Data Communication Networks
Multiple Access Control Sublayer

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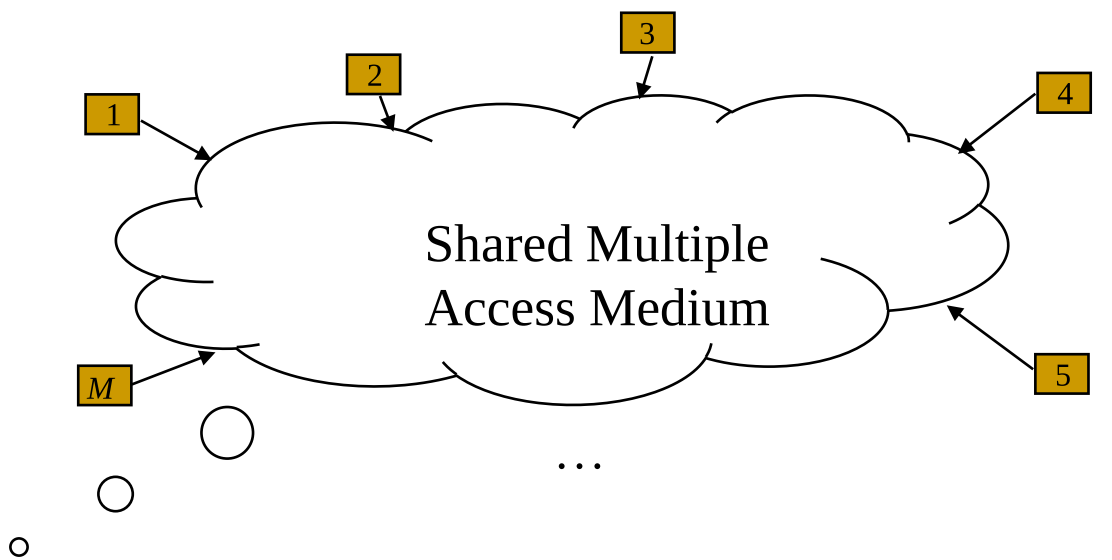
The Medium Access Sublayer

- A number of systems are connected to share the medium: Who gets access?
  - Used for LANs
  - Addressing
  - Broadcast



Network Protocol Design Goals

Static

- user gets a channel for the whole 'conversation'.

Dynamic

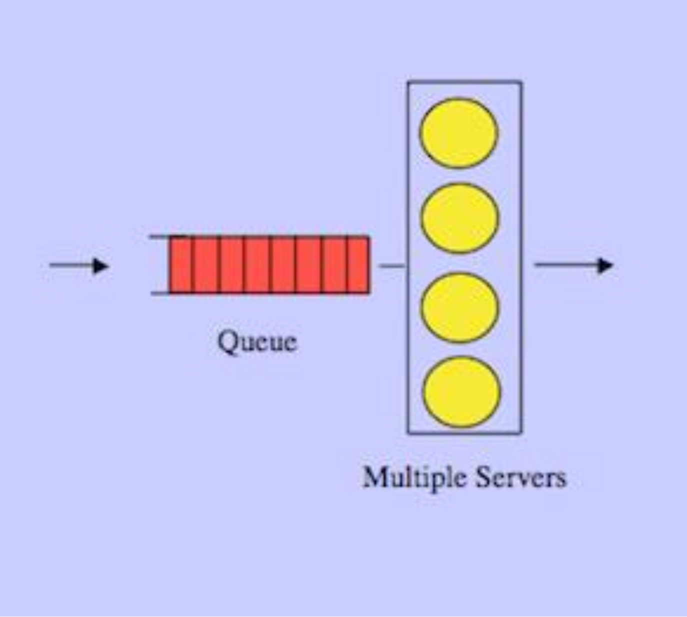
- Channel capacity allocated for a user is not fixed; depends on usage.

Static Channel Allocation

- Using FDM or TDM to divide channel capacity among N users
- Inefficient bandwidth use: some users may be idle
- Users may be denied access even when other users do not use there allocated capacity
- Long time service delay T

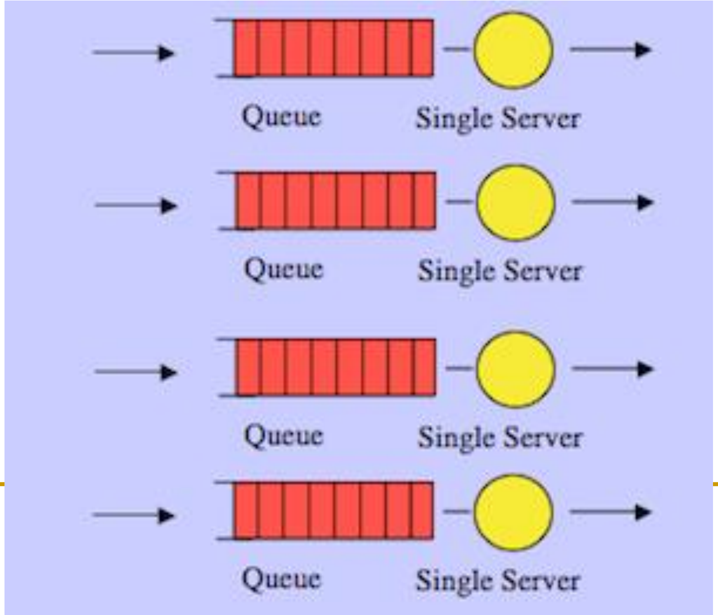
Static Channel Allocation

- Delay in a single M/M/1 Queue
  - Channel can transfer C bits/sec
  - Frames arrive randomly with an average rate of λ frames/sec and the inter-arrival times are exponentially distributed
  - Frame length values has an exponential distribution with an average length of $1/\mu$ bits.
  - Mean delay of frames in the queue is given by: $T = \frac{1}{\mu C - \lambda}$
  - Example: C=100 Mbps, $1/\mu$=10000 bits, λ=5000 frames/sec, T=200 μsec



Static Channel Allocation

- Delay if we divide the channel into N sections
  - Assume we divide the same stream into N smaller streams and serve each of them in a separate queue
  - There will be N channels with a capacity of C/N bits/sec for each
  - There will be N streams with an average rate of λ/N frames/sec each
  - Mean delay of each queue: $T_N = \frac{1}{\mu\left(\frac{C}{N}\right)-\frac{\lambda}{N}} = \frac{N}{\mu C-\lambda} = NT$
  - Example: If we divide the above queue into 4 sections, $T_N = 800\ \mu sec$



Dynamic Channel Allocation

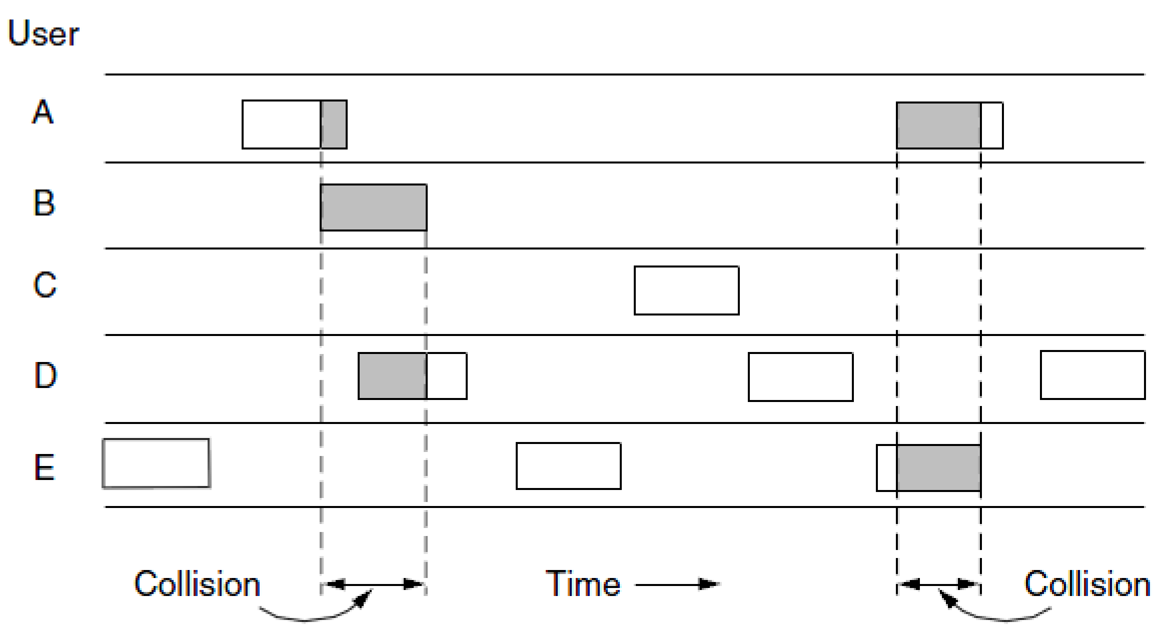
- In data communication, the peak to mean ratio of traffic can be very high.
- In many applications, users require the channel in random times
- Static allocation will be a waste of channel resources
- It is best to assign the channel based on user demand
- Different protocols for coordination:
  - ALOHA : pure and slotted
  - CSMA : carrier sense multiple access protocols
  - Ethernet
  - Wireless LAN protocols

Dynamic Channel Allocation

- Assumptions for analysis of dynamic channel allocation algorithms:
  - Station model:
    - N independent stations generating frames within interval Δt with probability = $\lambda \Delta t$ where λ is frame rate (frames/second)
  - Single communication channel
  - Collision occurs when 2 frames are transmitted simultaneously
  - Time is
    - a) continuous, or
    - b) slotted (discrete intervals)
  - Stations may have the hardware to notice:
    - Collision of frames
    - The presence of another signal on the channel (carrier sense)

Multiple Access Protocols

- ALOHA:
  - Station transmits as soon as it has a frame
  - If a collision is detected, it waits for a random time interval and then retransmits



ALOHA Efficiency

- Notes and assumptions:
  - Large number of stations
  - Frames of equal length
  - Transmit time for frame on the channel is normalized to unity
  - Stations can sense channel collision and re-try transmission if there is a collision
- Poisson distribution:
  - Poisson distribution is drived from the binomial distribution:
  - If event happens with probability p, the probability that the event happens exactly X times in N trials is:

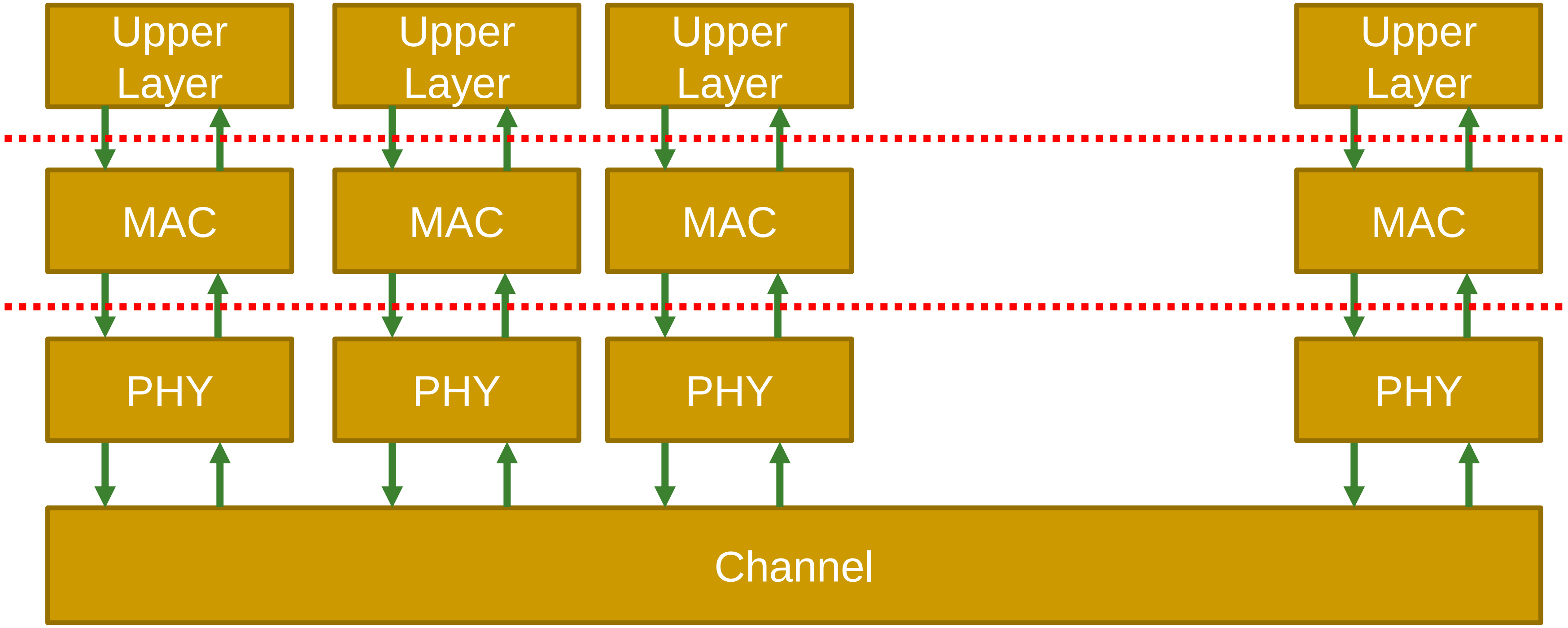
$$P(X) = \binom{X}{N} p^{X} (1-p)^{N-X}$$

  - If N is large and p is not close to 0 or 1 we get a Normal distribution
  - If N is large and p is small (rare event) we get a Poisson distribution
  - Probability of *k* events in a given time interval:

$$P_r[k] = \frac{G^k e^{-G}}{k!}$$

System Model

- Frames are buffered at MAC
- MAC controls transmission of frames on the channel



ALOHA Efficiency

- ***Analysis:***
  - All stations together, generate an average of S <u>new</u> frames per frame time
    - If S>1, every frame suffers a collision, so for reasonable operation, 0<S<1
    - A station does not send a new frame until the old frame has been transmitted successfully. So, S can be seen as a measure of throughput as well.
  - Probability of k attempts per frame time by all stations, old and new combined is Poisson with mean G per frame time.
  - Low load$\Rightarrow$ rare collision $\Rightarrow$ $S \approx G$
  - Increase the load $\Rightarrow$ More collisions $\Rightarrow$ $G>S$
  - Throughput is then the offered load, G, times the probability of no collision, P_0
    $\Rightarrow$ $S=G \times P_0$

ALOHA Efficiency

- Probability of k frames generated per frame-time (t) is (Poisson distribution)

$$P_r[k] = \frac{G^k e^{-G}}{k!}$$

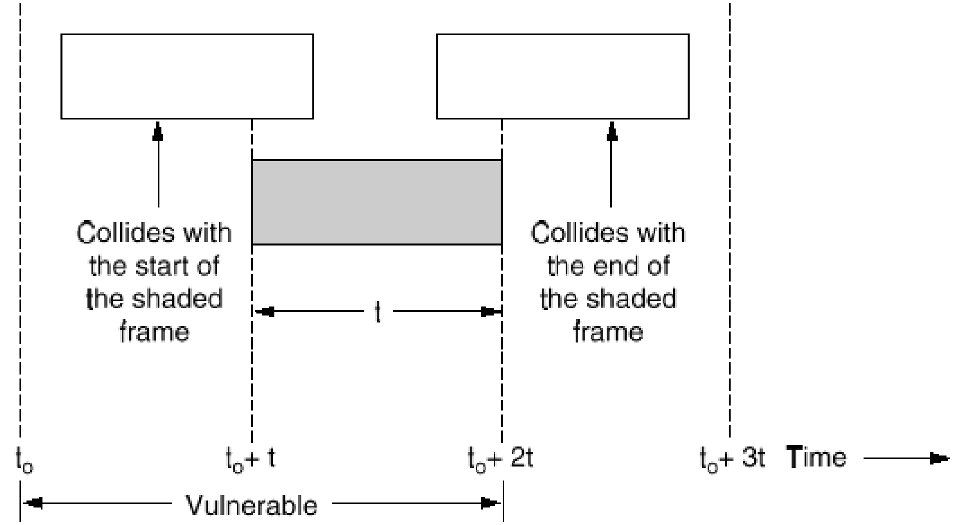
- Probability that there is no frame generated in a given interval t is

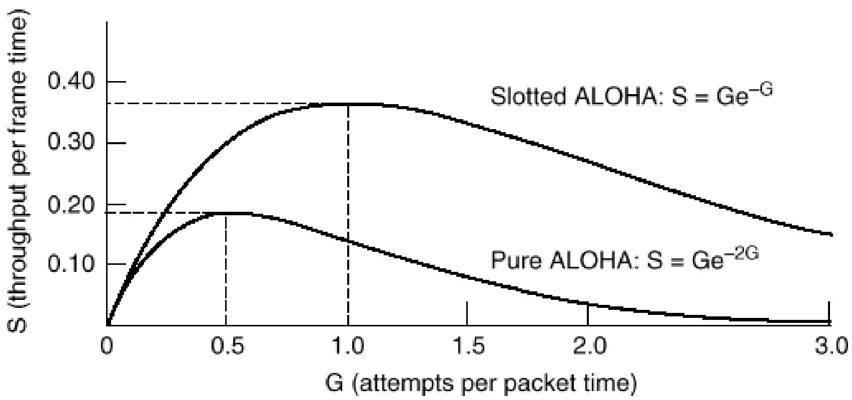
$$P_r[0] = e^{-G}$$

- No collision if no other frame generated in two frame-times.
- Mean number of frames generated during 2t sec is 2G so:

$$\Pr[k] = \frac{(2G)^k e^{-2G}}{k!} \Rightarrow \Pr[0] = e^{-2G}$$

- ALOHA Efficiency: $S = Ge^{-2G}$





Slotted ALOHA Efficiency

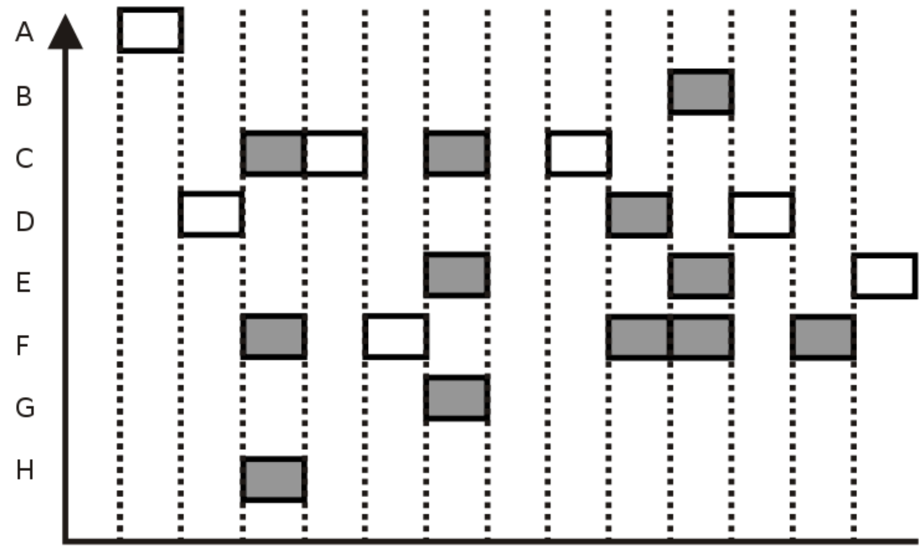
- Divide time in discrete intervals
- Users have to agree on slot boundaries
- In each slot, one or more users send their frames
- Probability of transmission success (no other frame is generated in a given interval) t is

$$\Pr[k] = \frac{(G)^k e^{-G}}{k!} \Rightarrow \Pr[0] = e^{-G}$$

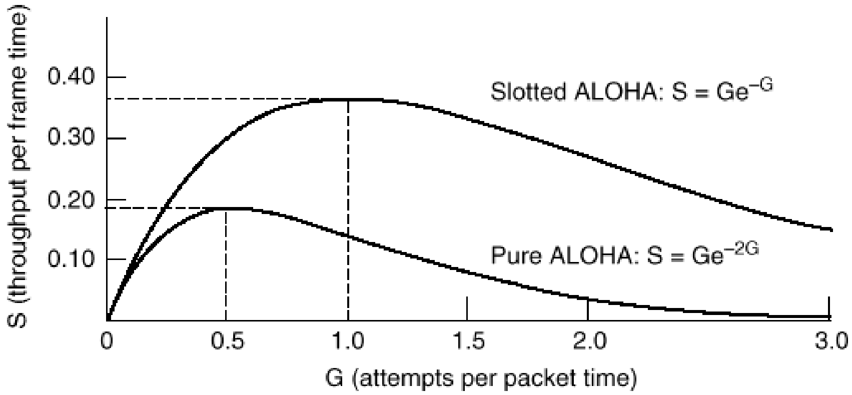
- Slotted ALOHA Efficiency:

$$S = Ge^{-G}$$

- Maximum channel utilization:
  - Pure Aloha : 18.4%
  - Slotted Aloha : 36.8% (37% empty slots, 26% collisions)



Slotted ALOHA protocol (shaded slots indicate collision)



Impact of Load

- Probability of transmission failure for a single frame in slotted ALOHA:

$$P = (1 - e^{-G})$$

- Probability of a transmission requiring exactly k attempts:

$$P_k = e^{-G}(1 - e^{-G})^{k-1}$$

- Expected Number of transmissions per frame is:

$$E = \sum_{k=1}^{\infty} kP_k = \sum_{k=1}^{\infty} ke^{-G}(1 - e^{-G})^{k-1} = e^{G}$$

- For ALOHA, with the same analysis, $E=e^{2G}$
- A small increase in channel load, G can results in exponentially increase in transmissions (most of which cause collisions) resulting:
  - Reduced system throughput (S)
  - Longer queues in MAC layer for accumulated, waiting frames.
  - Increase in average frame delay

Delay Analysis

- Frame transmission duration: X
- Frame propagation time: t_{prop}
- Average back-off time: B
- Average number of transmission attempts per frame (ALOHA): $G/S=e^{2G}$
- Average number of unsuccessful attempts per frame: $\varepsilon=G/S\text{-}1=e^{2G}\text{-}1$
- Successful transmission requires $X+t_{prop}$ seconds and each re-transmission requires $2t_{prop}+X+B$ seconds
- Therefore, average MAC delay in ALOHA is given by: $E[T_{ALOHA}]=X+t_{prop}+(e^{2G}-1)(X+2t_{prop}+B)$
- Normally, back-off time is uniformly distributed between 1 and K packet transmission times and therefore, $B=(K+1)X/2$
- For Slotted ALOHA, the MAC delay is given by:

$$E[T_{ALOHA}]=X+t_{prop}+(e^{G}-1)(X+2t_{prop}+B)$$

MAC Layer trade offs

- **Normalized Transfer Delay** (NTD):
  - A measure of delay caused by access control algorithm (Collisions, reservations, etc).

