Computer Networks

Chapter 4: Medium Access Control

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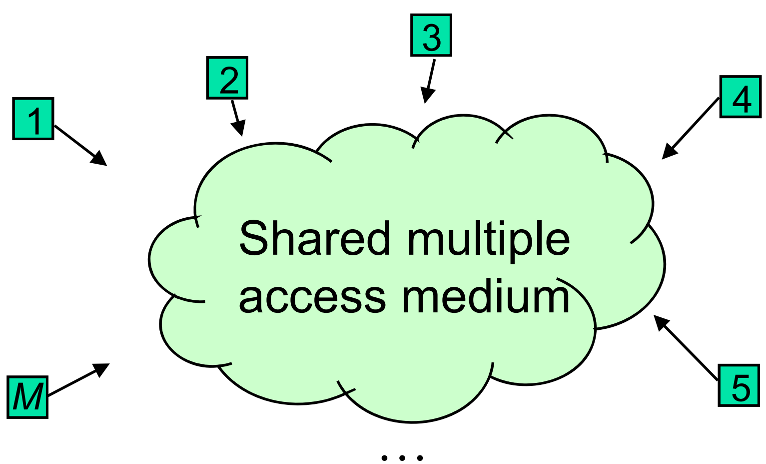
Outline

- 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?



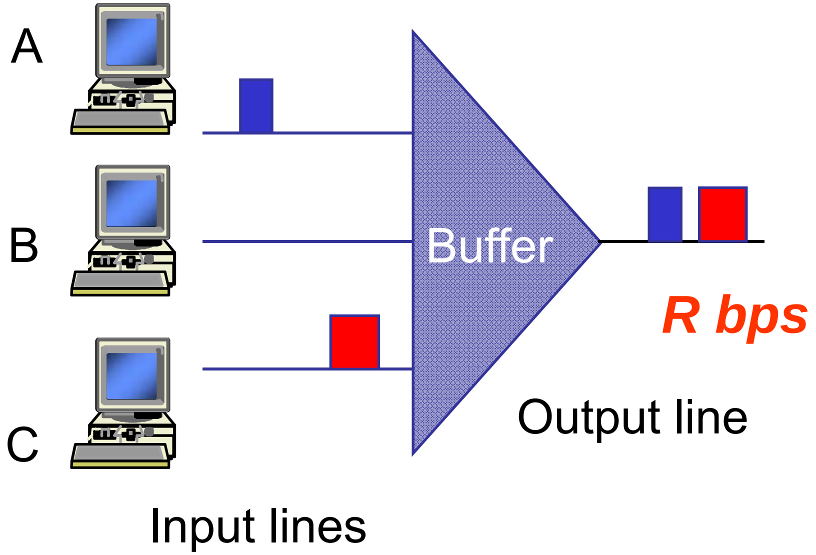
Notes on Several Confusing Terms

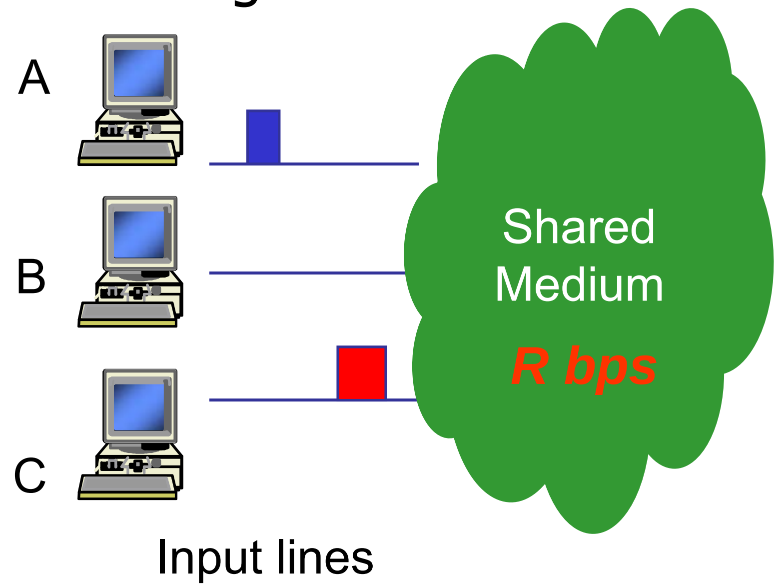
- Multiplexing
  - A node’s local function or two nodes’ point-to-point function
  - Examples: time division multiplexing (TDM), frequency division multiplexing (FDM), code division multiplexing, etc.
- Multiple Access
  - Function for multiple nodes’ PMP/mesh (covers point-to-point case)
  - Examples: random access, time division multiple access (TDMA), frequency division multiple access (FDMA), code division multiple access (CDMA), orthogonal frequency division multiple access (OFDMA) etc.
- 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

- Static channelization
- Dynamic medium access control
  - Scheduling
  - Random access

Static channelization

- 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

Random access

- 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)
- Efficiency
- Transfer delay
- Fairness
- Reliability
- Capability to carry different types of traffic
- Quality of service
- Cost

Channelization

Multiple Access and Channelization (1)

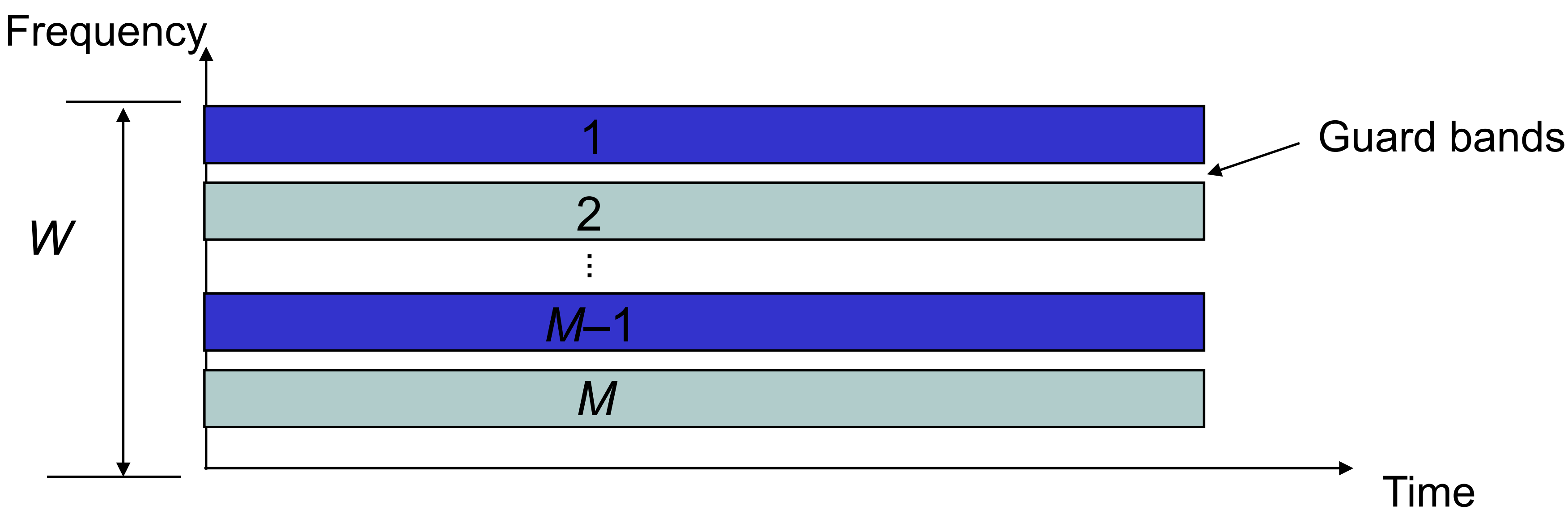
- Channelization
  - Semi-static bandwidth allocation of portion of shared medium to a given user
  - Highly efficient for constant-bit rate traffic
  - Preferred approach in
    - Cellular telephone networks
    - Terrestrial & satellite broadcast radio & TV
- Shortcomings
  - Inflexible in allocation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

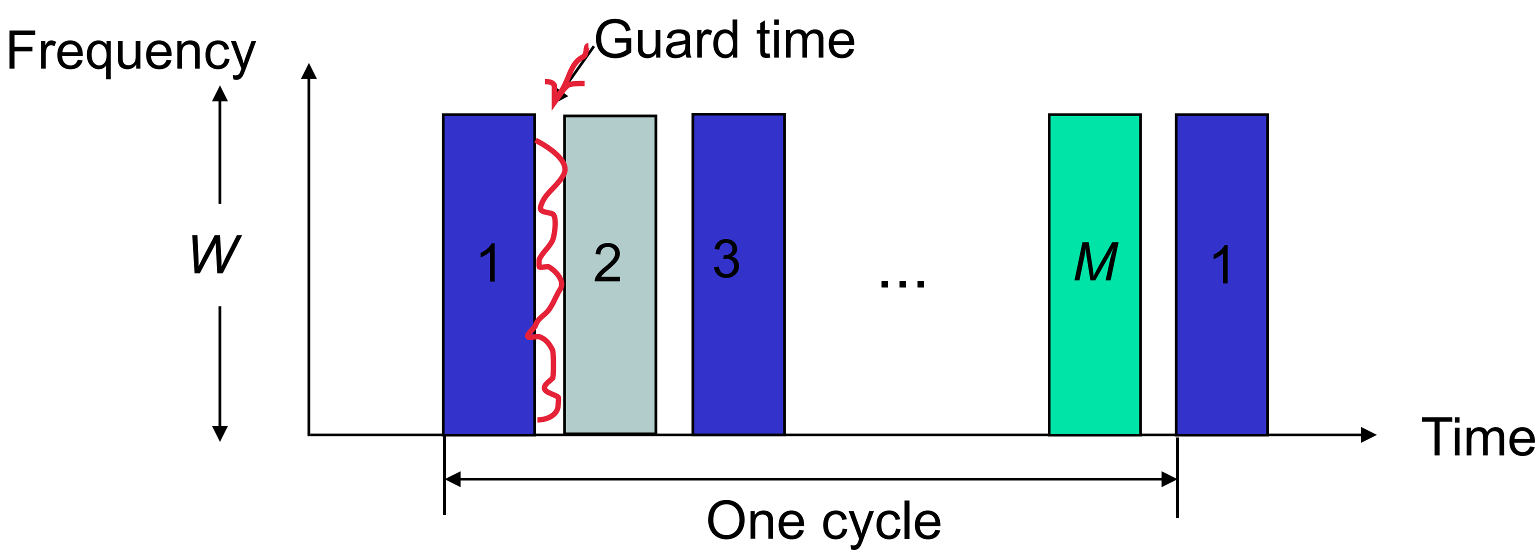
FDMA Channelization

- 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

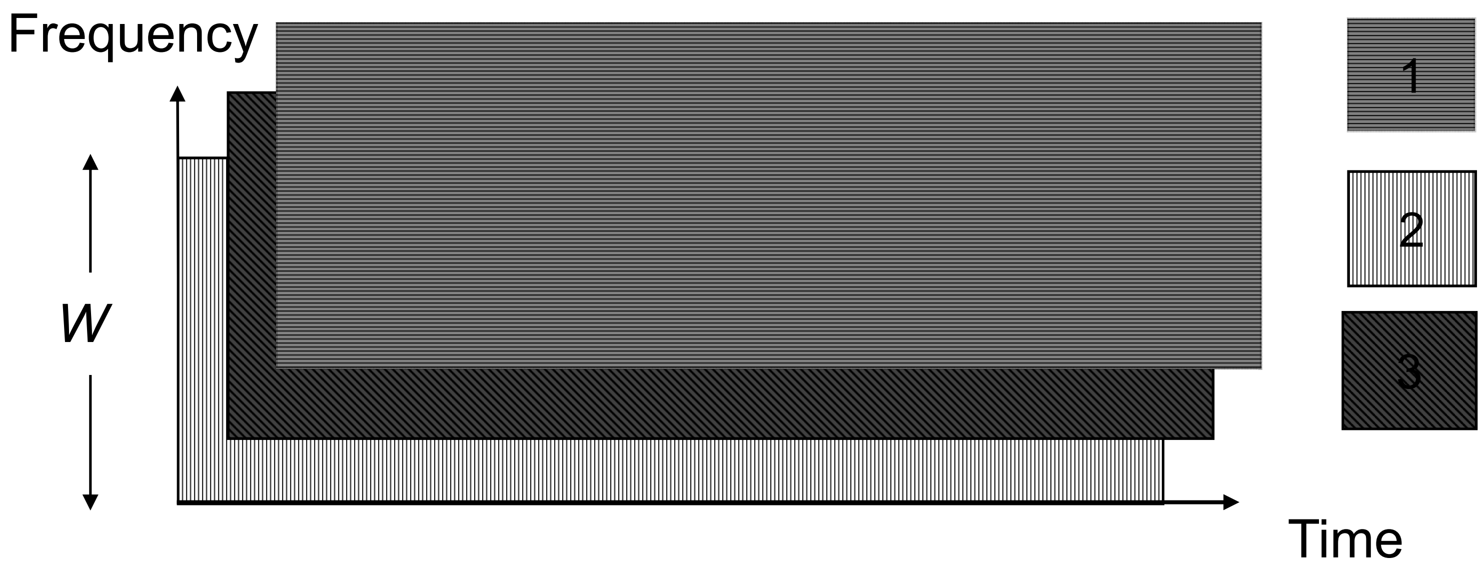


Guardbands

- 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

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

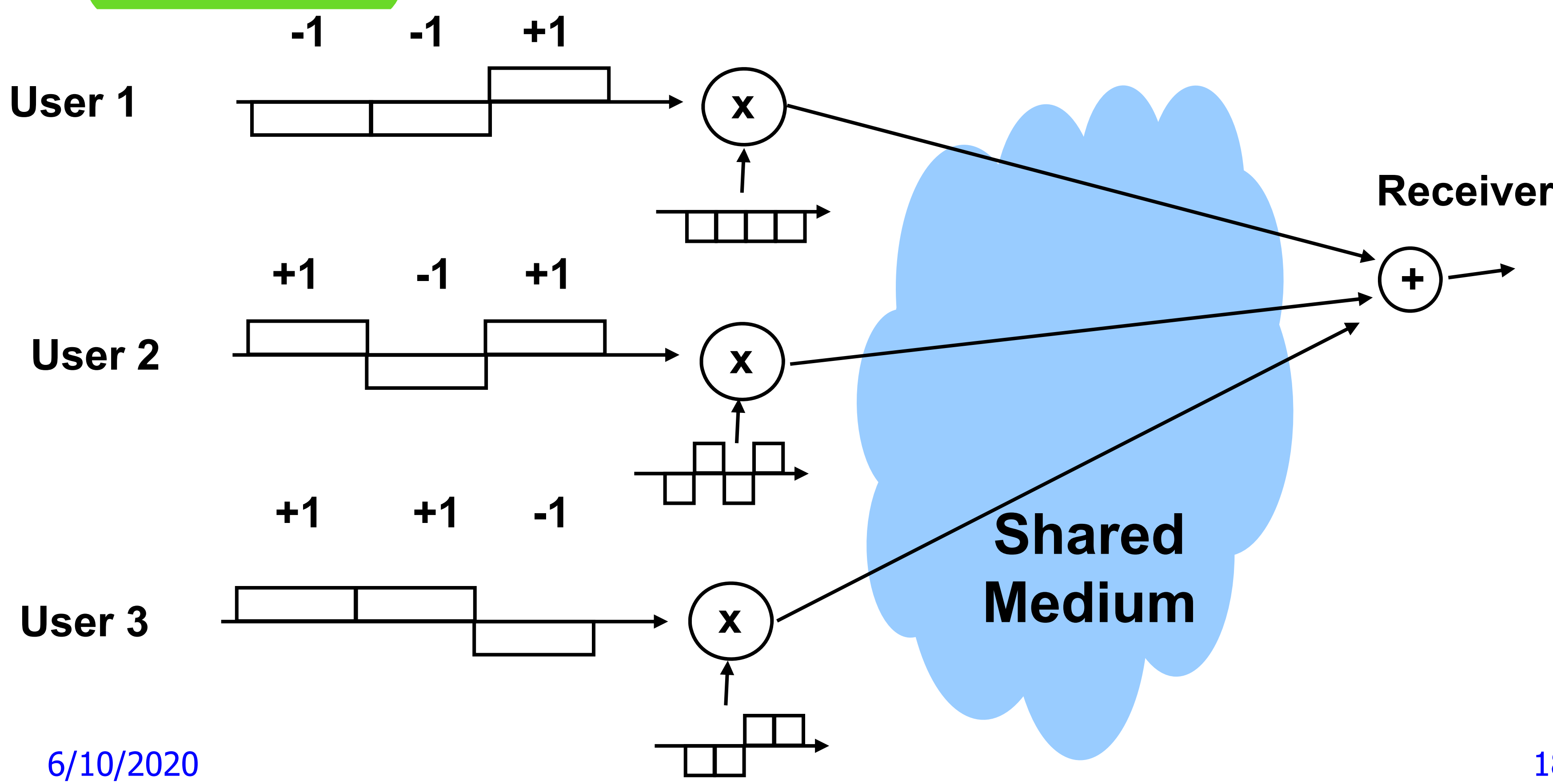


Channelization in Code Space

- 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

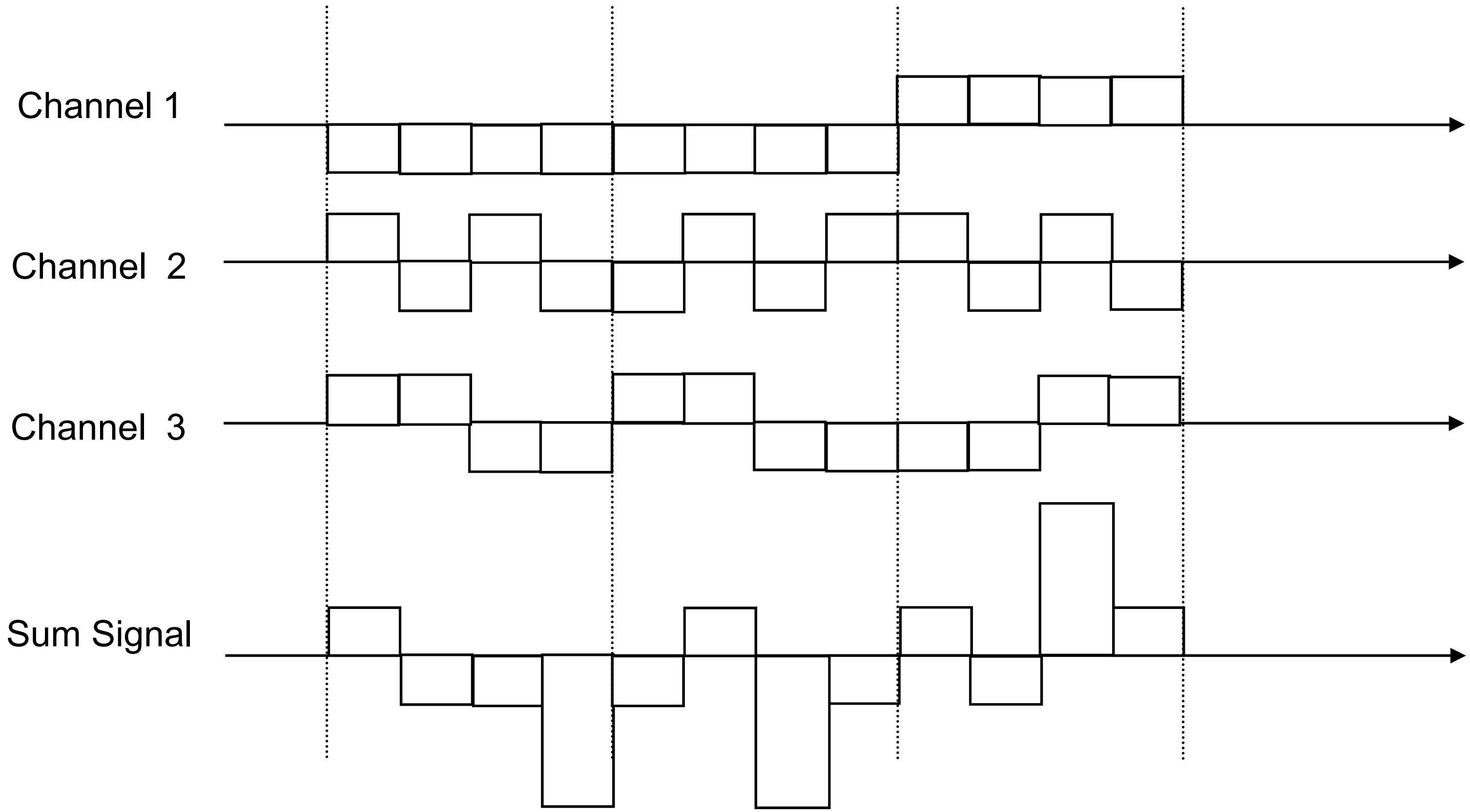
CDMA Example: 3 users

- 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},



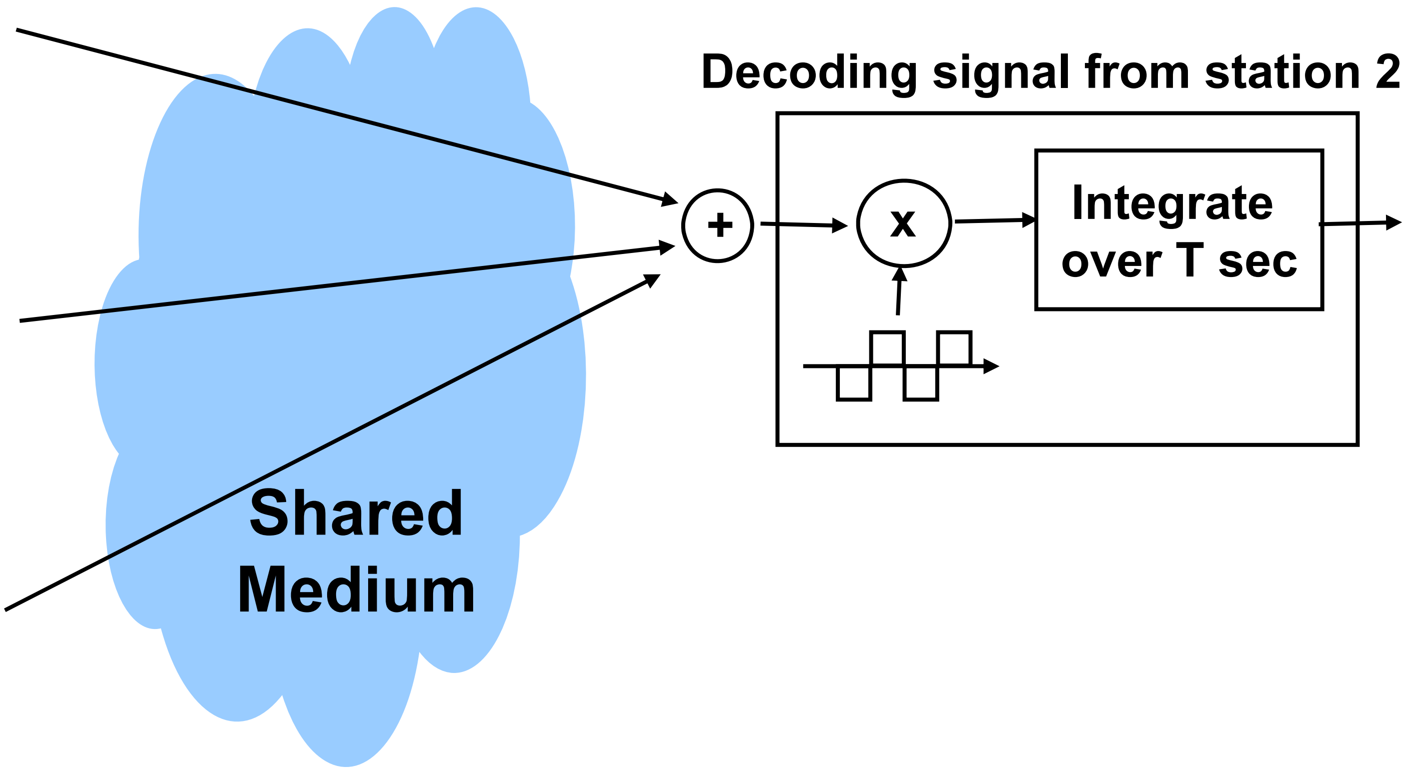
Sum signal is input to receiver

- **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)**



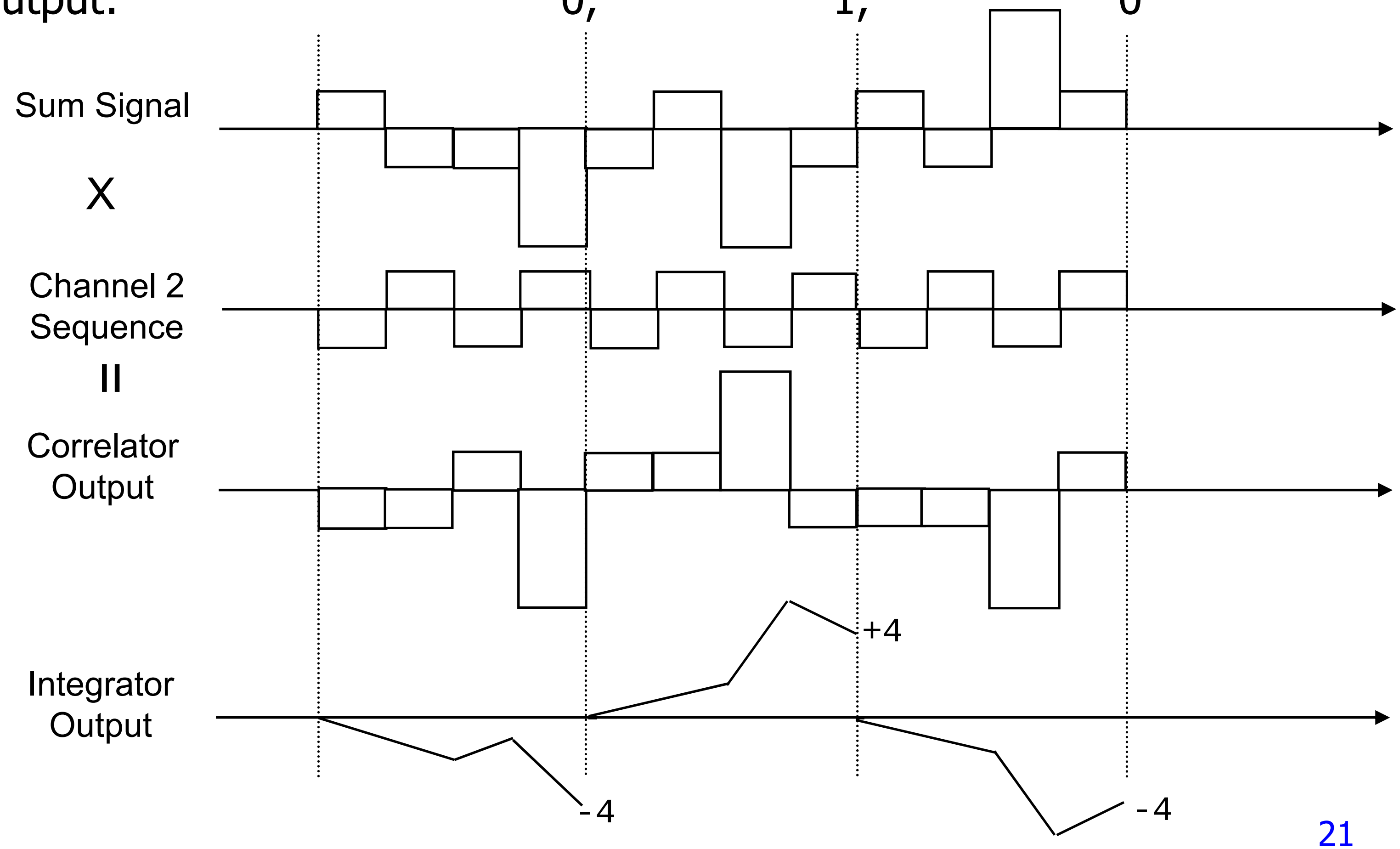
Receiver for Station 2

- 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



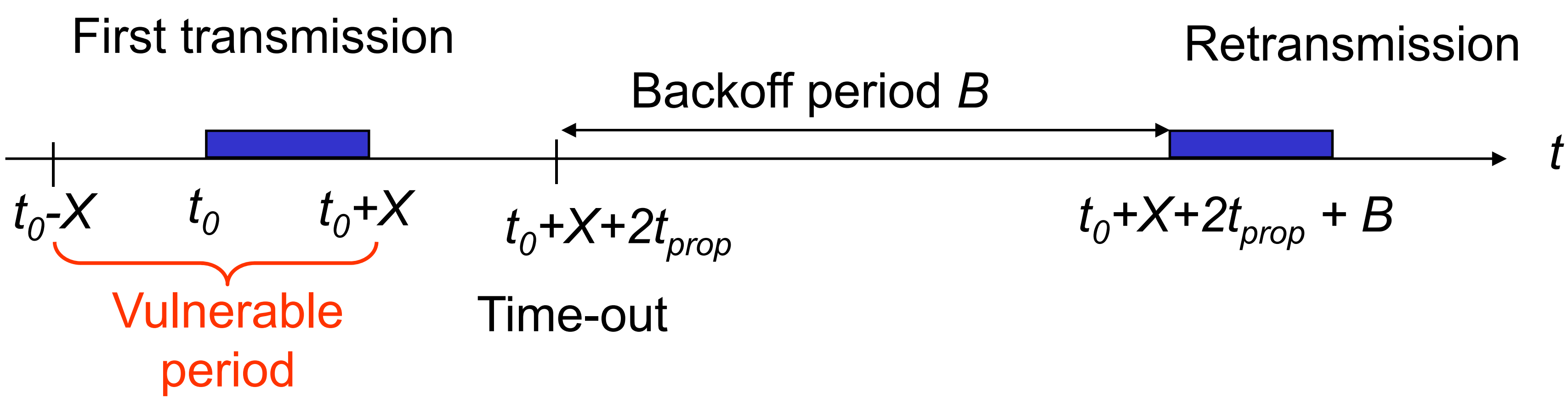
Channelization Example: Cellular Telephone Networks

