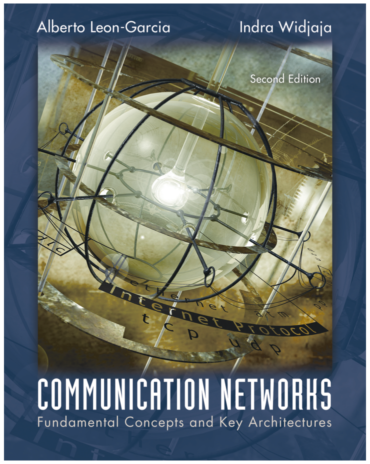
Chapter 6
Medium Access Control Protocols



Medium Access Control

pp. 339-348

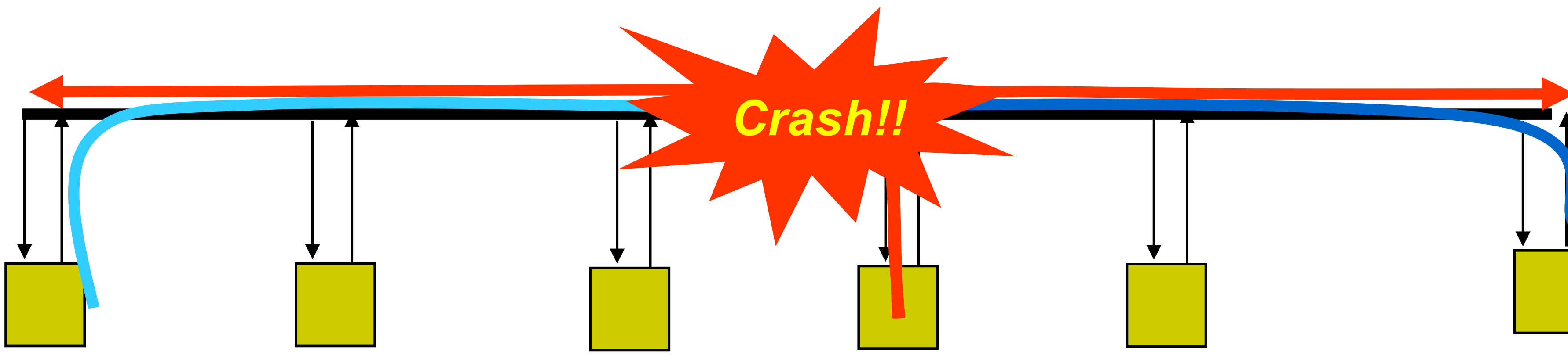
pp. 354-366

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

Example: Random Access

Multitapped Bus

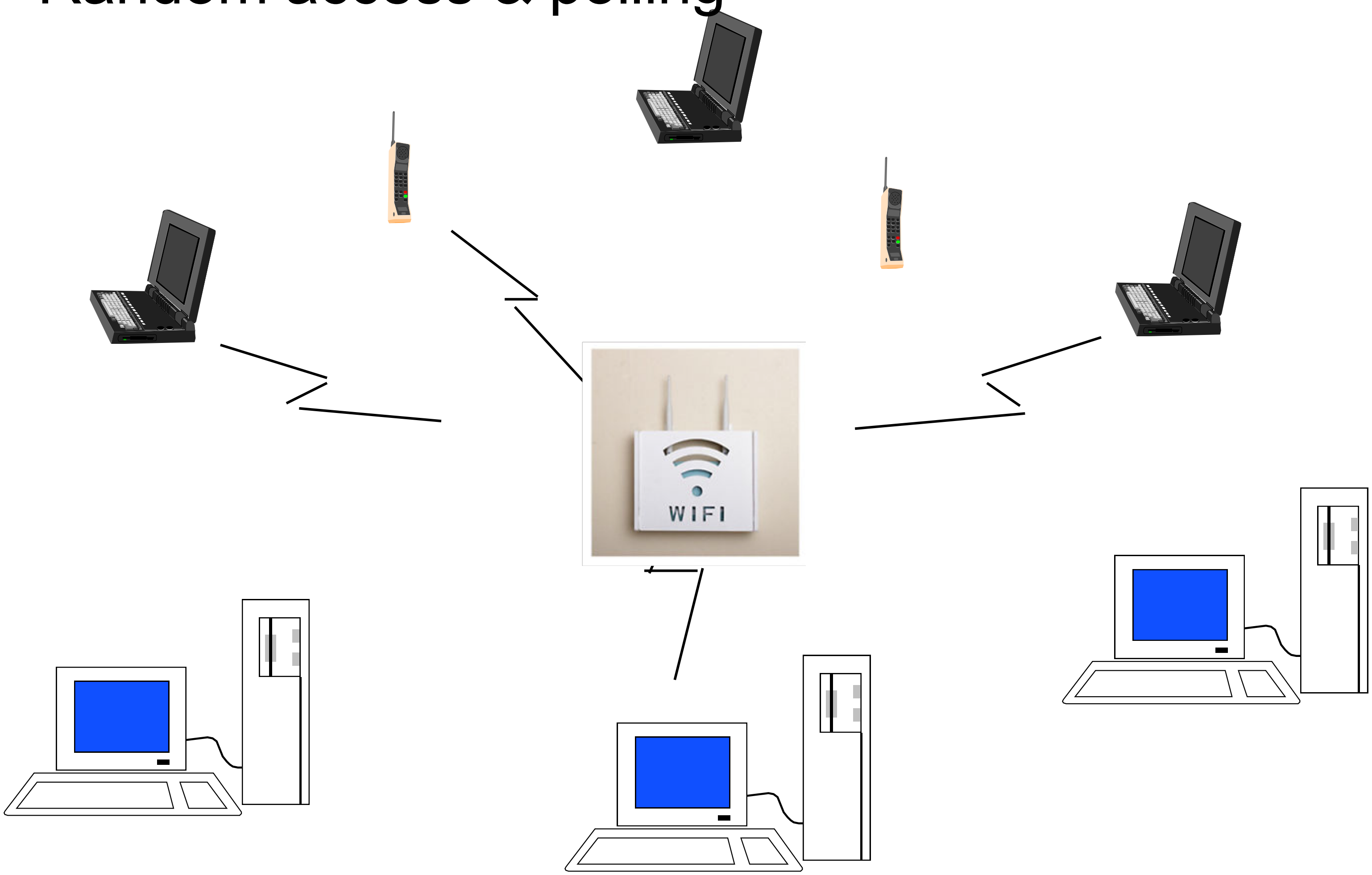


Transmit when ready

Collisions can occur; need retransmission strategy

Wireless LAN

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



Delay-Bandwidth Product

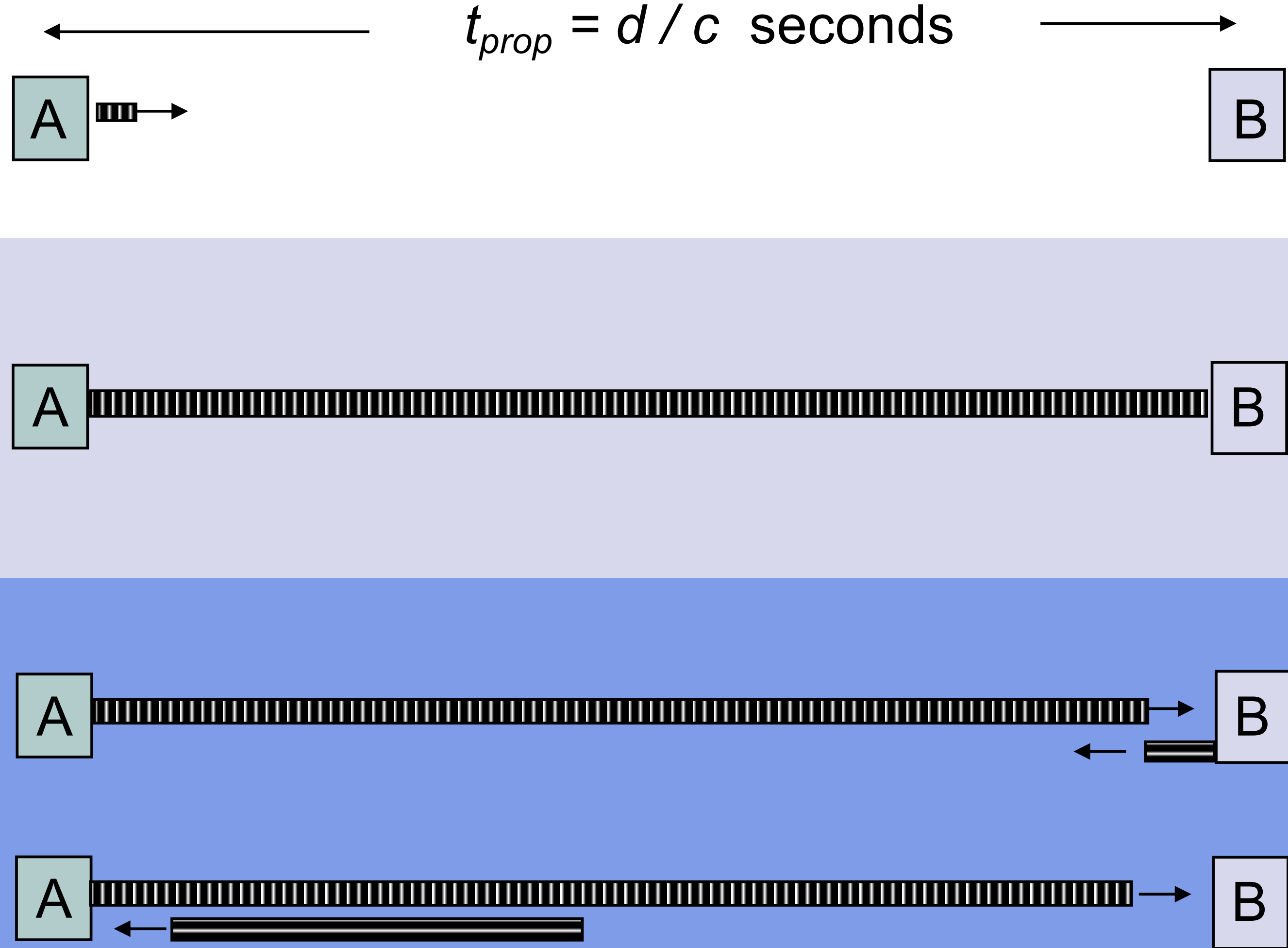
- *Delay-bandwidth product* key parameter
  - Coordination to share the medium uses bandwidth (explicitly or implicitly)
  - The larger the delay-bandwidth product, the more difficult to share the medium efficiently
- Consider a two-station example
  - Station with frame to send listens to medium and transmits if medium sensed idle
  - Station monitors medium to detect collision
  - If collision occurs, station that began transmitting earlier retransmits (propagation time is known)

Two-Station MAC Example

Two stations are trying to share a common medium

Distance *d* meters
$t_{prop} = d / c$ seconds

A transmits at $t = 0$



Case 1

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

Case 2

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

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

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

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

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

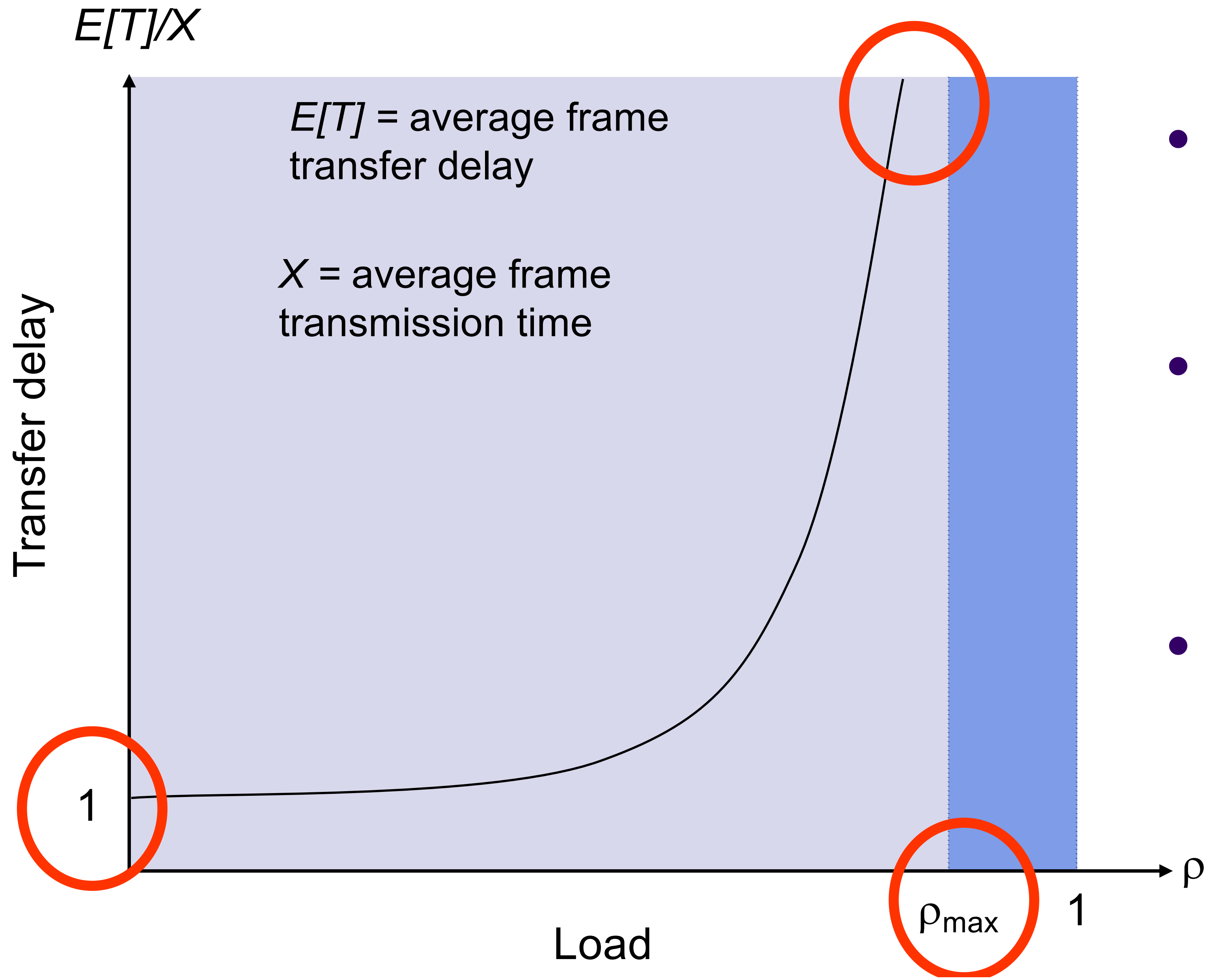
Normalized Delay-Bandwidth Product

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

Propagation delay

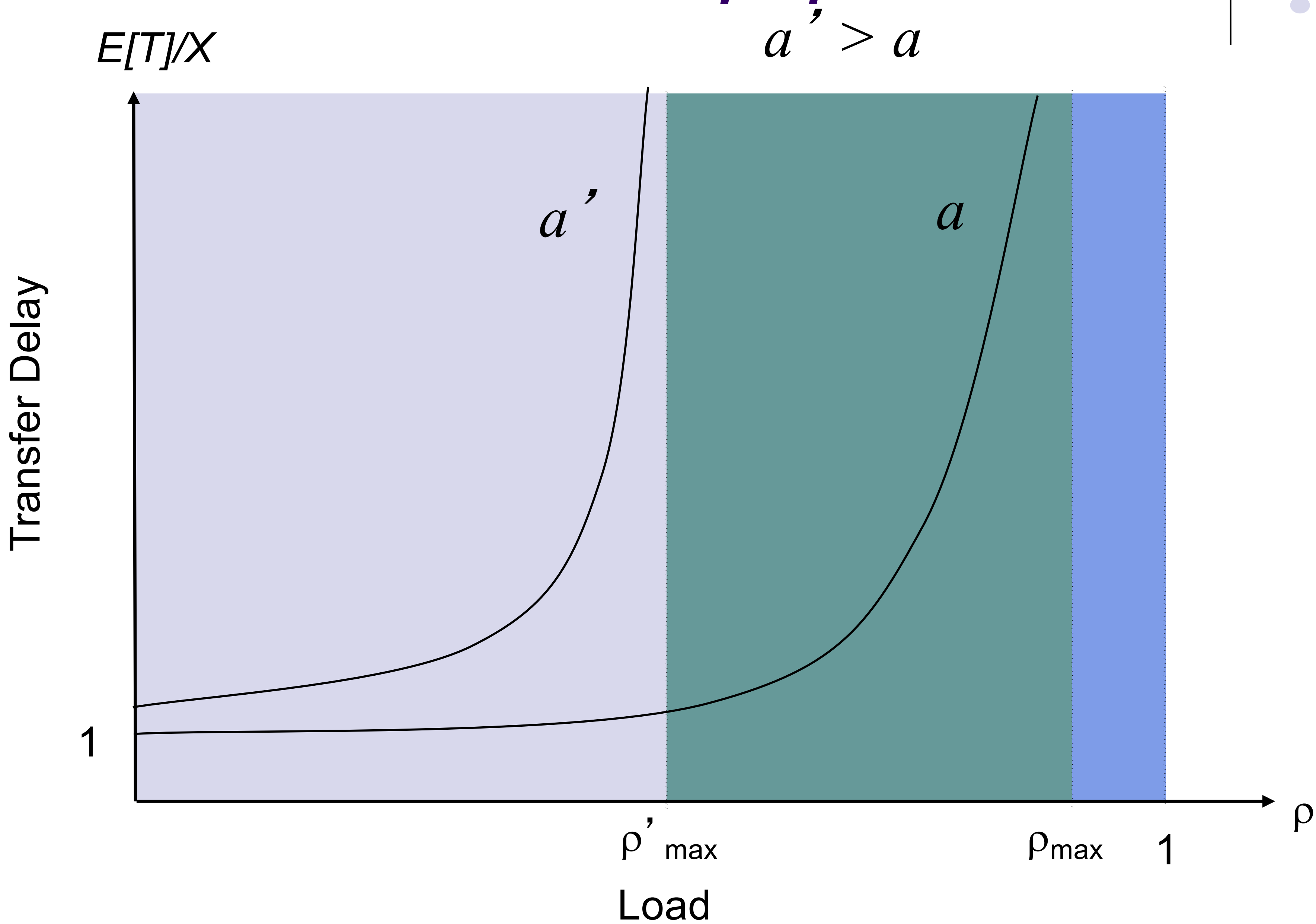
Time to transmit a frame

Normalized Delay versus Load



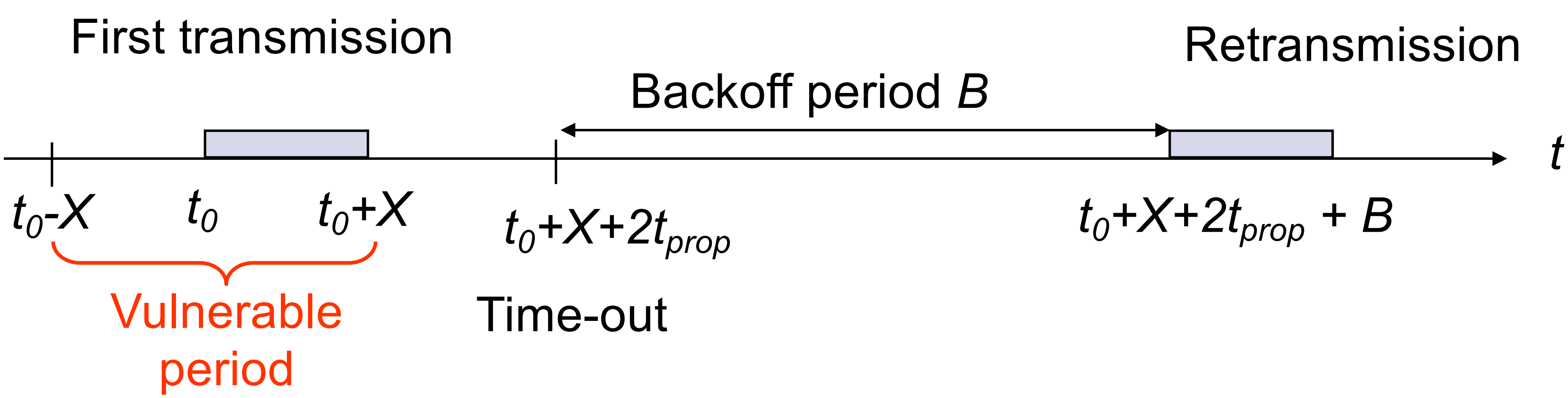
- At low arrival rate, only frame transmission time
- At high arrival rates, increasingly longer waits to access channel
- Max efficiency typically less than 100%

Dependence on Rt_{prop}/L



ALOHA

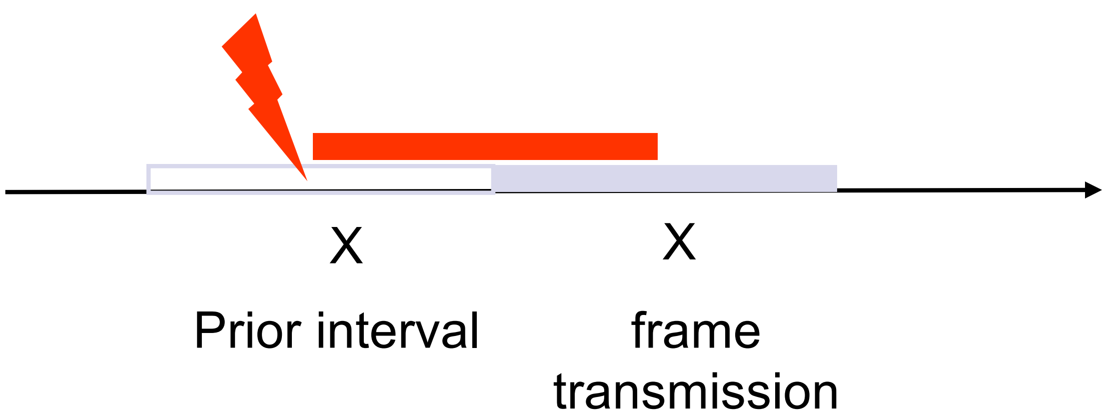
- Wireless link to provide data transfer between main campus & remote campuses of University of Hawaii
- Simplest solution: just do it
  - A station transmits whenever it has data to transmit
  - If more than one frames are transmitted, they interfere with each other (collide) and are lost
  - If ACK 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

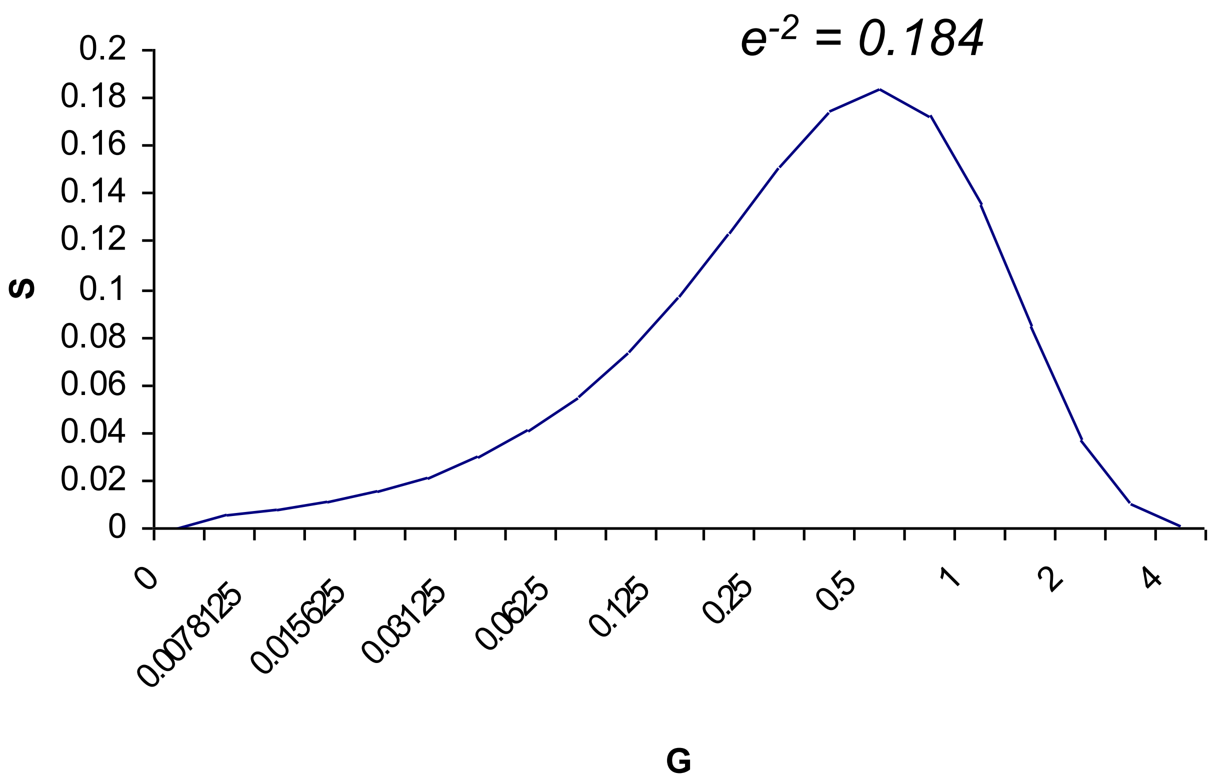
$$P_{success} = P[0 \text{ arrivals in 2X seconds}] =$$