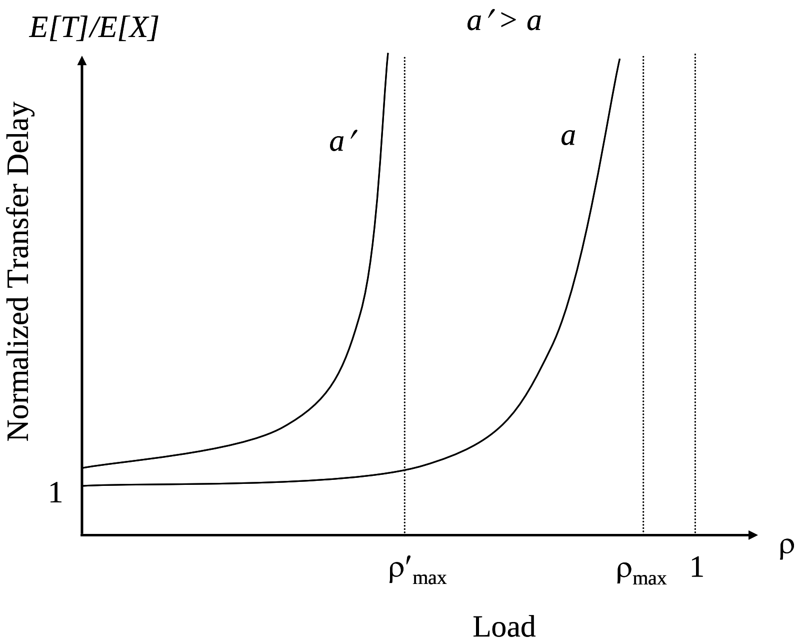
$$\boxed{NTD = \frac{E[T] \rightarrow (\text{Average Transfer Delay})}{E[X] \rightarrow (\text{Average Frame Transmission Time})}}$$

- **Normalized Delay Bandwidth** (a):
  - Number of lost frames due to a collision is proportional to *a*
  - Example: 1000 bit frames, 2 Mbps channel, 40 msec. one-way delay $\Rightarrow$

$$\boxed{a = \frac{\text{One way delay} \times \text{Bandwidth}}{\text{Average Frame Size}}}$$

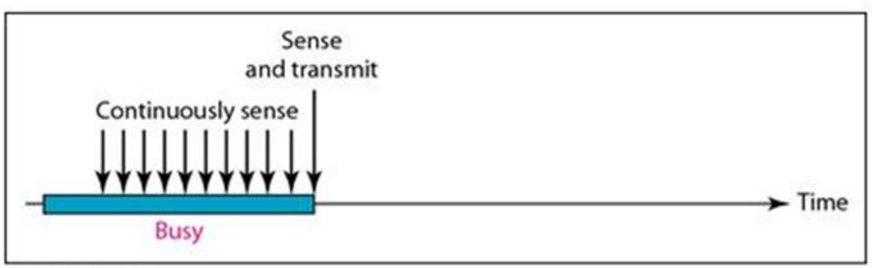
$$a = \frac{2 \times 10^6 \times 40 \times 10^{-3}}{1000} = 80$$

- For ALOHA type MACs, the trend is:
  - When Load is low, NTD is near 1. NTD increases steadily as load is increased.
  - Maximum achievable load is usually much less than 1.
  - Maximum achievable load decreases when *a* is increased ($\Rightarrow$ Cost of MAC is higher for long distance or high speed links)

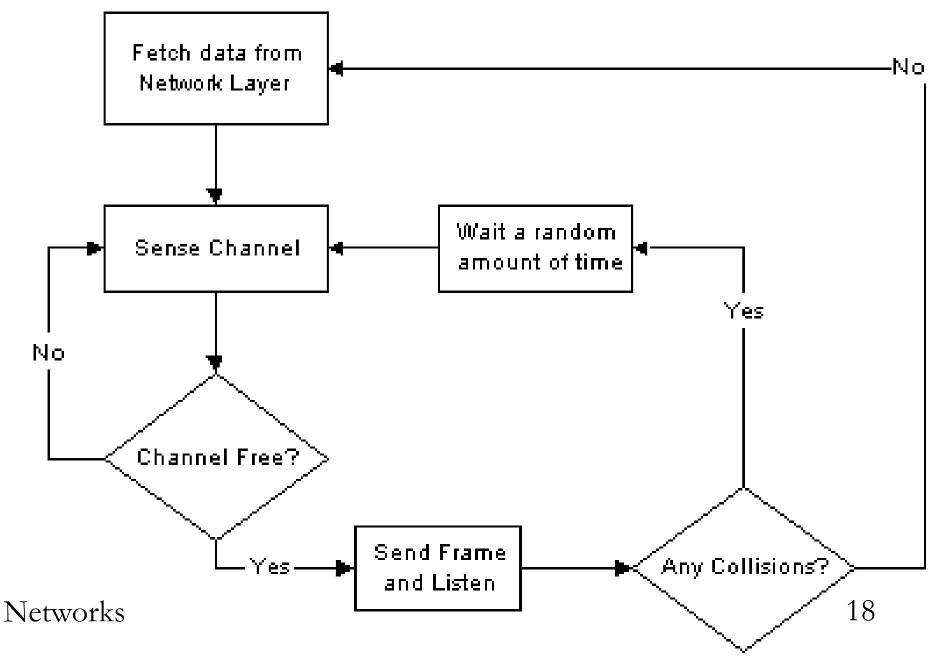


Carrier Sense Multiple Access Protocols (CSMA)

- Idea: The number of collisions can be reduced by sensing the carrier before transmission
- *1-persistent*
  - Listen to channel and transmit as soon as channel becomes idle
  - If collision, wait random time, and try again

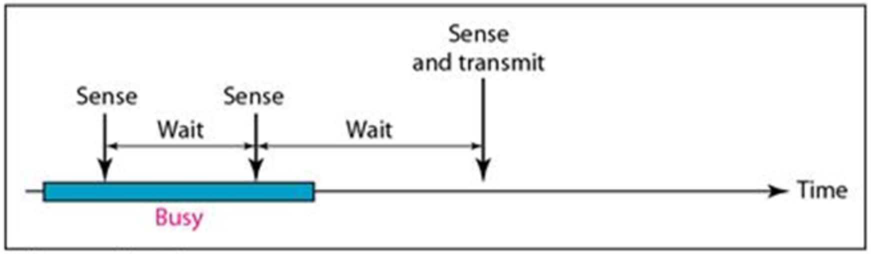


a. 1-persistent

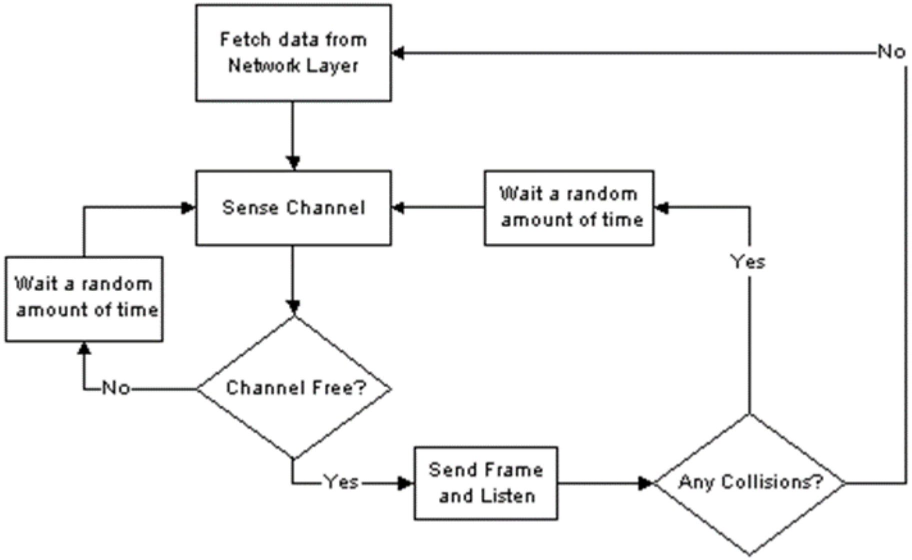


CSMA Protocols

- *Non-persistent*:
  - Sense channel; if idle, transmit. If not idle, wait a random period before sensing the channel
  - Better utilisation, however, longer delays