- 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

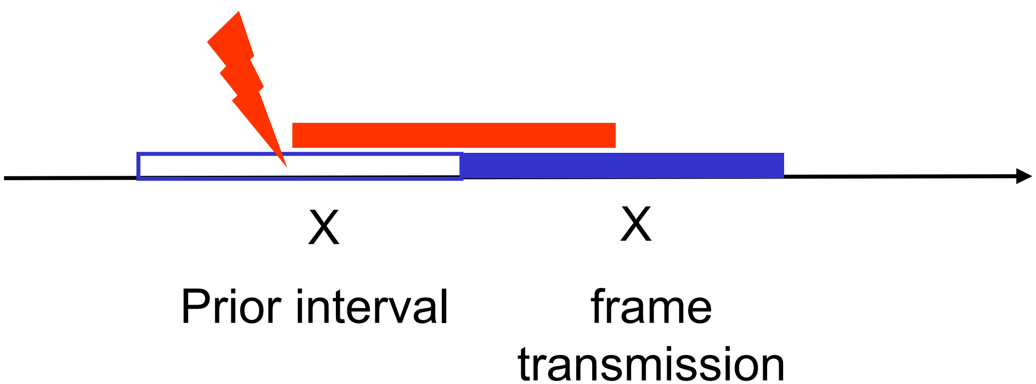
- Wireless link to provide data transfer between main campus & remote campuses of University of Hawaii
- Simplest solution
  - A station transmits whenever it has data to transmit
  - If more than one frames are transmitted, they interfere with each other (collide) and are lost
  - If ACK not received 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)
  - 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
- Divide X into n intervals of duration $\Delta = X/n$
- p = probability of arrival in Δ interval, then

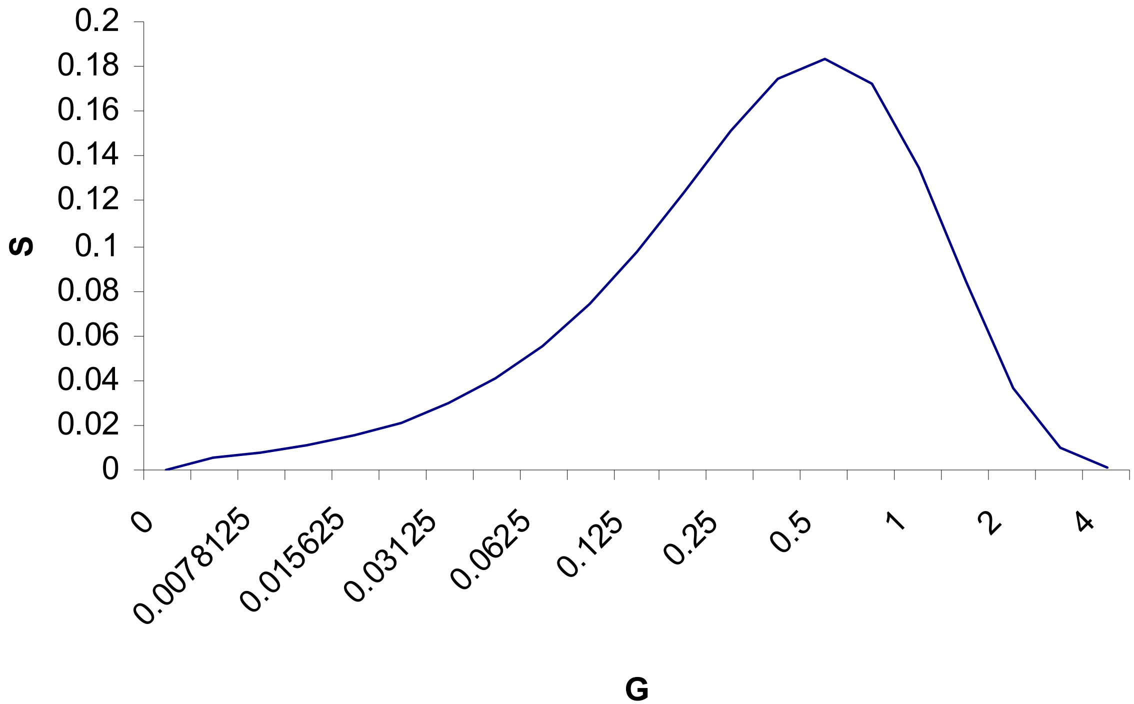
  $G = n\,p$ since there are n intervals in X seconds

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

Throughput of ALOHA

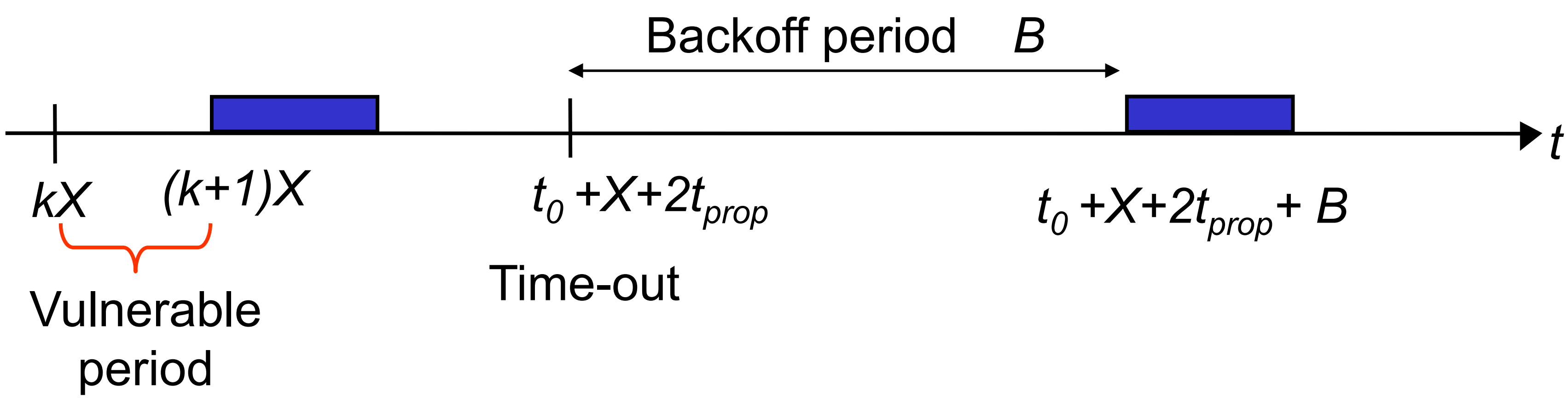
- Collisions are means for coordinating access
- Max throughput is $\rho_{max} = 1/2e$ *(18.4%)*
- Bimodal behavior:
  Small G, S≈G
  Large G, S →0
- Collisions can snowball and drop throughput to zero

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



Slotted ALOHA

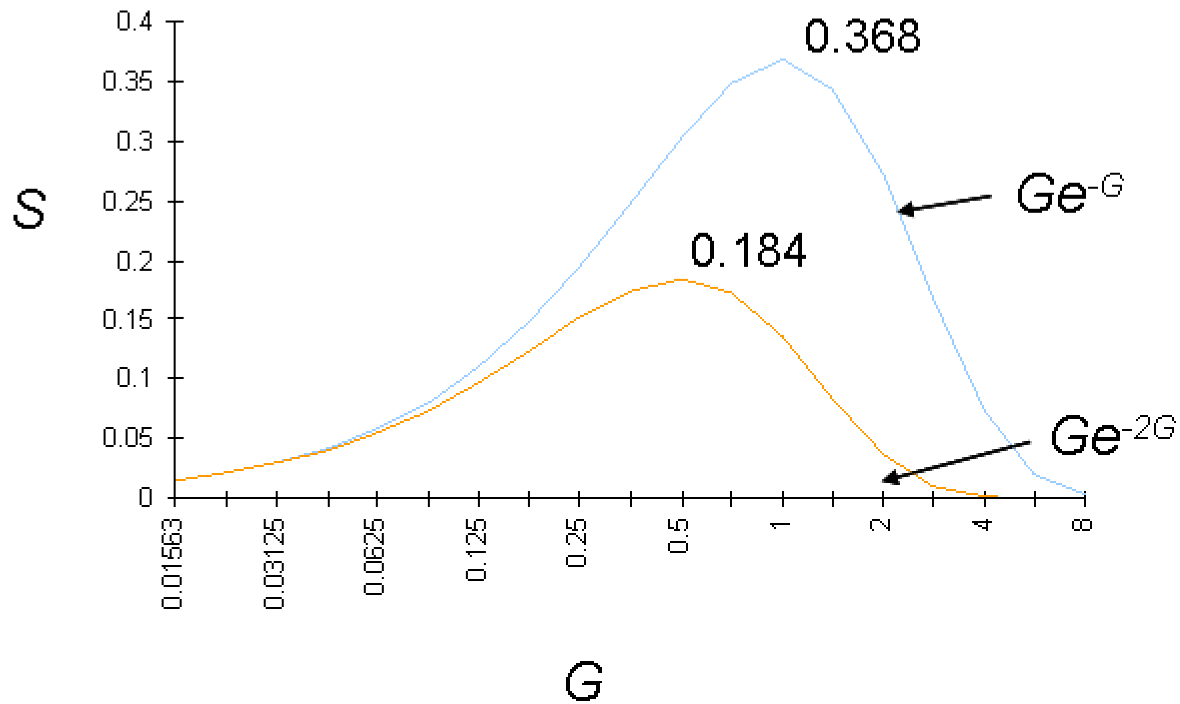
- Time is slotted in X seconds slots
- Stations are ***synchronized*** to frame times
- Stations transmit frames in first slot after frame arrival
- Backoff intervals in multiple slots



Only frames that arrive during prior X seconds collide

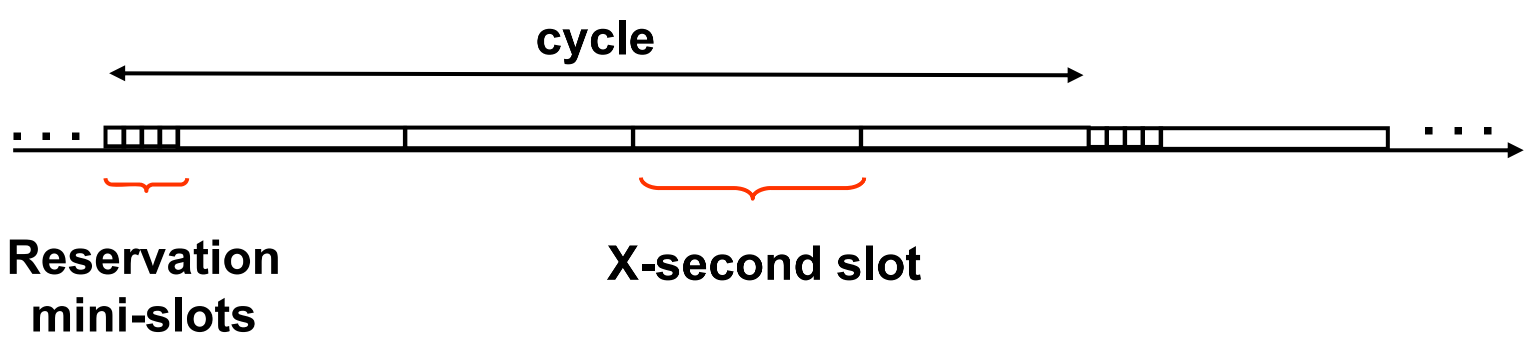
Throughput of Slotted ALOHA

$$S = GP_{success} = GP[\text{no arrivals in X seconds}]$$
$$= GP[\text{no arrivals in n intervals}]$$
$$= G(1-p)^n = G(1-\frac{G}{n})^n \rightarrow Ge^{-G}$$



Application of Slotted Aloha

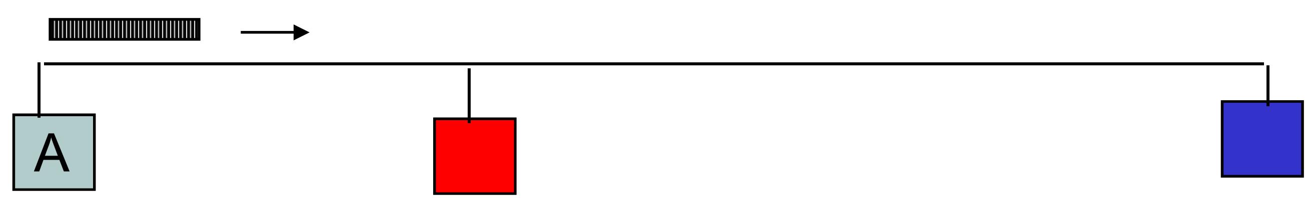
- Reservation protocol allows a large number of stations with infrequent traffic to reserve slots to transmit their frames in future cycles
- Each cycle has mini-slots allocated for making reservations (i.e. for sending request/response messages)
- Stations use slotted Aloha during mini-slots to request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



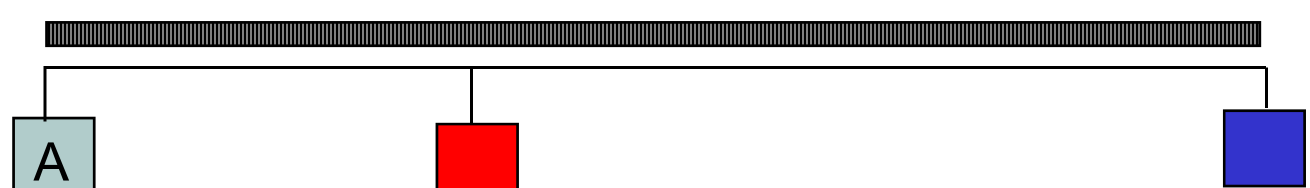
Carrier Sensing Multiple Access (CSMA)

- A station senses the channel before it starts transmission
  - If busy, either wait or schedule backoff (different options)
  - If idle, start transmission
  - Vulnerable period is reduced to *(t_{prop} or $2t_{prop}$?)* (due to delay in *channel capture* effect) 2t_{prop}
  - 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

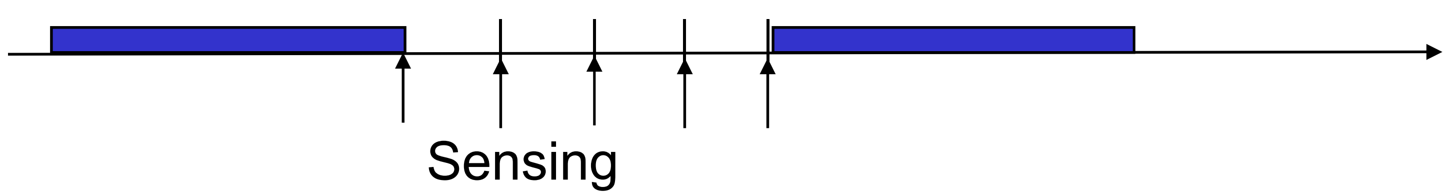


Station A captures channel at t = t_{prop}



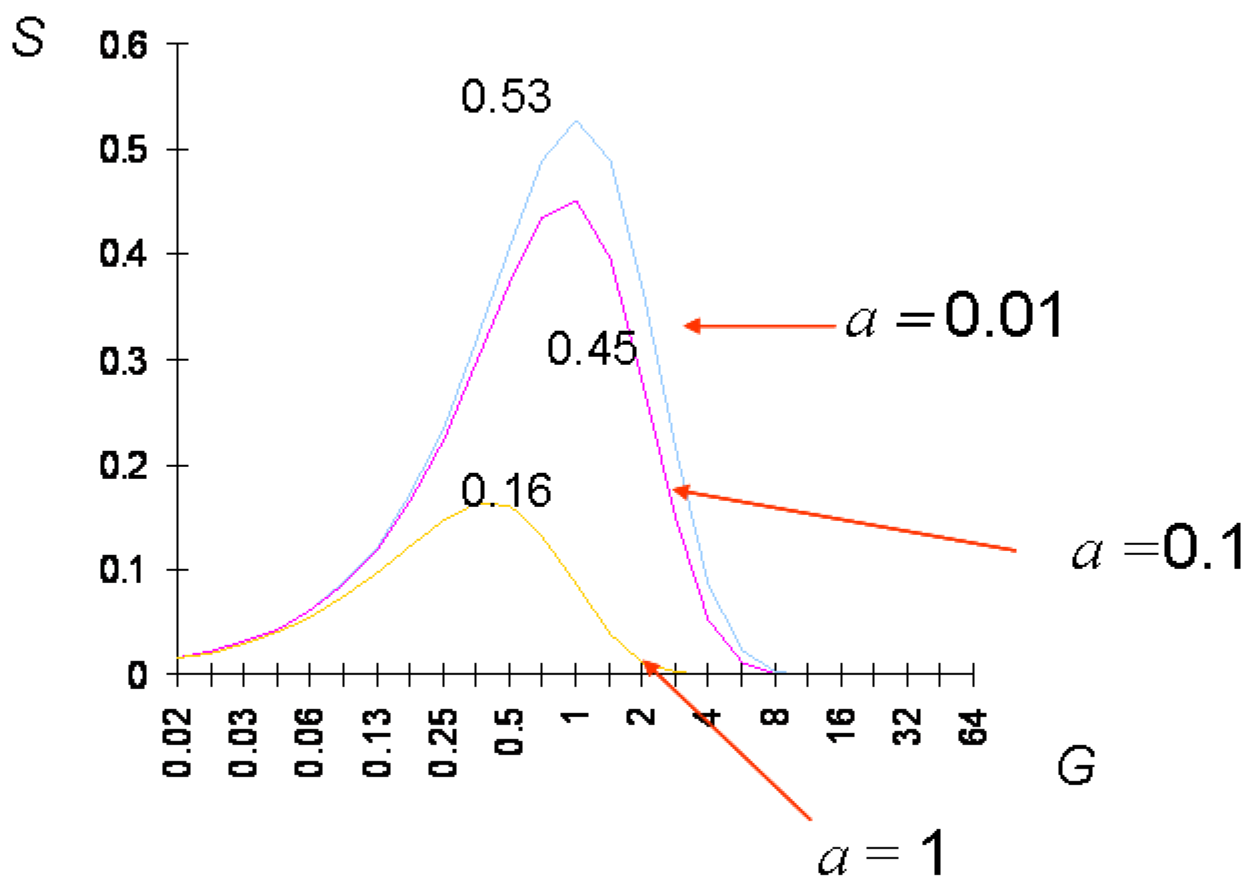
CSMA Options

- 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



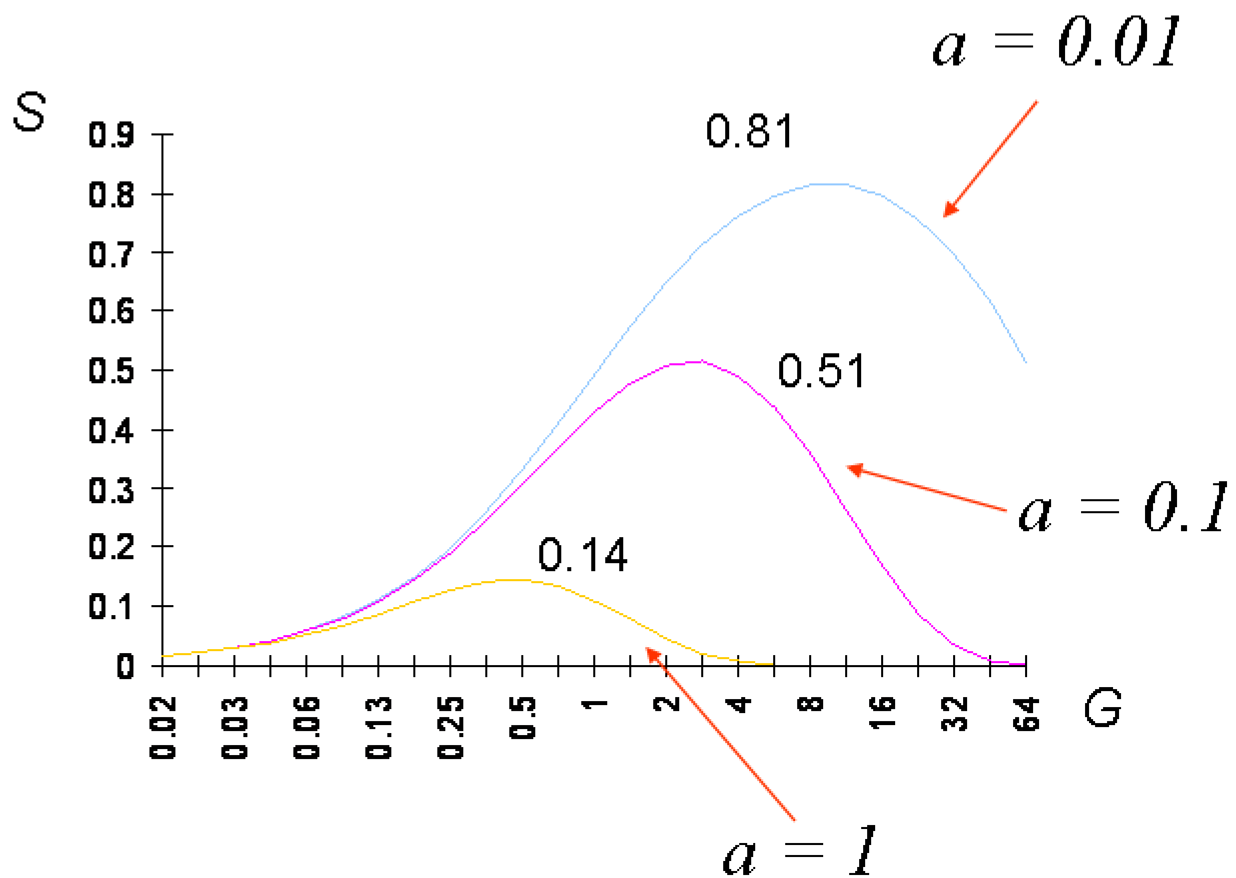
1-Persistent CSMA Throughput

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



Non-Persistent CSMA Throughput

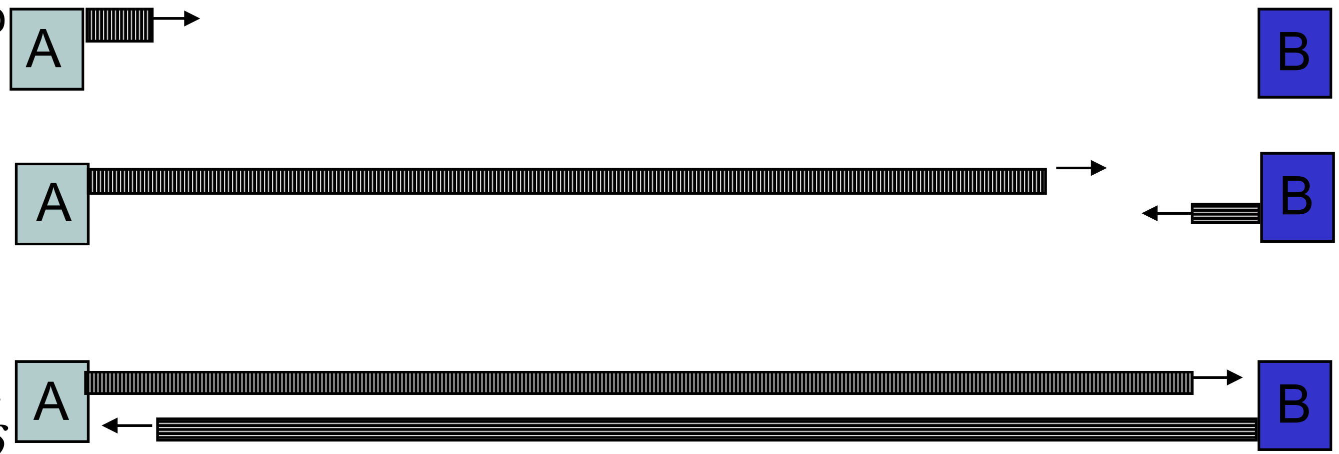
- Higher maximum throughput than 1-persistent for small a
- Worse than Aloha for $a > 1$