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

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

Throughput of ALOHA

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



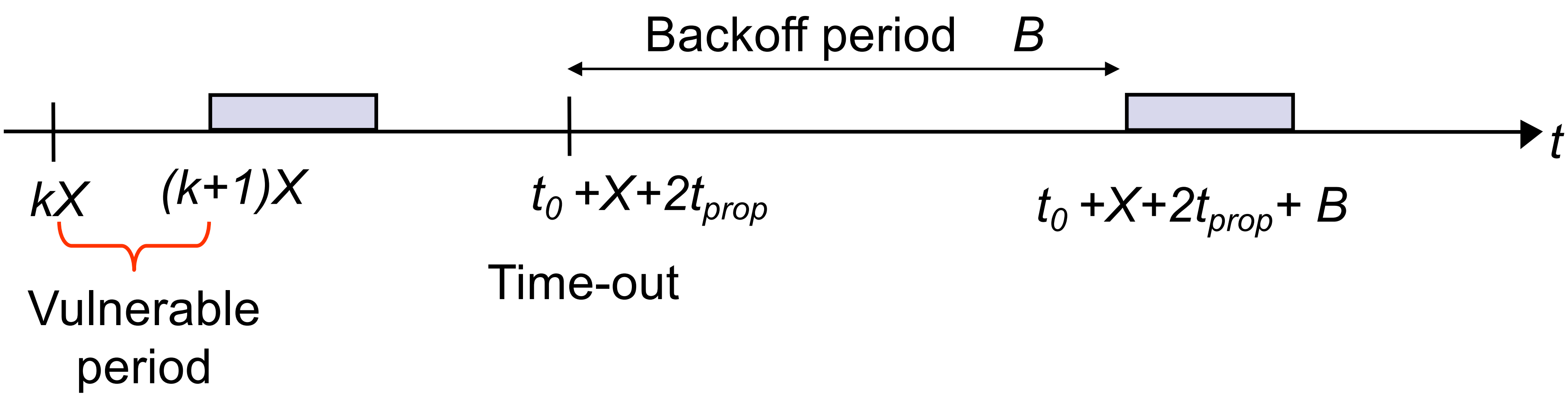
- Collisions are means for coordinating access
- Max throughput is ρ_{max}= 1/2*e (18.4%)*
- Bimodal behavior:

  Small G, S≈G

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

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



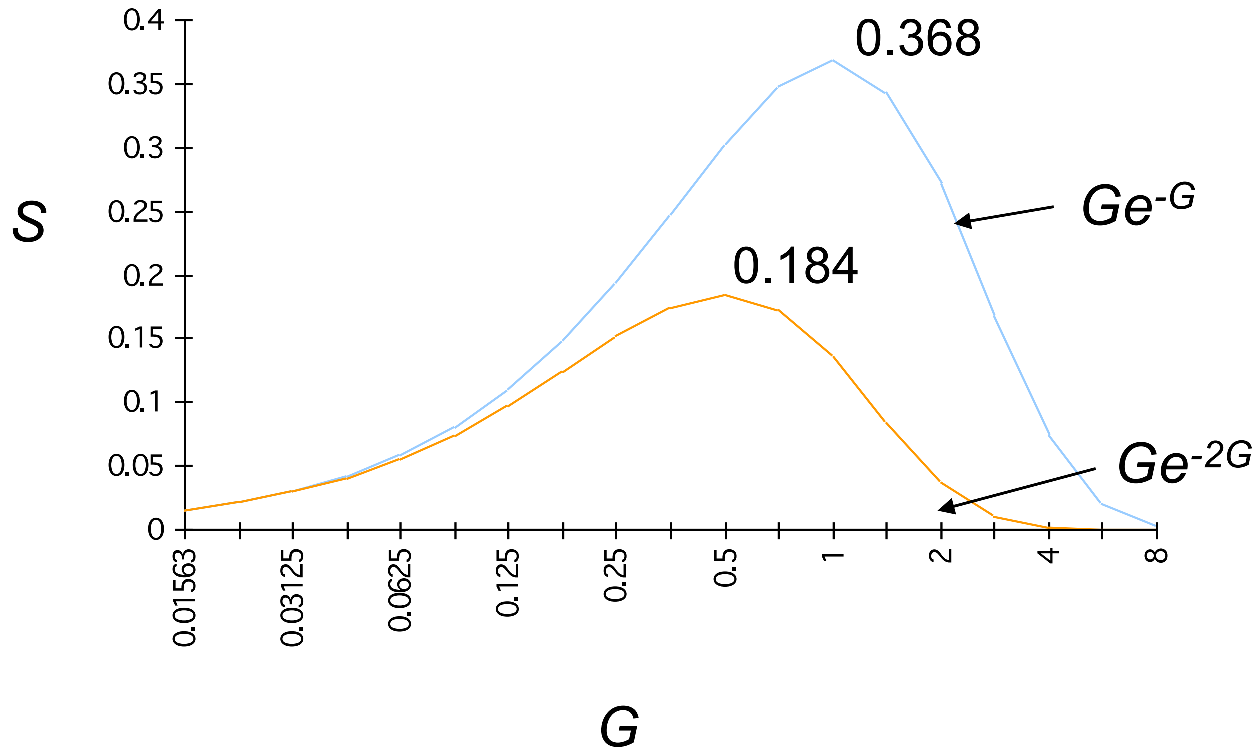
Only frames that arrive during prior X seconds collide

Throughput of Slotted ALOHA

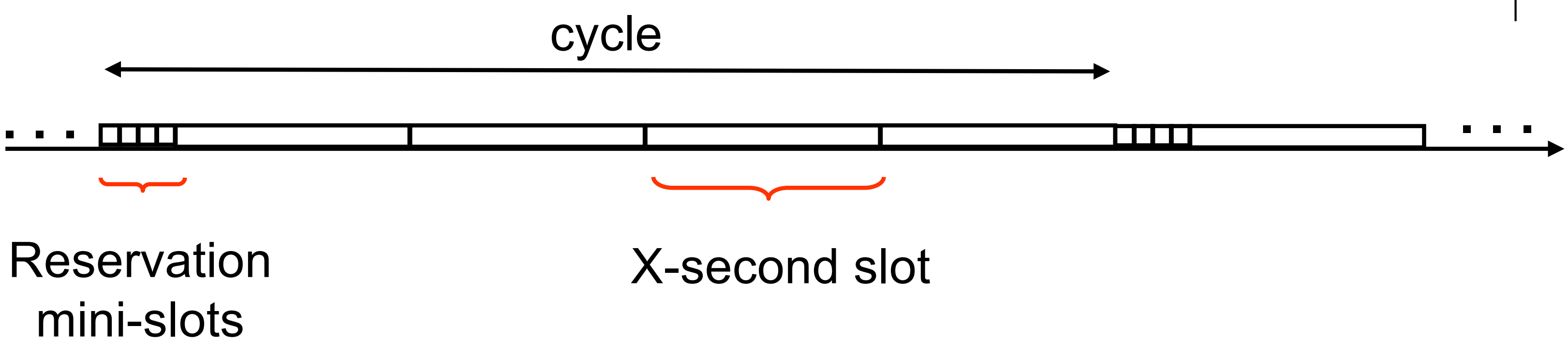
$$S = GP_{success} = GP[\text{no arrivals in X seconds}]$$

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

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



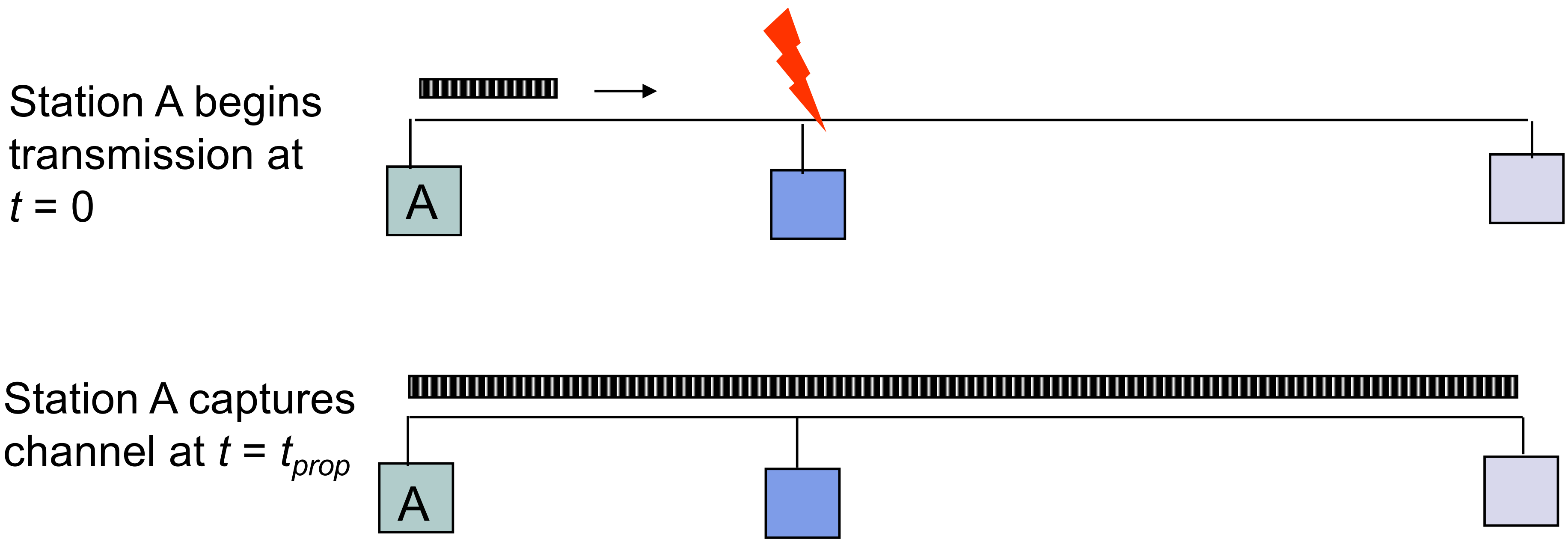
Application of Slotted Aloha



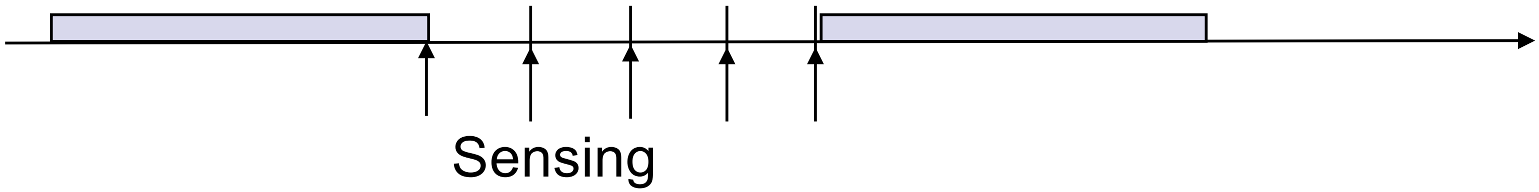
- Reservation protocol allows a large number of stations with infrequent traffic to reserve slots to transmit their frames in future cycles
- Each cycle has mini-slots allocated for making reservations
- Stations use slotted Aloha during mini-slots to request slots

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

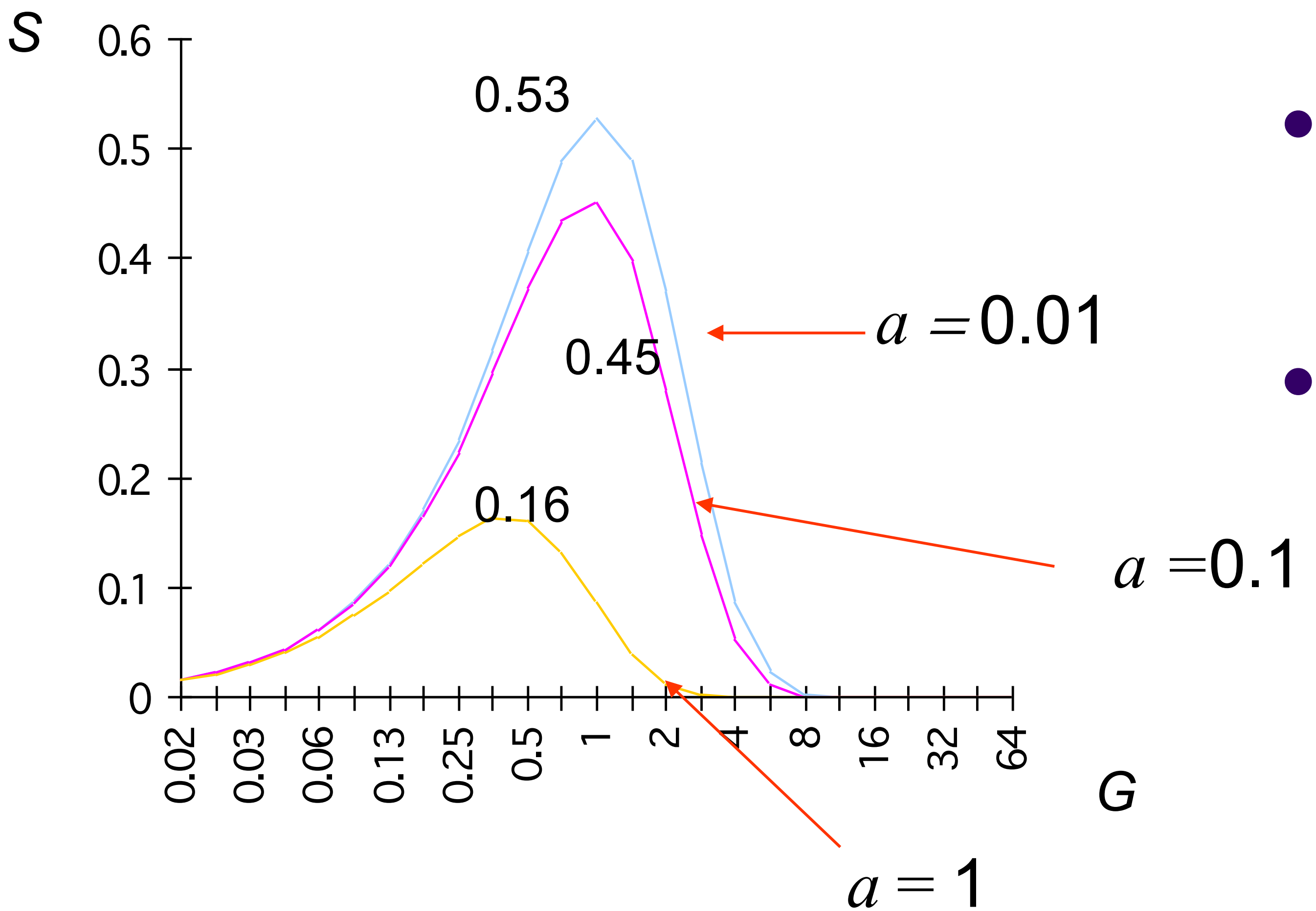


CSMA Options



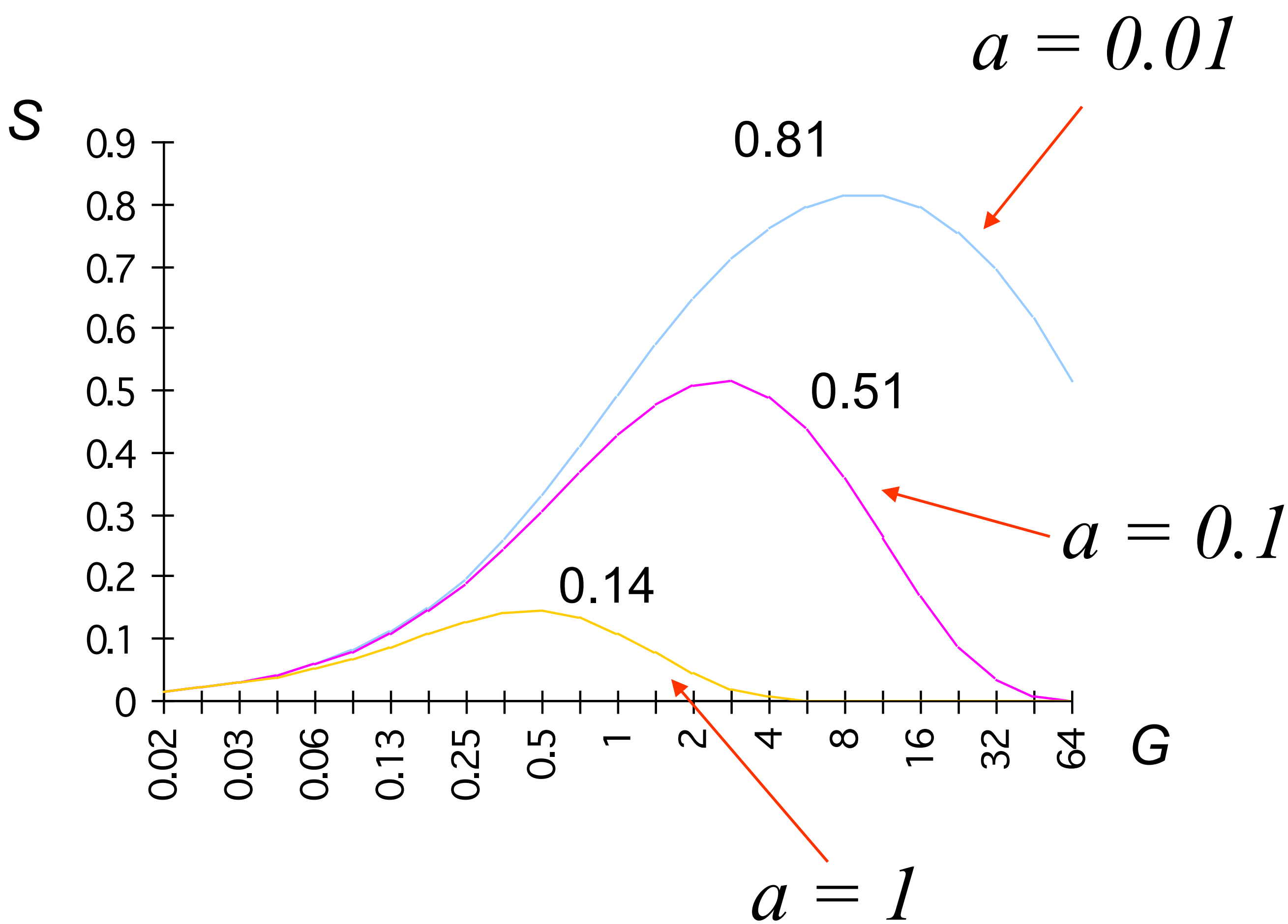
- Transmitter behavior when busy channel is sensed
  - 1-persistent CSMA (most greedy, aggressive)
    - Sense every slot until slot becomes idle, then transmit
    - Lower delay and lower efficiency
  - Non-persistent CSMA (least greedy, timid)
    - Sense slot, if busy then schedule a backoff period
    - If sense idle slot, transmit
    - Higher delay and higher efficiency
  - p-persistent CSMA (flip coin to spread transmissions)
    - Sense channel until it becomes idle, transmit with prob. p; or wait one mini-slot time & re-sense with probability 1-*p*
    - Delay and efficiency can be balanced by choice of p

1-Persistent CSMA Throughput



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

Non-Persistent CSMA Throughput

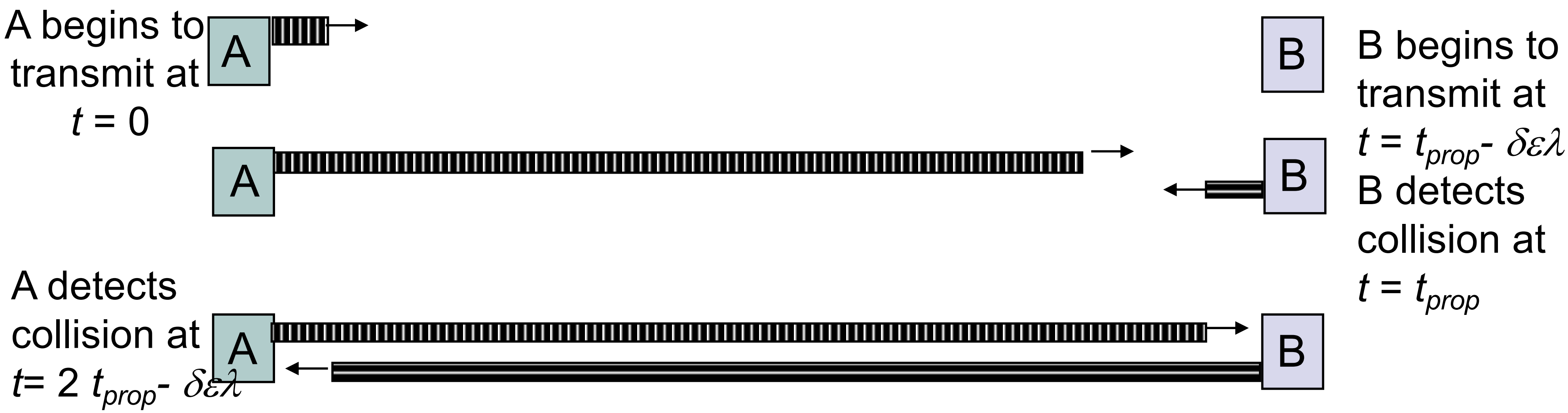


- Higher maximum throughput than 1-persistent for small a
- Worse than Aloha for $a > 1$

CSMA with Collision Detection (CSMA/CD)

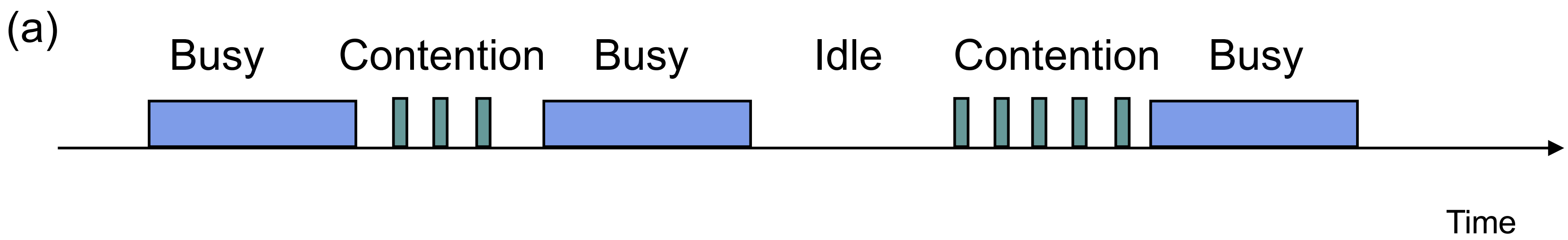
- Monitor for collisions & abort transmission
  - Stations with frames to send, first do carrier sensing
  - After beginning a transmission, a station continues listening to the medium to detect collisions
  - If a collision is detected, all stations involved stop their transmission, reschedule random backoff times, and try again at scheduled times
- CSMA collisions waste X seconds transmitting the entire frame
- CSMA-CD reduces wastage to time to detect collision and abort transmissions

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 and resolved in $2t_{prop}$
  - Time slots are $2t_{prop}$ seconds during contention periods
  - A busy station transmits with prob. p in each time slot
  - Contention ends when exactly one station transmits
  - The successful station captures the channel and transmits a frame (which takes X seconds)
  - 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:

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

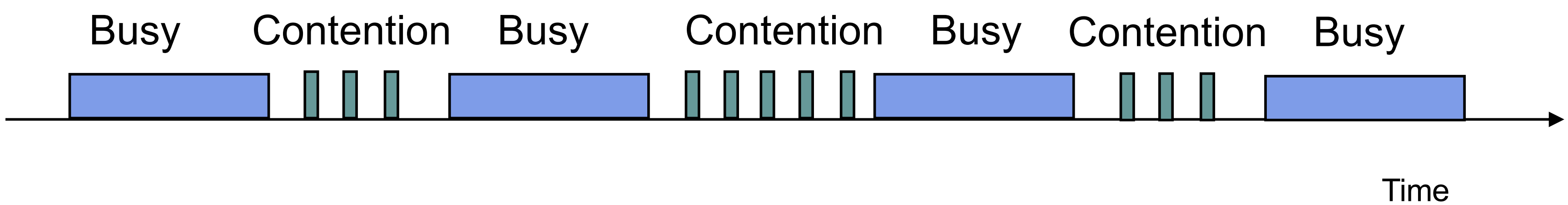
- By taking derivative of $P_{success}$ we find max occurs at p=1/n

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

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

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

CSMA/CD Throughput



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

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

- where:

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

  $a = t_{prop}/X$

  ν meters/sec. speed of light in medium

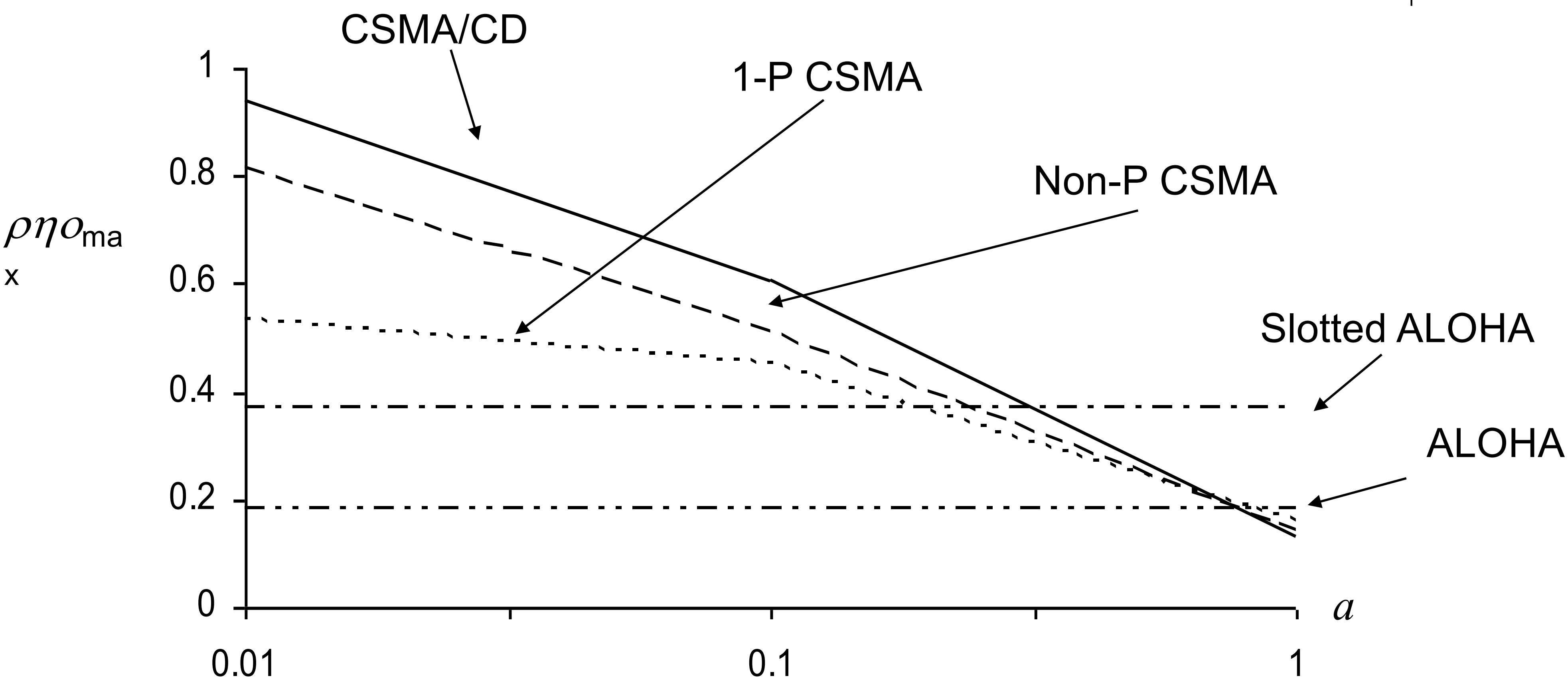
  d meters is diameter of system

  $2e+1 = 6.44$

CSMA-CD Application: Ethernet

- First Ethernet LAN standard used CSMA-CD
  - 1-persistent Carrier Sensing
  - R = 10 Mbps
  - t_{prop} = 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

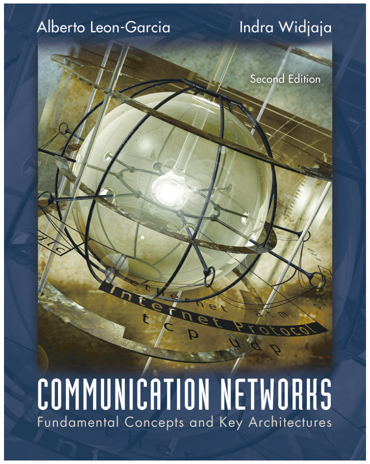


- For small a: CSMA-CD has best throughput
- For larger a: Aloha & slotted Aloha better throughput

Carrier Sensing and Priority Transmission

- Some 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 (WIFI)

Chapter 6
Local Area Networks



pp. 349-351

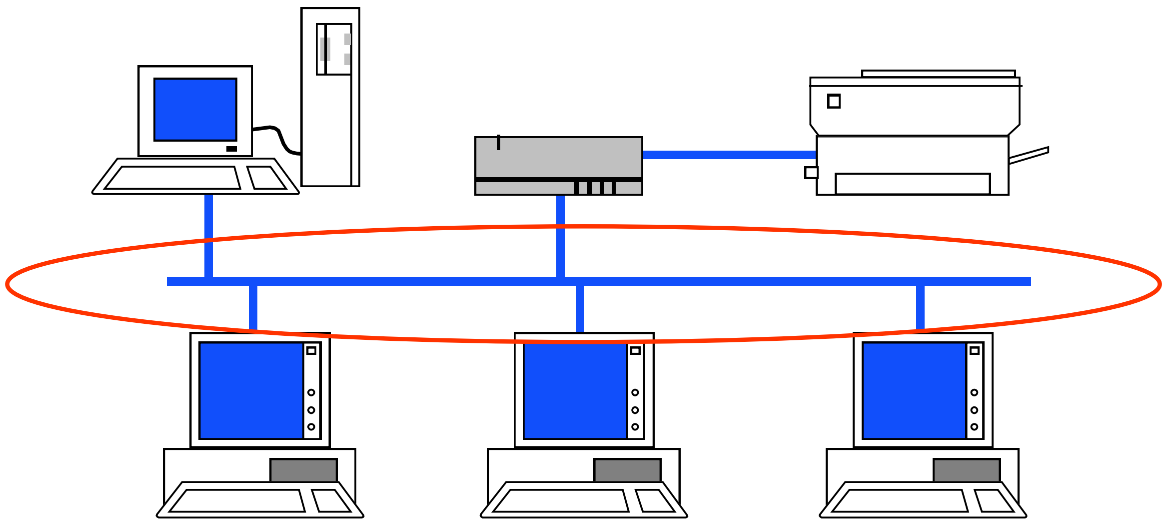
(details of LLC not covered)

What is a LAN?

