Chapter 6
Medium Access Control Protocols and Local Area Networks

Part I: Medium Access Control

Part II: Local Area Networks

Chapter 6
Medium Access Control Protocols and Local Area Networks

Contain slides by Leon-Garcia and Widjaja

Chapter Overview

- **Broadcast Networks**
  - All information sent to all users
  - No routing
  - Shared media
  - Radio
    - Cellular telephony
    - Wireless LANs
  - Copper & Optical
    - Ethernet LANs
    - Cable Modem Access
- ***Medium Access Control***
  - To coordinate access to shared medium
  - Data link layer since direct transfer of frames
- ***Local Area Networks***
  - High-speed, low-cost communications between co-located computers
  - Typically based on broadcast networks
  - Simple & cheap
  - Limited number of users

Chapter 6
Medium Access Control Protocols and Local Area Networks

Part I: Medium Access Control

Multiple Access Communications

Random Access

Scheduling

Channelization

Delay Performance

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Part II: Local Area Networks

Overview of LANs
Ethernet
Token Ring and FDDI
802.11 Wireless LAN
LAN Bridges

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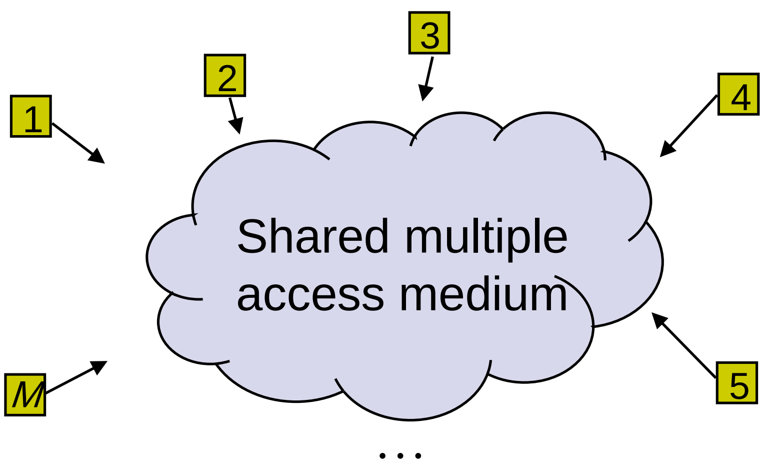
Medium Access Control Protocols and Local Area Networks

Multiple Access Communications

Multiple Access Communications

- Shared media basis for broadcast networks
  - Inexpensive: radio over air; copper or coaxial cable
  - M users communicate by broadcasting into medium
- Key issue: How to share the medium?



Approaches to Media Sharing

Medium sharing techniques

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

Static channelization

- Partition medium
- Dedicated allocation to users
- Satellite transmission
- Cellular Telephone

Scheduling

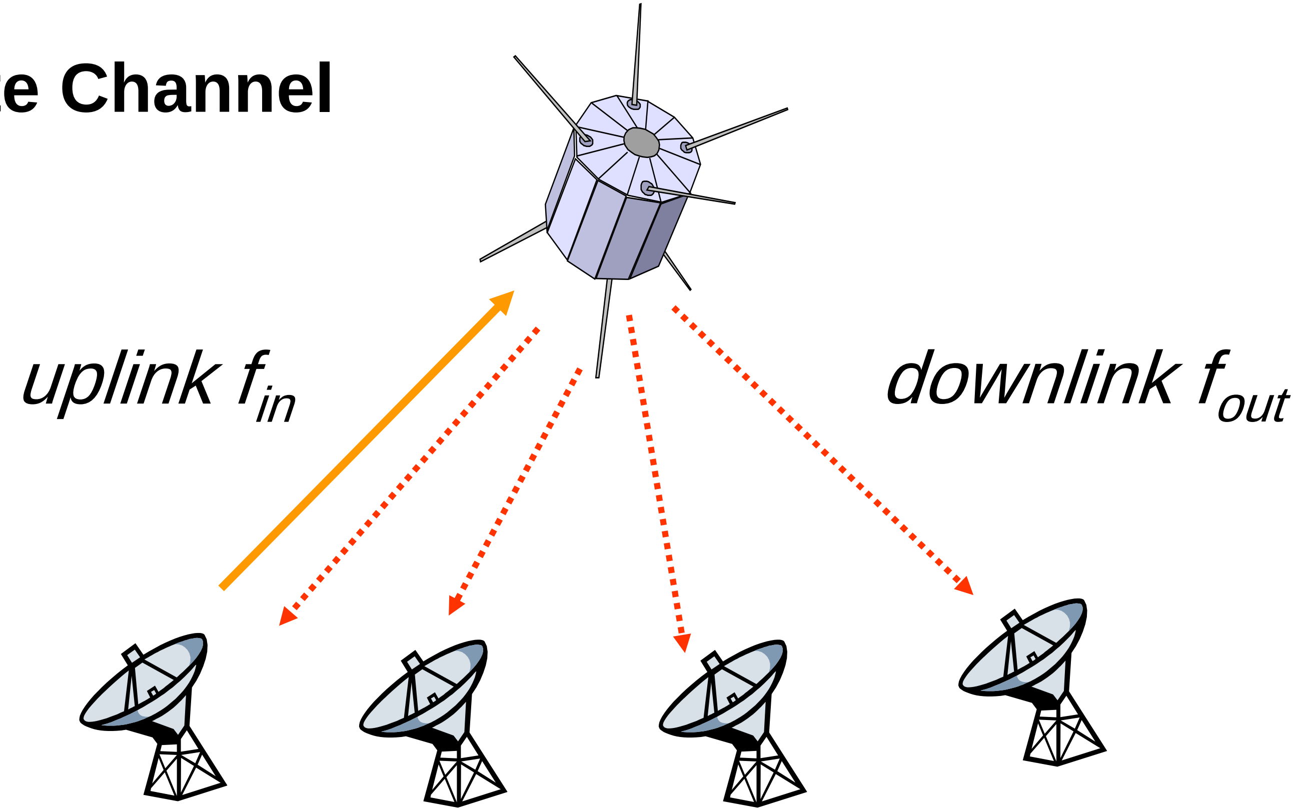
- Polling: take turns
- Request for slot in transmission schedule
- Token ring
- Wireless LANs

Random access

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

Channelization: Satellite

Satellite Channel

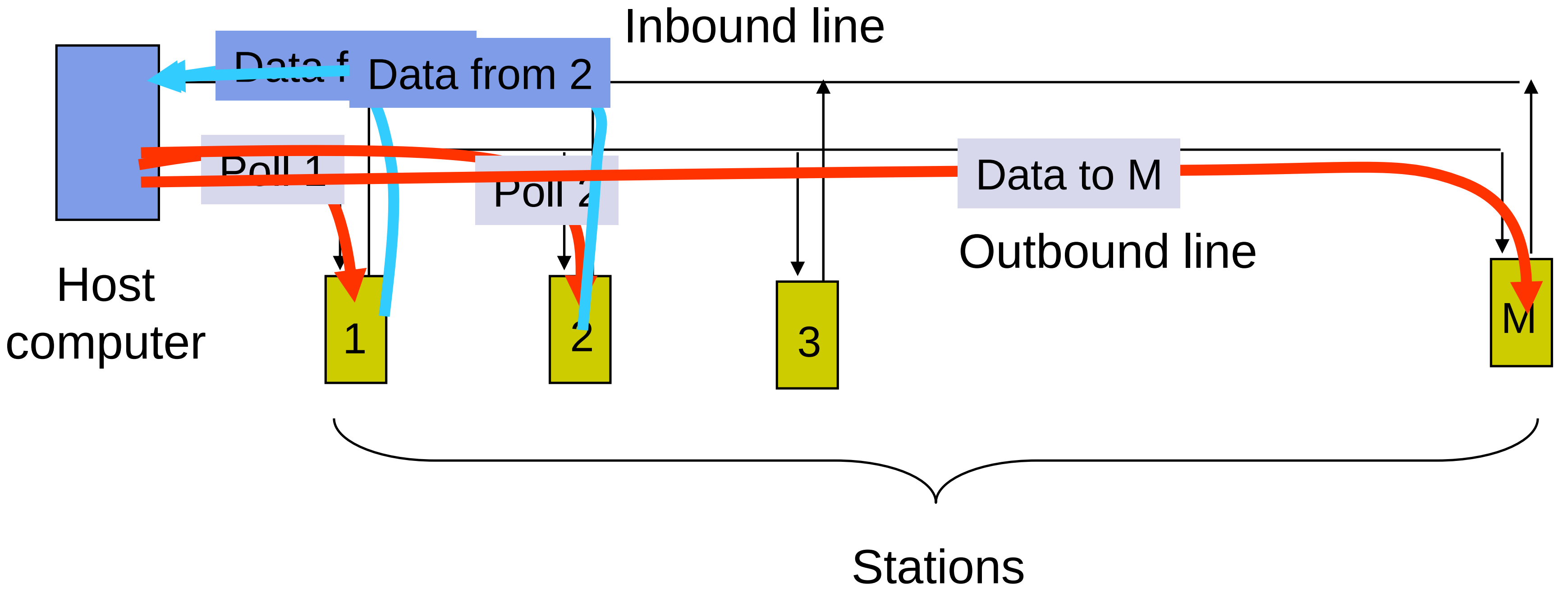


Channelization: Cellular

uplink f_1 ; downlink f_2

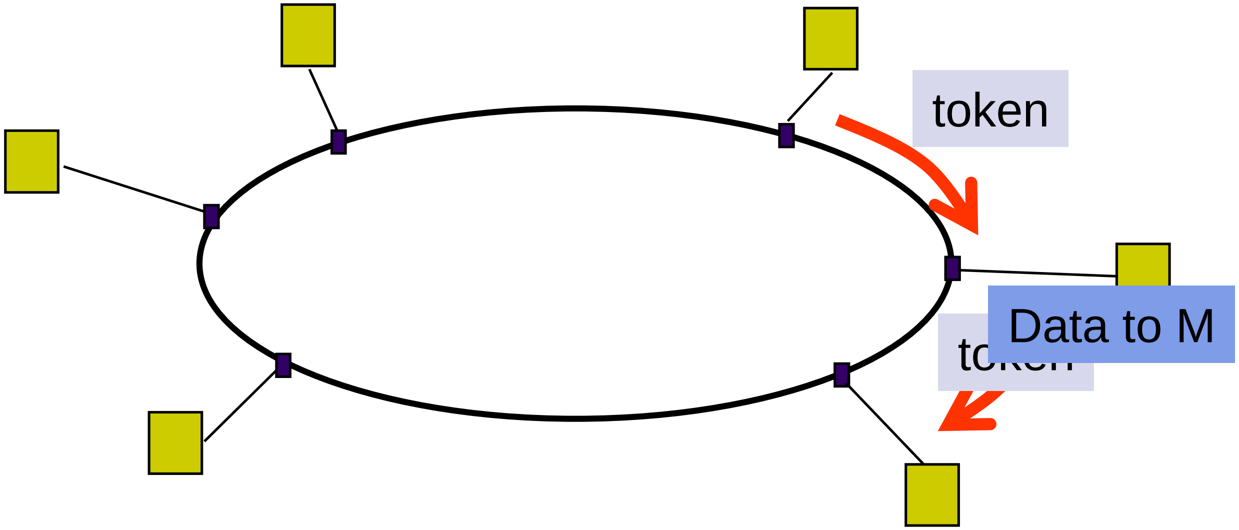
uplink f_3 ; downlink f_4

Scheduling: Polling



Scheduling: Token-Passing

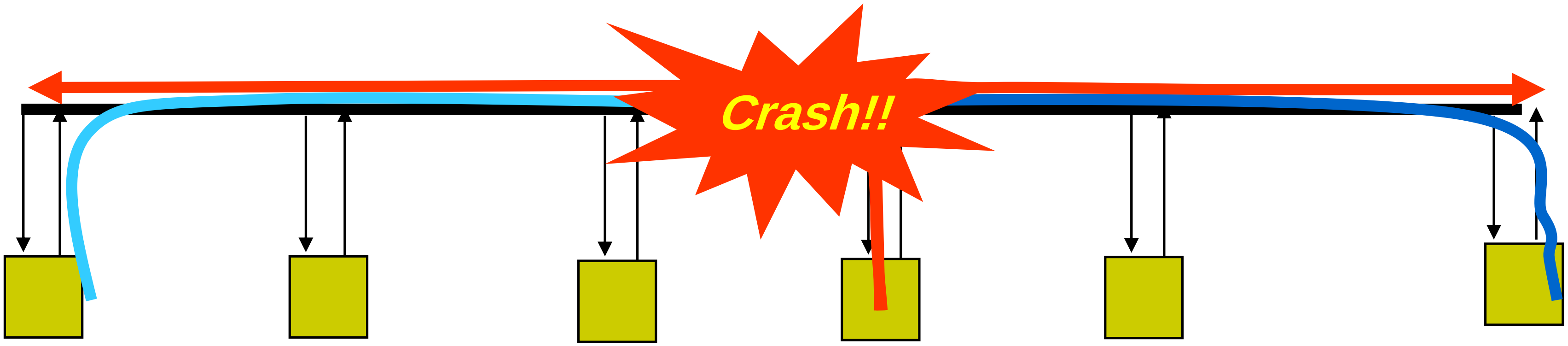
Ring networks



Station that holds token transmits into ring

Random Access

Multitapped Bus

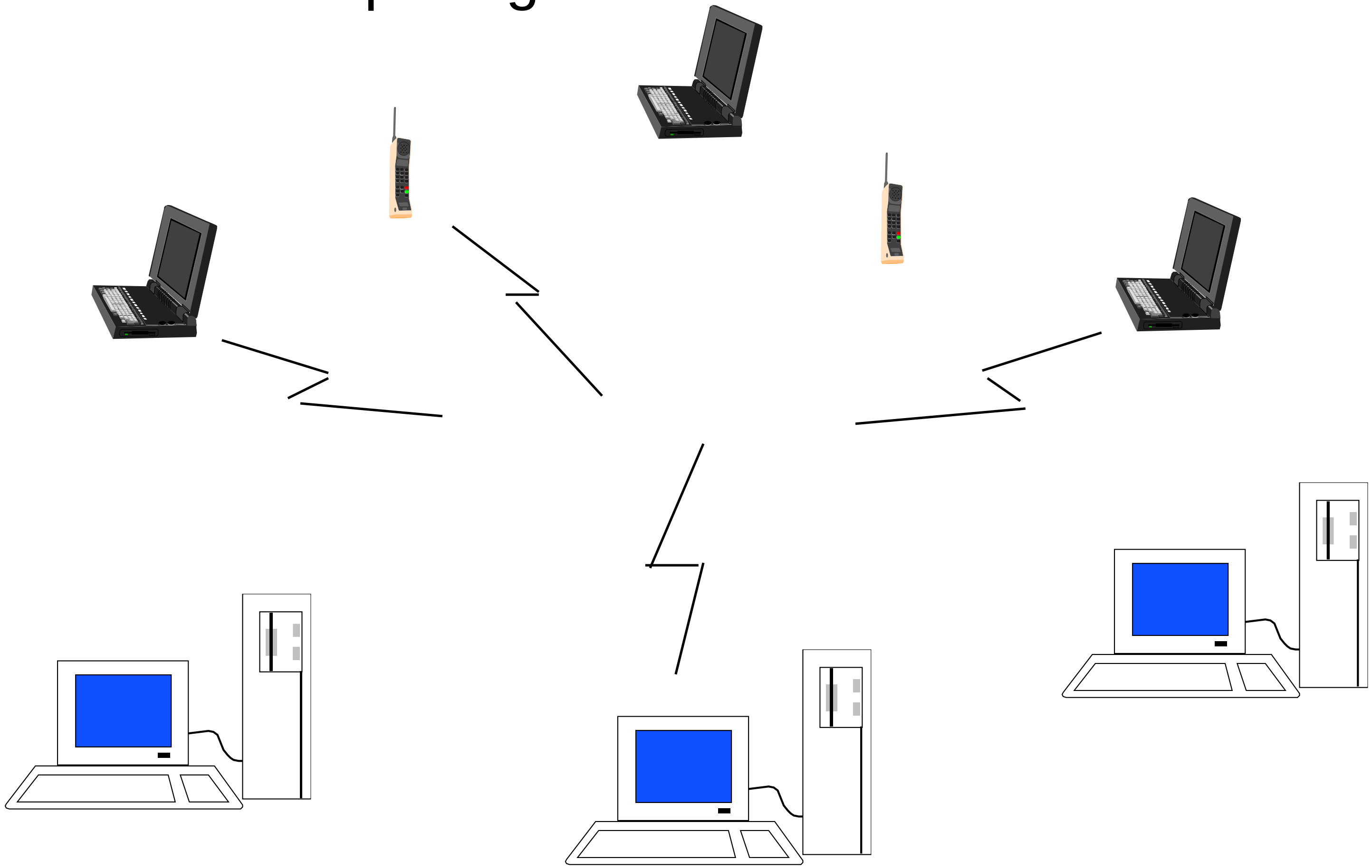


Transmit when ready

Transmissions can occur; need retransmission strategy

Wireless LAN

AdHoc: station-to-station
Infrastructure: stations to base station
Random access & polling



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?
- Current Examples:
  - Design MAC to provide wireless DSL-equivalent access to rural communities
  - Design MAC to provide Wireless-LAN-equivalent access to mobile users (user in car travelling at 130 km/hr)

Delay-Bandwidth Product

- *Delay-bandwidth* product key parameter
  - Coordination in sharing medium involves using bandwidth (explicitly or implicitly)
  - Difficulty of coordination commensurate with delay-bandwidth product
- Simple two-station example
  - Station with frame to send listens to medium and transmits if medium found idle
  - Station monitors medium to detect collision
  - If collision occurs, station that begin transmitting earlier retransmits (propagation time is known)

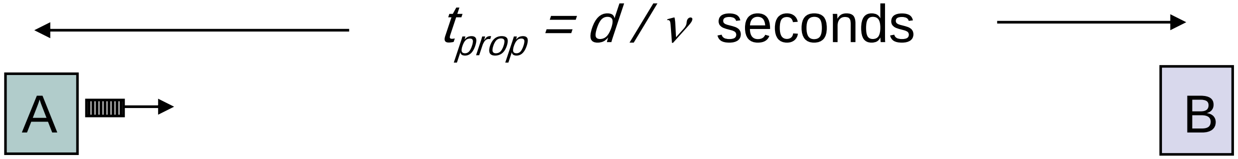
Two-Station MAC Example

Two stations are trying to share a common medium

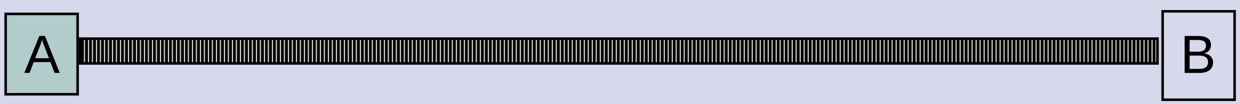
Distance d meters

$t_{prop} = d / \nu$ seconds

A transmits at $t = 0$

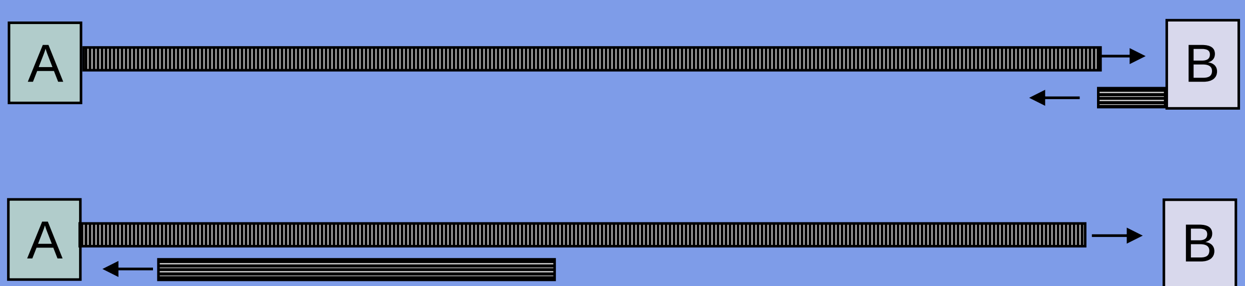


Case 1



B does not transmit before $t = t_{prop}$ & A captures channel

Case 2



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

B transmits before $t = t_{prop}$ and detects collision soon thereafter

Efficiency of Two-Station Example

- Each frame transmission requires $2t_{prop}$ of quiet time
  - Station B needs to be quiet t_{prop} before *and* after time when Station A transmits
  - *R* transmission bit rate
  - *L* bits/frame

$$Efficiency = \rho_{\max} = \frac{L}{L + 2t_{prop}R} = \frac{1}{1 + 2t_{prop}R/L} = \frac{1}{1+2a}$$

$$MaxThroughput = R_{eff} = \frac{L}{L/R + 2t_{prop}} = \frac{1}{1+2a}R \text{ bits/second}$$

Normalized Delay-Bandwidth Product

$$\boxed{a = \frac{t_{prop}}{L/R}}$$

Propagation delay

Time to transmit a frame

Typical MAC Efficiencies

Two-Station Example:

$$Efficiency = \frac{1}{1+2a}$$

CSMA-CD (Ethernet) protocol:

$$Efficiency = \frac{1}{1+6.44a}$$

Token-ring network

$$Efficiency = \frac{1}{1+a'}$$

a' = latency of the ring (bits)/average frame length

- If $a \ll 1$, then efficiency close to 100%
- As a approaches 1, the efficiency becomes low

Typical Delay-Bandwidth Products

Distance	10 Mbps	100 Mbps	1 Gbps	Network Type
1 m	3.33×10^{-02}	3.33×10^{-01}	3.33×10^{0}	Desk area network
100 m	3.33×10^{01}	3.33×10^{02}	3.33×10^{03}	Local area network
10 km	3.33×10^{02}	3.33×10^{03}	3.33×10^{04}	Metropolitan area network
1000 km	3.33×10^{04}	3.33×10^{05}	3.33×10^{06}	Wide area network
100000 km	3.33×10^{06}	3.33×10^{07}	3.33×10^{08}	Global area network

- Max size Ethernet frame: 1500 bytes = 12000 bits
- Long and/or fat pipes give large a

MAC protocol features

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

MAC Delay Performance

- Frame transfer delay
  - From first bit of frame arrives at source MAC
  - To last bit of frame delivered at destination MAC
- Throughput
  - Actual transfer rate through the shared medium
  - Measured in frames/sec or bits/sec
- Parameters

  R bits/sec & L bits/frame

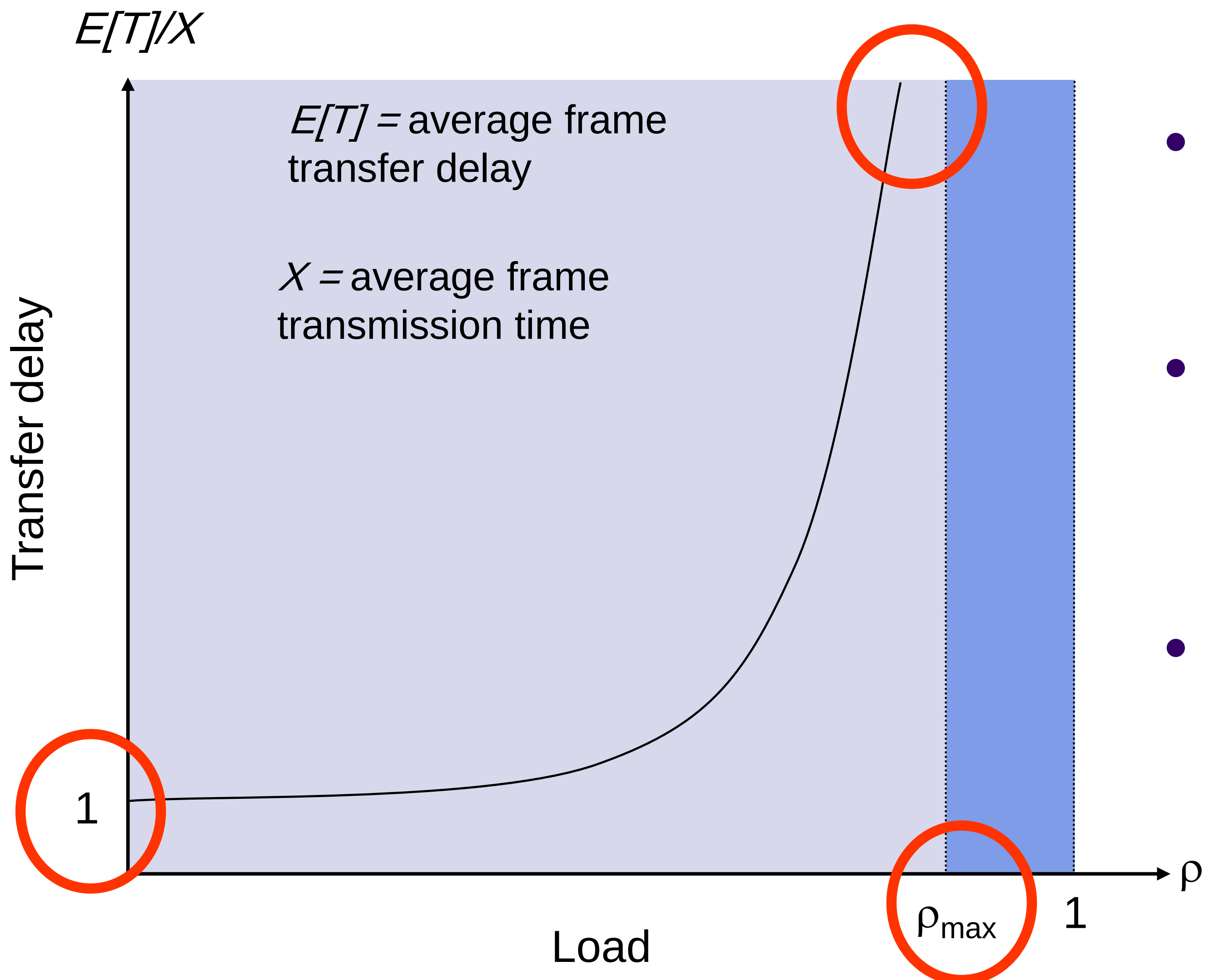
  $X = L/R$ seconds/frame

  λ frames/second average arrival rate

  Load $\rho = \lambda X$, rate at which “work” arrives

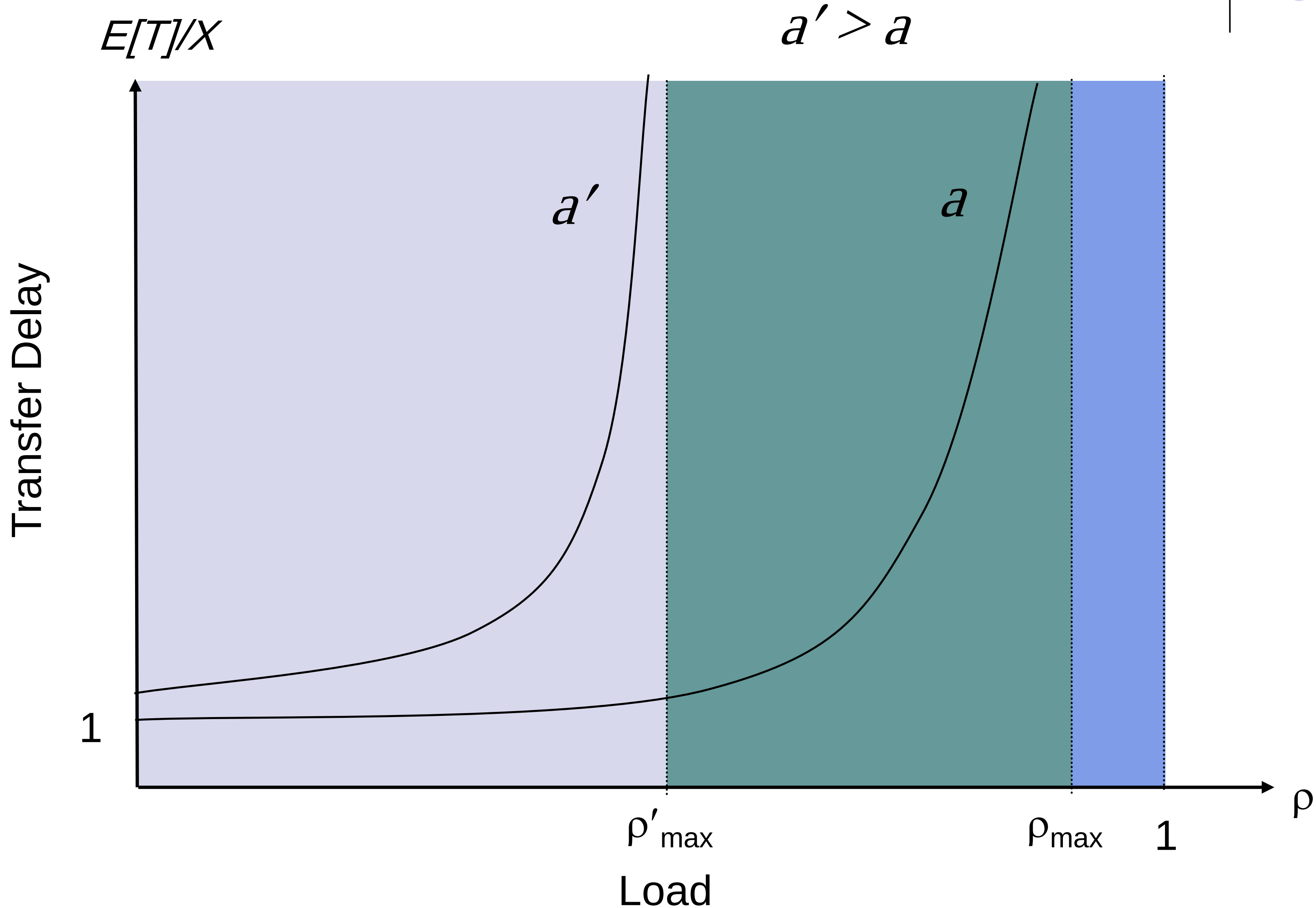
  Maximum throughput (@100% efficiency): R/L fr/sec

Normalized Delay versus Load



- At low arrival rate, only frame transmission time
- At high arrival rates, increasingly longer waits to access channel
- Max efficiency typically less than 100%

Dependence on Rt_{prop}/L



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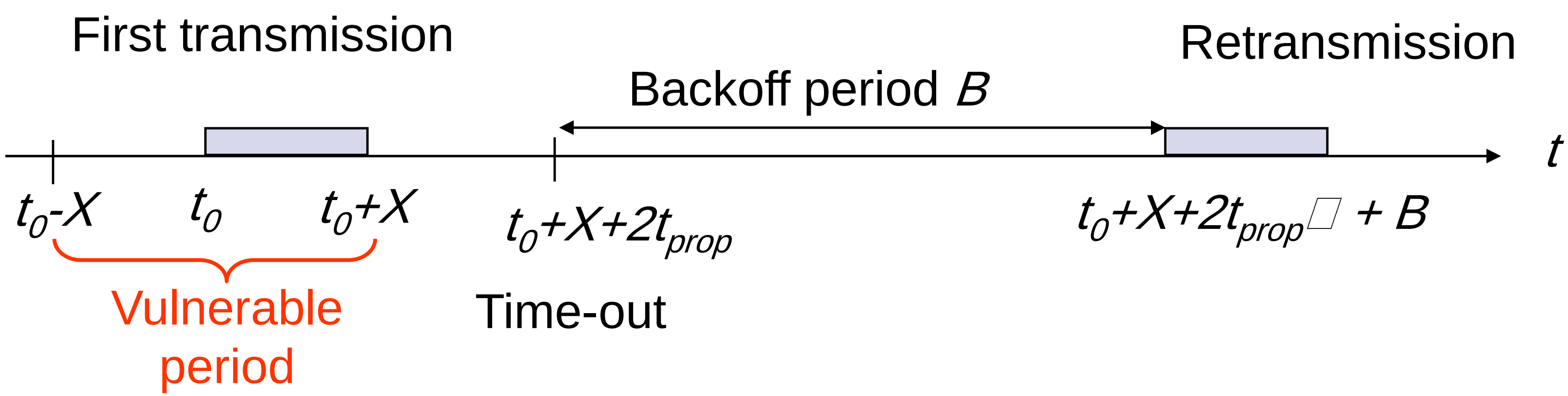
Random Access

ALOHA

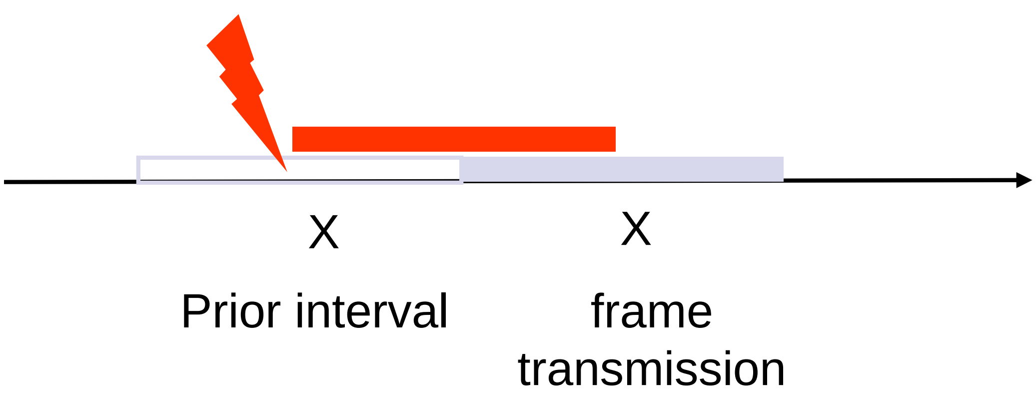
- Wireless link to provide data transfer between main campus & remote campuses of University of Hawaii
- Simplest solution: just do it
  - A station transmits whenever it has data to transmit
  - If more than one frames are transmitted, they interfere with each other (collide) and are lost
  - If ACK 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 probability of no arrivals in vulnerable period?*
- Abramson assumption: Effect of backoff algorithm 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

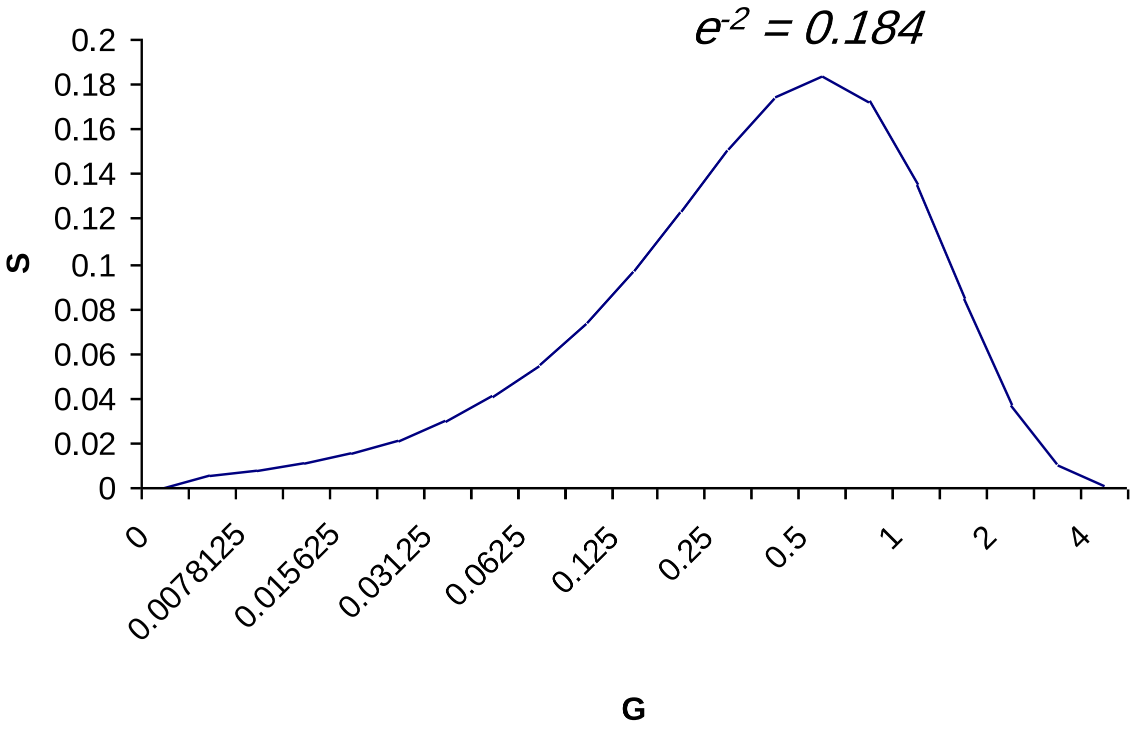
$$P_{success} = P[0 \text{ arrivals in } 2\text{X seconds}] =$$

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

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

Throughput of ALOHA

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



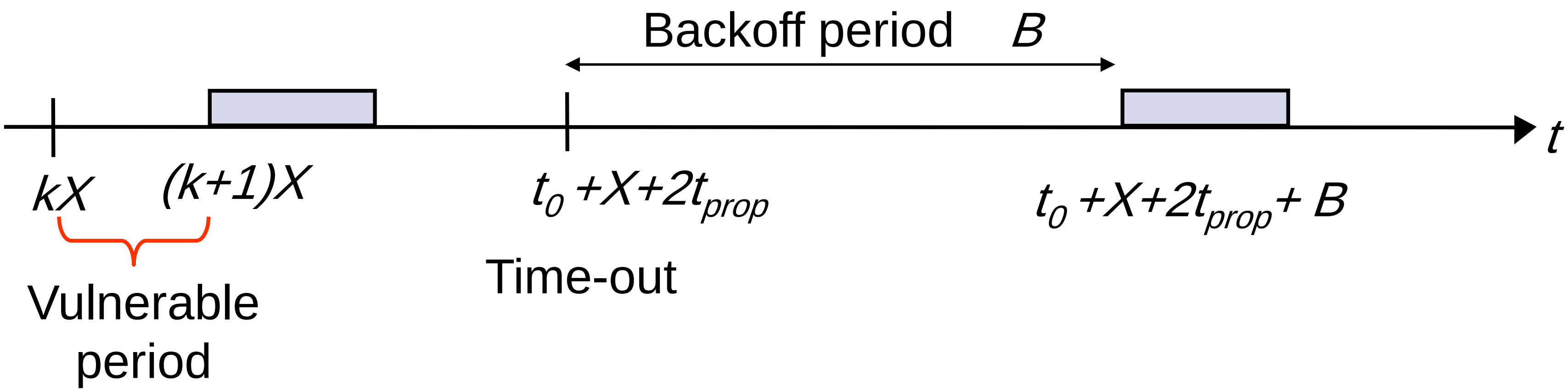
- Collisions are means for coordinating access
- Max throughput is $\rho_{max} = 1/2e$ *(18.4%)*
- Bimodal behavior:

  Small G, S≈G

  Large G, S↓0
- Collisions can snowball and drop throughput to zero

Slotted ALOHA

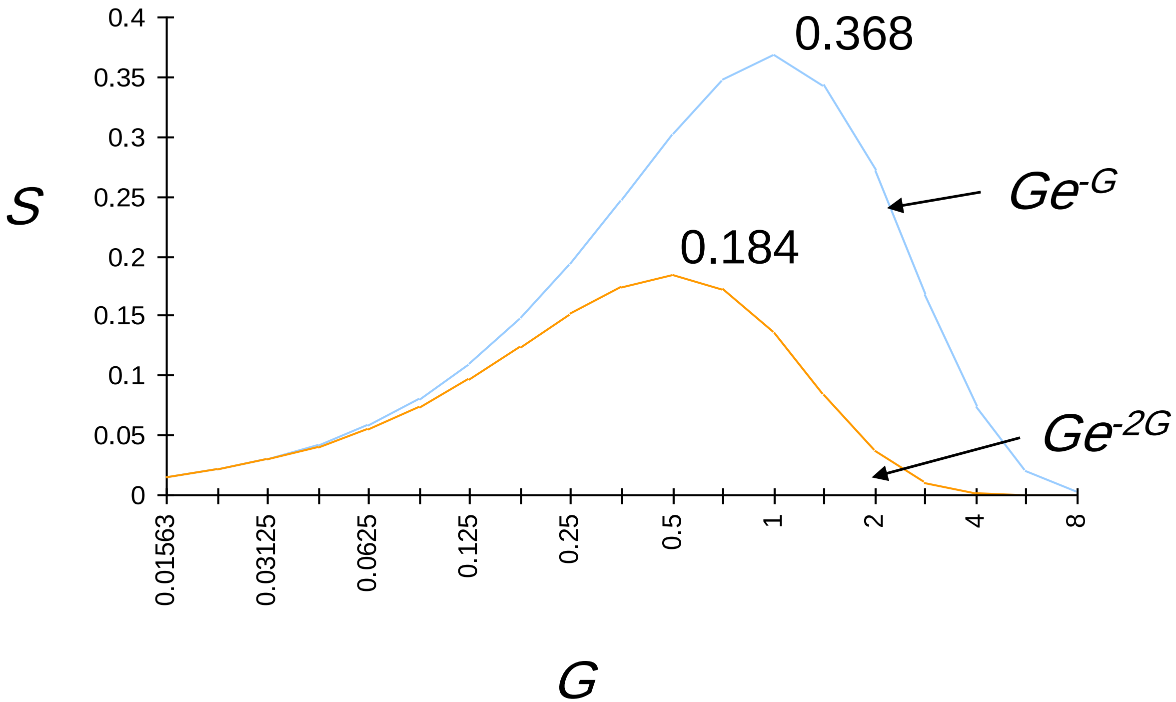
- Time is slotted in X seconds slots
- Stations synchronized to frame times
- Stations transmit frames in first slot after frame arrival
- Backoff intervals in multiples of slots



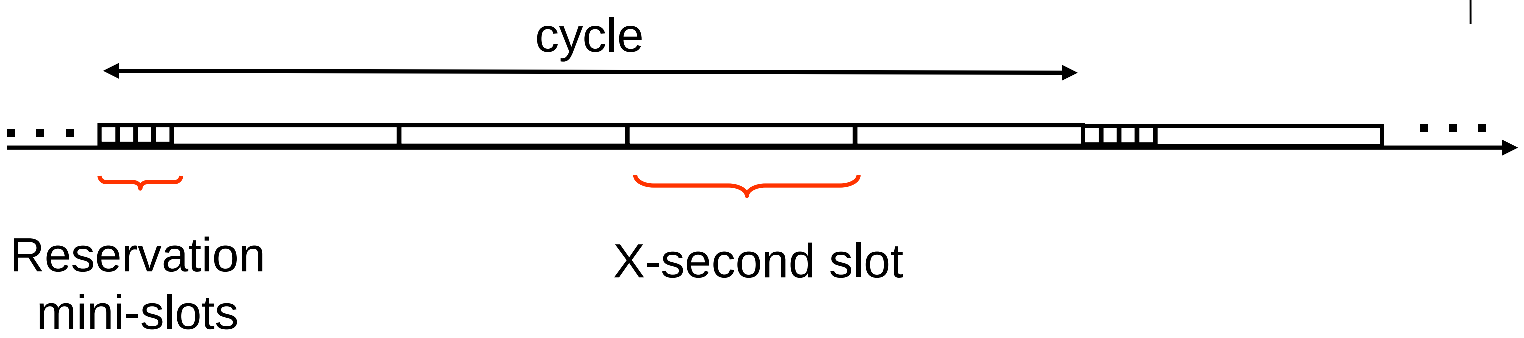
Only frames that arrive during prior X seconds collide