CSMA with Collision Detection (CSMA/CD)

- 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
- 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

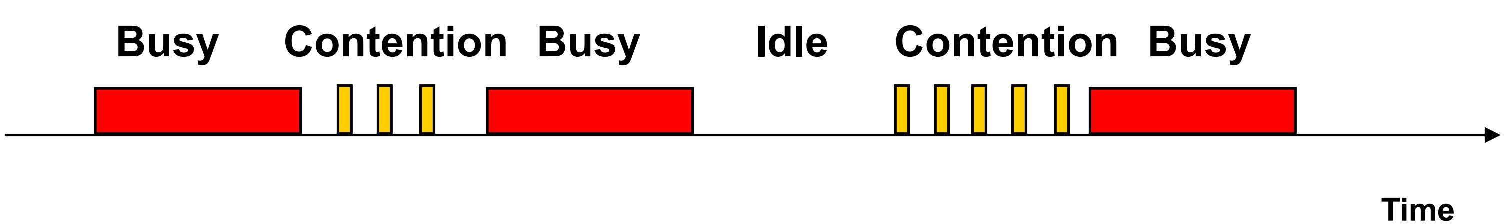
CSMA/CD reaction time



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:

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

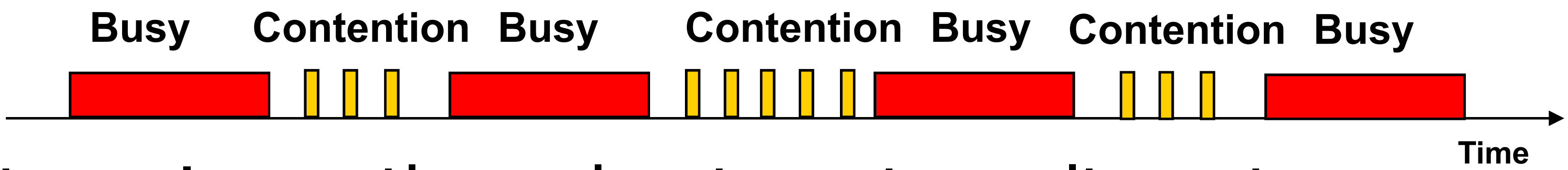
- By taking derivative of $P_{success}$ we find max occurs at p=1/n

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

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

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

CSMA/CD Throughput



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

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

- 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

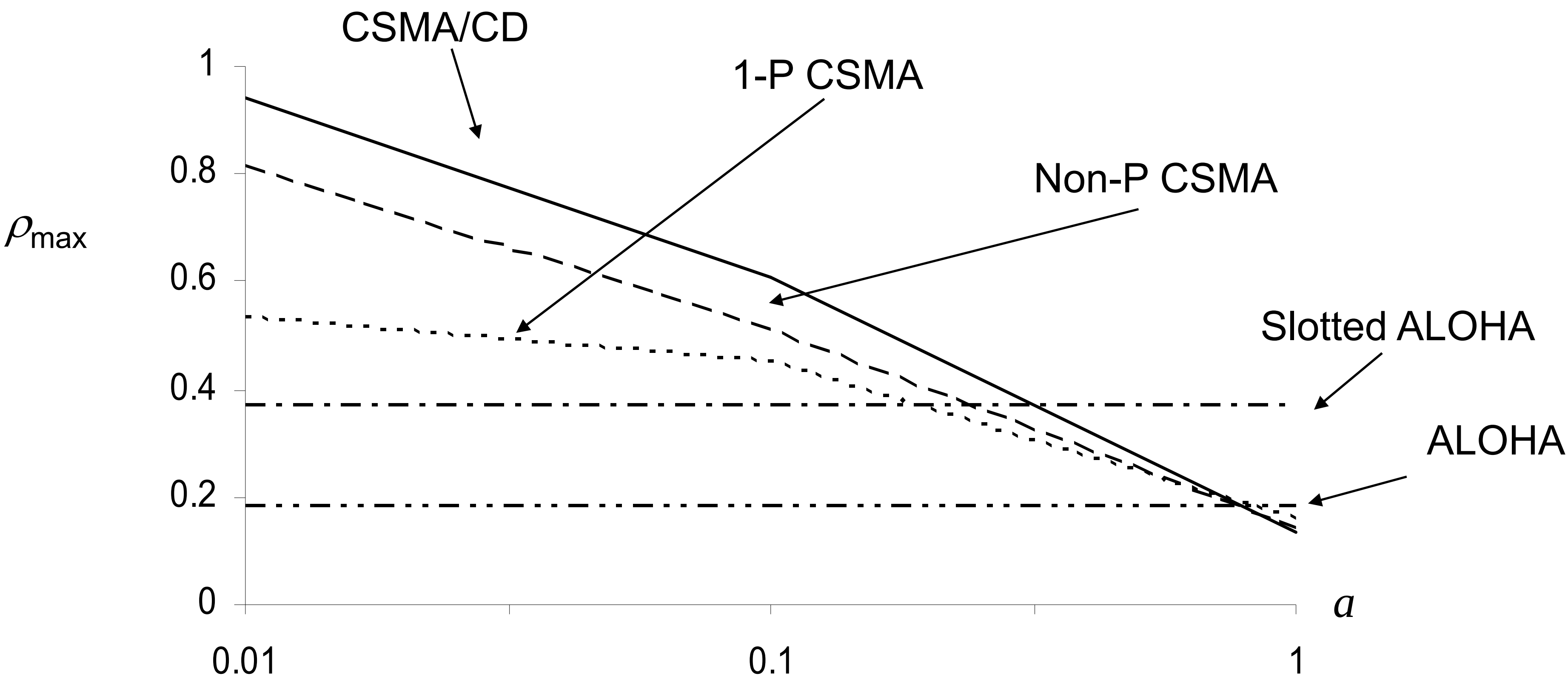
  $2e+1 = 6.44$

CSMA-CD Application: Ethernet

- First Ethernet LAN standard used CSMA-CD
  - 1-persistent Carrier Sensing
  - R = 10 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 $\{0, 1,\ldots, 2^k - 1\}$, where k=min(n, 10)

Throughput for Random Access MACs

- 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
  - High priority traffic sense channel for time τ_1
  - 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

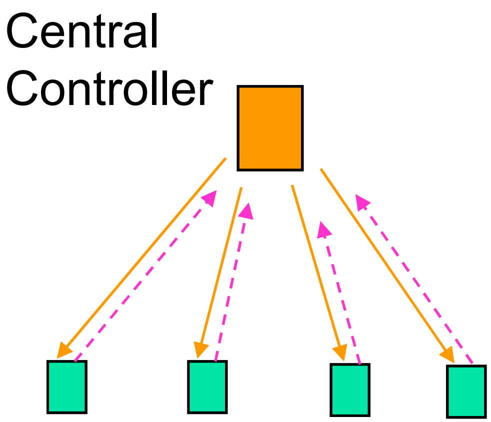
Scheduling

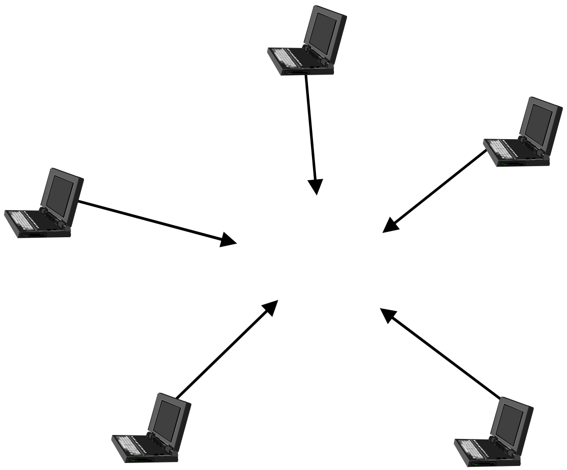
Scheduling

- 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

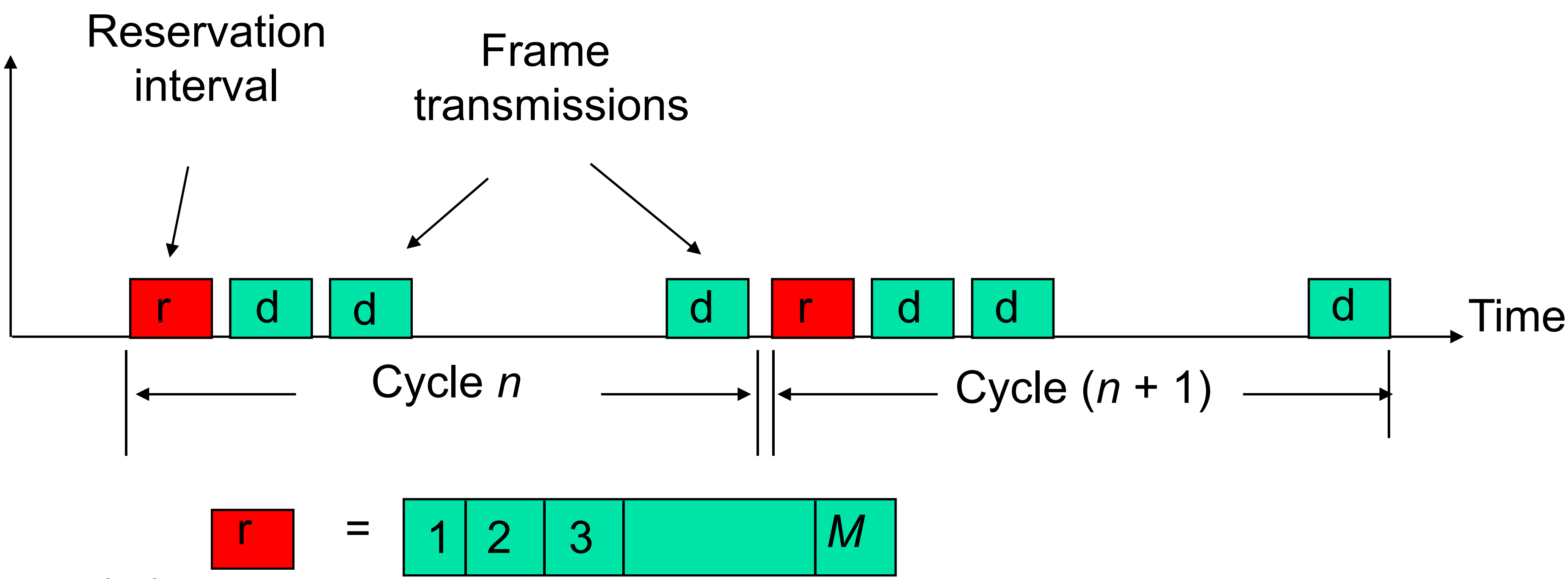
- *Centralized systems*: A central controller accepts requests from stations and issues grants to transmit
  - Frequency Division Duplex (FDD): Separate frequency bands for uplink & downlink
  - Time-Division Duplex (TDD): Uplink & downlink time-share the same channel
- *Distributed systems*: Stations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





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

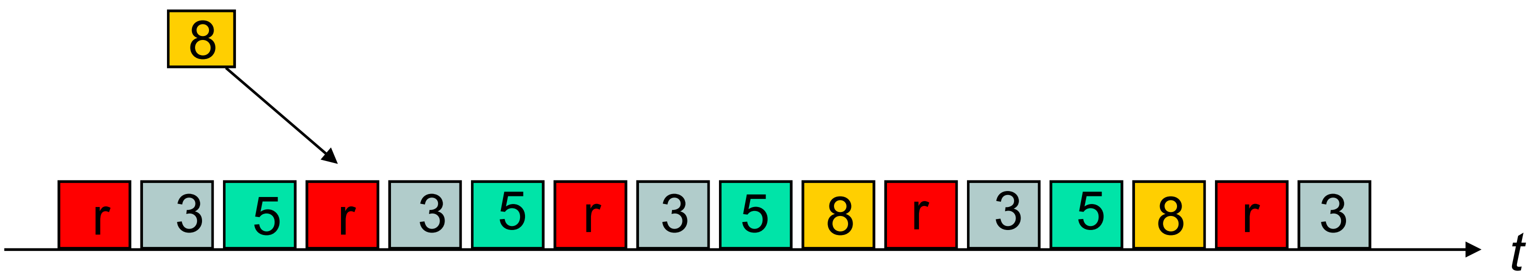


Reservation System Options

- 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
  - *Channelized (typically TDMA) reservation*: Reservation messages from different stations are multiplexed without any risk of collision
  - *Random access reservation*: Each station transmits its reservation message randomly until the message goes through

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

- Assume minislot duration = vX
- TDMA single frame reservation scheme
  - If propagation delay is negligible, a single frame transmission requires *(1+v)X* seconds
  - 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
  - Stations use slotted Aloha in reservation minislots
  - On average, each reservation takes at least *e* minislot attempts
  - Effective time required for the reservation is $2.71vX$

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

Example: GPRS

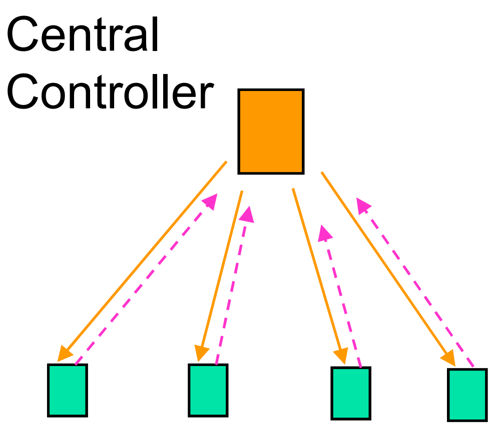
- General Packet Radio Service
  - Packet data service in GSM cellular radio
  - GPRS devices, e.g. cellphones or laptops, send packet data over radio and then to Internet
  - Slotted Aloha MAC used for reservations
  - Single & multi-slot reservations supported

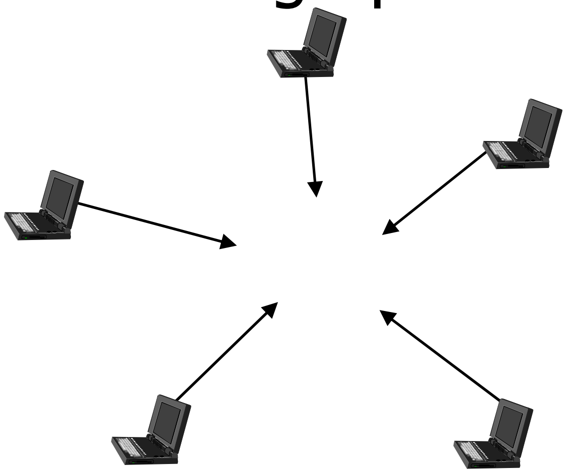
Reservation Systems and Quality of Service

- 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

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



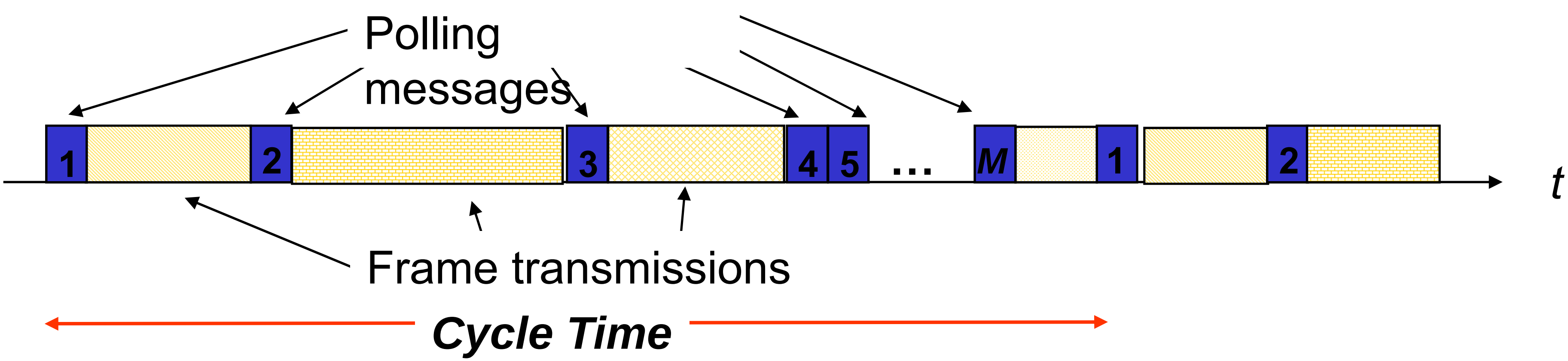


Polling System Options

- 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



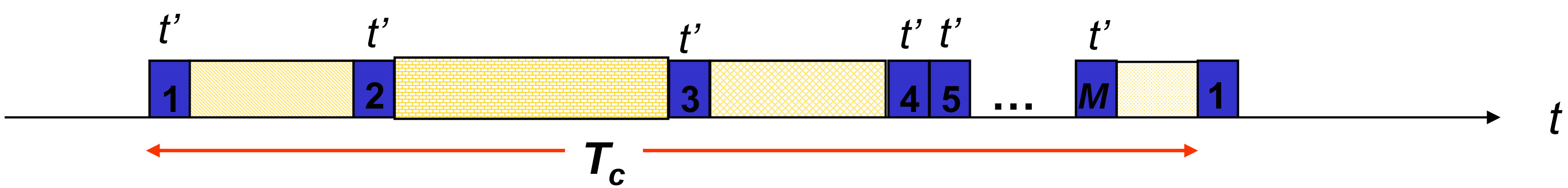
Average Cycle Time

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

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

- Average Cycle Time:

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



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:

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

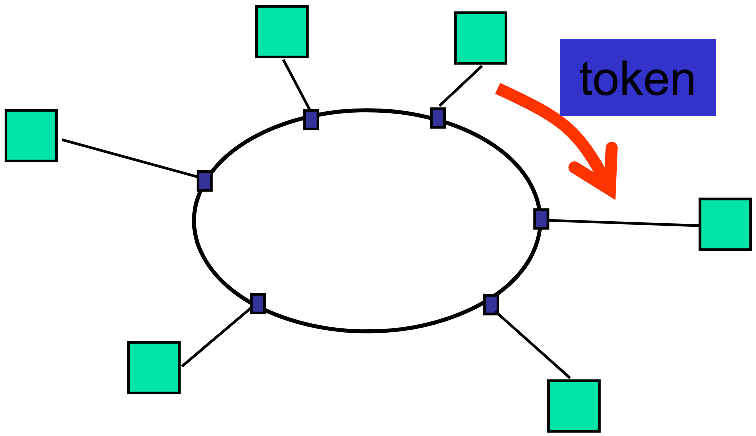
Can approach 100%

- 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

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

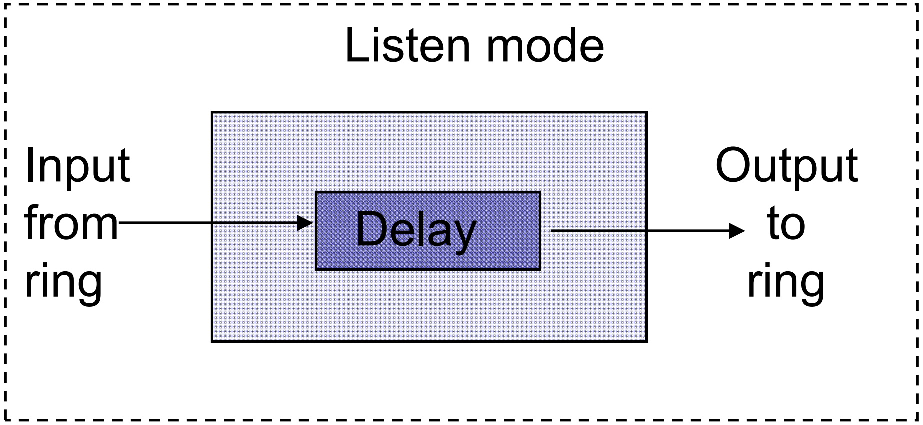
Single frame per poll

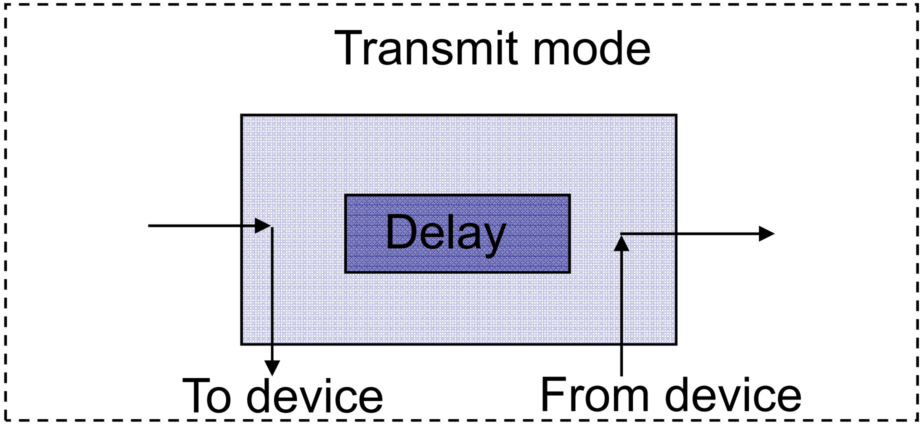
Application: Token-Passing Rings



Free Token = Poll

Frame Delimiter is Token
Free = 01111110
Busy = 01111111



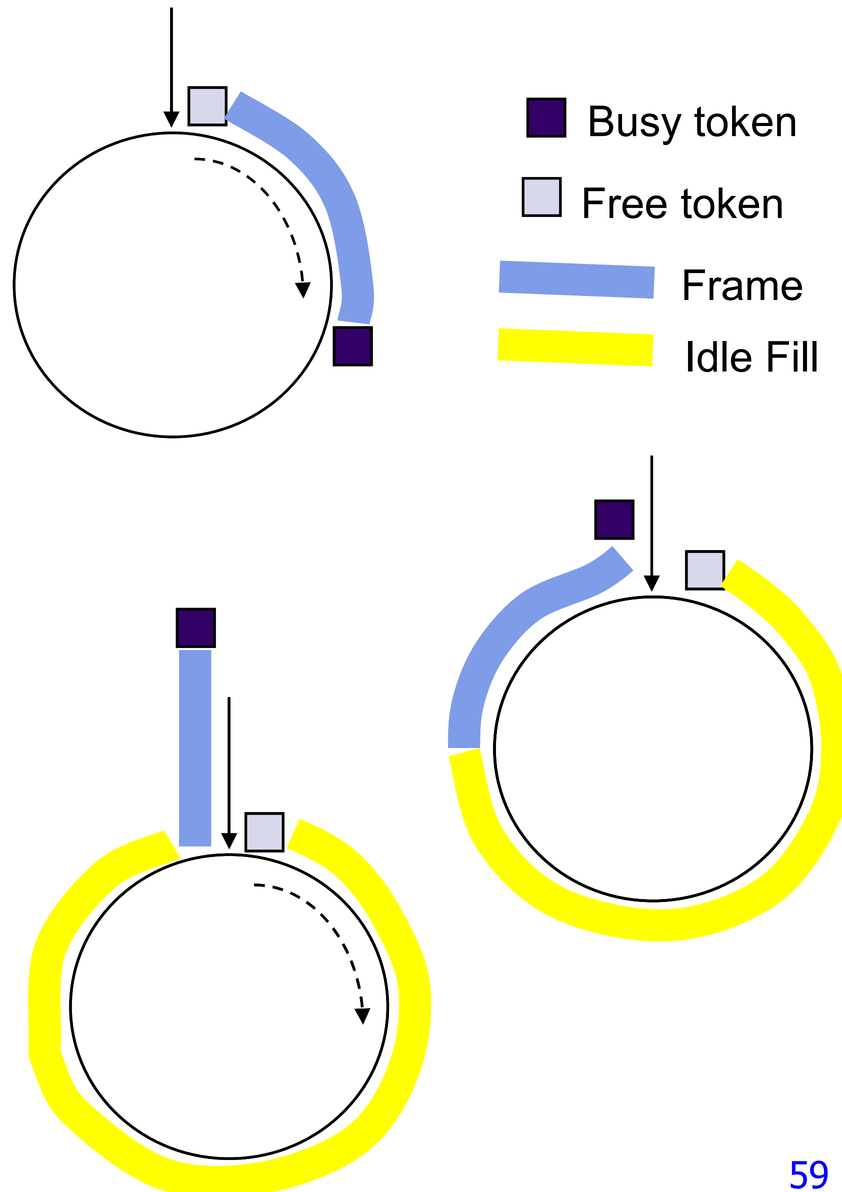


Ready station looks for free token

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

Methods of Token Reinsertion

- Ring latency: number of bits that can be simultaneously in transit on ring
- Multi-token operation
  - 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
  - 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:

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

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

Token Ring Throughput

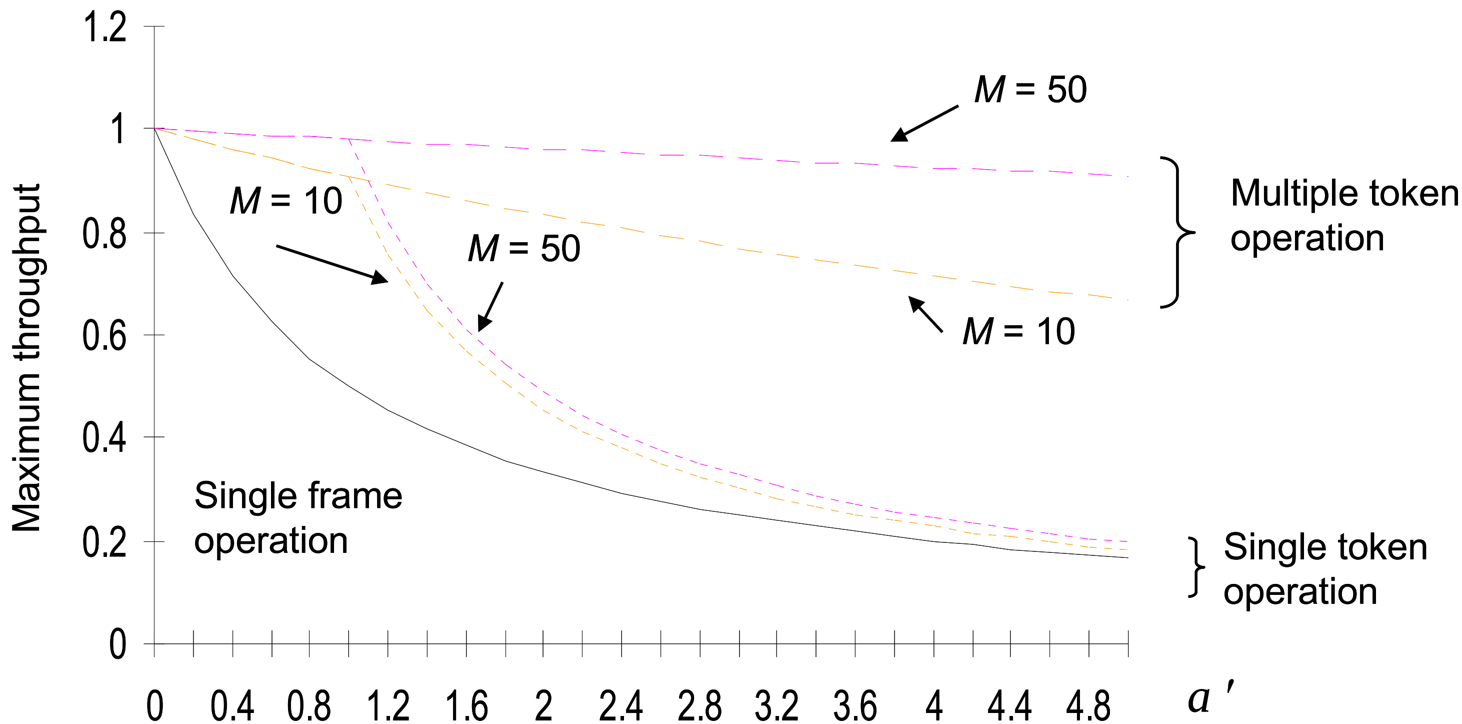
- *Single-token operation*
  - Effective frame transmission time is maximum of X and τ', therefore