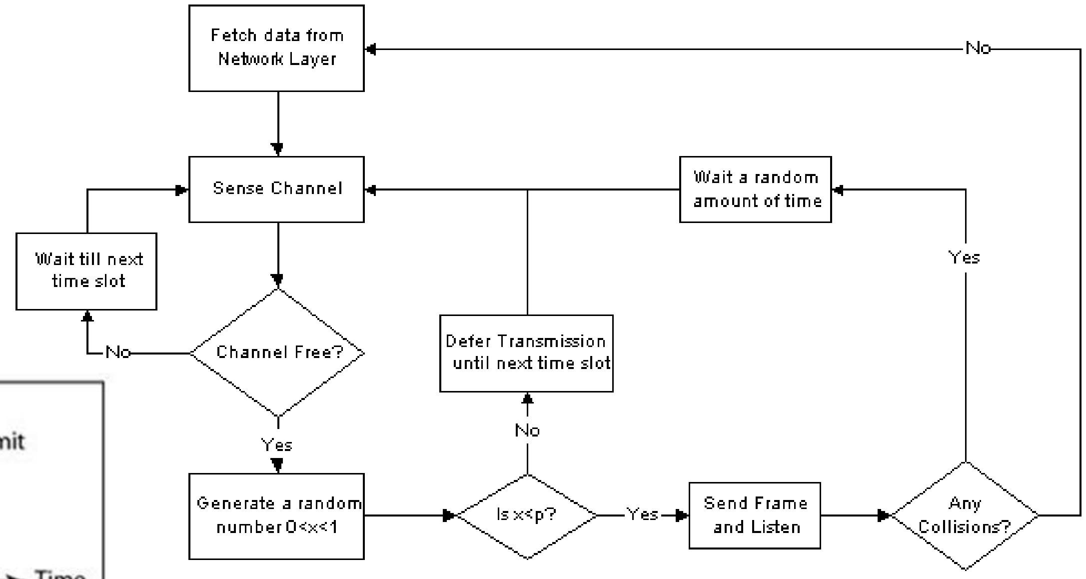


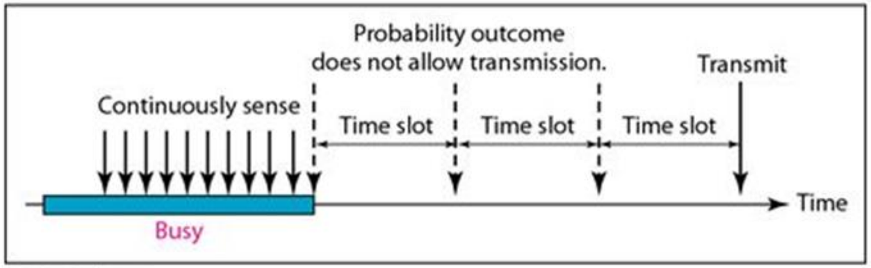
b. Nonpersistent



CSMA Protocols

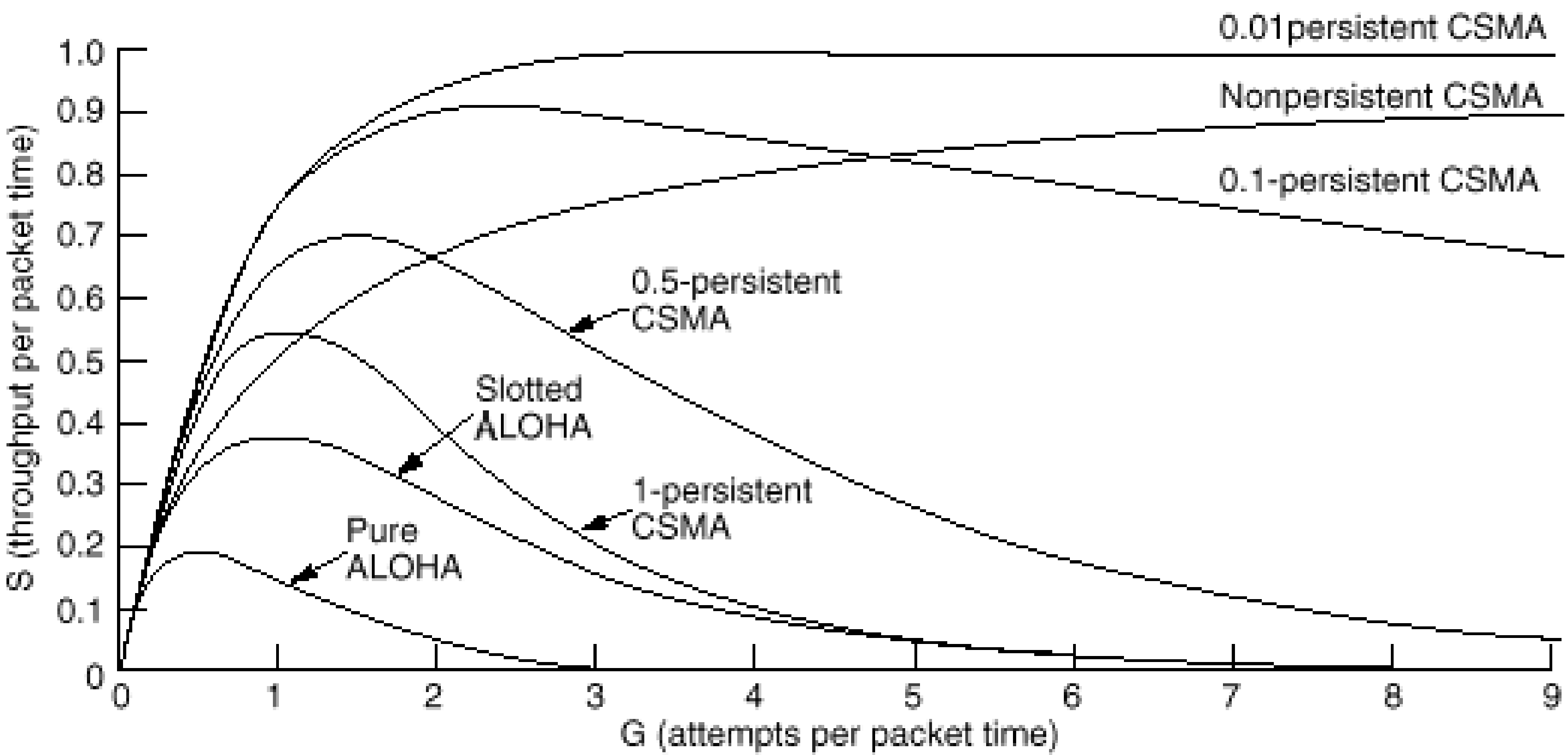
- *P-persistent:*
  - Sense channel, if idle, transmit with probability p, defer With probability 1-p to the next slot.
  - If next slot idle repeat the same algorithm
  - If busy the first time, wait till next time slot and try again





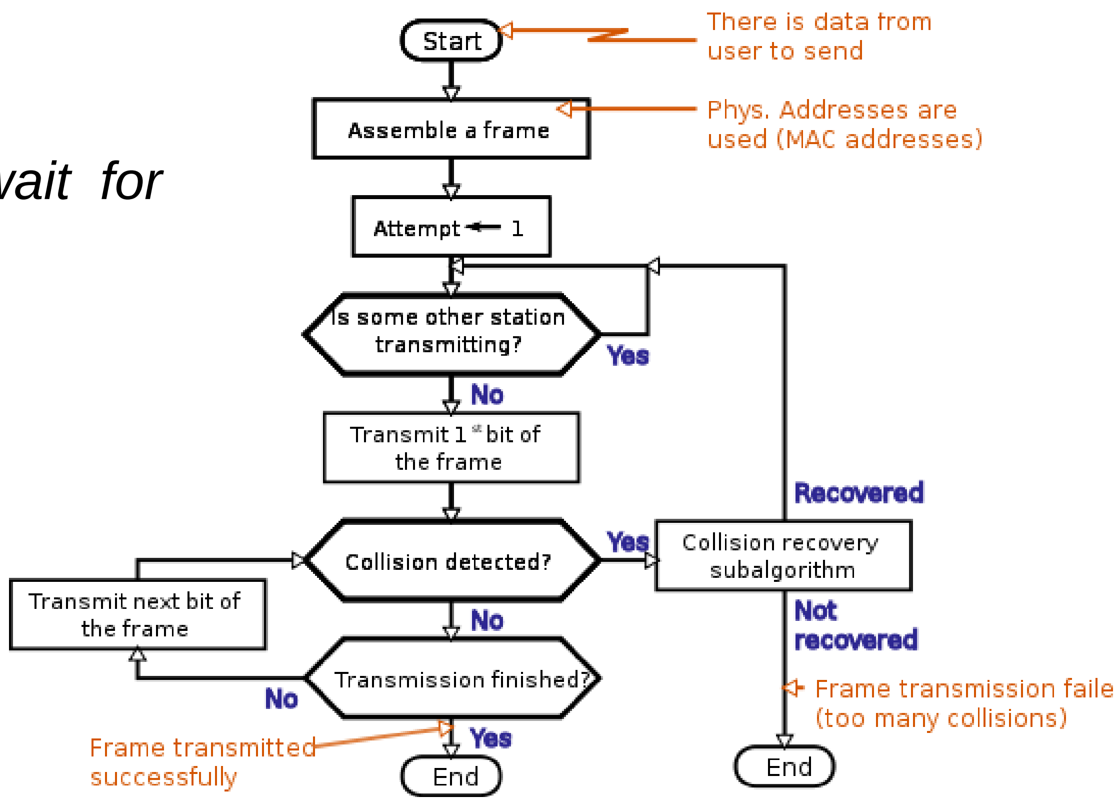
c. p-persistent

Throughput of ALOHA and CSMA

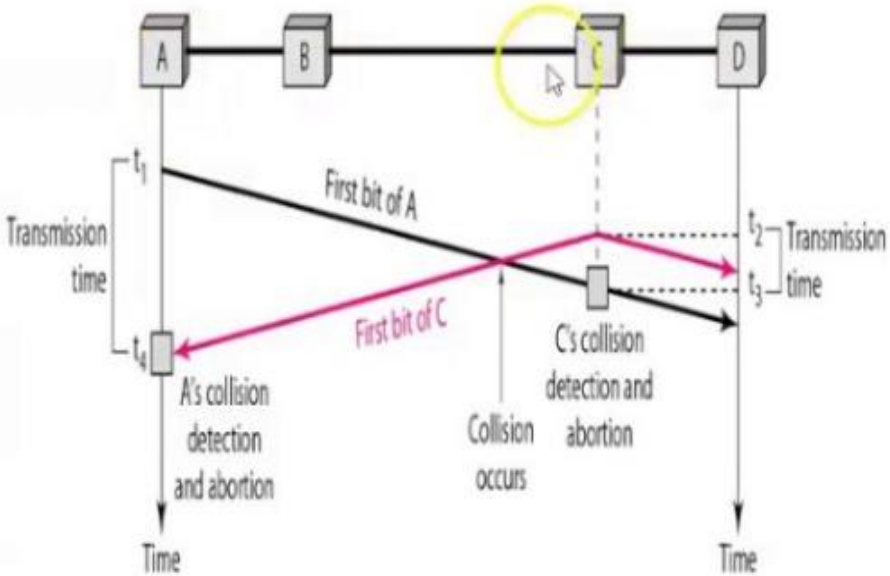


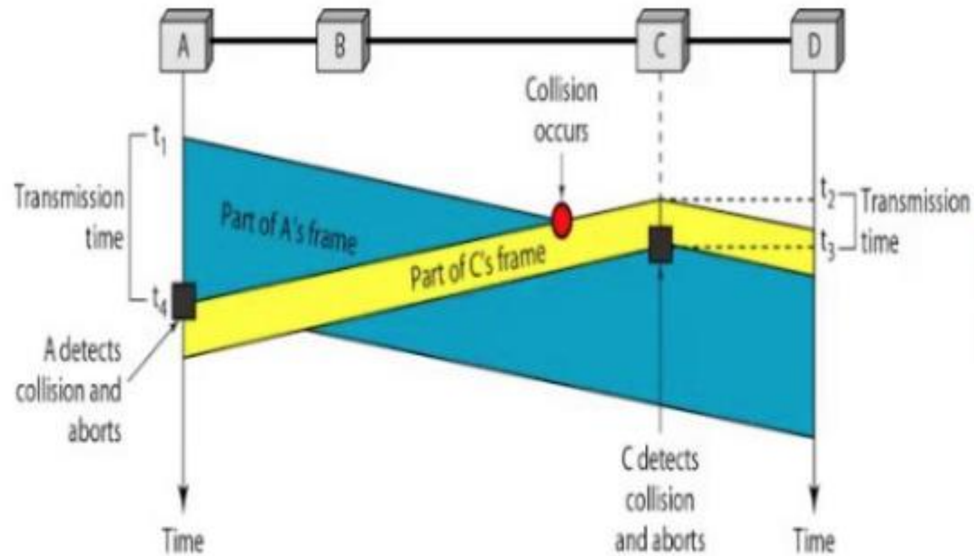
CSMA with Collision Detection

- Widely used on LANs in MAC sublayer (IEEE 802.3; Ethernet)
- Idea: *stop directly after detecting collision and wait for a random period*