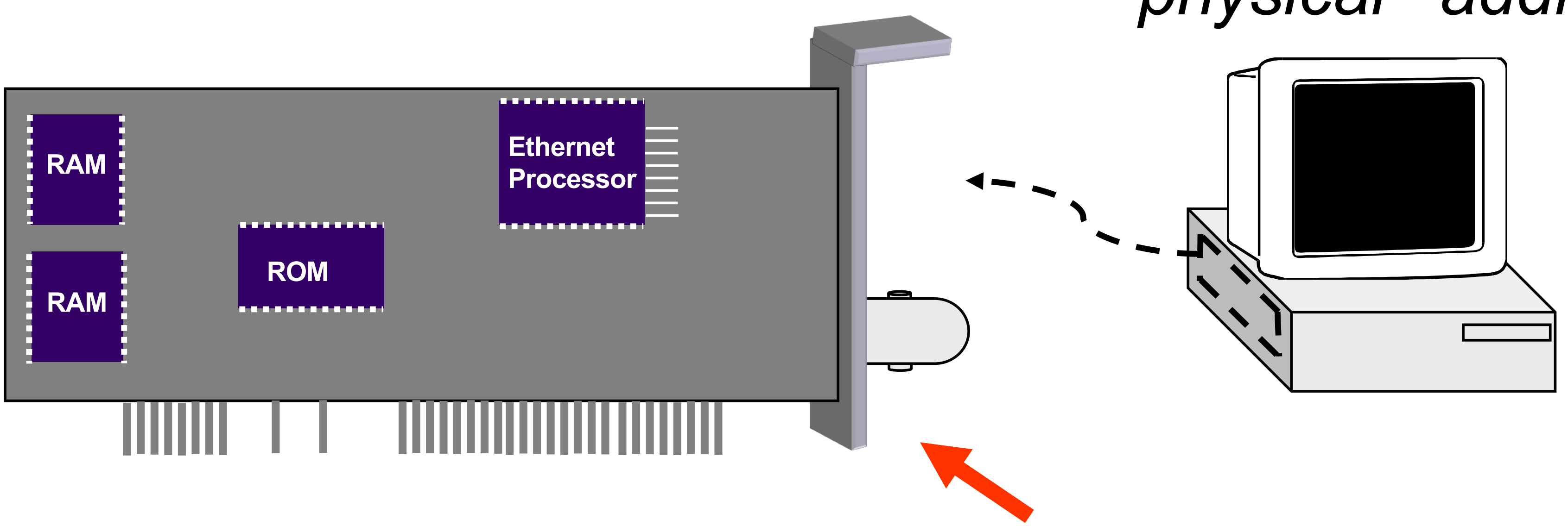
Local area (usually) means:

- Private ownership
  - Free from regulatory constraints of Wide Area Networks
- 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*

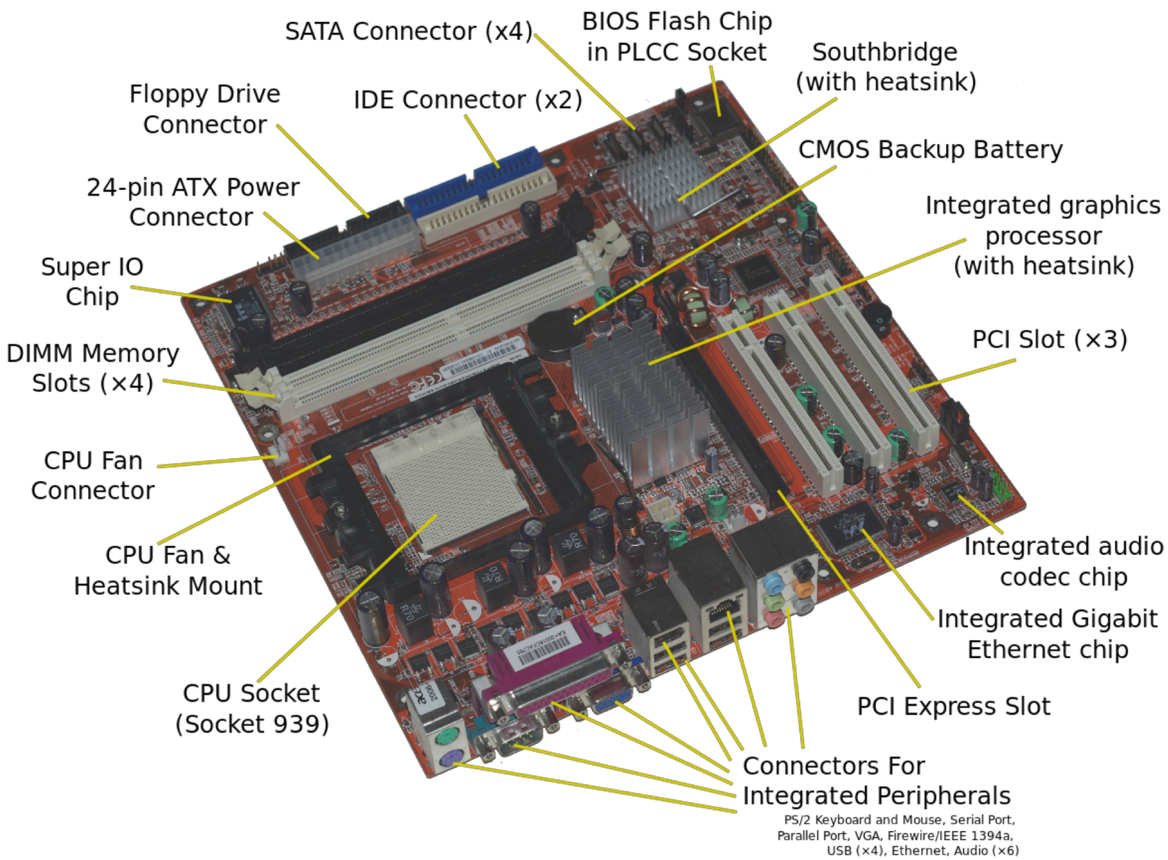
Old LAN Structure



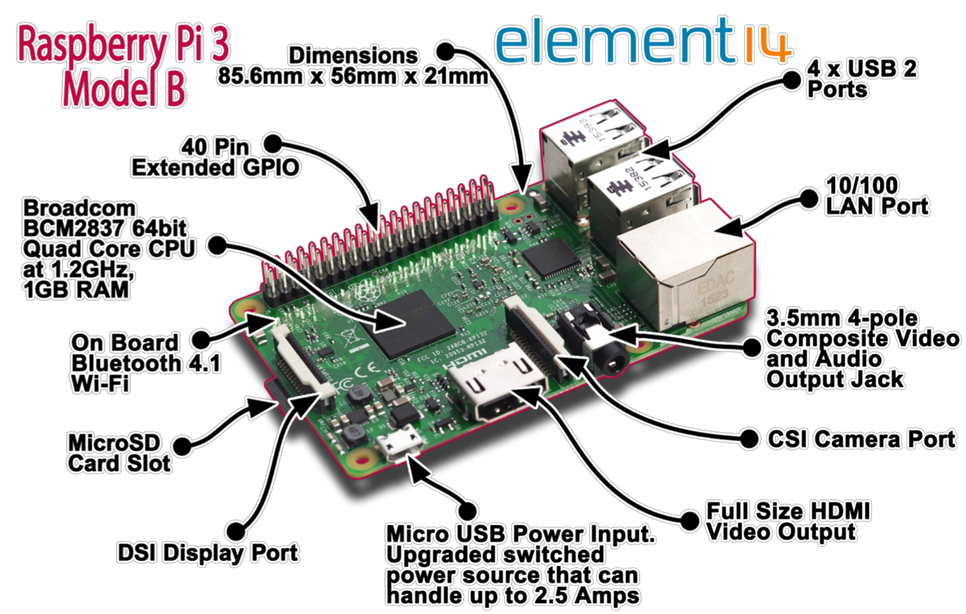
- Transmission Medium
- Network Interface Card (NIC)
- *Unique MAC "physical" address*



Acer Desktop ~2007



Raspberry Pi ~2017

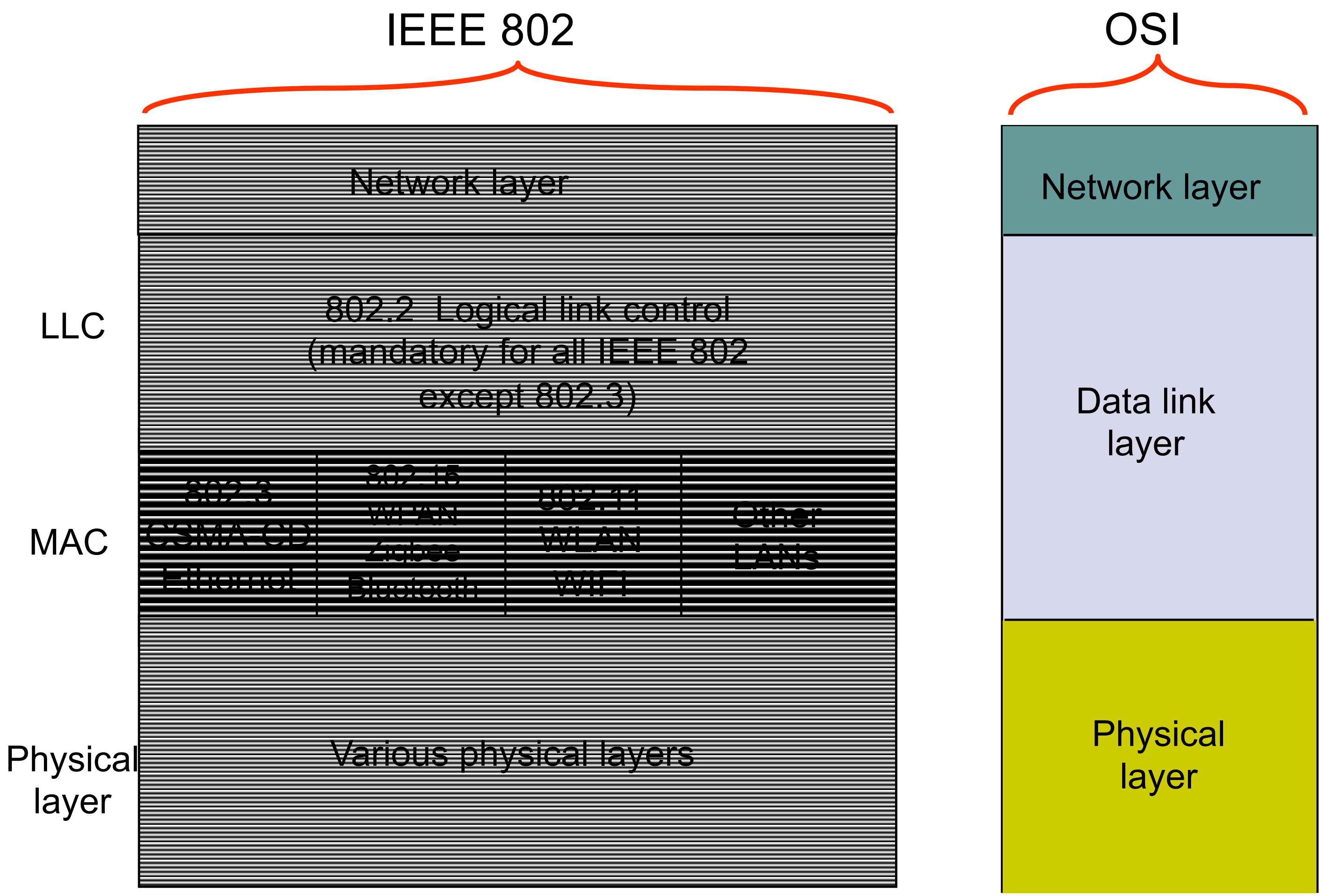


Medium Access Control Sublayer

- In IEEE 802.1, Data Link Layer divided into:

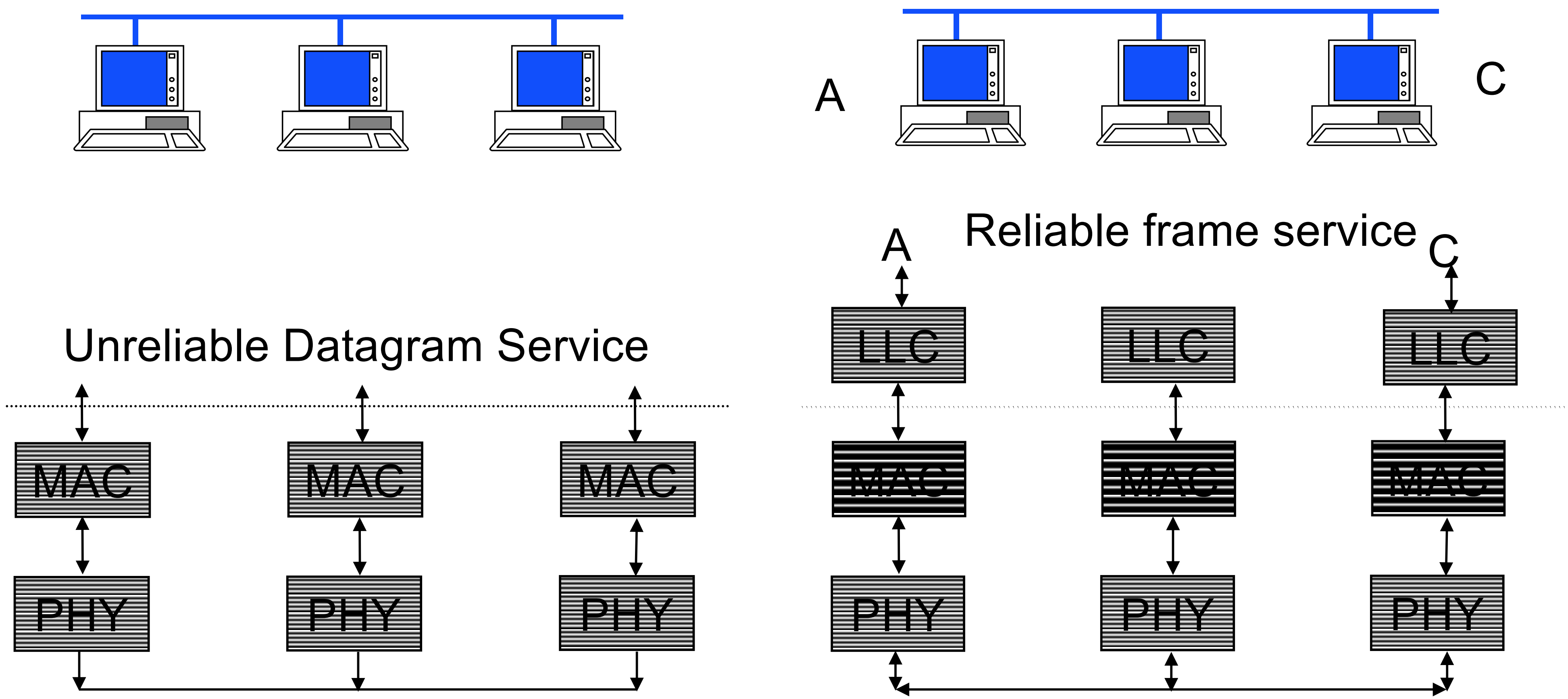
1. Medium Access Control Sublayer
   - Coordinate access to medium
   - Connectionless frame transfer service
   - Machines identified by MAC/physical address
   - Broadcast frames with MAC addresses
2. Logical Link Control Sublayer
   - Between Network layer & MAC sublayer

MAC Sub-layer

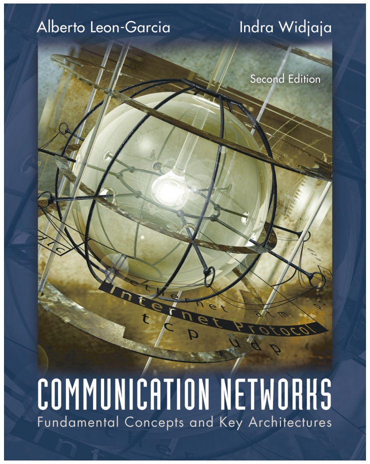


Logical Link Control Layer

- IEEE 802.2: LLC enhances service provided by MAC
- Requires additional sublayer encapsulation



Chapter 6
Ethernet

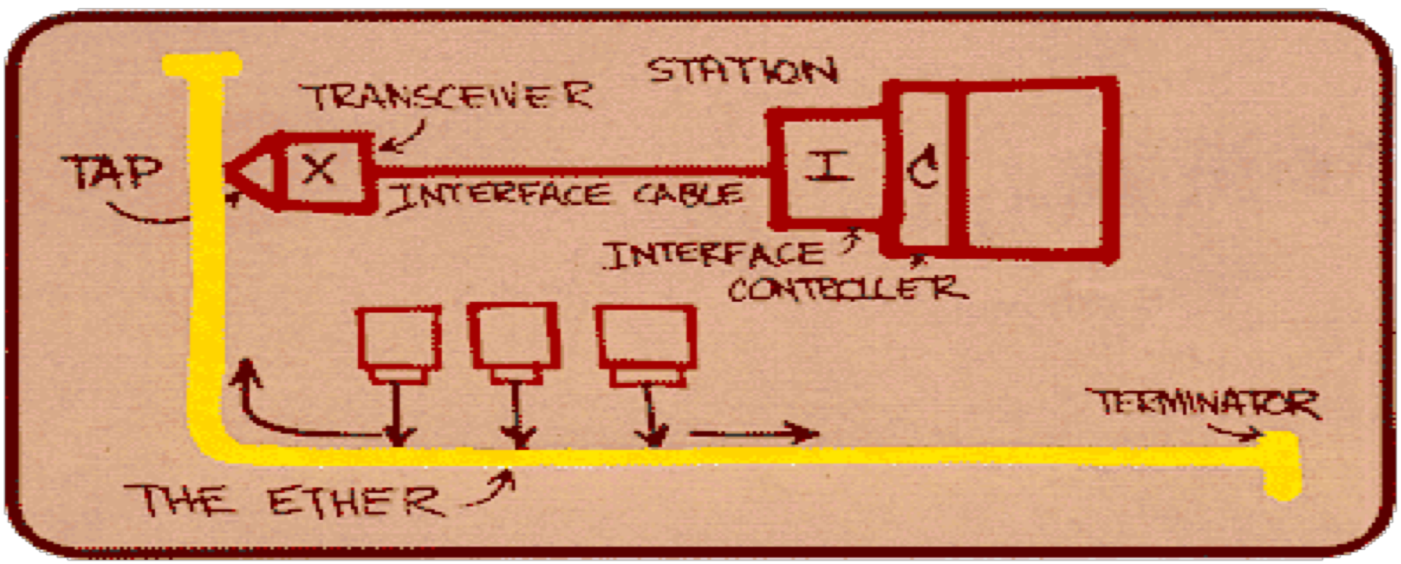


pp. 398-408

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- 10/100/400 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
    - time to acquire channel
    - 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 μιχροsec
  - 51.2 μιχροsec 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*

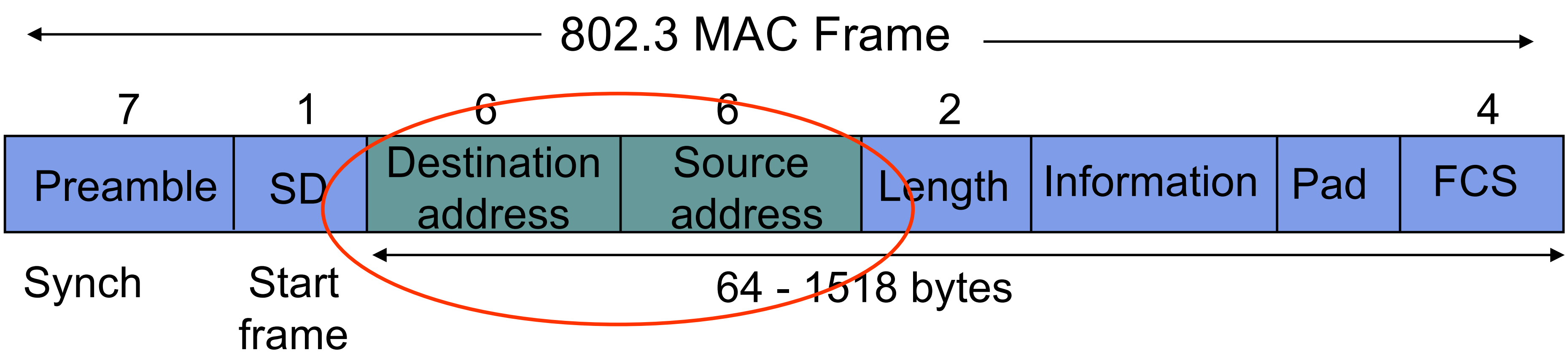
IEEE 802.3 MAC Frame

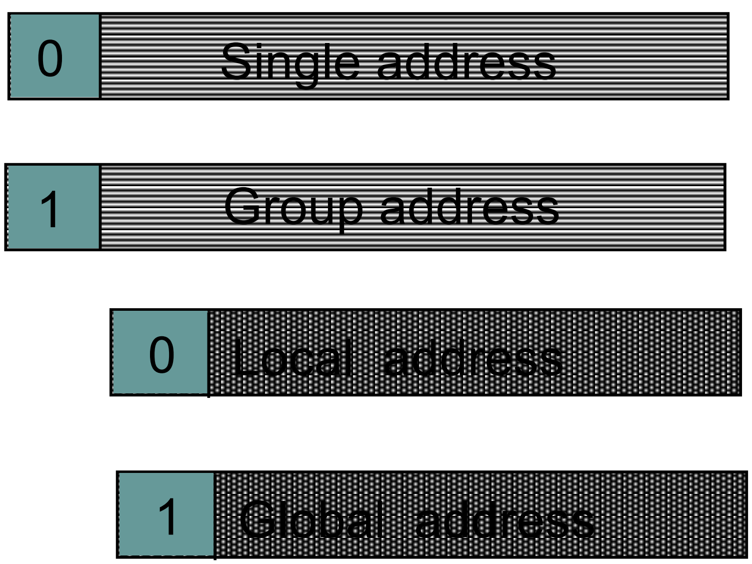
802.3 MAC Frame

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

- 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

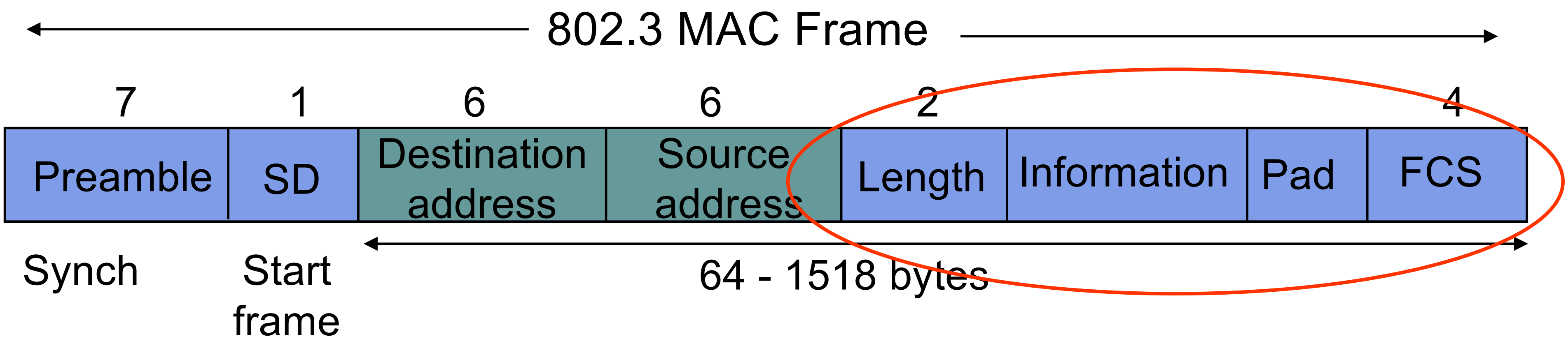




- Destination address
  - single address
  - group address
  - broadcast = 111...111

