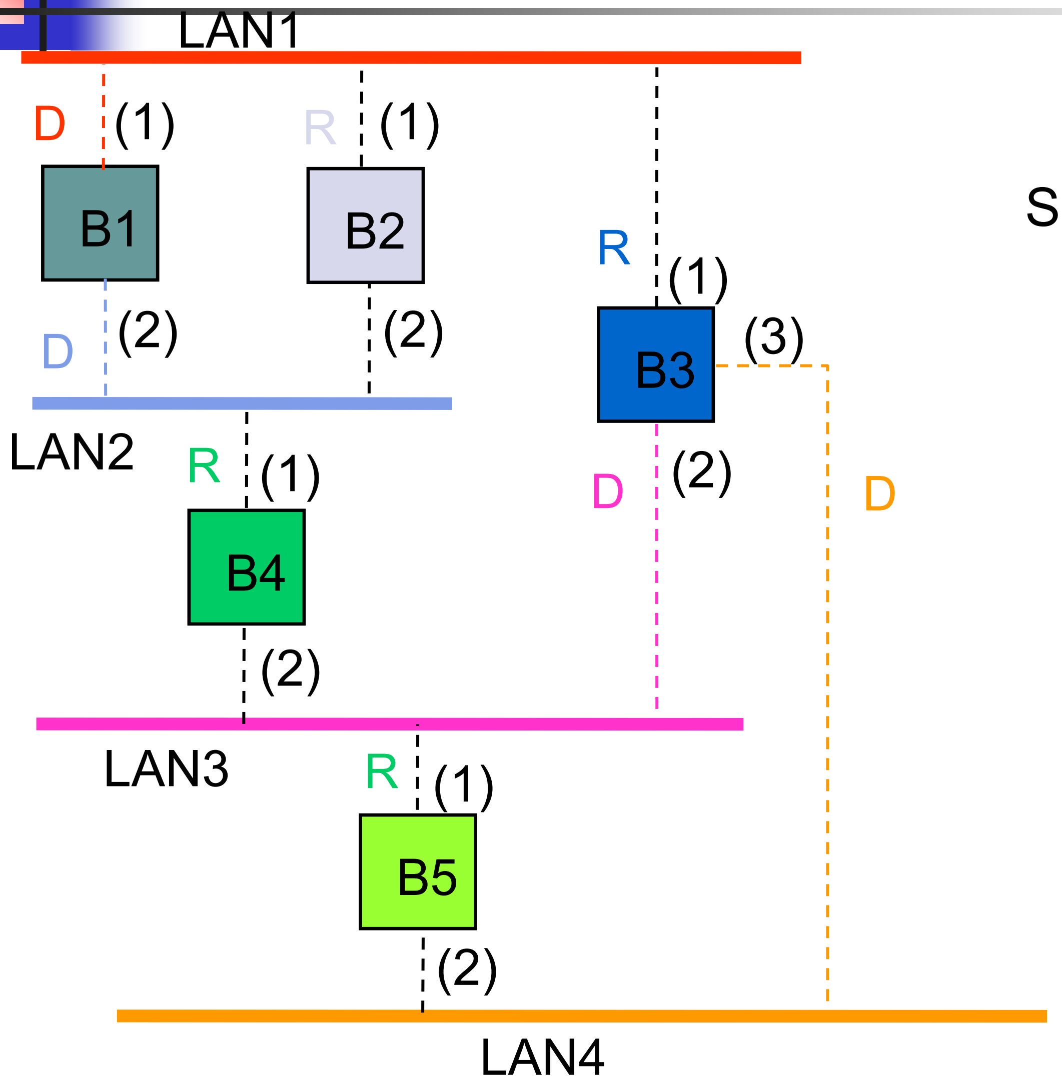
Bridge 1 selected as root bridge

Example (3)