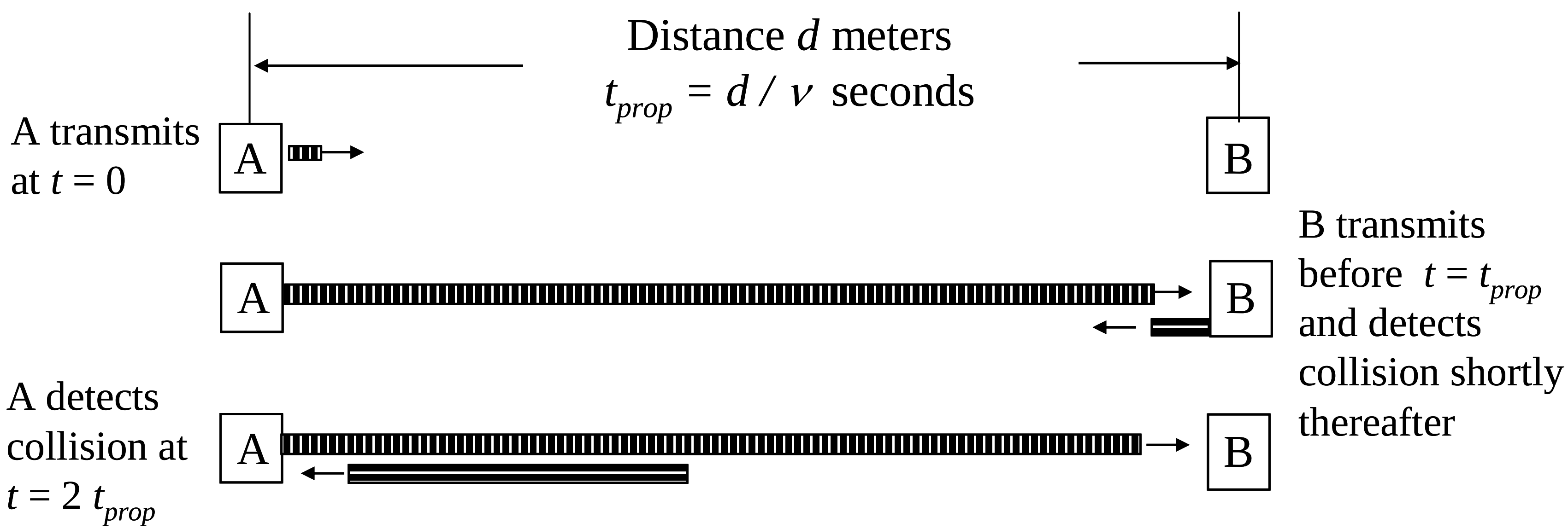
CSMA with Collision Detection





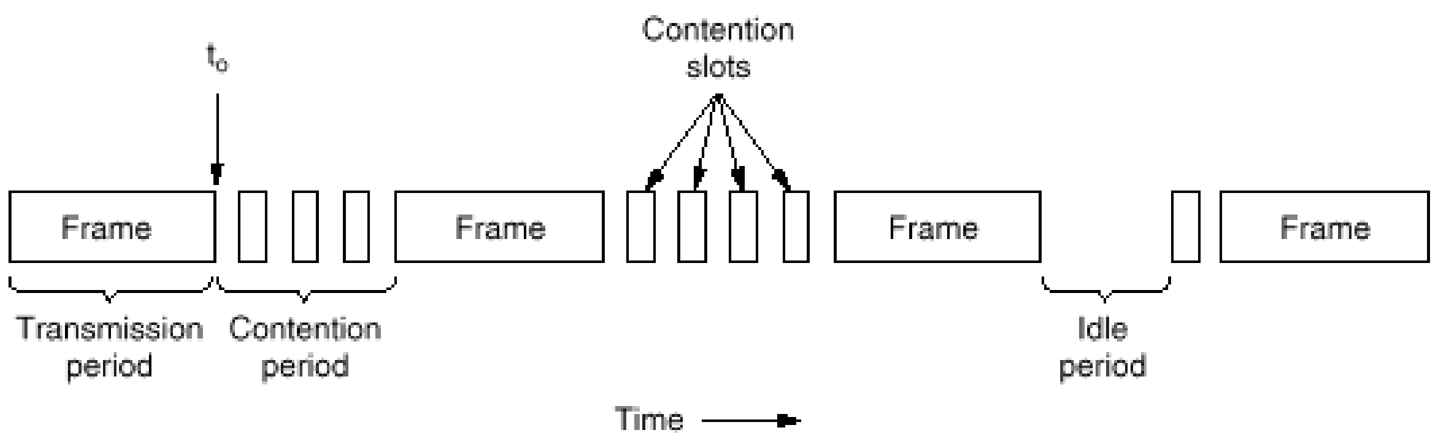
CSMA with Collision Detection

- How long does it take to detect collision?
  - Assuming a max travel time of t_{prop}, it takes $2t_{prop}$ to be sure (contention period) (10 μsec on 1 km cable)



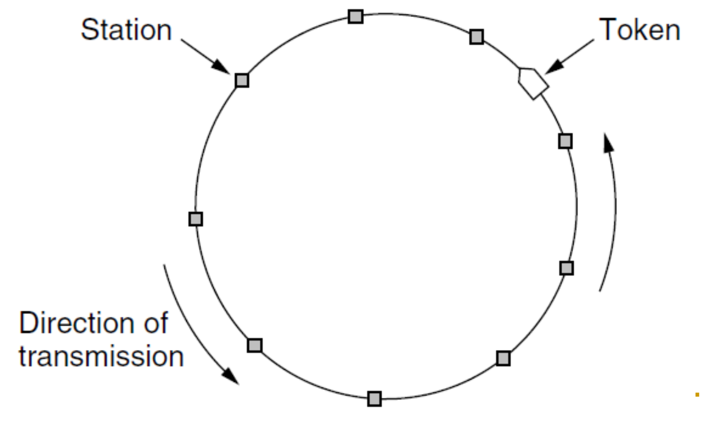
CSMA with Collision Detection

- Although CSMA/CD avoids collisions once a station has seized the channel; collisions still occurs during the contention period
- Contention period may become large for long (fibre) cables



Token Passing

- Some MAC protocols rely on token.
- The token represents permission to send
- If a station has a frame queued for transmission when it receives the token, it can send that frame before it passes the token to the next station.
- If it has no queued frame, it simply passes the token.
- In a token ring protocol, the topology of the network is used to define the order in which stations send.
- Token passing can also be used in a bus mode where stations pass token to each other in a predefined order.
- Examples:
  - Token Ring
  - Token Bus
  - FDDI
  - RPR



IEEE 802 standards

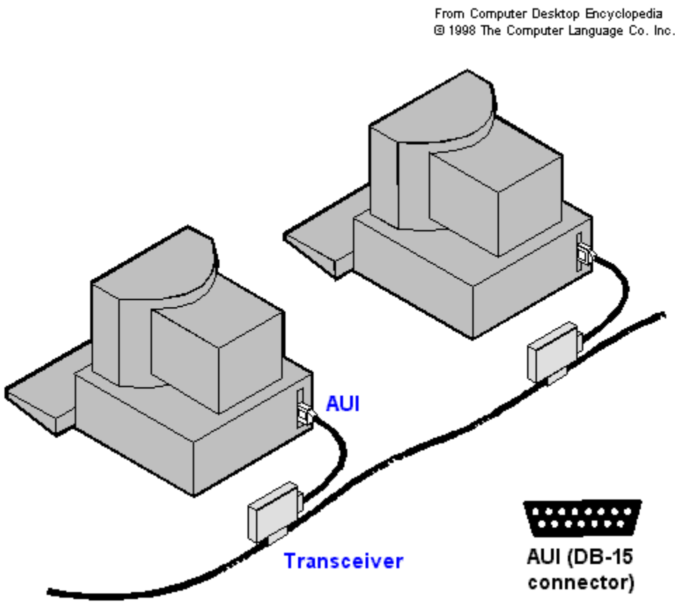
- IEEE 802 refers to a family of IEEE standards dealing with local area networks and metropolitan area networks:
  - IEEE 802: Overview & Architecture
  - IEEE 802.1 Bridging & Management
  - IEEE 802.2: Logical Link Control
  - IEEE 802.3: CSMA/CD Access Method (Ethernet)
  - IEEE 802.5: Token Ring Access Method
  - IEEE 802.11: Wireless Local Area Networks (LAN)
  - IEEE 802.15: Wireless Personal Area Networks (PAN)
  - IEEE 802.16: Broadband Wireless Metropolitan Area Networks (MAN)
  - IEEE 802.17: Resilient Packet Rings (RPR)
  - IEEE 802.20: Mobile Broadband Wireless Access
  - IEEE 802.21: Media Independent Handoff
  - IEEE 802.22: Wireless Regional Area Network
  - IEEE 802.23: Emergency Services Working Group

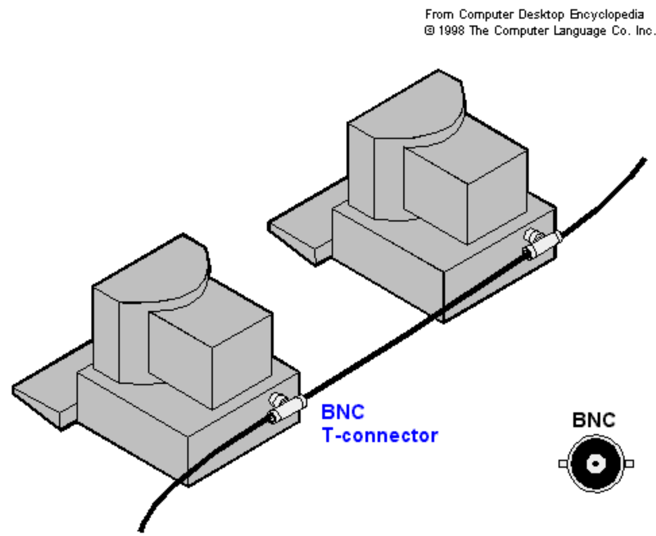
Ethernet

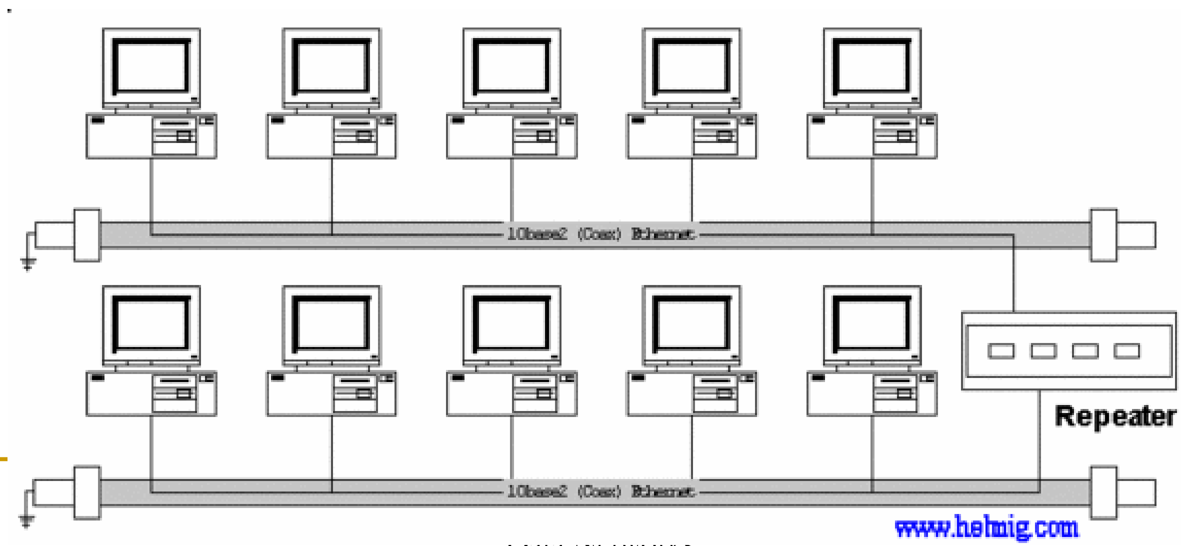
- Original design for 1-10 Mbps
- Various media, first used on 50 ohm coaxial cable
- Started as ALOHA system on Hawaiian Islands
- Carrier sensing was added by Xerox