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

- *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

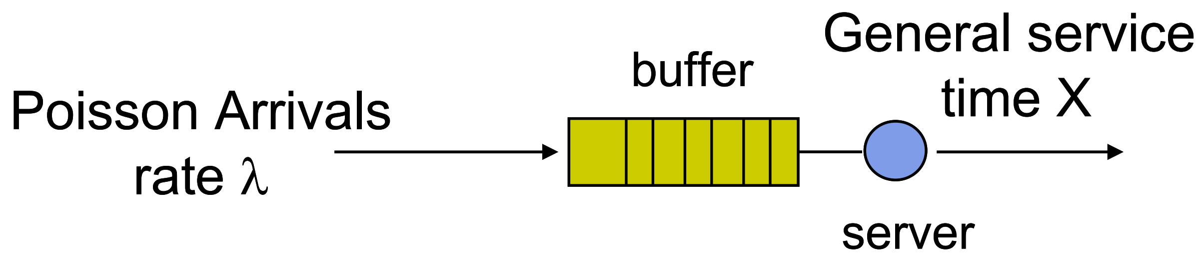
Comparison of MAC approaches

- 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
  - 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

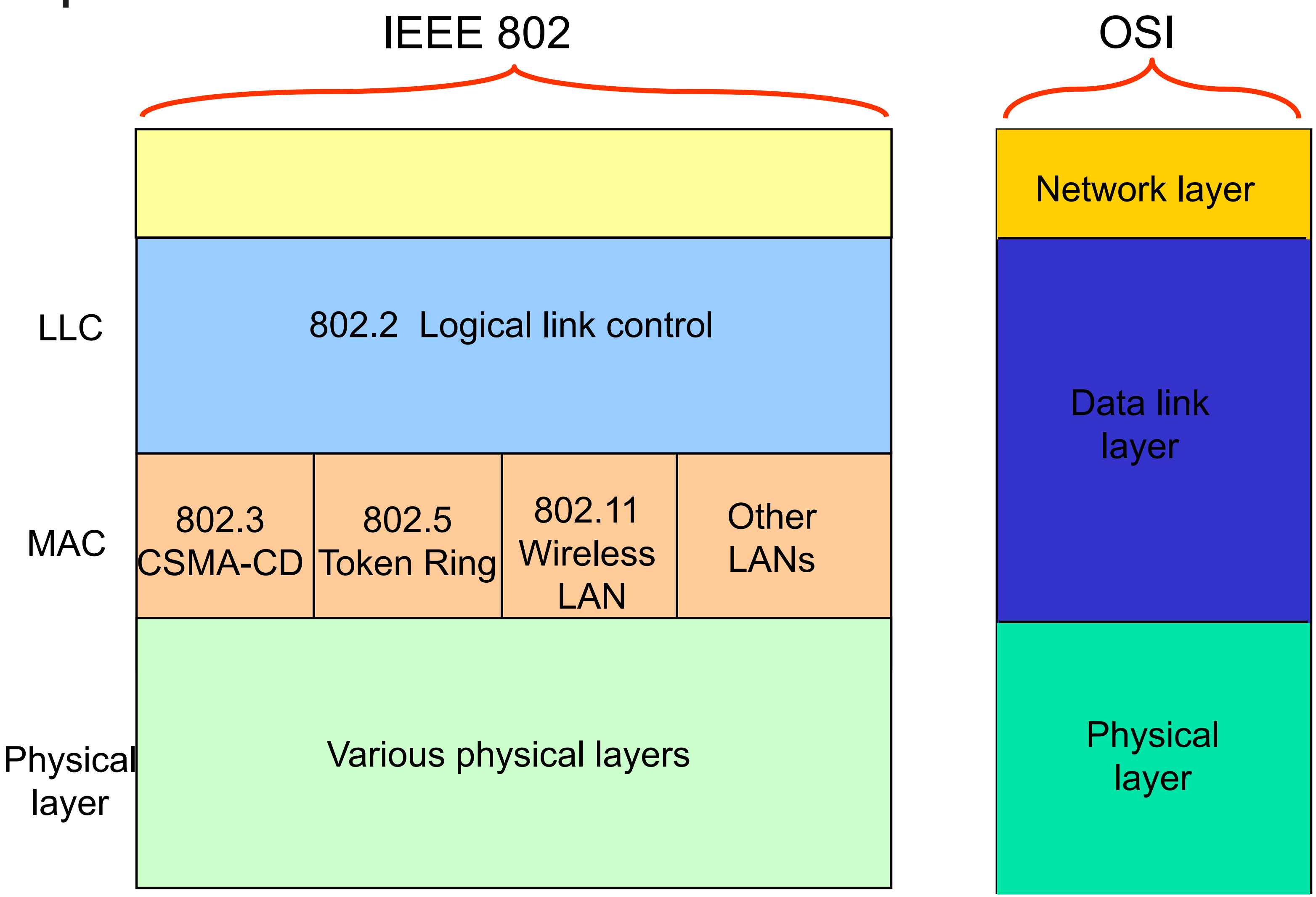
- In M/G/1 model, a frame arriving to an empty multiplexer begins transmission immediately
- In many MACs, there is a delay before transmission can begin
- *M/G/1 Vacation Model*: when system empties, server goes away on vacation for random time V

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

Extra delay term

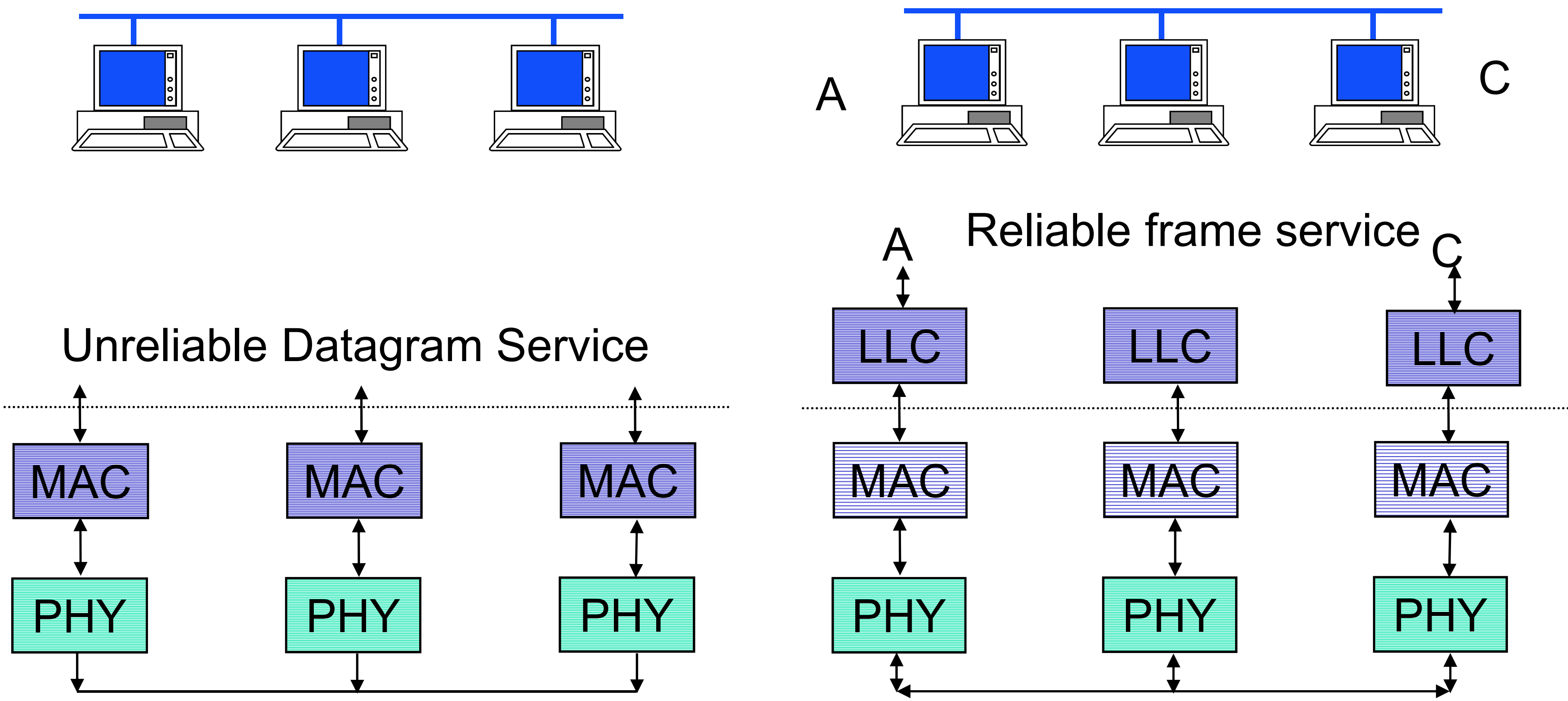
MAC in Different Networks

IEEE 802 Networks



Logical Link Control Layer

- IEEE 802.2: LLC enhances service provided by MAC

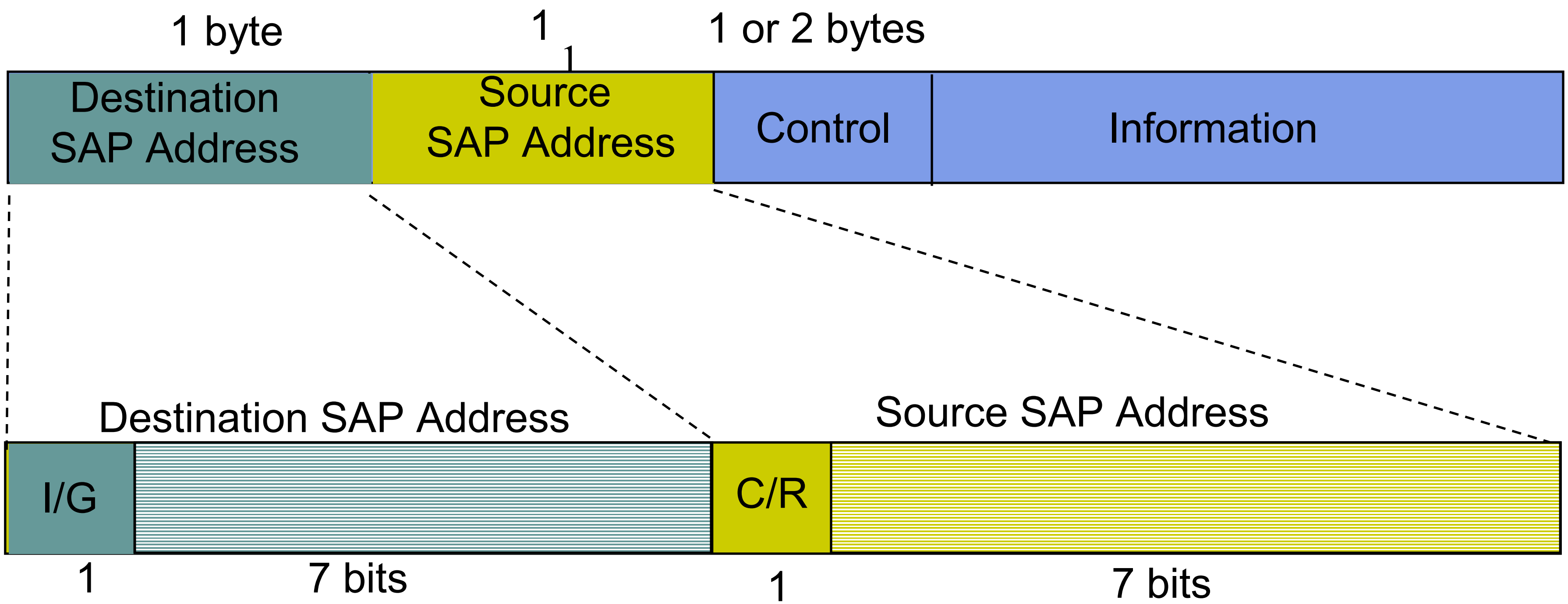


Logical Link Control Services

- 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).

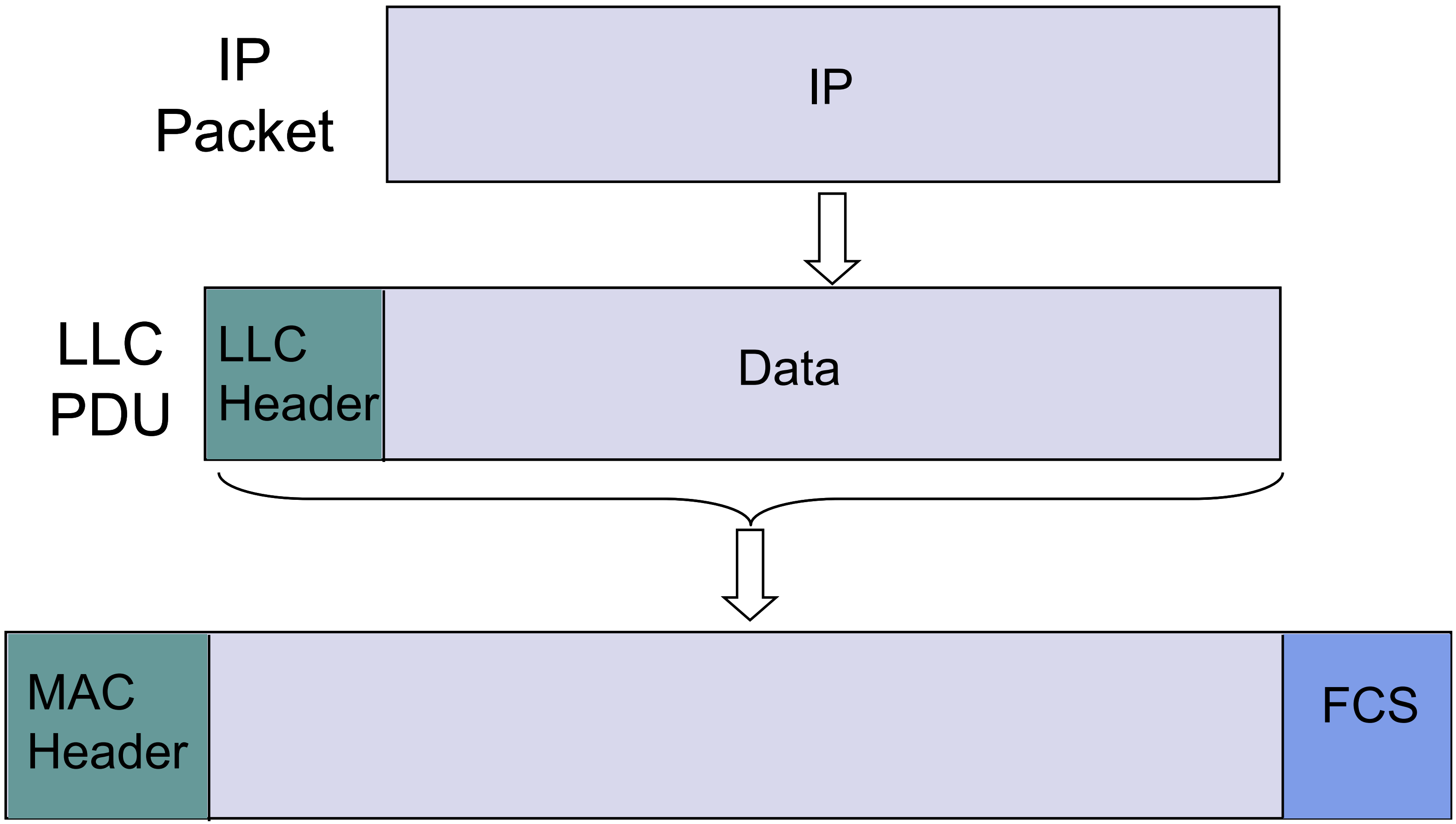
LLC PDU Structure



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{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

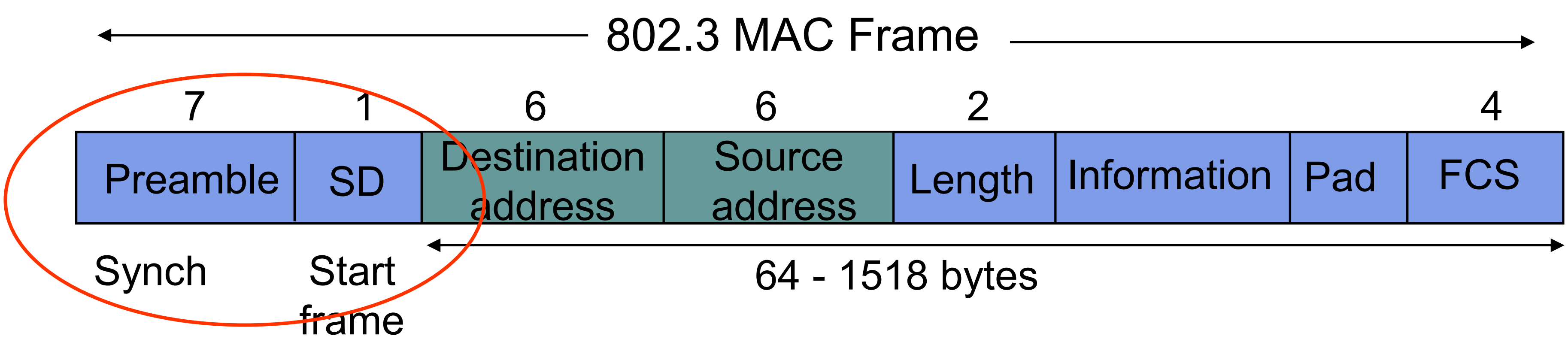
IEEE 802.3 Original Parameters

- Transmission Rate: 10 Mbps
- Min Frame: 512 bits = 64 bytes
- Slot time: 512 bits/10 Mbps = 51.2 μsec
  - 51.2 μsec x 2x10^5 km/sec =10.24 km, 1 way
  - 5.12 km round trip distance
- Max Length: 2500 meters + 4 repeaters

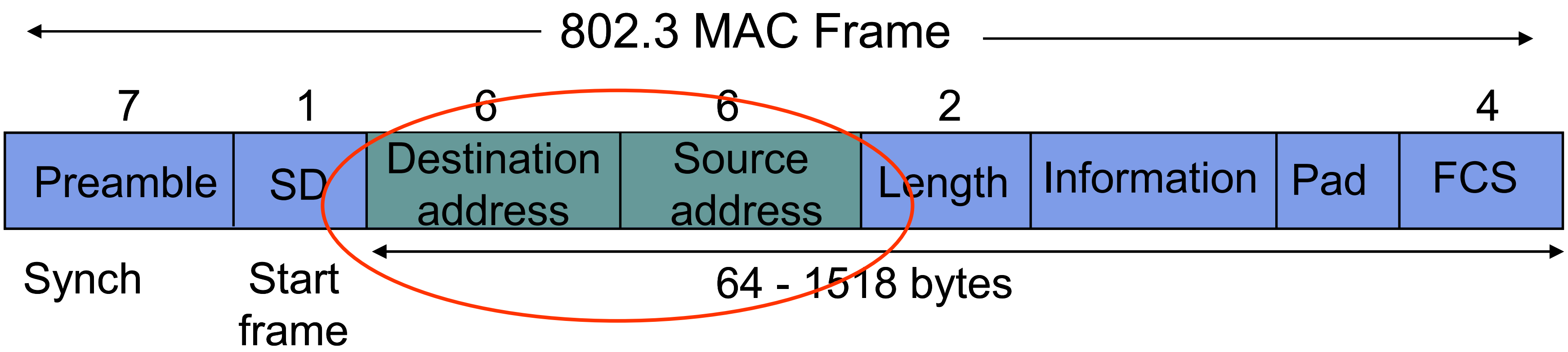
- *Each x10 increase in bit rate, must be accompanied by x10 decrease in distance*

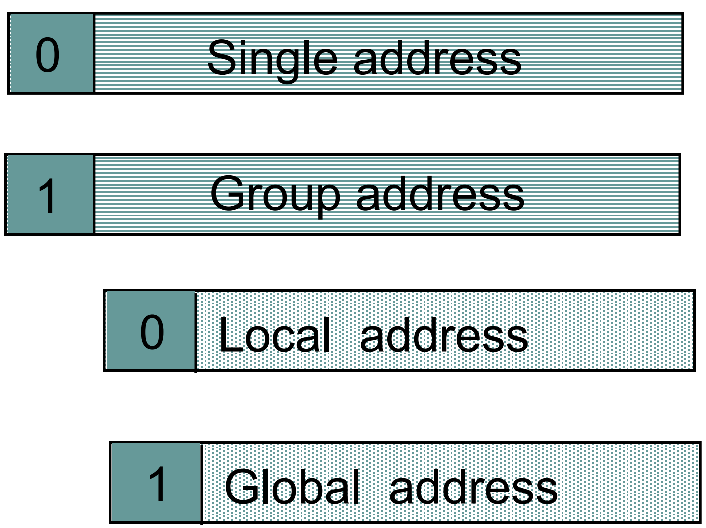
IEEE 802.3 MAC Frame

- 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

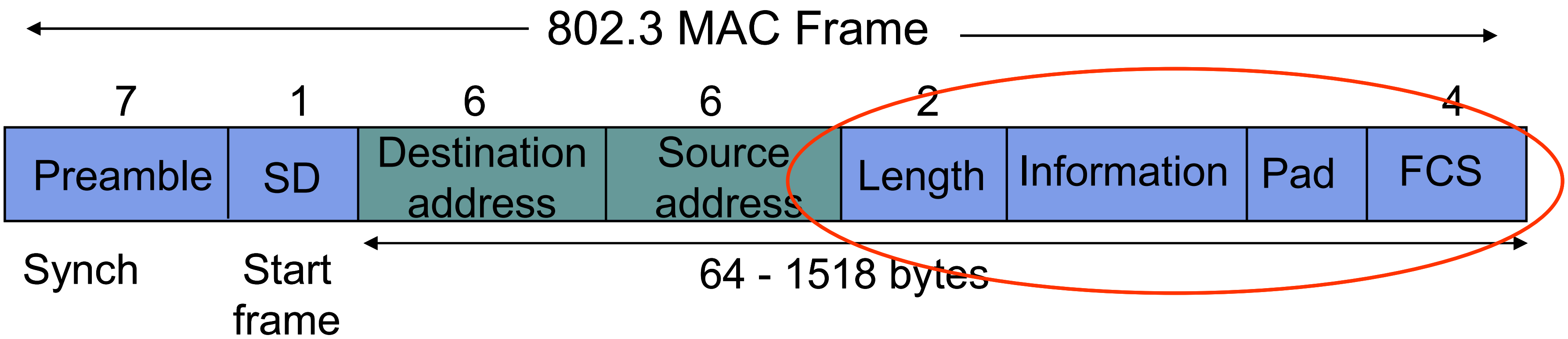




- Destination address
  - single address
  - group address
  - broadcast = 111...111

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

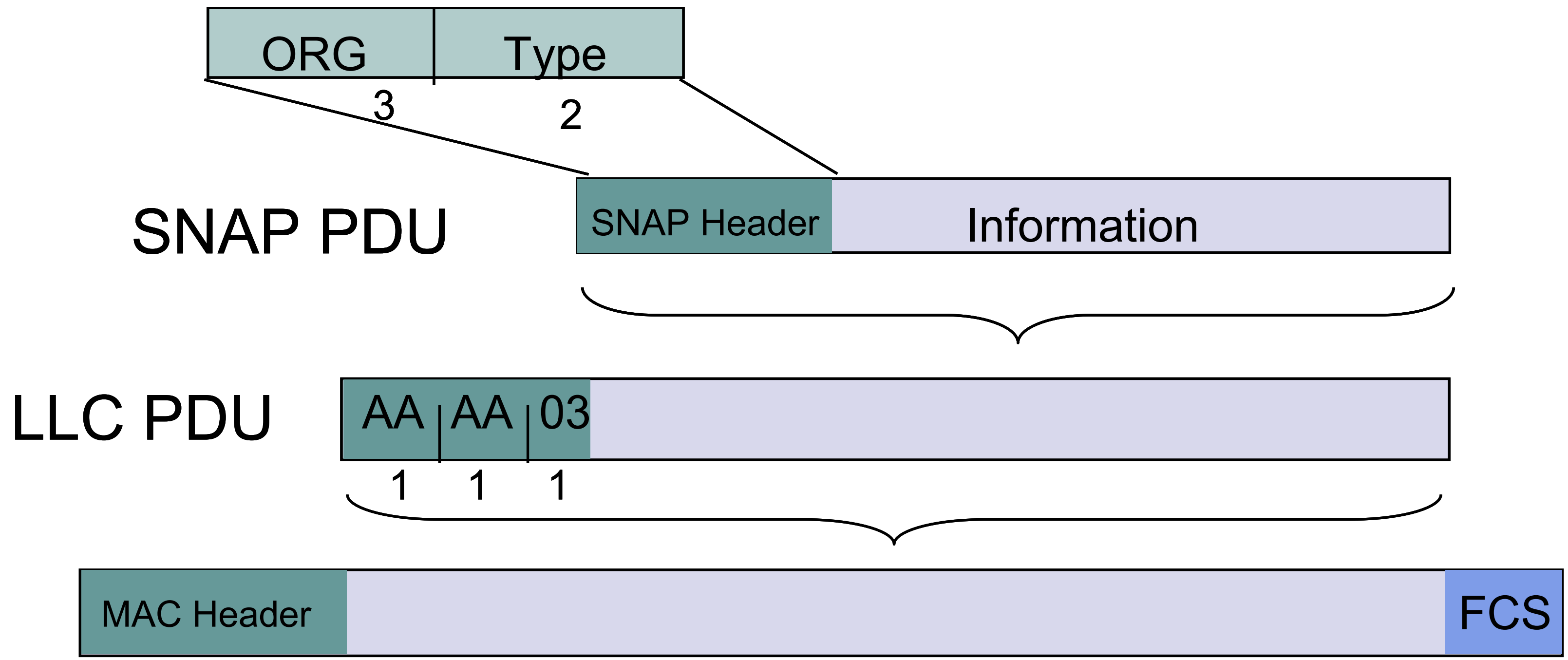
IEEE 802.3 MAC Frame



- 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

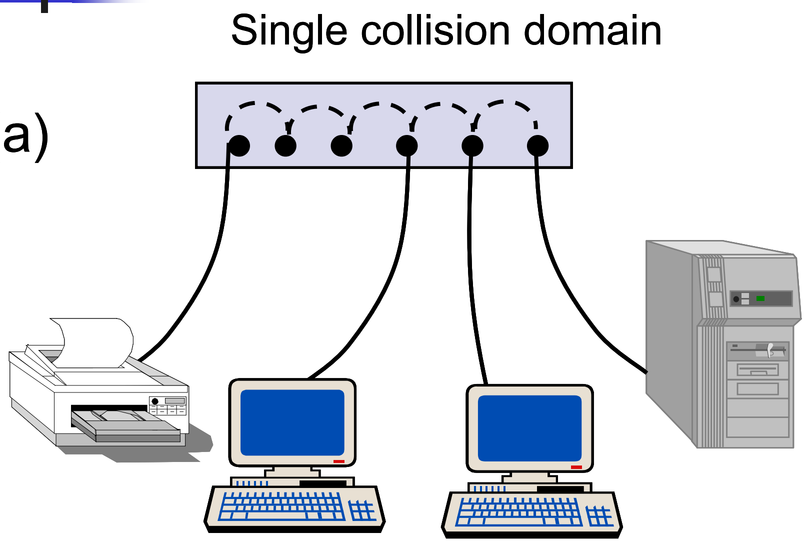
SubNetwork Access Protocol (SNAP)