Throughput of Slotted ALOHA

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



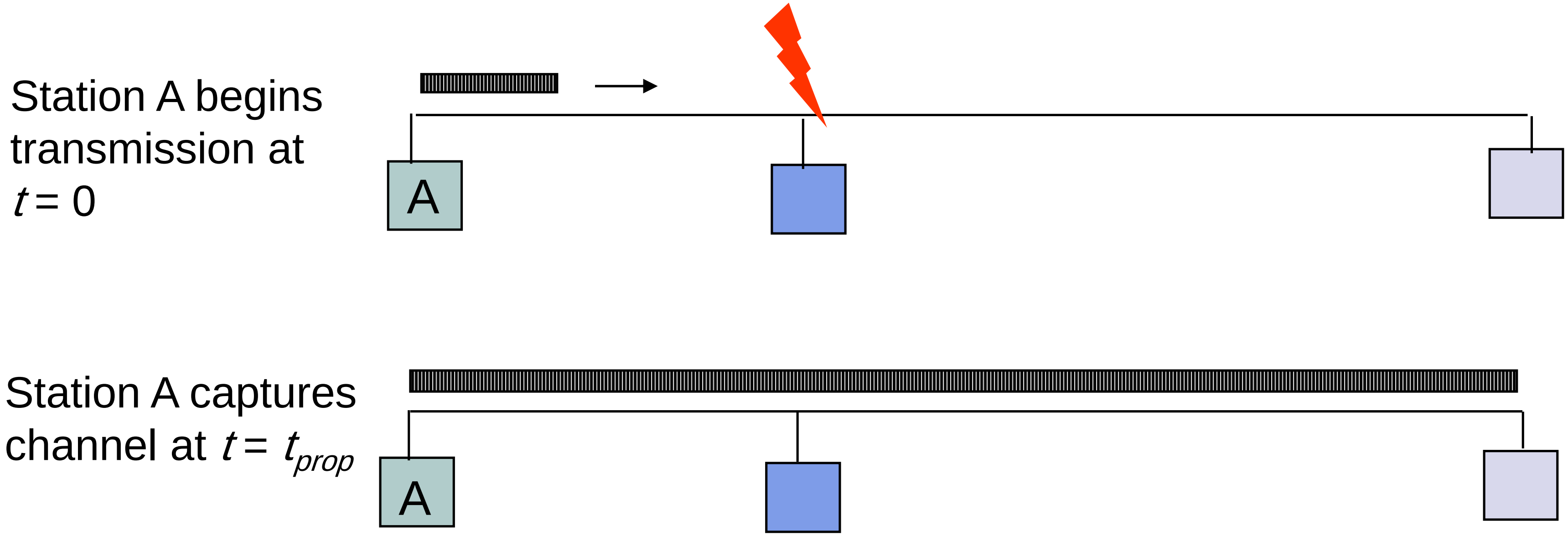
Application of Slotted Aloha



- 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
- Stations use slotted Aloha during mini-slots to request slots

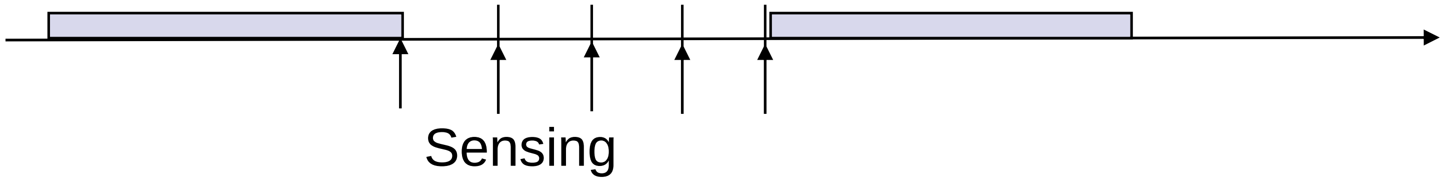
Carrier Sensing Multiple Access (CSMA)

- 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} (due to *channel capture* effect)
  - When collisions occur they involve entire frame transmission times
  - If t_{prop} >X (or if a>1), no gain compared to ALOHA or slotted ALOHA

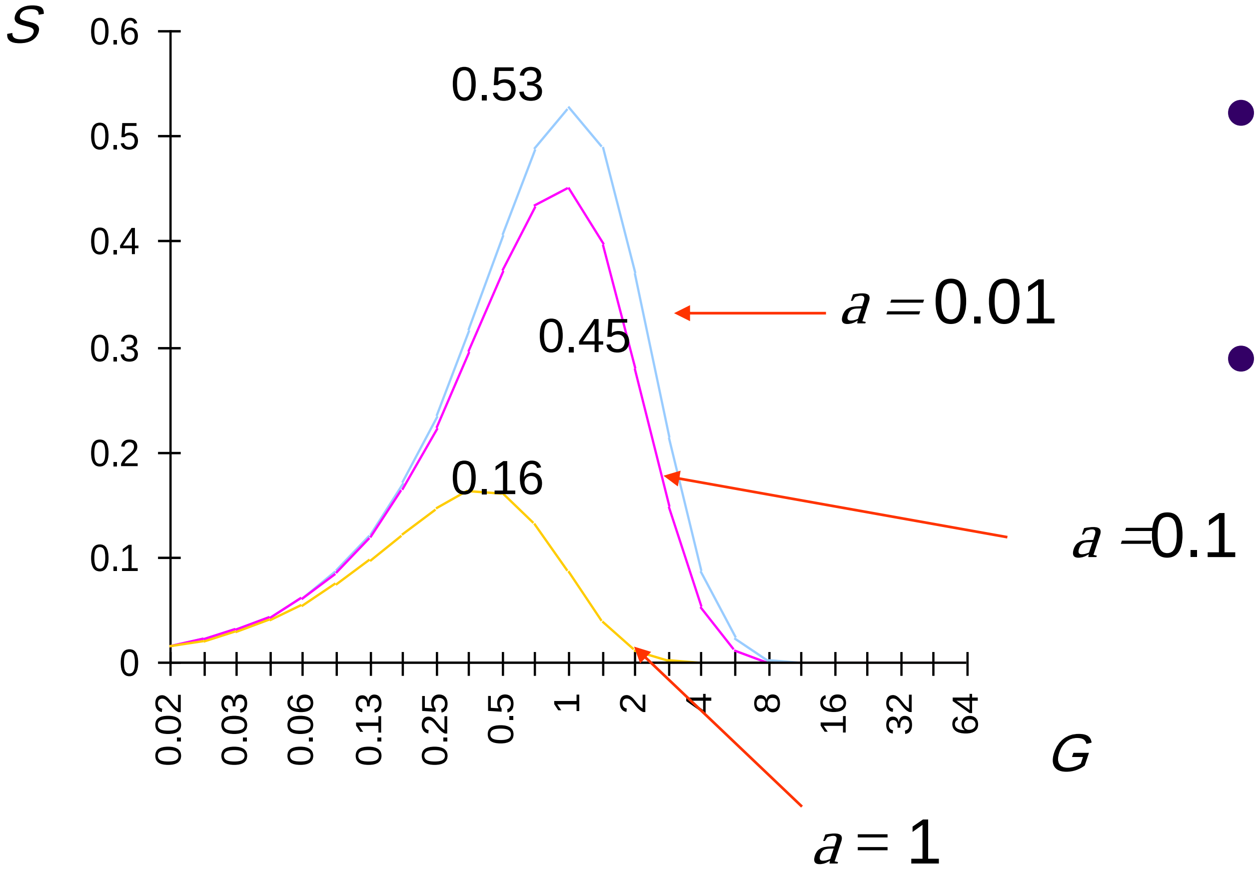


CSMA Options

- 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

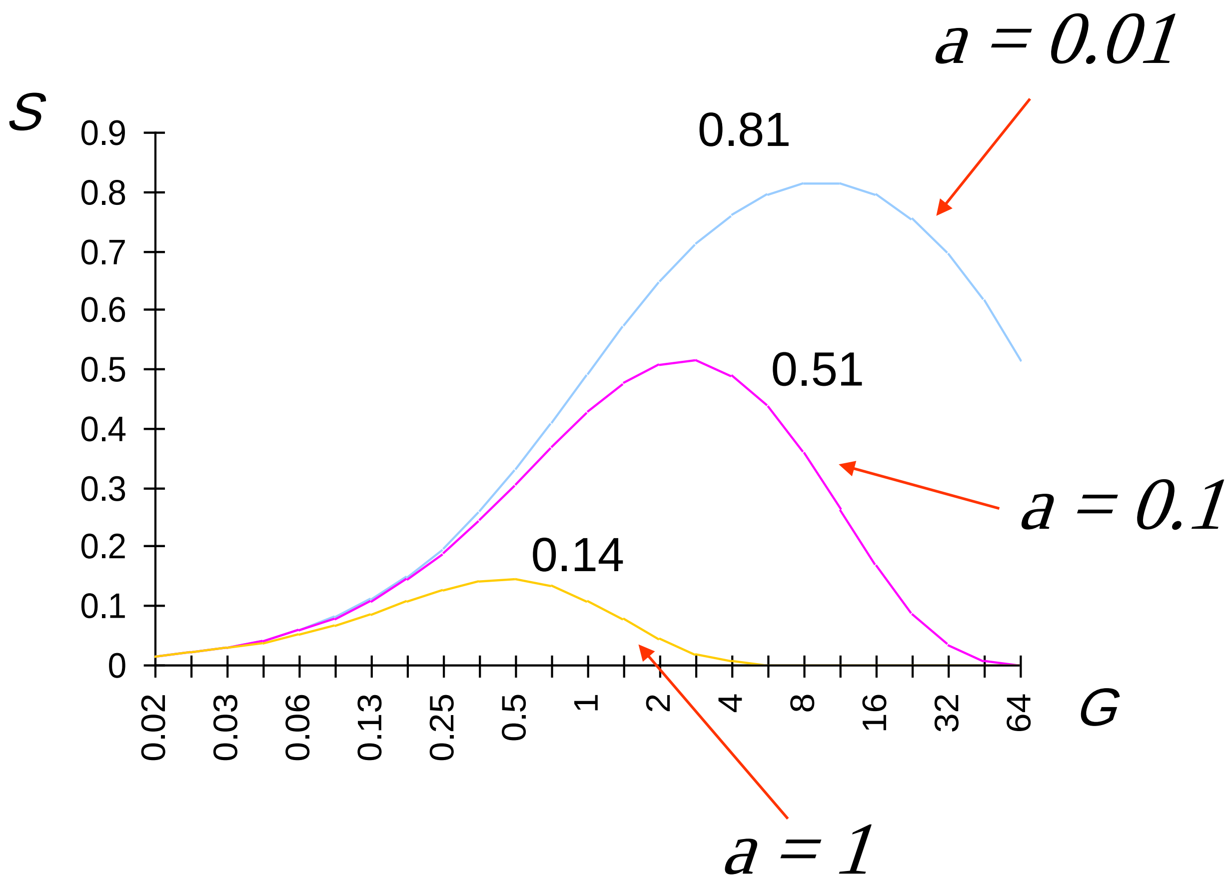


1-Persistent CSMA Throughput



- 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 to time to detect collision and abort transmission

CSMA/CD reaction time

A begins to transmit at $t = 0$

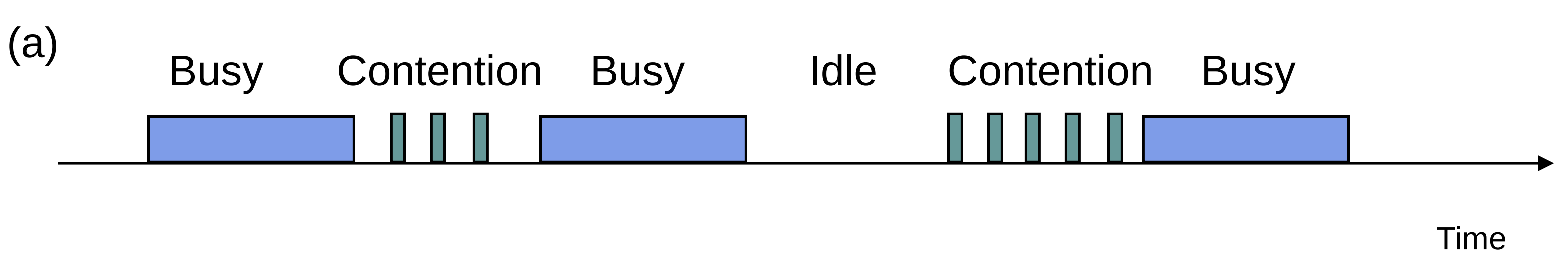
B begins to transmit at $t = t_{prop} - \delta$;□
B detects collision at $t = t_{prop}$

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

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

CSMA-CD Model

- Assumptions
  - Collisions can be detected and resolved in $2t_{prop}$
  - Time slotted in $2t_{prop}$ slots 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 t_{prop} before the next contention period starts.



Contention Resolution

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

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

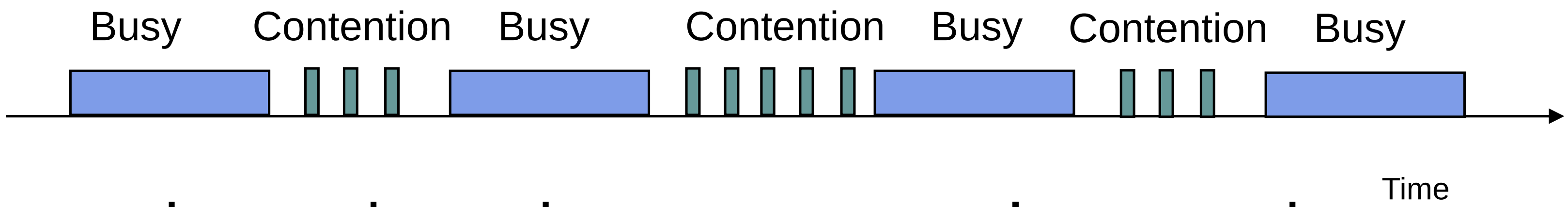
- By taking derivative of $P_{success}$ we find max occurs at p=1/n

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

- 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, systems alternates between contention periods and frame transmission times

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

- where:

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

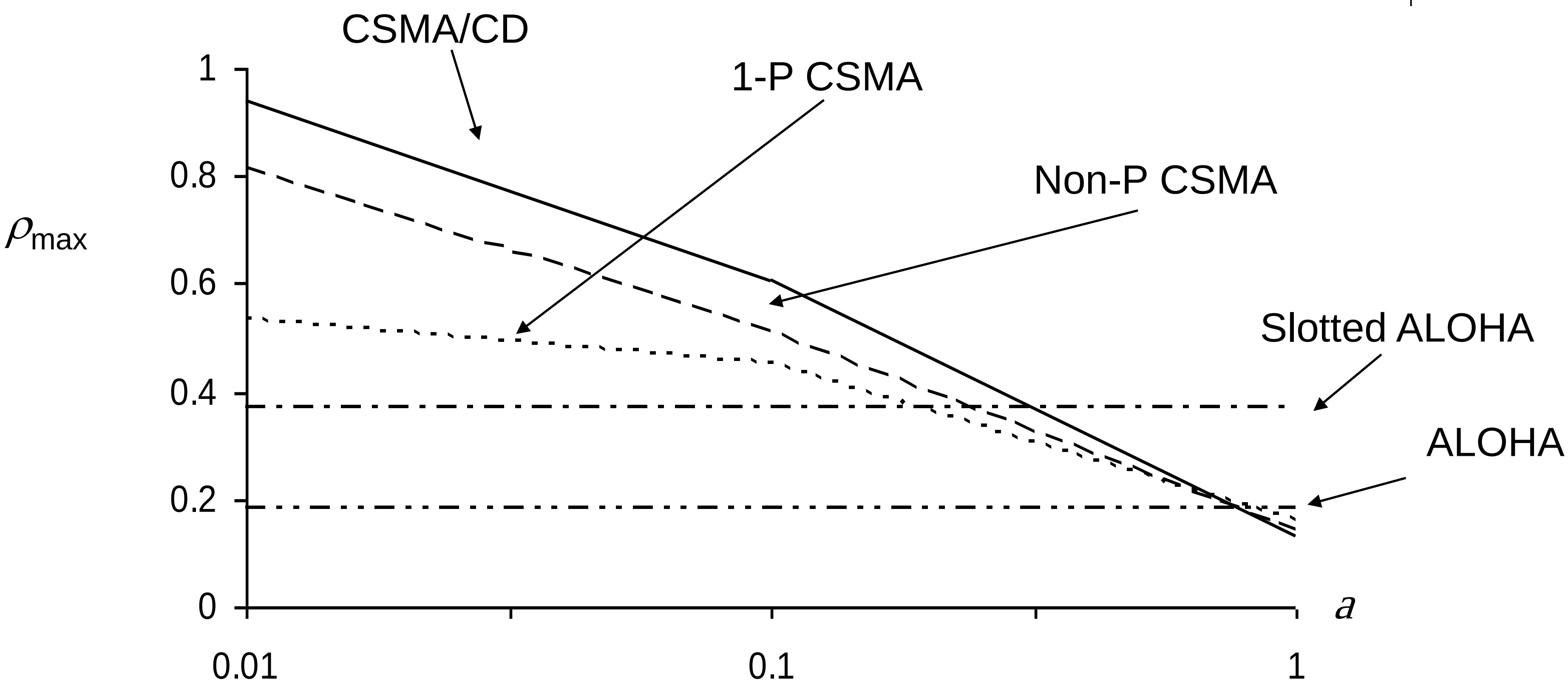
$a = t_{prop}/X$

$2e+1 = 6.44$

CSMA-CD Application: Ethernet

- First Ethernet LAN standard used CSMA-CD
  - 1-persistent Carrier Sensing
  - R = 10 Mbps
  - t_{prop} = 51.2 microseconds
    - 512 bits = 64 byte slot
    - accommodates 2.5 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

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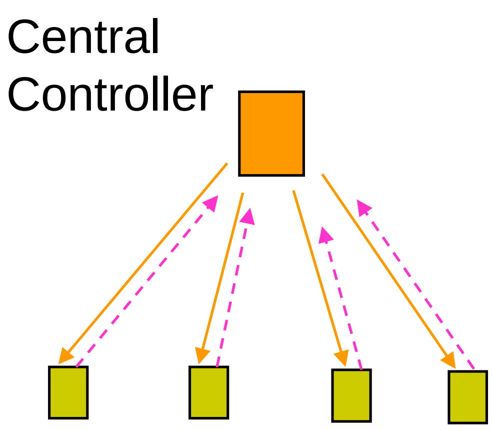
Scheduling

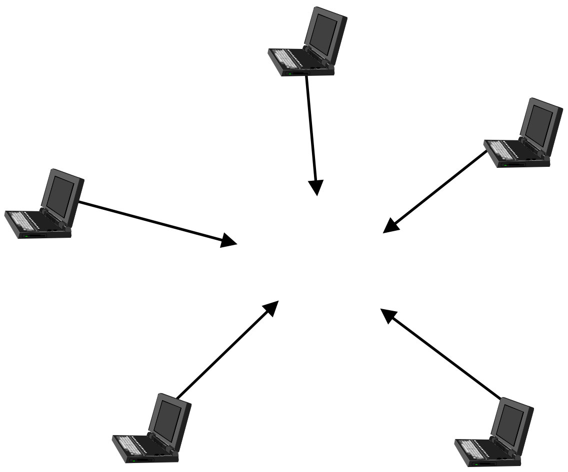
Scheduling for Medium Access Control

- 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

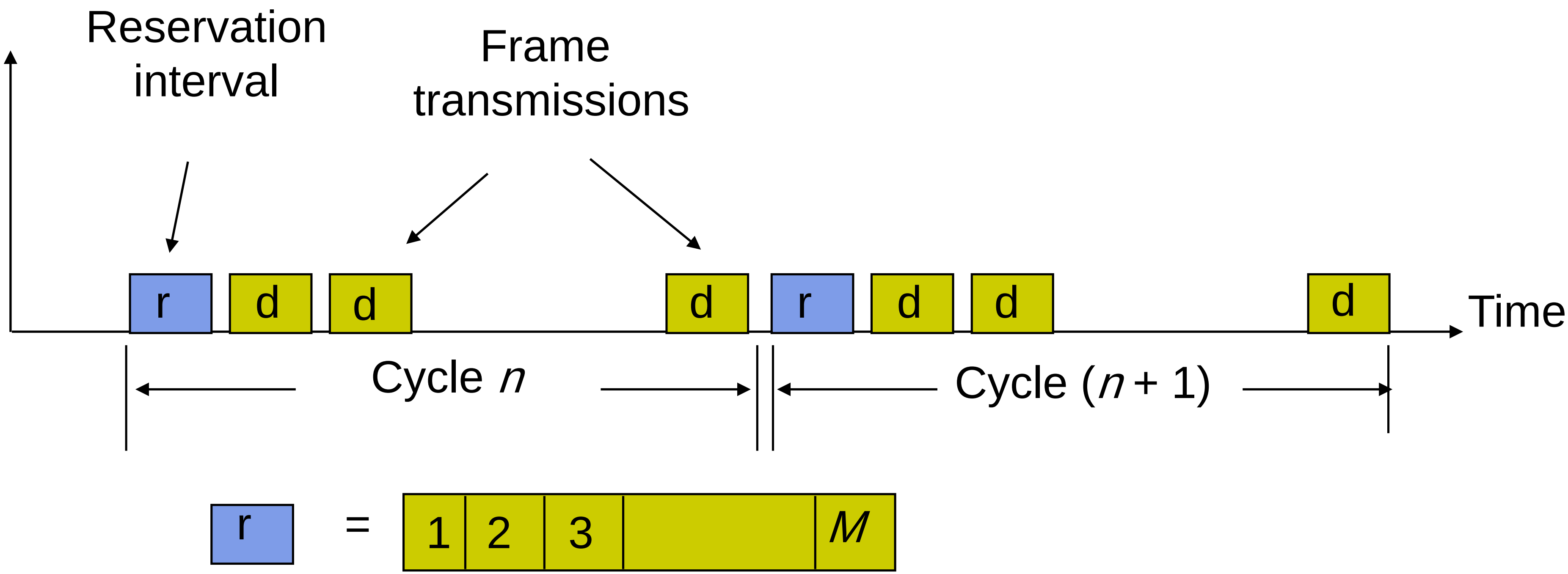
Reservations Systems

- *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 frame
- 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

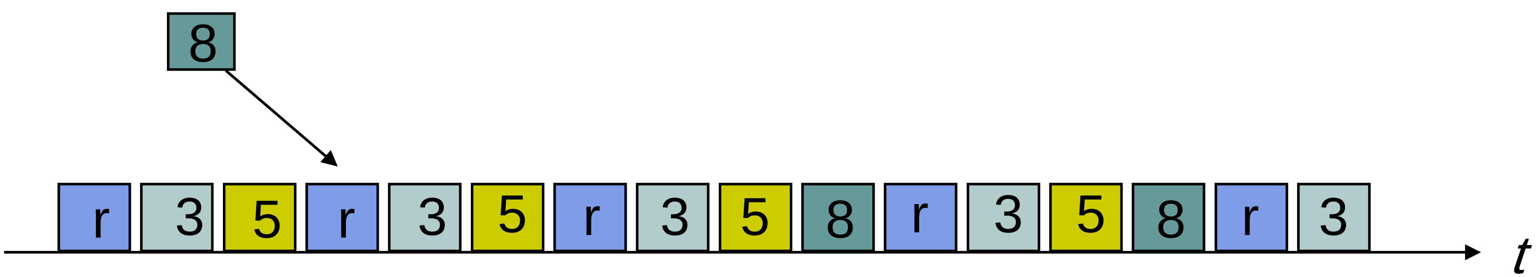
Example

- Initially stations 3 & 5 have reservations to transmit frames

(a)

- Station 8 becomes active and makes reservation
- Cycle now also includes frame transmissions from station 8

(b)



Efficiency of Reservation Systems

- Assume minislot duration = vX
- TDM 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:

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

- TDM *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:

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

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 on 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

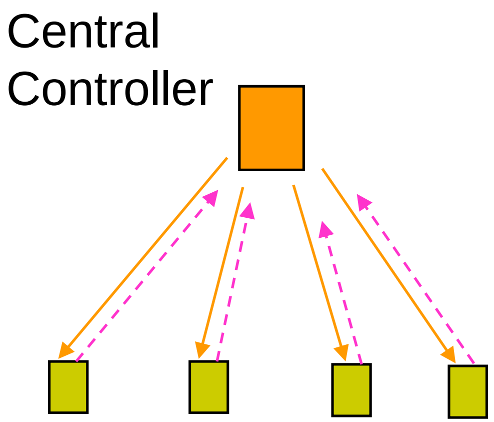
- General Packet Radio Service
  - Packet data service in GSM cellular radio
  - GPRS devices, e.g. cellphones or laptops, send packet data over radio and then to Internet
  - Slotted Aloha MAC used for reservations
  - Single & multi-slot reservations supported

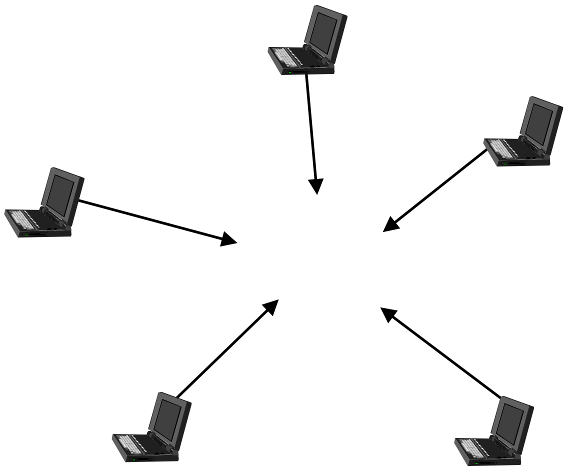
Reservation Systems and Quality of Service

- 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 makes 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



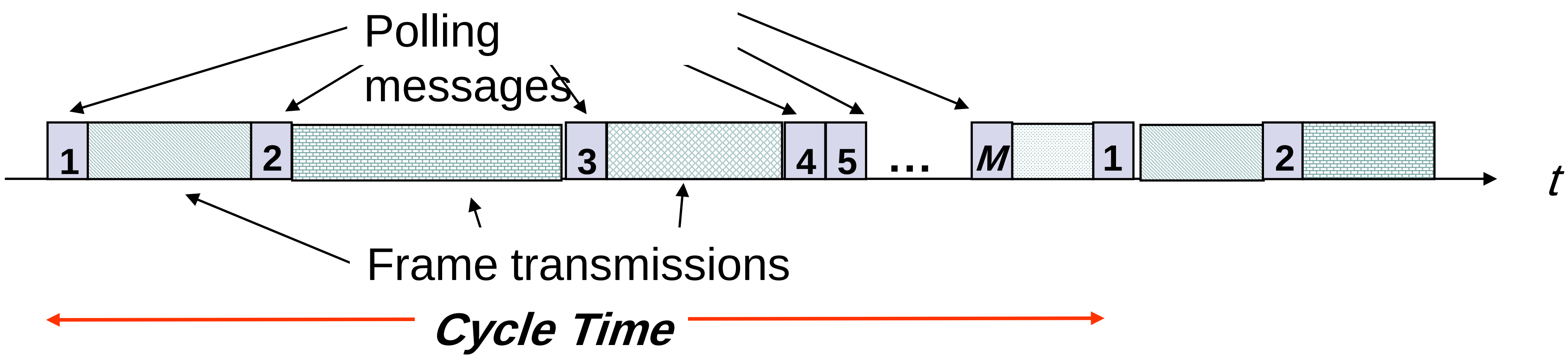


Polling System Options

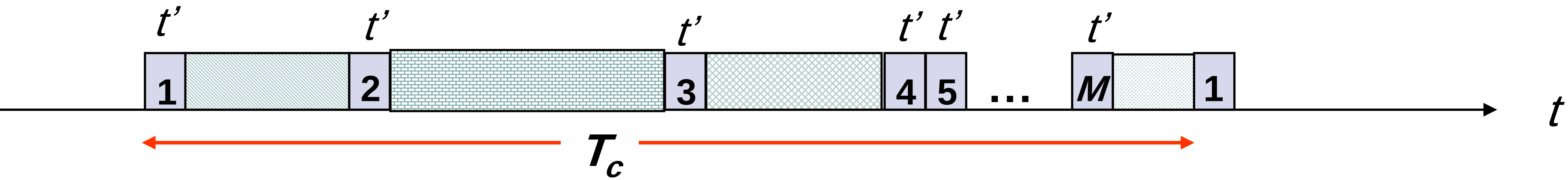
- Service Limits: How much is a station allowed to transmit per poll?
  - *Exhaustive*: until station's data buffer is empty (including new frame arrivals)
  - *Gated*: all data in buffer when poll arrives
  - *Frame-Limited*: one frame per poll
  - *Time-Limited*: up to some maximum time
- Priority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

Walk Time & Cycle Time

- Assume polling order is round robin
- Time is "wasted" 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/M be frame arrival rate at a station
- 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:

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

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:

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

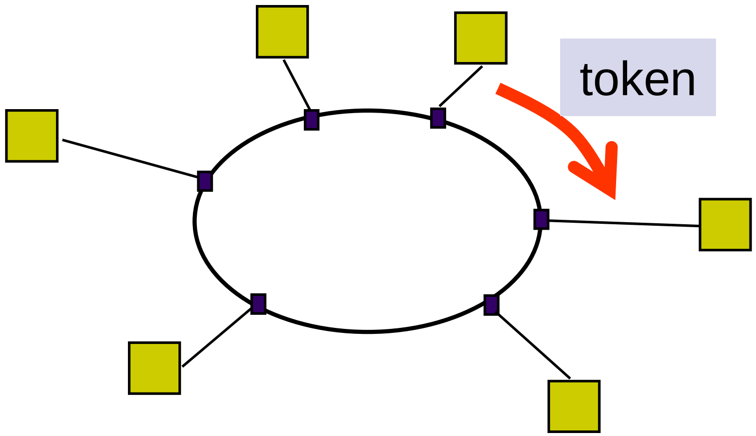
Can approach 100%

- 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

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

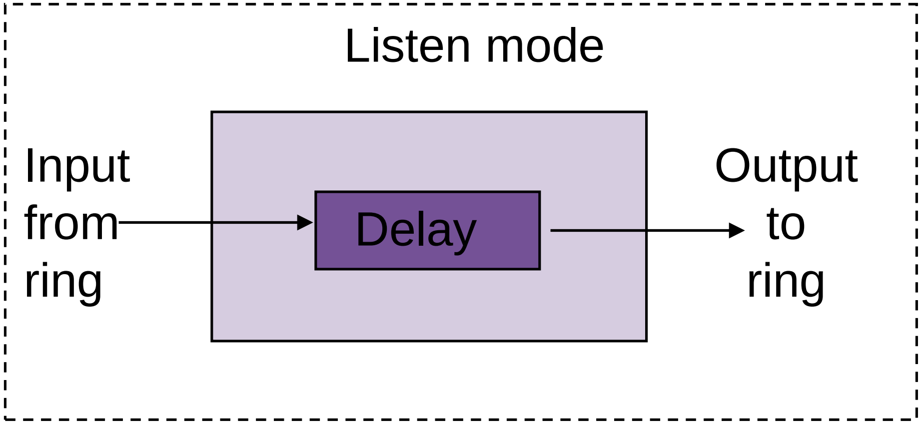
Single frame per poll

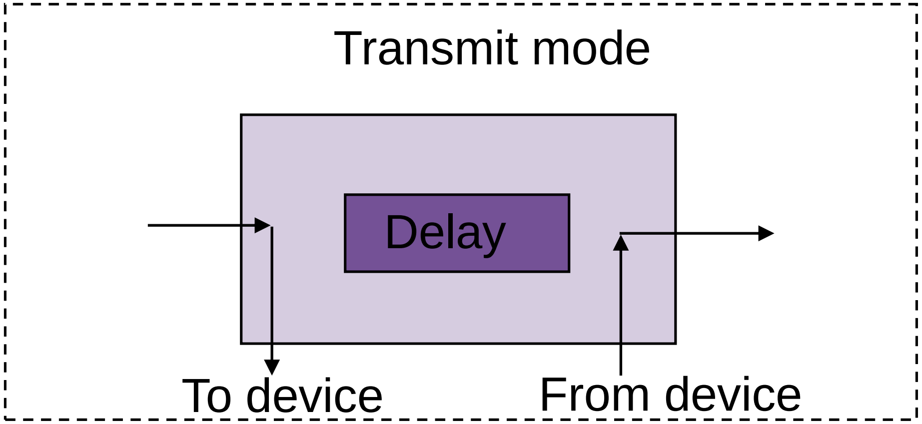
Application: Token-Passing Rings



Free Token = Poll

Frame Delimiter is Token
Free = 01111110
Busy = 01111111



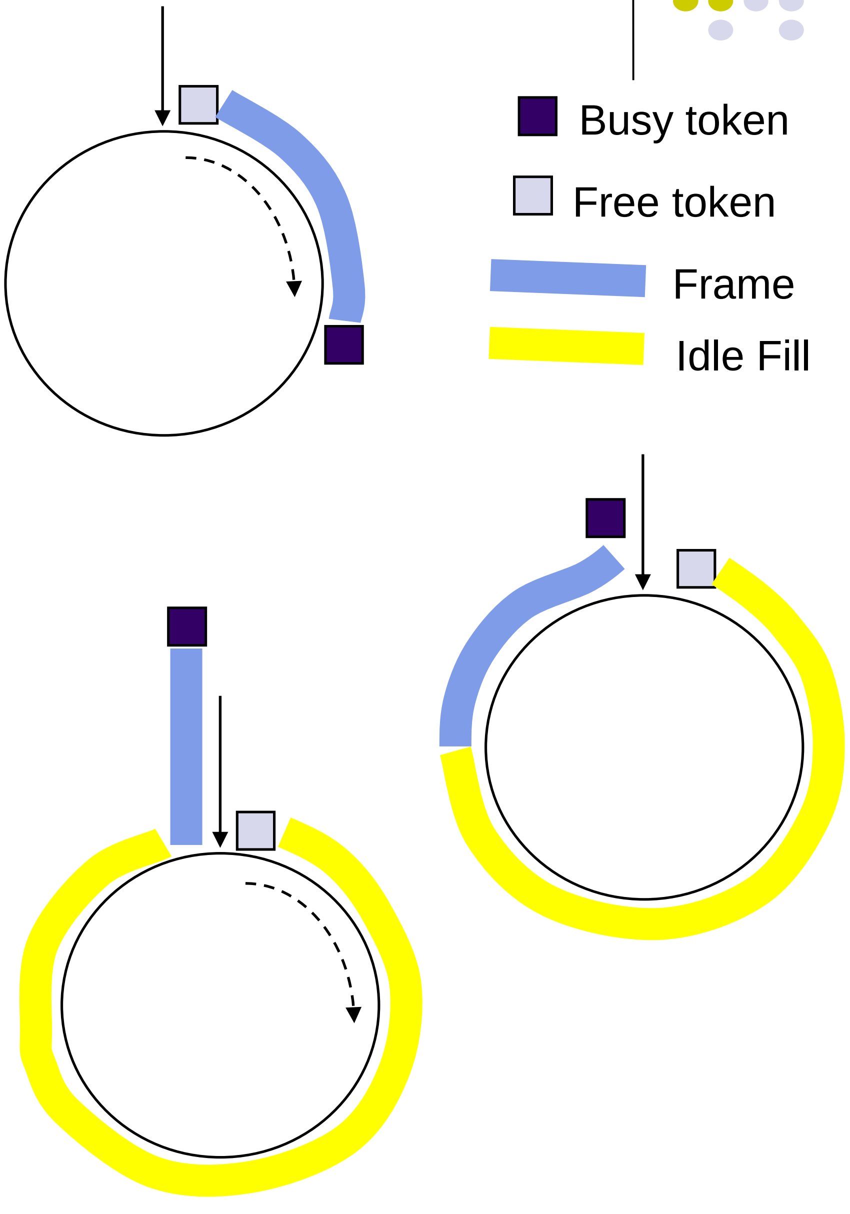


Ready station looks for free token
Flips bit to change free token to busy

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

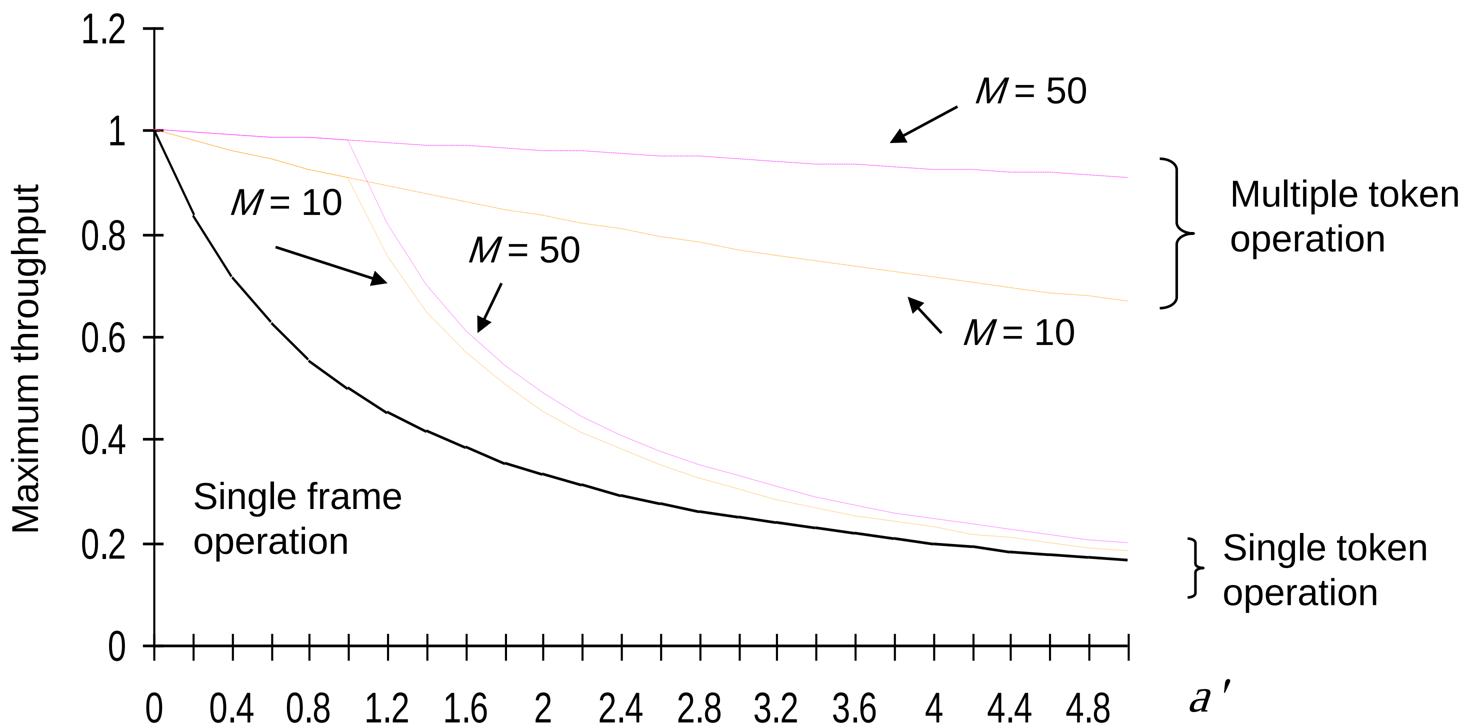
- *Single-frame operation*
  - Effective frame transmission time is maximum of X and τ', therefore

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

- *Single-token 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
- $a \approx 1$, 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
- Multitoken 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
- CSMA-CD
  - Quick transfer and high efficiency for low delay-bandwidth product
  - Can accommodate 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 multiplexing
  - Provides fairness through regular access opportunities
  - Can provide bounds on access delay
  - Performance deteriorates with large delay-bandwidth product

Chapter 6
Medium Access Control Protocols and Local Area Networks

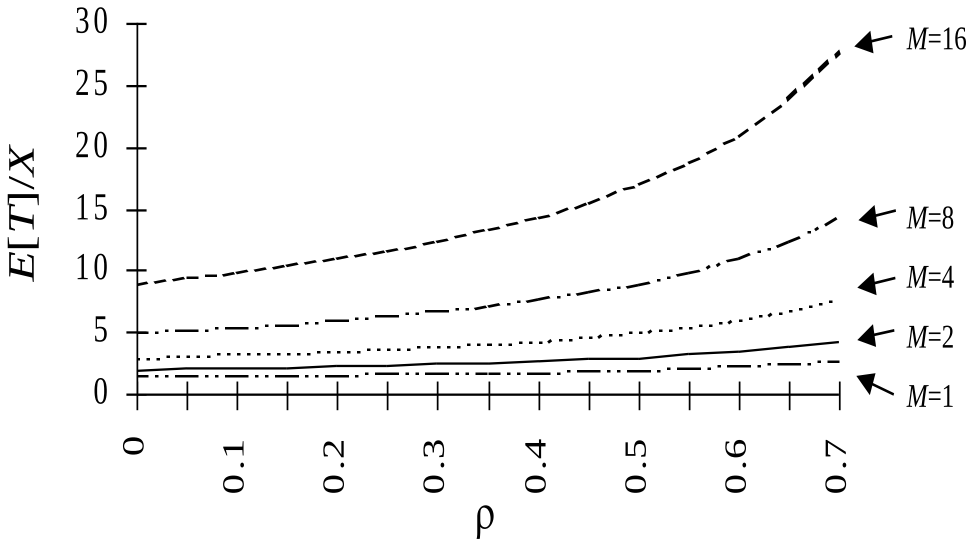
Channelization

Why Channelization?

- 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

Why not Channelization?