Name	Cable	Max. segment	Nodes/seg.	Advantages
10Base5	Thick coax	500 m	100	Good for backbones
10Base2	Thin coax	200 m	30	Cheapest system
10Base-T	Twisted pair	100 m	1024	Easy maintenance
10Base-F	Fiber optics	2000 m	1024	Best between buildings

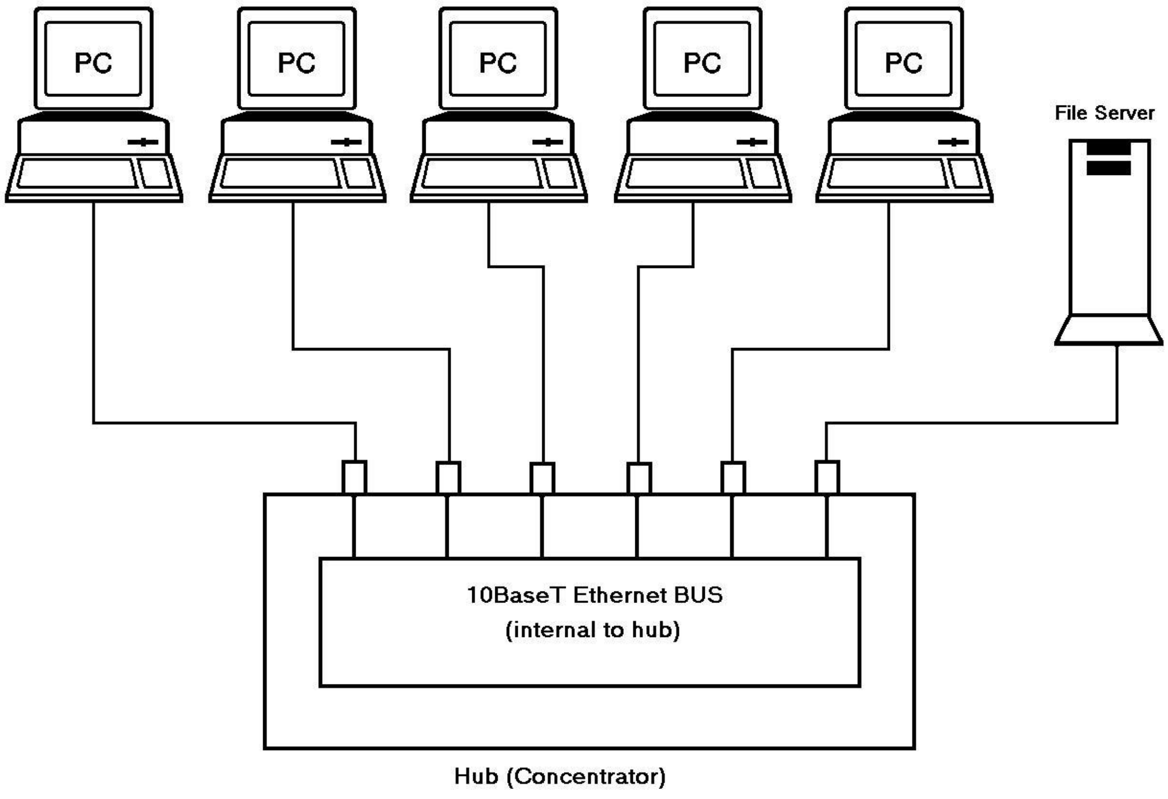
Ethernet Topology



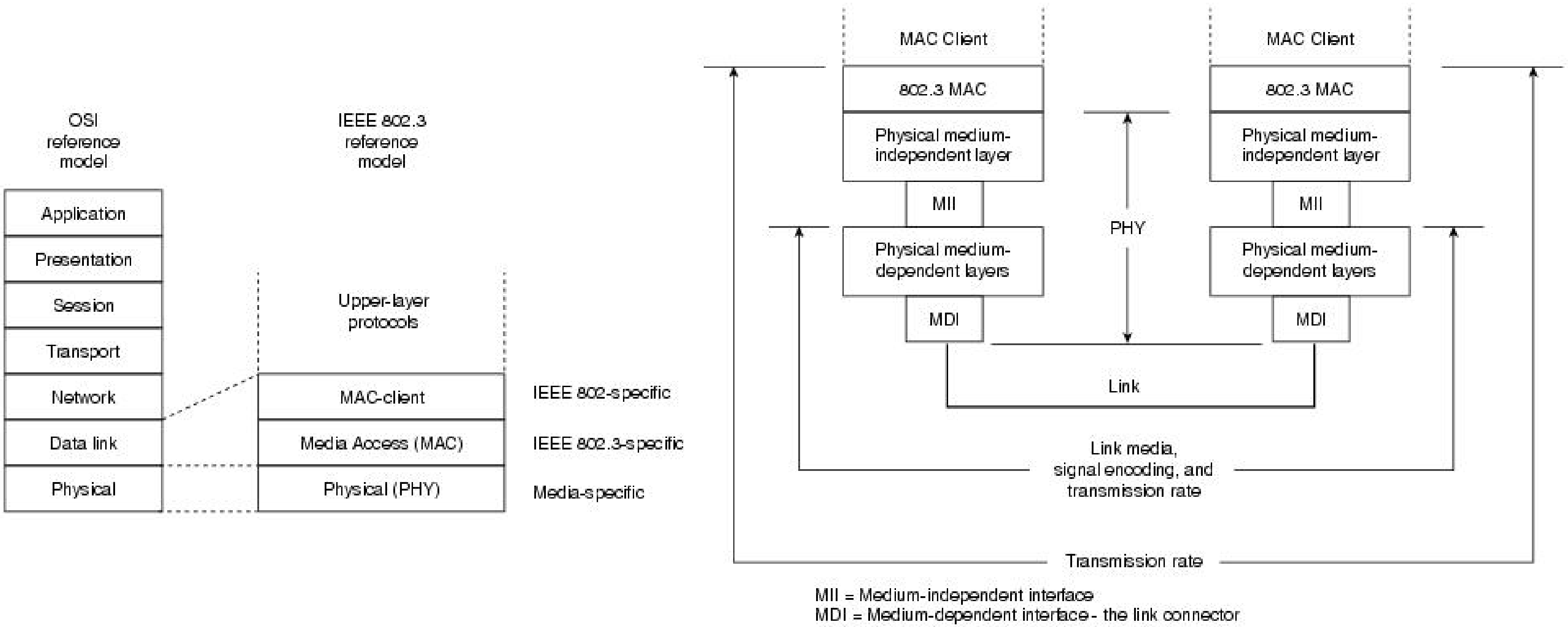




Ethernet Topology



Ethernet Reference Model



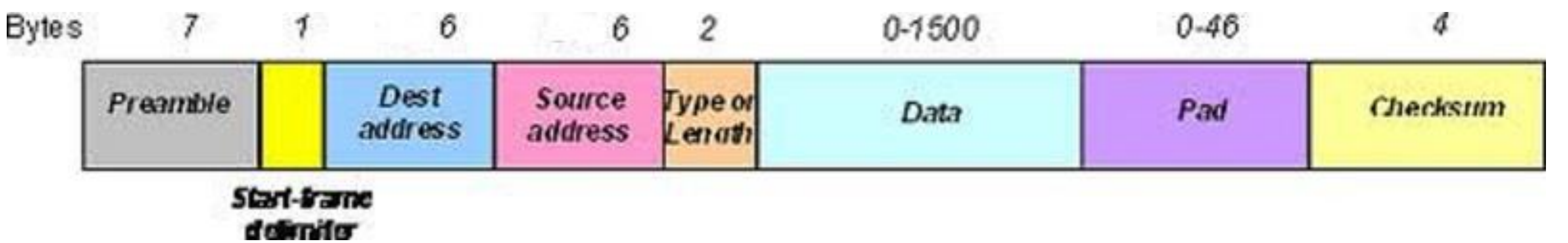
802.3 Frame Structure

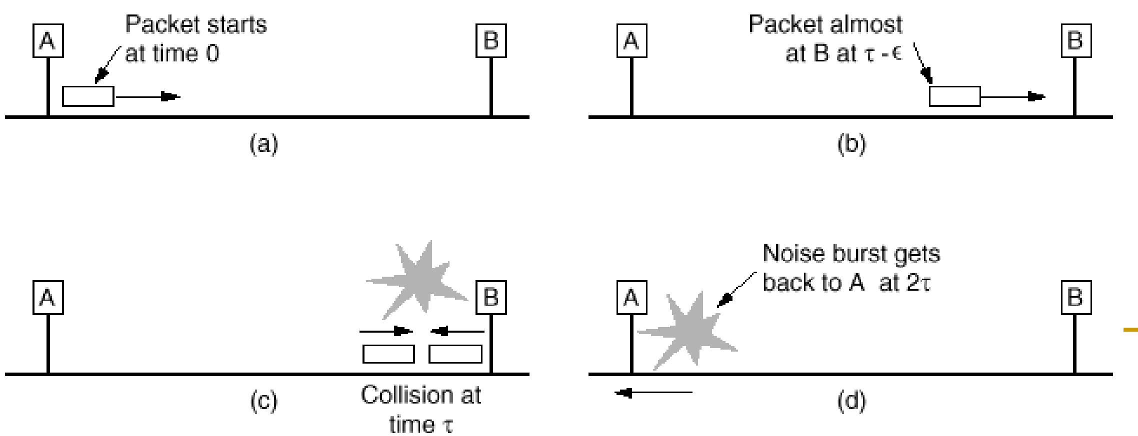
- Preamble: 7 x 1010.1010 pattern
  - Creates 10 MHz square wave of 5.6 microsecond for synchronization
- Start field: 1010.1011 denotes start of frame

Ethernet Frame Format

802.3 Framing

- Length field: 0-1500 bytes
- Data: payload
- Ethernet frames should be long enough to allow collision detection at the source. Therefore, a Pad field is defined to extend the length of short frames.
- Pad: ensure minimum frame length = 64 bytes.