- 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

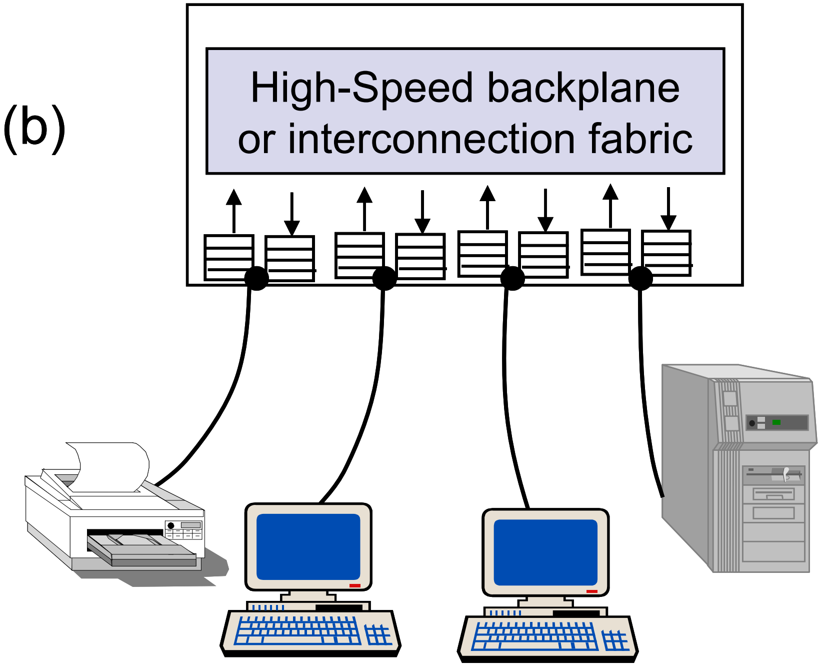


Ethernet Hubs & Switches

(a)



(b)

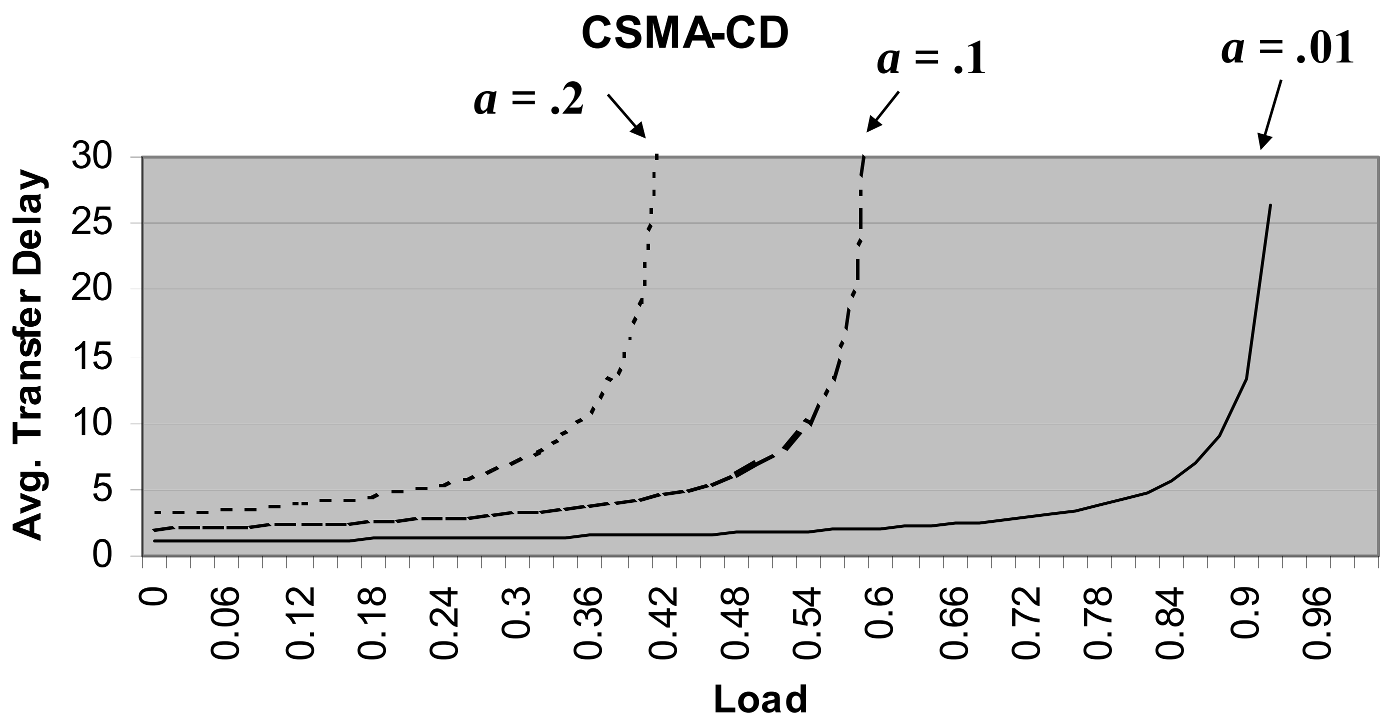


Twisted Pair Cheap
Easy to work with
Reliable
Star-topology CSMA-CD

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

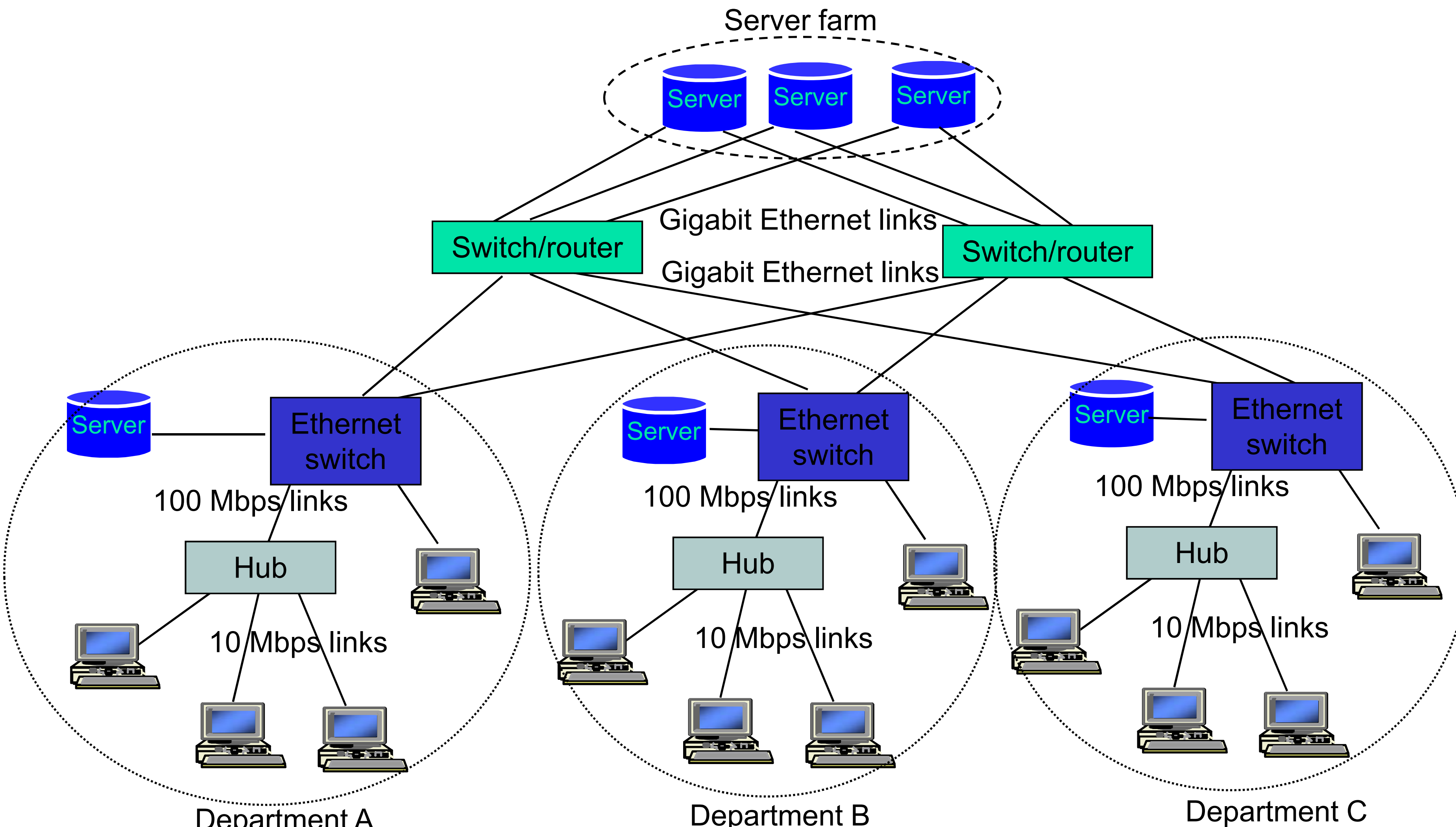
	100baseT4	**100baseT**	**100baseFX**
Medium	Twisted pair category 3 UTP 4 pairs	Twisted pair category 5 UTP two pairs	Optical fiber multimode Two strands
Max. Segment Length	100 m	100 m	2 km
Topology	Star	Star	Star

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



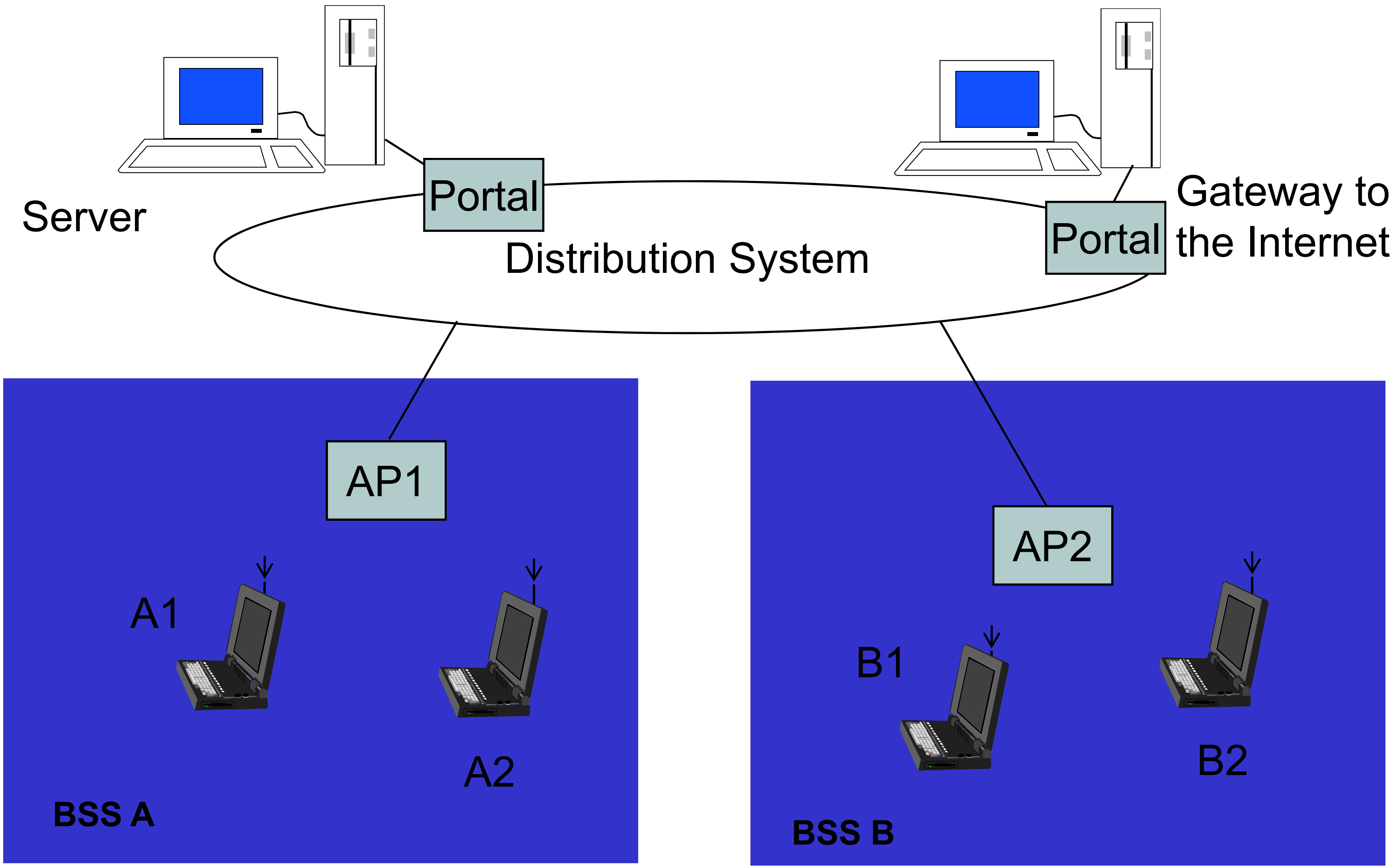
IEEE 802.11 Wireless LAN

- 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

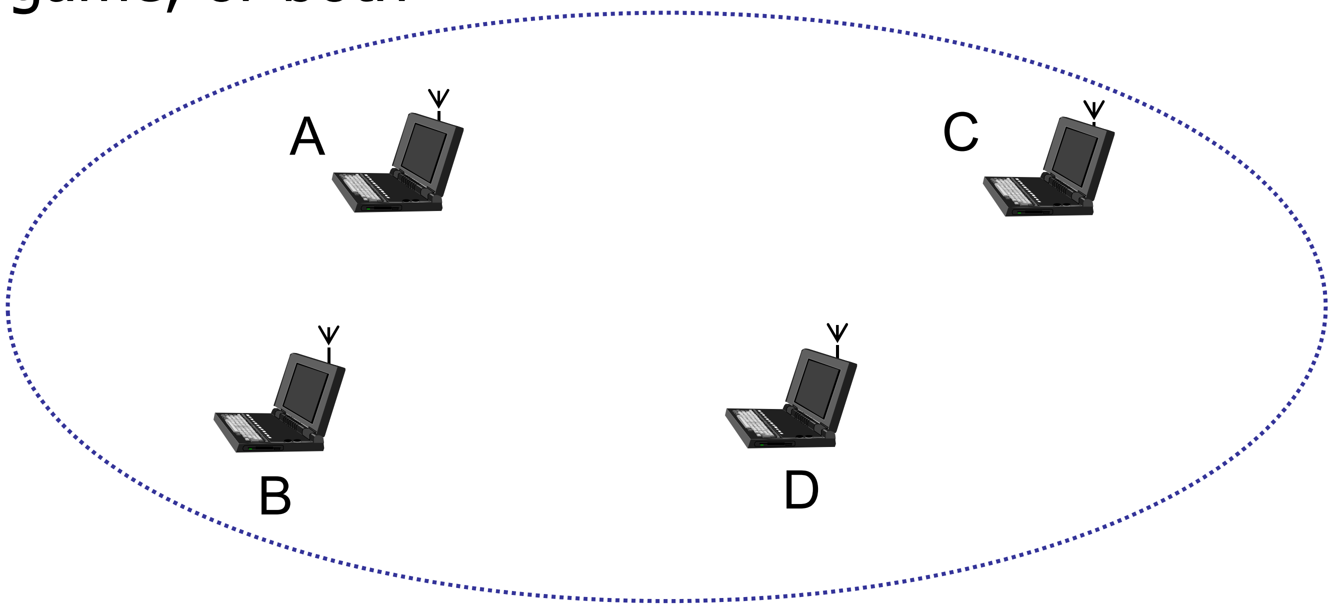
- *Basic Service Set* (BSS)
  - Group of stations that *coordinate their access* using a given instance of MAC
  - Located in a *Basic Service Area* (BSA)
  - Stations in BSS can communicate with each other
  - Distinct collocated BSS's can coexist
- *Extended Service Set* (ESS)
  - Multiple BSSs interconnected 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

- 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

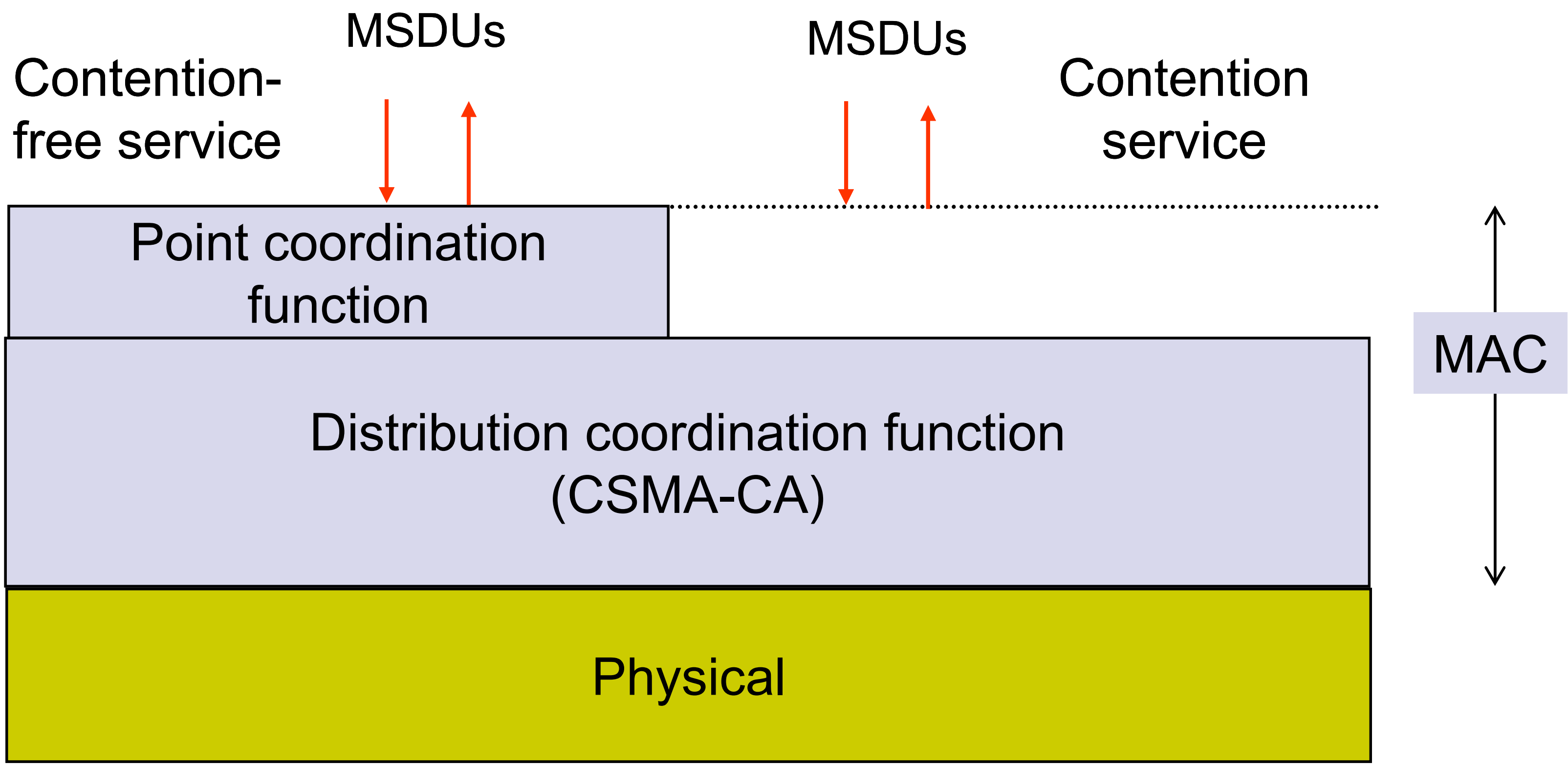
- Select AP and establish *association* with AP
  - Then can send/receive frames via AP & DS
- *Reassociation service* to move from one AP to another AP
- *Dissociation service* to terminate association
- *Authentication service* to establish identity of other stations
- *Privacy service* to keep contents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

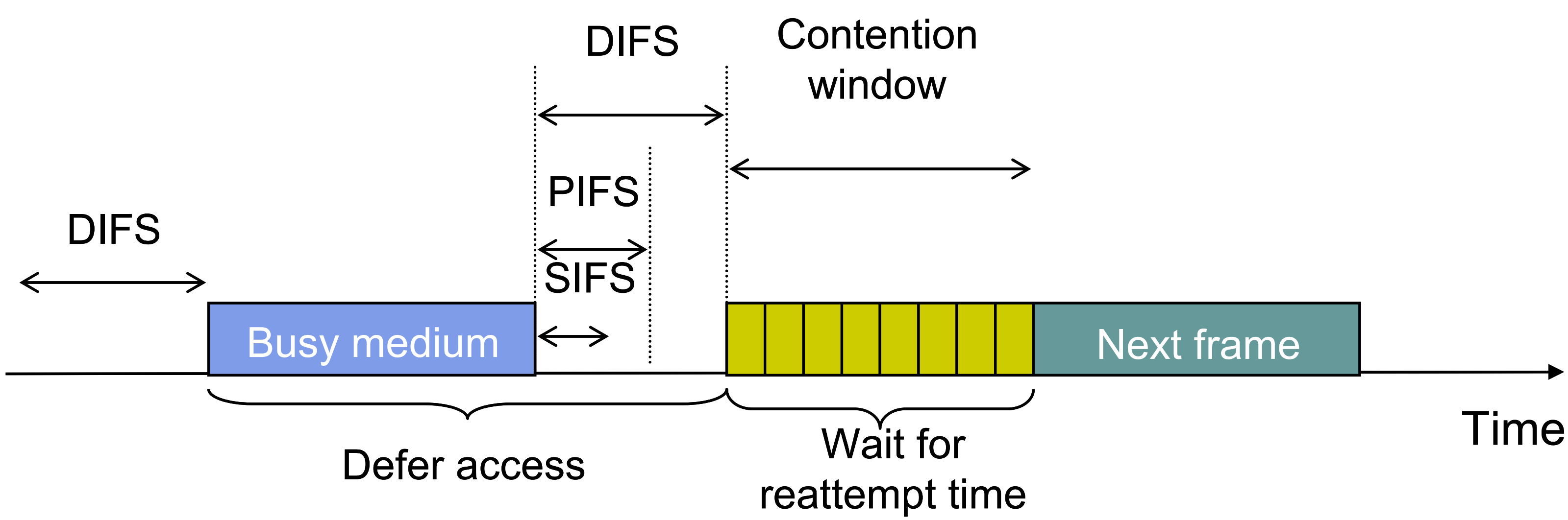
MAC Services

- 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)*



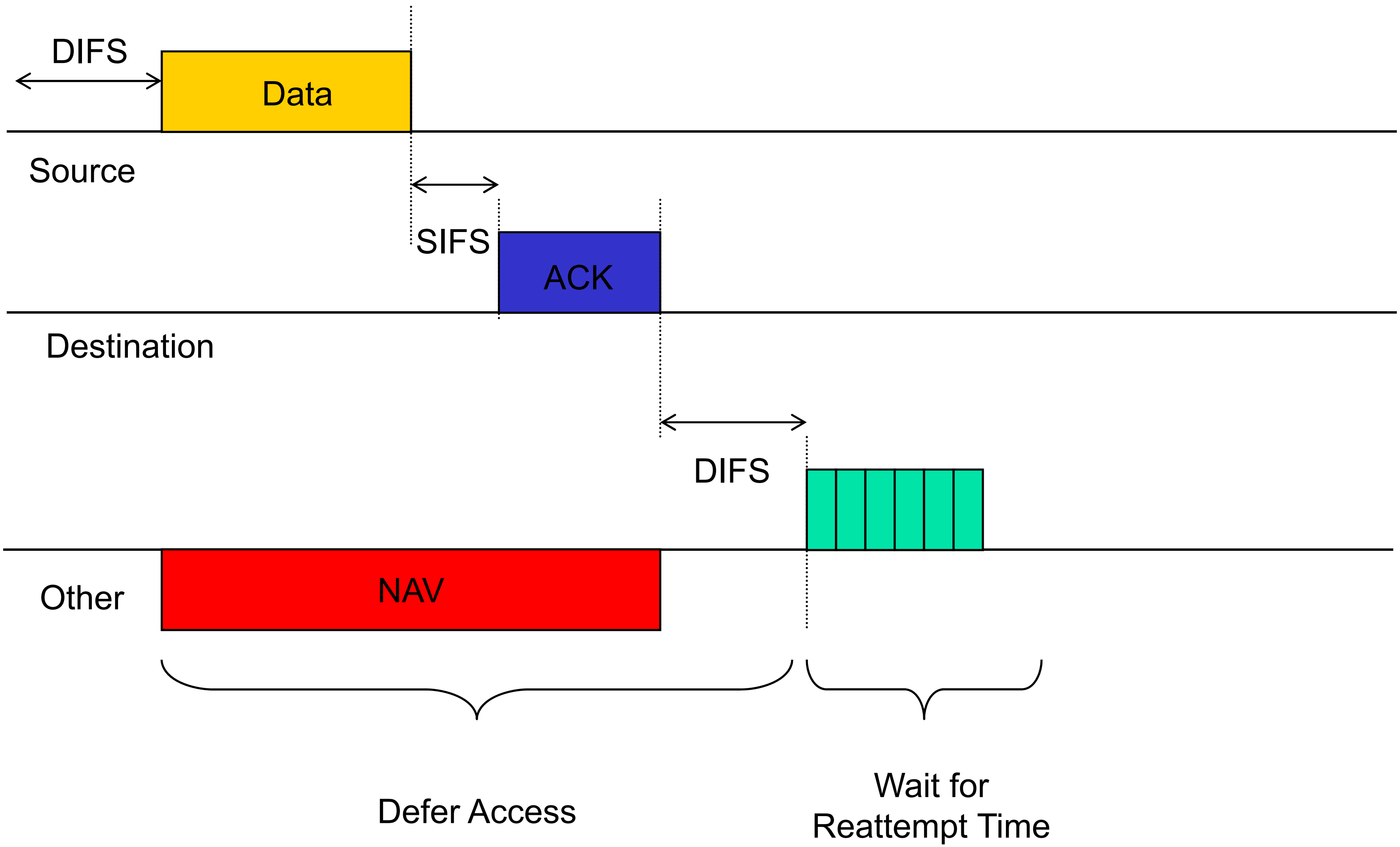
Carrier Sensing in 802.11

- *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 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