- 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

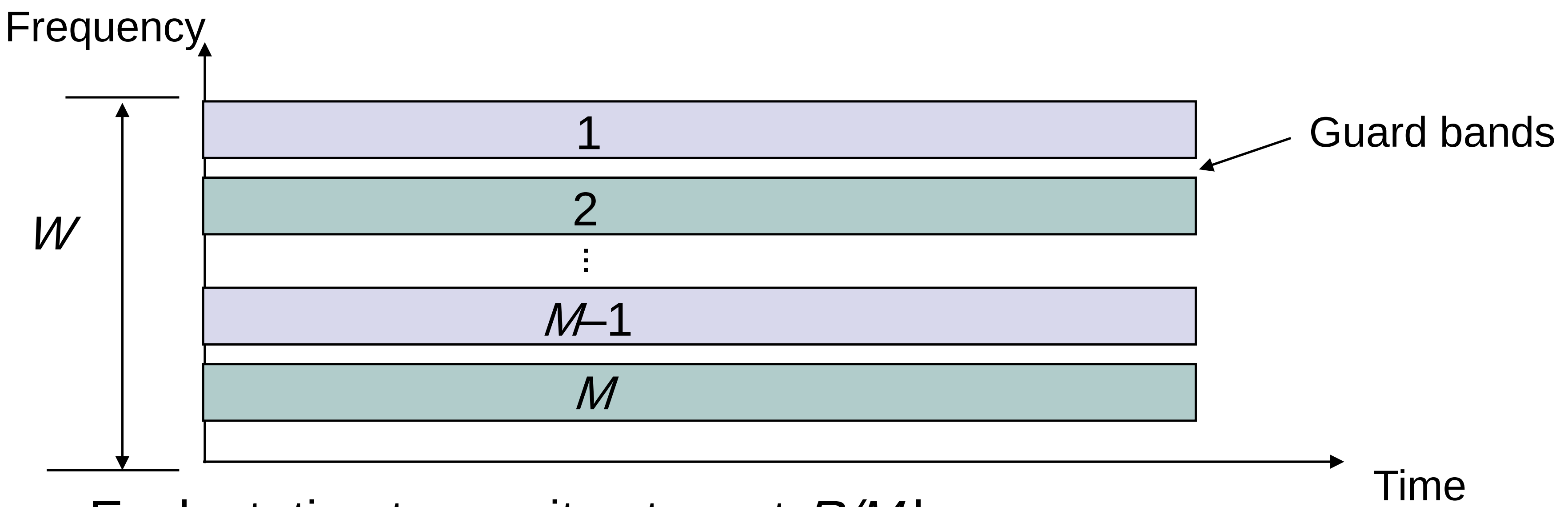


Channelization Approaches

- *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

Channelization: FDMA

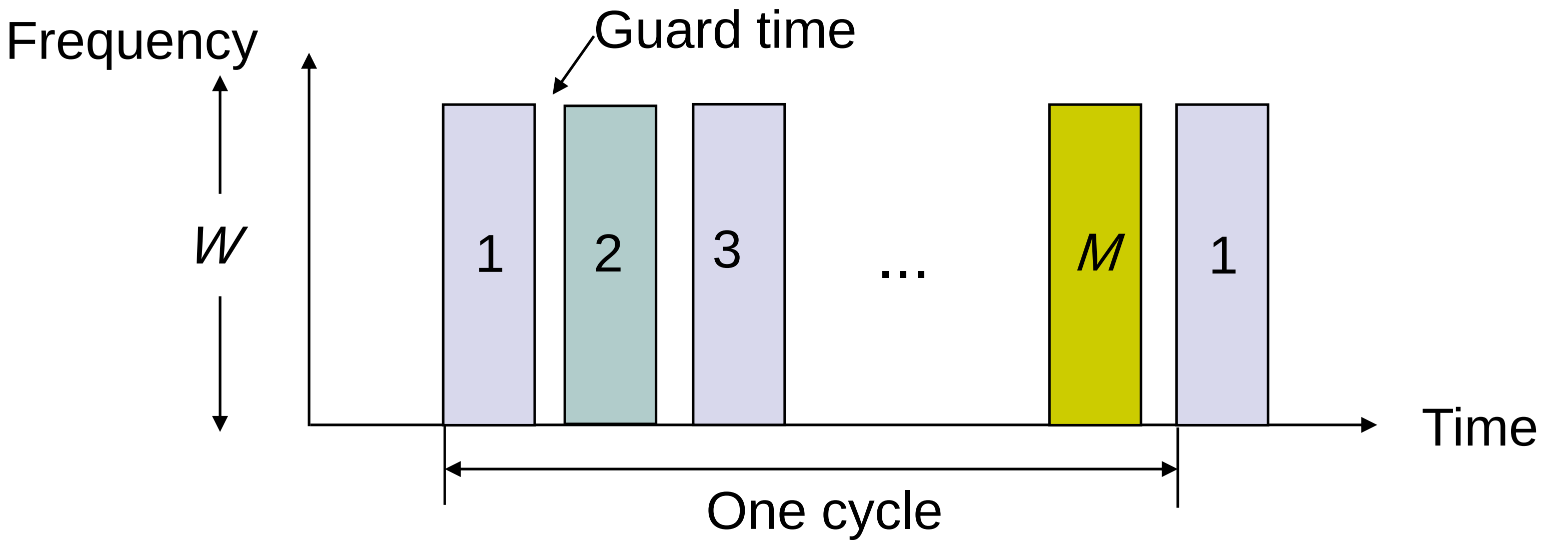
- Divide channel into *M* frequency bands
- Each station transmits and listens on assigned bands



- Each station transmits at most *R/M* bps
- Good for stream traffic; Used in connection-oriented systems
- Inefficient for bursty traffic

Channelization: TDMA

- 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

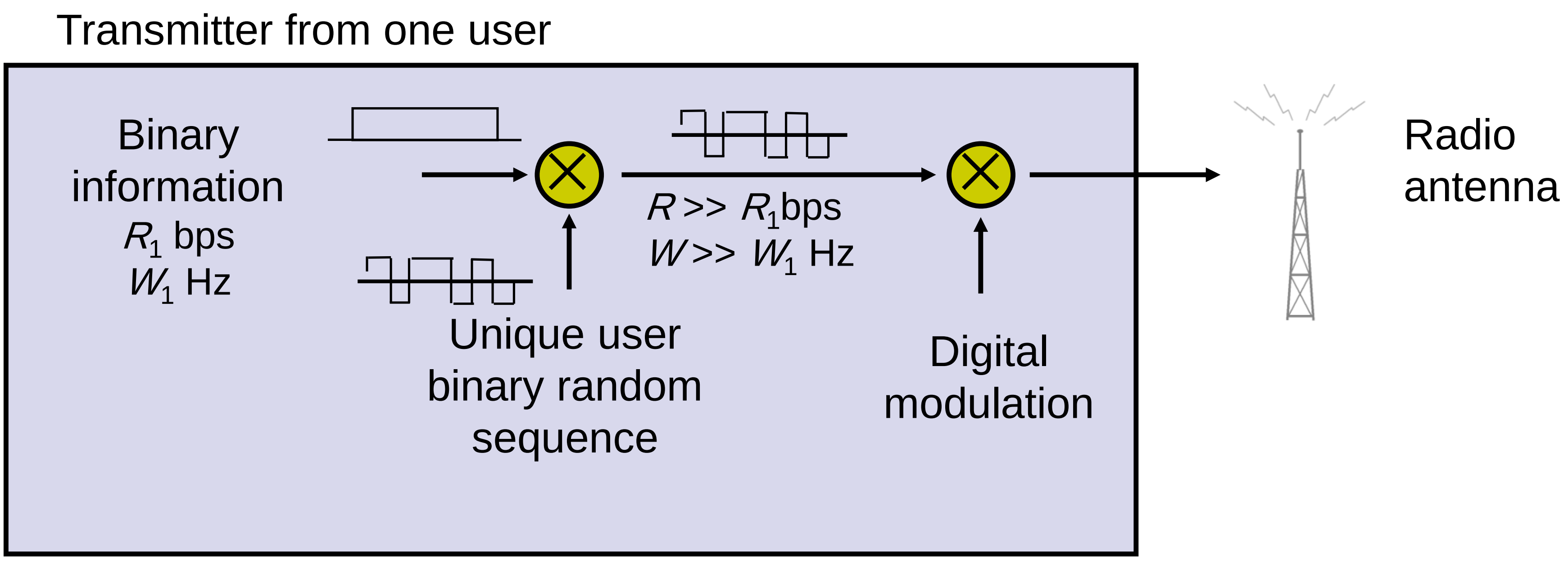
Guardbands

- 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

Channelization: CDMA

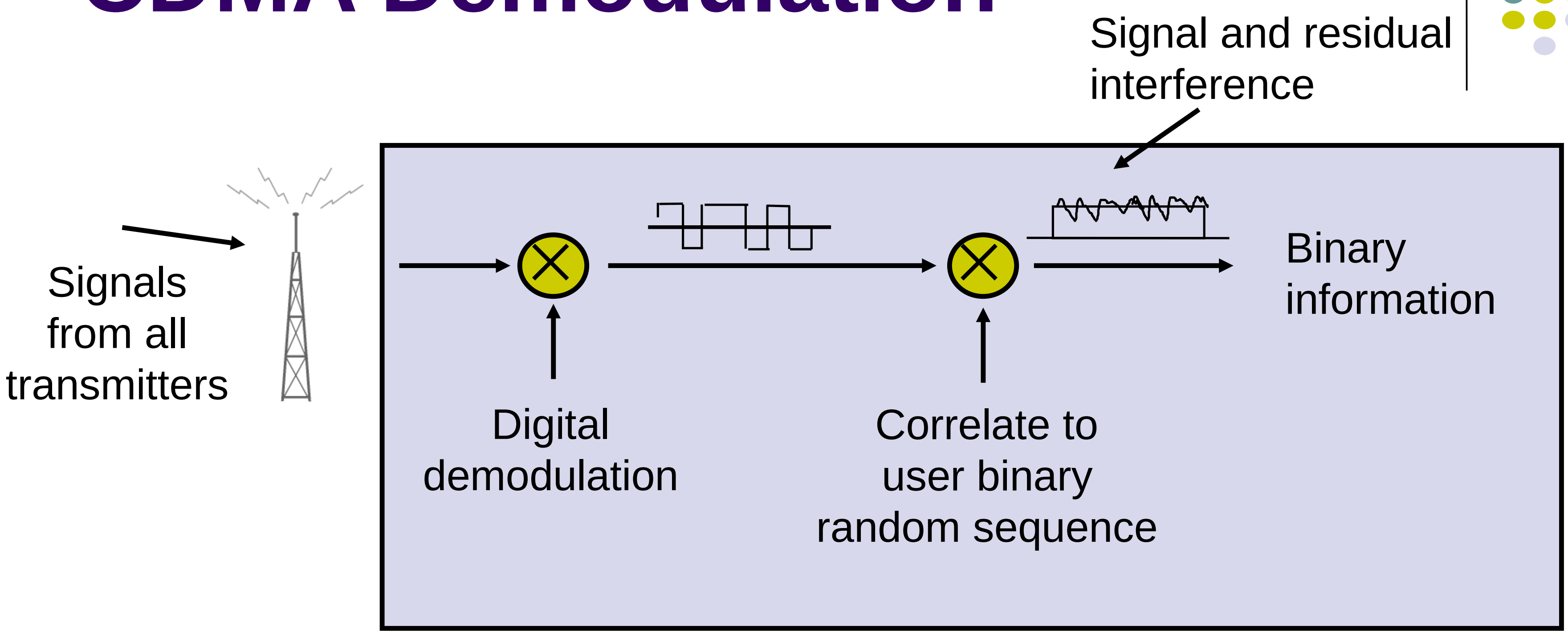
- Code Division Multiple Access
  - Channels determined by a code used in modulation and demodulation
- Stations transmit over entire frequency band all of the time!

CDMA Spread Spectrum Signal



- User information mapped into: +1 or -1 for T sec.
- Multiply user information by pseudo- random binary pattern of G "chips" of +1's and -1's
- Resulting spread spectrum signal occupies G times more bandwidth: $W = GW_1$
- Modulate the spread signal by sinusoid at appropriate f_c

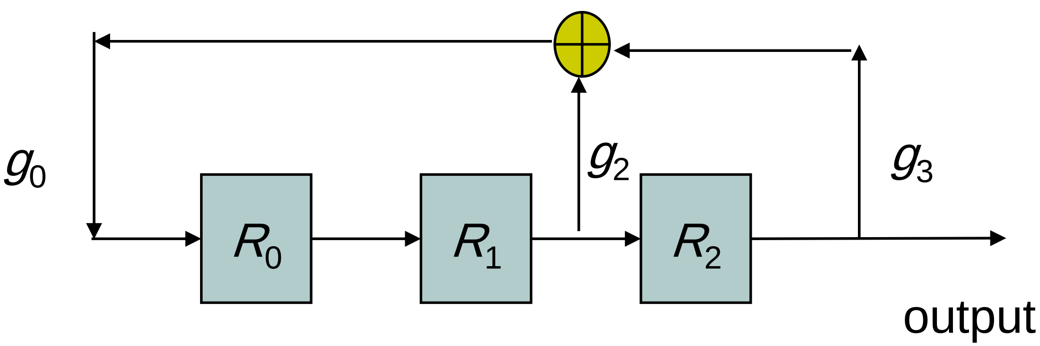
CDMA Demodulation



- Recover spread spectrum signal
- Synchronize to and multiply spread signal by ***same*** pseudo-random binary pattern used at the transmitter
- In absence of other transmitters & noise, we should recover the original +1 or -1 of user information
- Other transmitters using different codes appear as residual noise

Pseudorandom pattern generator

- Feedback shift register with appropriate feedback taps can be used to generate pseudorandom sequence



$$g(x) = x^3 + x^2 + 1$$

The coefficients of a primitive generator polynomial determine the feedback taps

Time	R_0	R_1	R_2
0	1	0	0
1	0	1	0
2	1	0	1
3	1	1	0
4	1	1	1
5	0	1	1
6	0	0	1
7	1	0	0

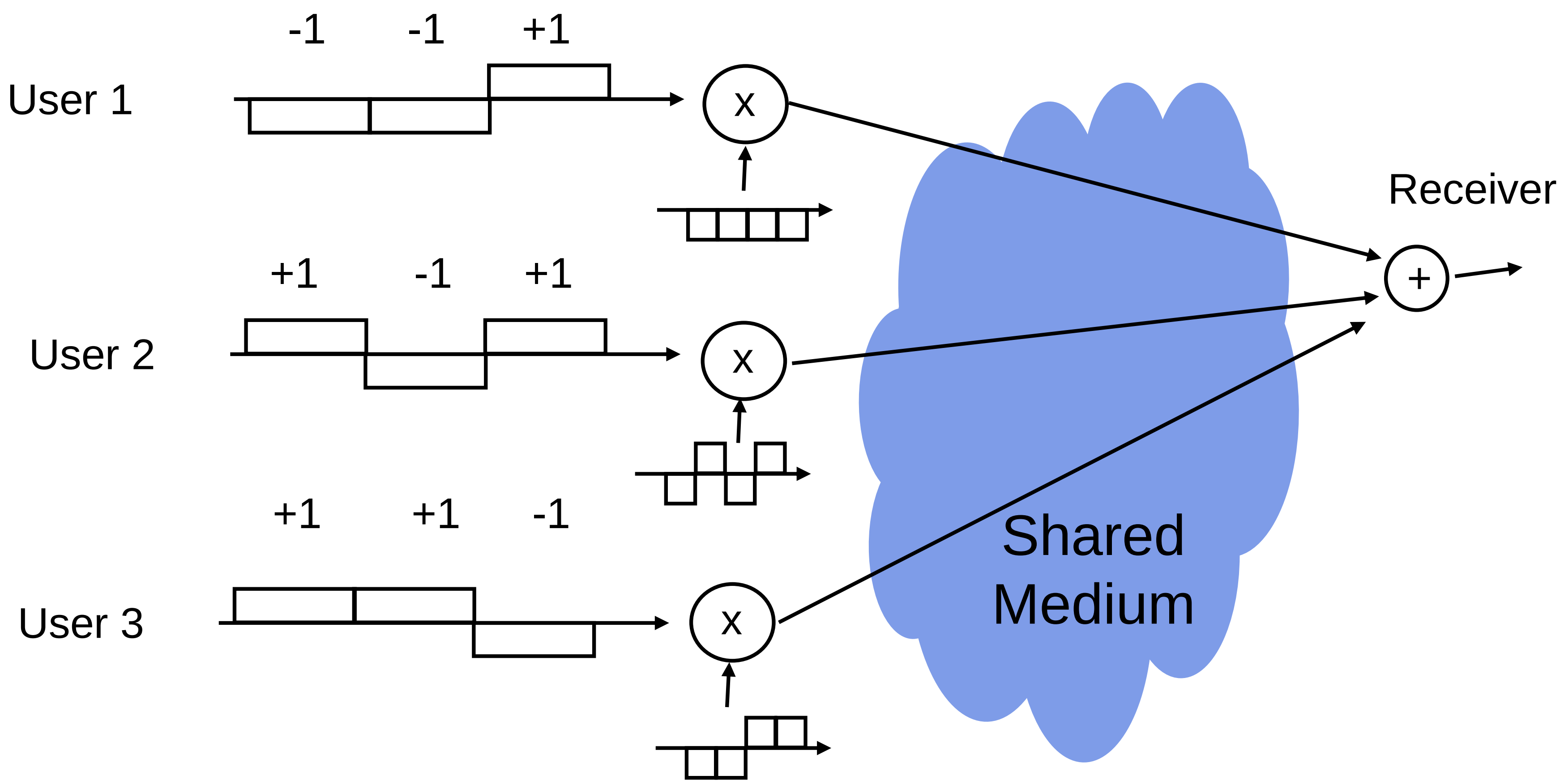
Sequence repeats from here onwards

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 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 is codes are selected so they are *orthogonal* and if receivers and transmitters are synchronized
  - Shown in next example

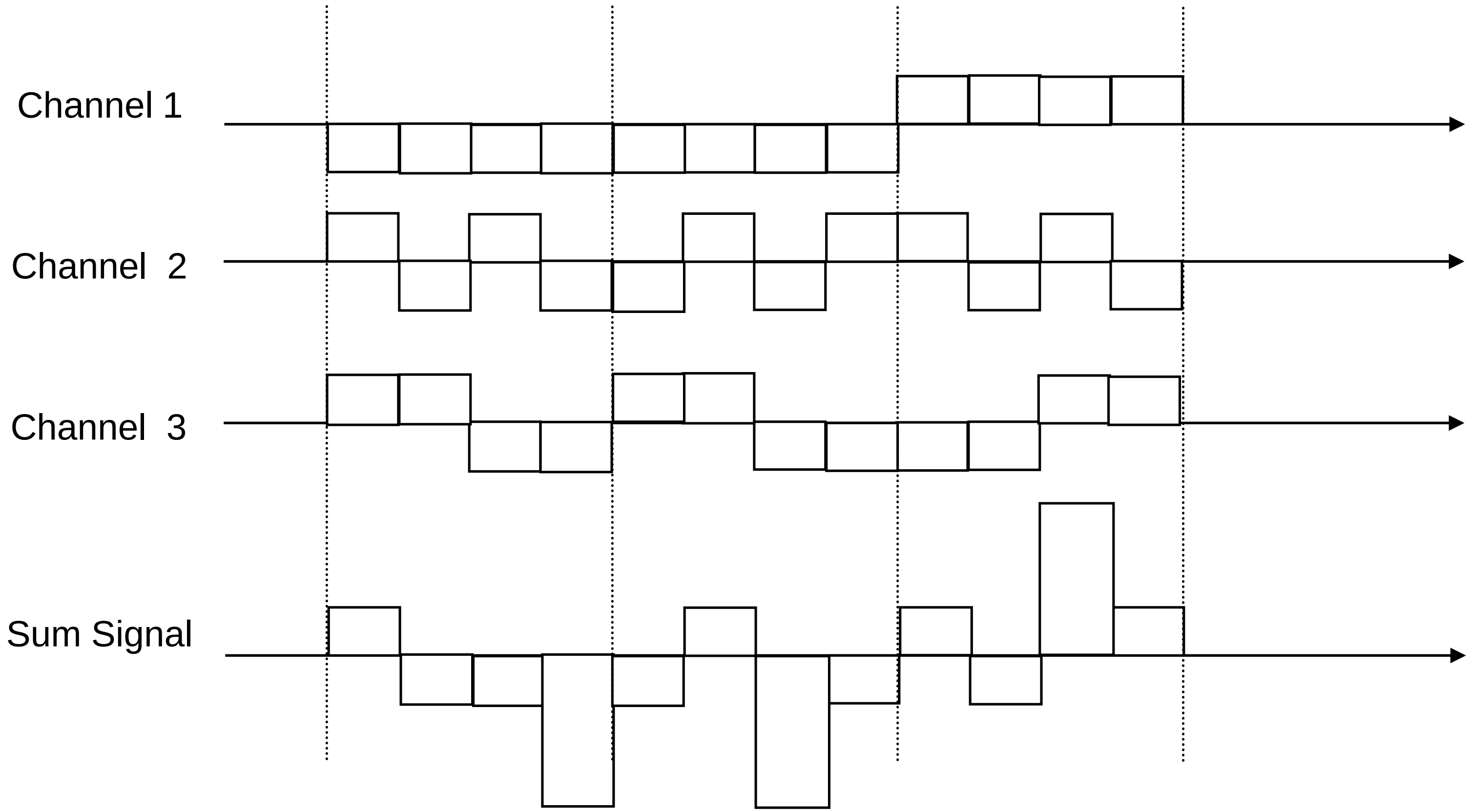
Example: CDMA with 3 users

- 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},



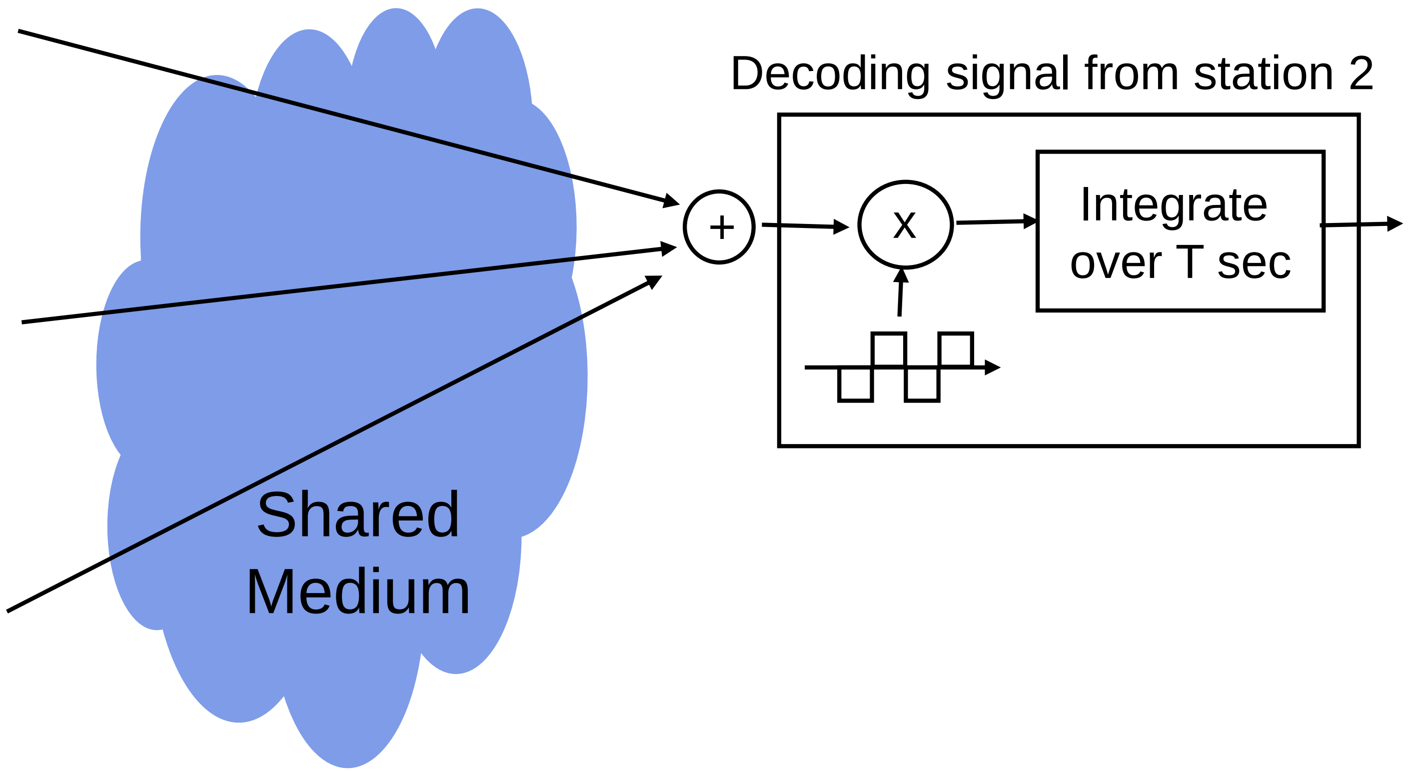
Sum signal is input to receiver

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)`



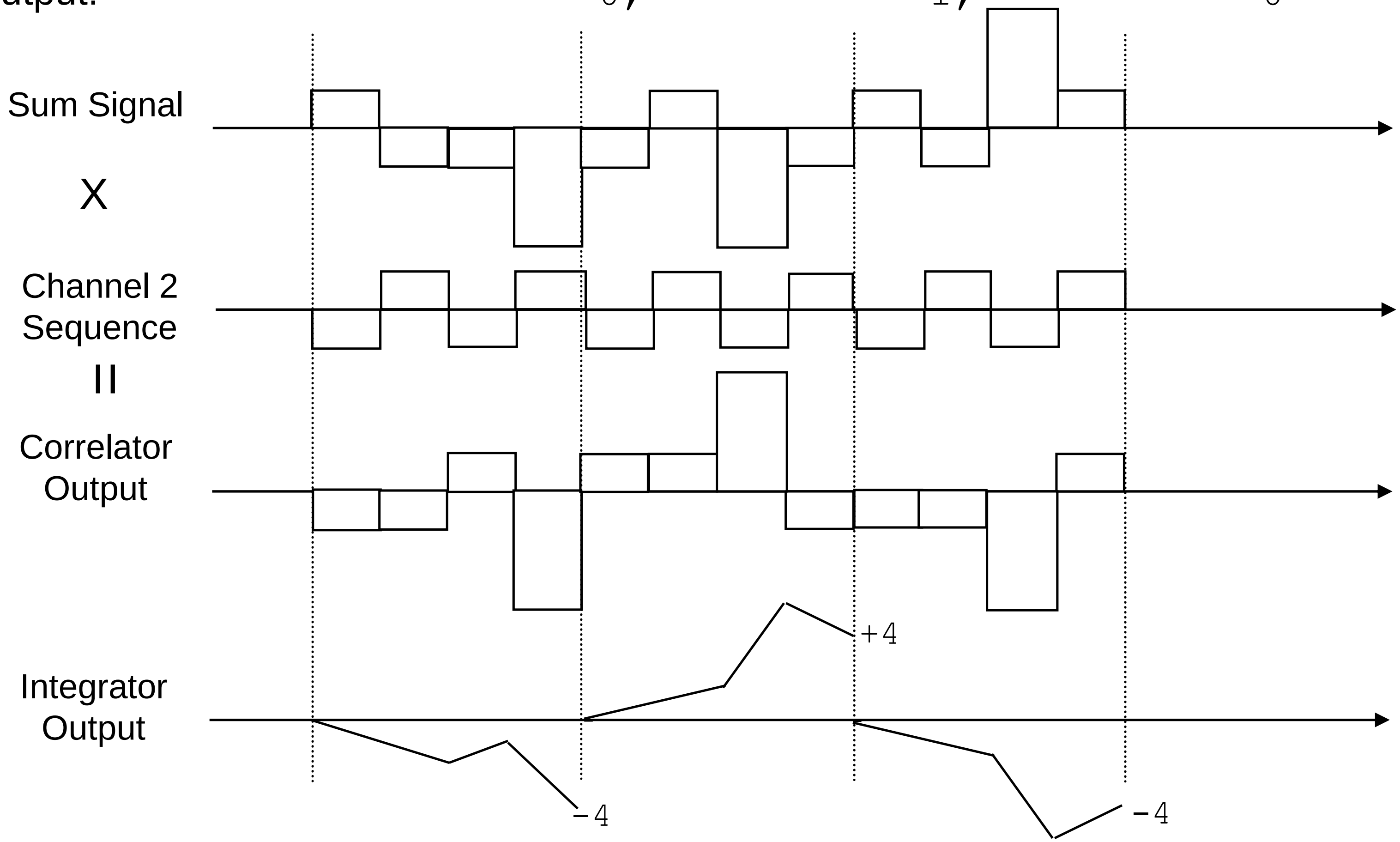
Example: Receiver for Station 2

- 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

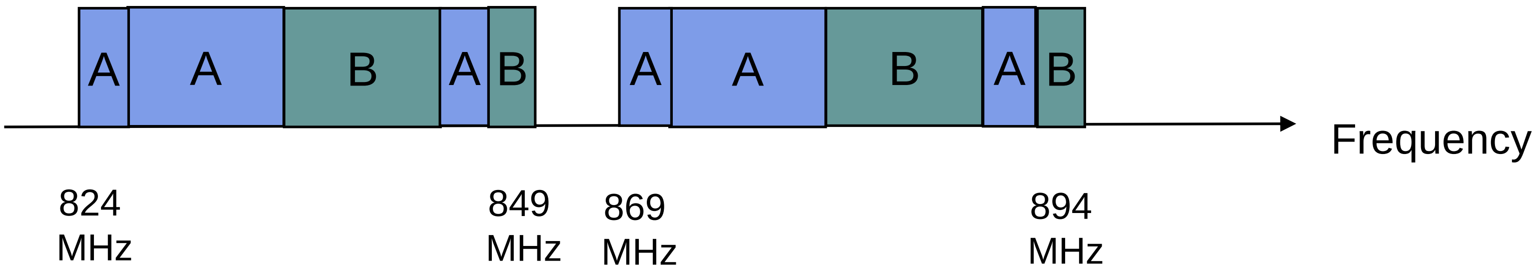


Channelization in Cellular Telephone Networks

- Cellular networks use frequency reuse
  - Band of frequencies reused in other cells that are sufficiently far 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

Advanced Mobile Phone System

- Advanced Mobile Phone System (AMPS)
  - First generation cellular telephone system in US
  - Analog voice channels of 30 kHz
  - Forward channels from base station to mobiles
  - Reverse channels from mobiles to base
- Frequency band 50 MHz wide in 800 MHz region allocated to two service providers: “A” and “B”



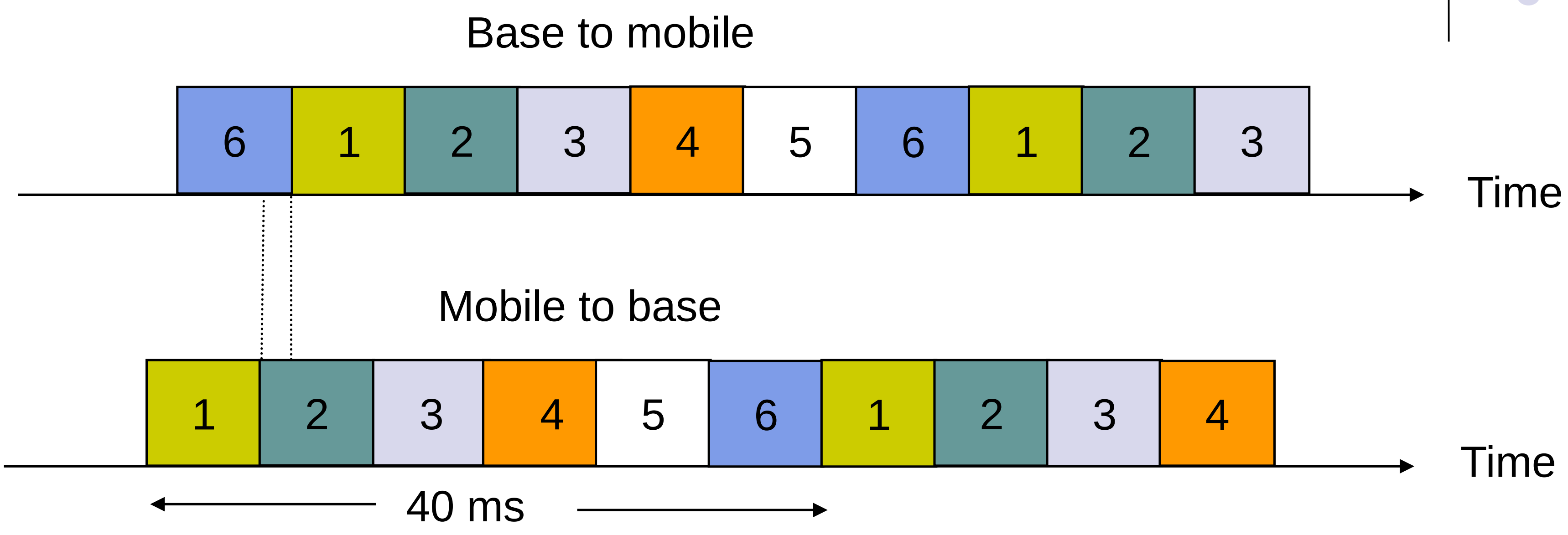
AMPS Spectral Efficiency

- 50 MHz @ 30kHz gives 832 2-way channels
- Each service provider has
  - 416 2-way channels
  - 21 channels used for call setup & control
  - 395 channels used for voice
  - AMPS uses 7-cell frequency reuse pattern, so each cell has 395/7 voice channels
- AMPS spectrum efficiency: #calls/cell/MHz
  - (395.7)/(25 MHz) = 2.26 calls/cell/MHz

Interim Standard 54/136

- IS-54, and later IS-136, developed to meet demand for cellular phone service
- Digital methods to increase capacity
- A 30-kHz AMPS channel converted into several TDMA channels
  - 1 AMPS channel carries 48.6 kbps stream
  - Stream arranged in 6-slot 40 ms cycles
  - 1 slot = 324 bits $\rightarrow$ 8.1 kbps per slot
  - 1 *full-rate channel*: 2 slots to carry 1 voice signal
- 1 AMPS channel carries 3 voice calls
- 30 kHz spacing also used in 1.9 GHz PCS band

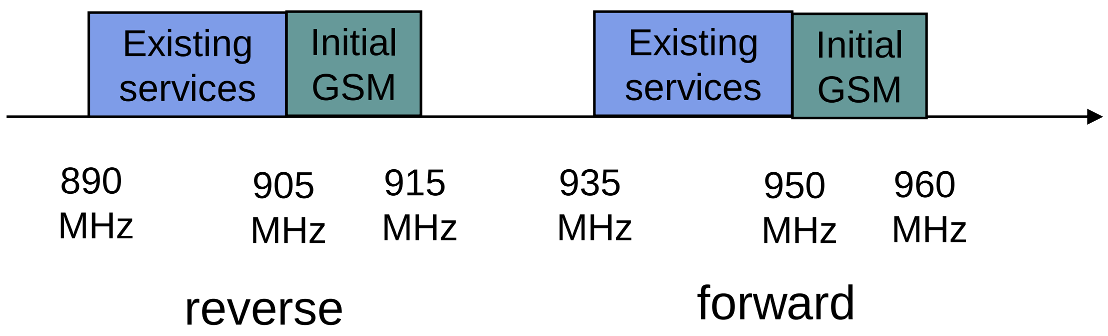
IS-54 TDMA frame structure



- 416 AMPS channels x 3 = 1248 digital channels
- Assume 21 channels for calls setup and control
- IS-54 spectrum efficiency: #calls/cell/MHz
  - (1227/7)/(25 MHz) = 3 calls/cell/MHz

Global System for Mobile Communications (GSM)

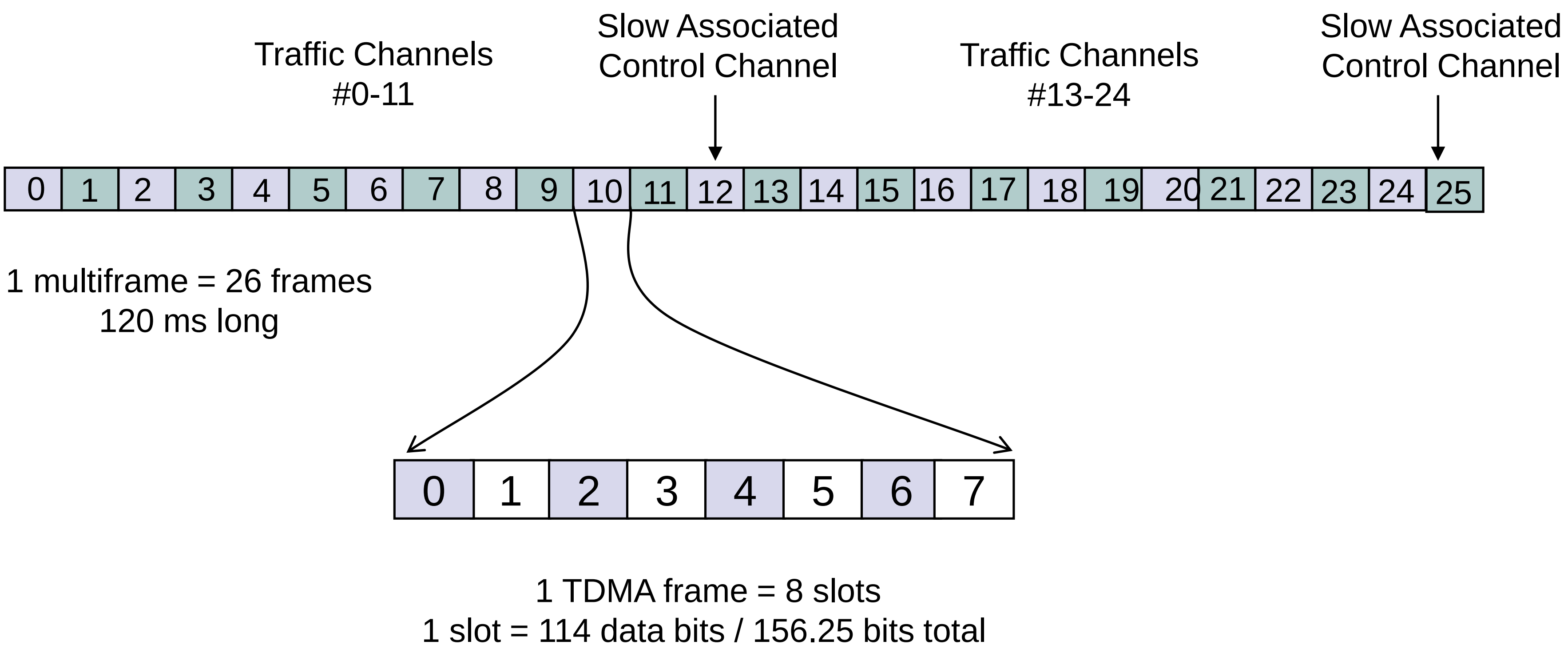
- European digital cellular telephone system
- 890-915 MHz & 935-960 MHz band
- PCS: 1800 MHz (Europe), 1900 MHz (N.Am.)
- Hybrid TDMA/FDMA
  - Carrier signals 200 kHz apart
  - 25 MHz give 124 one-way carriers



GSM TDMA Structure

- Each carrier signal carries traffic and control channels
- 1 full rate traffic channel = 1 slot in every traffic frame

  24 slots x 114 bits/slot / 120 ms = 22.8 kbps



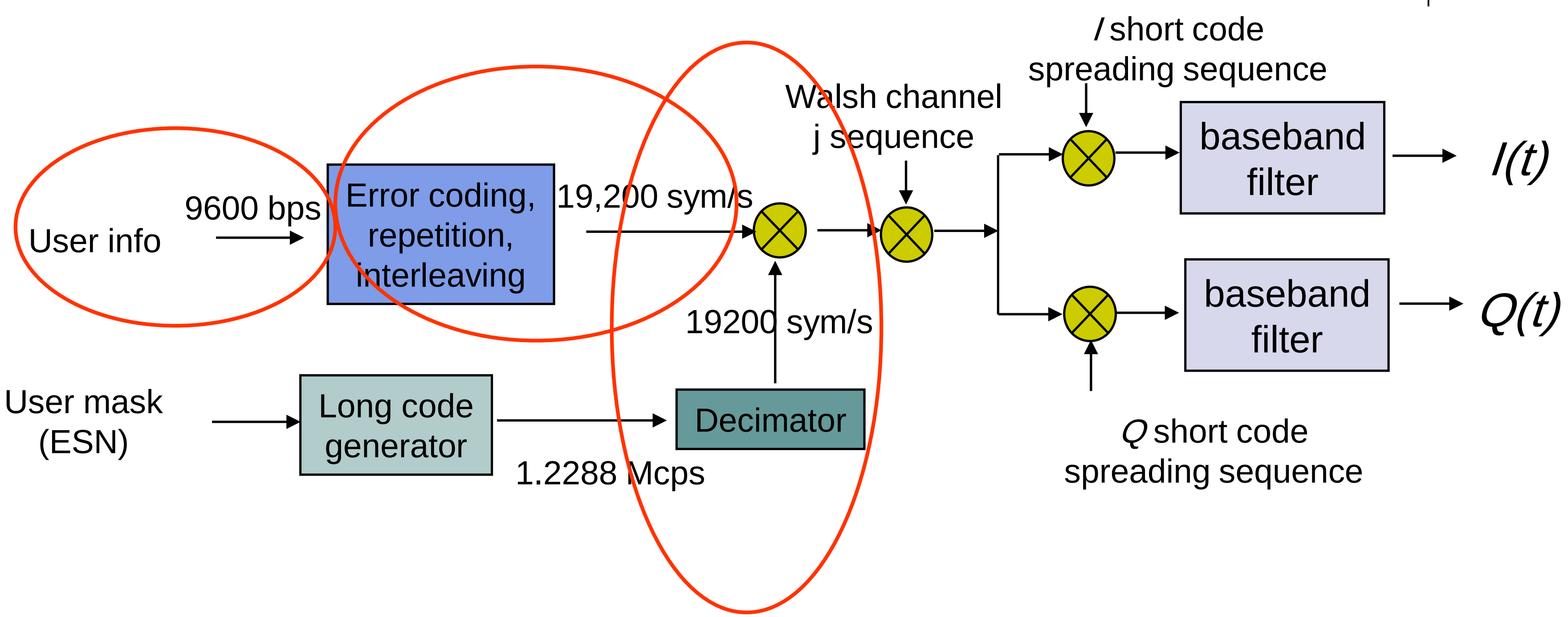
GSM Spectrum Efficiency

- Error correction coding used in 22.8 kbps to carry 13 kbps digital voice signal
- Frequency reuse of 3 or 4 possible
- 124 carriers x 8 = 992 traffic channels
- Spectrum efficiency for GSM:
  - (992/3)/50MHz = 6.61 calls/cell/MHz

Interim Standard 95 (IS-95)

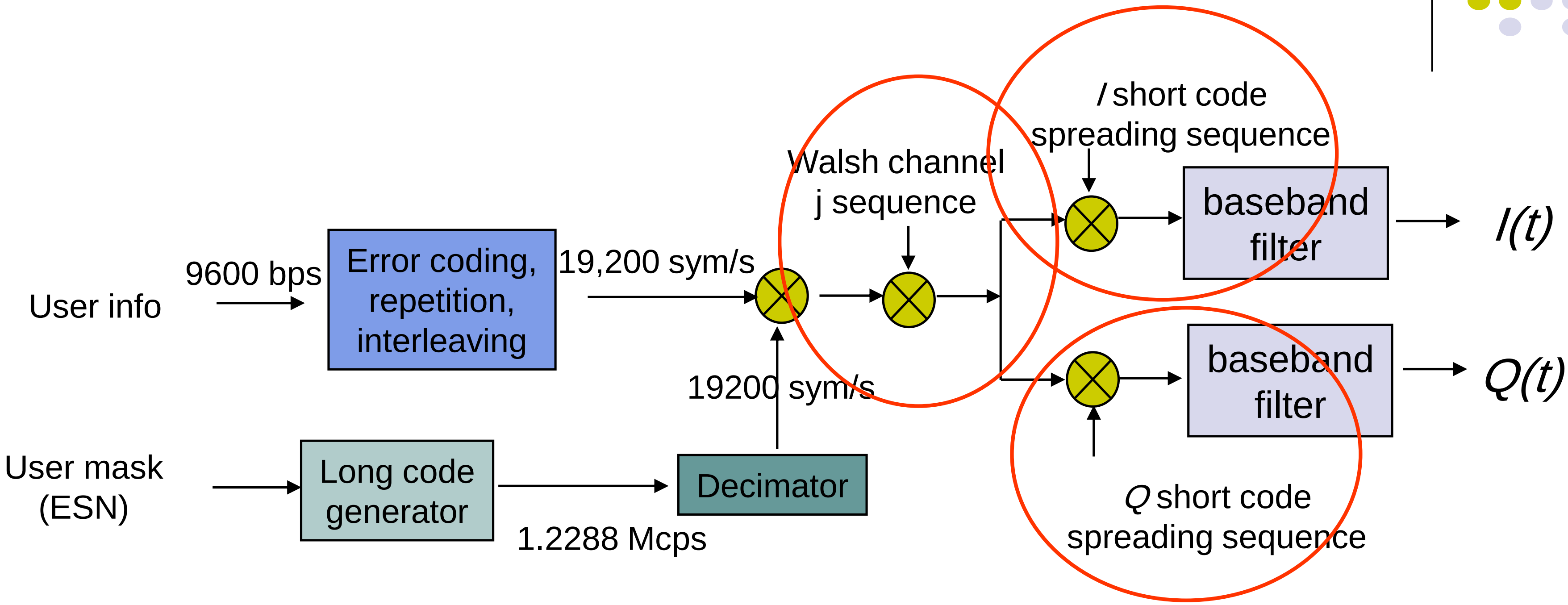
- CDMA digital cellular telephone system
- Operates in AMPS & PCS bands
- 1 signal occupies 1.23 MHz
  - 41 AMPS signals
- All base stations are synchronized to a common clock
  - Global Positioning System accuracy to 1 μsec
- Forward channels use orthogonal spreading
- Reverse channels use non-orthogonal spreading