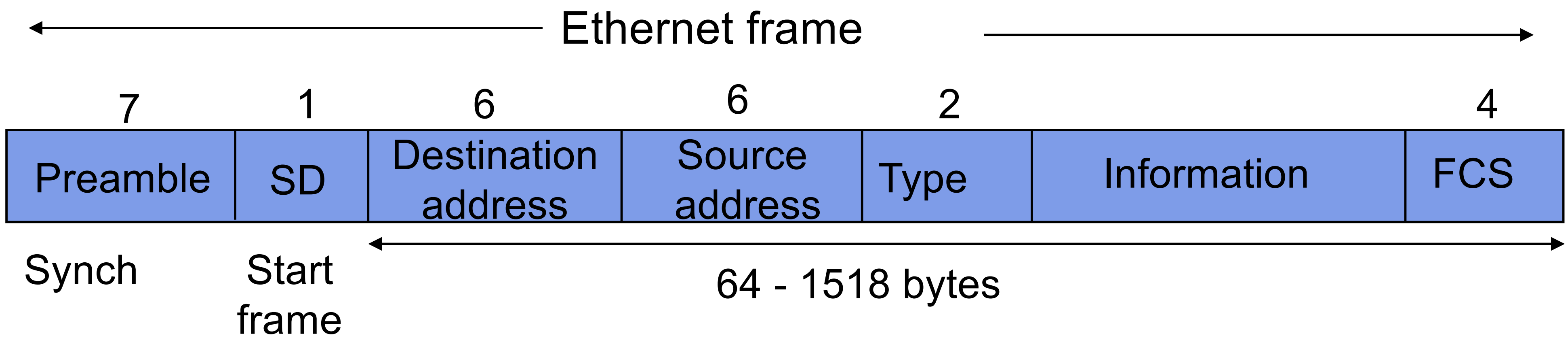
Addresses
  - local or global
- Global addresses
  - first 24 bits assigned to manufacturer;
  - next 24 bits assigned by manufacturer
  - Cisco 00-00-0C
  - 3COM 02-60-8C

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



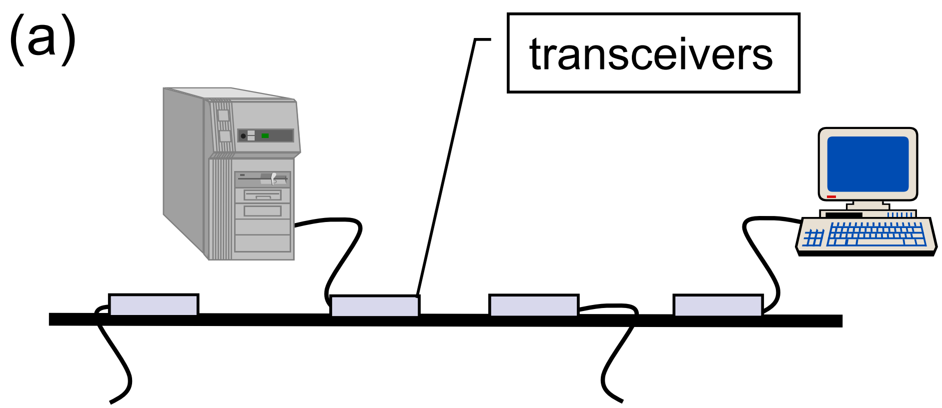
- DIX: Digital, Intel, Xerox joint Ethernet specification
- Type Field: to identify protocol of PDU in information field, e.g. IP, ARP
- Framing: How does receiver know frame length?
  - physical layer signal, byte count, FCS
- IEEE 802.3 allows Ethernet II Frames without LLC

IEEE 802.3 Physical Layer

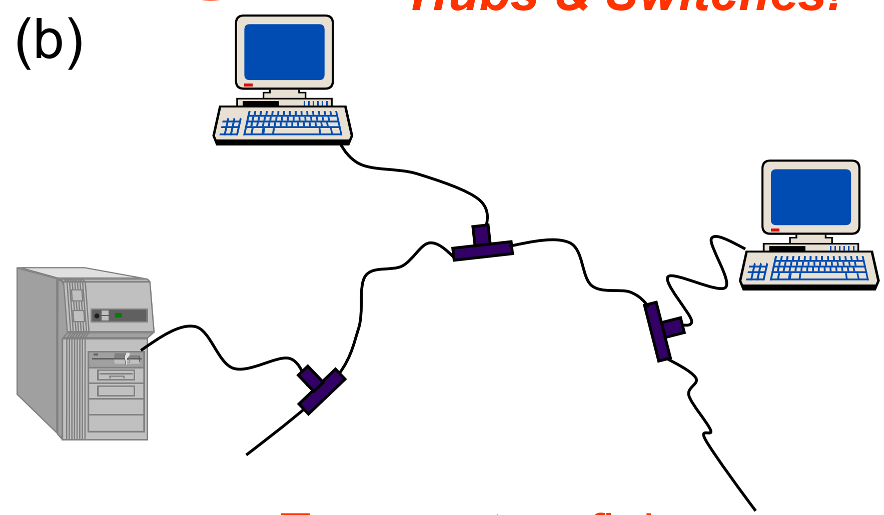
Table 6.2 IEEE 802.3 10 Mbps medium alternatives

	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!

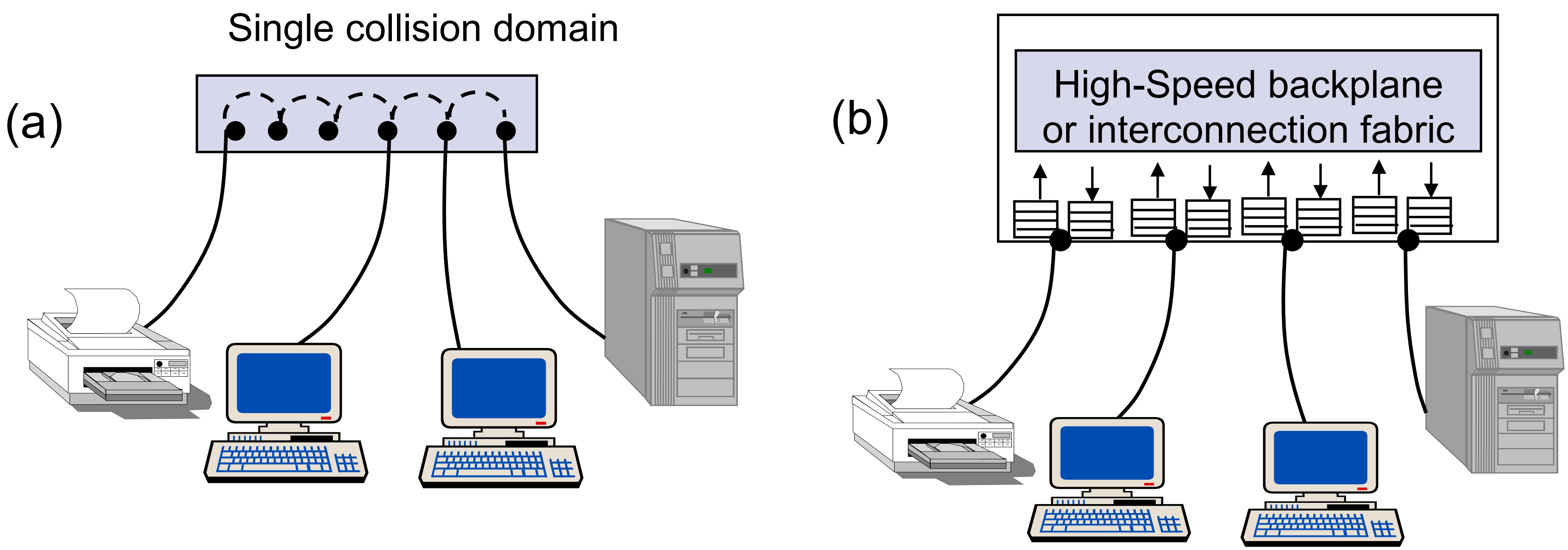


Thick Coax: Stiff, hard to work with



T connectors flaky

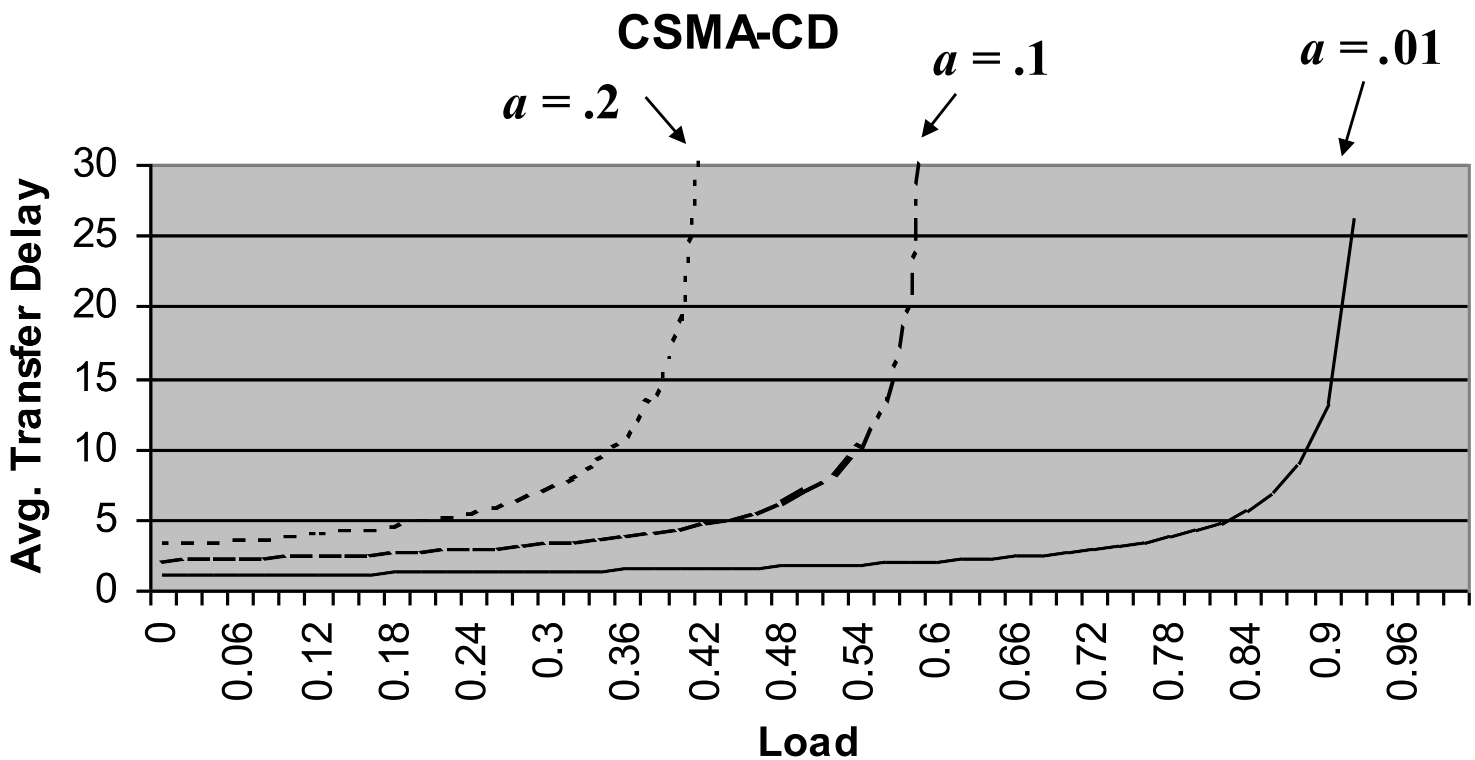
Ethernet Hubs & Switches



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

- Twisted Pair to Bridge or Switch
- Bridging increases scalability
- Separate collision domains
- Full duplex operation eliminates collisions

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)

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

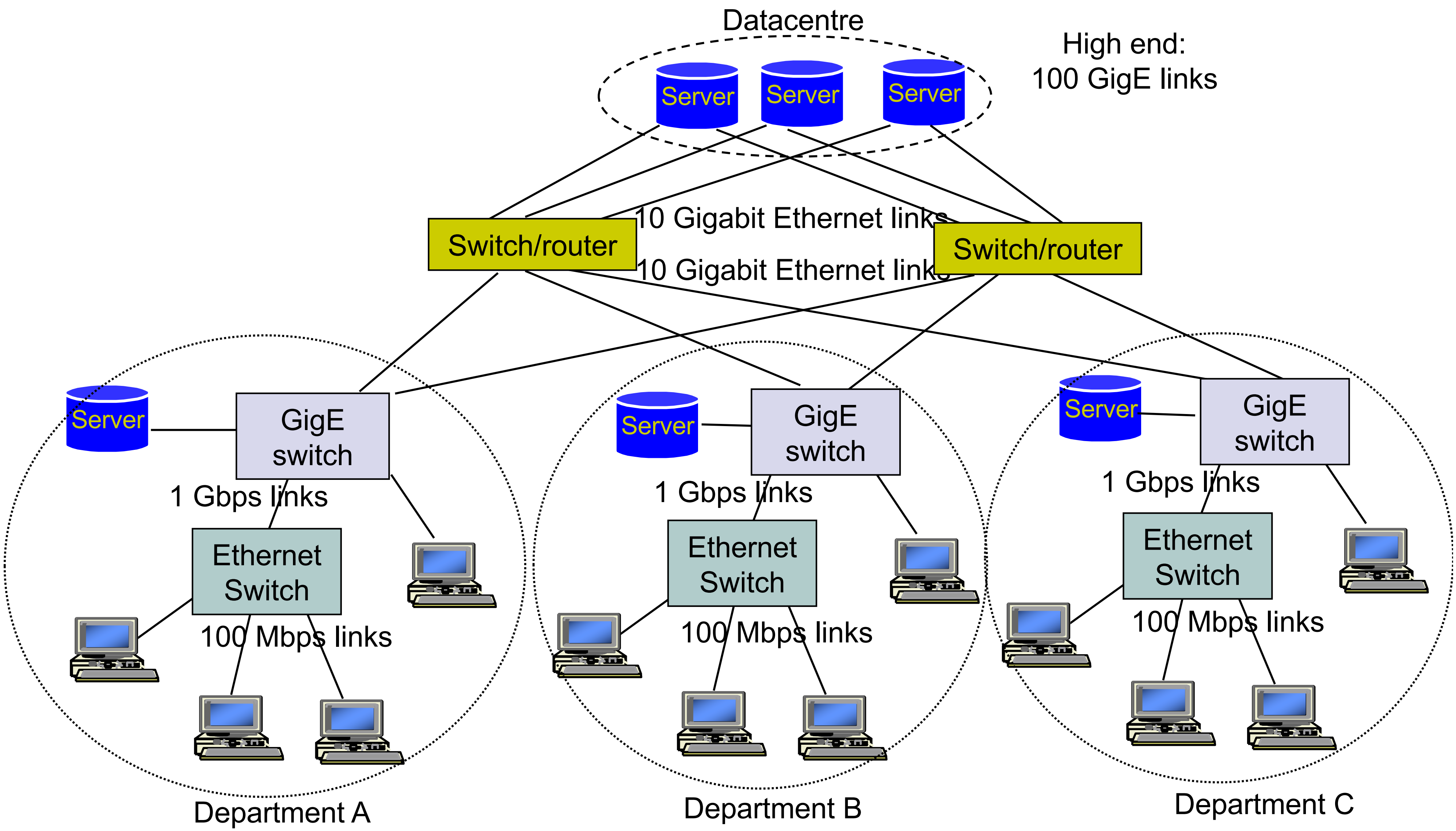
10 Gigabit Ethernet

Table 6.5 IEEE 802.3 10 Gbps Ethernet medium alternatives

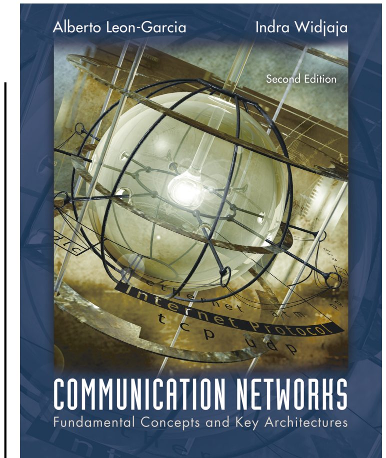
	10GbaseSR	10GBaseLR	10GbaseEW	10GbaseLX4
Medium	Two optical fibers Multimode at 850 nm 64B66B code	Two optical fibers Single-mode at 1310 nm 64B66B	Two optical fibers Single-mode at 1550 nm SONET compatibility	Two optical fibers multimode/single-mode with four wavelengths at 1310 nm band 8B10B code
Max. 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
Local Area Networks



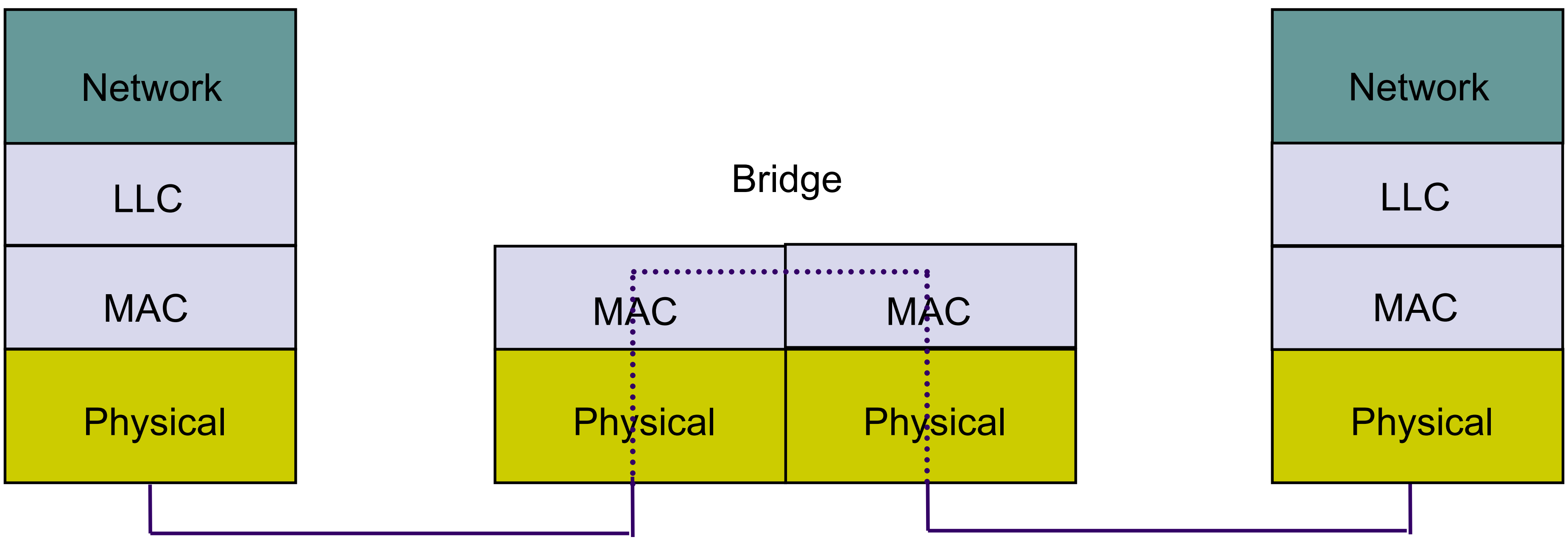
LAN Bridges

pp 437-445

Tagged VLANs

Wikipedia: IEEE 802.1Q

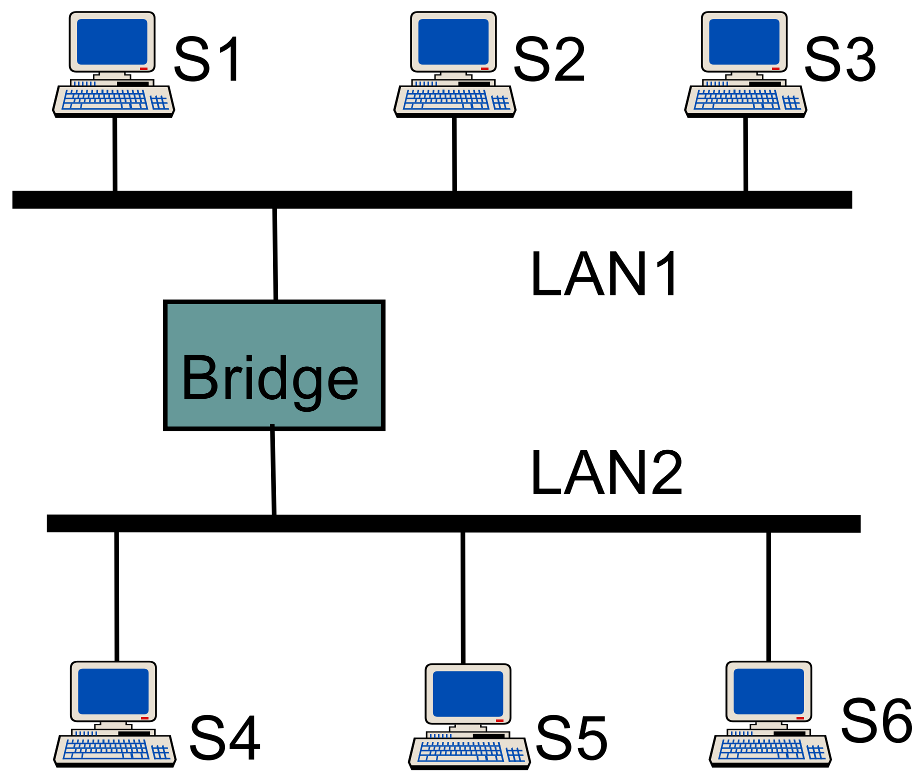
Bridges

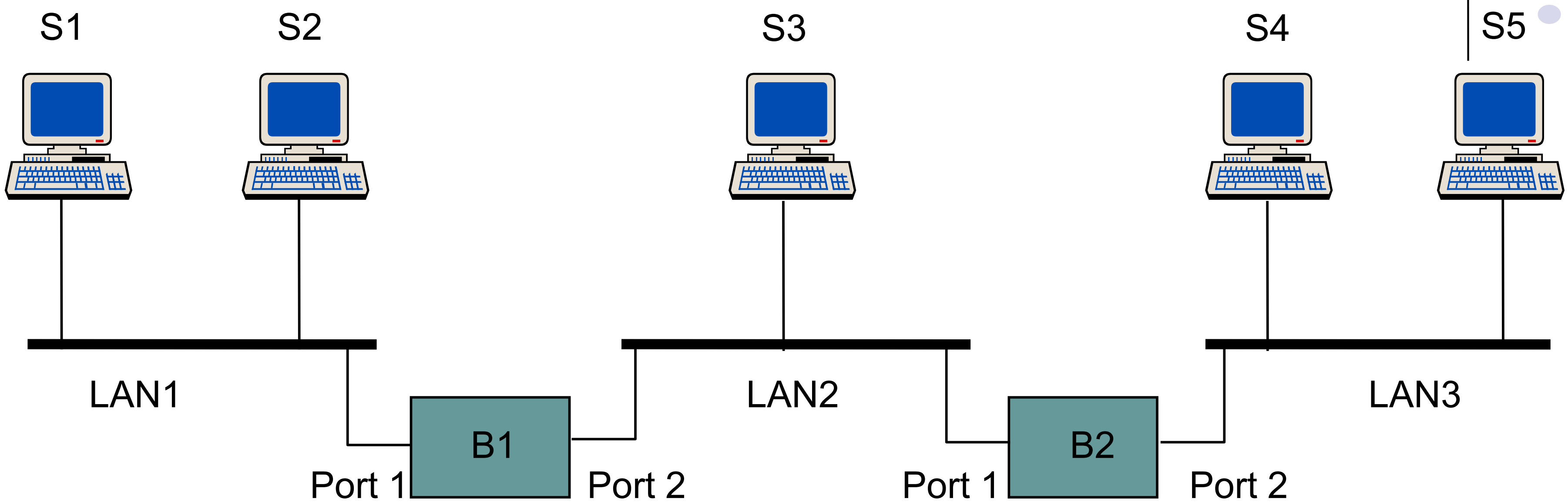


- Exchange of frames between LANs
- Bridging is done at MAC level
- Common case involves LANs of same type

Transparent Bridges

- Interconnection of IEEE LANs with complete transparency
- Use table lookup for each frame:
  - 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