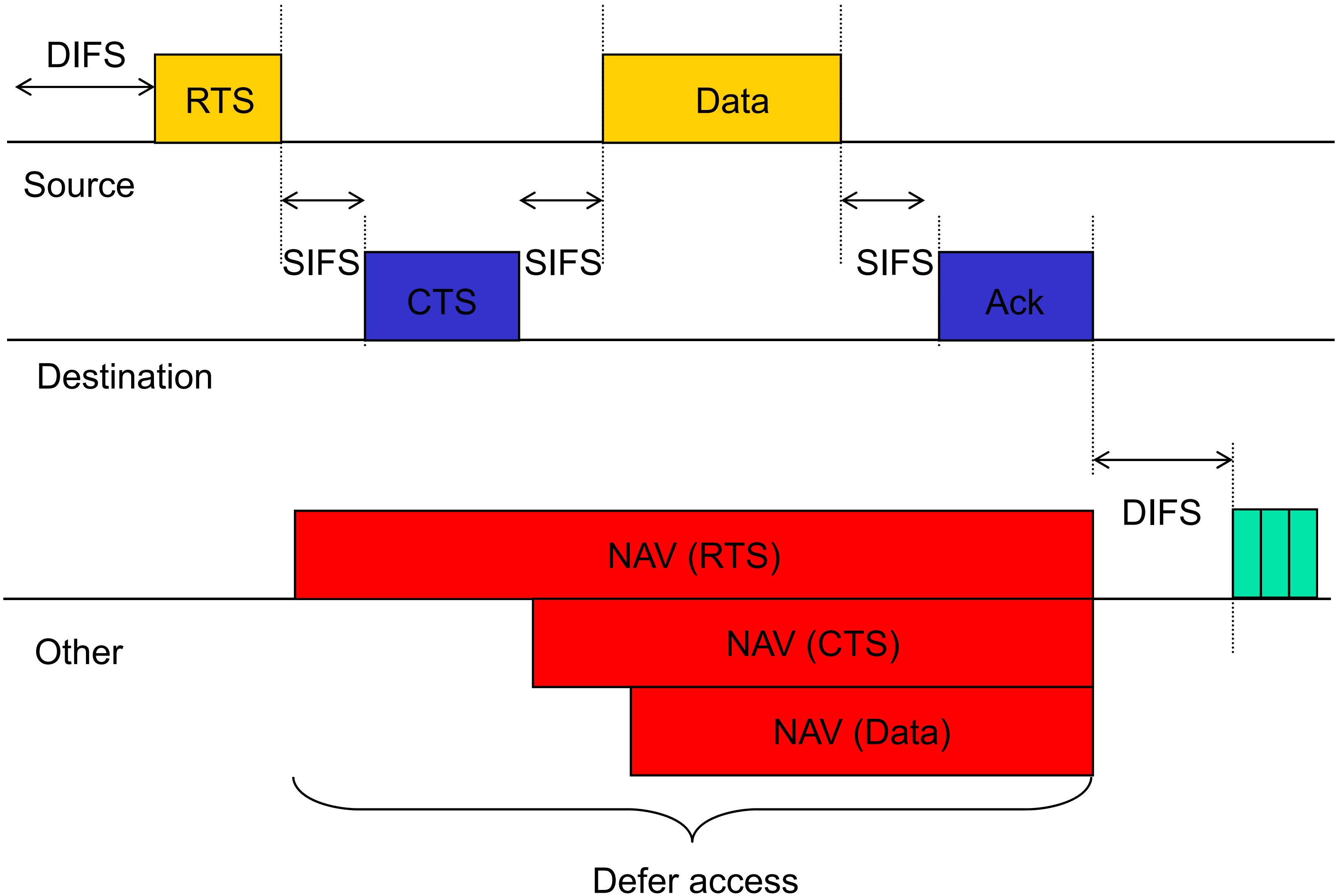
Contention & Backoff Behavior

- 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



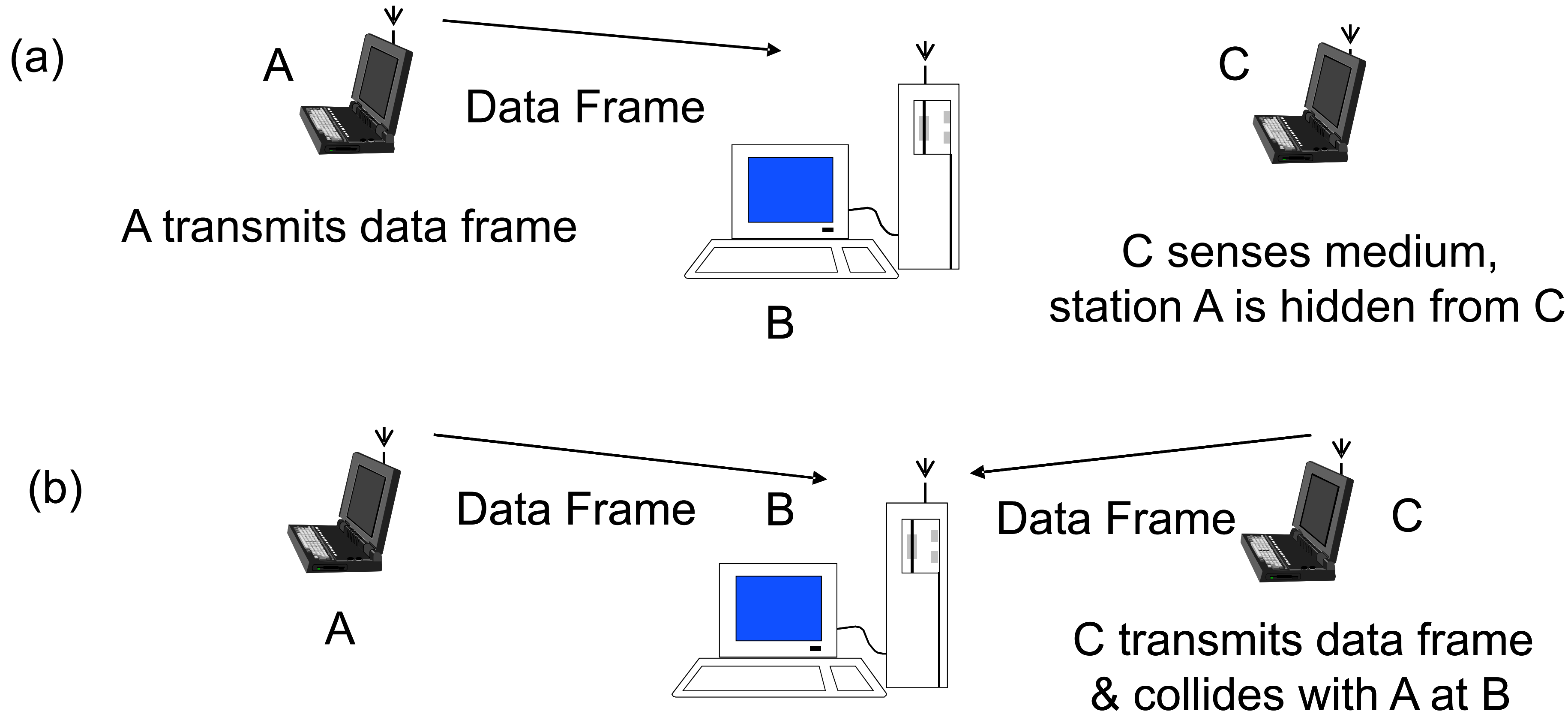
Transmission of MPDU with RTS/CTS



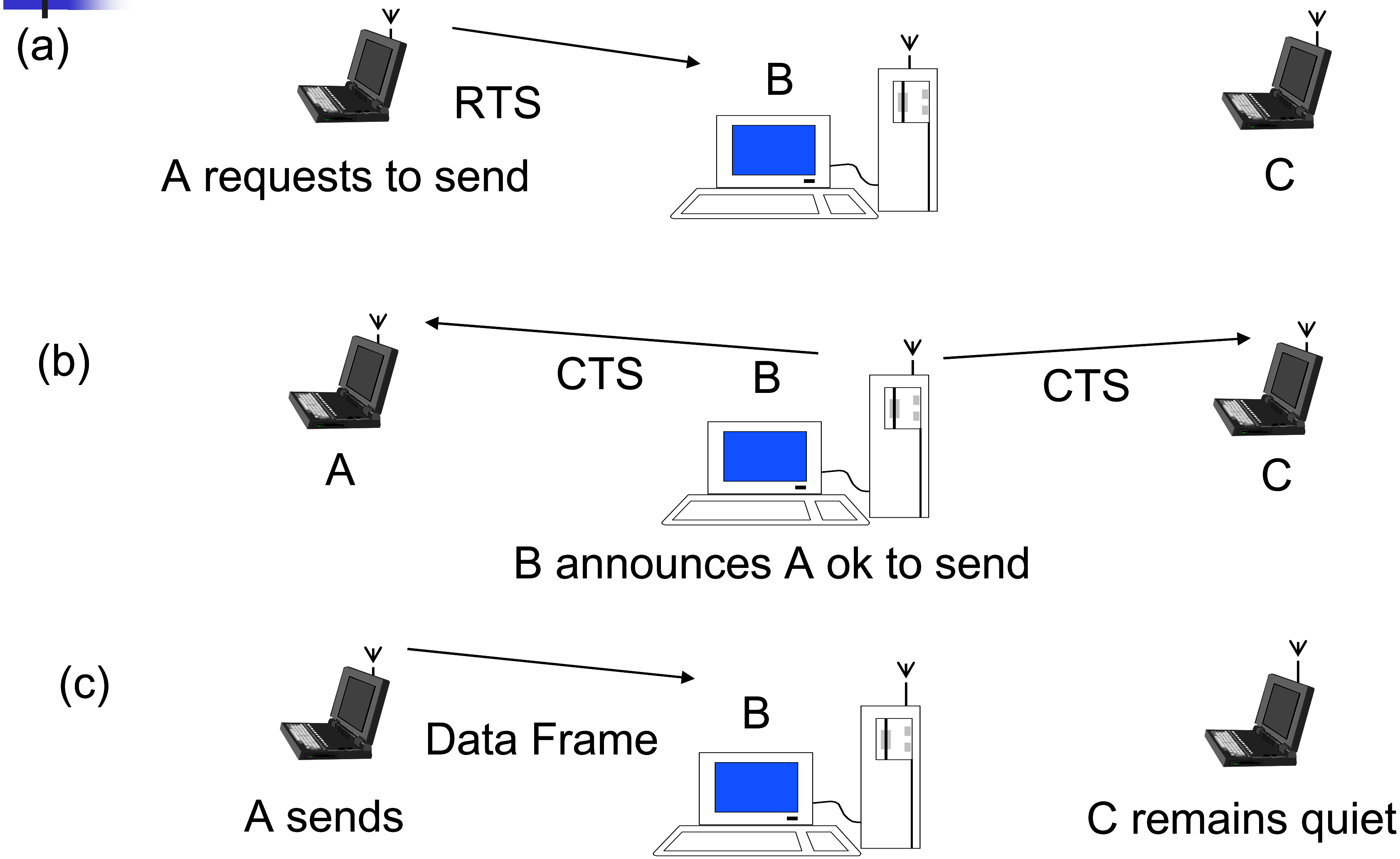
Collisions, Losses & Errors

- 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



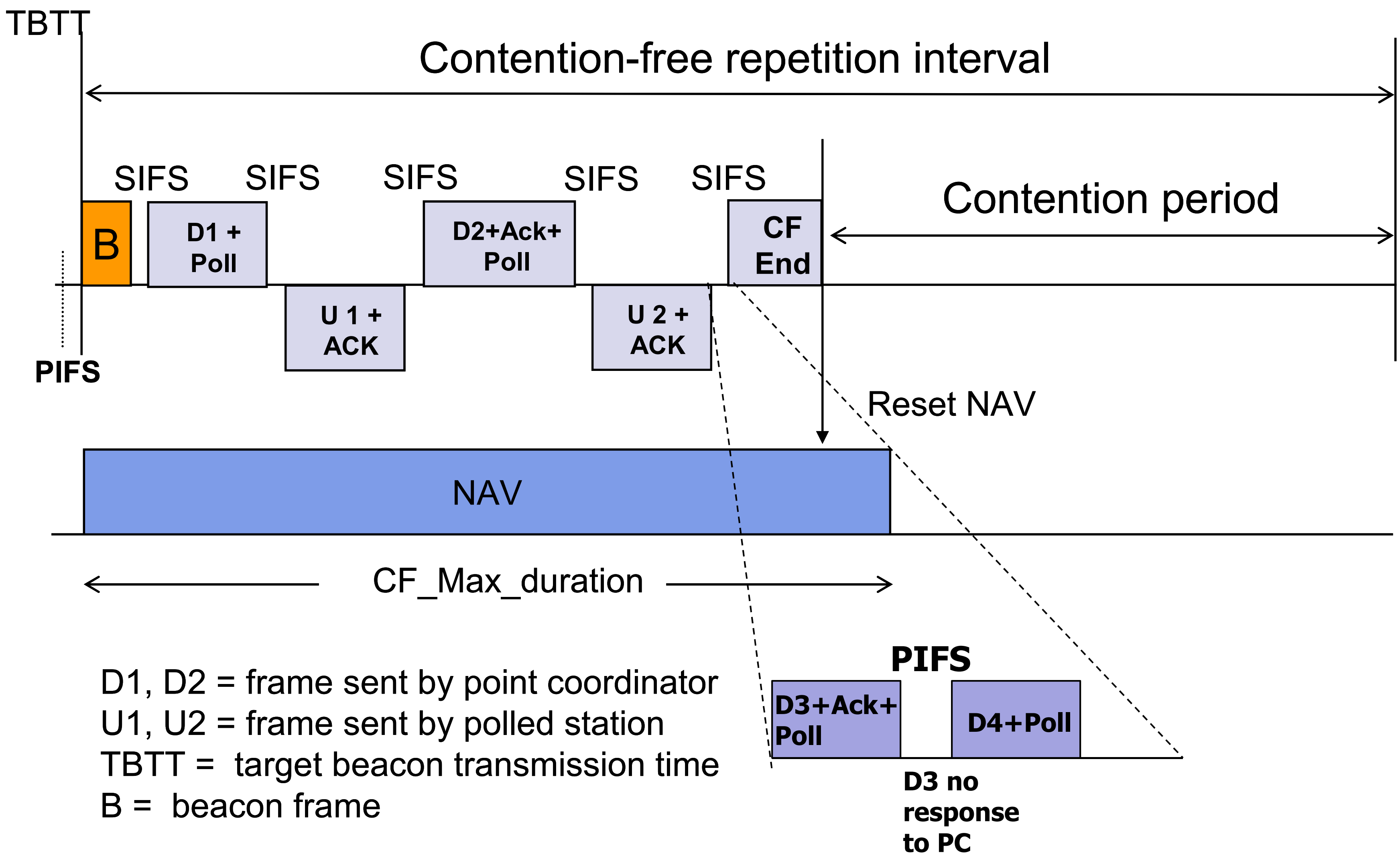
Collision avoidance and virtual carrier sensing



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



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

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

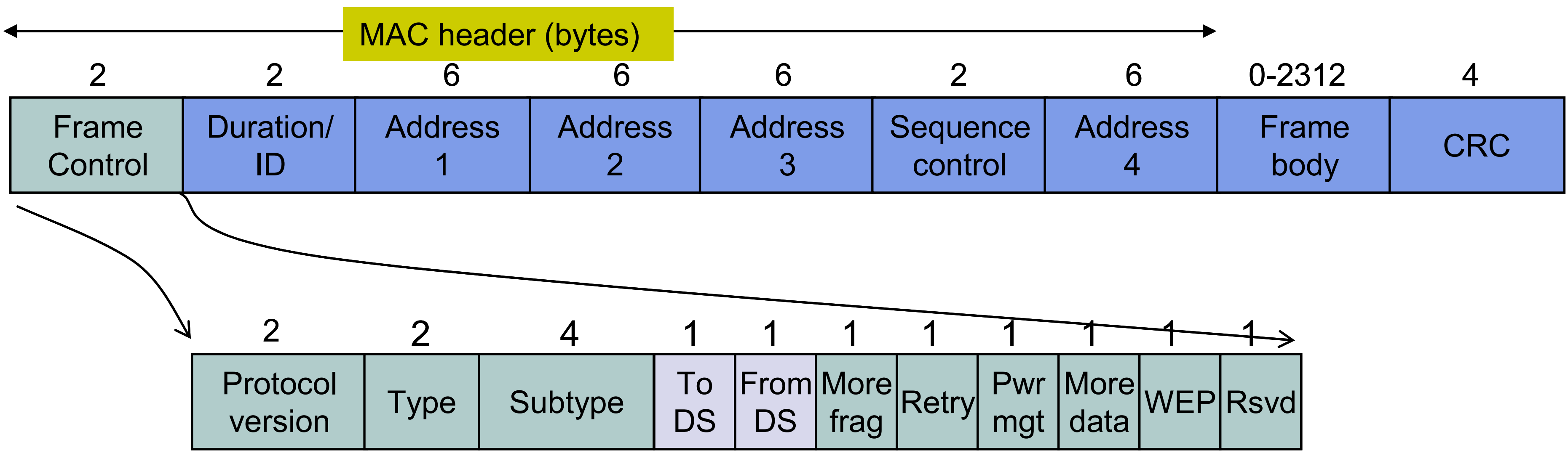
- MAC Header: 30 bytes
- Frame Body: 0-2312 bytes
- CRC: CCITT-32 4 bytes CRC over MAC header & frame body

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)

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

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

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

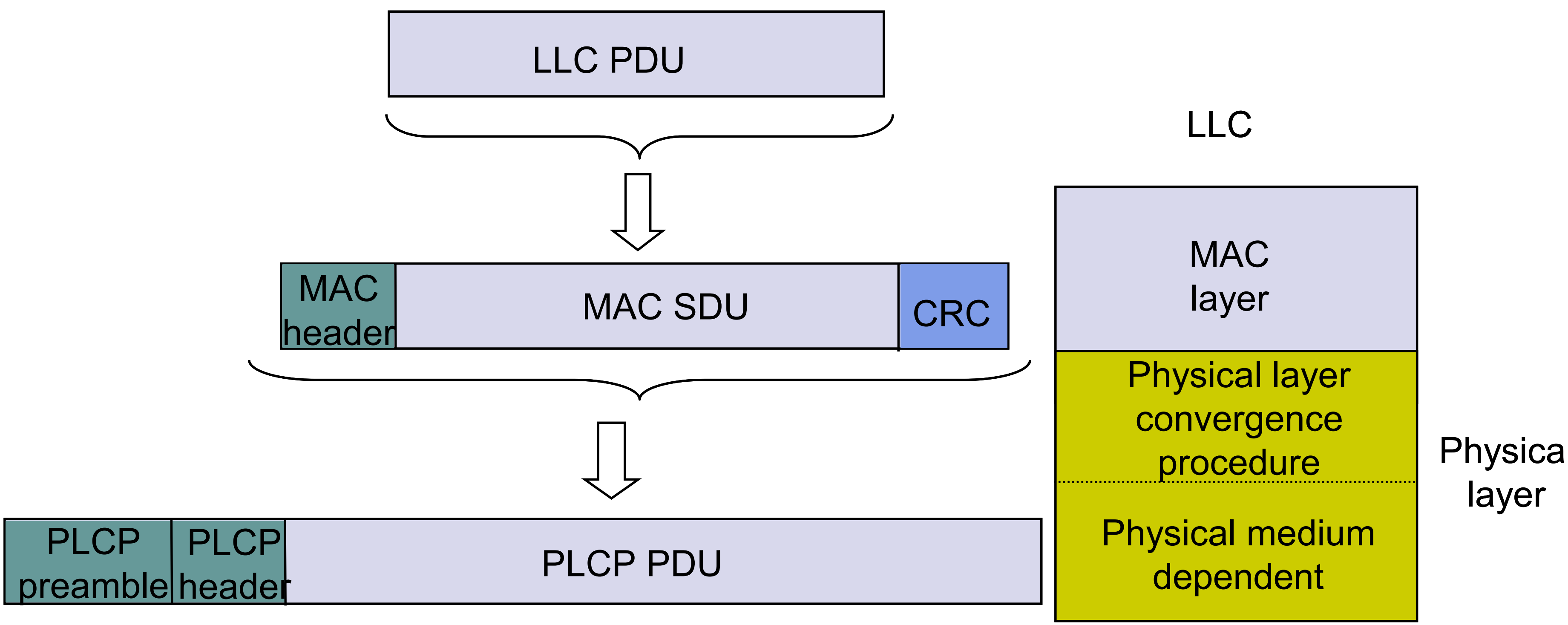
MAC header (bytes)

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

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

802.11 protocol layers

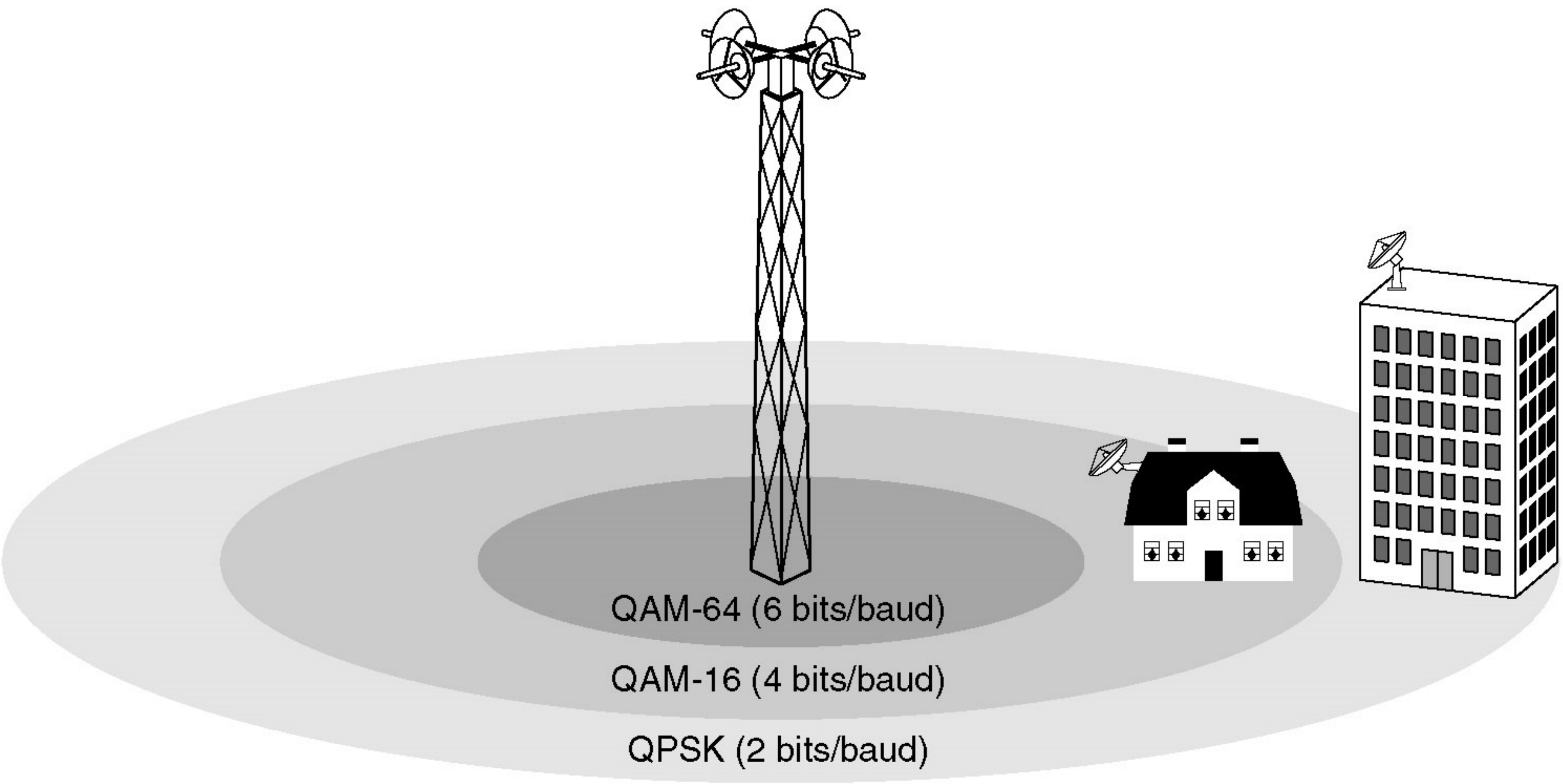
- 802.11 designed to
  - Support LLC
  - Operate over many physical layers