Base-to-Mobile Channels



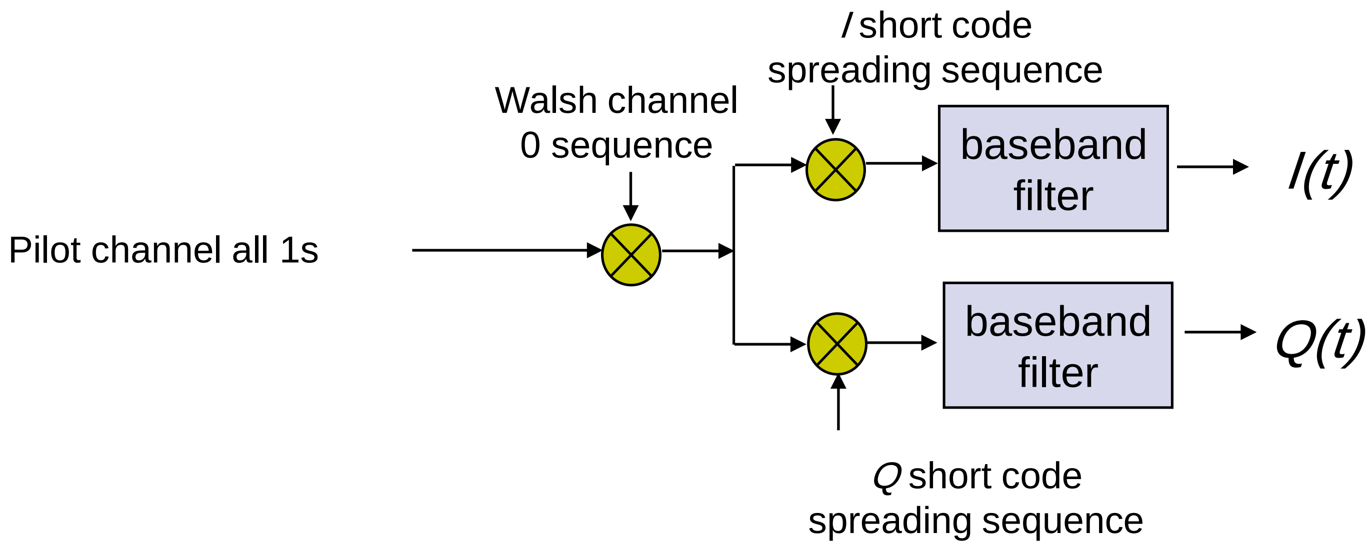
- Basic user information rate is 9.6 kbps
- Doubled after error correction coding
- Converted to $\pm$1s
- Multiplied by 19.2 ksym/sec stream derived from 42-bit register long-code sequence generator which depends on electronic serial number

Base-to-Mobile Channels



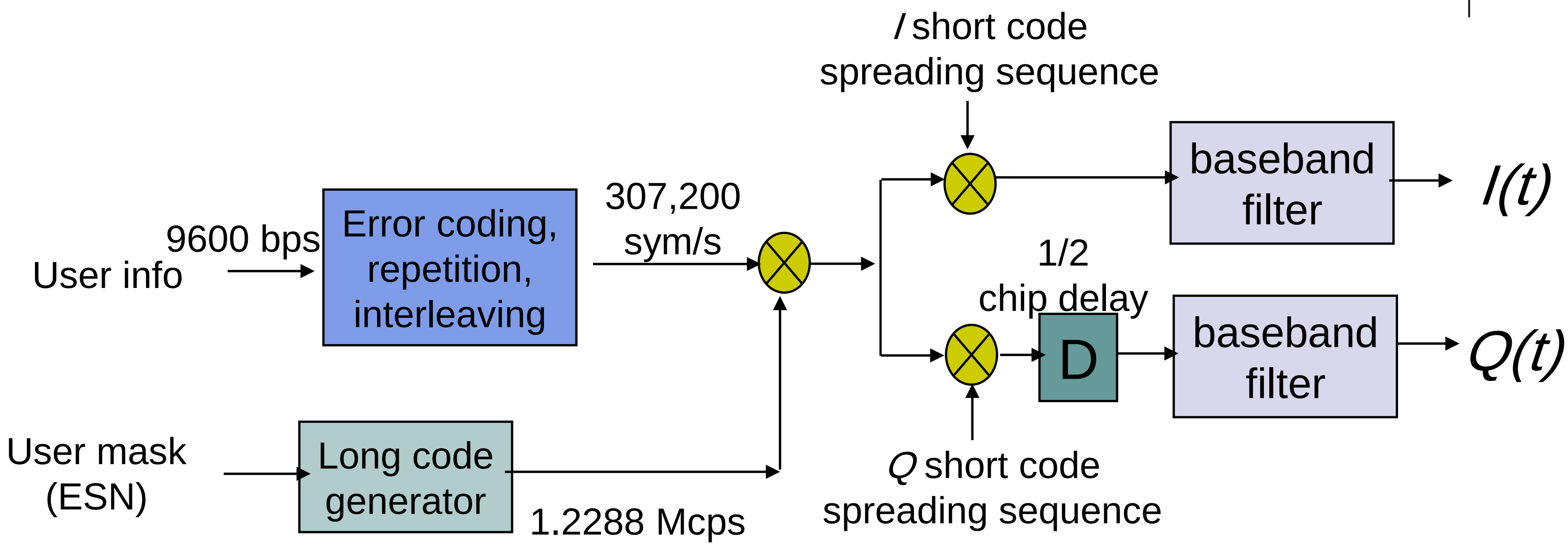
- Each symbol multiplied by 64-bit chip Walsh orthogonal sequence (19200 x 64 = 1.2288 Msym/sec)
- Each base station uses the same 15-bit register short sequence to spread signal prior to transmission
- Base station synchronizes all its transmissions

Pilot Tone & Synchronization



- All 0’s Walsh sequence reserved to generate pilot tone
- Short code sequences transmitted to all receivers
- Receivers can then recover user information using Walsh orthogonal sequence
- Different base stations use different phase of same short sequence
- Mobiles compare signal strengths of pilots from different base stations to decide when to initiate handoff

Mobile-to-Base Channels



- 9.6 kbps user information coded and spread to 307.2 kbps
- Spread by 4 by multiplying by long code sequence
- Different mobiles use different phase of long code sequence
- Multiplied by short code sequence
- Transmitted to Base

IS-95 Spectrum Efficiency

- Spread spectrum reduces interference
  - Signals arriving at a base station from within or from outside its cell are uncorrelated because mobiles have different long code sequences
  - Signals arriving at mobiles from different base stations are uncorrelated because they use different phases of the short code sequence
- *Enables reuse factor of 1*
- Goodman [1997] estimates spectrum efficiency for IS-95 is:
  - between 12 & 45 call/cell/MHz
- *Much higher spectrum efficiency than IS-54 & GSM*

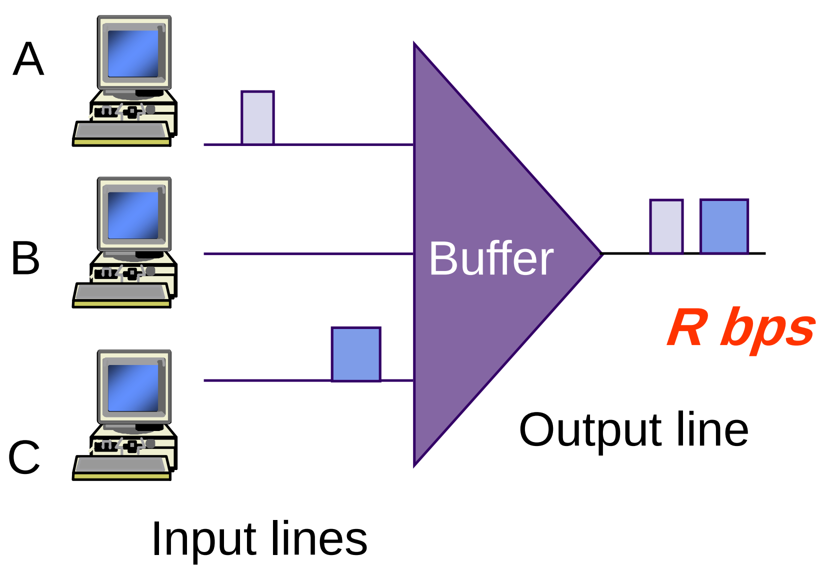
Chapter 6
Medium Access Control Protocols and Local Area Networks

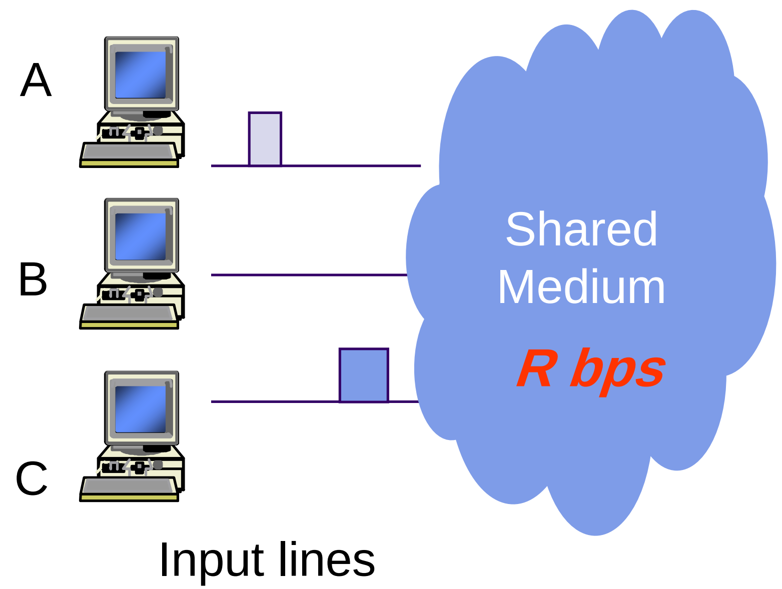
Delay Performance

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





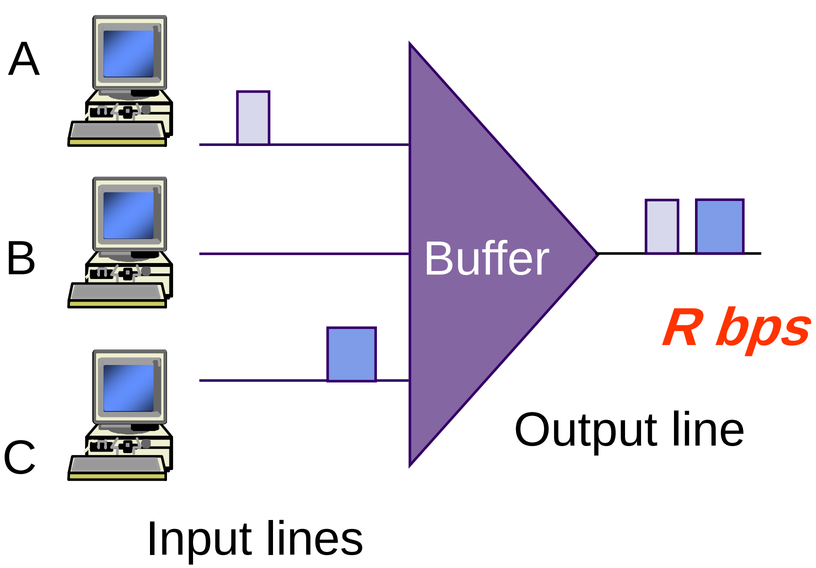
Performance Issues in Statistical Multiplexing & Multiple Access

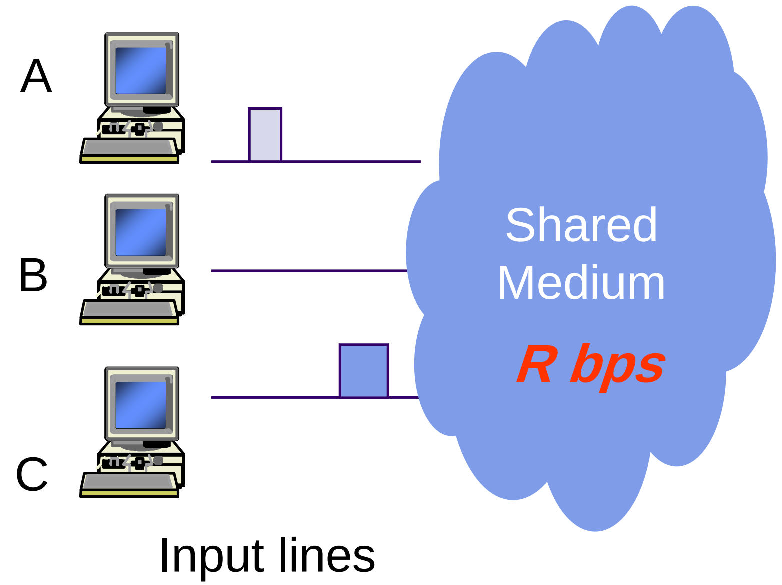
Application Properties

- How often are packets generated?
- How long are packets?
- What are loss & delay requirements?

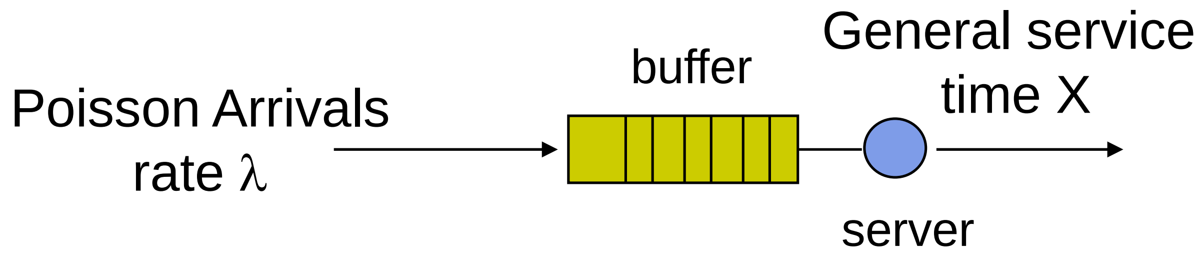
System Performance

- Transfer Delay
- Packet/frame Loss
- Efficiency & Throughput
- Priority, scheduling, & QoS





M/G/1 Queueing Model for Statistical Multiplexer



- 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: $\rho<1$

We will use M/G/1 model as baseline for MAC performance

M/G/1 Performance Results

(From Appendix A)

Total Delay = Waiting Time + Service Time

Average Waiting Time:

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

Average Total Delay:

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

Example: M/D/1

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

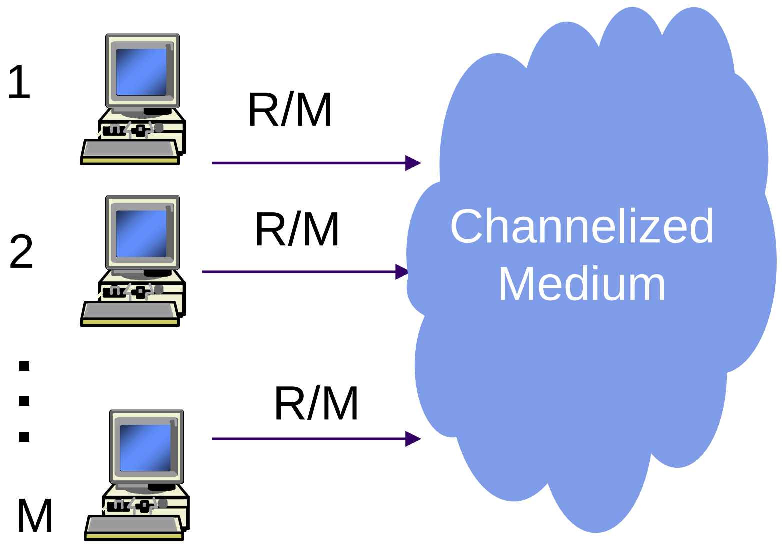
M/G/1 Vacation Model

- 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

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

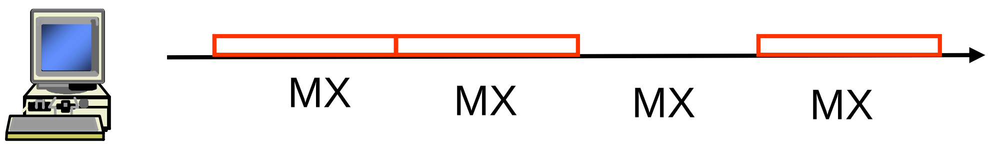
Extra delay term

Performance of FDMA & CDMA Channelization Bursty Traffic



- M stations do not interact
- Poisson arrivals λ/M fr/sec
- Constant frame length L bits
- Transmission time at full rate
  - $X=L/R$
- Station bit rate is R/M
  - Neglect guardbands
- Transmission time from station
  - $L/(R/M)=M(L/R)=MX$
  - M times longer
- Load at one station:
  - $\rho=(\lambda/M)MX=\lambda X$

Transfer Delay for FDMA and CDMA



- Time-slotted transmission from each station
- When station becomes empty, transmitter goes on vacation for 1 time slot of constant duration V=MX

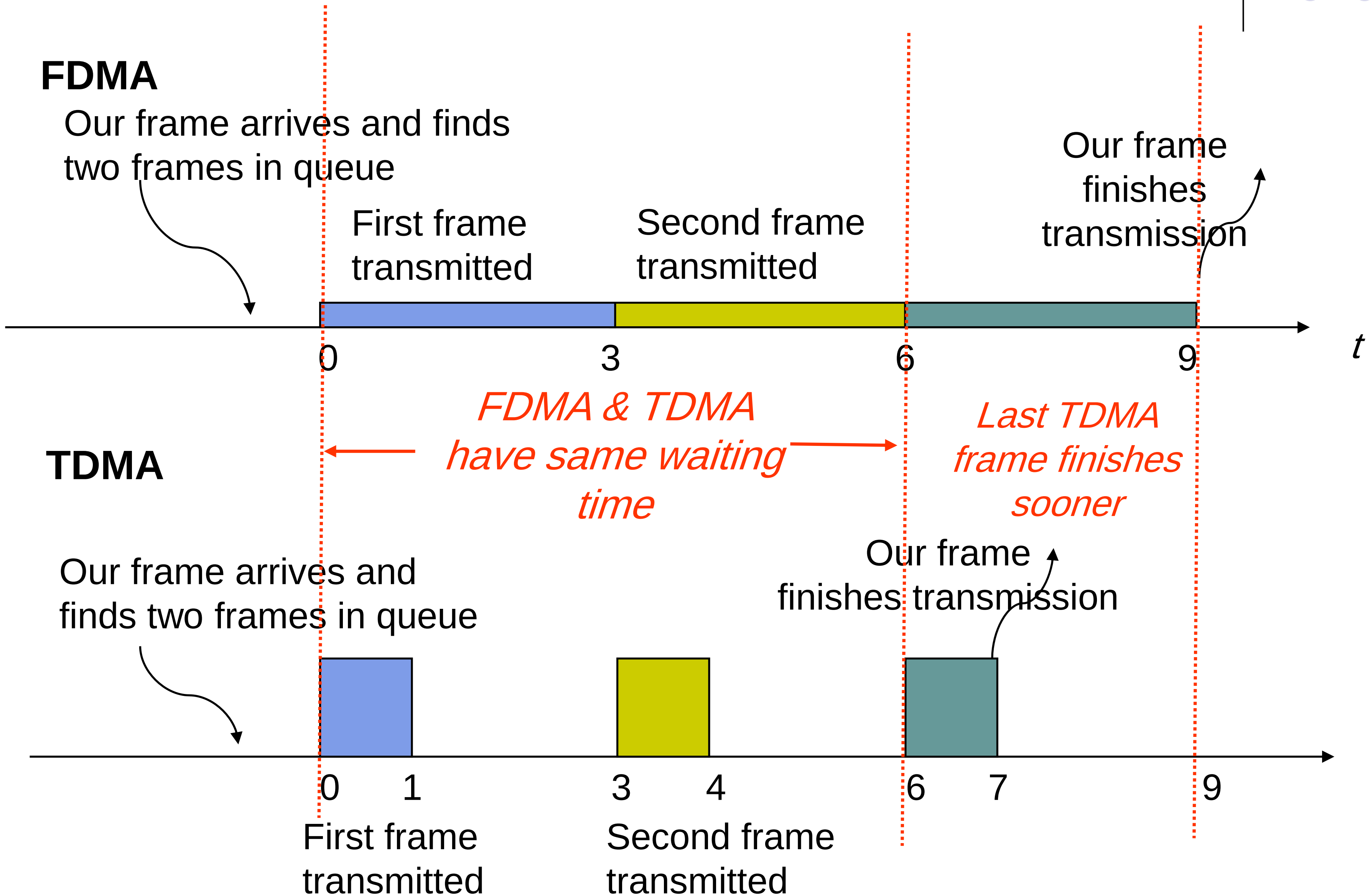
$$E[W_{FDMA}] = \frac{\rho}{2(1-\rho)} MX + \frac{V}{2} = \frac{\rho}{2(1-\rho)} MX + \frac{MX}{2}$$

- Average Total Transfer Delay is:

$$E[T_{FDMA}] = E[T_{FDMA}] + MX = \frac{\rho}{2(1-\rho)} MX + \frac{MX}{2} + MX$$

- The delay increases in proportion with M, the number of stations
- Allocated bandwidth to a given station is wasted when other stations have data to send

Transfer Delay of TDMA & CDMA



Transfer Delay for TDMA

- Time-slotted transmission from each station
- Same waiting time as FDMA

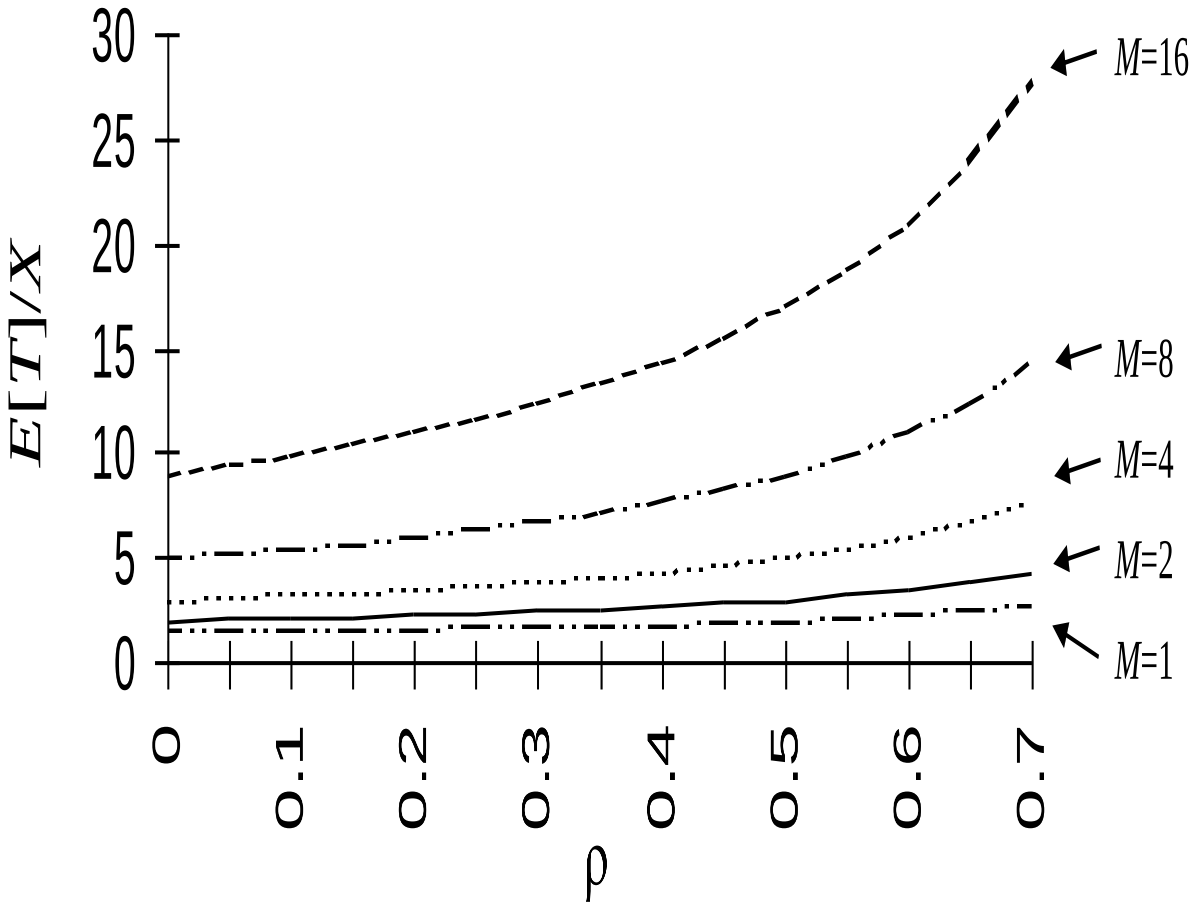
$$E[W_{TDMA}] = \frac{\rho}{2(1-\rho)} MX + \frac{MX}{2}$$

- Frame service time is X
- Average Total Transfer Delay is:

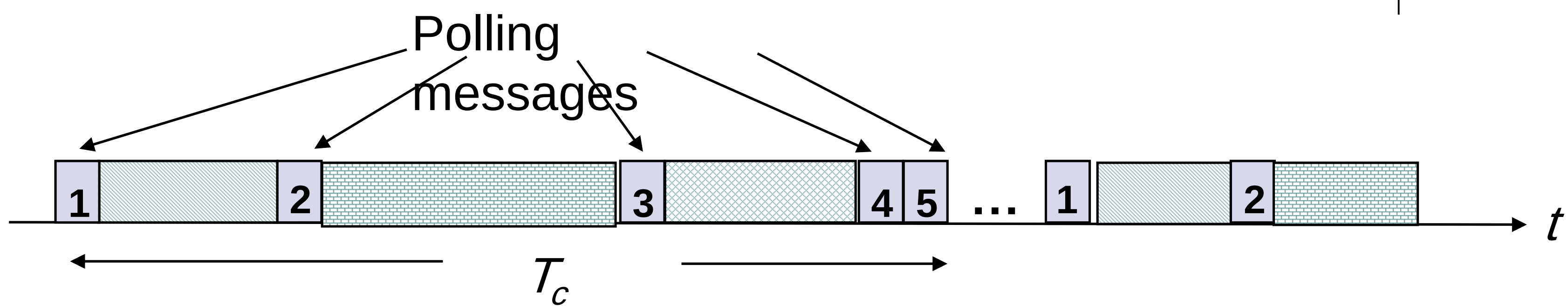
$$E[T_{TDMA}] = \frac{\rho}{2(1-\rho)} MX + \frac{MX}{2} + X$$

- Better than FDMA & CDMA
- Total Delay still grows proportional to M

TDMA Average Transfer Delay



Delay in Polling Systems



- Assume “exhaustive service” where a station keeps token until its buffer is empty
- Average cycle time is:

$$T_c = \frac{\tau'}{1-\rho}$$

where τ' is total walk time required to poll all stations without transmissions.

Polling Systems

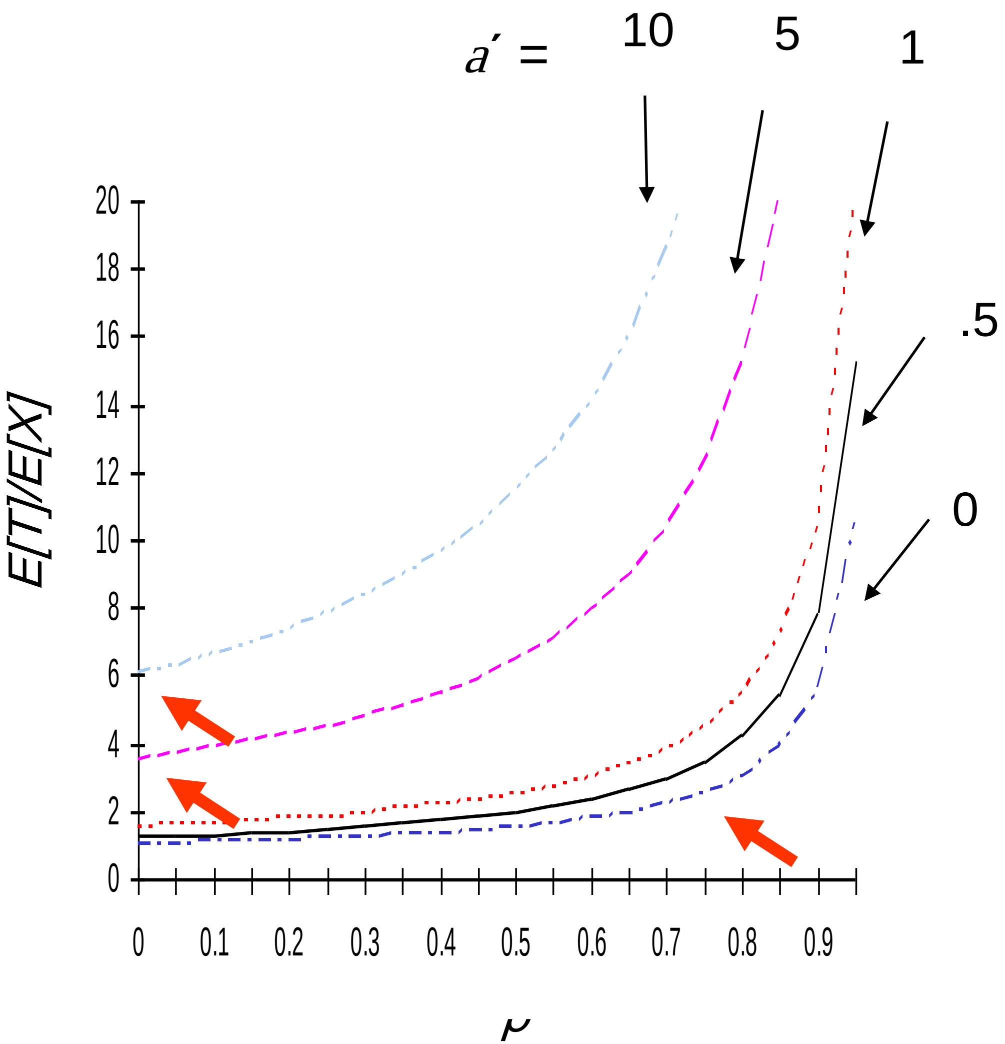
- The transfer delay has three components:
  - residual cycle time (approximate by $\overline{T_c}/2$)
  - mean waiting time (approximate by M/G/1)
  - packet transmission time
  - propagation time from source to destination ($\tau_{average}$)
- We obtain the following approximation:

$$T = E[X] = \tau_{average} + \frac{\tau'}{2(1-\rho)} + \frac{\rho}{2(1-\rho)} E[X]$$

- A precise analysis of the this model gives:

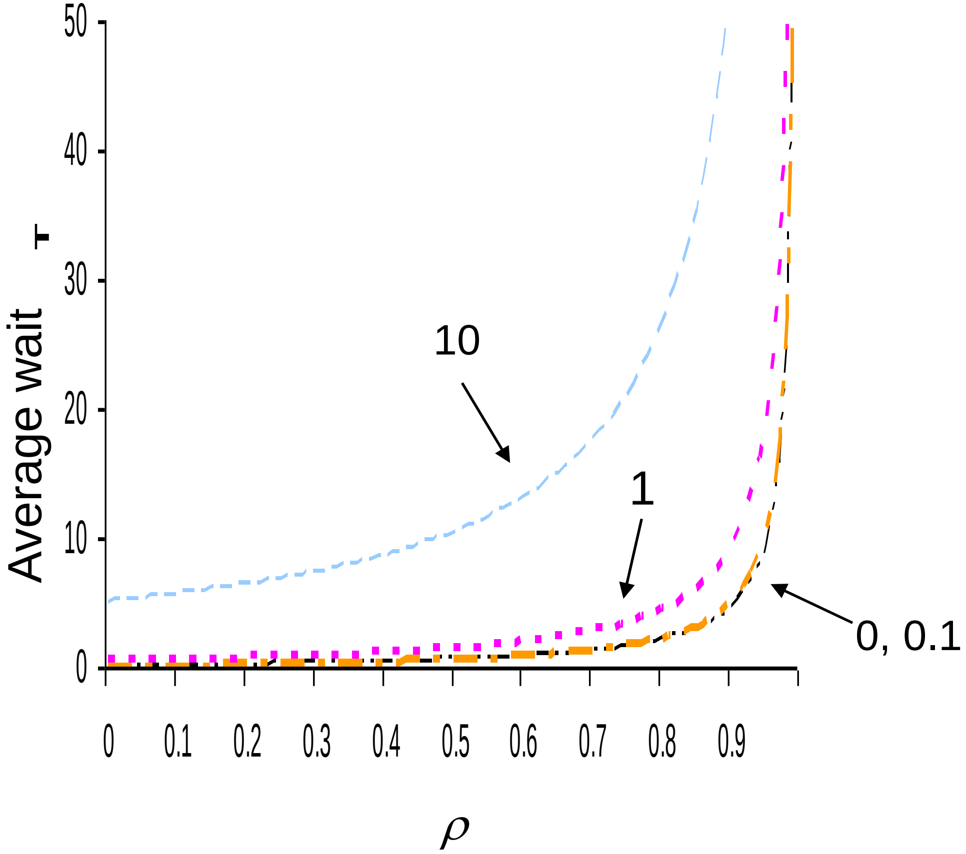
$$T = E[X] = \tau_{average} + \frac{\tau'(1-\rho/M)}{2(1-\rho)} + \frac{\rho}{2(1-\rho)} E[X]$$

Example: Transfer Delay in Polling System



- Exhaustive service
- For *a'* <<1, essentially M/D/1 performance
- *Much better than channelization*
- For larger *a'*, delay proportional to *a'*
- Mild, indirect dependence on M, since *a'* = Mt'/X

Example: Transfer Delay in Ring LAN

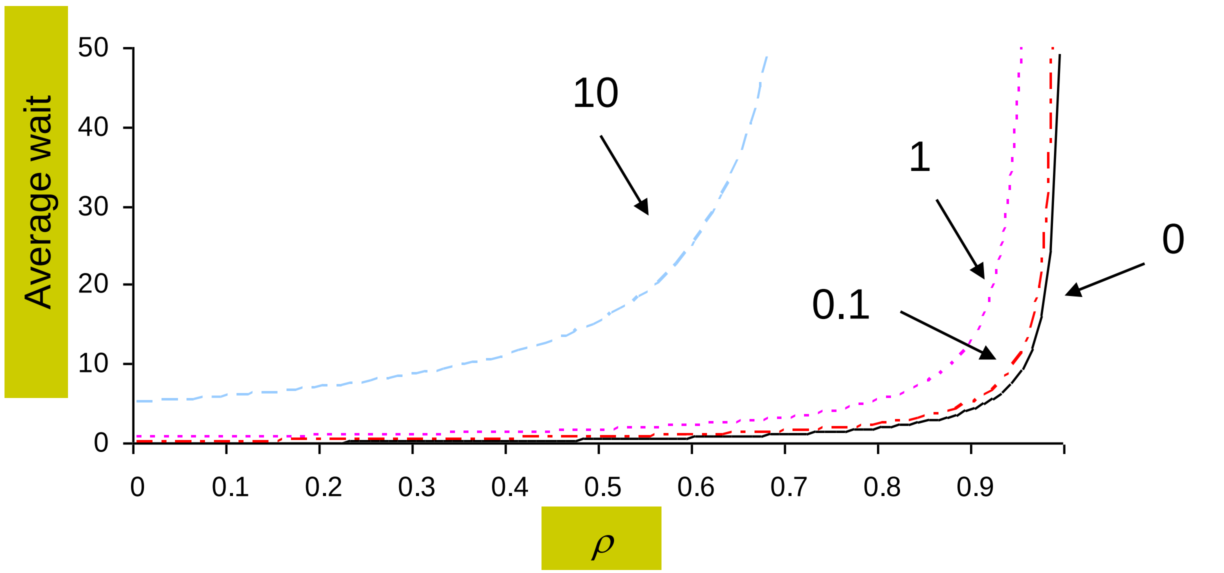


- Exhaustive service
- M=32 stations
- *Much better than channelization*
- For larger a', delay proportional to a'

Mean Waiting Time Token Ring

$M = 32$

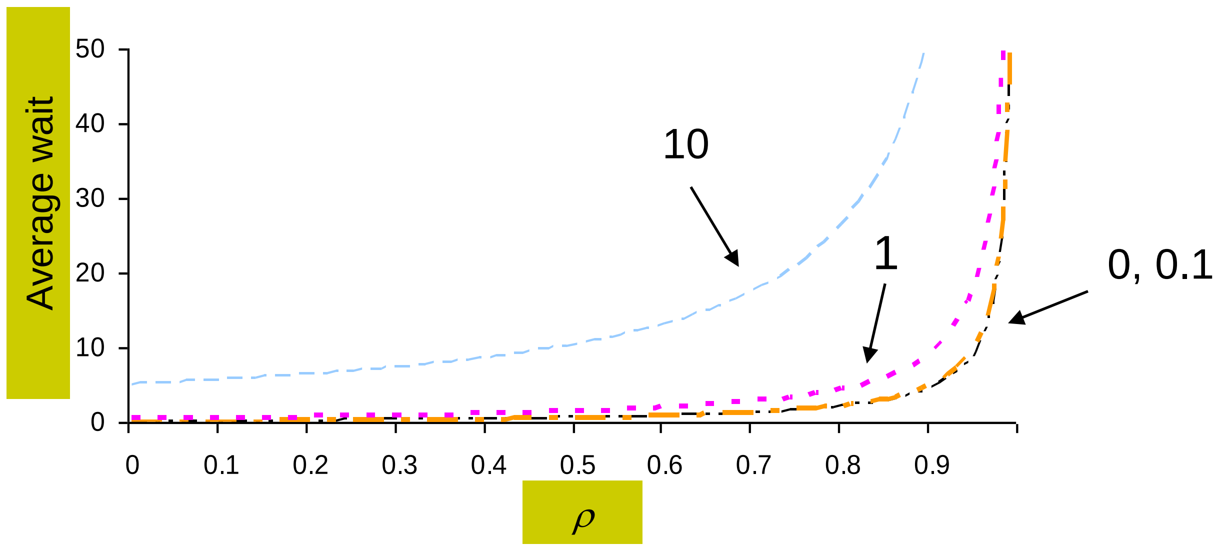
Unlimited service/token



$M = 32$

I packet/token

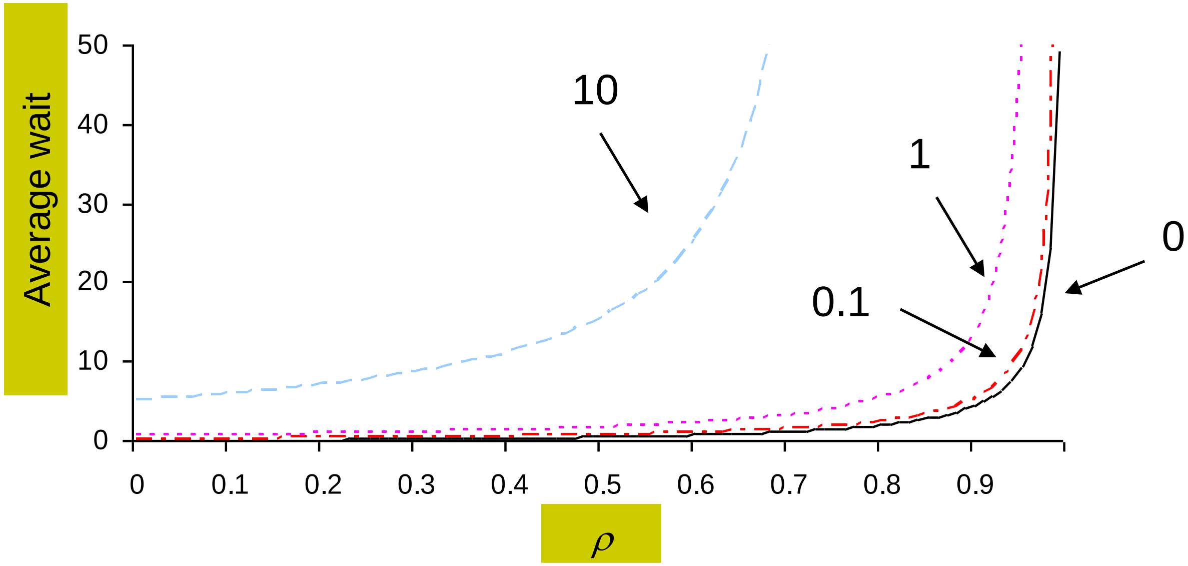
Multitoken ring



Mean Waiting Time Token Ring

M = 32

Unlimited service/token

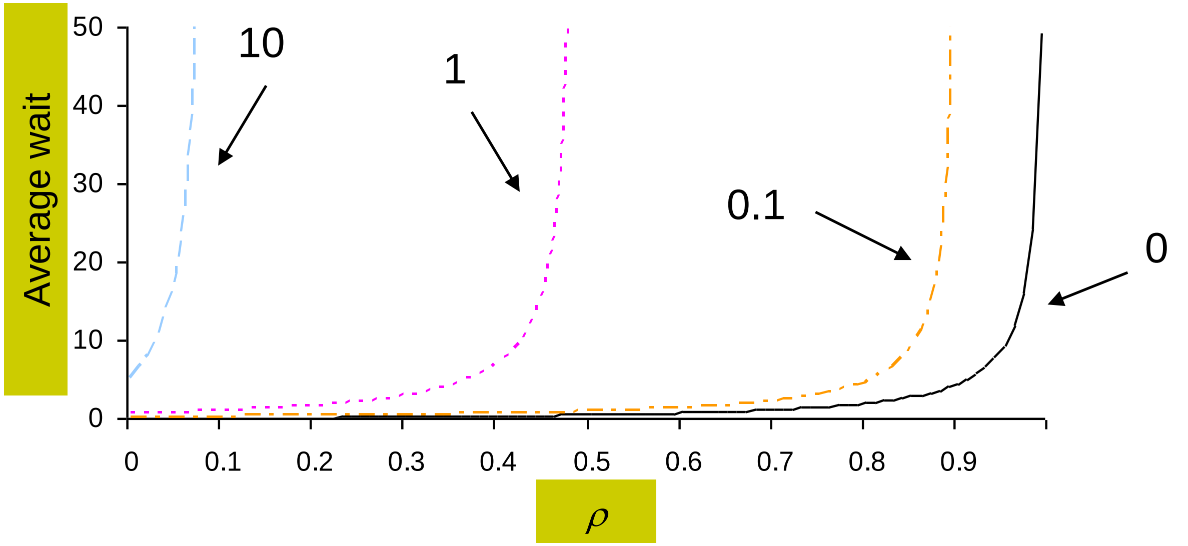


M = 32

I packet/token

Single token ring

Ring latency limits throughput severely



Chapter 6
Medium Access Control Protocols and Local Area Networks

Part II: Local Area Networks

Overview of LANs
Ethernet
Token Ring and FDDI
802.11 Wireless LAN
LAN Bridges

Chapter 6

Medium Access Control Protocols and Local Area Networks

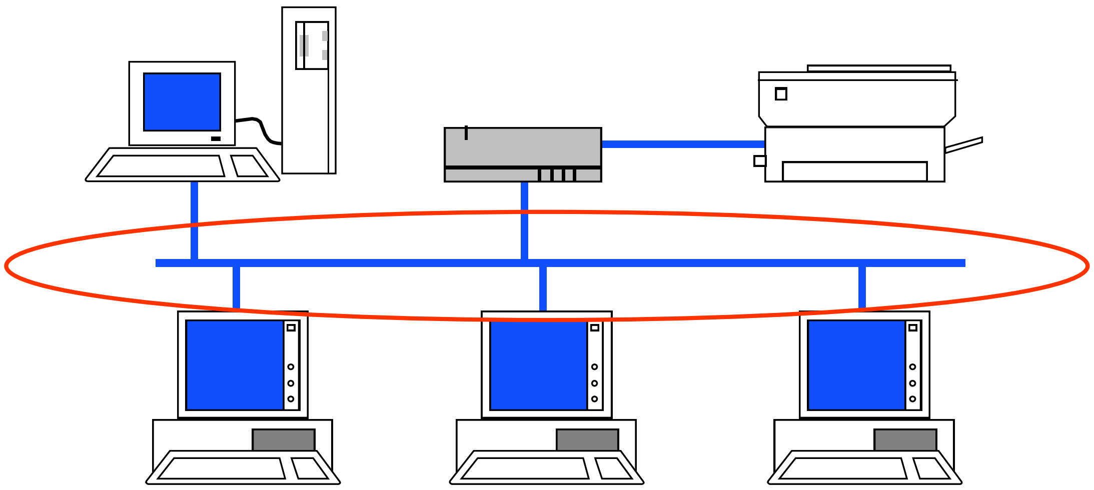
Overview of LANs

What is a LAN?