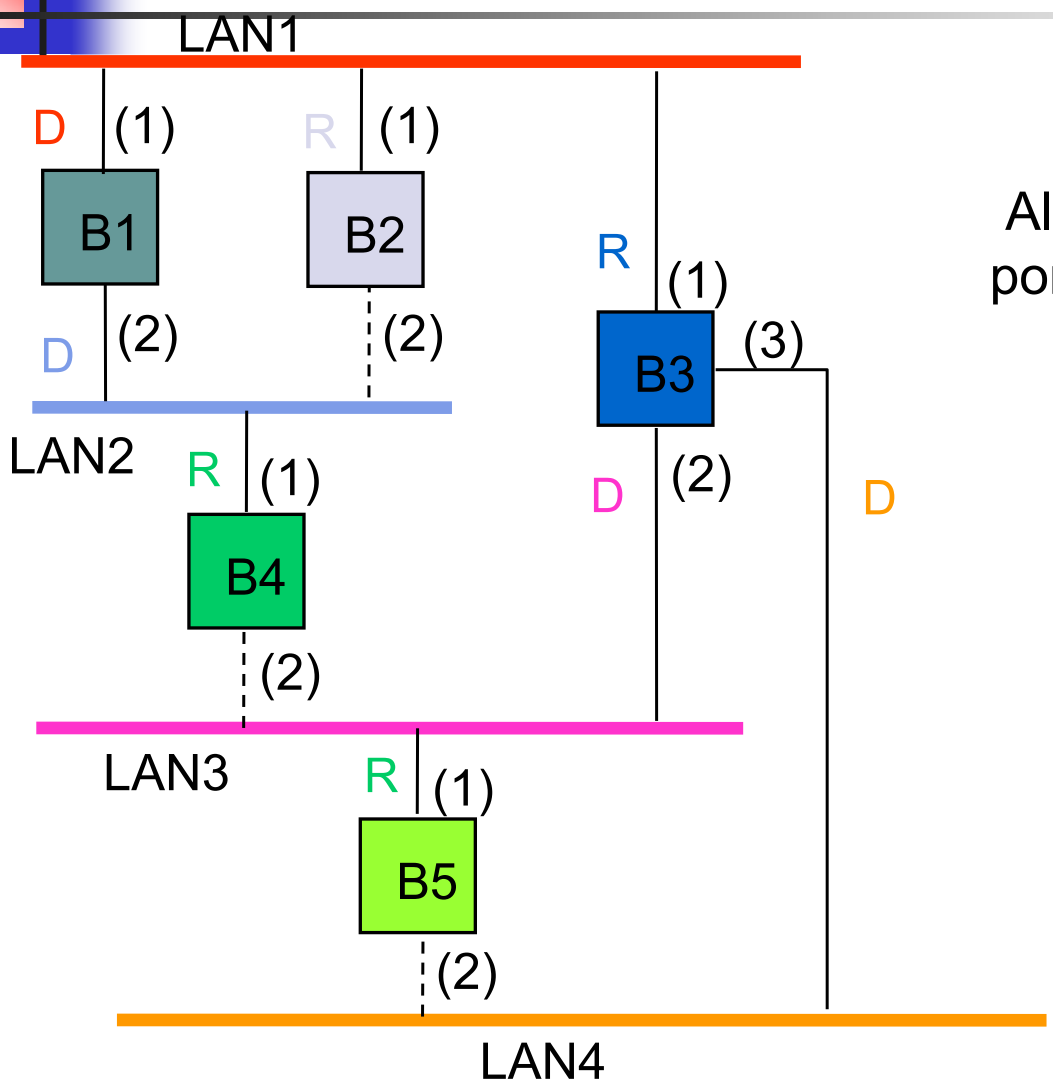
Root port selected for every bridge except root bridge

Example (4)