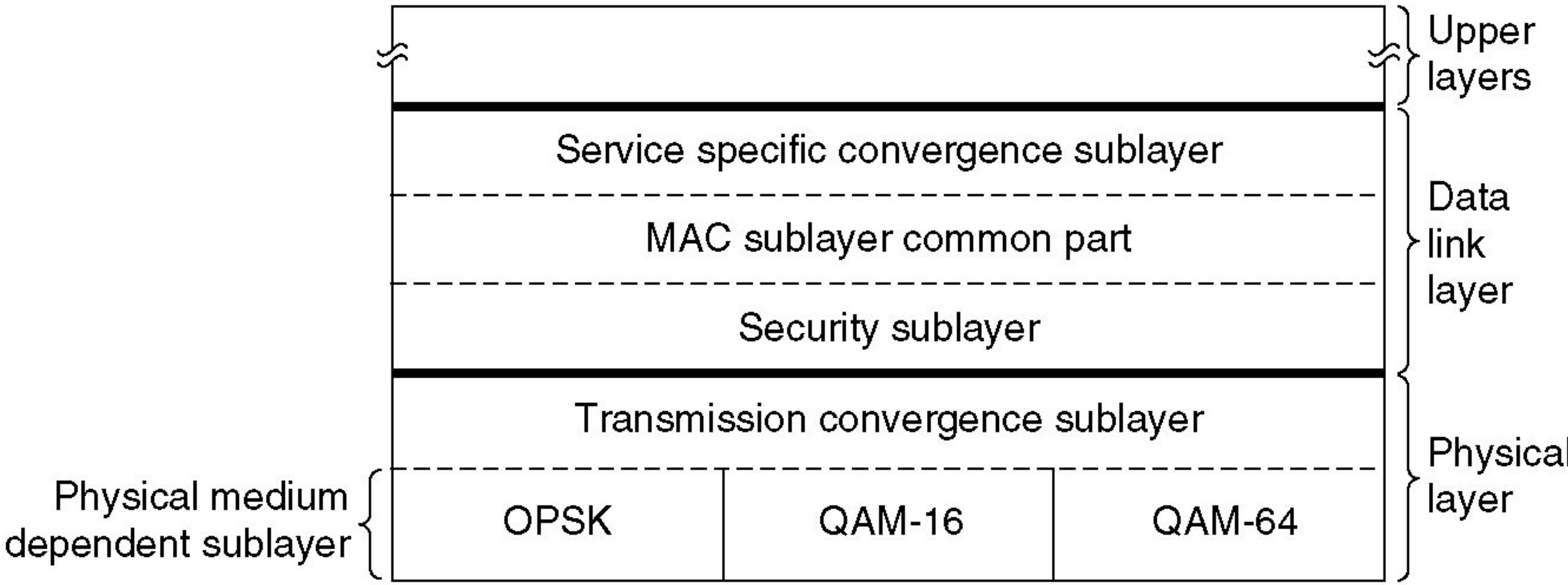
802.11 Phy options

	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

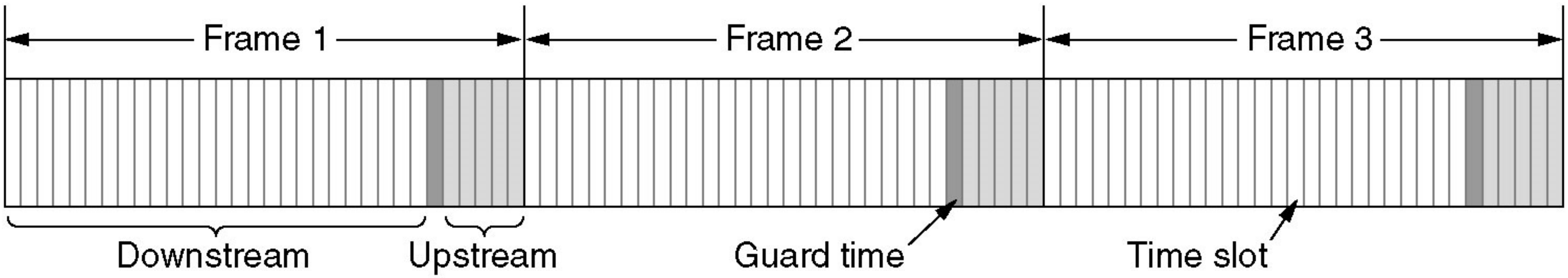


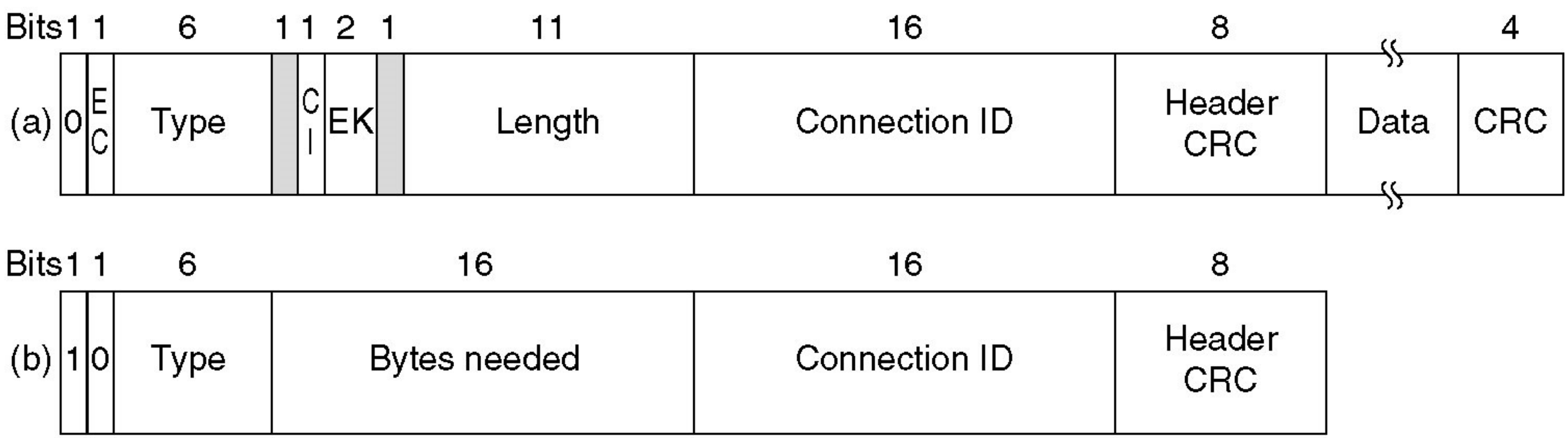
802.16 Protocol Stack



Services and Frame Structure

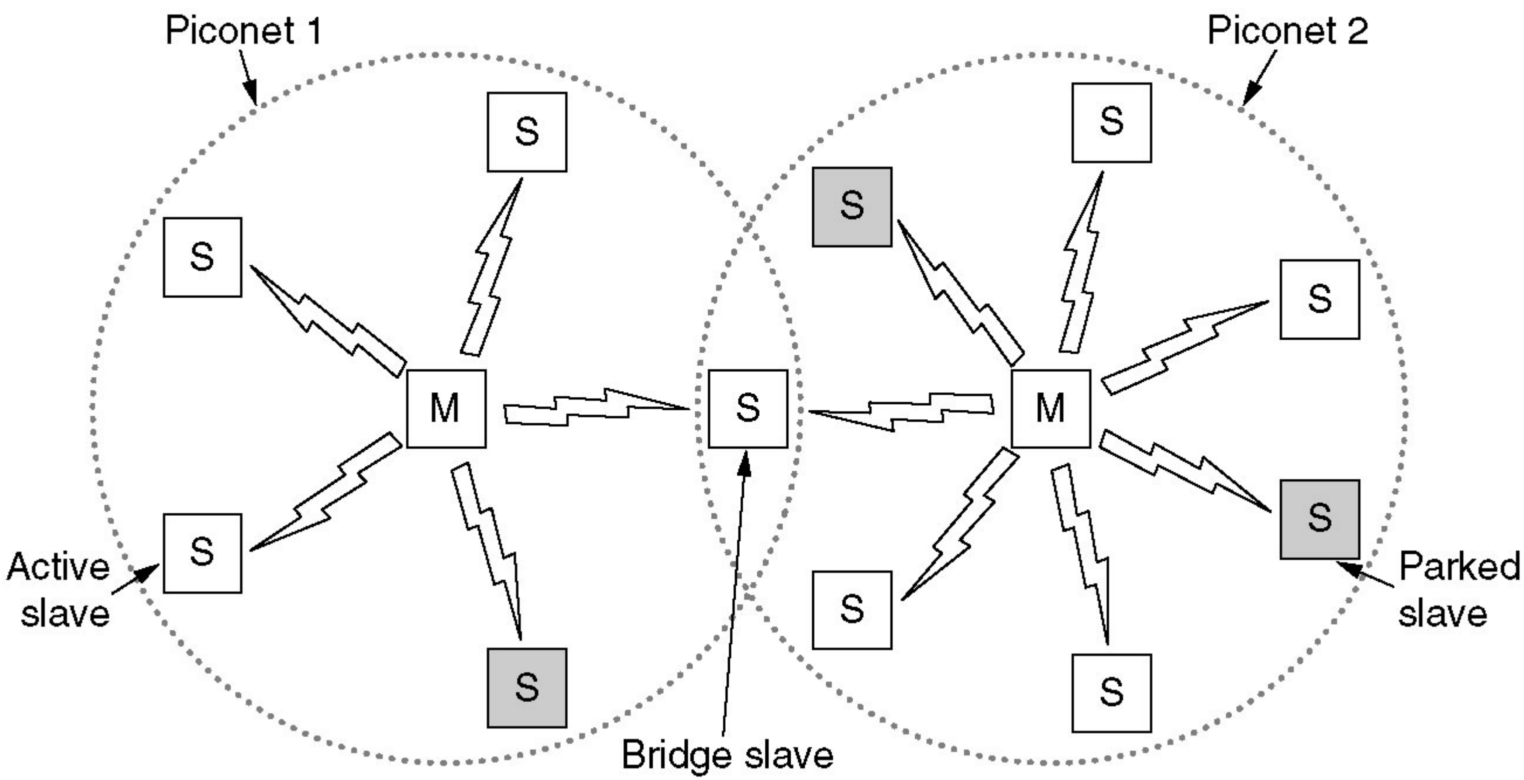
- Constant bit rate service
- Real-time variable bit rate service
- Non-real-time variable bit rate service
- Best efforts service





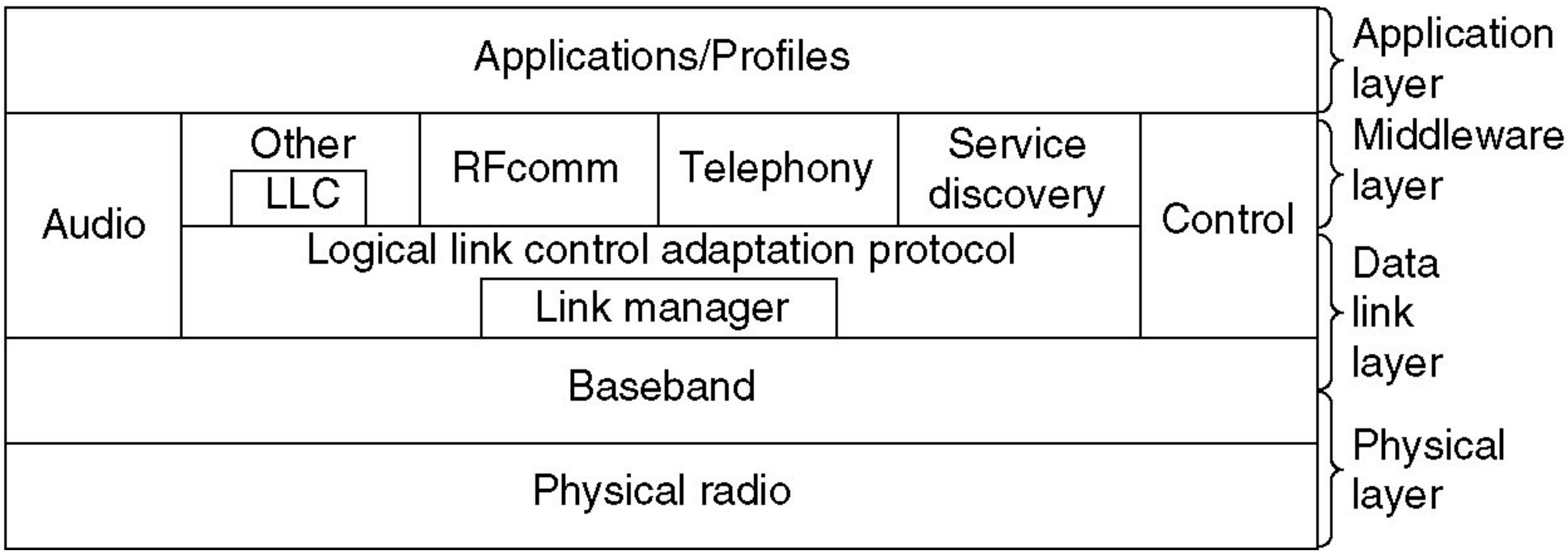
(a) **A generic frame.** (b) **A bandwidth request frame.**

Bluetooth

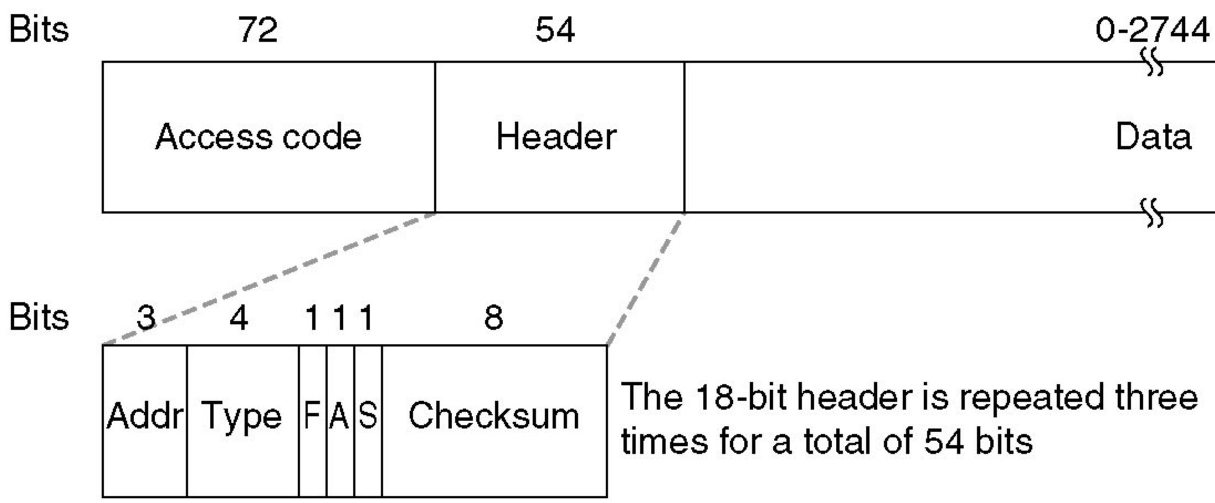


Piconet 1
Piconet 2
S
S
S
S
S
M
M
S
S
S
S
S
S
S
S
Active slave
Parked slave
Bridge slave

Bluetooth Protocol Stack



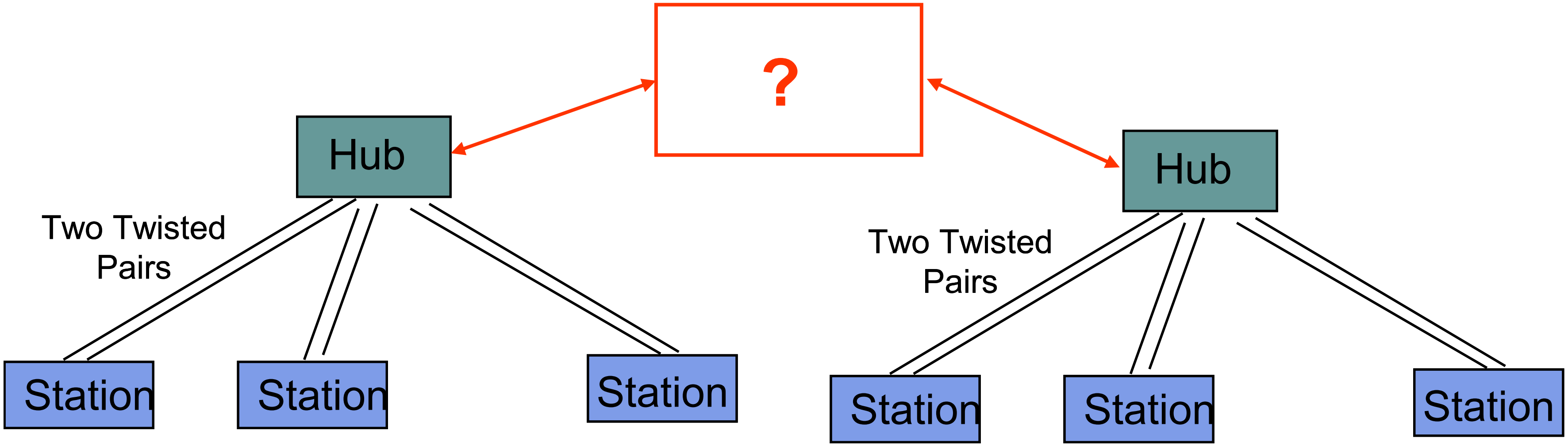
Bluetooth Frame Structure



Bridging and Switching

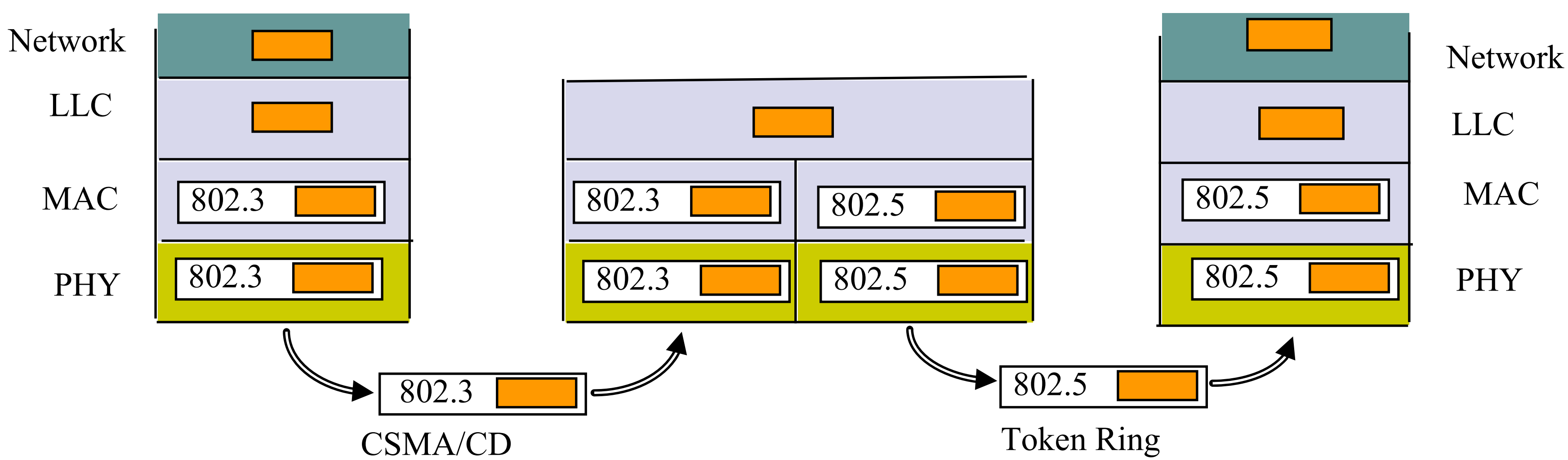
Hubs, Bridges & Routers

- 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

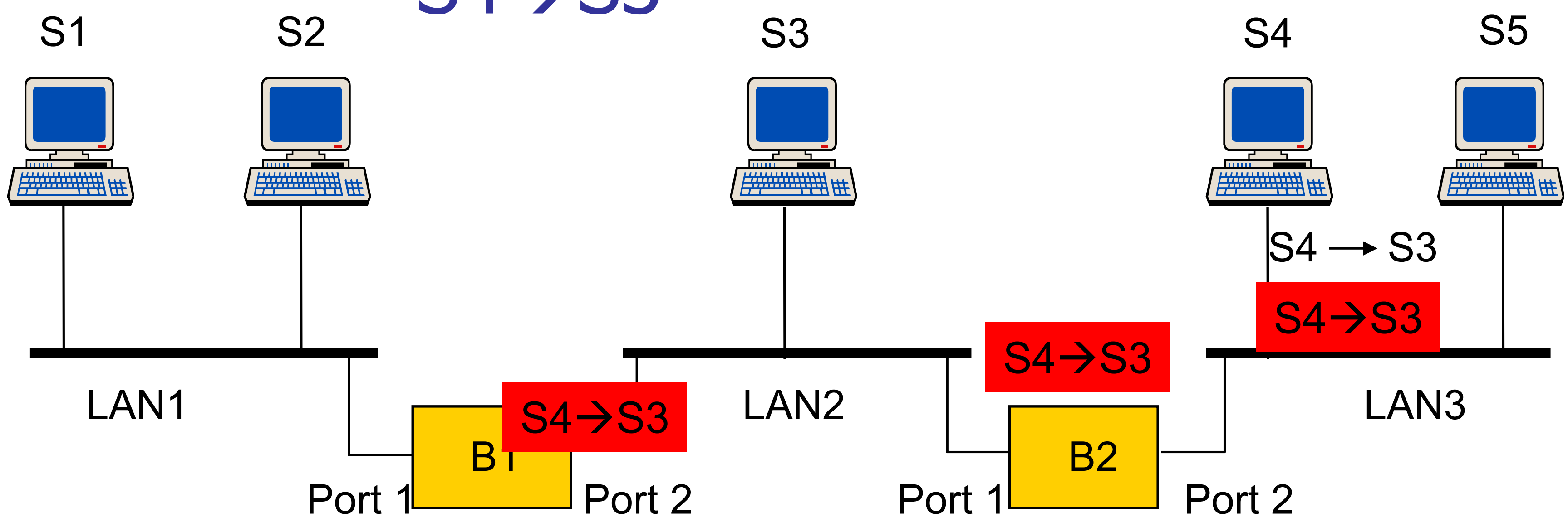


Transparent Bridges

- 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→S3



Address	Port
S1	1
S3	2
S4	2

Address	Port
S1	1
S3	1
S4	2

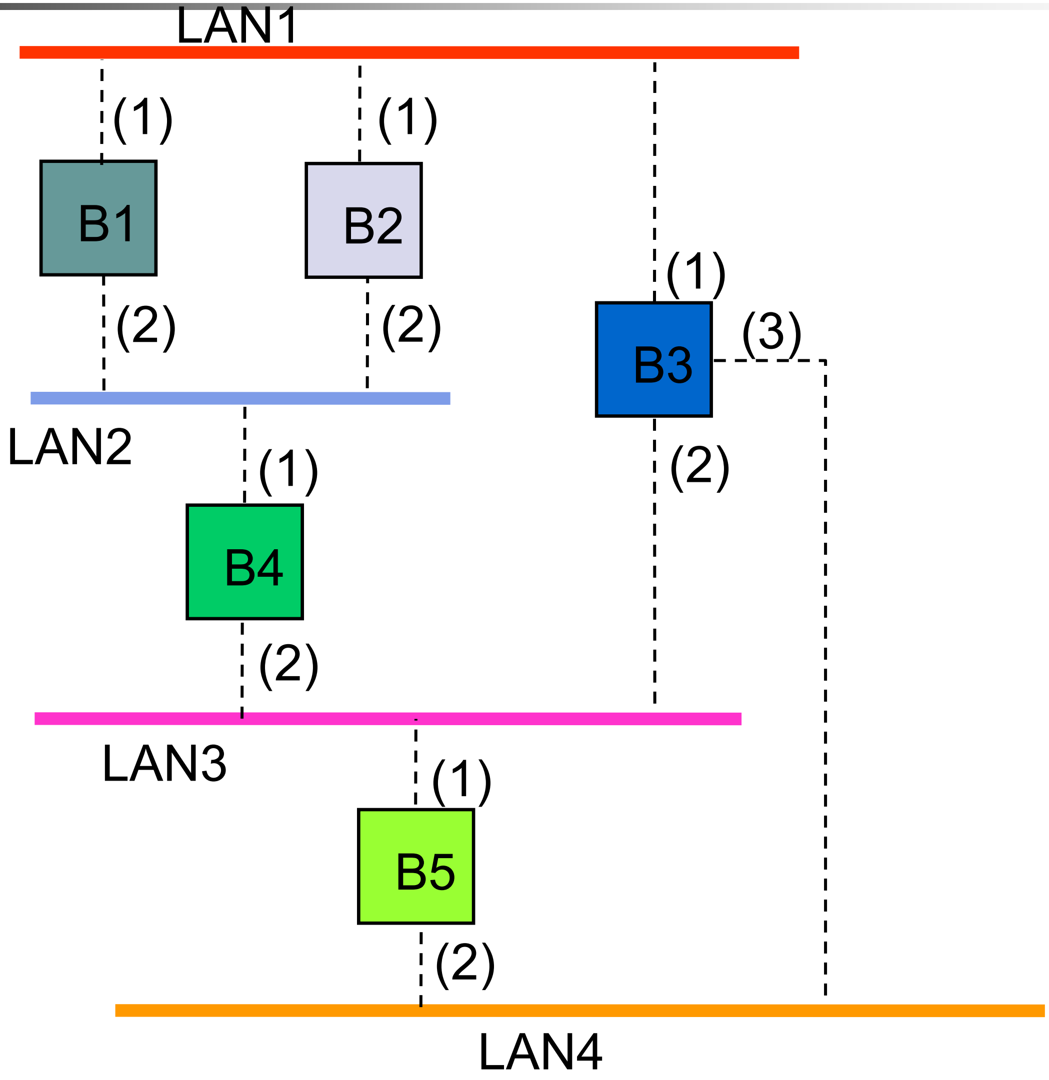
Adaptive Learning

- 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

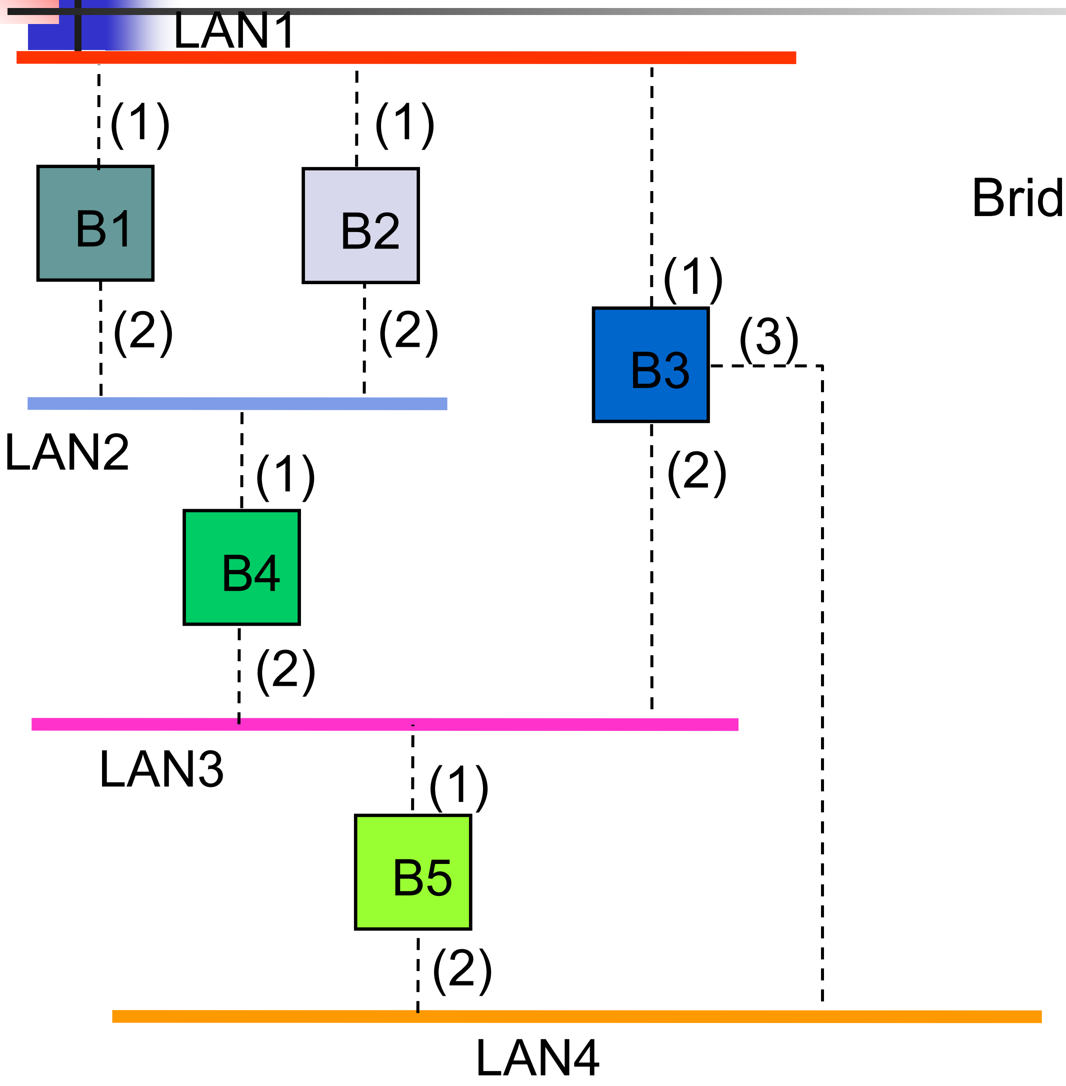
Spanning Tree Algorithm

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)