802.3 Pad Field

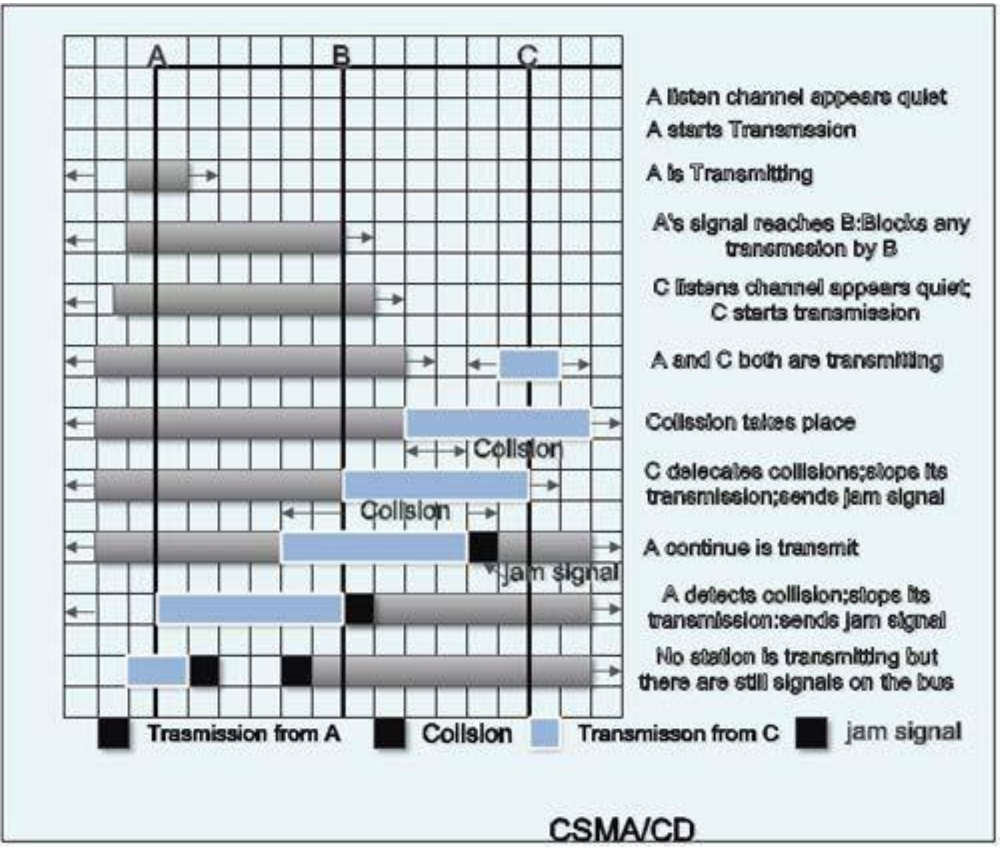
- LAN Length (L) = 500 m (per segment) x 5 segments = 2500 meters
- Velocity of propagation on the cable (V) = $2 * 10^8$ meters/sec
- Delay added by repeater (D) = ~3uSec x 2 (Bi-Direction) x 4 Repeaters = 24uSec
- Round Trip Delay (RTD) = (Total Distance/V) + Repeater Delays (D)

  Total Distance/V = $(2*2500/2 * 10^8)$ = $25 * 10^{-6}$ sec or 25usec

  Hence RTD = 25 + 24 = 49 usec
- Now, time to transmit 64 bytes = 512 bits / $10 * 10^6$ = $51.2\ 10^{-6}$ sec or 51.2 usec (referred to as slot time in the 802.3) which is greater than the RTD of 49 usec.
- Hence the minimum frame size for the IEEE 802.3 (Ethernet) is 64 bytes.

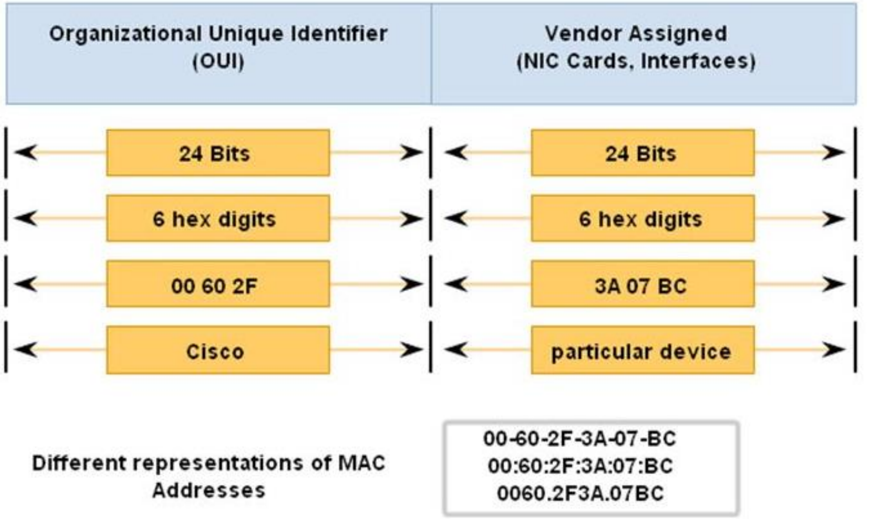
802.3 Framing

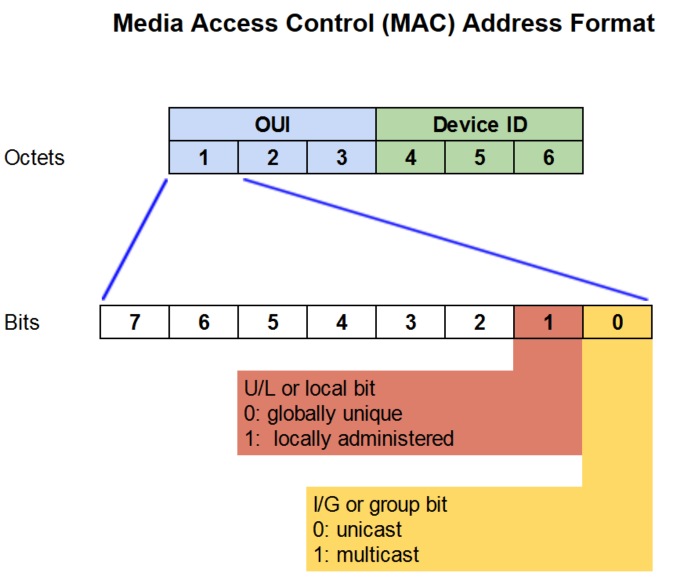
- Jam Signal: When a collision is detected during a frame transmission, the transmission is not terminated immediately. A station noting a collision has occurred sends a 4 to 6 bytes long pattern composed of 16 1-0 bit combinations.
- The purpose of this is to ensure that any other nodes which may currently be receiving a frame will receive the jam signal in place of the correct 32-bit MAC CRC, this causes the other receivers to discard the frame due to a CRC error.



802.3 MAC Address

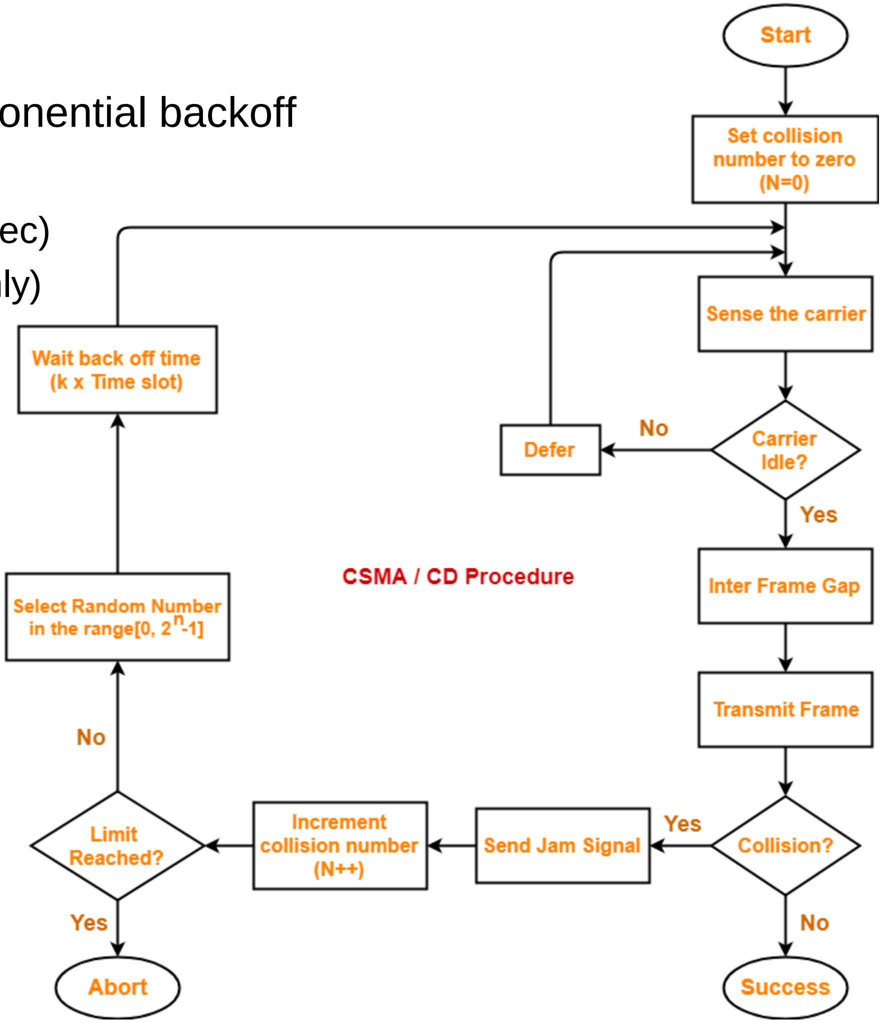
- An Ethernet MAC address consists of a 6-digit hexadecimal vendor OUI code followed by a 6-digit hexadecimal vendor-assigned value
- OUI address is managed by IEEE. It has two bits that specify:
  - Address is unicast or multicast
  - Address is locally administered or globally unique





802.3 MAC

- 802.3 MAC uses CSMS/CD with binary exponential backoff
- Binary Exponential Back off
  - After collision wait 0 or more slots (of 51.2 msec)
  - First collision: wait 0 or 1 slot (choose randomly)
  - Second collision: wait 0, 1, 2 or 3 slots
  - N-th collision: wait 0 - 2^{N-1} slots
  - N max = 10 => wait between 0 - 1023 slots
  - Give up after 16 trials and leave recovery to higher layers
- Algorithm ensures low latency at low load and fairly resolves collisions when the load is high.