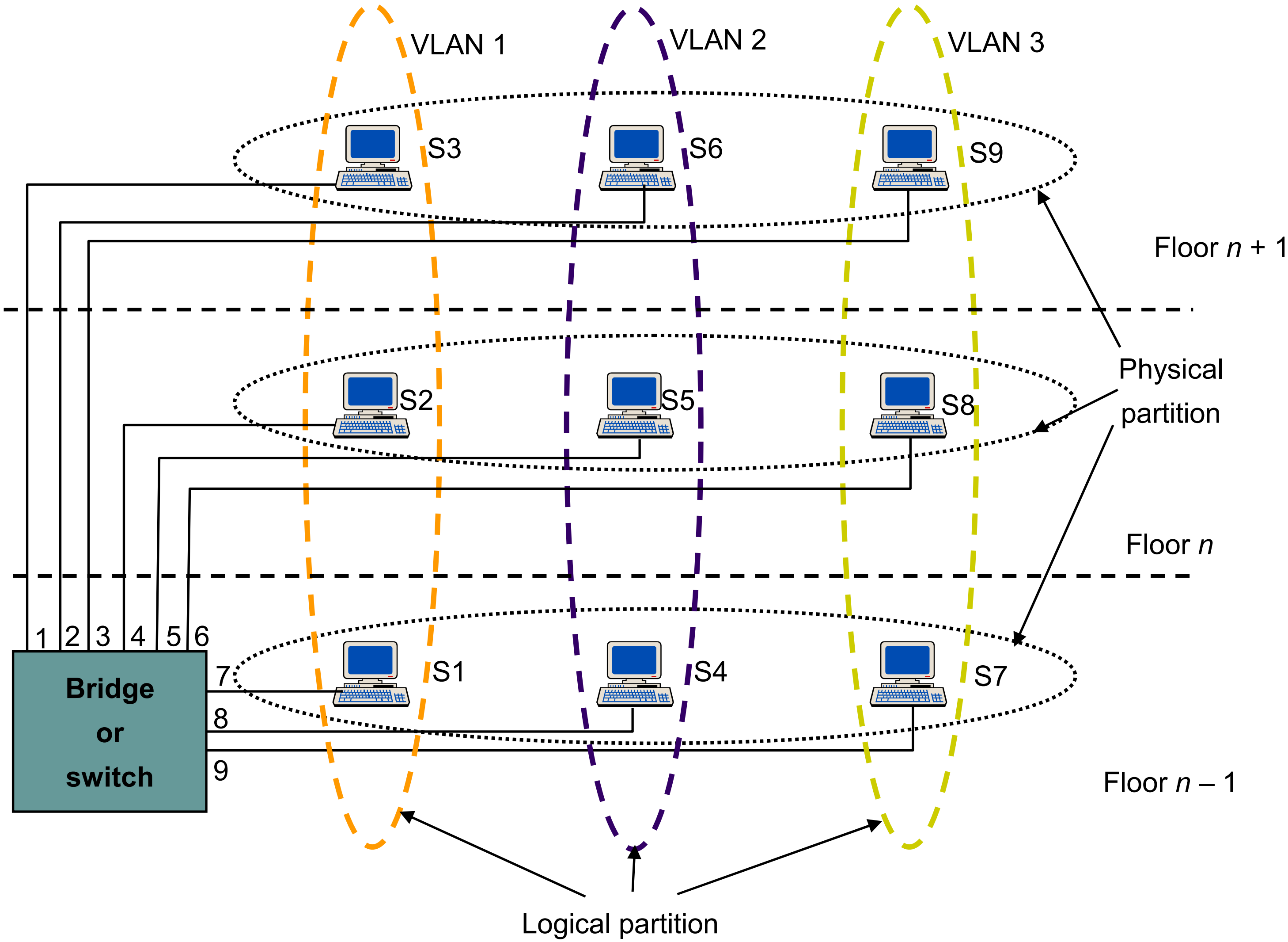
Select designated bridge for each LAN

Example (5)