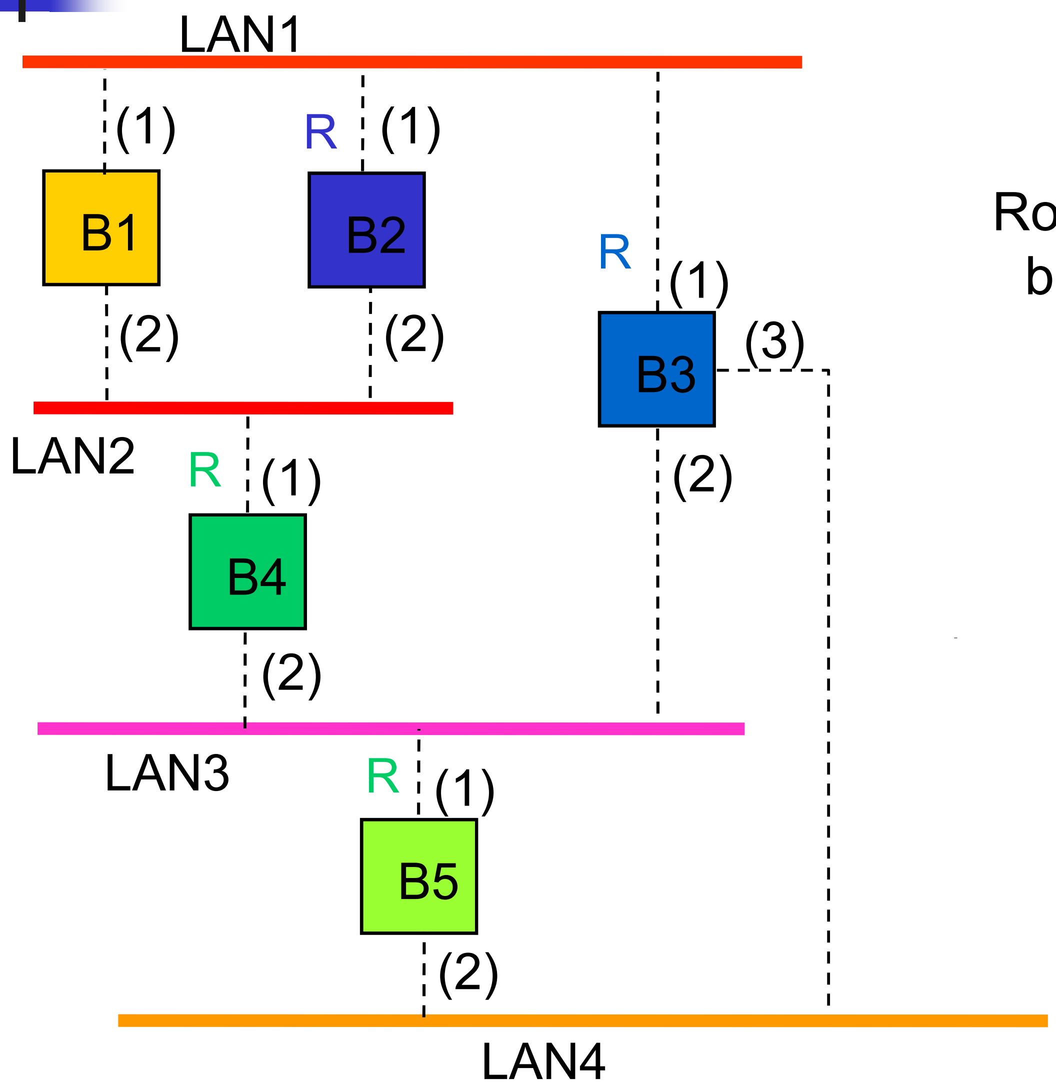


Example (2)



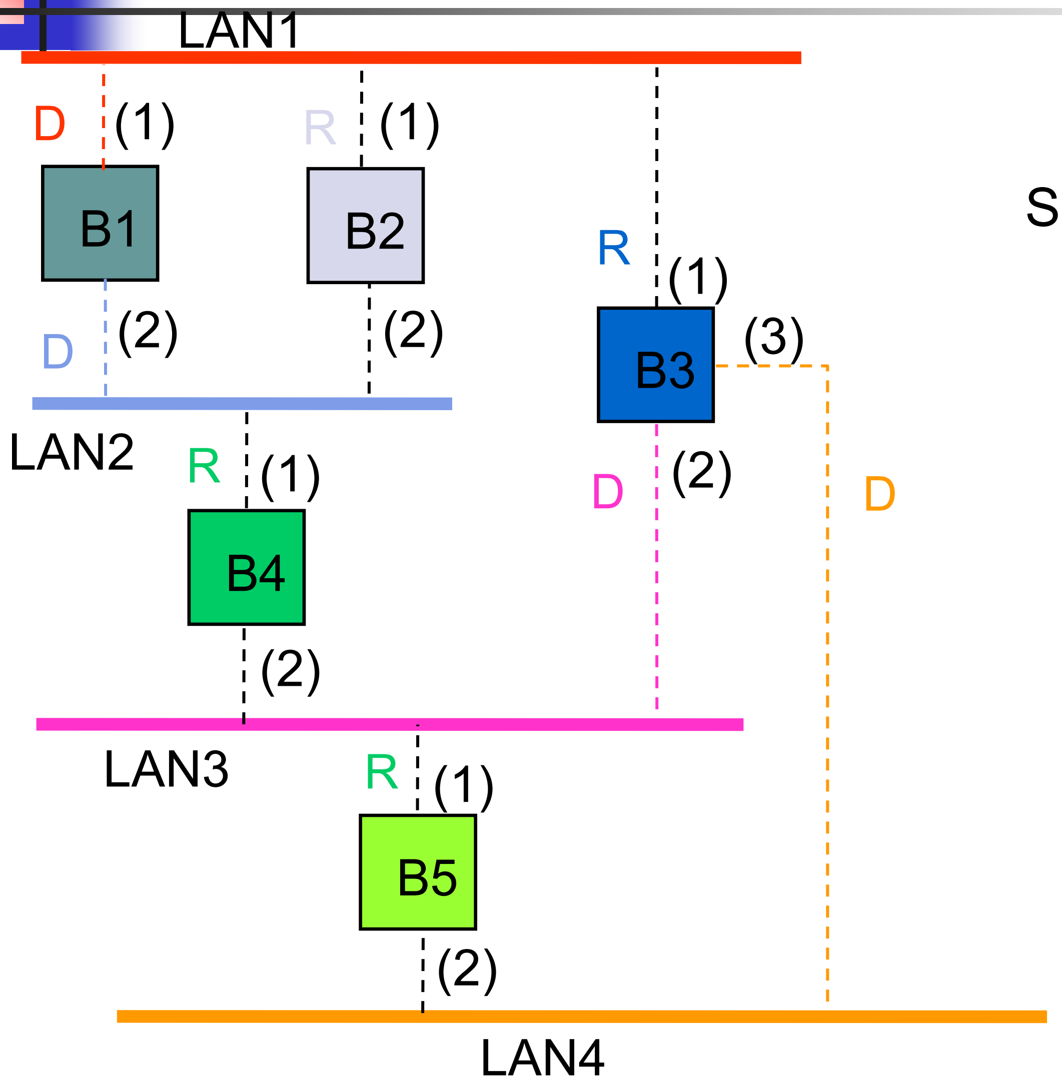
Bridge 1 selected as root bridge

Example (3)



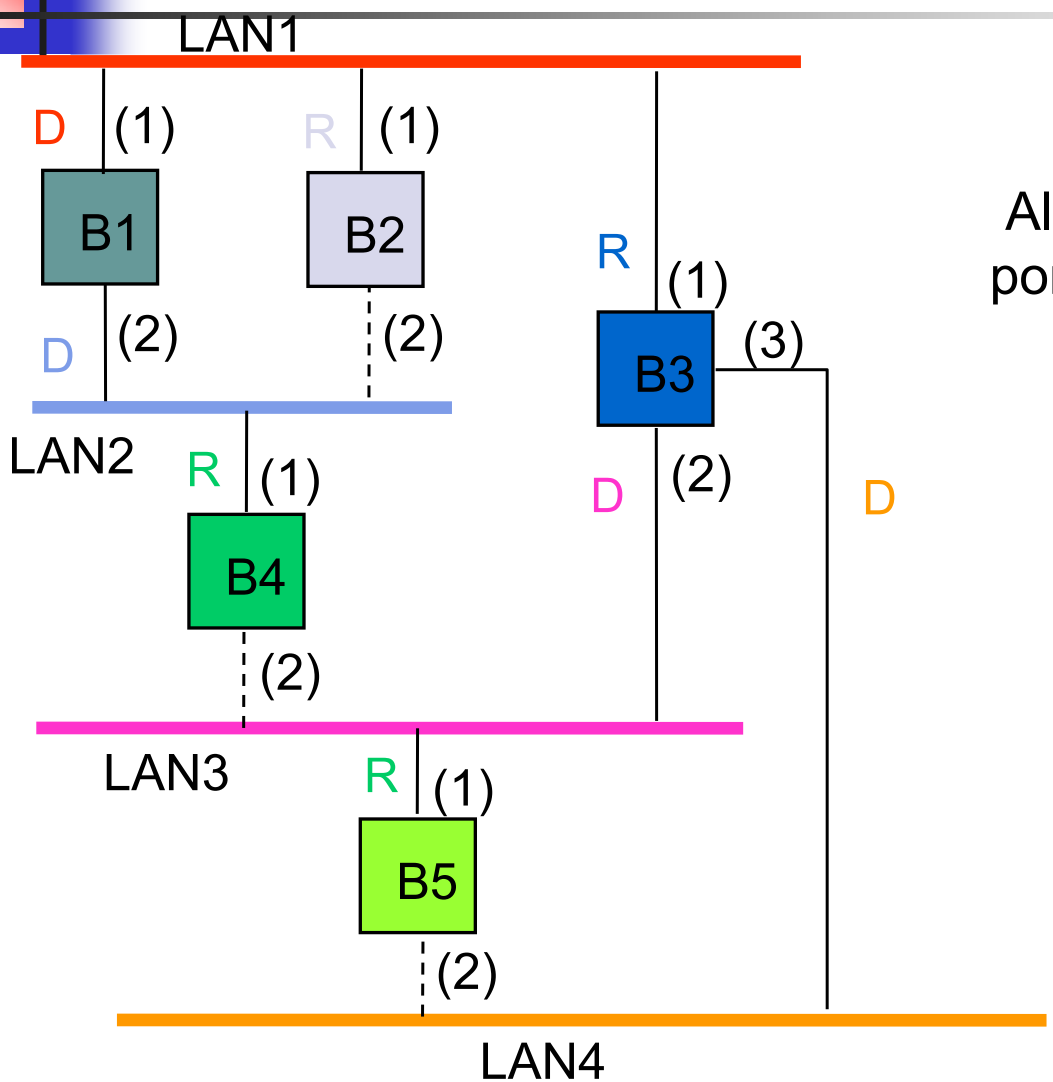
Root port selected for every bridge except root bridge

Example (4)



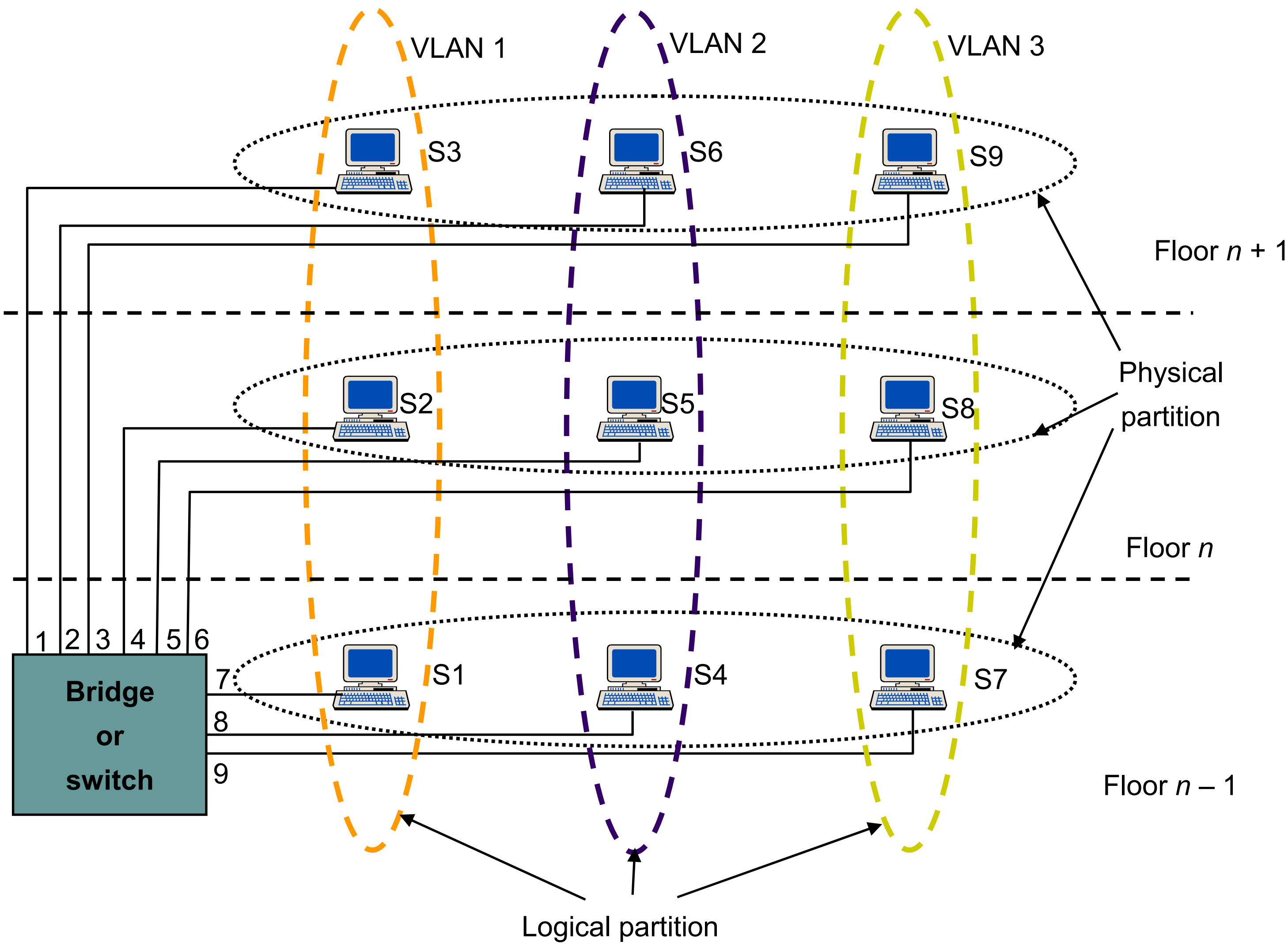
Select designated bridge for each LAN

Example (5)

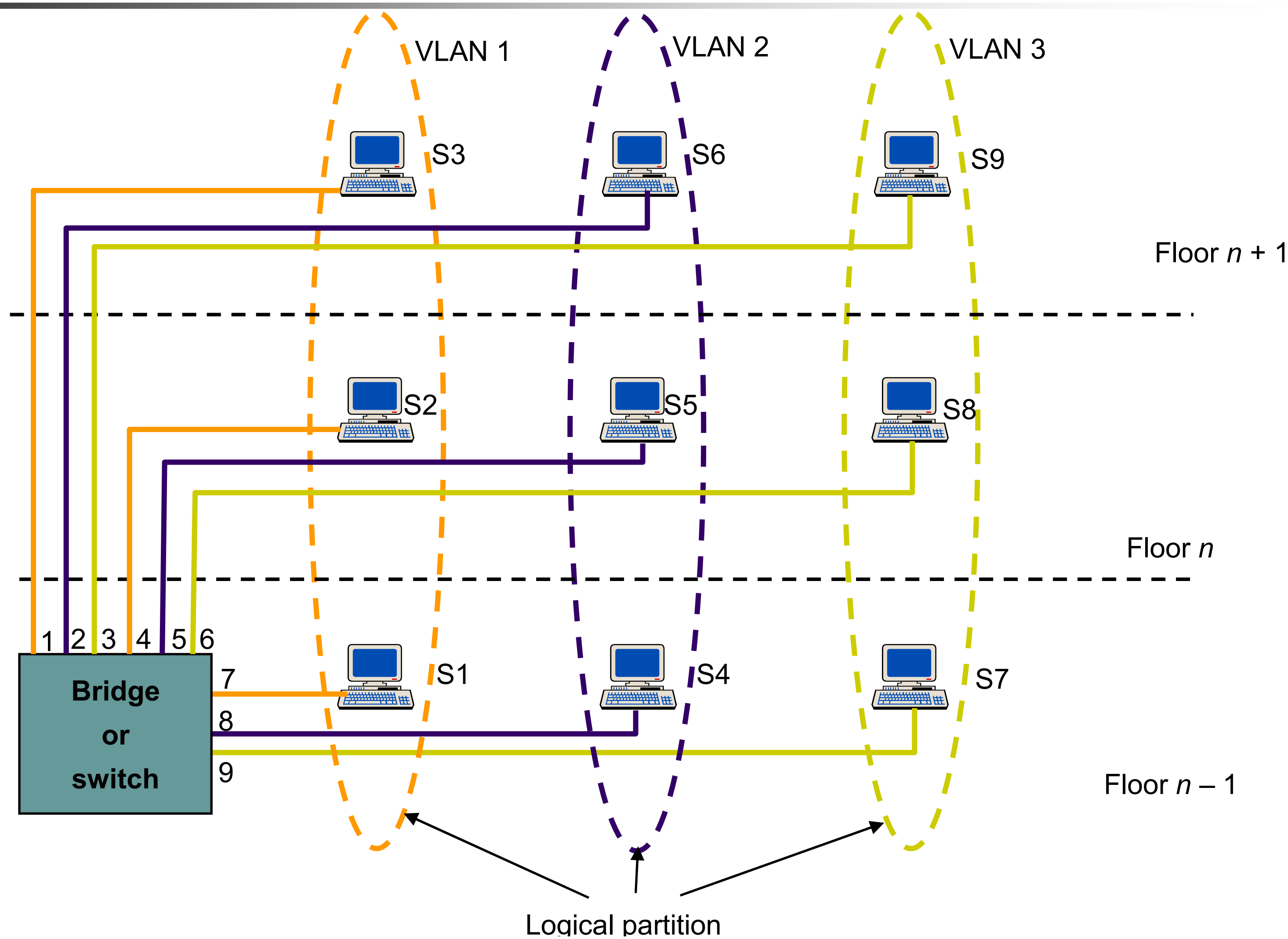


All root ports & designated ports put in forwarding state

Virtual LAN


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

Per-Port VLANs

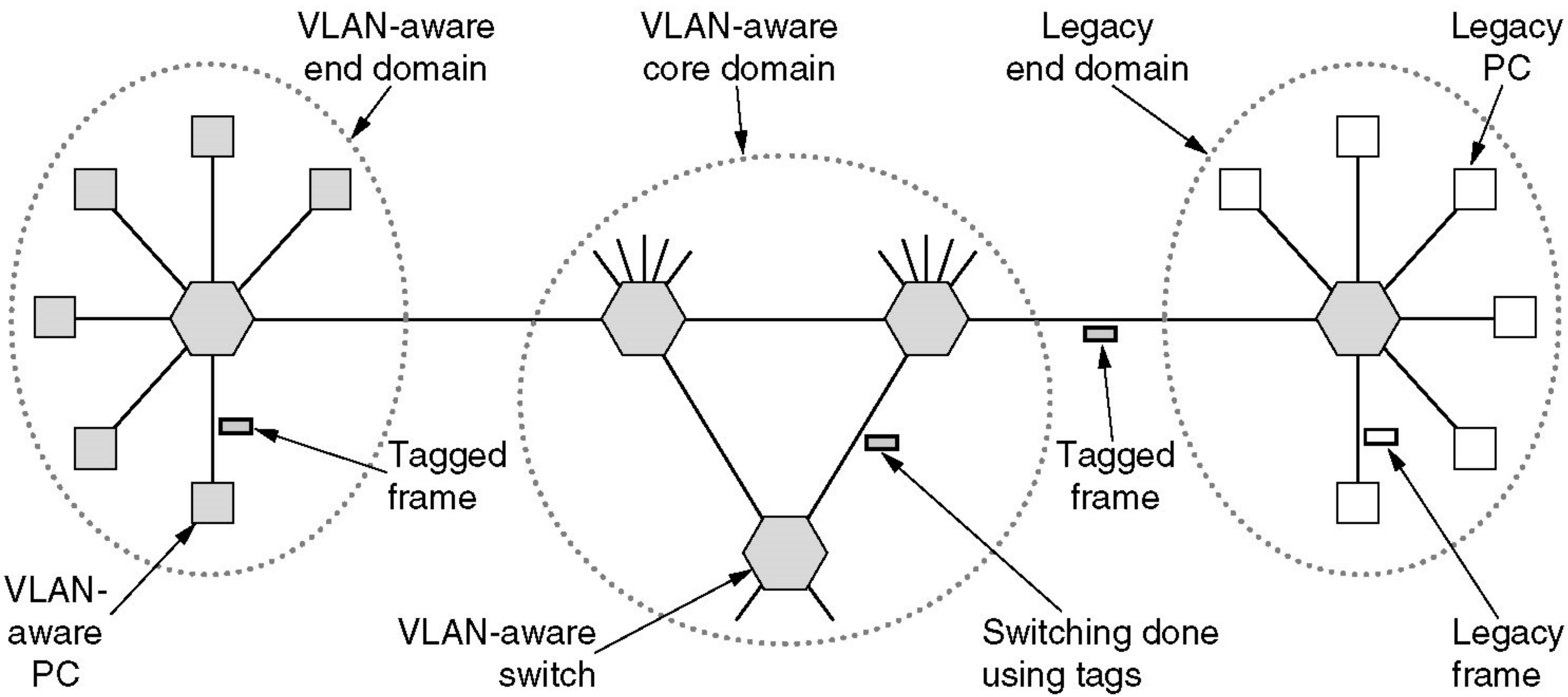


The bridge only forwards frames to outgoing ports associated with the same VLAN of the incoming port.

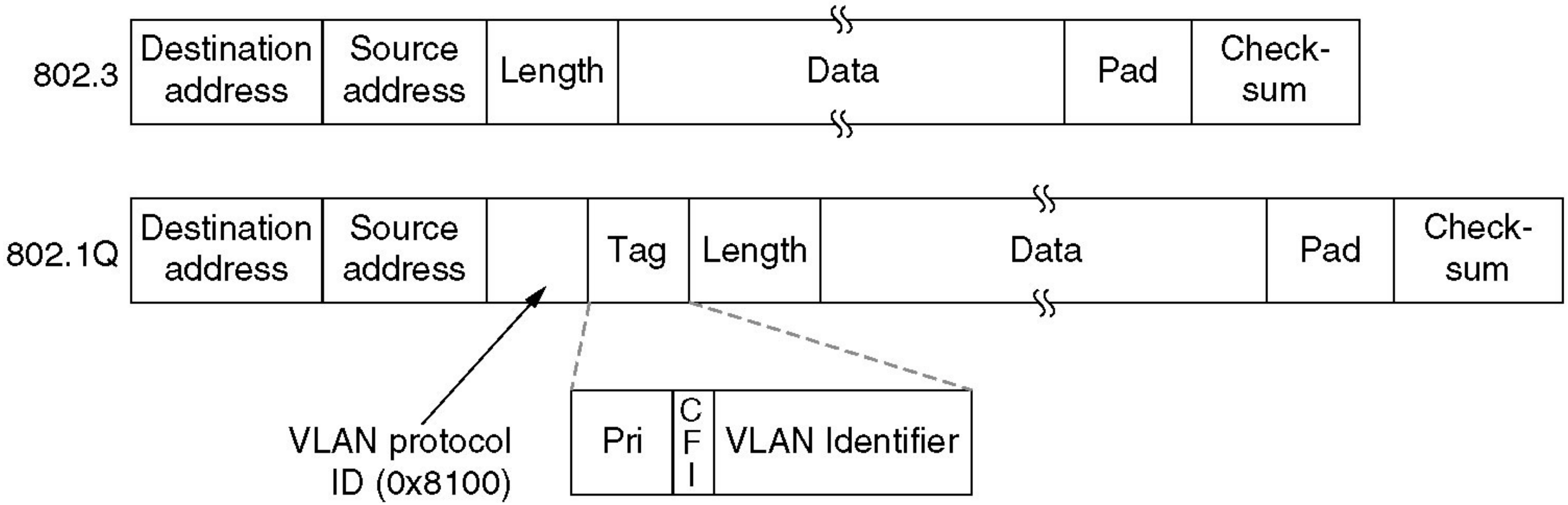
Tagged VLANs

- 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