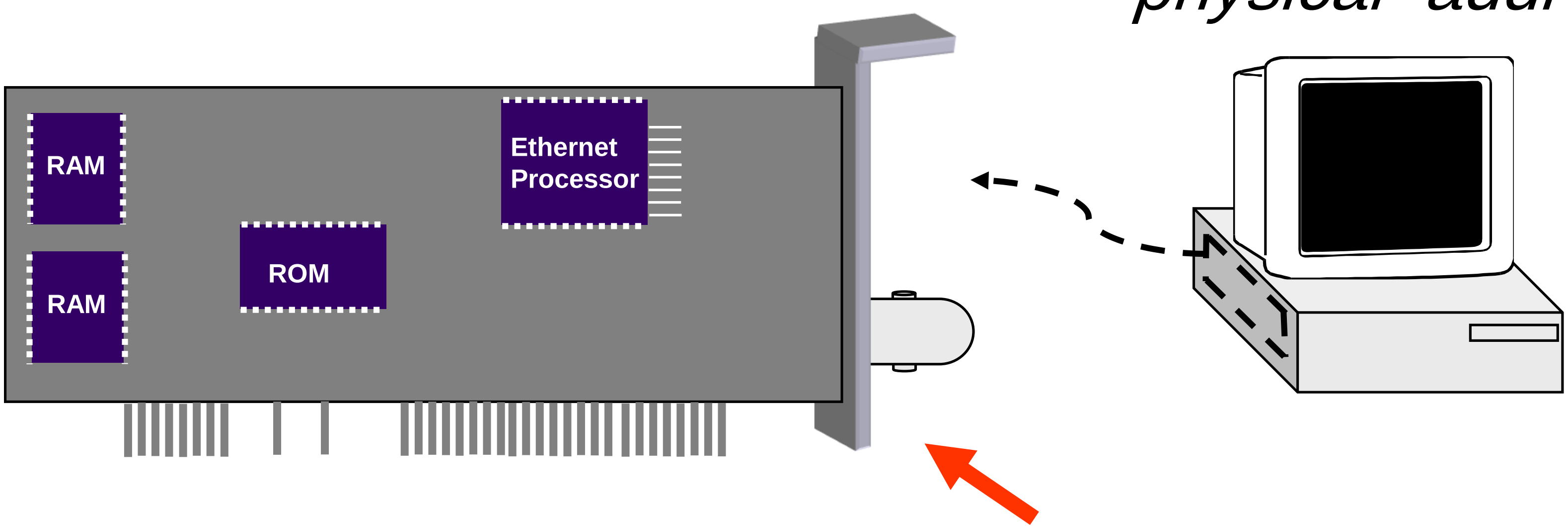
Local area means:

- Private ownership
  - freedom from regulatory constraints of WANs
- Short distance (~1km) between computers
  - low cost
  - very high-speed, relatively error-free communication
  - complex error control unnecessary
- Machines are constantly moved
  - Keeping track of location of computers a chore
  - Simply give each machine a unique address
  - ***Broadcast*** *all messages to all machines in the LAN*
- Need a *medium access control protocol*

Typical LAN Structure



- Transmission Medium
- Network Interface Card (NIC)
- *Unique MAC "physical" address*

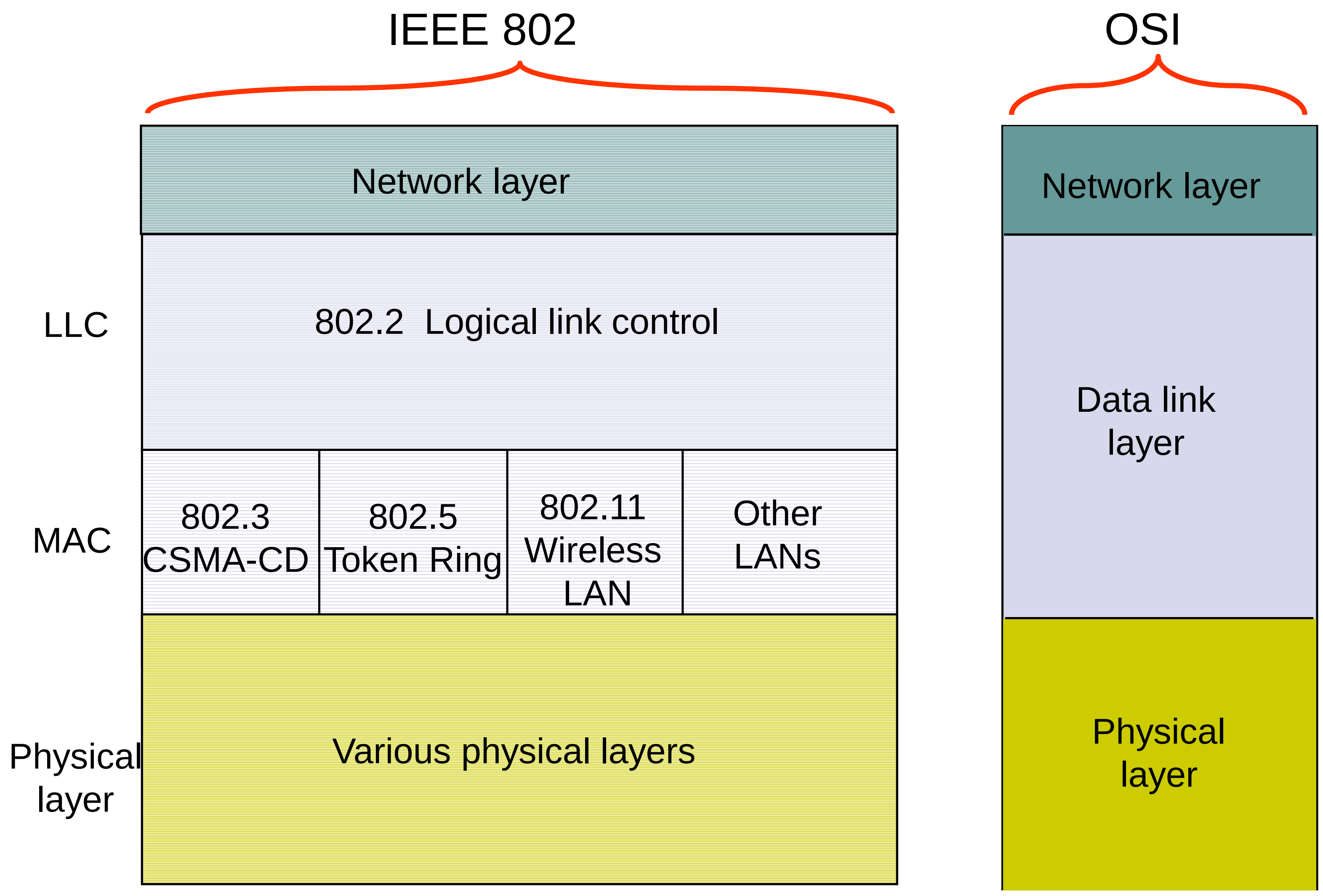


Medium Access Control Sublayer

- In IEEE 802.1, Data Link Layer divided into:

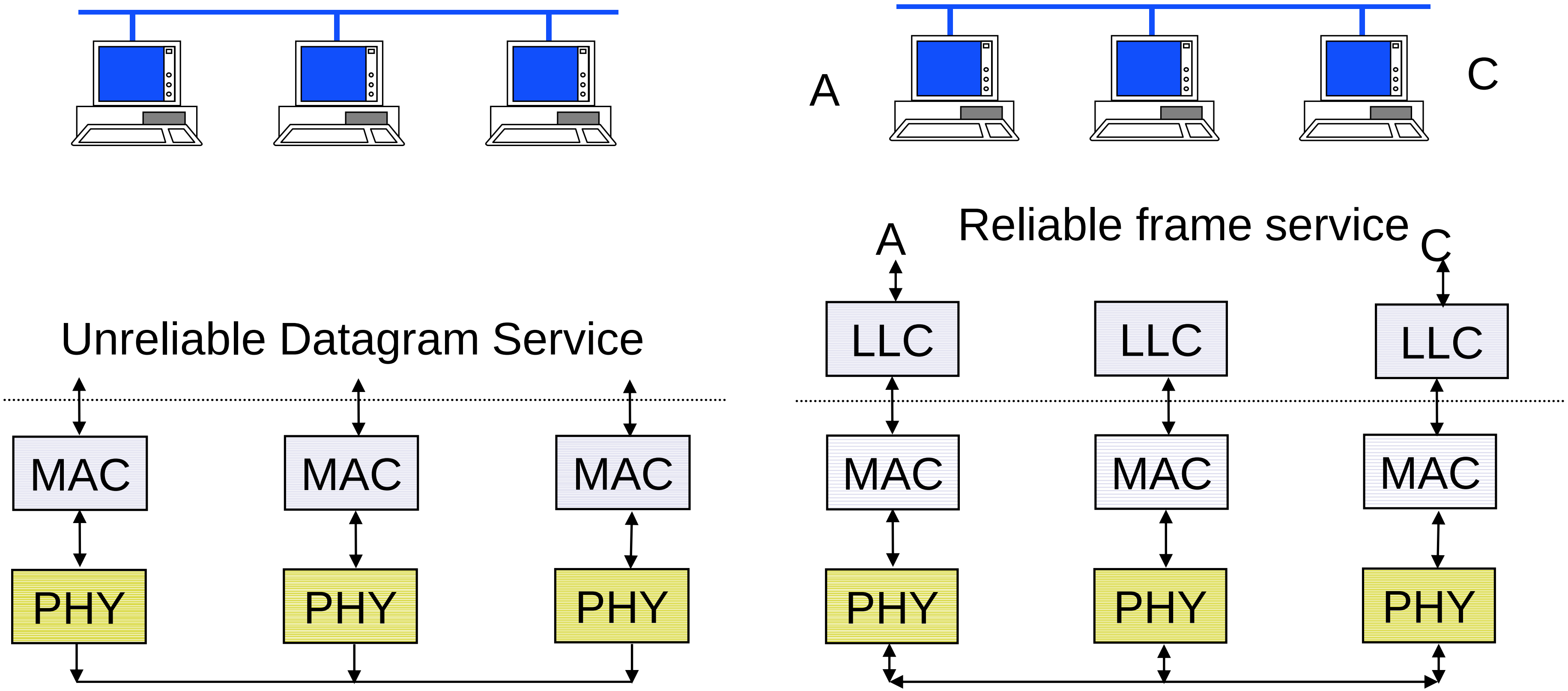
1. Medium Access Control Sublayer
   - Coordinate access to medium
   - Connectionless frame transfer service
   - Machines identified by MAC/physical address
   - Broadcast frames with MAC addresses
2. Logical Link Control Sublayer
   - Between Network layer & MAC sublayer

MAC Sub-layer



Logical Link Control Layer

- IEEE 802.2: LLC enhances service provided by MAC

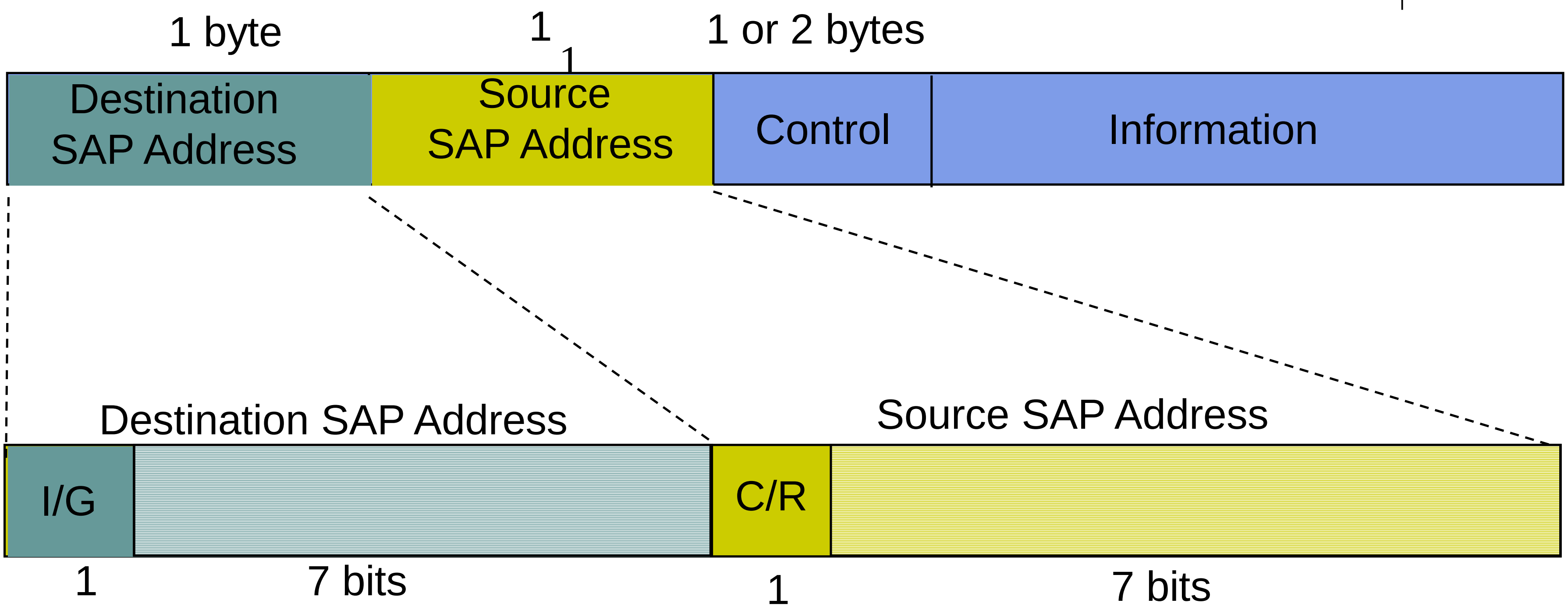


Logical Link Control Services

- 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

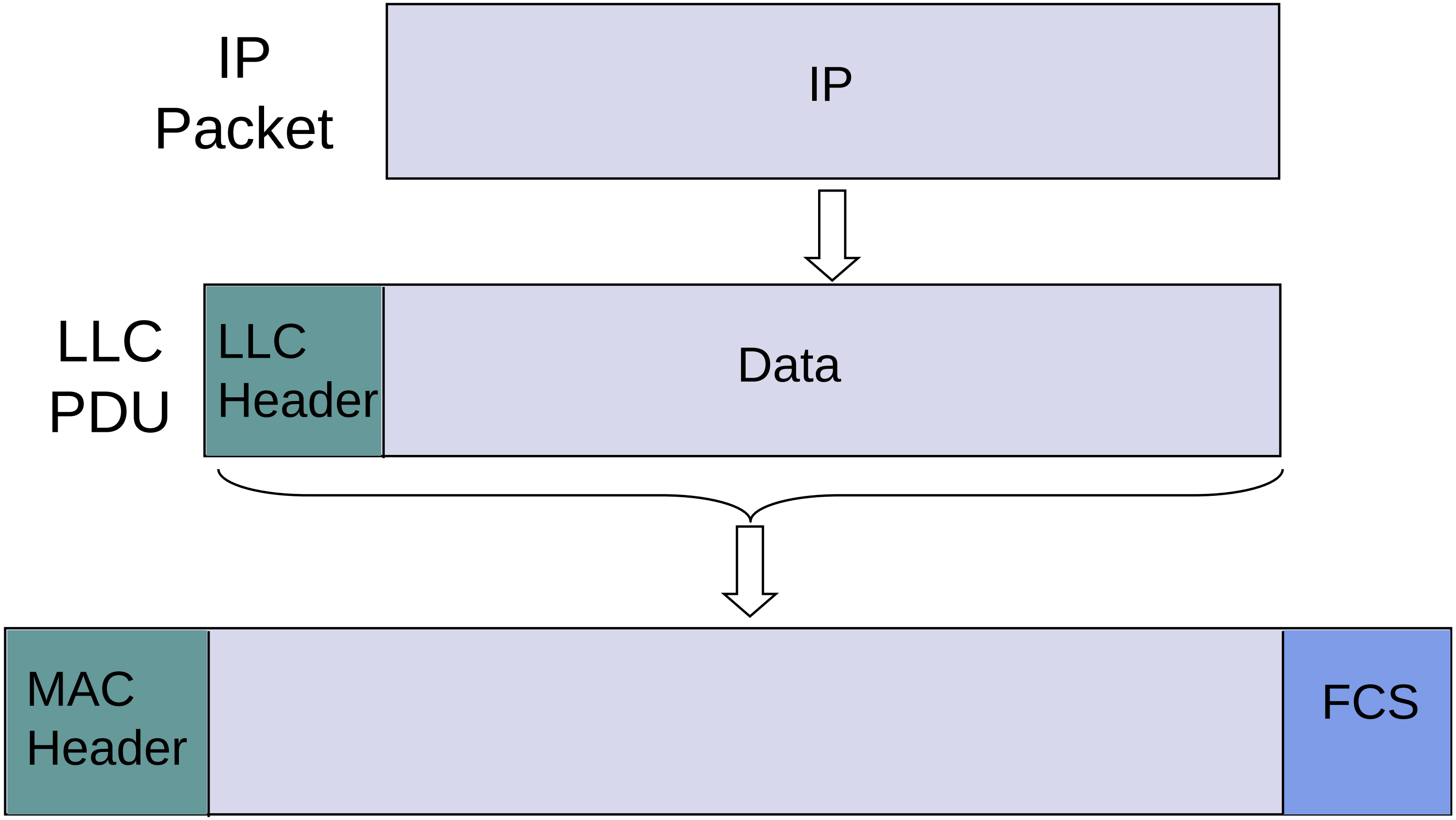


I/G = Individual or group address
C/R = Command or response frame

Examples of SAP Addresses:

06	IP packet
E0	Novell IPX
FE	OSI packet
AA	SubNetwork Access protocol (SNAP)

Encapsulation of MAC frames



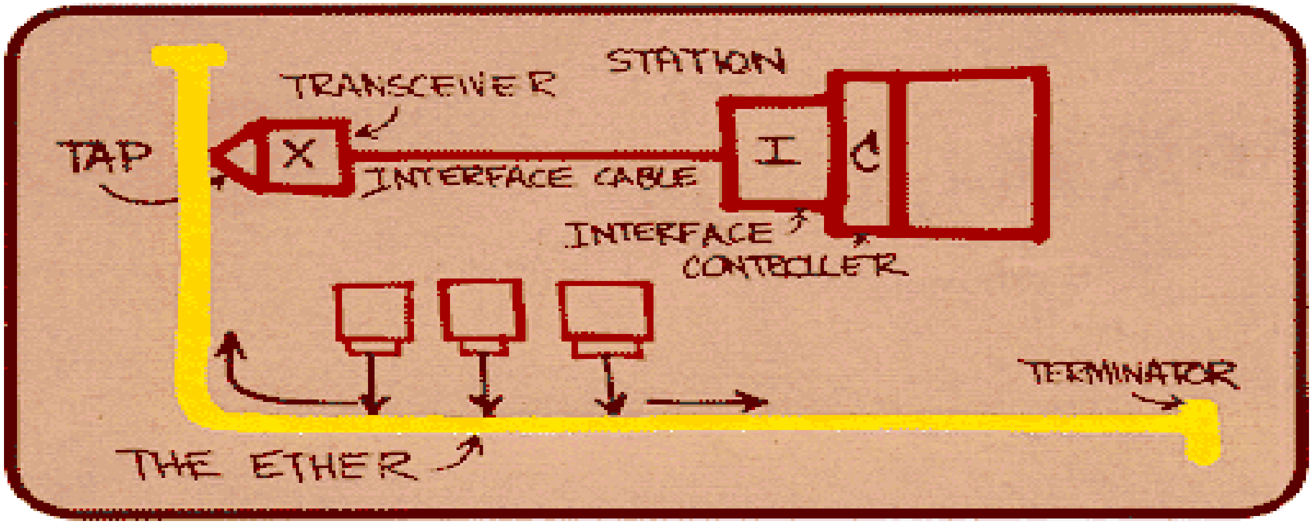
Chapter 6
Medium Access Control Protocols and Local Area Networks

Ethernet

A bit of history…

- 1970 ALOHAnet radio network deployed in Hawaiian islands
- 1973 Metcalf and Boggs invent Ethernet, random access in wired net
- 1979 DIX Ethernet II Standard
- 1985 IEEE 802.3 LAN Standard (10 Mbps)
- 1995 Fast Ethernet (100 Mbps)
- 1998 Gigabit Ethernet
- 2002 10 Gigabit Ethernet
- Ethernet is the dominant LAN standard

Metcalf's Sketch



IEEE 802.3 MAC: Ethernet

MAC Protocol:

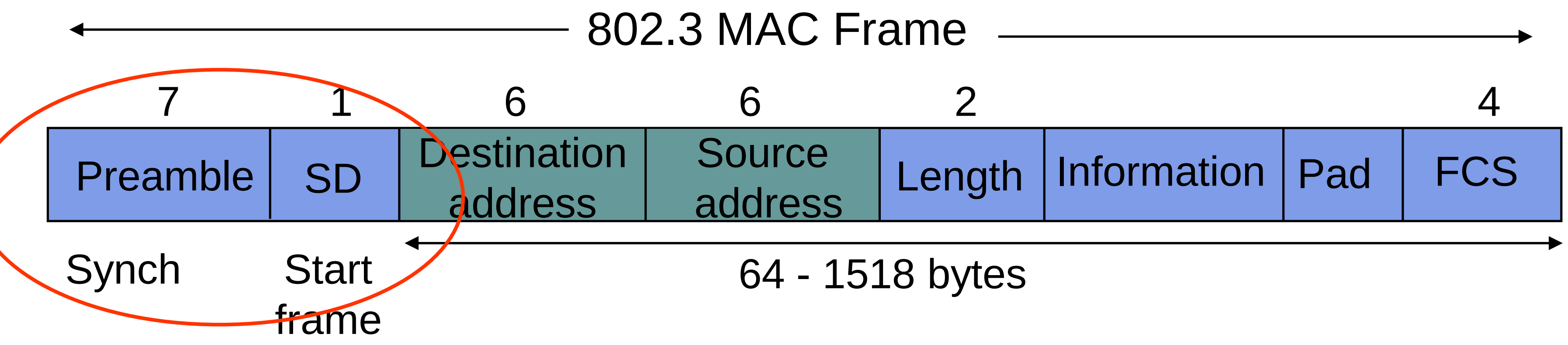
- CSMA/CD
- *Slot Time* is the critical system parameter
  - upper bound on time to detect collision
  - upper bound on time to acquire channel
  - upper bound on length of frame segment generated by collision
  - quantum for retransmission scheduling
  - max{round-trip propagation, MAC jam time}
- Truncated 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

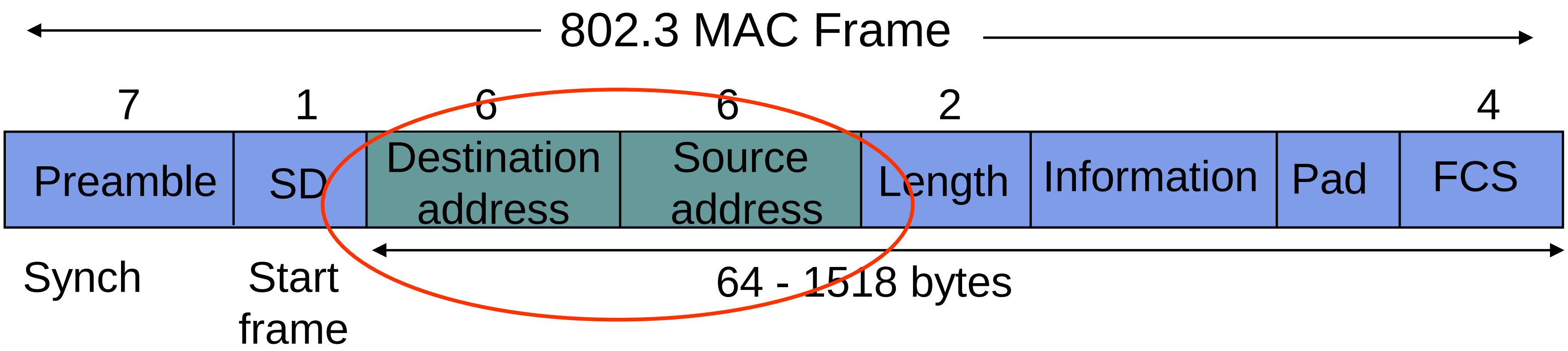
- *Each x10 increase in bit rate, must be accompanied by x10 decrease in distance*

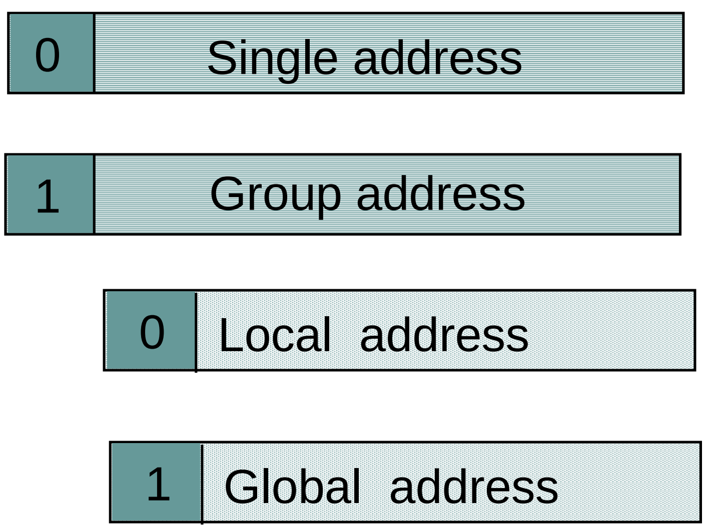
IEEE 802.3 MAC Frame



- 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

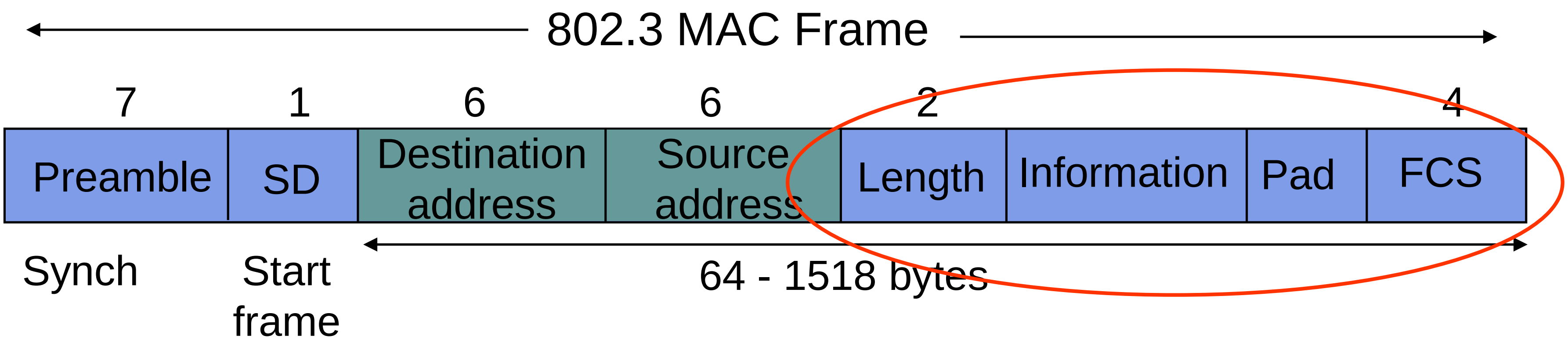




- Destination address
  - single address
  - group address
  - broadcast = 111...111

  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

DIX Ethernet II Frame Structure

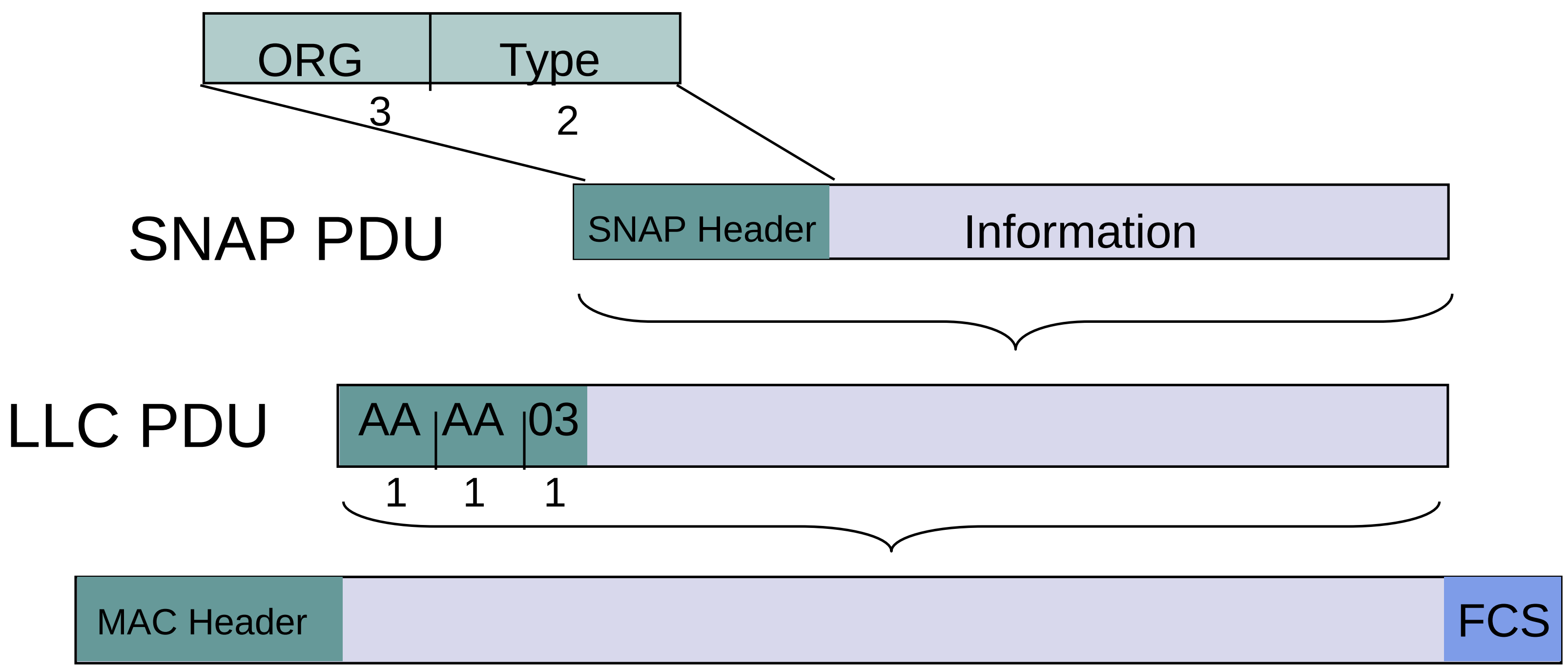
Ethernet frame

7	1	6	6	2		4
Preamble	SD	Destination address	Source address	Type	Information	FCS
Synch	Start frame	64 - 1518 bytes				

- DIX: Digital, Intel, Xerox joint Ethernet specification
- Type Field: to identify protocol of PDU in information field, e.g. IP, ARP
- Framing: How does receiver know frame length?
  - physical layer signal, byte count, FCS

SubNetwork Address 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 II frames



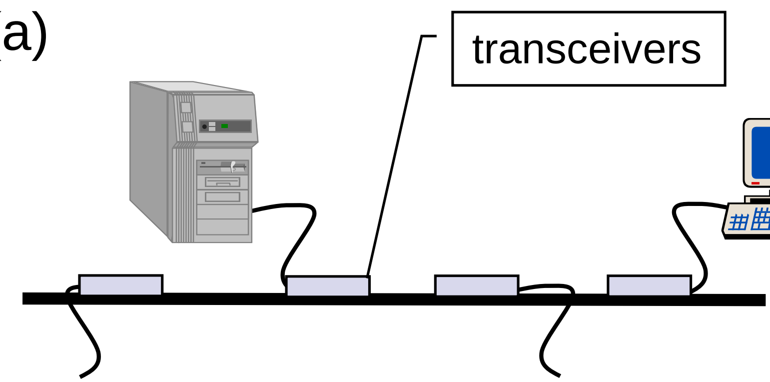
IEEE 802.3 Physical Layer

Table 6.2 IEEE 802.3 10 Mbps medium alternatives

	10base5	**10base2**	**10baseT**	**10baseFX**
Medium	Thick coax	Thin coax	Twisted pair	Optical fiber
Max. Segment Length	500 m	200 m	100 m	2 km
Topology	Bus	Bus	Star	Point-to-point link

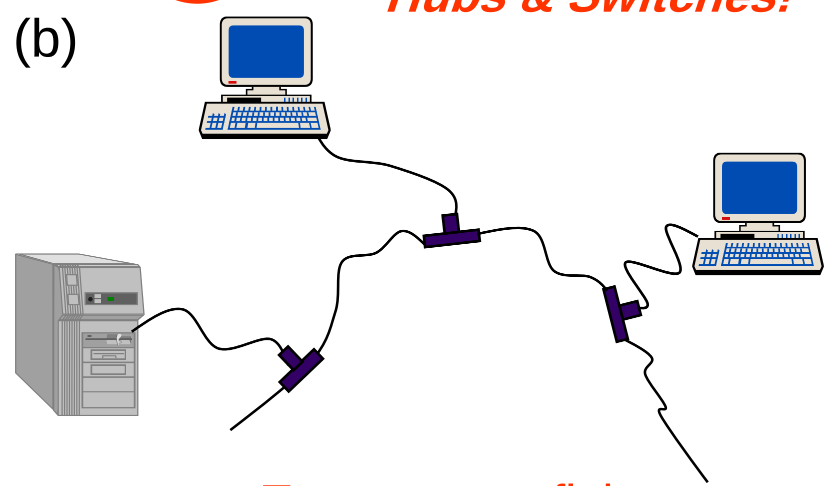
Hubs & Switches!

(a)



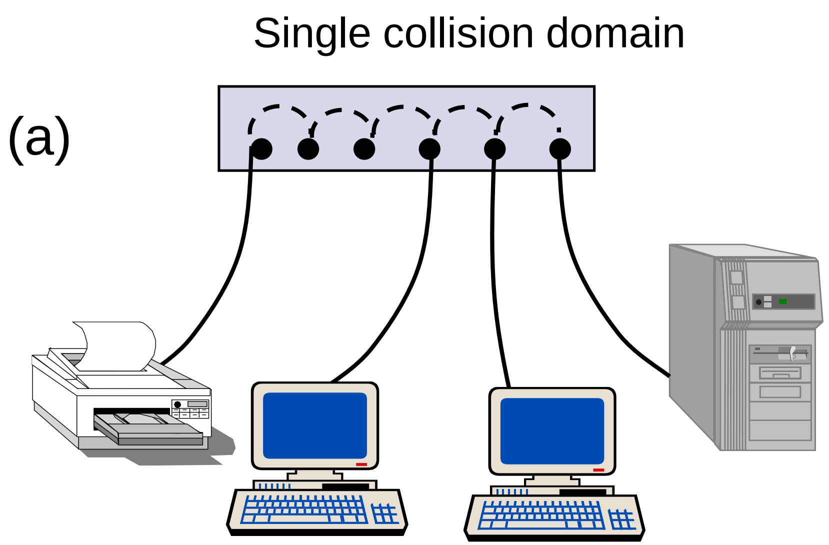
Thick Coax: Stiff, hard to work with

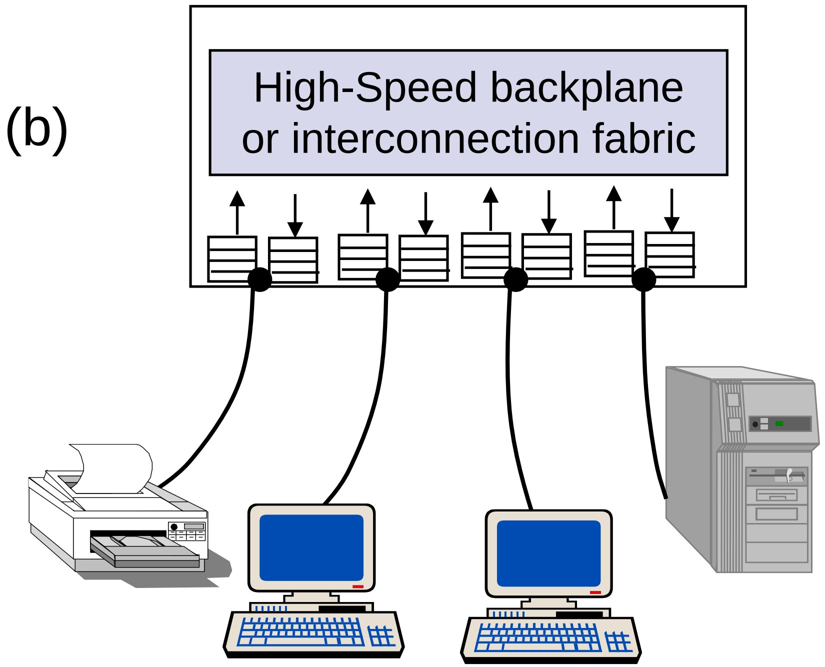
(b)