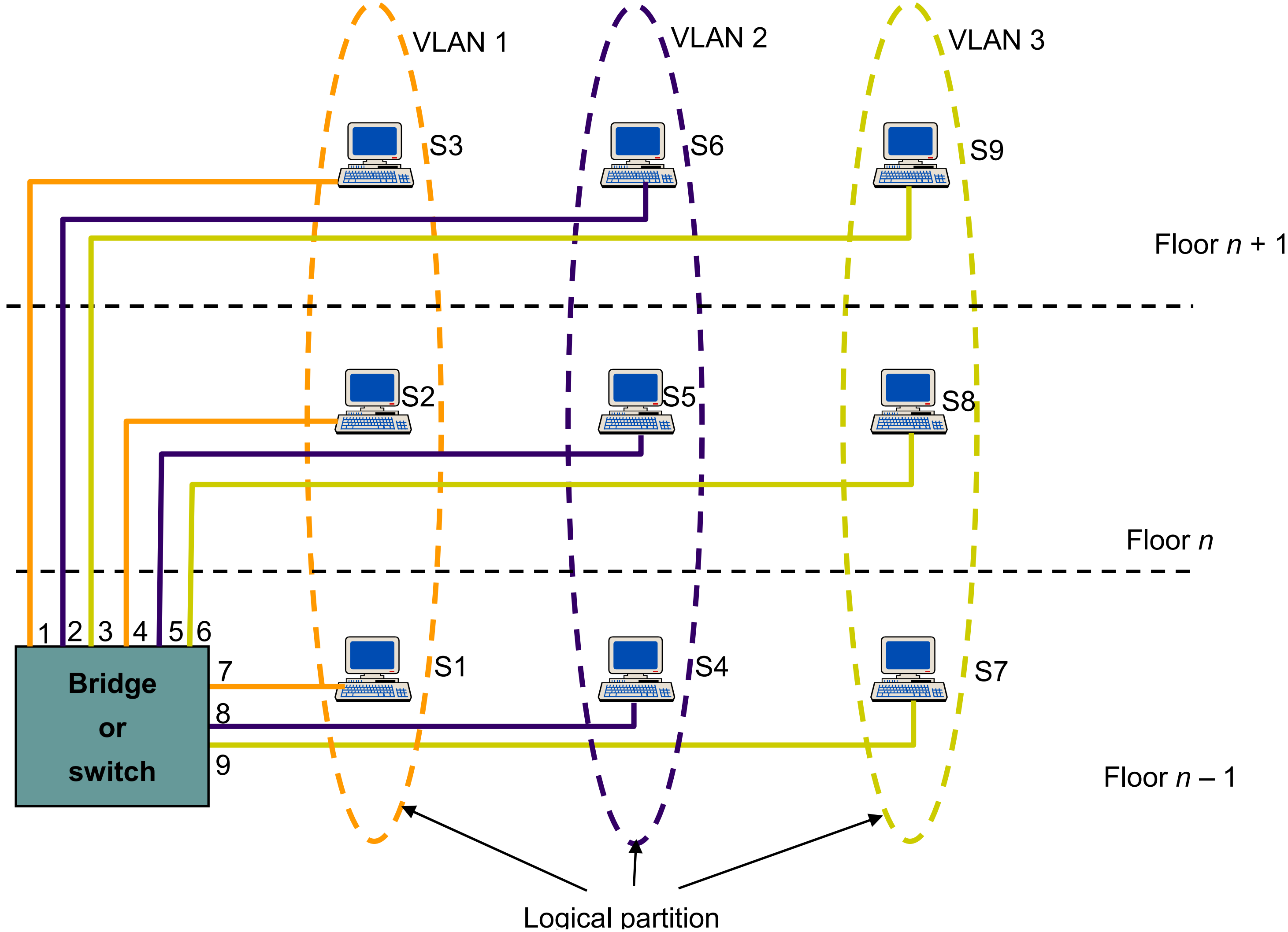
All root ports & designated ports put in forwarding state

Virtual LAN



VLAN 1
VLAN 2
VLAN 3
S3
S6
S9
Floor n + 1
S2
S5
S8
Physical
partition
Floor n
1
2
3
4
5
6
7
8
9
Bridge
or
switch
S1
S4
S7
Floor n – 1
Logical partition