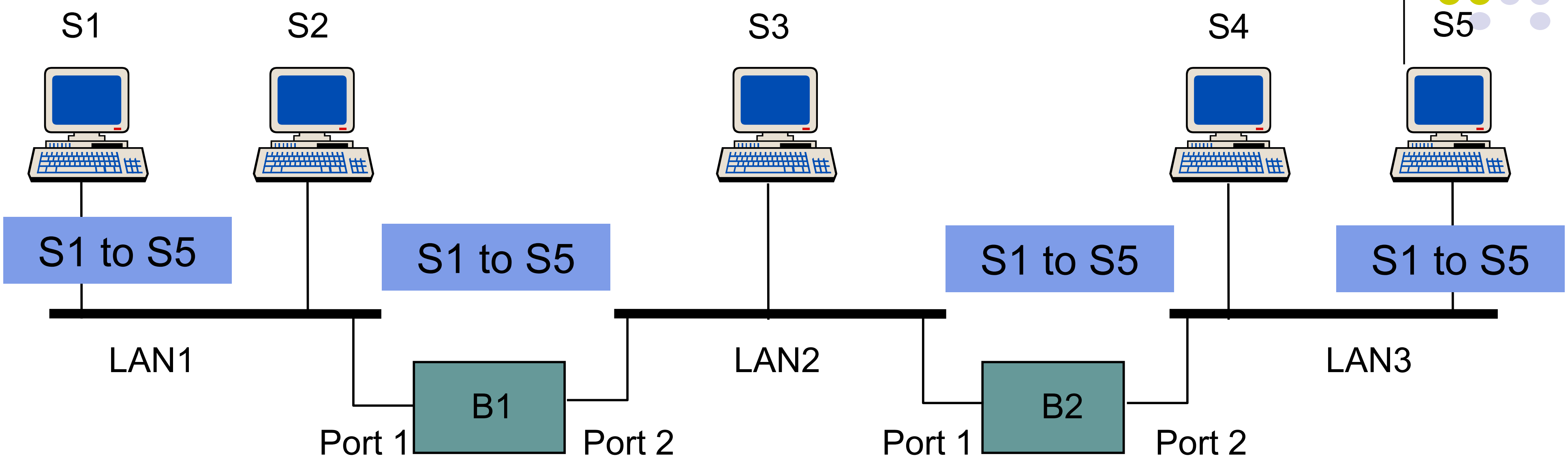




Address	Port

Address	Port

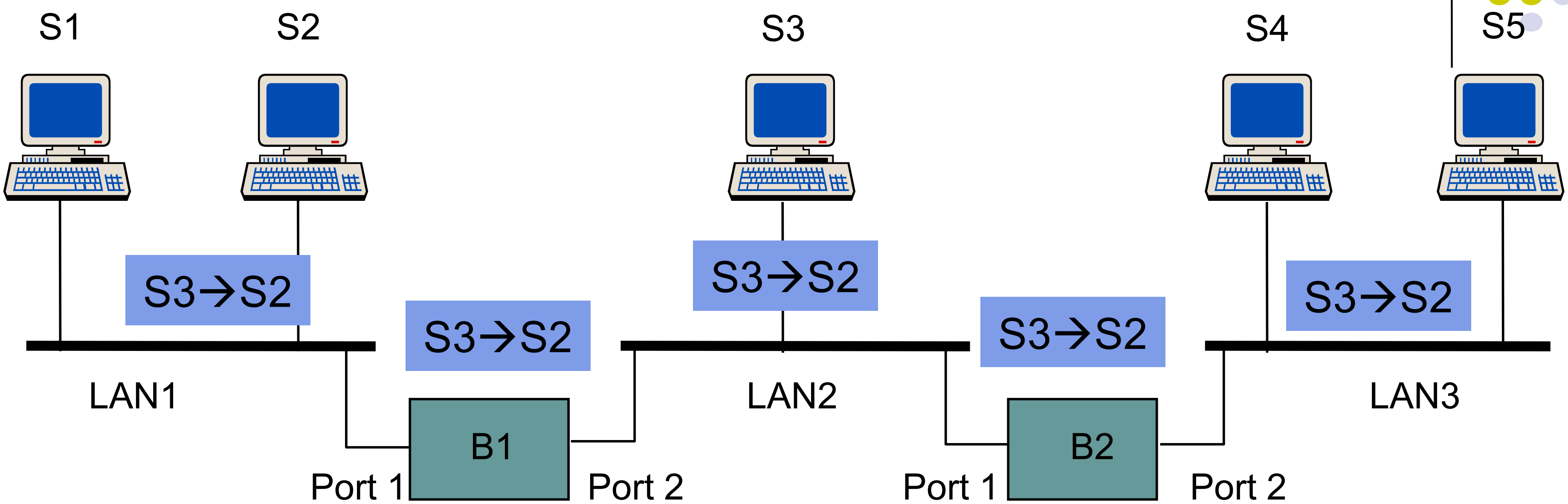
S1→S5



Address	Port
S1	1

Address	Port
S1	1

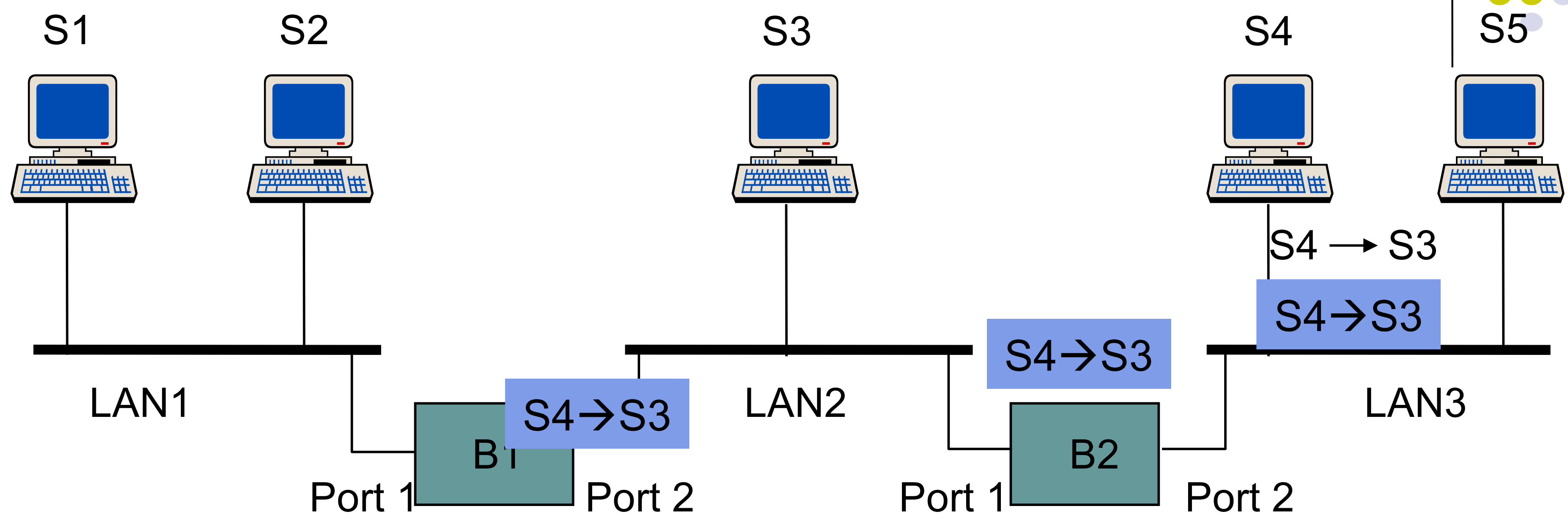
S3→S2



Address	Port
S1	1
S3	2

Address	Port
S1	1
S3	1

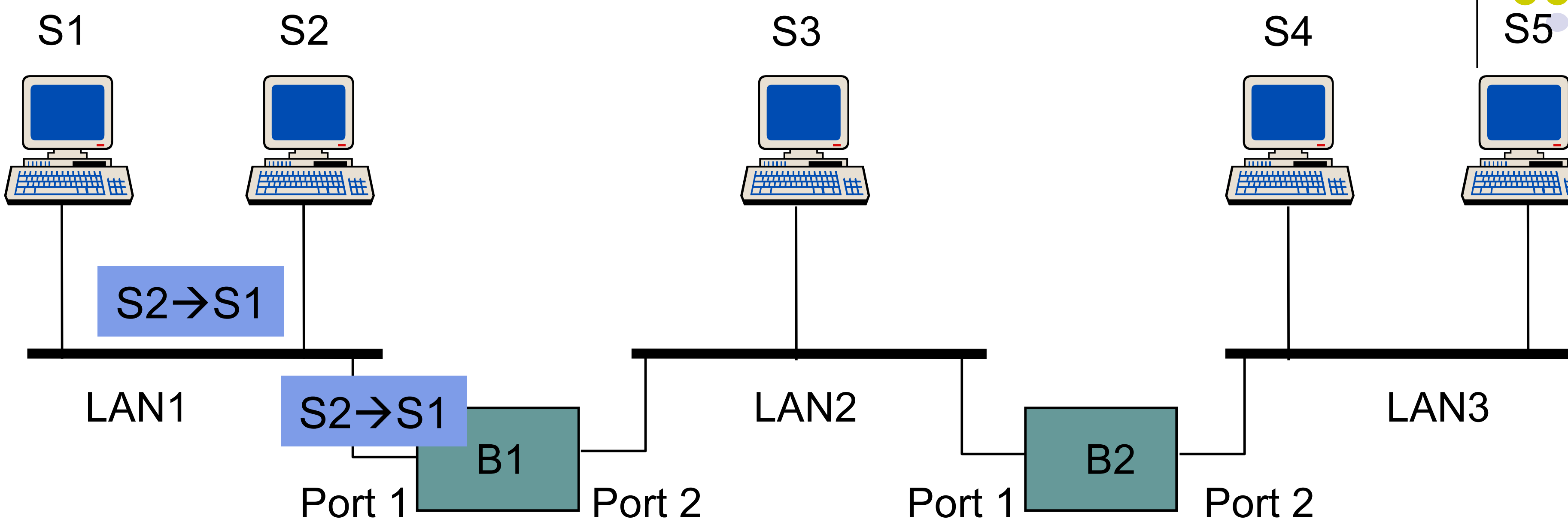
S4→S3



Address	Port
S1	1
S3	2
S4	2

Address	Port
S1	1
S3	1
S4	2

S2→S1



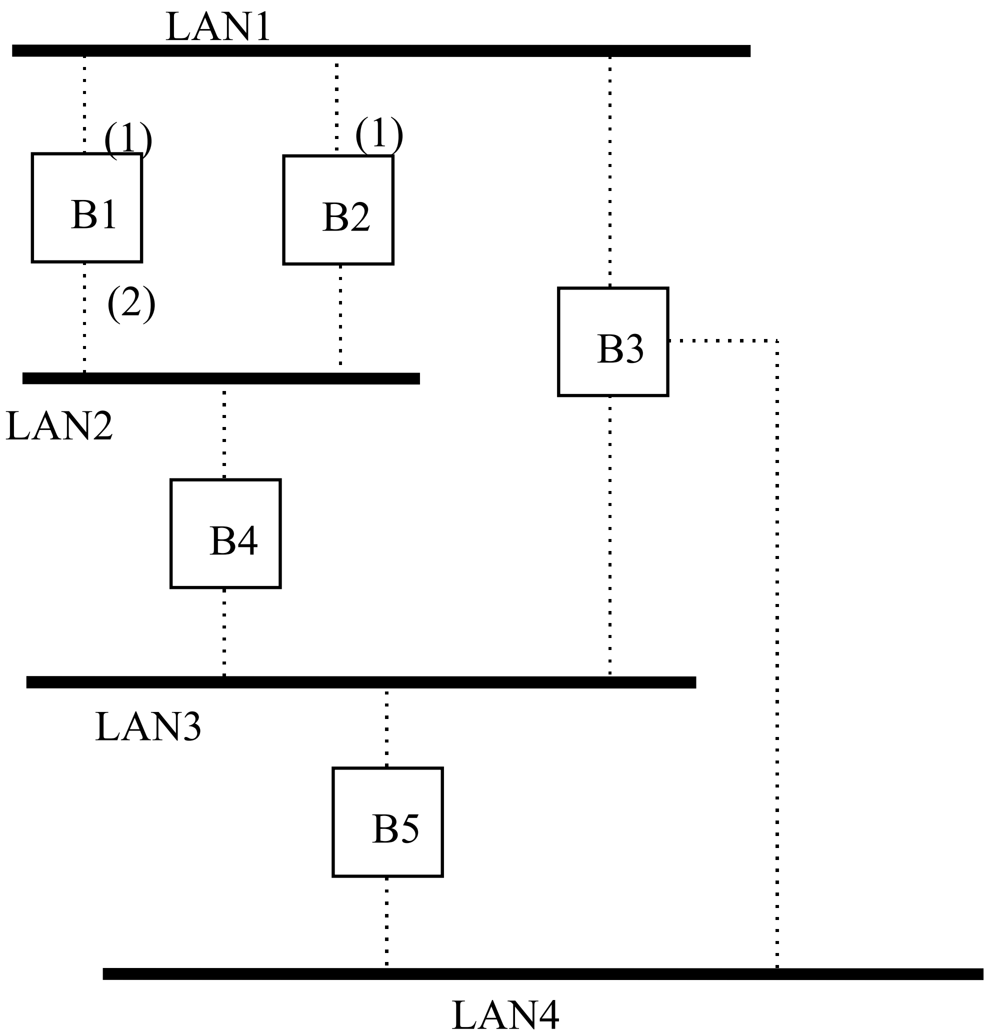
Address	Port
S1	1
S3	2
S4	2
S2	1

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



- As more LANs are interconnected, there is risk of forming loops
- Embed a spanning tree that has a single path to each destination
- All frames must traverse links in the spanning tree
- *Spanning Tree Algorithm*

Spanning Tree Algorithm

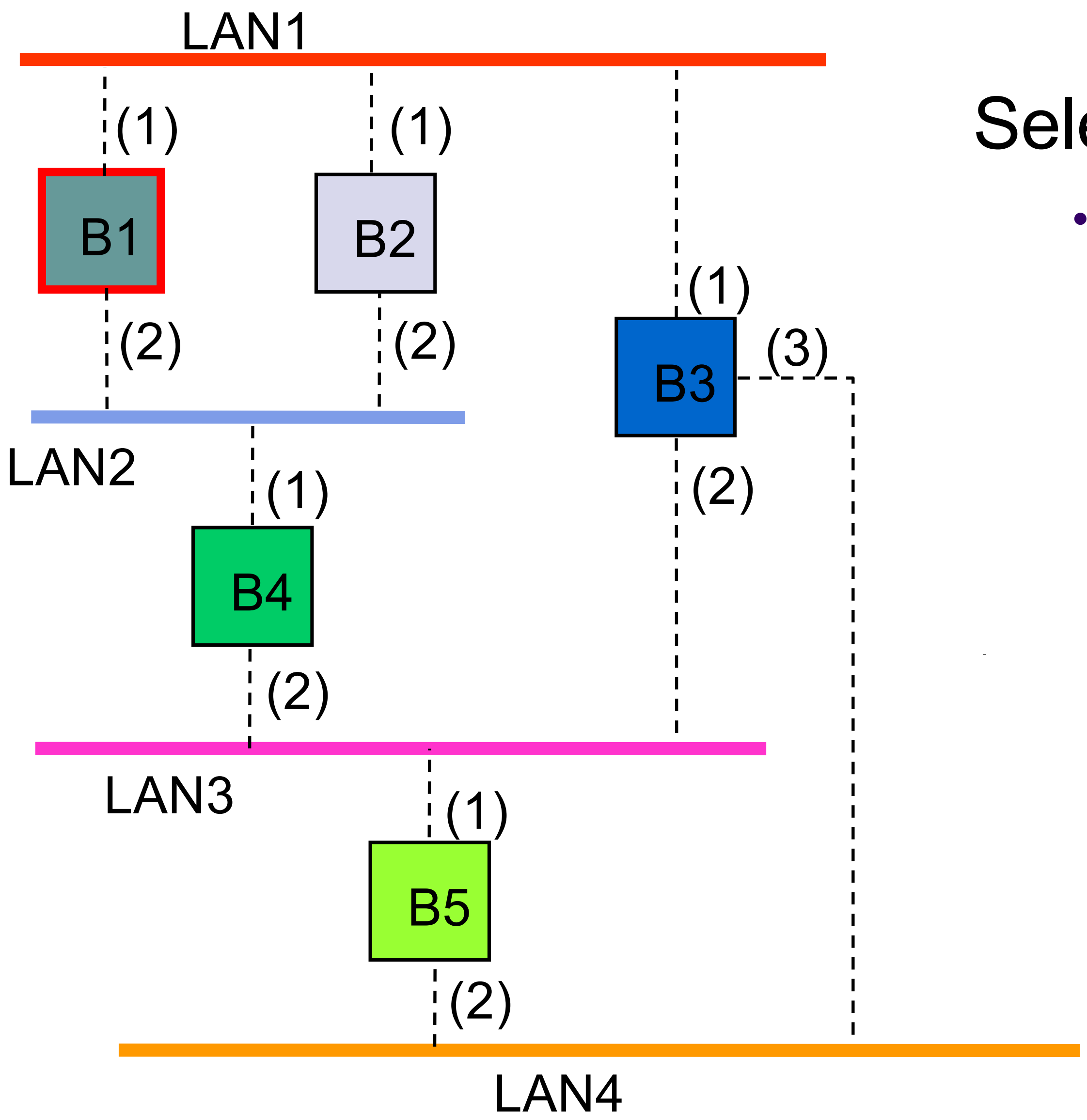
Embed a spanning tree that has a single path to each destination:

1. Select the *root bridge* among all the bridges.
   - *root bridge = the lowest bridge ID*.
2. Each bridge (except root) selects the *root port*:
   - *root port = port with the **shortest path** to the root bridge*
   - If tie, select lowest port number
3. Each LAN selects the *designated bridge*
   - designated bridge = bridge has ***shortest path*** from the LAN to the root bridge.
   - If tie, select lowest bridge number
   - *designated port* connects LAN and 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.

Configuration Messaging

1. Each switch sends a message to its neighbors:
   - Sender ID, ID of presumed root, Distance to presumed root.
2. Upon receiving a message, each switch must determine if there is a better solution:
   - Root with lower ID?
   - Same root & lower distance?
   - Same root, same distance, sender has lower id
3. Algorithm eventually converges & bridges configure their ports
4. Root periodically resends configuration messages

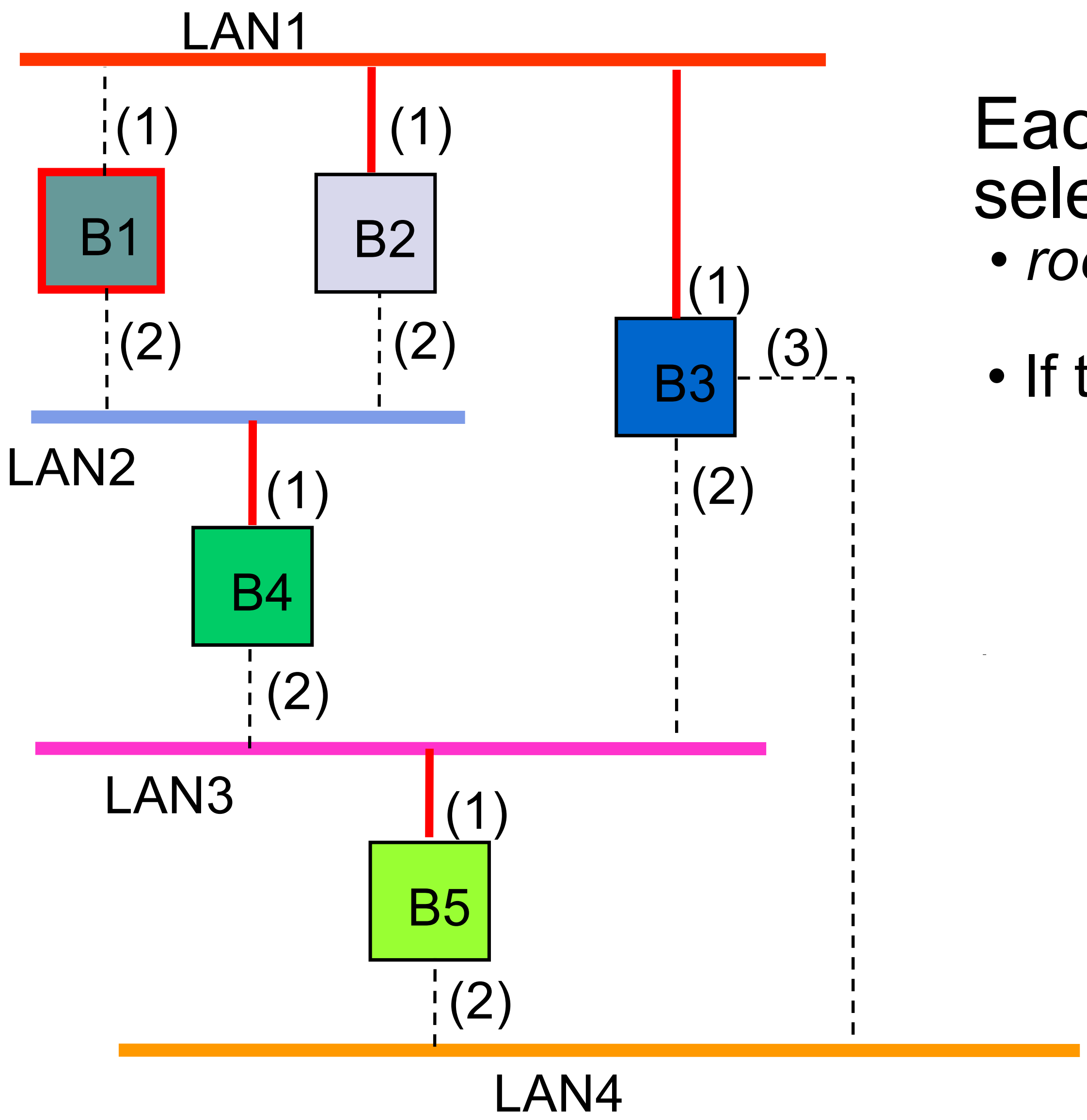
Spanning Tree Algorithm-1



Select *root bridge*

- *root bridge = bridge with lowest ID*.

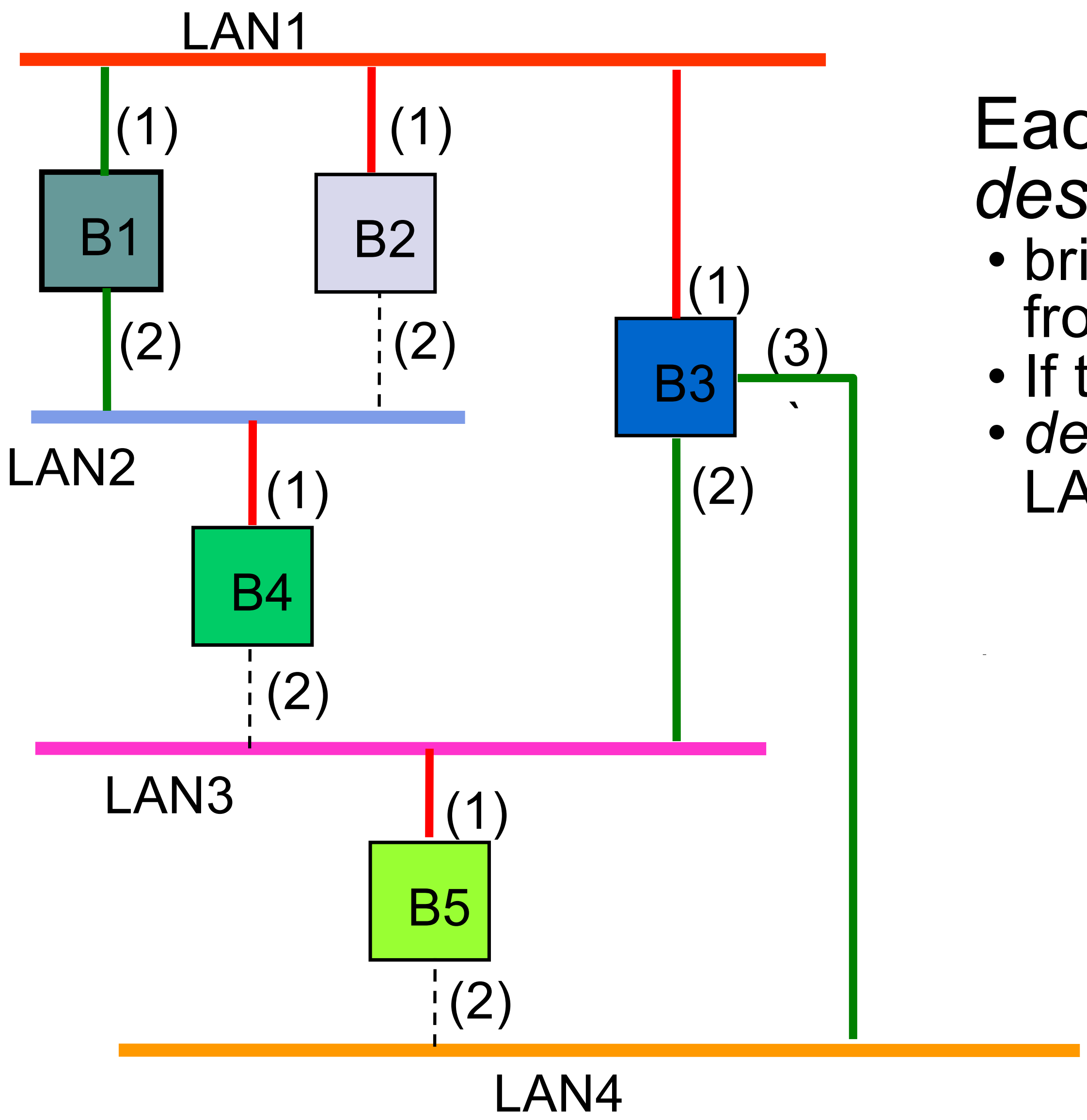
Spanning Tree Algorithm-2



Each bridge (except root) selects its *root port*:

- *root port = port with* ***shortest path*** *to the root bridge*
- If tie, select lowest port #