T connectors flaky

Ethernet Hubs & Switches

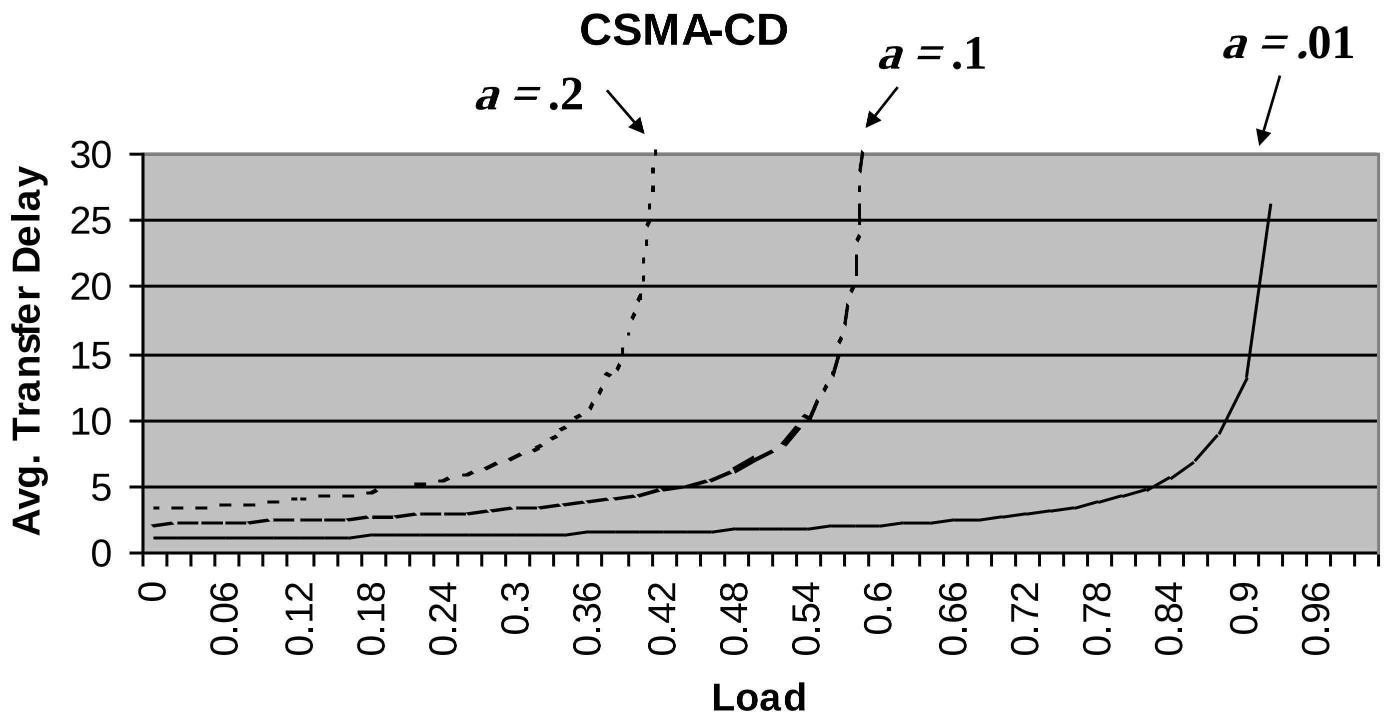




Twisted Pair Cheap
Easy to work with
Reliable
Star-topology CSMA-CD

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

Table 6.4 IEEE 802.3 100 Mbps Ethernet medium alternatives

	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

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

Gigabit Ethernet

Table 6.3 IEEE 802.3 1 Gbps Fast Ethernet medium alternatives

	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

- 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

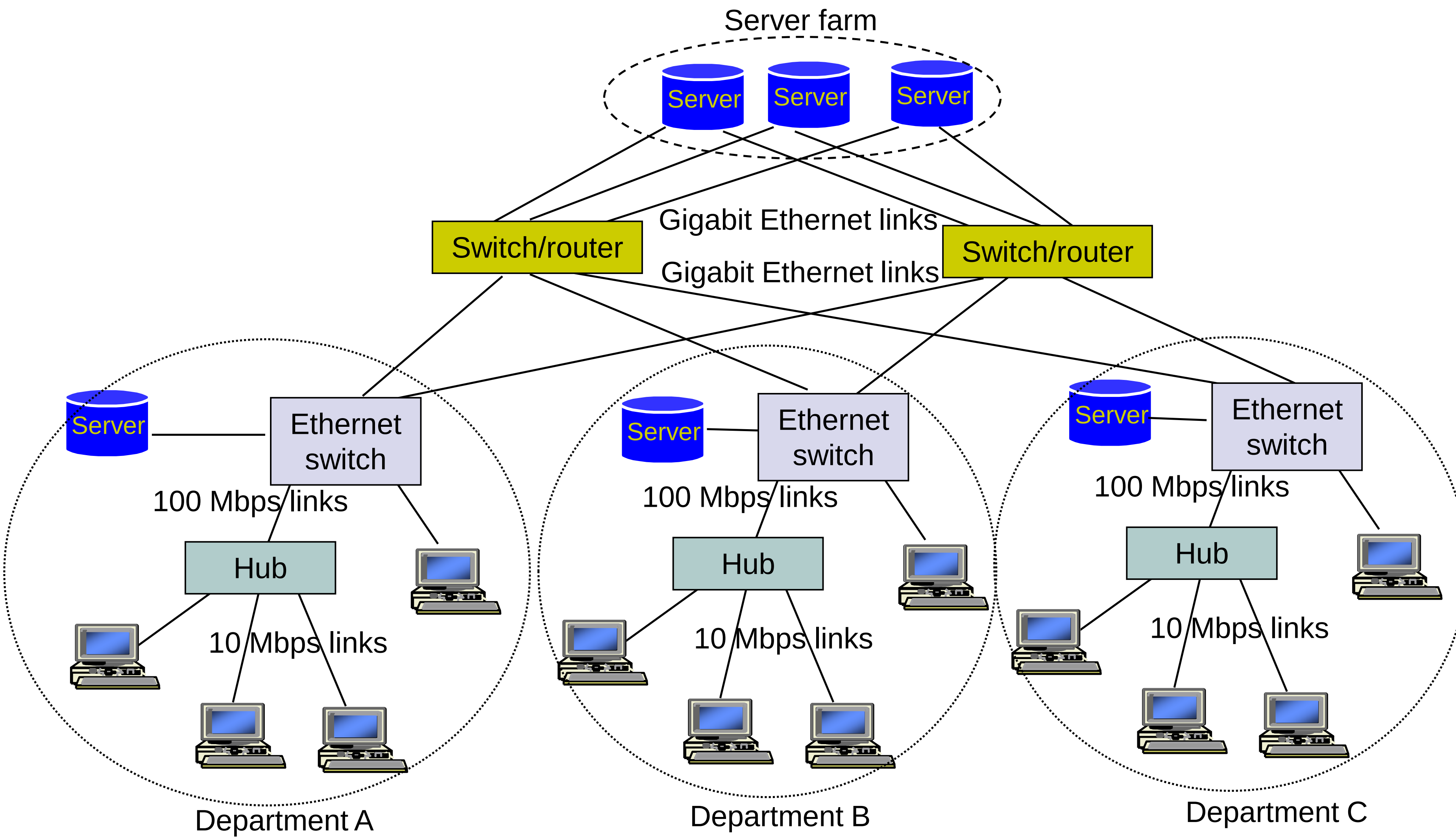
10 Gigabit Ethernet

Table 6.5 IEEE 802.3 10 Gbps Ethernet medium alternatives

	10GbaseSR	10GBaseLR	10GbaseEW	10GbaseLX4
Medium	Two optical fibers Multimode at 850 nm 64B66B code	Two optical fibers Single-mode at 1310 nm 64B66B	Two optical fibers Single-mode at 1550 nm SONET compatibility	Two optical fibers multimode/single-mode with four wavelengths at 1310 nm band 8B10B code
Max. Segment Length	300 m	10 km	40 km	300 m – 10 km

- Frame structure preserved
- CSMA-CD protocol officially abandoned
- LAN PHY for local network applications
- WAN PHY for wide area interconnection using SONET OC-192c
- Extensive deployment in metro networks anticipated

Typical Ethernet Deployment



Chapter 6
Medium Access Control Protocols and Local Area Networks

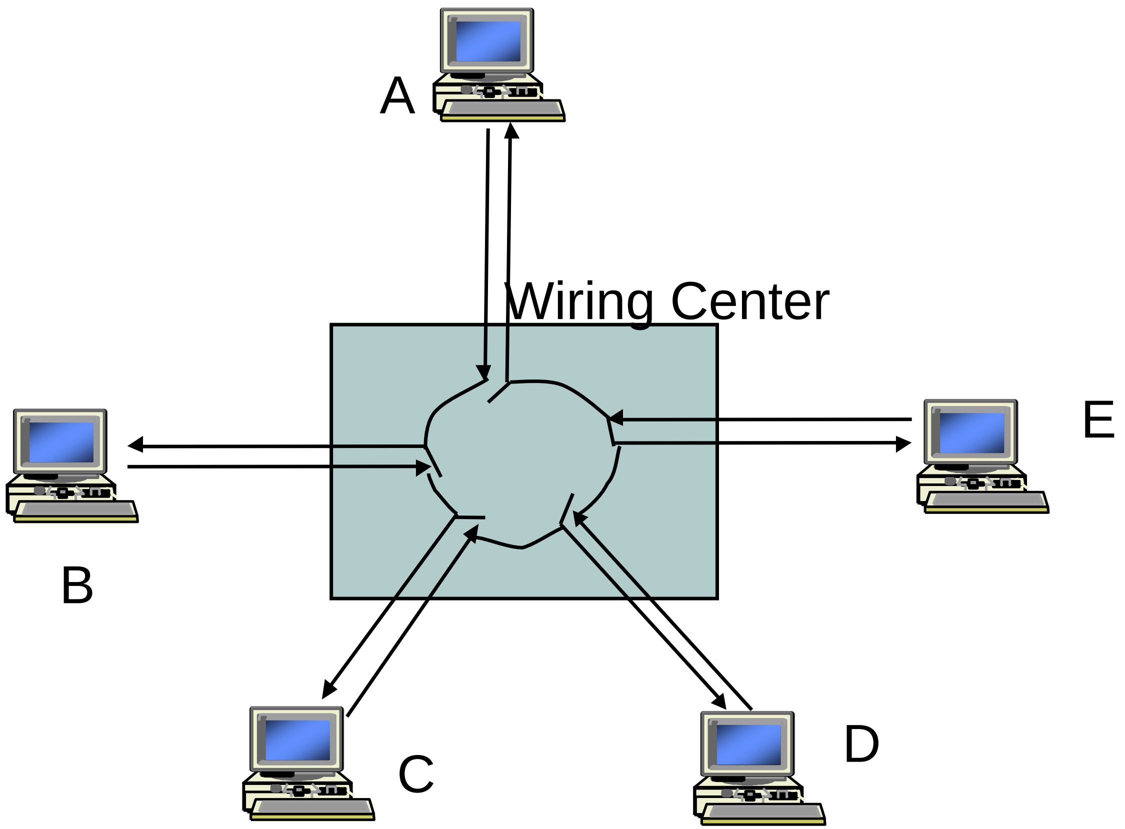
Token Ring and FDDI

IEEE 802.5 Ring LAN

- Unidirectional ring network
- 4 Mbps and 16 Mbps on twisted pair
  - Differential Manchester line coding
- Token passing protocol provides access
  - ✓ Fairness
  - ✓ Access priorities
  - ✗ Breaks in ring bring entire network down
- Reliability by using star topology

Star Topology Ring LAN

- Stations connected in star fashion to wiring closet
  - Use existing telephone wiring
- Ring implemented inside equipment box
- Relays can bypass failed links or stations



Token Frame Format

Data frame format

1	1	1	6	6		4	1	1
SD	AC	FC	Destination address	Source address	Information	FCS	ED	FS

Token frame format

SD	AC	ED

Starting delimiter

J	K	0	J	K	0	0	0

J, K nondata symbols (line code)
J begins as “0” but no transition
K begins as “1” but no transition

Access control

P P P	T	M	R R R

PPP=priority; **T=token bit**
M=monitor bit; RRR=reservation
T=0 token; T=1 data

Ending delimiter

J	K	1	J	K	1	I	E

I = intermediate-frame bit
E = error-detection bit

Data Frame Format

Data frame format

1	1	1	6	6		4	1	1
SD	AC	FC	Destination address	Source address	Information	FCS	ED	FS

Frame control

F F	Z Z Z Z Z Z

FF = frame type; FF=01 data frame
FF=00 MAC control frame
ZZZZZZ type of MAC control

Addressing 48 bit format as in 802.3

Information Length limited by allowable token holding time

FCS CCITT-32 CRC

Frame status

A	C	x x	A	C	x x

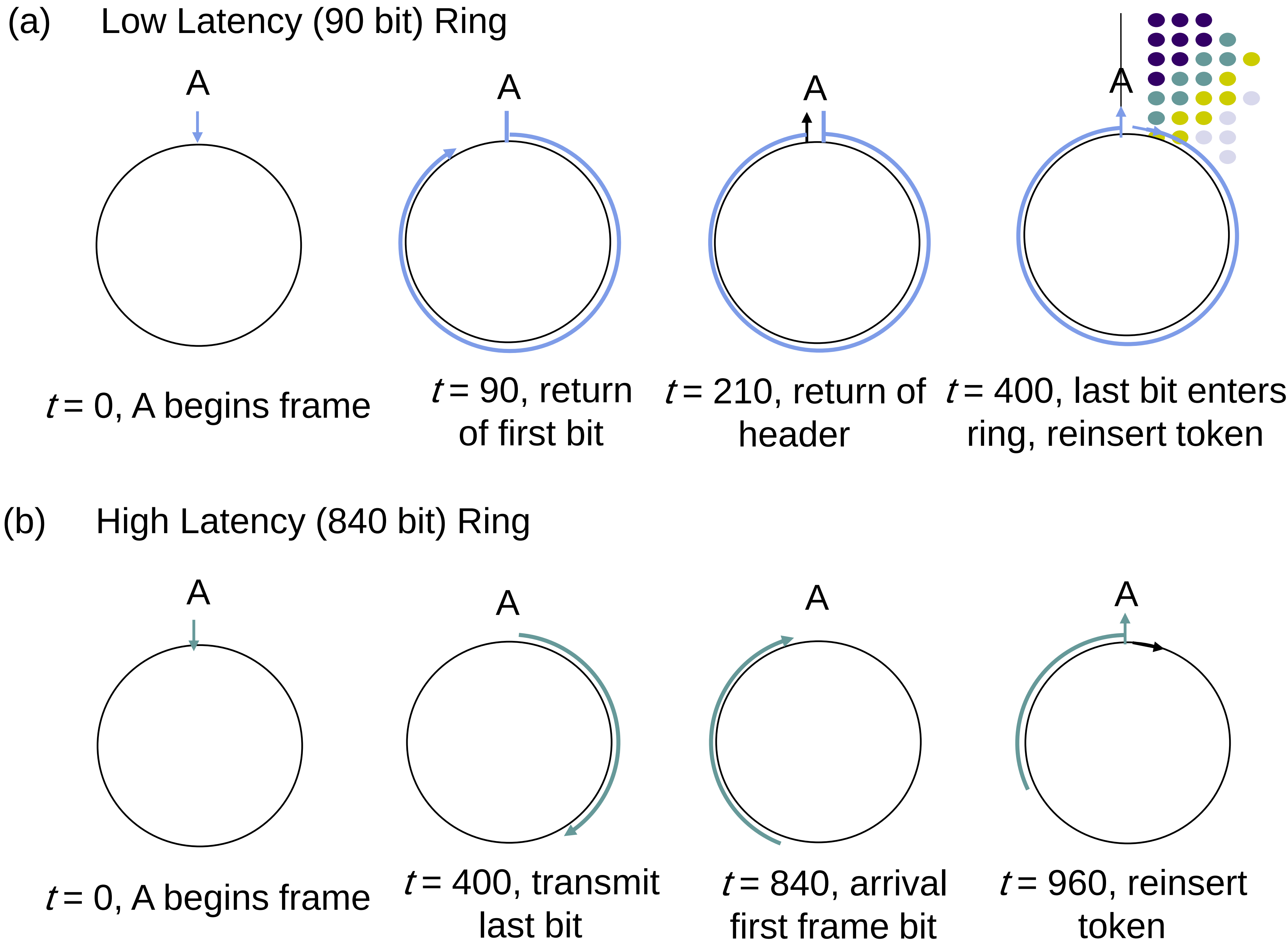
A = address-recognized bit
xx = undefined
C = frame-copied bit

Other Ring Functions

- Priority Operation
  - PPP provides 8 levels of priority
  - Stations wait for token of equal or lower priority
  - Use RRR bits to “bid up” priority of next token
- Ring Maintenance
  - Sending station must remove its frames
  - Error conditions
    - Orphan frames, disappeared token, frame corruption
  - *Active monitor station* responsible for removing orphans

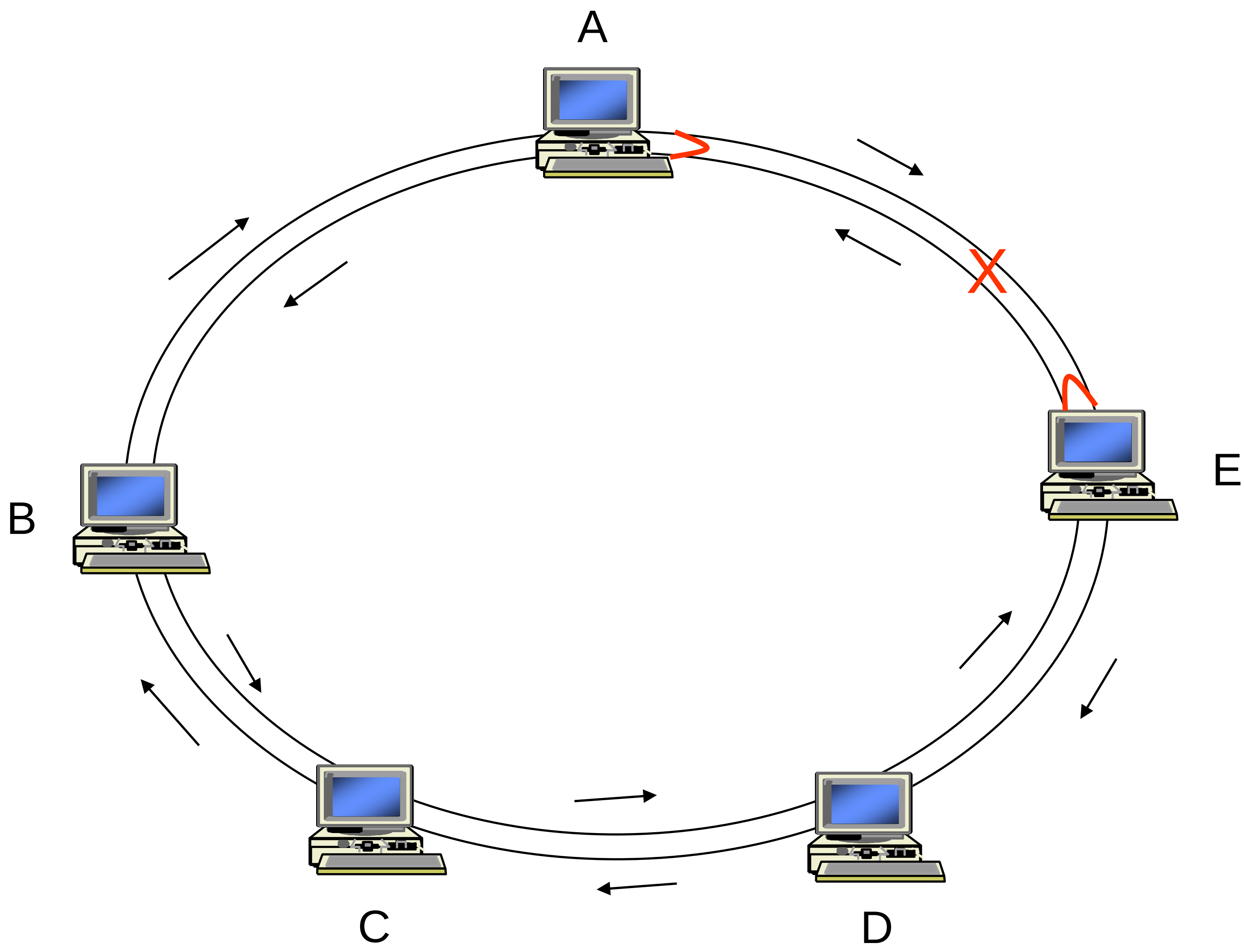
Ring Latency & Ring Reinsertion

- M stations
- b bit delay at each station
  - B=2.5 bits (using Manchester coding)
- Ring Latency:
  - $\tau' = d/\nu + Mb/R$ seconds
  - $\tau' R = dR/\nu + Mb$ *bits*
- Example
  - Case 1: R=4 Mbps, M=20, 100 meter separation
    - Latency = $20 \times 100 \times 4 \times 10^6/(2 \times 10^8) + 20 \times 2.5 = 90$ bits
  - Case 2: R=16 Mbps, M=80
    - Latency = 840 bits


(a) Low Latency (90 bit) Ring
A
A
A
A
t = 0, A begins frame
t = 90, return of first bit
t = 210, return of header
t = 400, last bit enters ring, reinsert token
(b) High Latency (840 bit) Ring
A
A
A
A
t = 0, A begins frame
t = 400, transmit last bit
t = 840, arrival first frame bit
t = 960, reinsert token

Fiber Distributed Data Interface (FDDI)

- Token ring protocol for LAN/MAN
- Counter-rotating dual ring topology
- 100 Mbps on optical fiber
- Up to 200 km diameter, up to 500 stations
- Station has 10-bit “elastic” buffer to absorb timing differences between input & output
- Max frame 40,000 bits
- 500 stations @ 200 km gives ring latency of 105,000 bits
- FDDI has option to operate in multitoken mode



Dual ring becomes a single ring

FDDI Frame Format

Data Frame Format

8	1	1	6	6		4	1	1
PRE	SD	FC	Destination Address	Source Address	Information	FCS	ED	FS

Preamble

Frame control	CLFFZZZZ	C = synch/asynch L = address length (16 or 48 bits) FF = LLC/MAC control/reserved frame type

CLFFZZZZ = 10000000 or 11000000 denotes token frame

Token Frame Format

PRE	SD	FC	ED

Timed Token Operation

- Two traffic types
  - Synchronous
  - Asynchronous
- All stations in FDDI ring agree on *target token rotation time (TTRT)*
- Station i has S_i max time to send synch traffic
- Token rotation time is less than 2*TTRT if
  - $S_1 + S_2 + \ldots + S_{M-1} + S_M <$ TTRT
  - FDDI guarantees access delay to synch traffic

Station Operation

- Maintain Token Rotation Timer (TRT): time since station last received token
- When token arrives, find Token Holding Time
  - THT = TTRT – TRT
  - THT > 0, station can send all synchronous traffic up to S_i + THT-S_i data traffic
  - THT < 0, station can only send synchronous traffic up to S_i
- As ring activity increases, TRT increases and asynch traffic throttled down

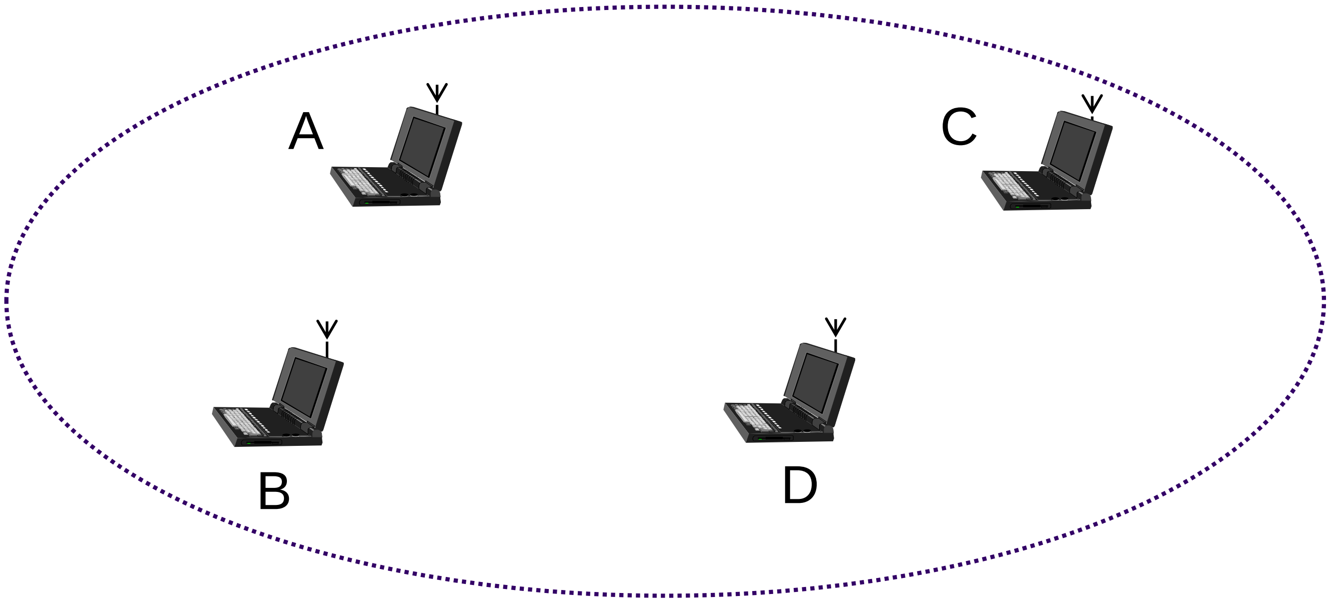
Chapter 6
Medium Access Control Protocols and Local Area Networks

802.11 Wireless LAN

Wireless Data Communications

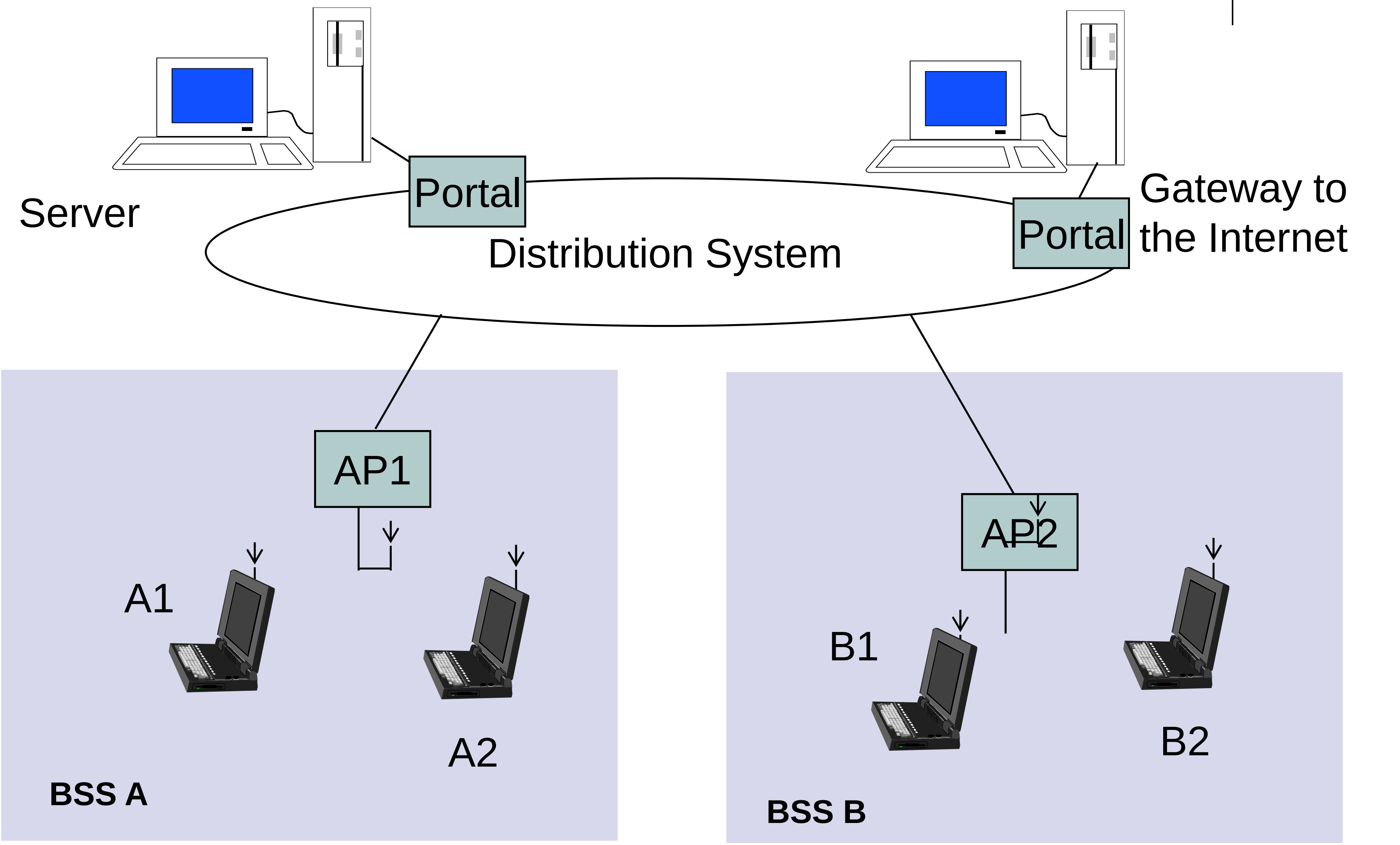
- Wireless communications compelling
  - ✓ Easy, low-cost deployment
  - ✓ Mobility & roaming: Access information anywhere
  - ✓ Supports personal devices
    - ✓ PDAs, laptops, data-cell-phones
  - ✓ Supports communicating devices
    - ✓ Cameras, location devices, wireless identification
  - ✗ Signal strength varies in space & time
  - ✗ Signal can be captured by snoopers
  - ✗ Spectrum is limited & usually regulated

Ad Hoc Communications



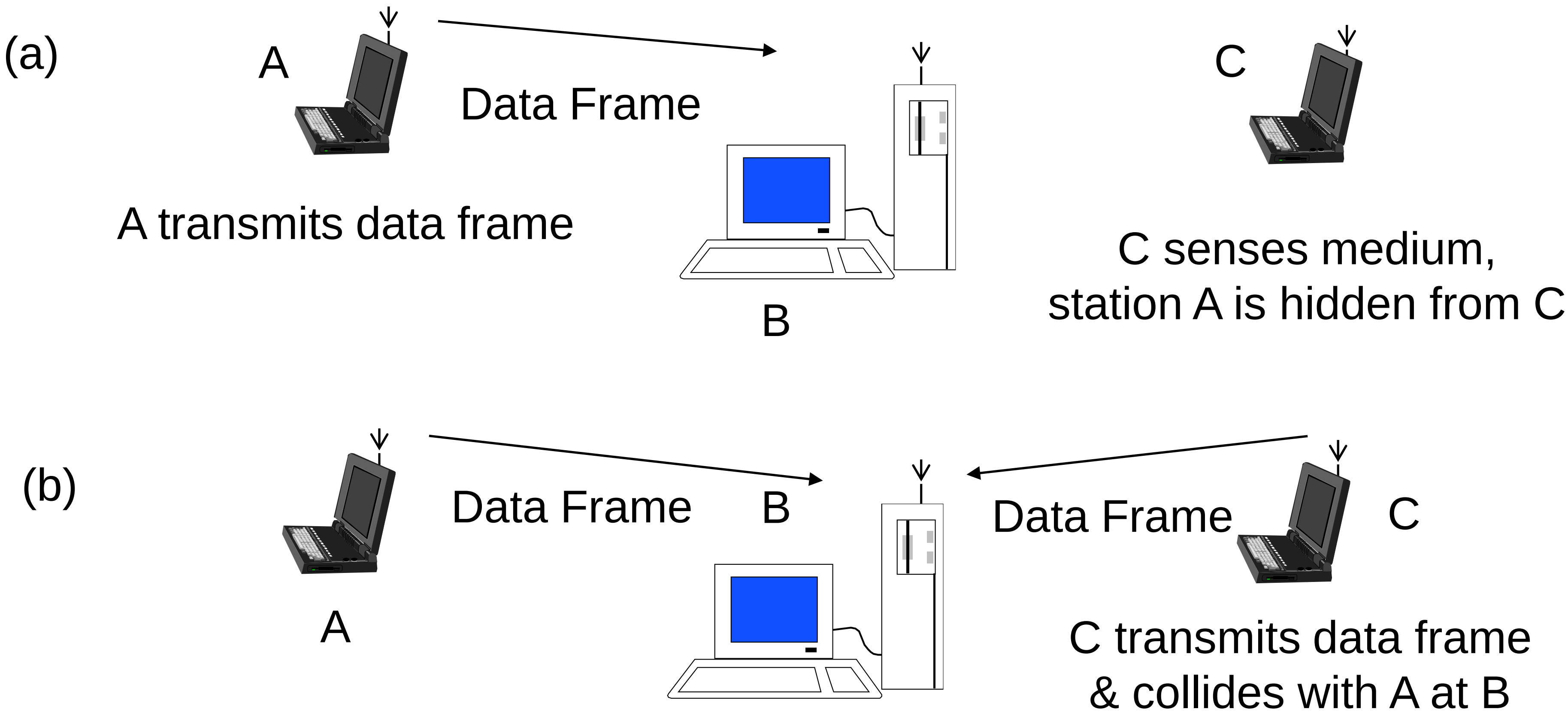
- Temporary association of group of stations
  - Within range of each other
  - Need to exchange information
  - E.g. Presentation in meeting, or distributed computer game, or both

Infrastructure Network



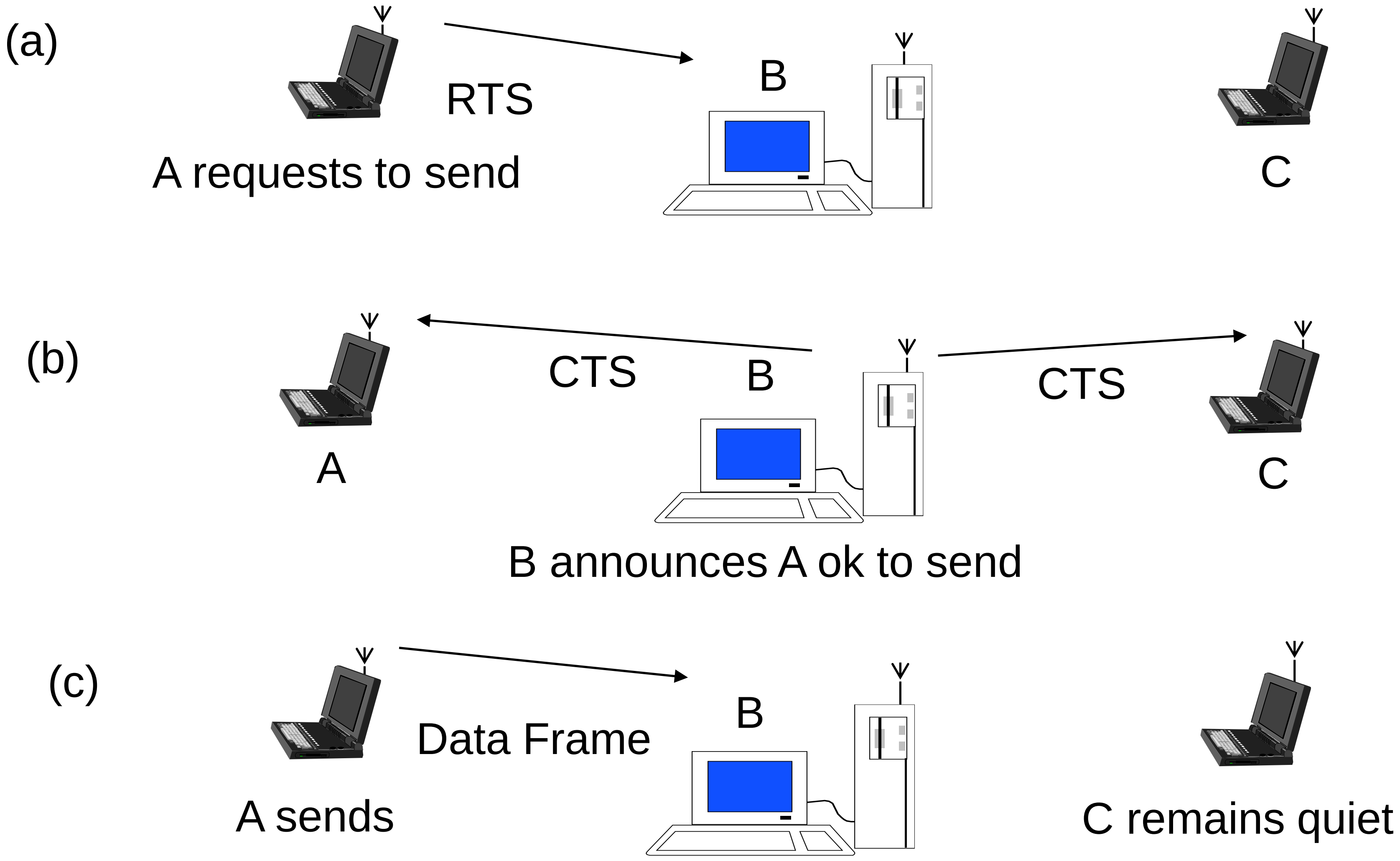
- Permanent Access Points provide access to Internet

Hidden Terminal Problem



- New MAC: CSMA with *Collision Avoidance*

CSMA with Collision Avoidance



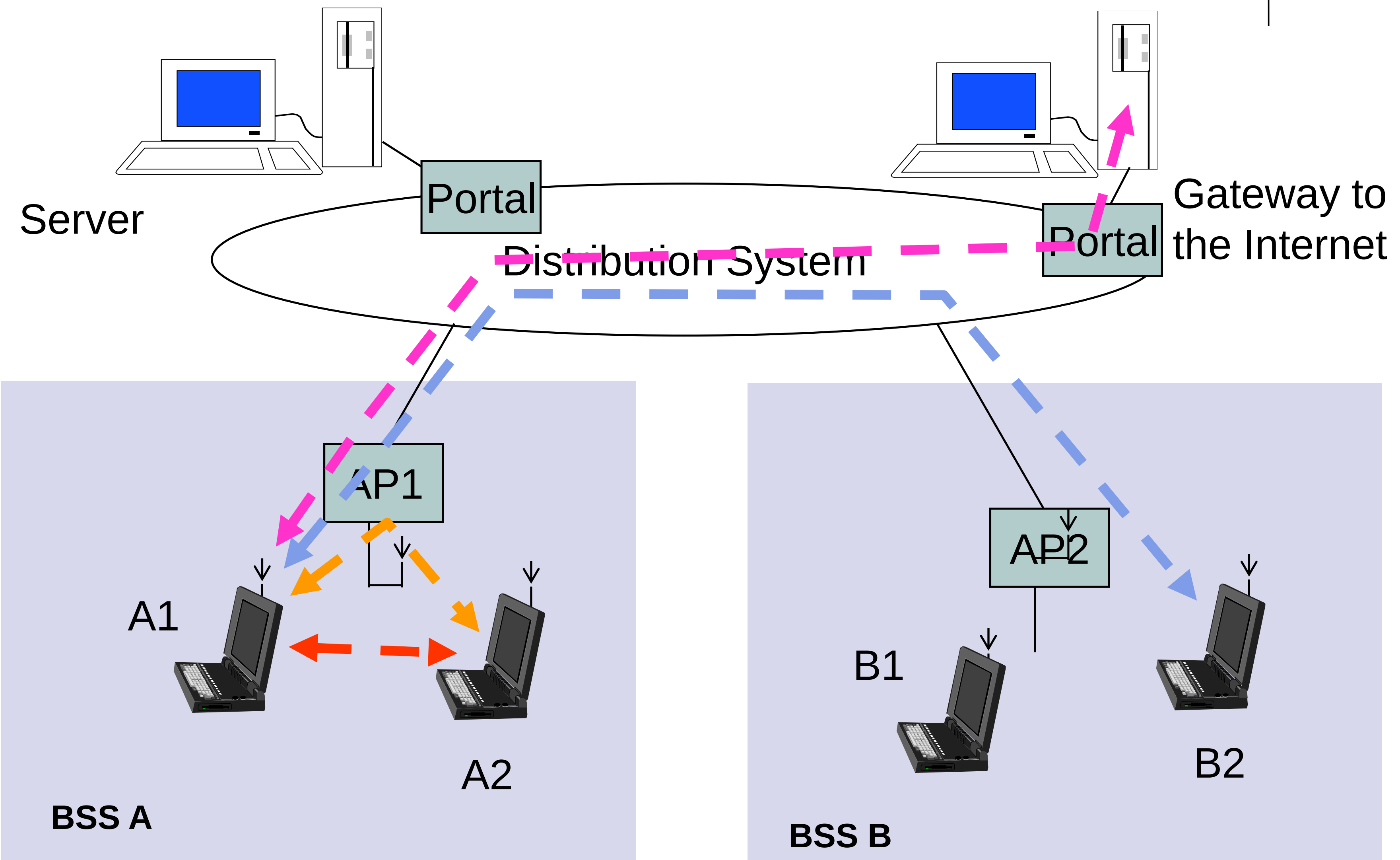
IEEE 802.11 Wireless LAN

- 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



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

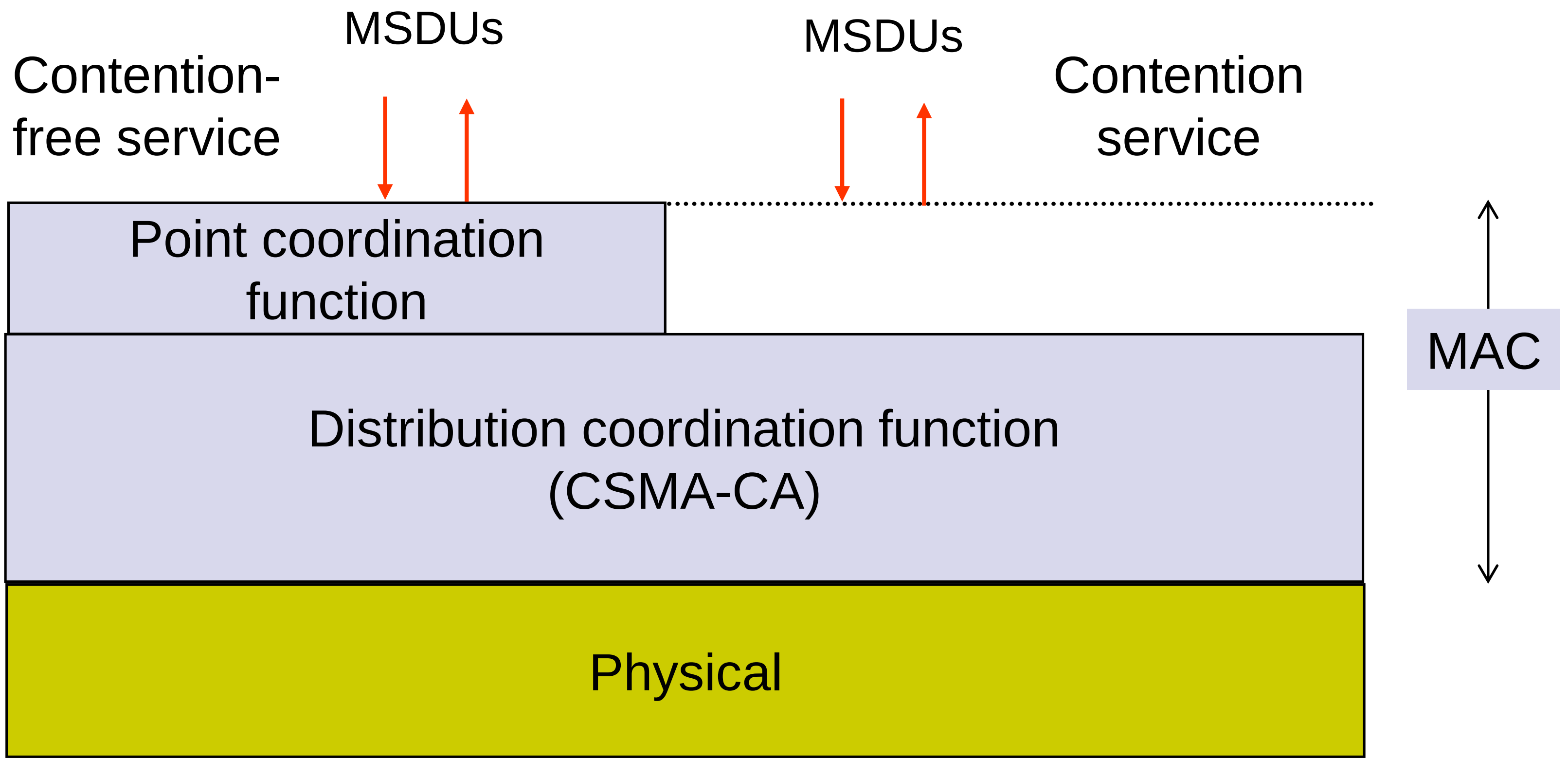
- Select AP and establish *association* with AP
  - Then can send/receive frames via AP & DS
- *Reassociation service* to move from one AP to another AP
- *Dissociation service* to terminate association
- *Authentication service* to establish identity of other stations
- *Privacy service* to keep contents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