Per-Port VLANs

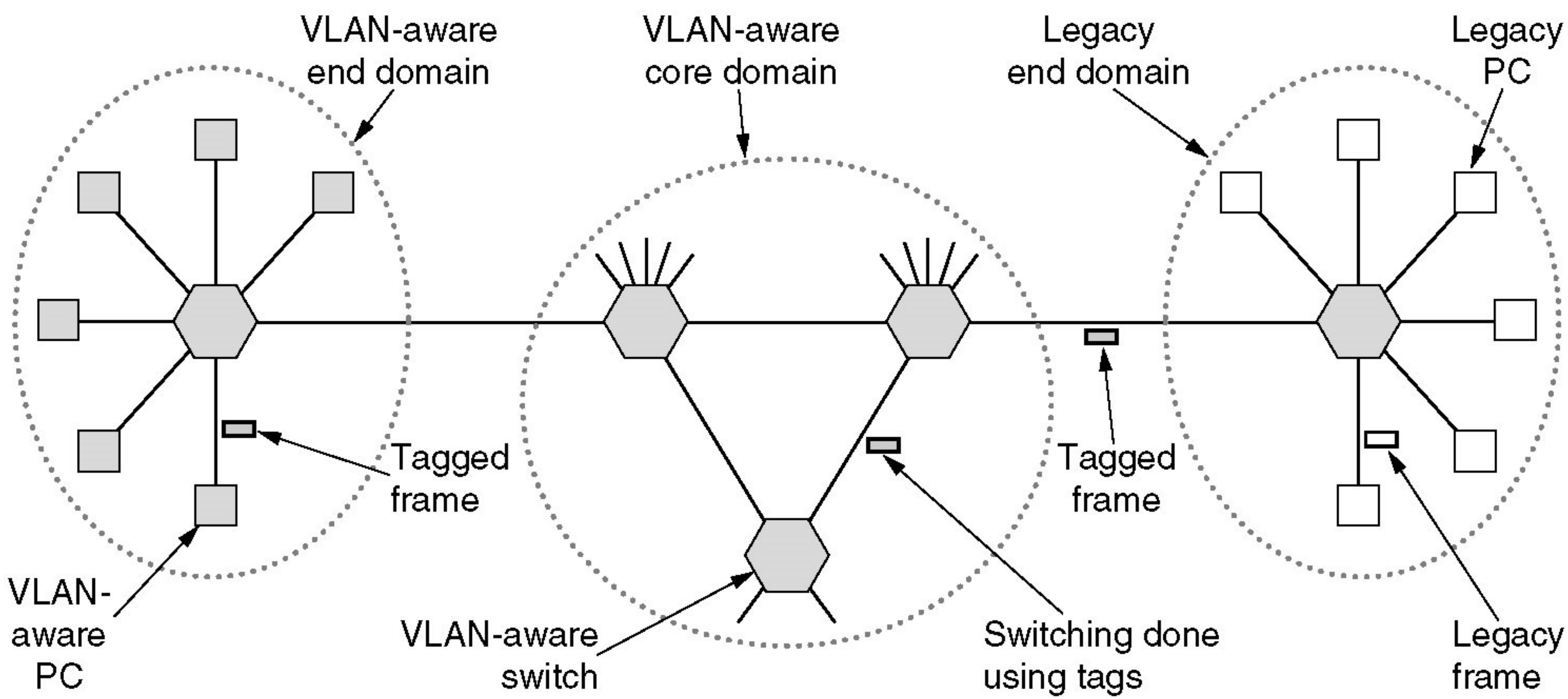


The bridge only forwards frames to outgoing ports associated with the same VLAN of the incoming port.

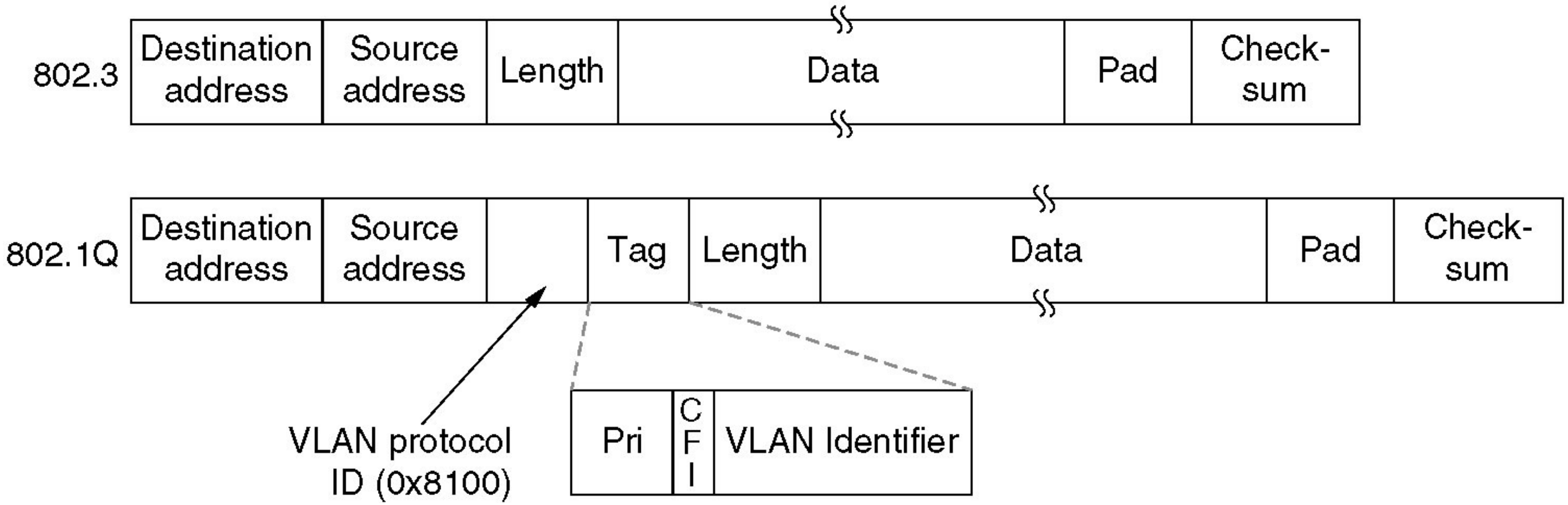
Tagged VLANs

- 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


802.3
Destination address
Source address
Length
Data
Pad
Check-sum
802.1Q
Destination address
Source address
Tag
Length
Data
Pad
Check-sum
VLAN protocol ID (0x8100)
Pri
C F I
VLAN Identifier