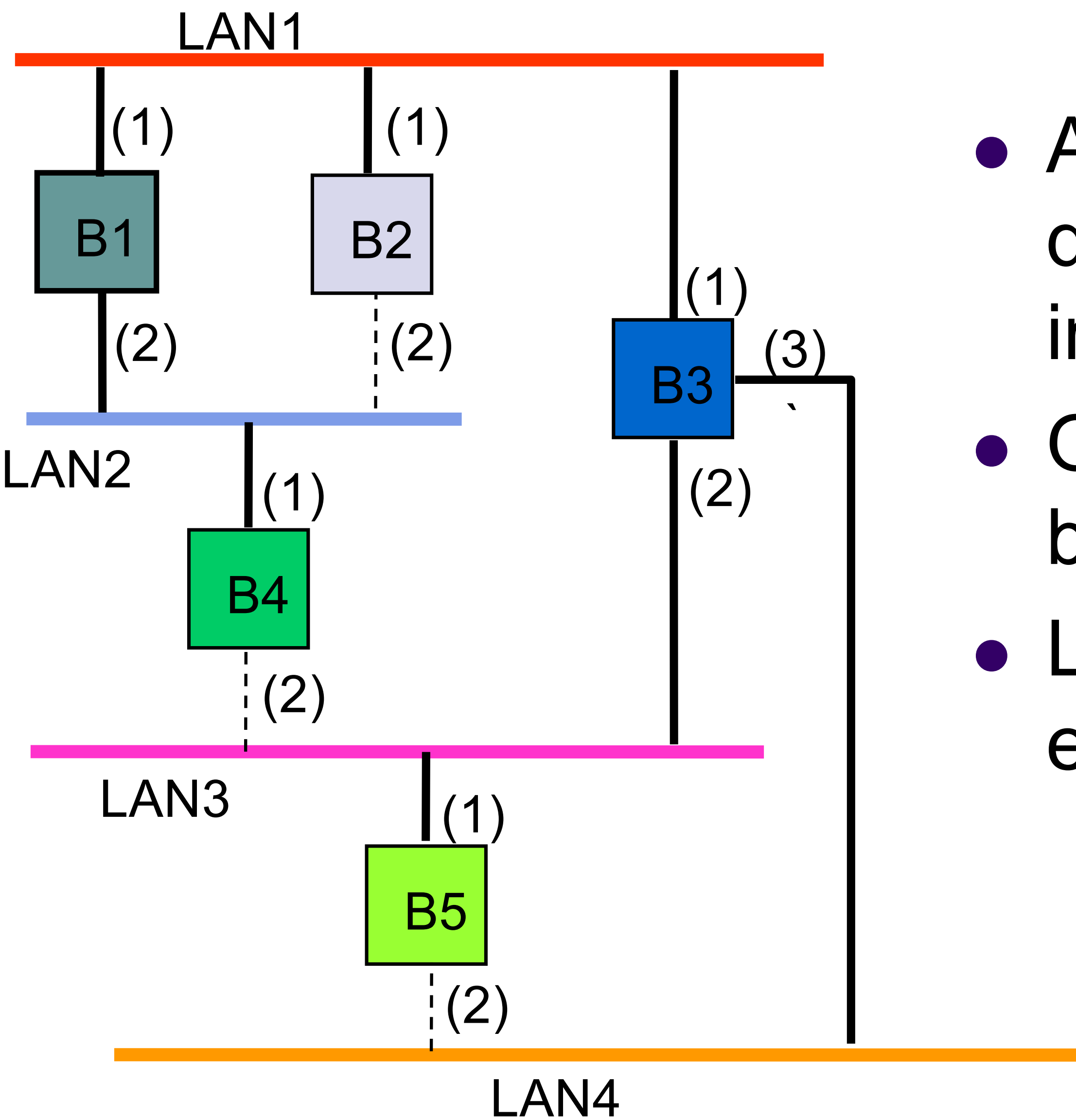
Spanning Tree Algorithm-3



Each LAN selects its *designated bridge*

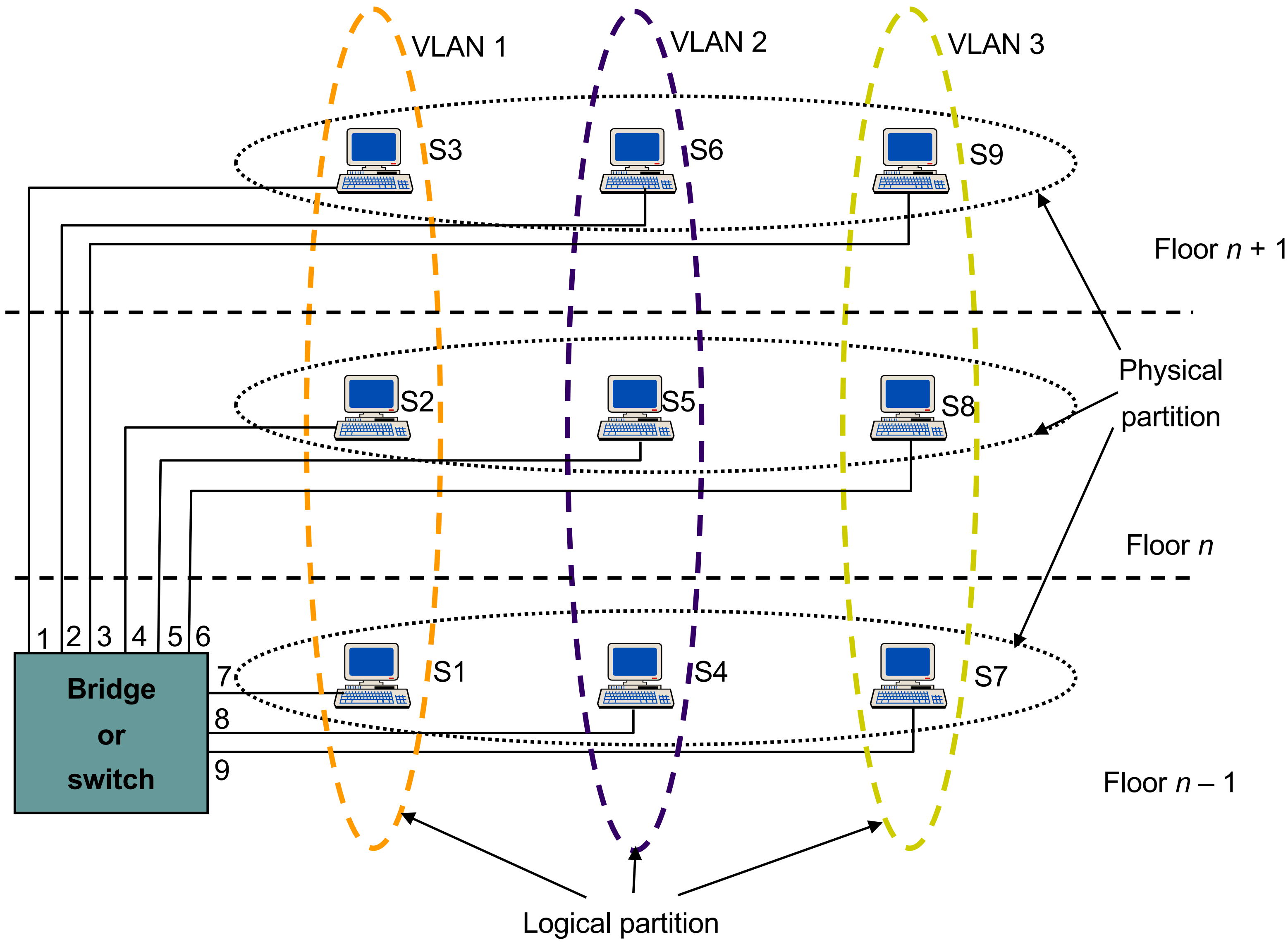
- bridge with ***shortest path*** from LAN to root bridge.
- If tie, select lowest bridge #
- *designated port* connects LAN and designated bridge

Spanning Tree Algorithm-4



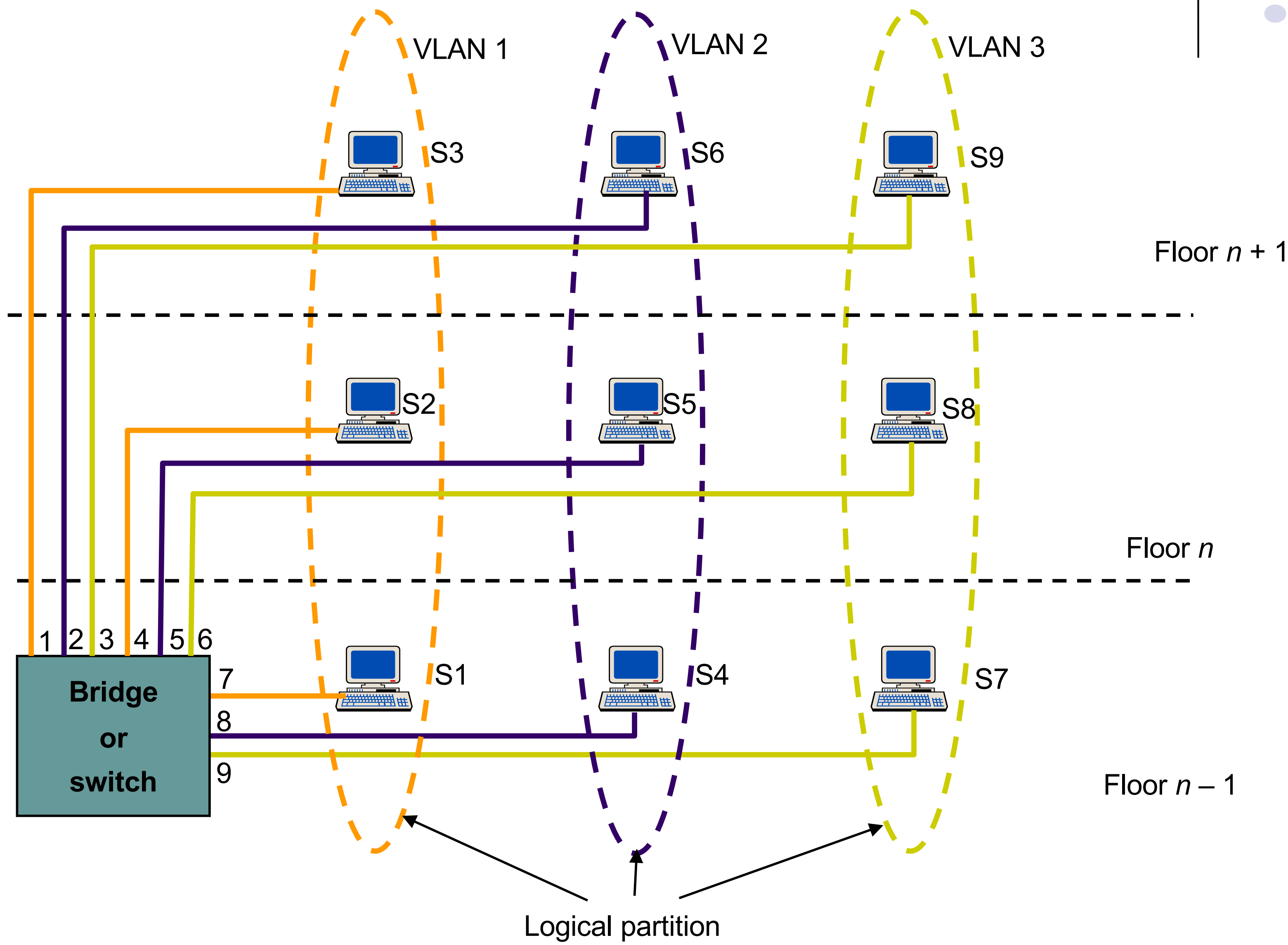
- All root ports & designated ports put in forwarding state
- Other ports put in blocking state
- Loops have been eliminated

Virtual LAN



VLAN 1
VLAN 2
VLAN 3
S3
S6
S9
S2
S5
S8
S1
S4
S7
Floor n + 1
Physical
partition
Floor n
Floor n – 1
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

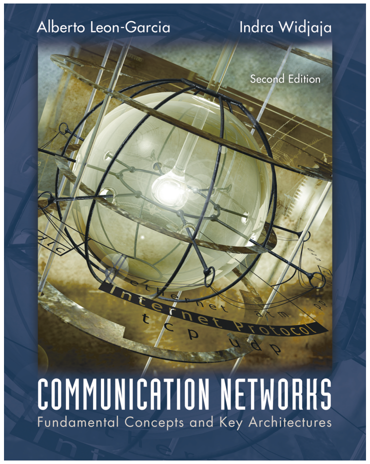
Tagged VLANs

- 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

7	1	6	6	2			4
Preamble	SD	Destination address	Source address	Type	Information	Pad	FCS

Tag Protocol ID (0x8100)	Priority, Drop, VLAN ID
16 bits	3 bits, 1 bit, 12 bits

Chapter 6
Medium Access Control Protocols and Local Area Networks

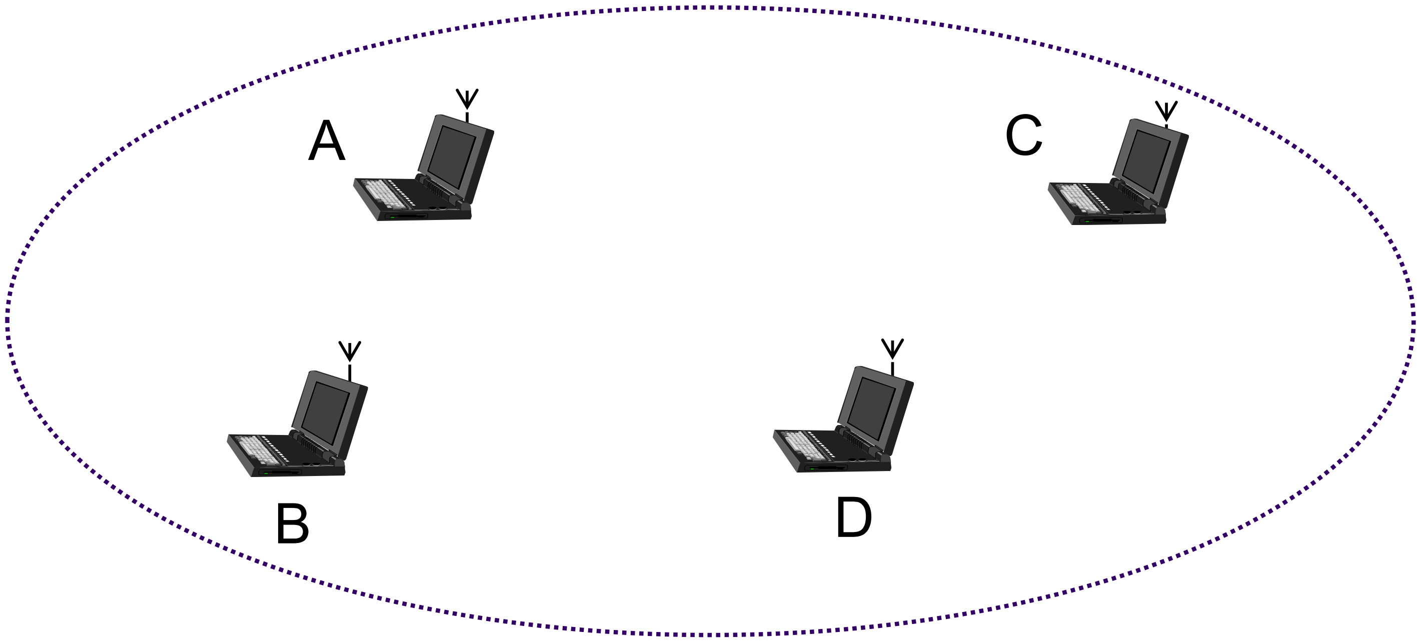


802.11 Wireless LAN
Pp. 417-436

Wireless Data Communications

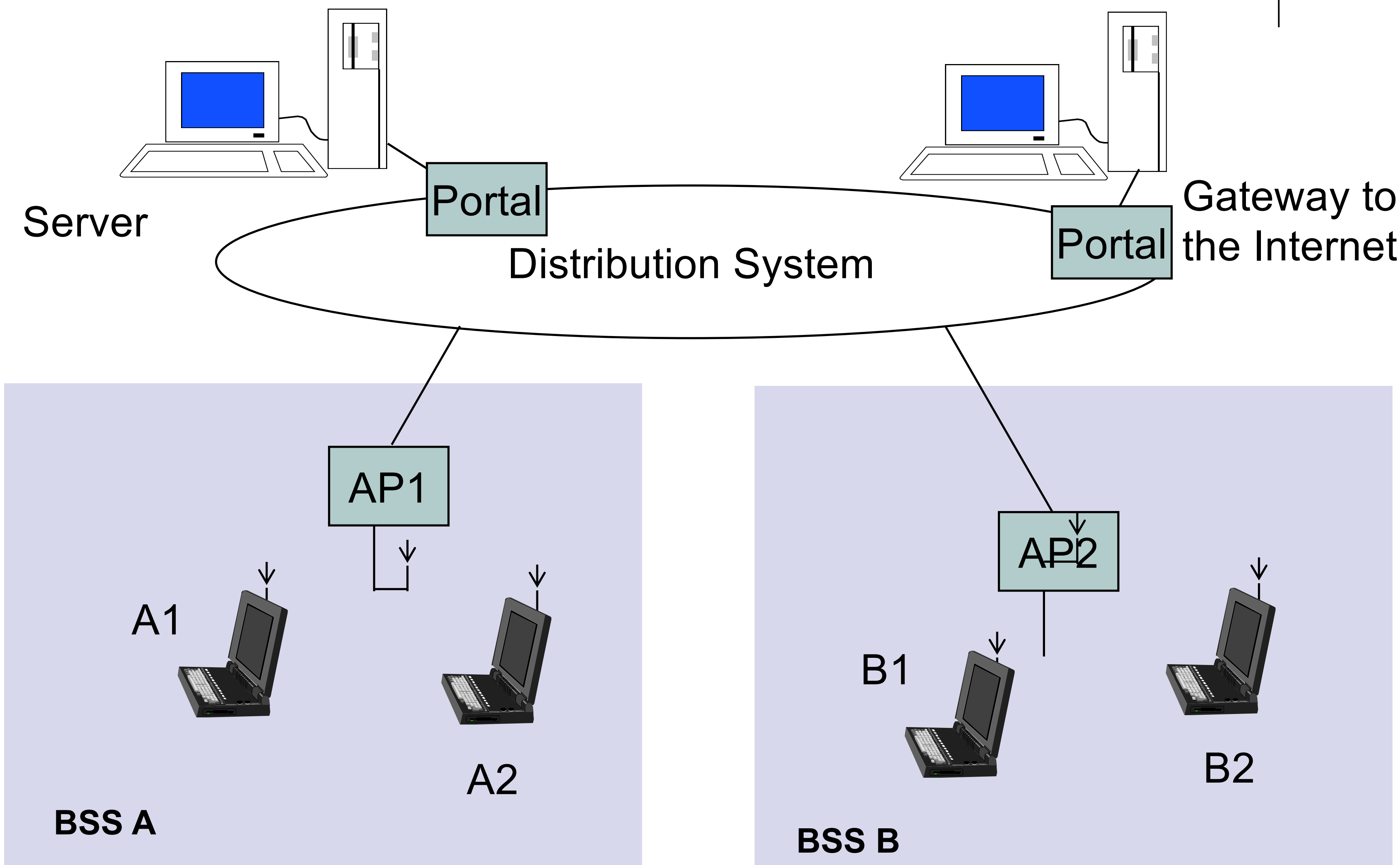
- Wireless communications compelling
  - ✓ Easy, low-cost deployment
  - ✓ Mobility & roaming: Access information anywhere
  - ✓ Supports mobile devices
    - ✓ Laptops, pads, smart phones
  - ✓ Supports communicating devices
    - ✓ Cameras, location devices, sensors
  - ✗ Signal strength varies in 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

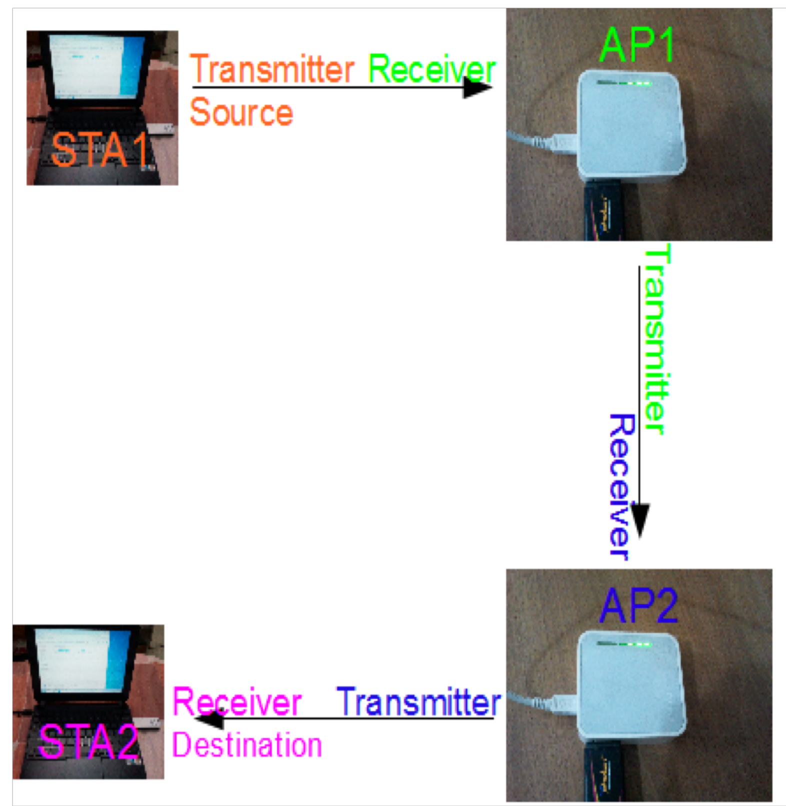
Infrastructure Network



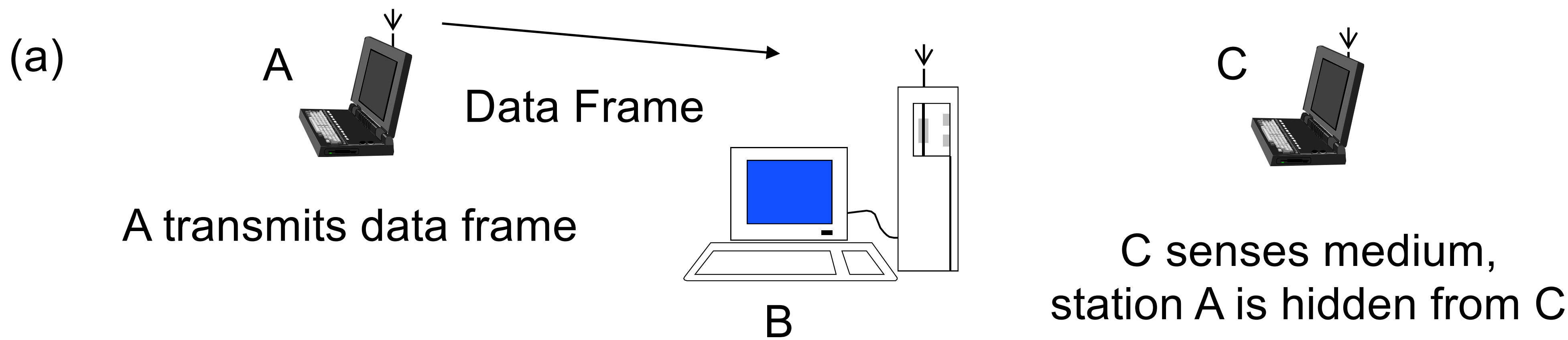
- Permanent Access Points provide access to Internet

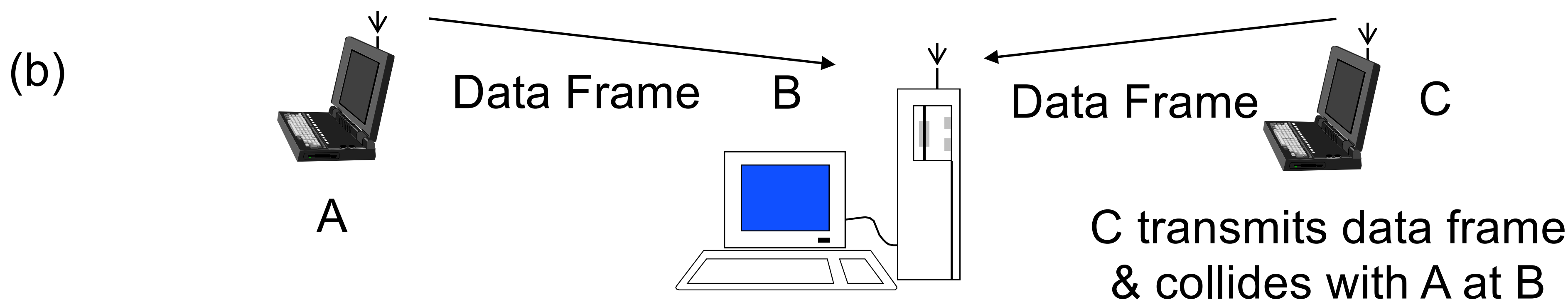
Why 4 WIFI addresses?