IEEE 802.11 MAC

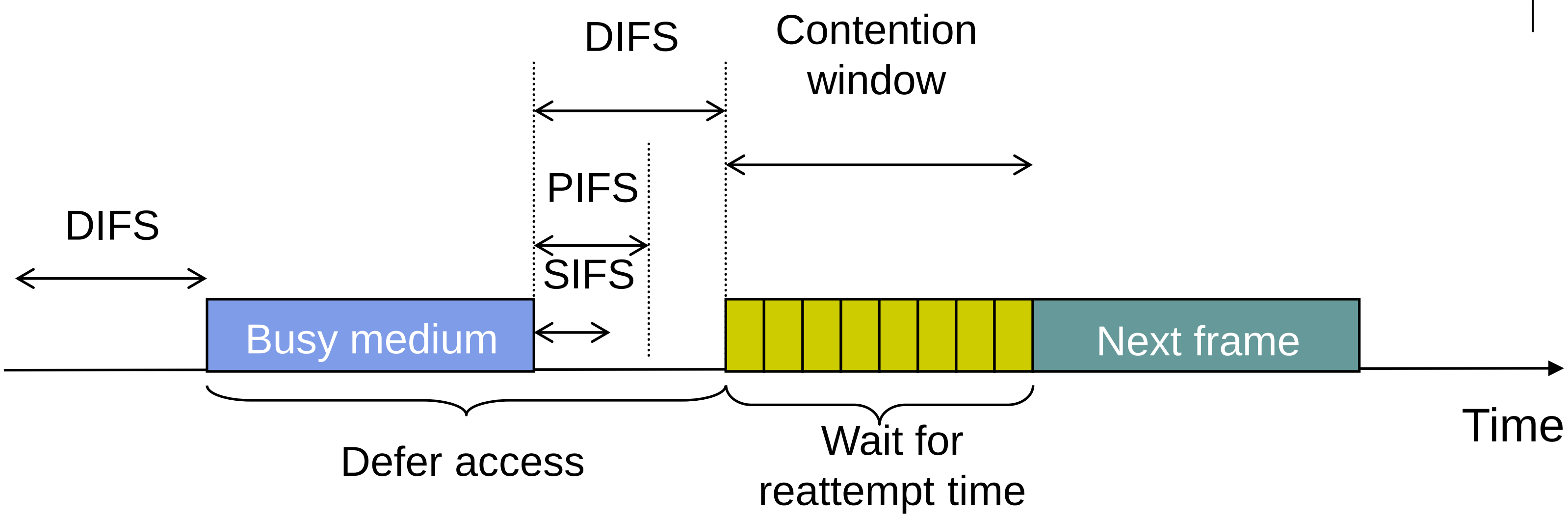
- MAC sublayer responsibilities
  - Channel access
  - PDU addressing, formatting, error checking
  - Fragmentation & reassembly of MAC SDUs
- MAC security service options
  - Authentication & privacy
- MAC management services
  - Roaming within ESS
  - Power management

MAC Services

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

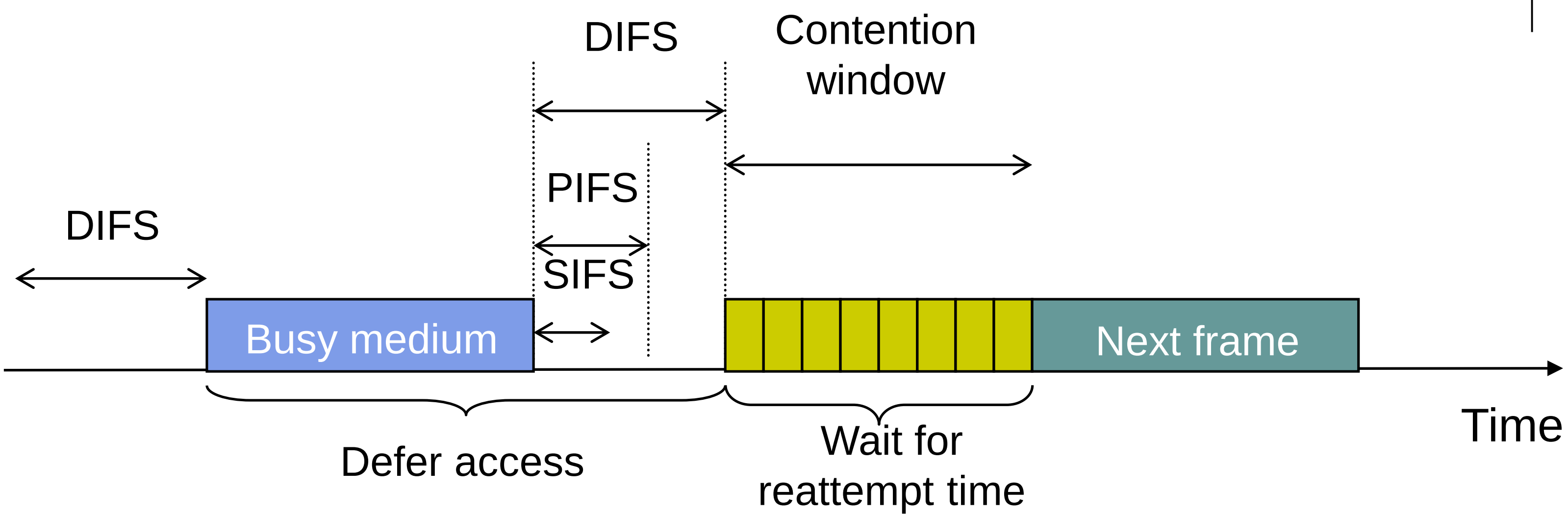


Distributed Coordination Function (DCF)



- 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)*

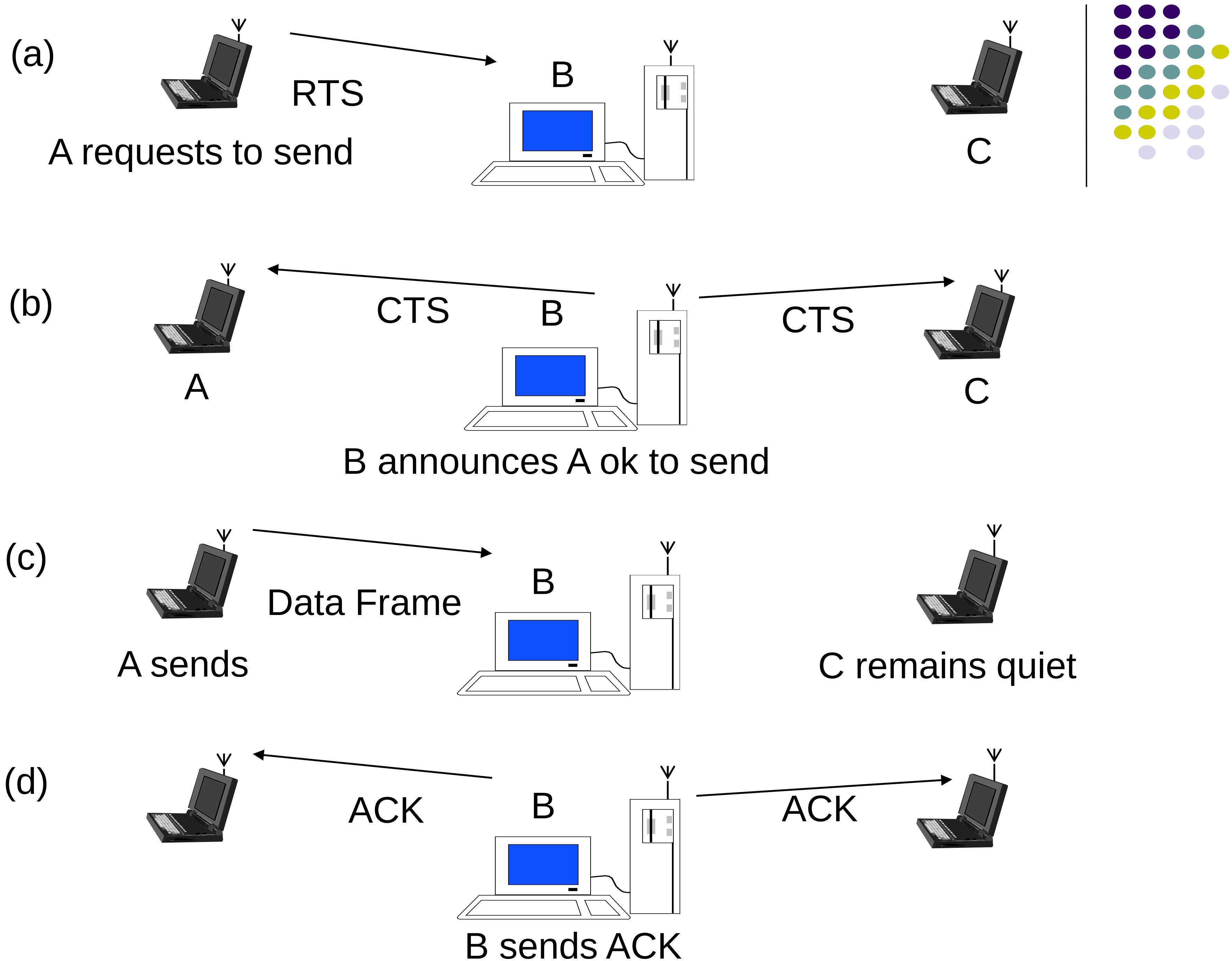
Priorities through Interframe Spacing



- High-Priority frames wait Short IFS (SIFS)
  - Typically to complete exchange in progress
  - ACKs, CTS, data frames of segmented MSDU, etc.
- PCF IFS (PIFS) to initiate Contention-Free Periods
- DCF IFS (DIFS) to transmit data & MPDUs

Contention & Backoff Behavior

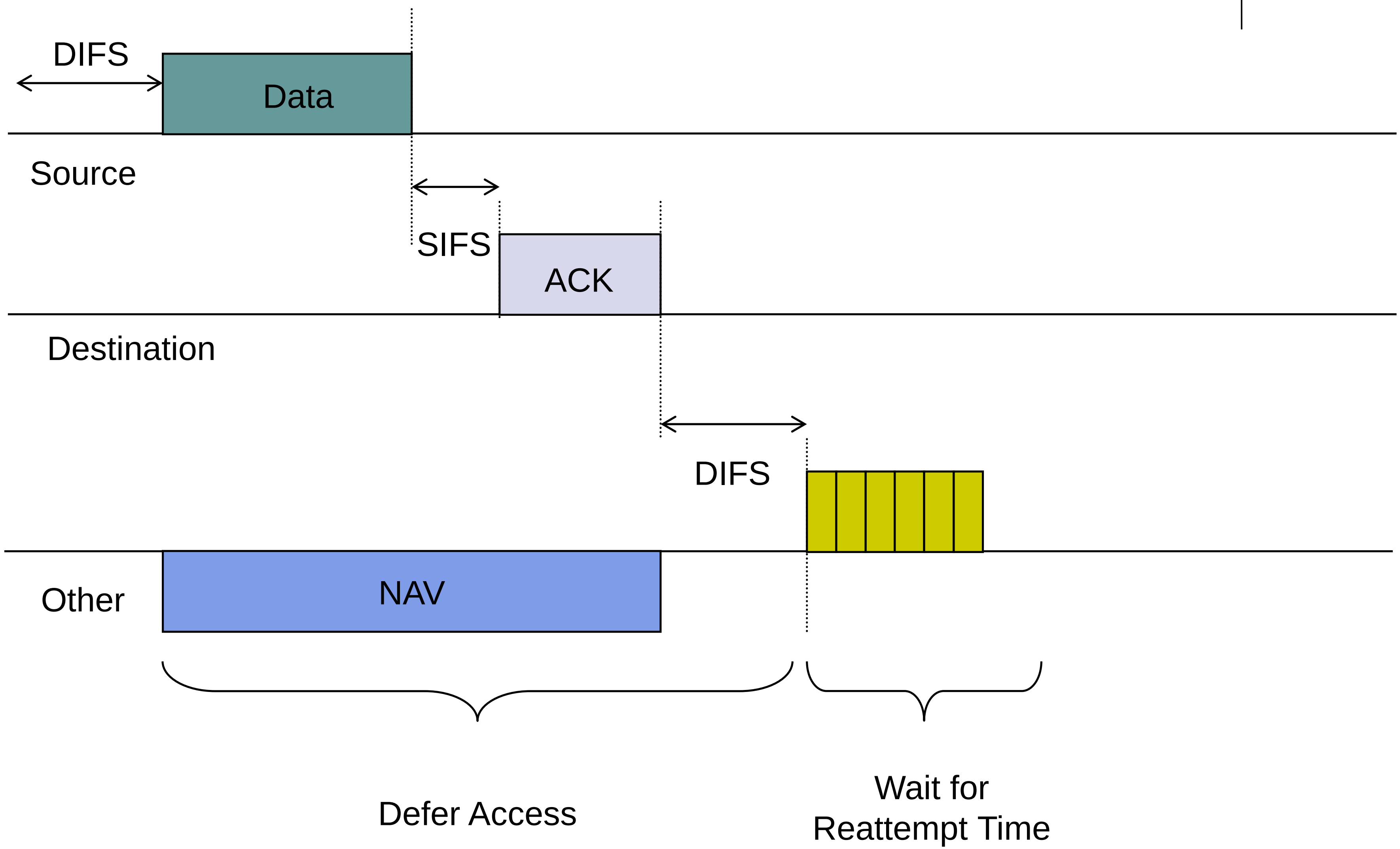
- If channel is still idle after DIFS period, ready station can transmit an *initial* MPDU
- If channel becomes busy before DIFS, then station must schedule *backoff* time for reattempt
    - Backoff period is integer # of *idle contention time slots*
    - Waiting station monitors medium & decrements backoff timer each time an idle contention slot transpires
    - 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


(a)
RTS
B
A requests to send
C
(b)
CTS
B
CTS
A
C
B announces A ok to send
(c)
B
Data Frame
A sends
C remains quiet
(d)
ACK
B
ACK
B sends ACK

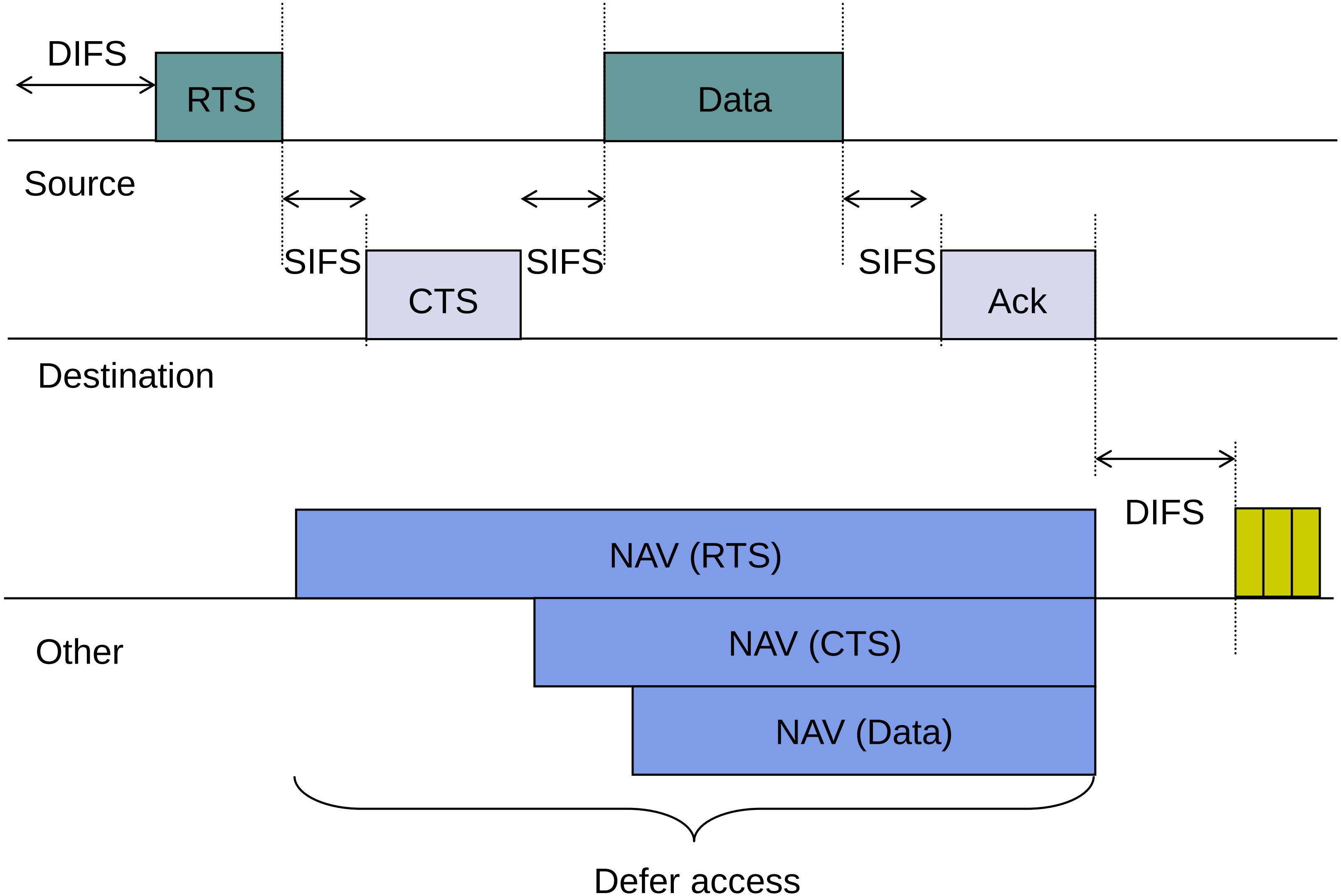
Carrier Sensing in 802.11

- *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

Transmission of MPDU without RTS/CTS



Transmission of MPDU with RTS/CTS



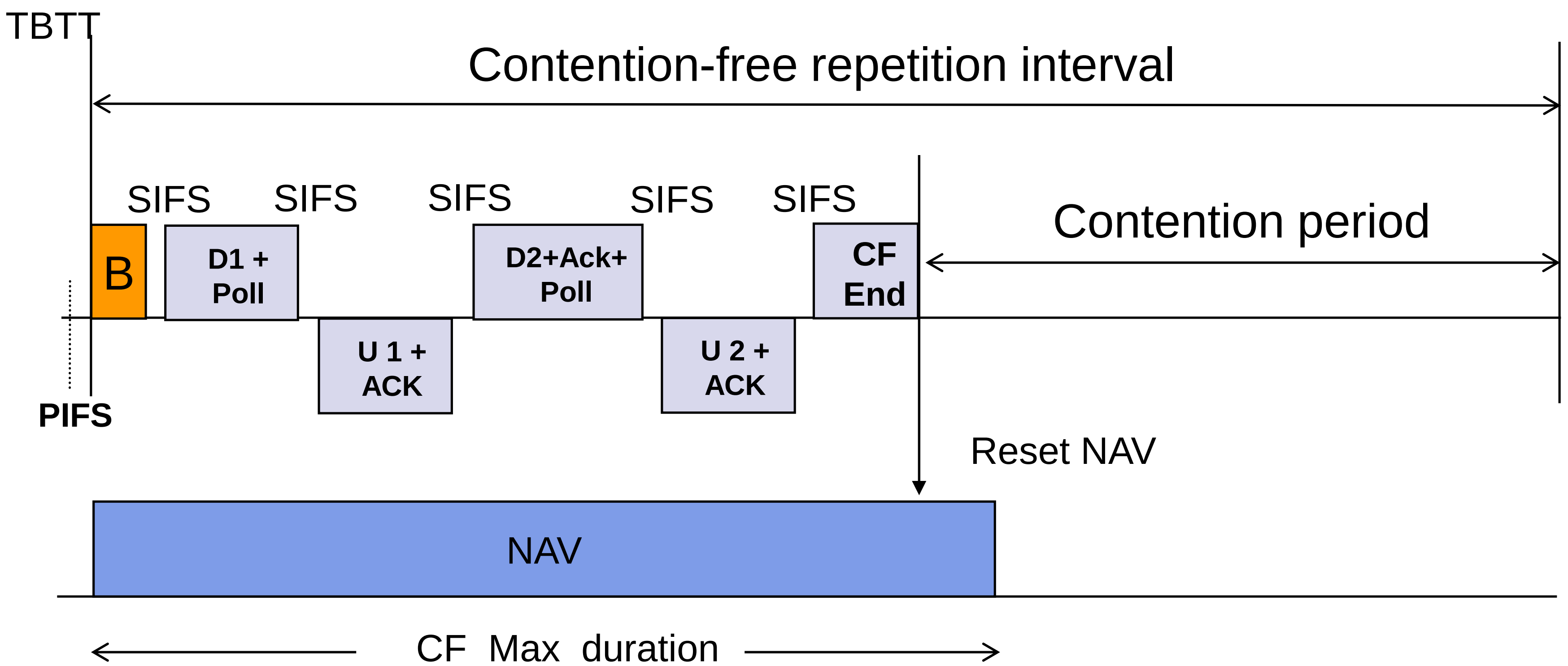
Collisions, Losses & Errors

- 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
- 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

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

IEEE 802.11 Physical Layer 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

Chapter 6
Medium Access Control Protocols and Local Area Networks

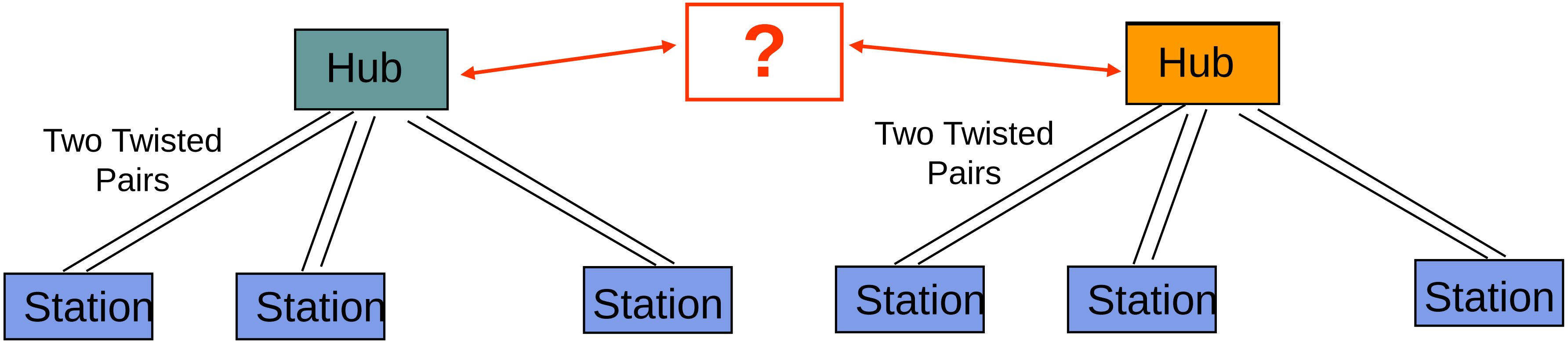
LAN Bridges

Hubs, Bridges & Routers

- Hub: Active central element in a star topology
  - Twisted Pair: inexpensive, easy to insall
  - Simple repeater in Ethernet LANs
  - “Intelligent hub”: fault isolation, net configuration, statistics
  - Requirements that arise:

User community grows, need to interconnect hubs

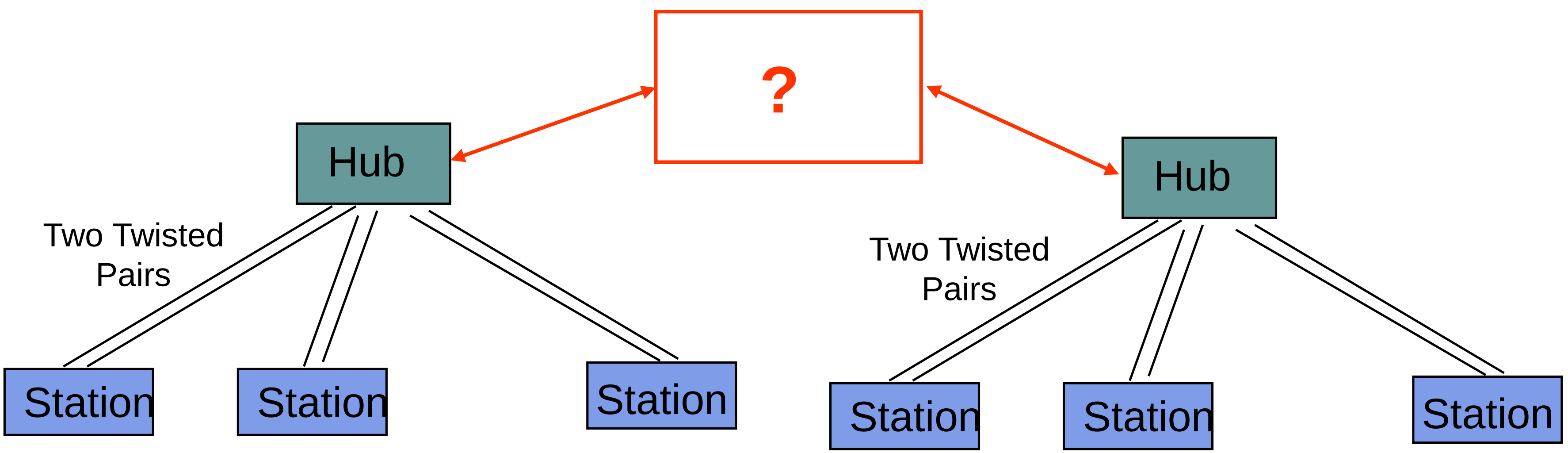
Hubs are for different types of LANs



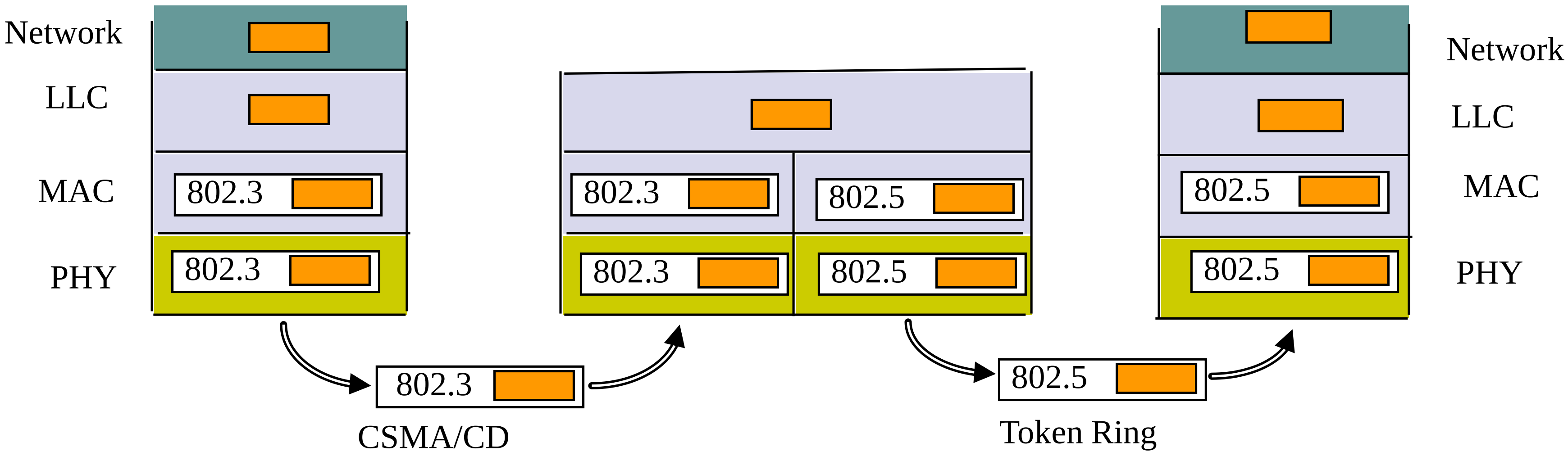
Hubs, Bridges & Routers

- Interconnecting Hubs
  - Repeater: Signal regeneration
    - All traffic appears in both LANs
  - Bridge: MAC address filtering
    - Local traffic stays in own LAN
  - Routers: Internet routing
    - All traffic stays in own LAN

Higher Scalability

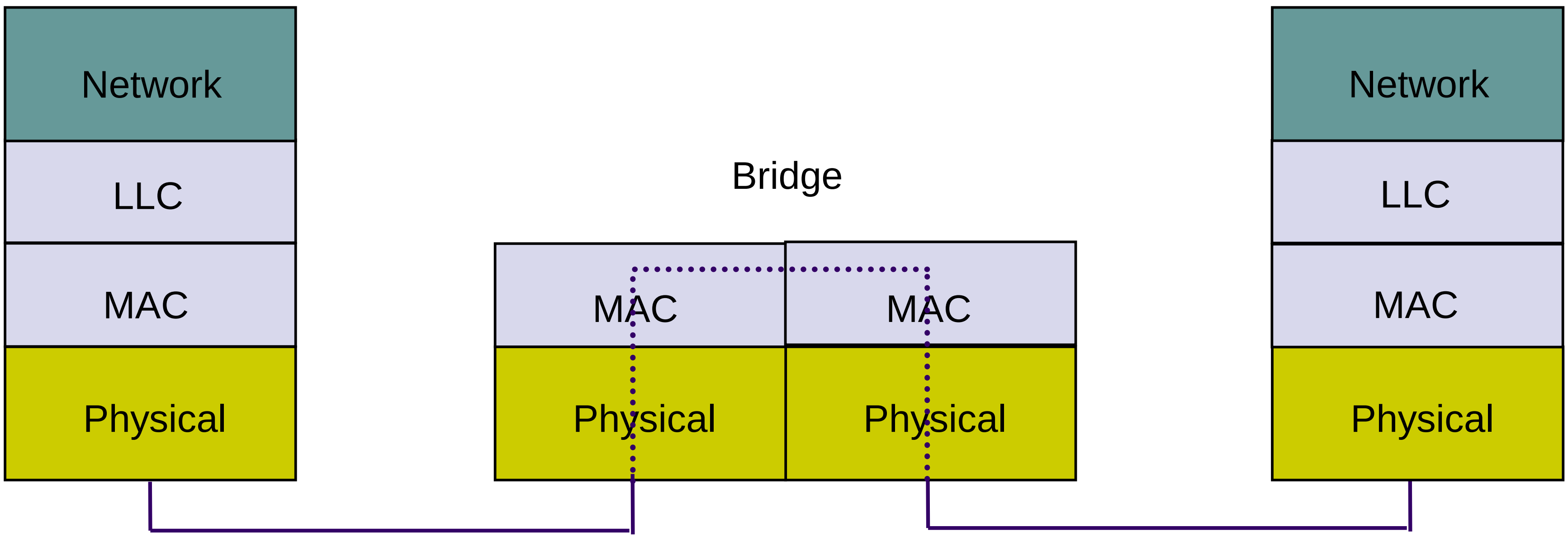


General Bridge Issues



- 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

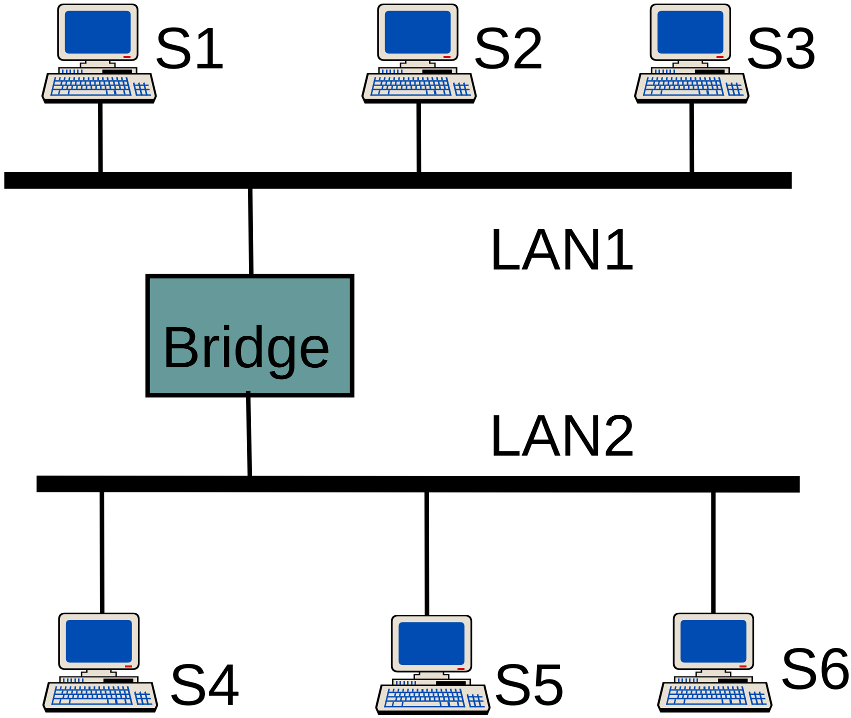
Bridges of Same Type

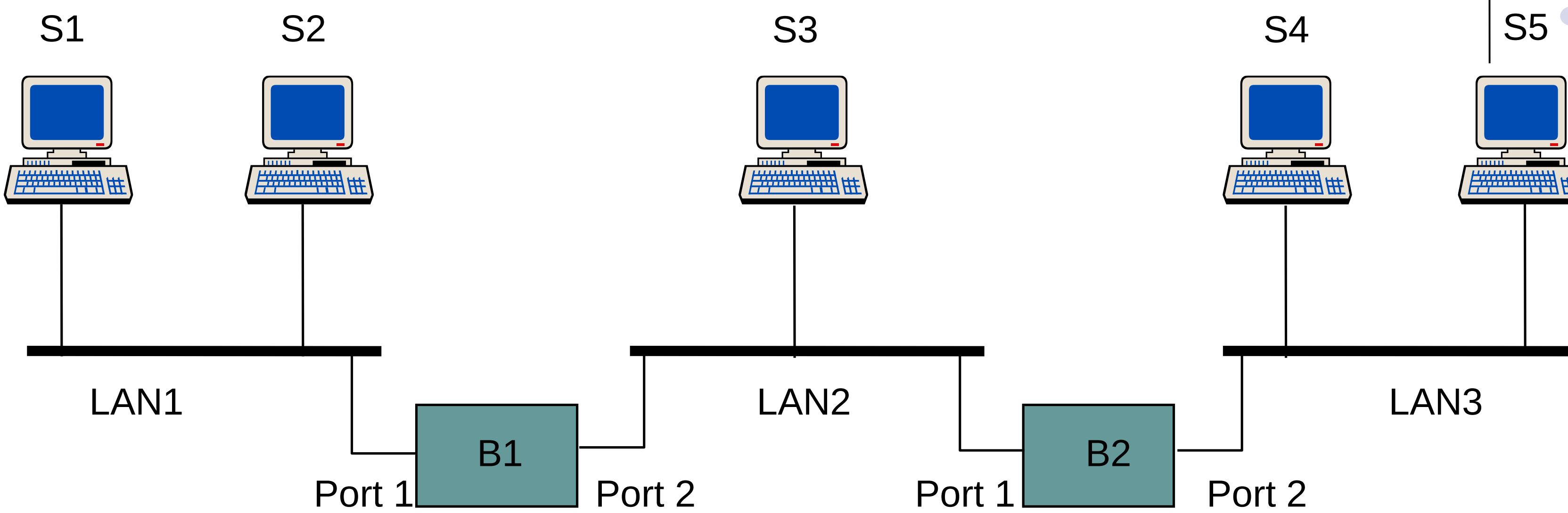


- Common case involves LANs of same type
- Bridging is done at MAC level

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

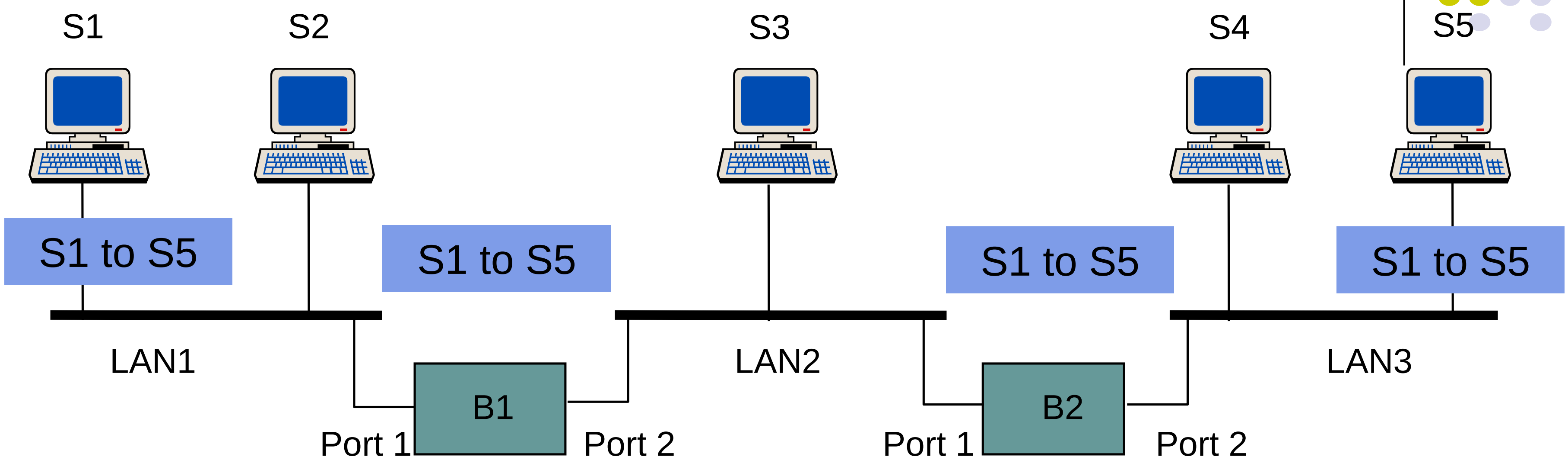




Address	Port

Address	Port

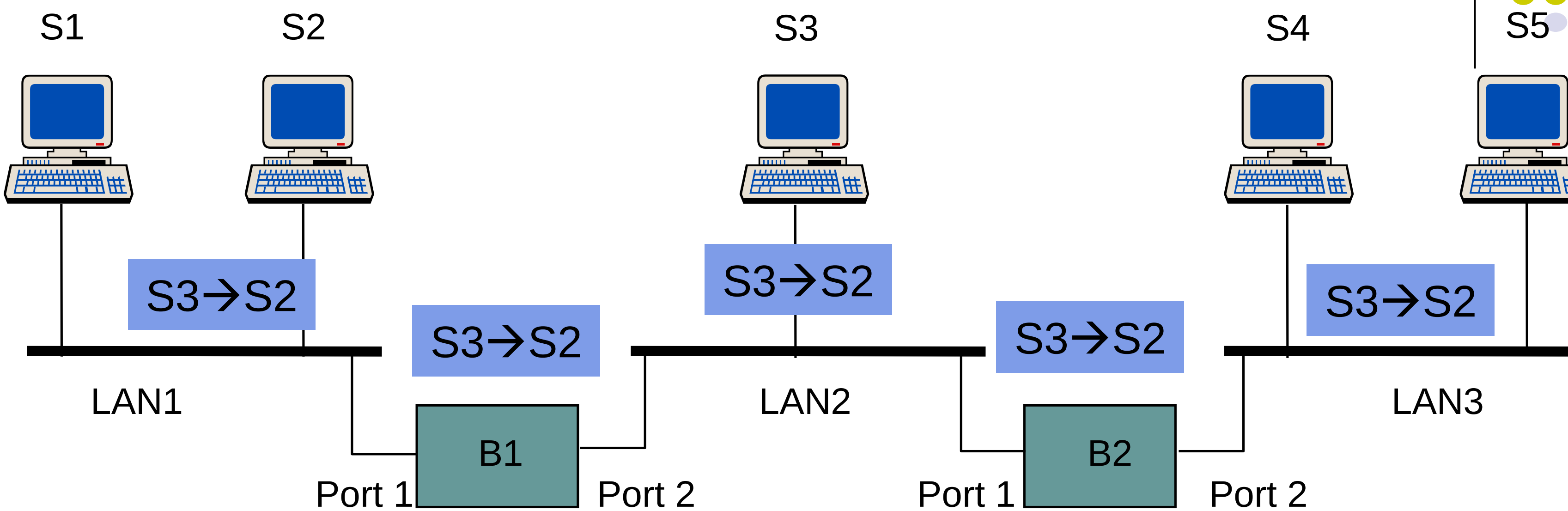
S1→S5



Address	Port
S1	1

Address	Port
S1	1

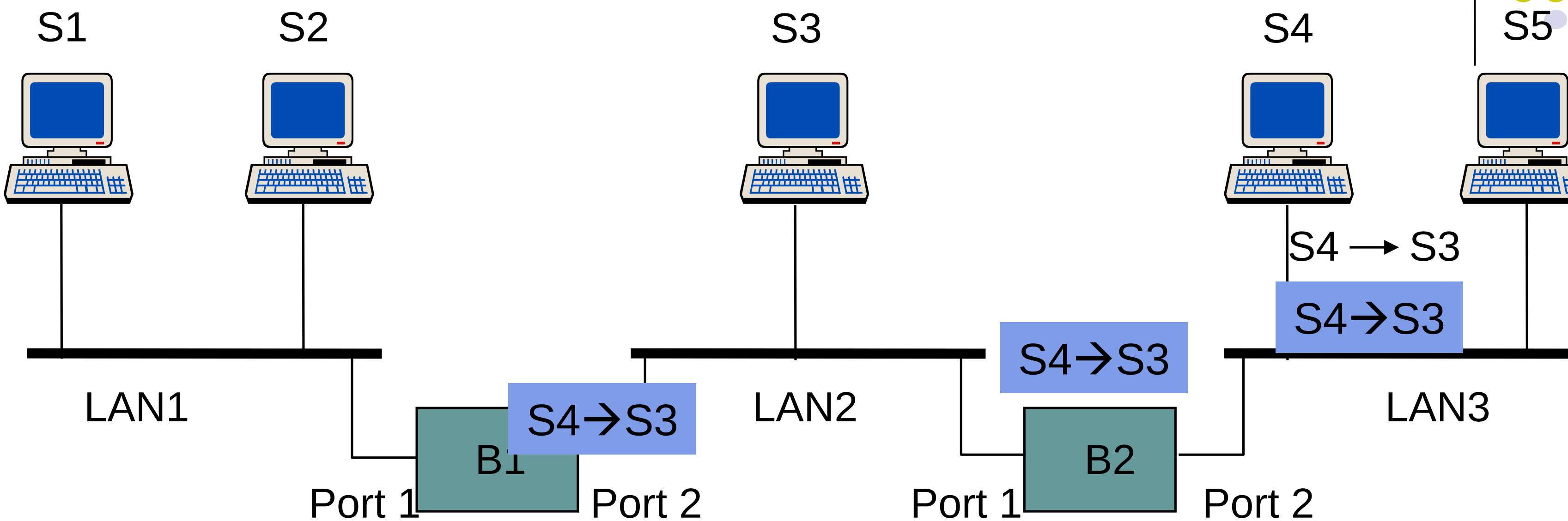
S3→S2



Address	Port
S1	1
S3	1

Address	Port
S1	1
S3	1

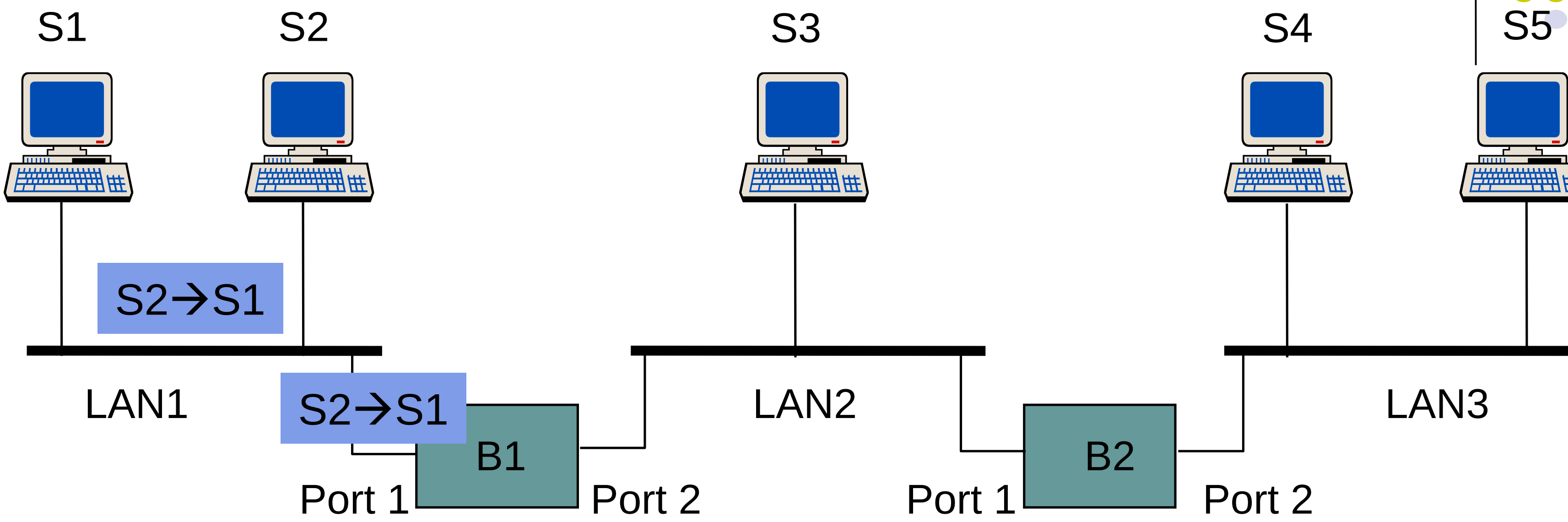
S4→S3



Address	Port
S1	1
S3	2
S4	2

Address	Port
S1	1
S3	1
S4	2

S2→S1



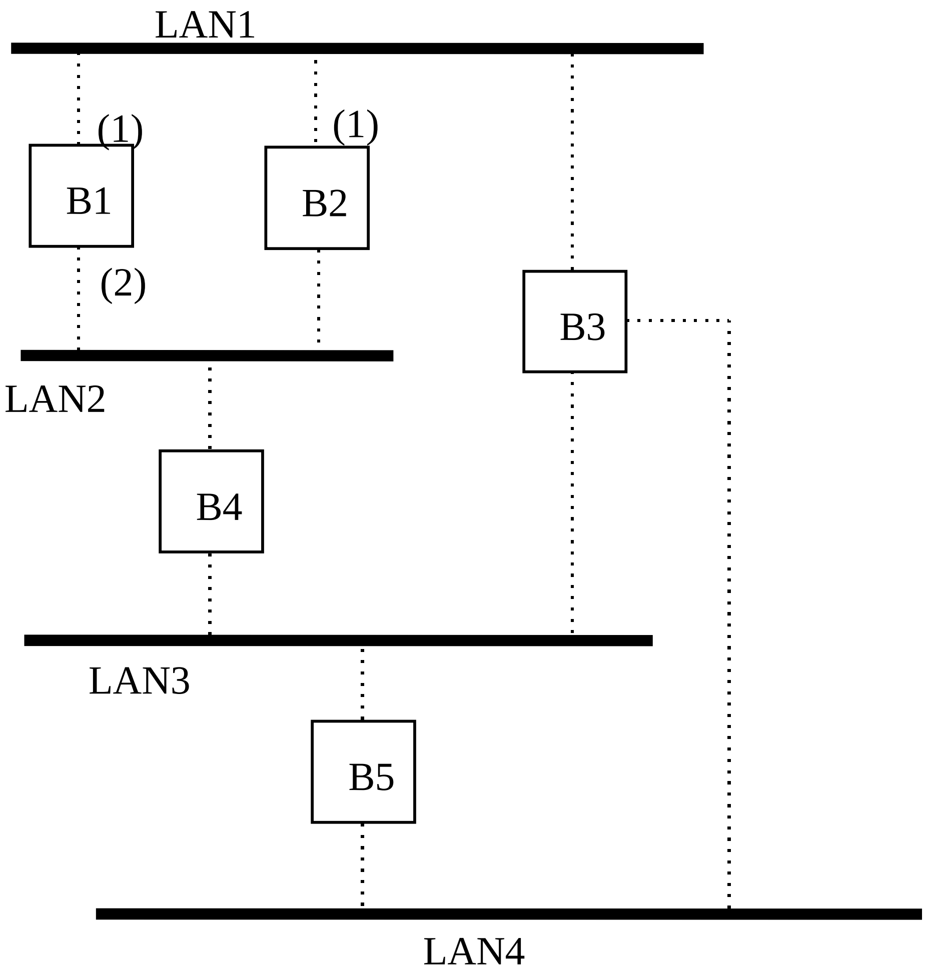
Address	Port
S1	1
S3	2
S4	2
S2	1

Address	Port
S1	1
S3	1
S4	2

Adaptive Learning

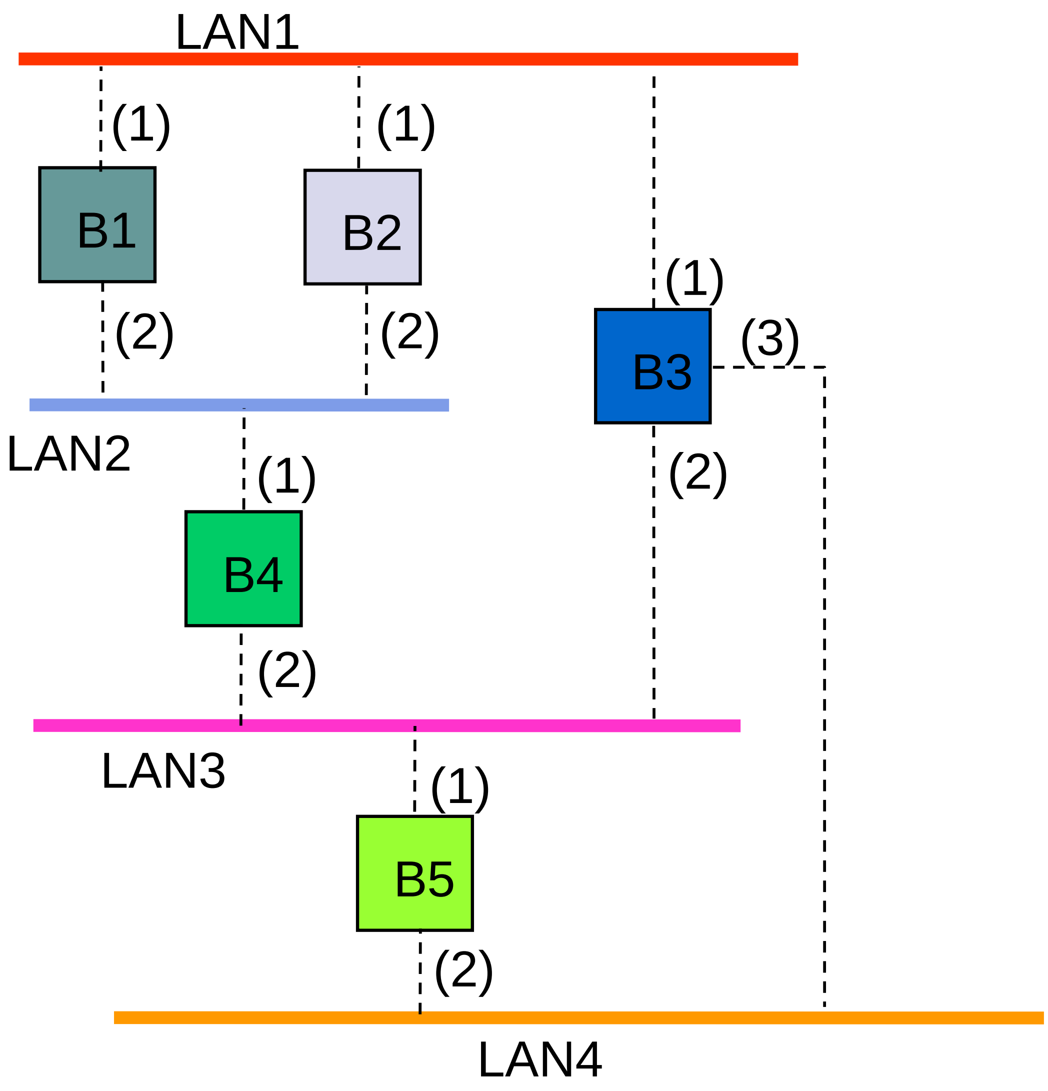
- In a static network, tables eventually store all addresses & learning stops
- In practice, stations are added & moved all the time
  - Introduce timer (minutes) to age each entry & force it to be relearned periodically
  - If frame arrives on port that differs from frame address & port in table, update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

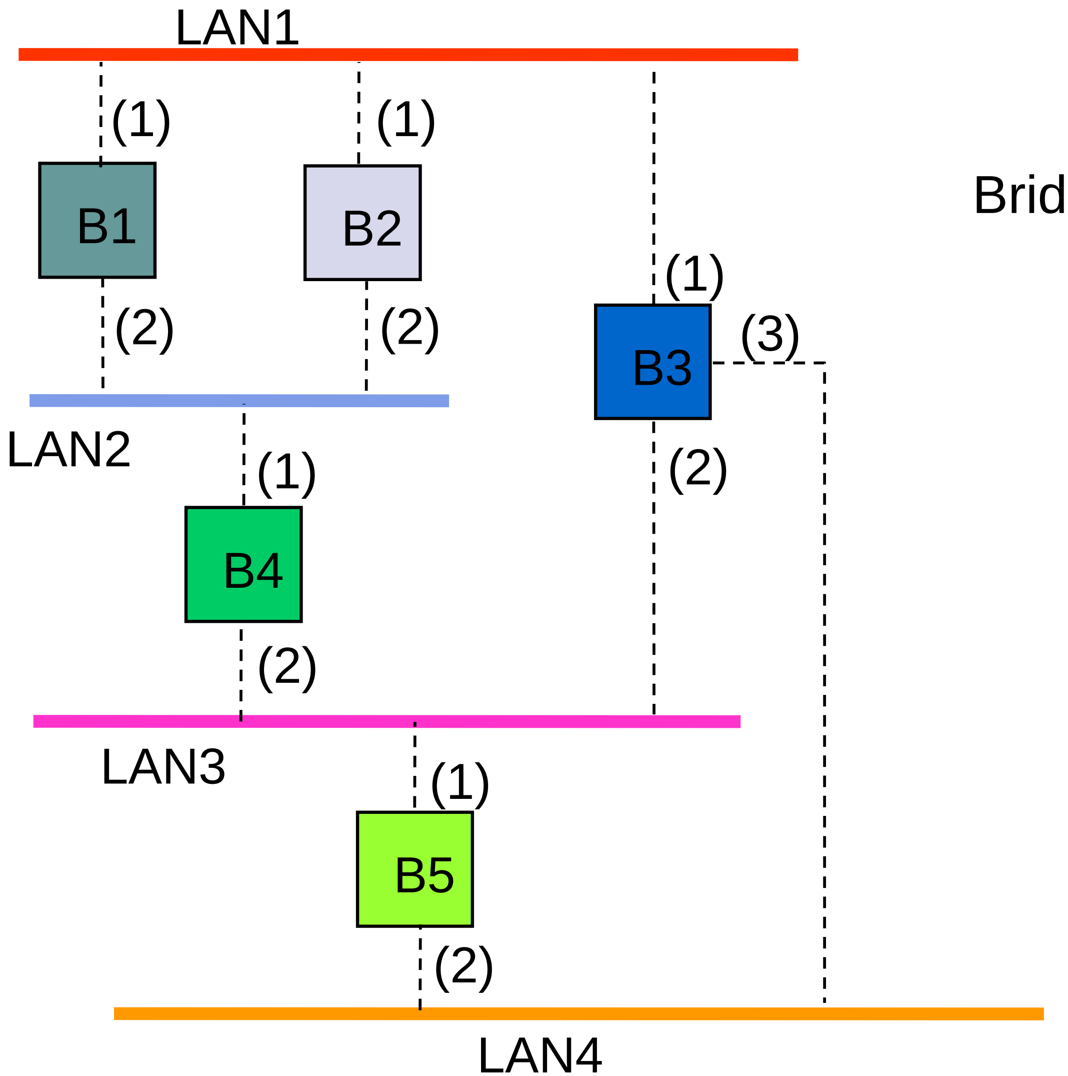
Avoiding Loops



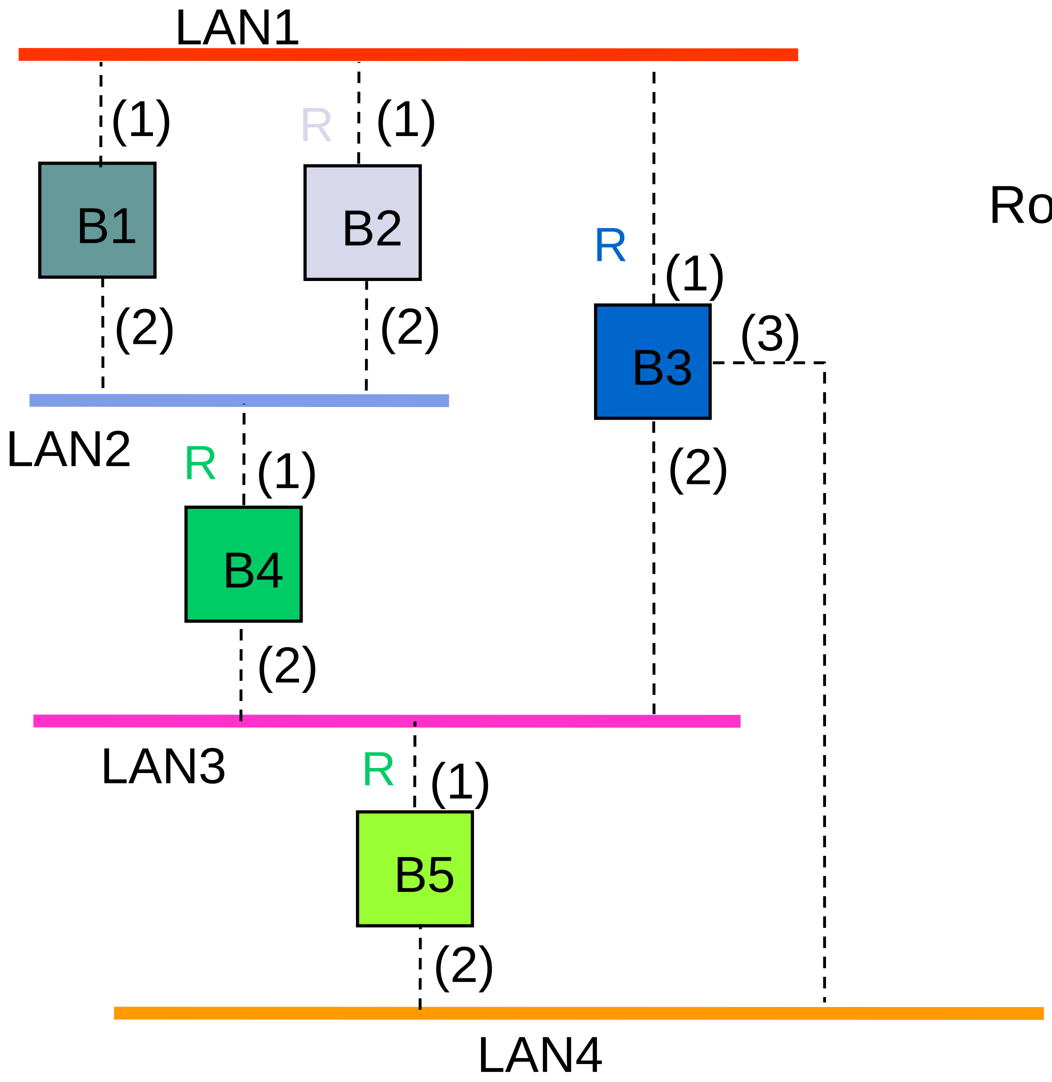
Spanning Tree Algorithm

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.

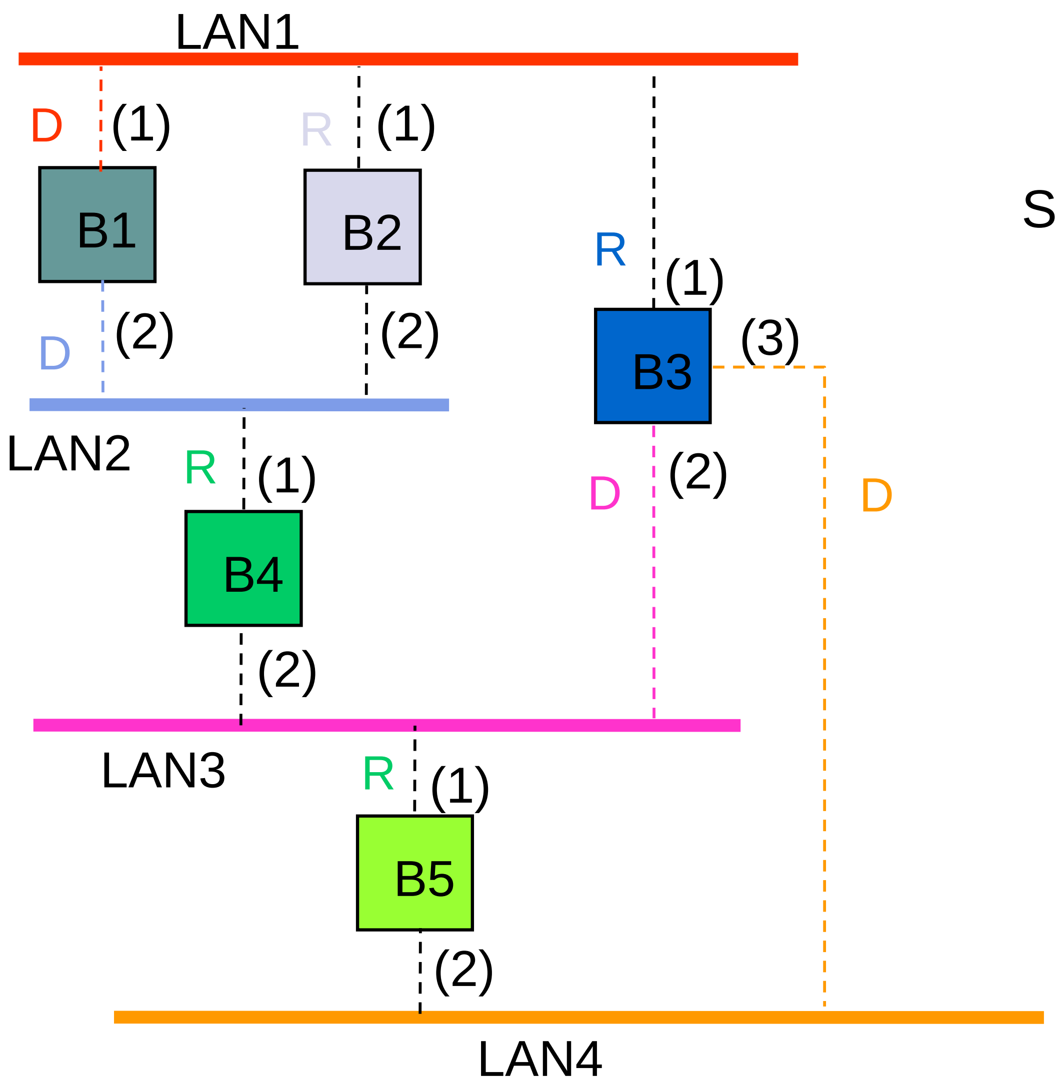

LAN1
(1)
(1)
B1
B2
(1)
(2)
(2)
(3)
B3
LAN2
(1)
(2)
B4
(2)
LAN3
(1)
B5
(2)
LAN4



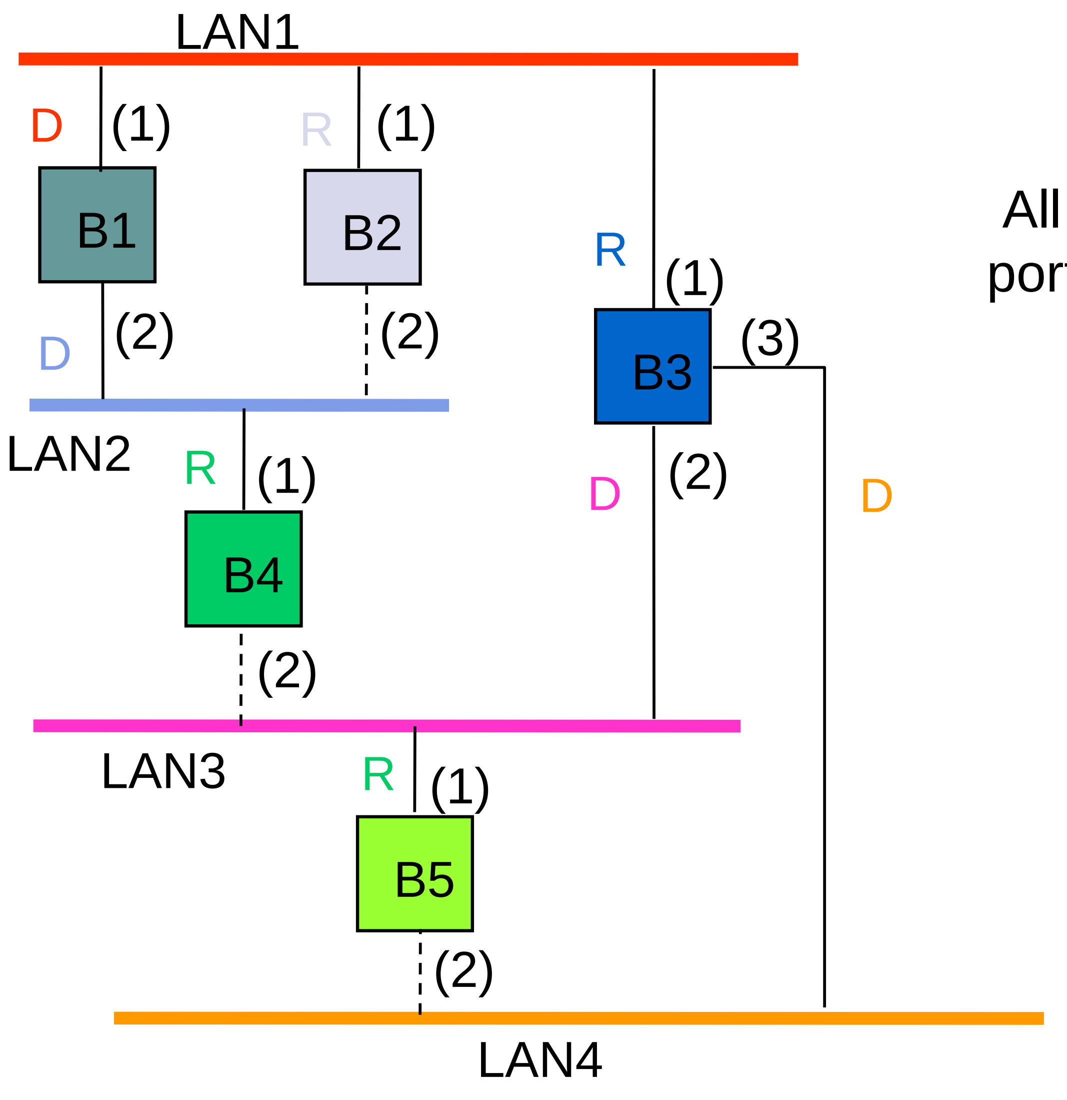
Bridge 1 selected as root bridge



Root port selected for every bridge except root port



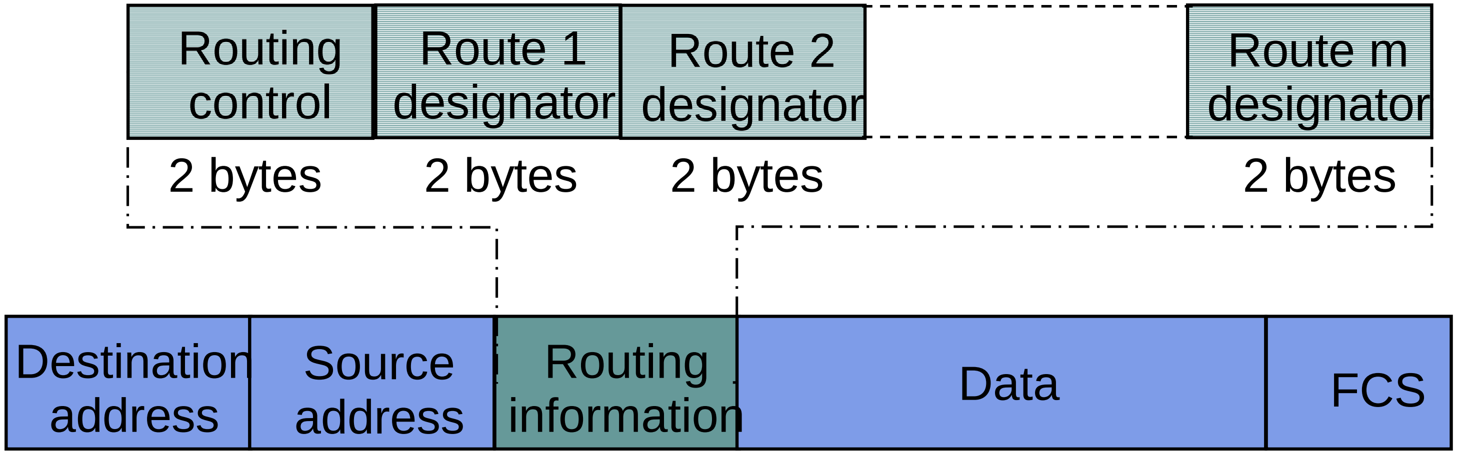
Select designated bridge
for each LAN



All root ports & designated ports put in forwarding state

Source Routing Bridges

- To interconnect IEEE 802.5 token rings
- Each source station determines route to destination
- Routing information inserted in frame



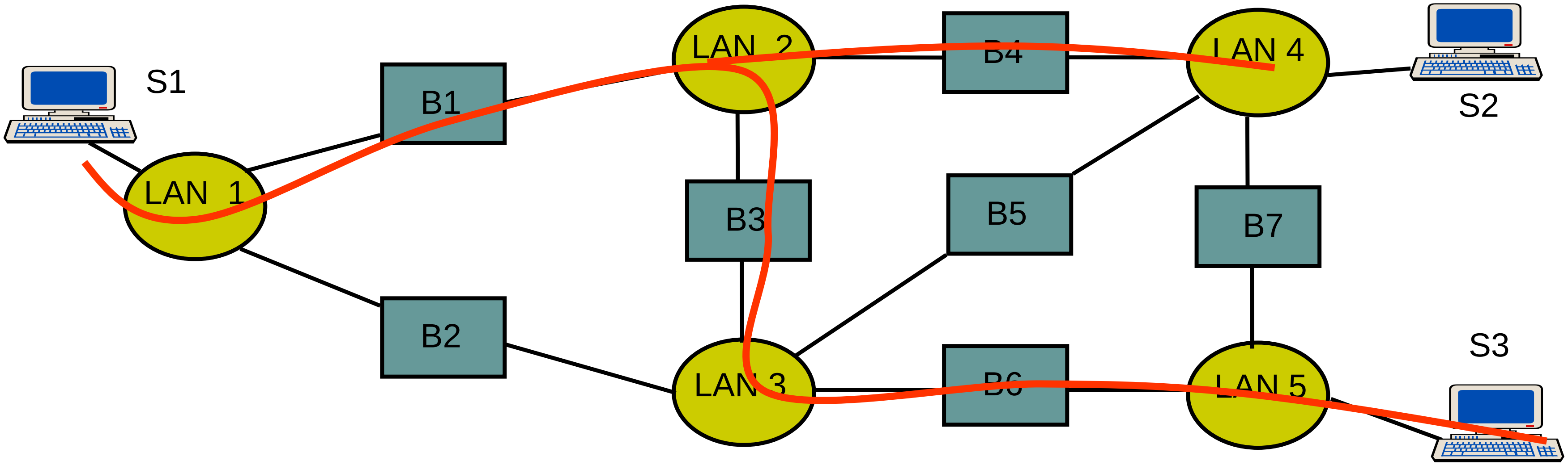
Route Discovery

- To discover route to a destination each station broadcasts a *single-route broadcast frame*
- Frame visits every LAN once & eventually reaches destination
- Destination sends *all-routes broadcast frame* which generates all routes back to source
- Source collects routes & picks best

Detailed Route Discovery

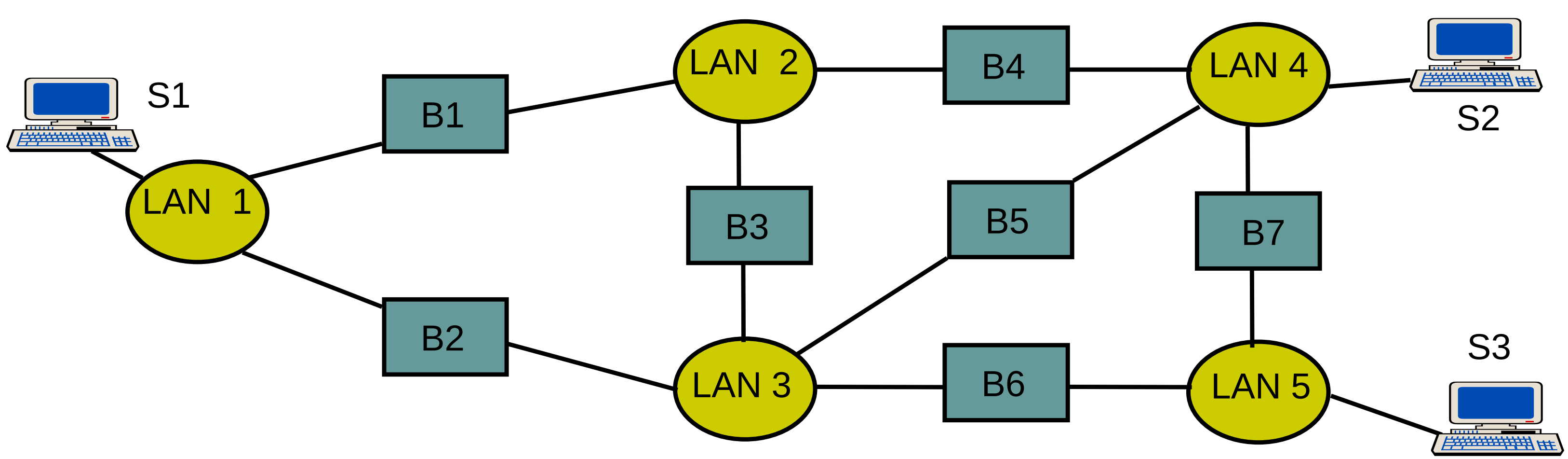
- Bridges must be configured to form a spanning tree
- Source sends *single-route frame* without route designator field
- Bridges in first LAN add incoming LAN #, its bridge #, outgoing LAN # into frame & forwards frame
- Each subsequent bridge attaches its bridge # and outgoing LAN #
- Eventually, *one* single-route frame arrives at destination
- When destination receives single-route broadcast frame it responds with *all-routes broadcast frame* with no route designator field
- Bridge at first hop inserts incoming LAN #, its bridge #, and outgoing LAN # and forwards to outgoing LAN
- Subsequent bridges insert their bridge # and outgoing LAN # and forward
- Before forwarding bridge checks to see if outgoing LAN already in designator field
- Source eventually receives all routes to destination station

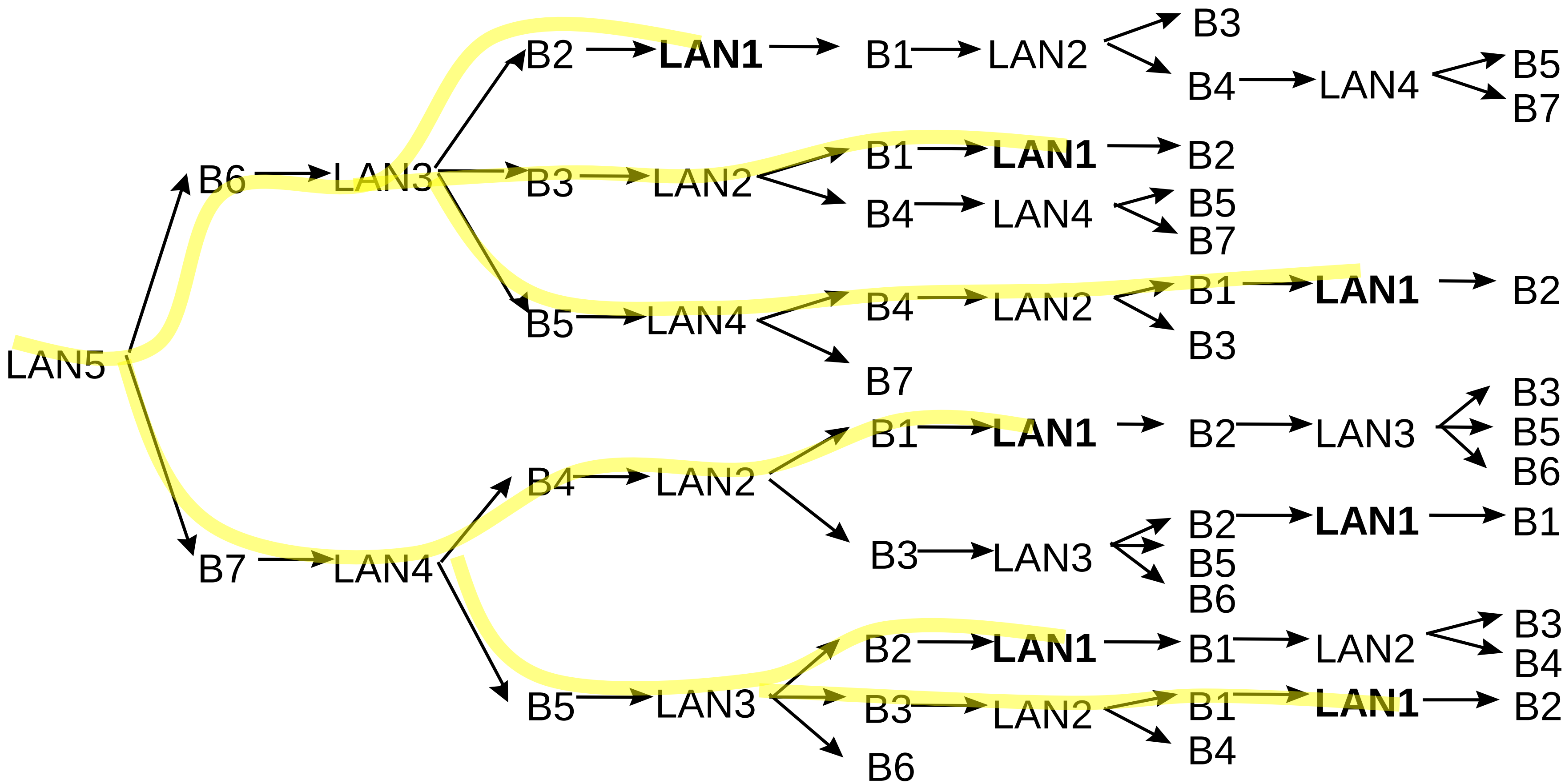
Find routes from S1 to S3



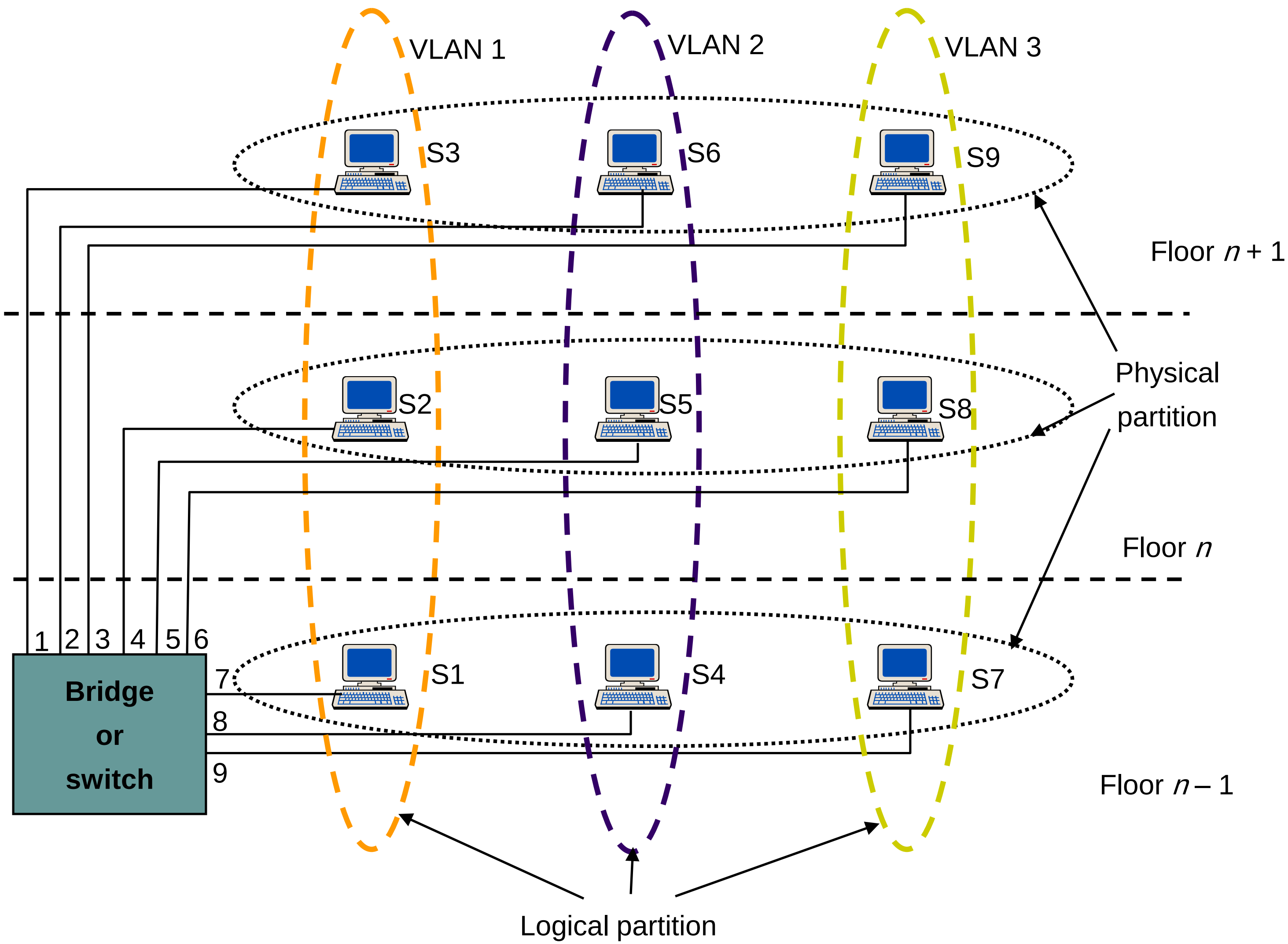
LAN1 → B1 → LAN2 → B3 → LAN3 → B6 → LAN5

LAN1 → B1 → LAN2 → B4 → LAN4

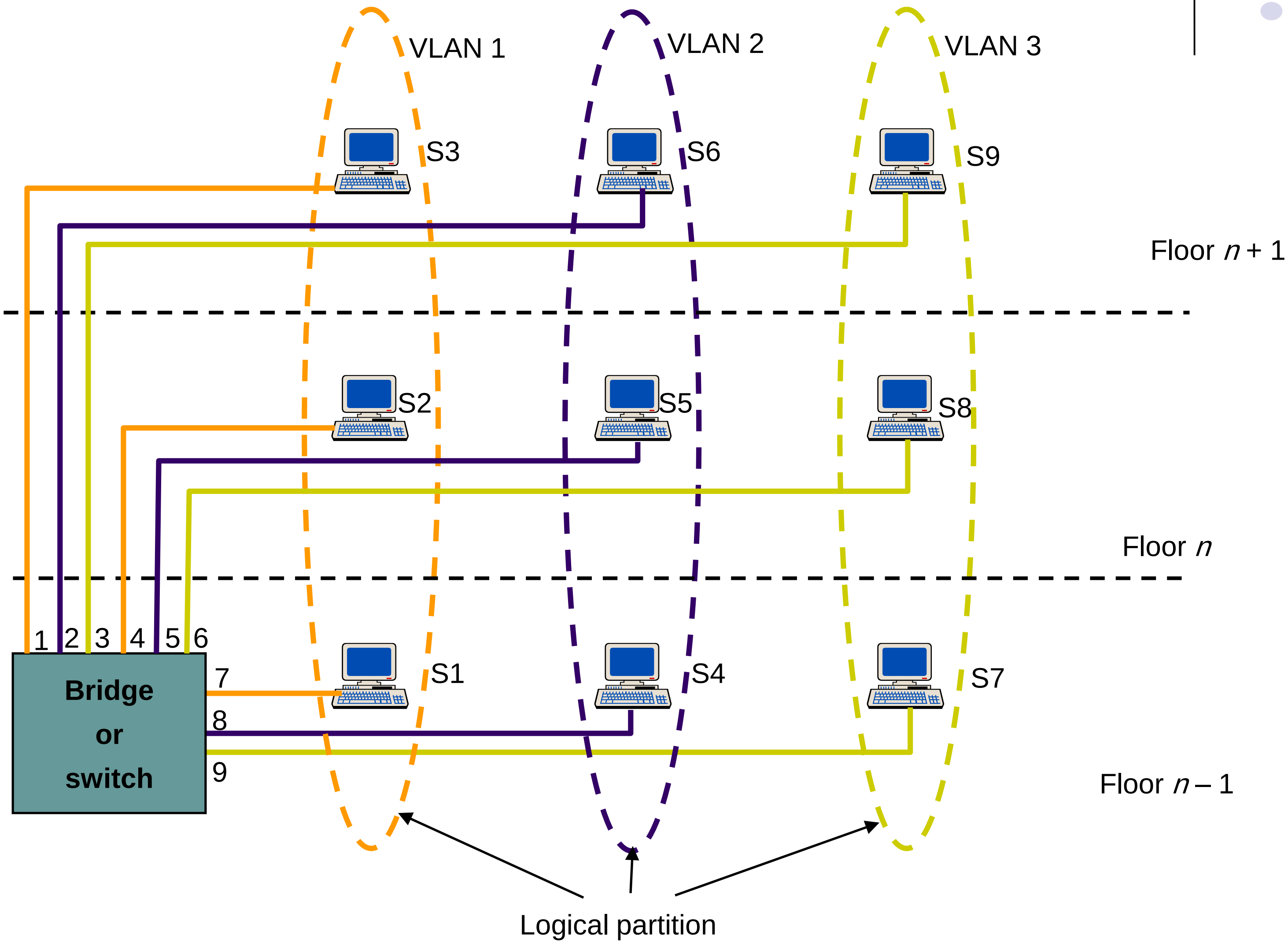

S1
B1
LAN 2
B4
LAN 4
S2
LAN 1
B3
B5
B7
B2
LAN 3
B6
LAN 5
S3


LAN5
B6 → LAN3
B2 → LAN1 → B1 → LAN2 → B3, B4 → LAN4 → B5, B7
B3 → LAN2 → B1 → LAN1 → B2
B4 → LAN4 → B5, B7
B5 → LAN4 → B4 → LAN2 → B1 → LAN1 → B2
B3
B7
B7 → LAN4
B4 → LAN2 → B1 → LAN1 → B2 → LAN3 → B3, B5, B6
B3 → LAN3 → B2 → LAN1 → B1
B5
B6
B5 → LAN3 → B2 → LAN1 → B1 → LAN2 → B3, B4
B3 → LAN2 → B1 → LAN1 → B2
B4
B6

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
1
2
3
4
5
6
7
8
9
Bridge
or
switch
Logical partition

Per-Port VLANs



Bridge only forwards frames to outgoing ports associated with same VLAN

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