- WIFI Frame can hold up to 4 addresses
- SA(Source Address): Source of the data (MSDU) --> STA1
- TA(Transmitter Address) : STA that transmitted the frame --> STA1, AP1, AP2
- RA(Receiver Address) : Immediate recipient of the frame --> AP1, AP2, STA2
- DA(Destination Address) : Final recipient of the data (MSDU) --> STA2
- BSSID (Basic Service Set IDentifier) : Unique identifier of the BSS, e.g, the MAC address of the AP in an infrastructure network --> AP1, AP2



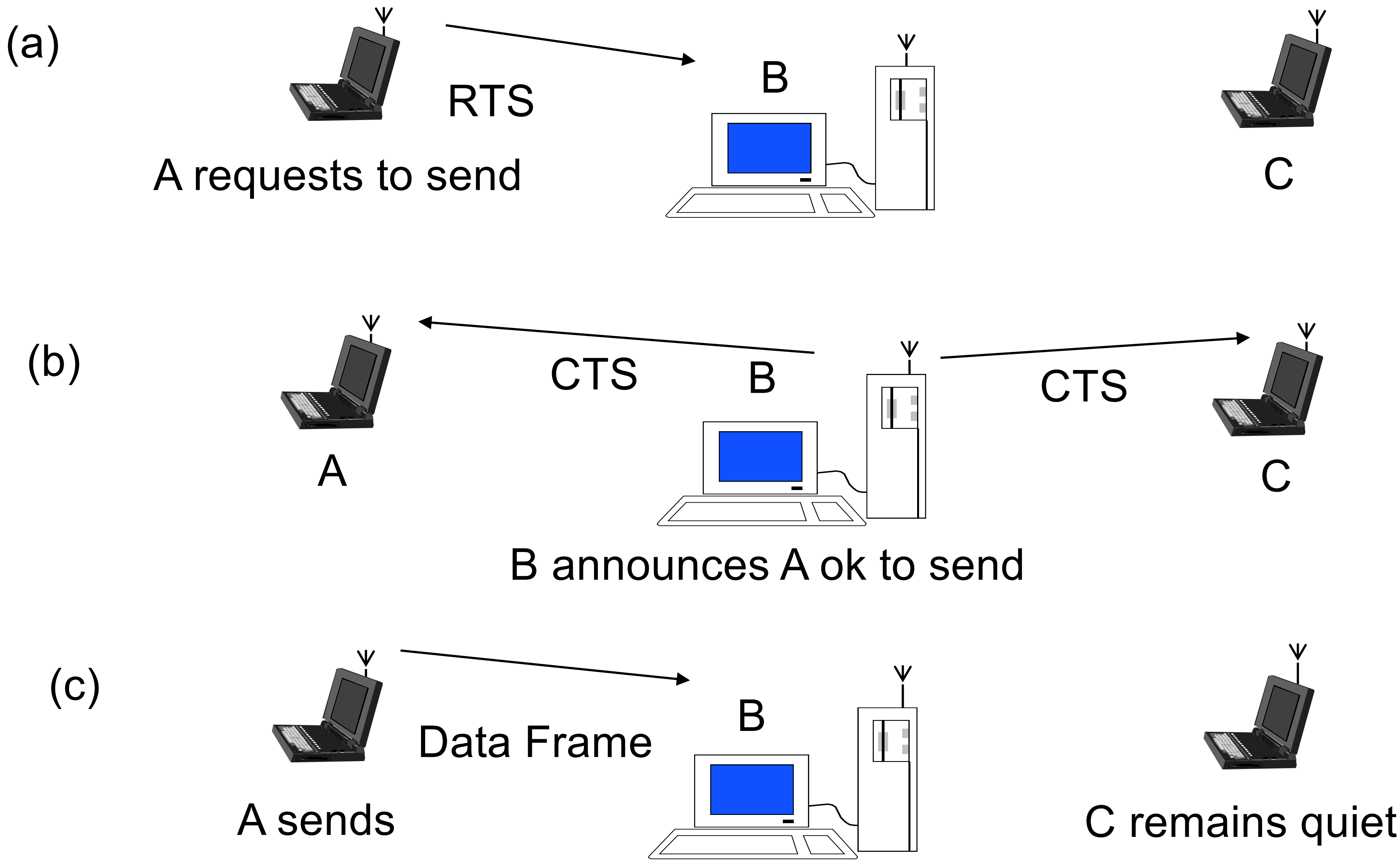
Hidden Terminal Problem





- New MAC: CSMA with *Collision Avoidance*

CSMA with Collision Avoidance



IEEE 802.11 Wireless LAN

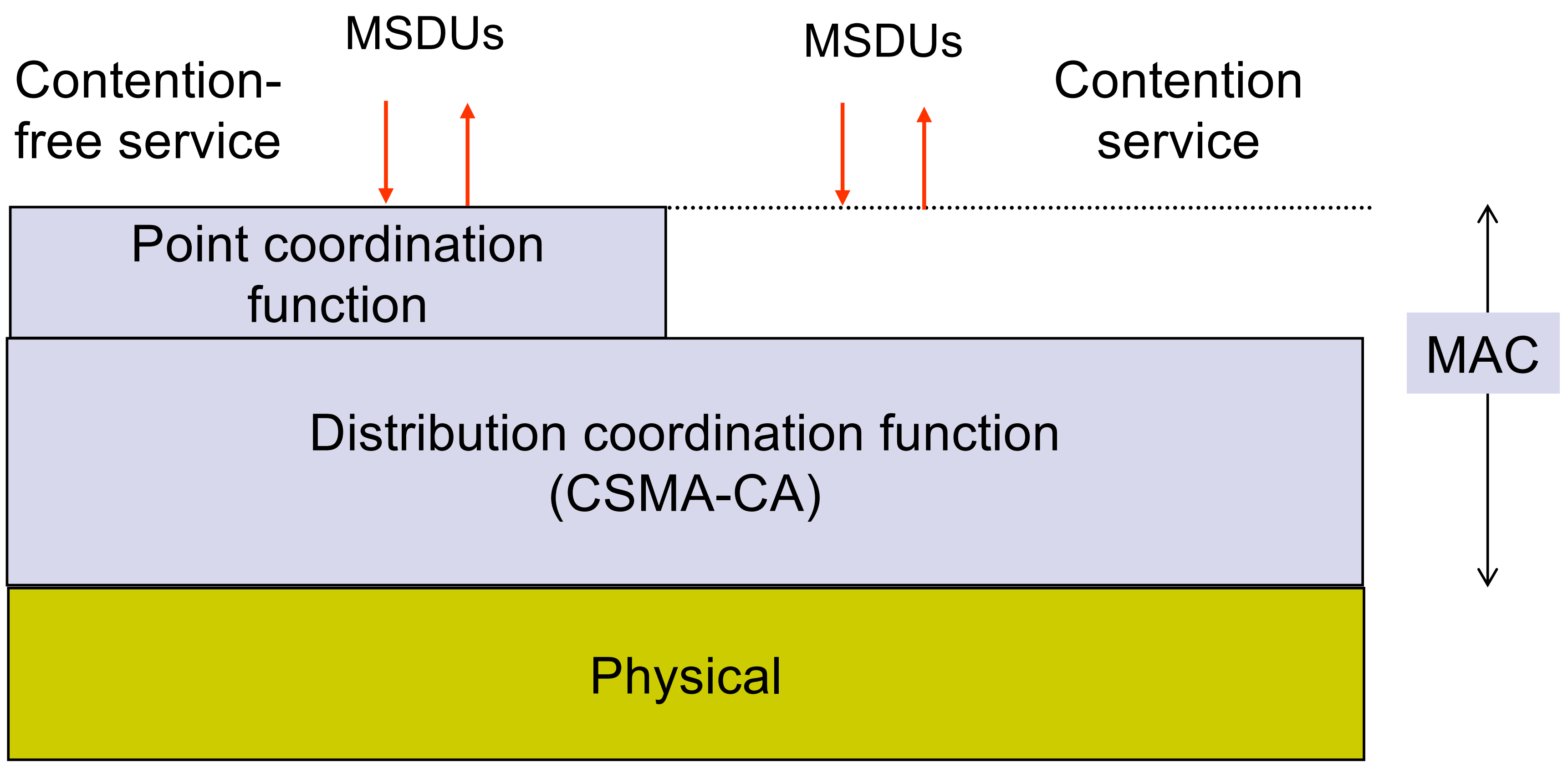
- Stimulated by availability of *unlicensed spectrum*
  - U.S. Industrial, Scientific, Medical (ISM) bands
  - 902-928 MHz, 2.400-2.4835 GHz, 5.725-5.850 GHz
- Targeted wireless LANs @ 20 Mbps
- MAC for high speed wireless LAN
- Ad Hoc & Infrastructure networks
- Variety of physical layers

IEEE 802.11 MAC

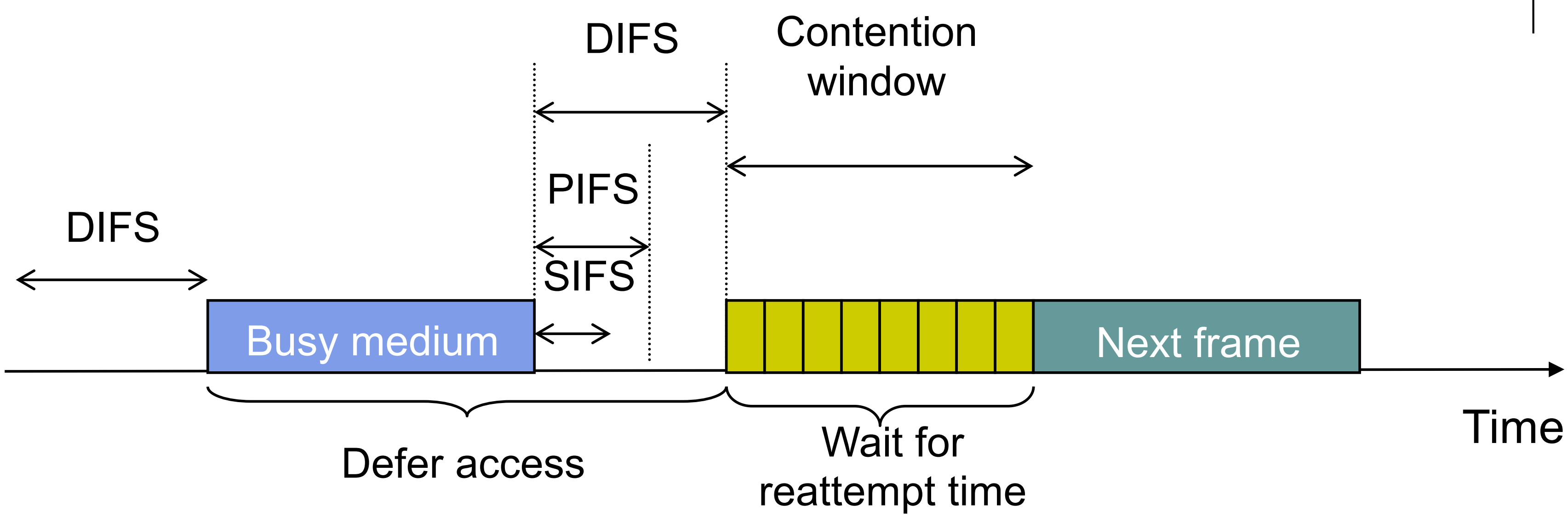
- MAC sublayer responsibilities
  - Channel access
  - PDU addressing, formatting, error checking
  - Fragmentation & reassembly of MAC SDUs
- MAC security service options
  - Authentication & privacy
- MAC management services
  - Roaming within ESS
  - Power management

MAC Services

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

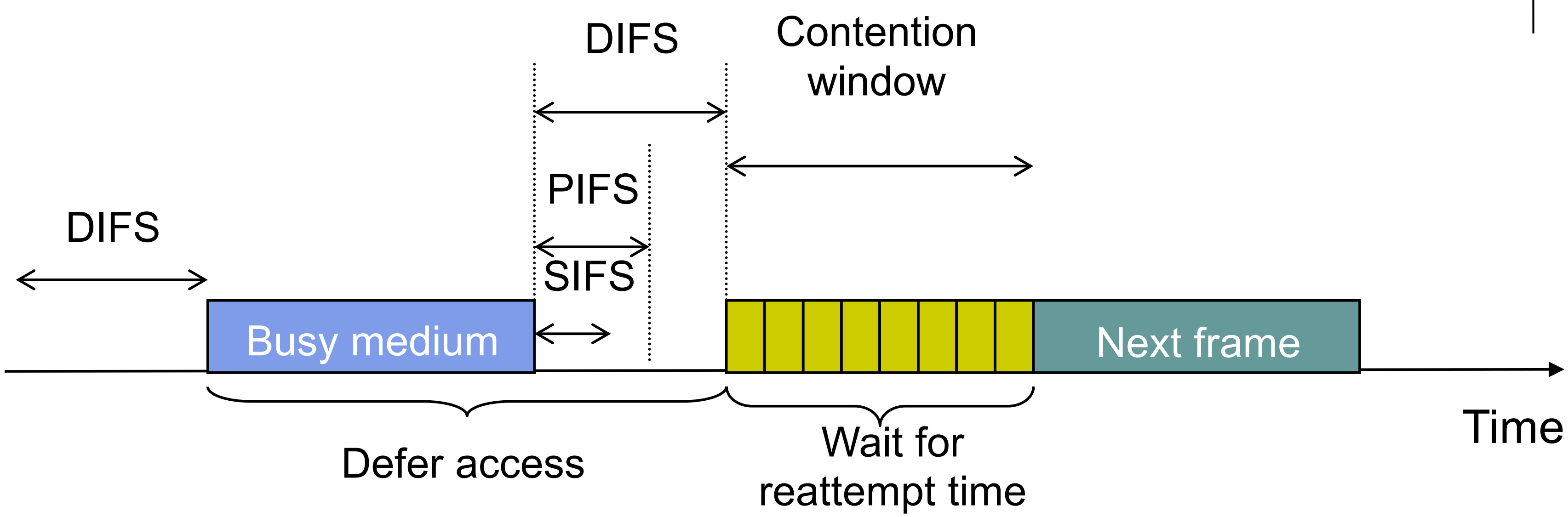


Distributed Coordination Function (DCF)



- 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)*

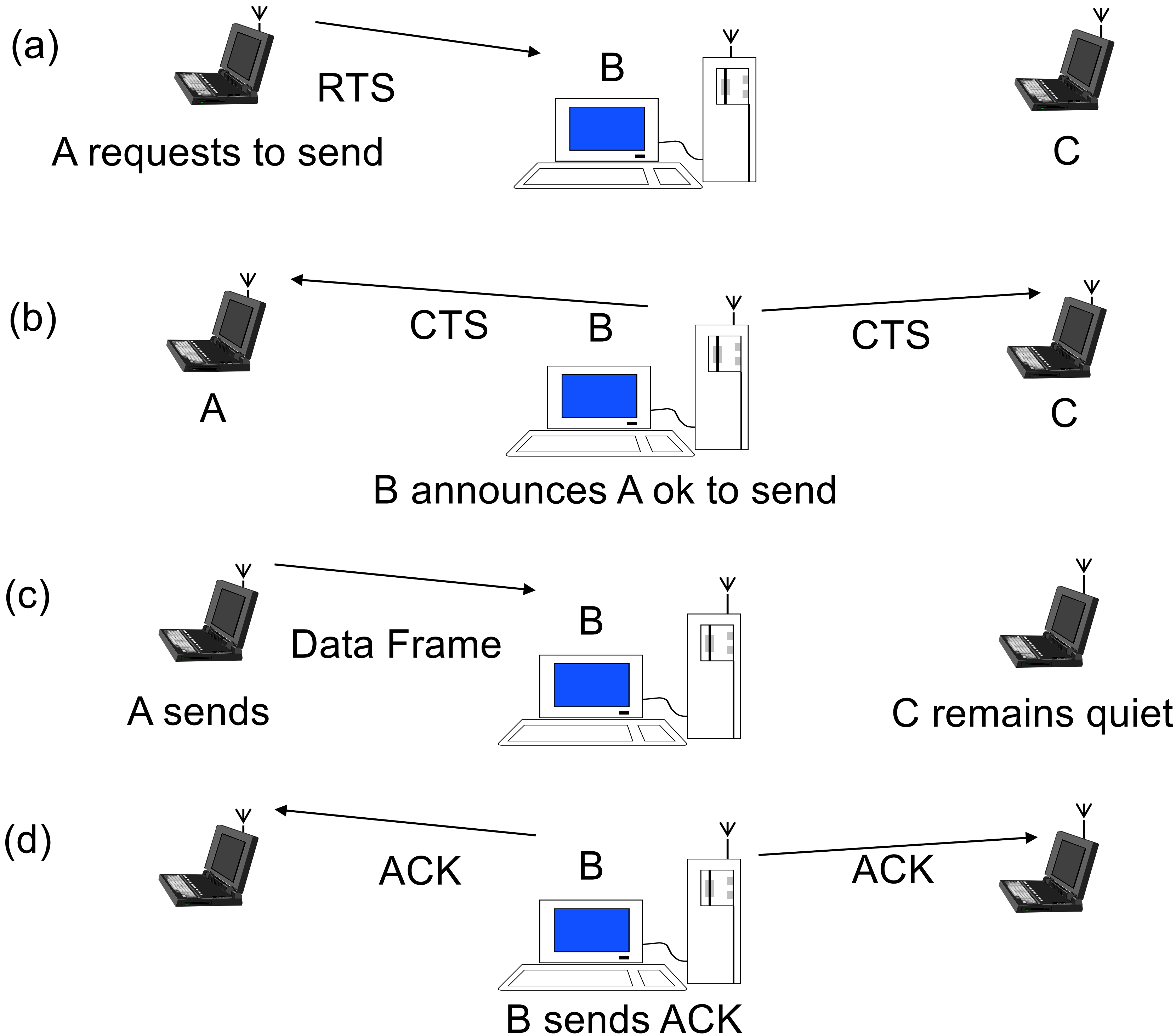
Priorities through Interframe Spacing



- 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

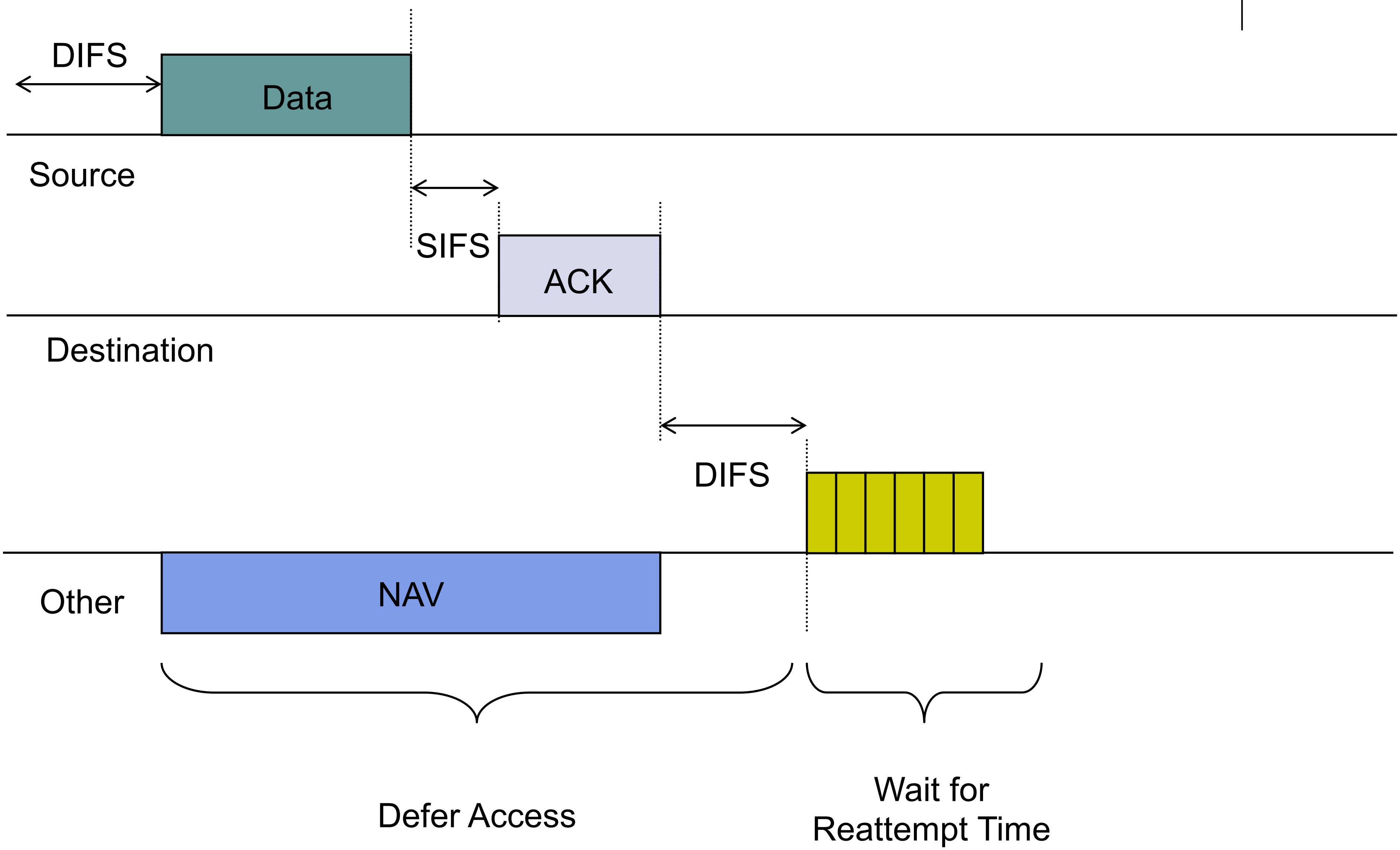
- If channel is still idle after DIFS period, ready station can transmit an *initial* MPDU
- If channel becomes busy before DIFS, then station must schedule *backoff* time for reattempt
  - Backoff period is integer # of *idle contention time slots*
  - Waiting station monitors medium & decrements backoff 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)
Data Frame
B
A sends
C remains quiet
(d)
ACK
B
ACK
B sends ACK

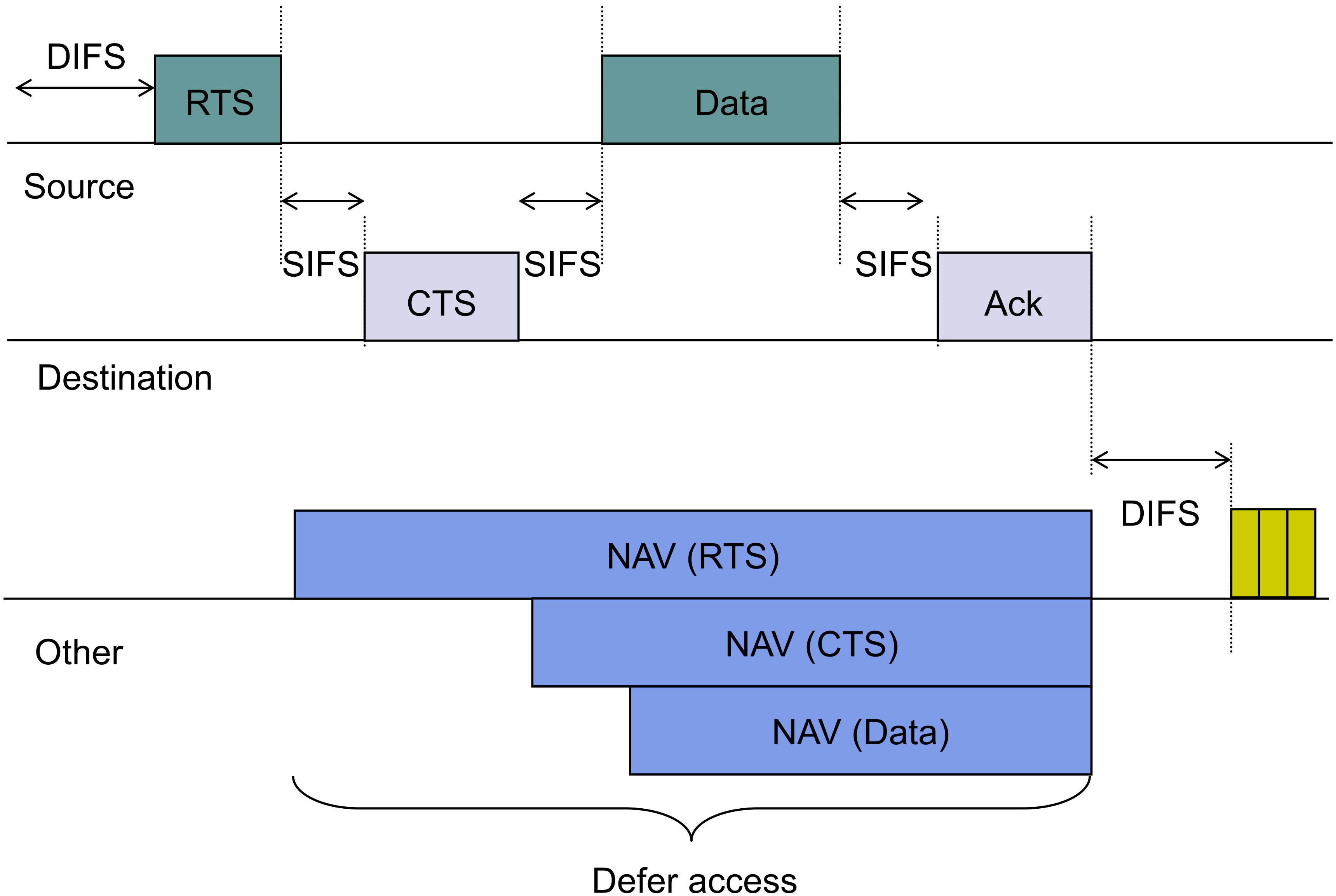
Carrier Sensing in 802.11

- *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

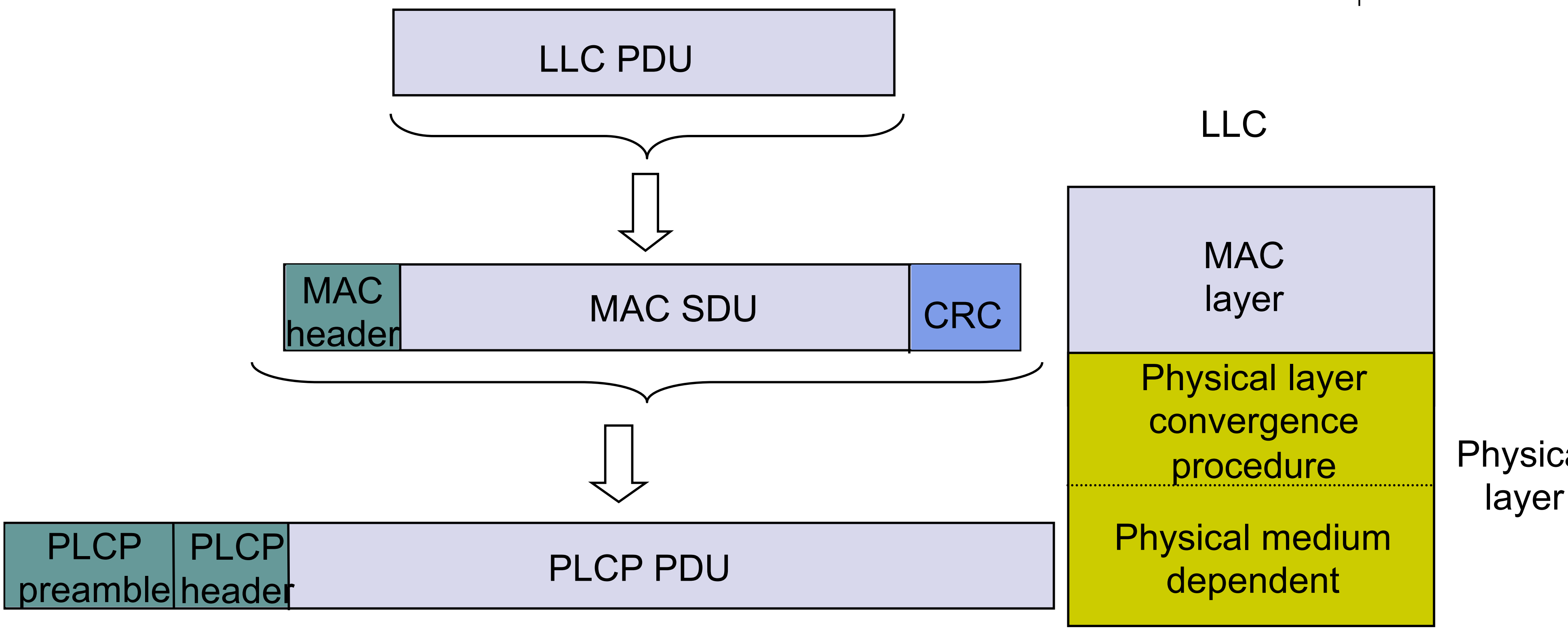
- PCF provides connection-oriented, contention-free service through *polling*
- *Point coordinator (PC)* in AP performs PCF
- Polling table up to implementor
- CFP repetition interval
  - Determines frequency with which CFP occurs
  - Initiated by *beacon frame* transmitted by PC in AP
  - Contains CFP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

Frame Structure

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

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

Physical Layers

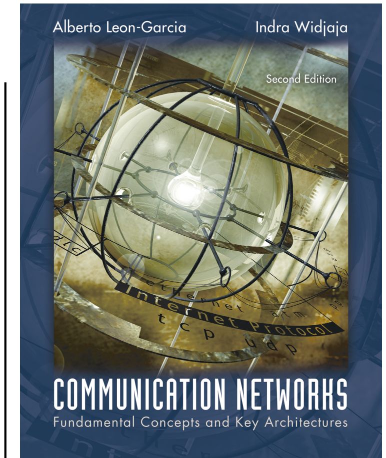


- 802.11 designed to
  - Support LLC
  - Operate over many physical layers

IEEE 802.11 Physical Layer Options

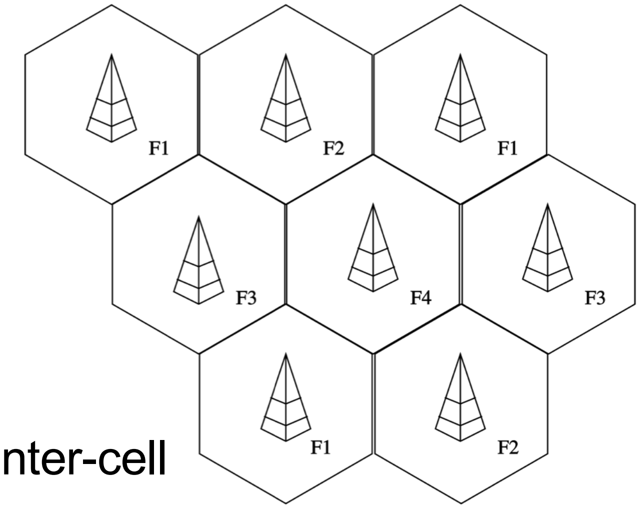
	Frequency Band	Bit Rate	Modulation Scheme
802.11	2.4 GHz	1-2 Mbps	Frequency-Hopping Spread Spectrum, Direct Sequence Spread Spectrum
802.11b	2.4 GHz	11 Mbps	Complementary Code Keying & QPSK
802.11g	2.4 GHz	54 Mbps	Orthogonal Frequency Division Multiplexing & CCK for backward compatibility with 802.11b
802.11a	5-6 GHz	54 Mbps	Orthogonal Frequency Division Multiplexing
802.11n	2.4 GHz 5 GHz	Up to 600 Mbps	MIMO up to 4 40MHz spatially separated channels

Mobile Cellular Networks



From GSM to LTE

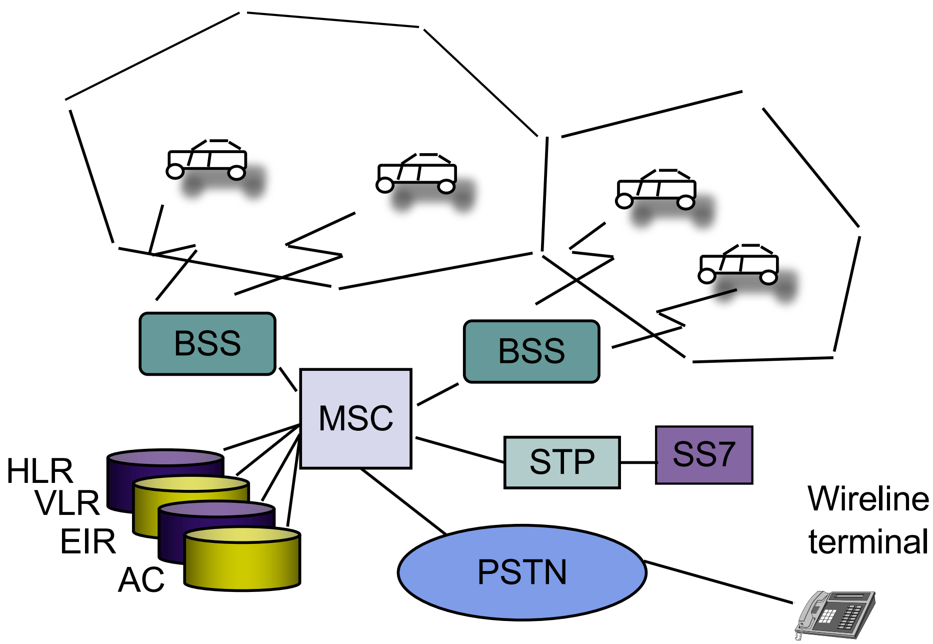
Cellular Communications



Two basic concepts:

- Frequency Reuse
  - A region is partitioned into *cells*
  - Each cell is covered by *base station*
  - Power transmission levels controlled to minimize inter-cell interference
  - Spectrum can be reused in other cells
- Handoff
  - Procedures to ensure continuity of call as user moves from cell to another
  - Involves setting up call in new cell and tearing down old one

Cellular Network



AC = authentication center
BSS = base station subsystem
EIR = equipment identity register
HLR = home location register

MSC = mobile switching center
PSTN = public switched telephone network
STP = signal transfer point
VLR = visitor location register

Base station

- Transmits to users on *forward channels*
- Receives from users on *reverse channels*

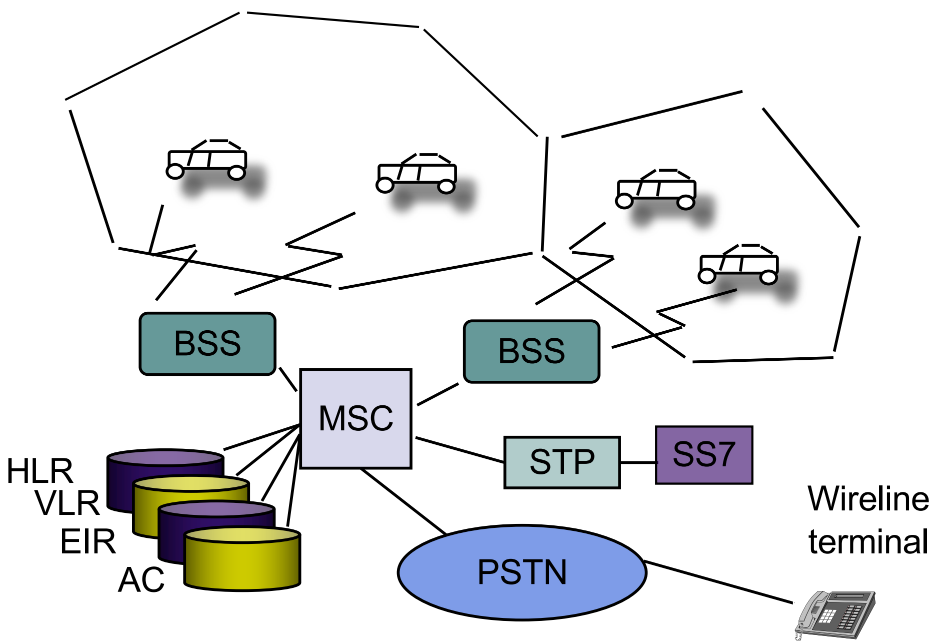
Mobile Switching Center

- Controls connection setup within cells & to telephone network

Setup channels

- For call setup & handoff
- Mobile unit selects setup channel with strongest signal & monitors this channel

Incoming call to mobile unit

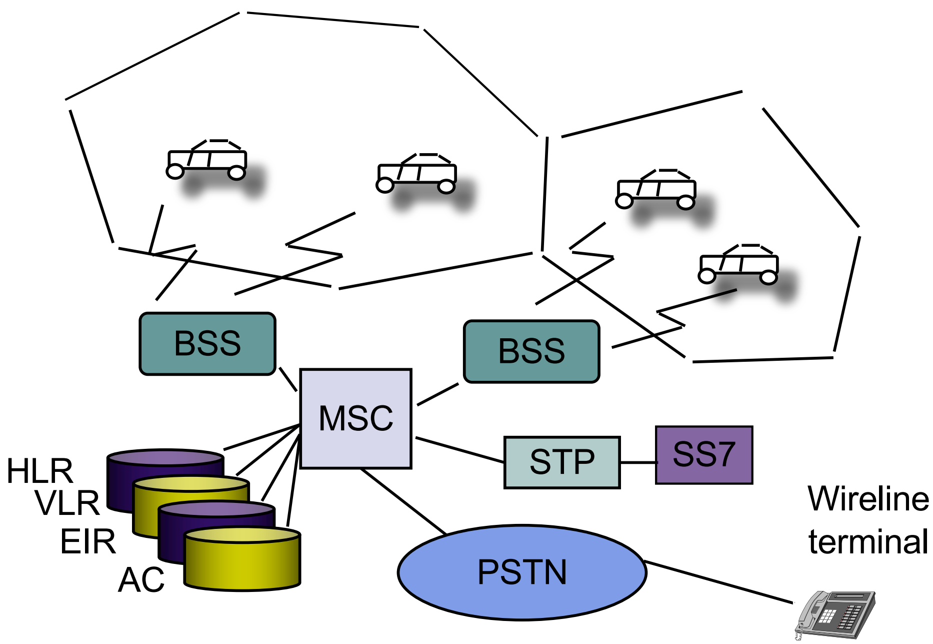


AC = authentication center
BSS = base station subsystem
EIR = equipment identity register
HLR = home location register

MSC = mobile switching center
PSTN = public switched telephone network
STP = signal transfer point
VLR = visitor location register

- MSC sends call request to all BSSs
- BSSs broadcast request on all setup channels
- Mobile unit replies on reverse setup channel
- BSS forwards reply to MSC
- BSS assigns forward & reverse voice channels
- BSS informs mobile to use these
- Mobile phone rings

Mobile Originated Call

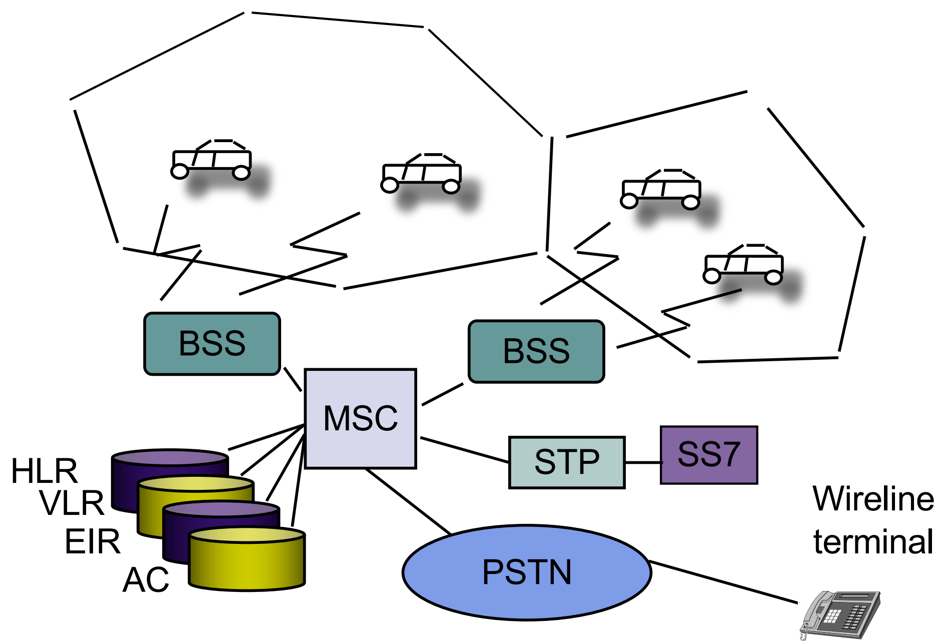


AC = authentication center
BSS = base station subsystem
EIR = equipment identity register
HLR = home location register

MSC = mobile switching center
PSTN = public switched telephone network
STP = signal transfer point
VLR = visitor location register

- Mobile sends request in reverse setup channel
- Message from mobile has serial # & authentication info
- BSS forwards message to MSC
- MSC consults HLR for info about the subscriber; may also consult Authentication center
- MSC establishes call to PSTN
- BSS assigns forward & reverse channel

Handoff



AC = authentication center
BSS = base station subsystem
EIR = equipment identity register
HLR = home location register

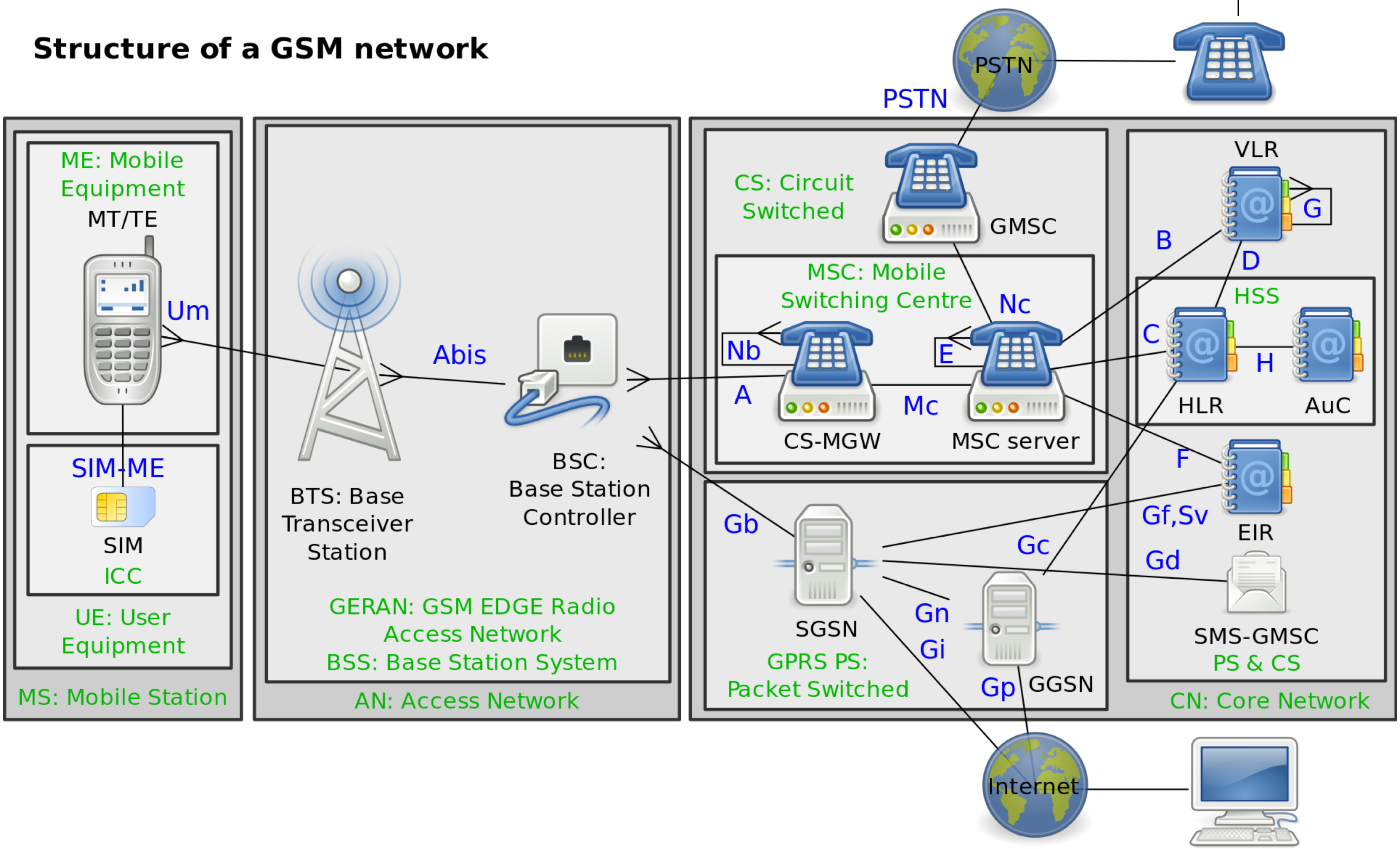
MSC = mobile switching center
PSTN = public switched telephone network
STP = signal transfer point
VLR = visitor location register

- Base station monitors signal levels from its mobiles
- If signal level drops below threshold, MSC notified & mobile instructed to transmit on setup channel
- Nearby base stations told to monitor signal from mobile on setup channel
- Results sent to MSC, which selects new cell
- Current BSS & mobile told to prepare for handoff
- MSC releases connection to first BSS;sets up connection to new BSS
- Mobile changes to new channels in new cell

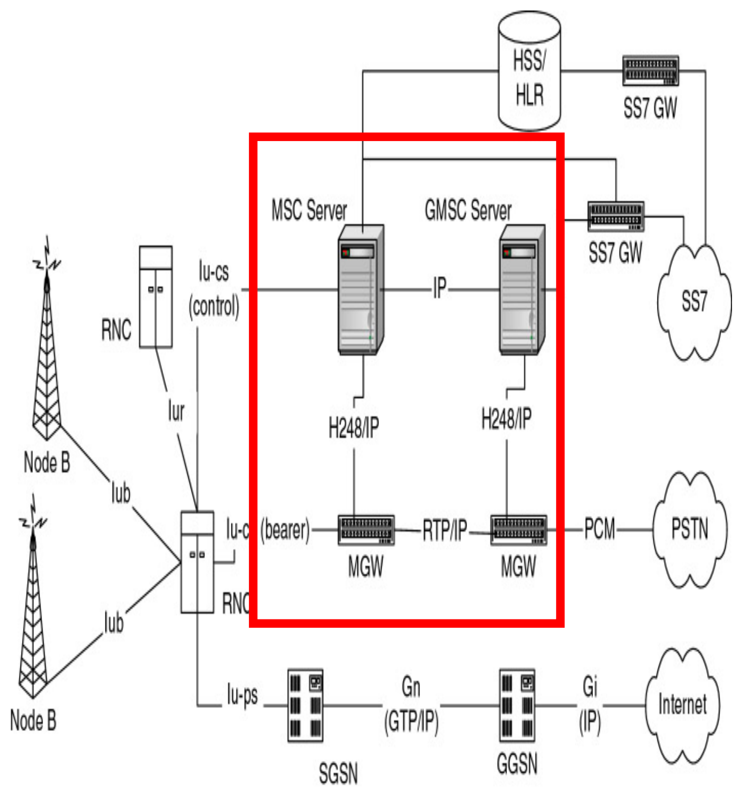
Roaming

- Users subscribe to roaming service to use service outside their home region
- Signaling network used for message exchange between home & visited network
- Roamer uses setup channels to register in new area
- MSC in visited areas requests authorization from user’s Home Location Register
- Visitor Location Register informed of new user
- User can now receive & place calls

GSM Voice & Data Services

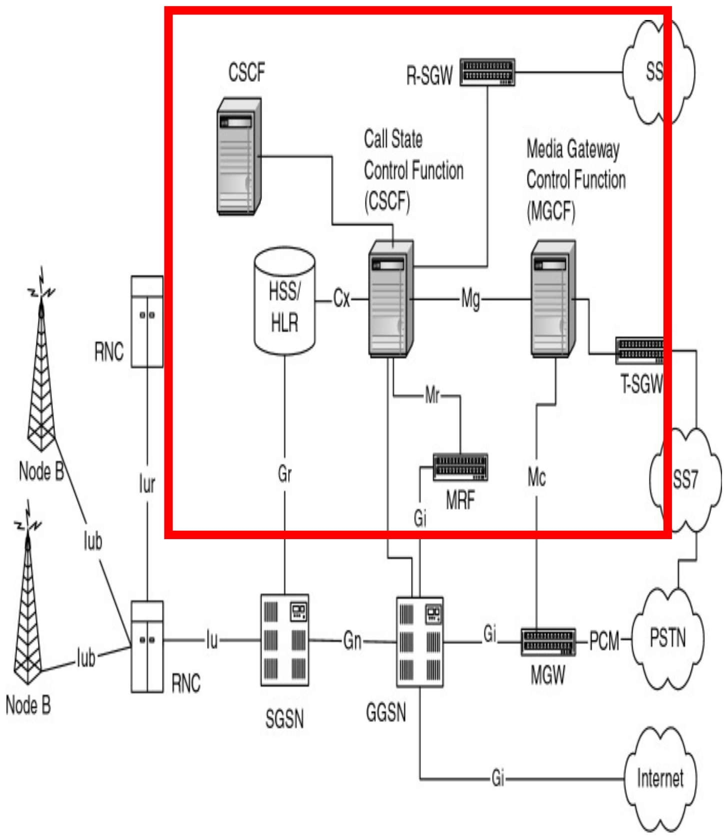


3G Release 4: All IP Network



- MSC divided into:
  - MSC server
  - *Media gateway* (MGW)
- MSC server
  - mobility management
  - call control logic
- Media gateway
  - Switching matrix
  - Controlled by MSC server
- Gateway MSC (GMSC)
  - Controls MGW at i/f with other network (PSTN)
  - MGW converts voice format

3G Release 5: SIP-based Signalling



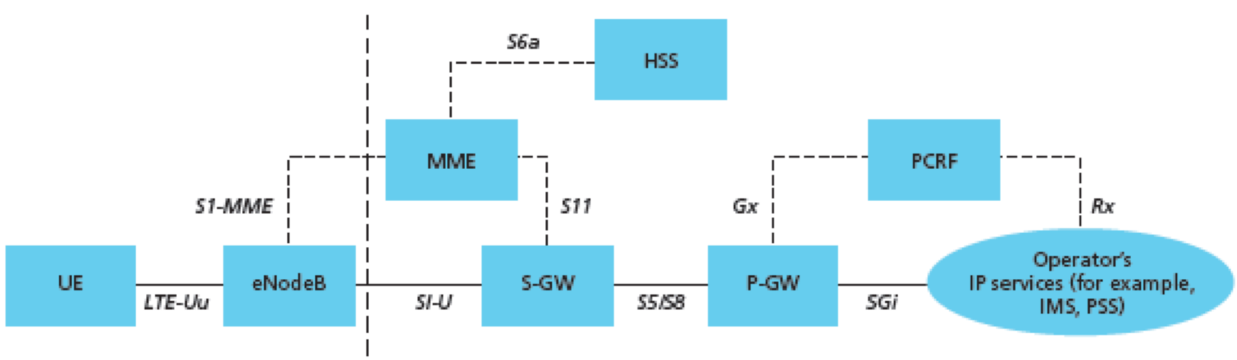
IP Multimedia Subsystem is introduced

- Change to SIP-based signaling
- Voice and data largely handled in same manner all the way from user terminal to ultimate destination

LTE (4G) Architecture

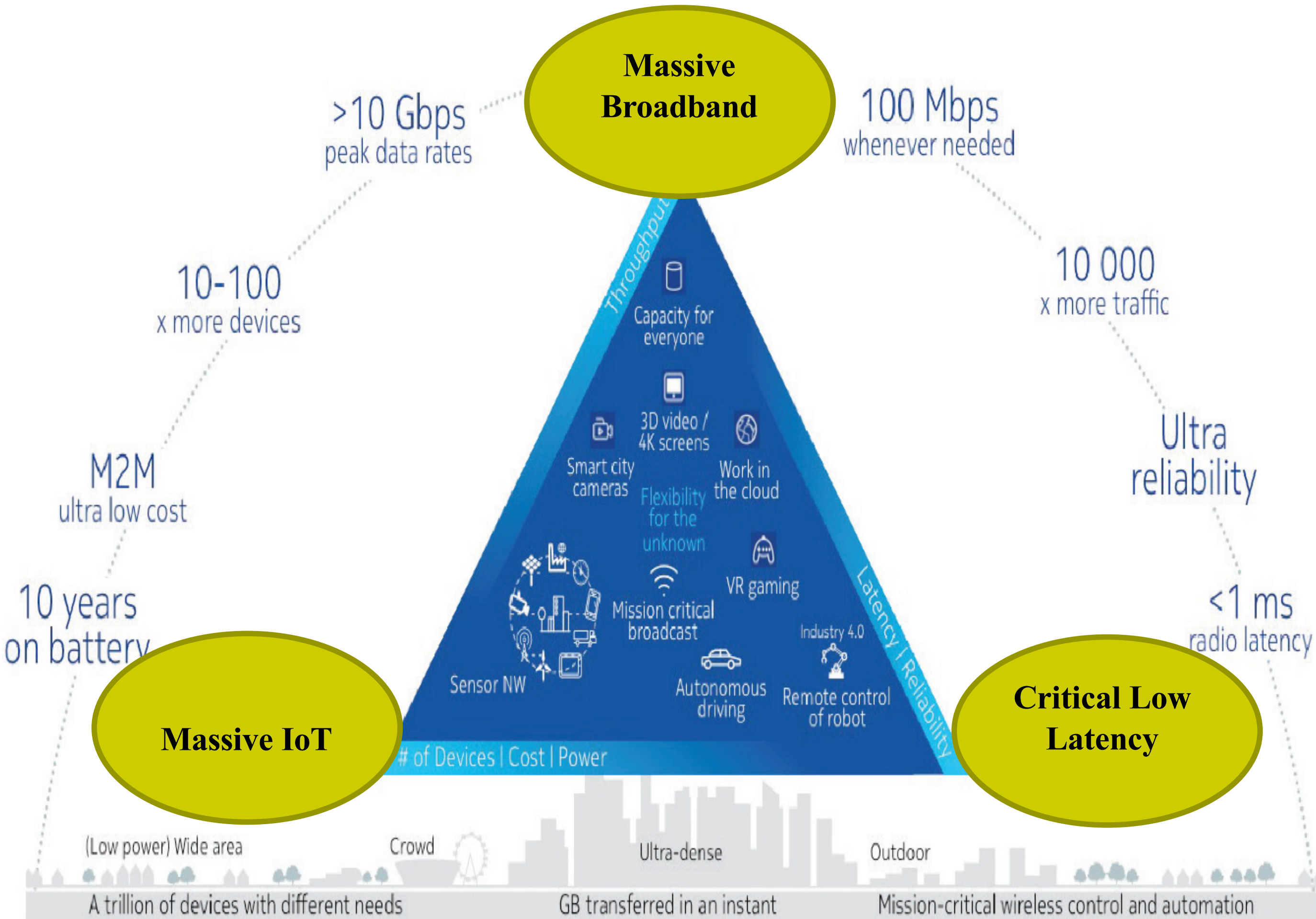
- All IP traffic from GW to UE
- eNodeB one network element
- Home Subscriber Server
- Policy Control and Charging Rules Function
- EPS: single bearer path with given QoS
- IMS: controls multimedia applications
- IMS outside EPS

Figure 1. The EPS network elements



What is 5G?

- New capabilities in bandwidth, latency, and scale
- But 5G is NOT just about more speed or lower latency
- 5G is intended to revolutionize other industries via wireless communications



5G: One Network for Multiple Industries