802.3 Performance Analysis

- Assume constant transmission probability p (no exp back off)
- Probability A of acquiring a slot (by one of k stations):

$$A = kp(1-p)^{k-1}$$

- Probability that contention interval, W, has precisely j slots:

$$A(1-A)^{j-1}$$

- Therefore, the average #slots per contention is given by

$$\sum_{j=0}^{\infty} jA(1-A)^{j-1} = \frac{1}{A}$$

- Each slot has a duration interval 2τ
- Mean contention interval is $W = 2\tau/A$
- p optimal (= 1/k) $\Rightarrow$ A = $(1\text{-}1/k)^{k\text{-}1}$ =1/e (for k $\rightarrow\infty$ heavy load) $\Rightarrow$ $W=2\tau e=5.4\tau$

802.3 Standard

- Channel Utilization
  - Assume each frame takes T seconds to be transmitted.
  - When many stations have frames to send

$$U = \frac{T}{T + 2\tau / A} = \frac{1}{1 + 2BLe / cF}$$

  - F=frame length,
  - L =cable length,
  - B=network rate,
  - c= propagation speed,
  - e=contention slots per frame
  - (Note: τ=L/c and T=F/B)

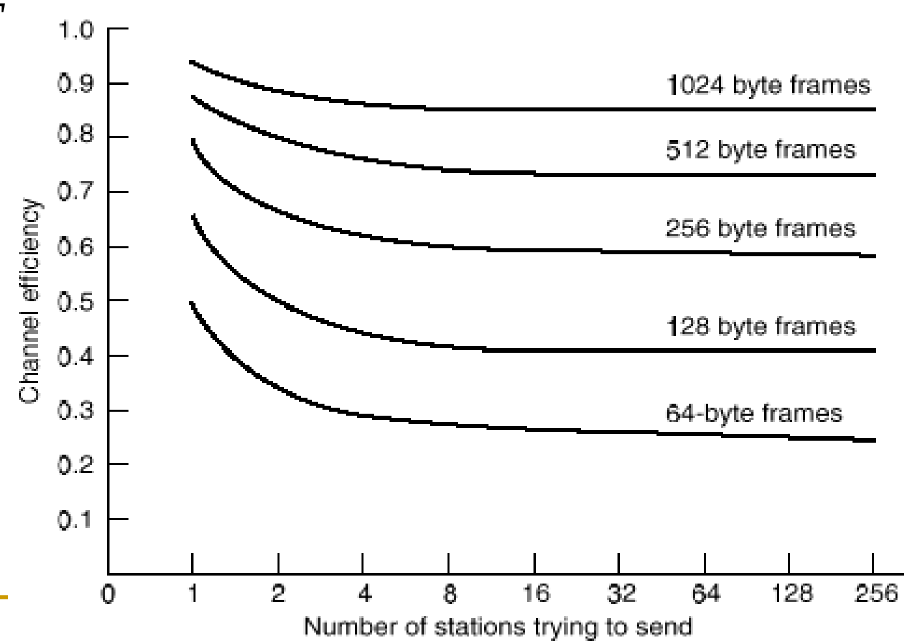
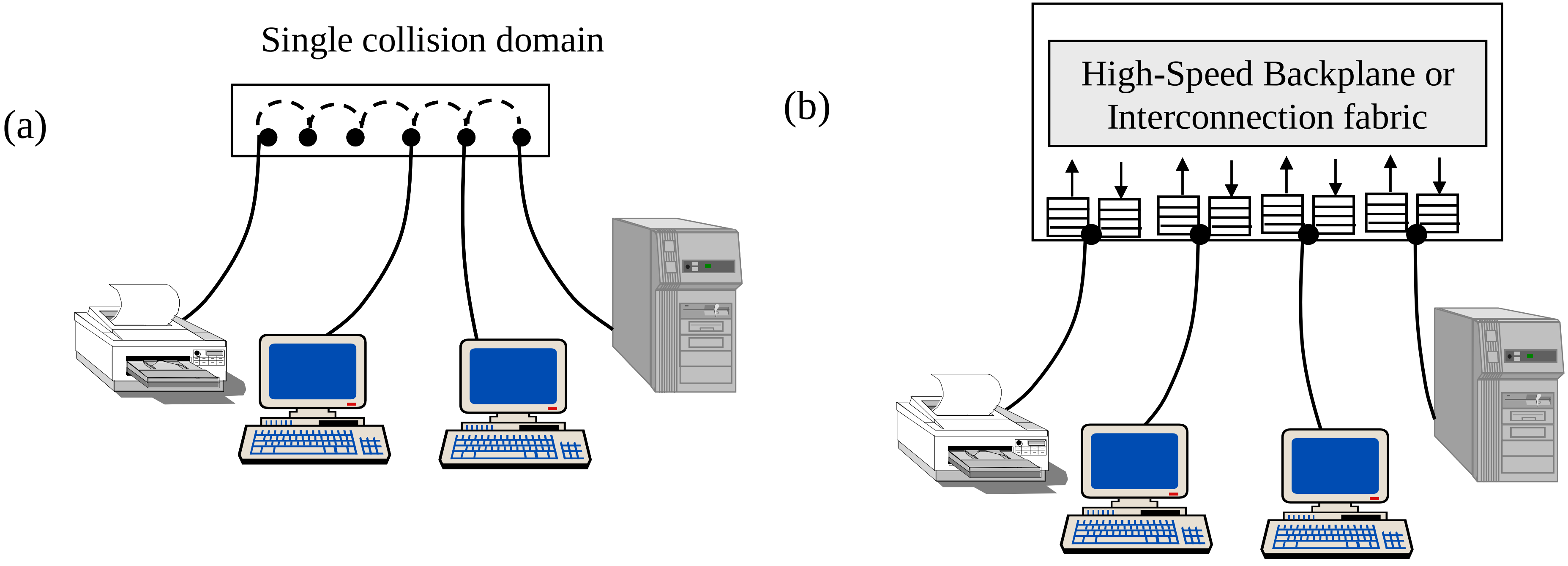
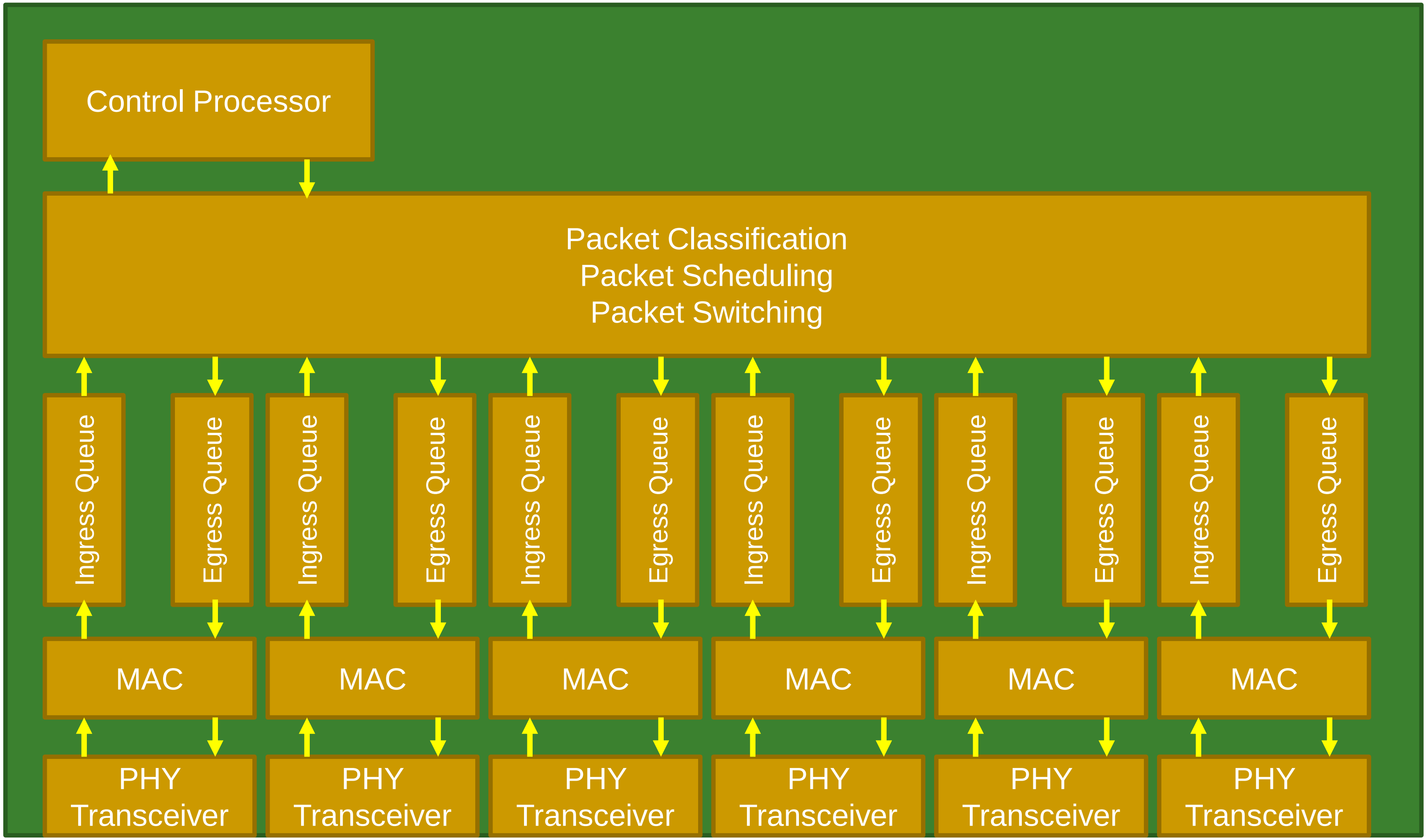


Fig. 4-23. Efficiency of 802.3 at 10 Mbps with 512-bit slot times.

Ethernet Switch



Basic Ethernet Switch Architecture



Ethernet Switch

- To improve the performance of the system, an Ethernet switch can be used
- Each port of the system receives the frame of only one sender and stores it in the switch ingress buffers.
- Central switch fabric reads the frames from ingress buffers and forwards it to the egress output buffers.
- There will be no media collision
- Depending on the traffic pattern, buffers can be filled which may results packet drop.

Fast Ethernet

- Media Transmission Speed: 100 Mbps
- No multi-drop cables
- Two modes of operation
  - HUB Mode: a hub is a single collision domain. CSMA/CD is used
  - Switched Mode: frames are buffered and switched in the hub/switch. No CSMA/CD. (100BaseFx works only in this mode)

Fast Ethernet

- Types of Media
  - Twisted Pair: Most Common
    - 100 BaseTX: Operates in full duplex mode. Uses two UTP5 wires, one for transmission and one for reception. 4B/5B encoding at 125 MHz clock to send 100 Mbps.
  - Fiber Optics
    - 100BaseFX: Operates in full duplex mode. Uses two strands of multimode fibers to transmit and receive 100 Mbps in each directions up to 2km.
    - 100BASE-SX: 100 Mbit/s Ethernet over multi-mode fiber. Maximum length is 300 meters.
    - 100BASE-BX10: 100 Mbit/s Ethernet bidirectionally over a single strand of single-mode optical fiber.
    - 100BASE-LX10: 100 Mbit/s Ethernet up to 10 km over a pair of single-mode fibers, using 1310 wavelength, full-duplex only.

Gigabit Ethernet

- Media Transmission Speed: 1 Gbps
- Only Full duplex mode: send and receive independently to a switch and no media contention
- Physical interfaces
  - 1000 base-X:
    - Various standards for optical fiber-based transmission
    - Supports multimode and single mode fibers
    - Distance up to 120km
  - 1000base-T:
    - Various standards for copper-based media
    - Distance up to 100m

10 Gigabit Ethernet

- Media Transmission Speed: 10 Gbps
- Physical interfaces
  - Copper based backplane:
    - Used in backplane for high-speed communication between cards
    - Distance up 1m
  - Copper based cables:
    - Coaxial cable, Twin-axial cables and twisted pairs
    - Distance up to 100m
  - Fiber-optic based cables:
    - Multi-mode and single-mode fibers
    - Distance up to 80km

25 Gigabit Ethernet

- Media Transmission Speed: 25 Gbps
- Physical interfaces
  - Copper based backplane:
    - Used in backplane for high-speed communication between cards
    - Distance up 1m
  - Copper based cables:
    - Twin-axial cables up to 8m
    - Twisted pair cable up to 30m
  - Fiber-optic based cables:
    - Multi-mode fiber up to 100m
    - Single-mode fiber up to 30km using CWDM

40 Gigabit Ethernet

- Media Transmission Speed: 40 Gbps
- Physical interfaces
  - Copper based backplane:
    - Used in backplane for high-speed communication between cards
    - Distance up 1m
  - Copper based cables:
    - Twin-axial cables up to 7m
    - Twisted pair cable up to 30m
  - Fiber-optic based cables:
    - Multi-mode fiber up to 150m
    - Single-mode fiber up to 40km

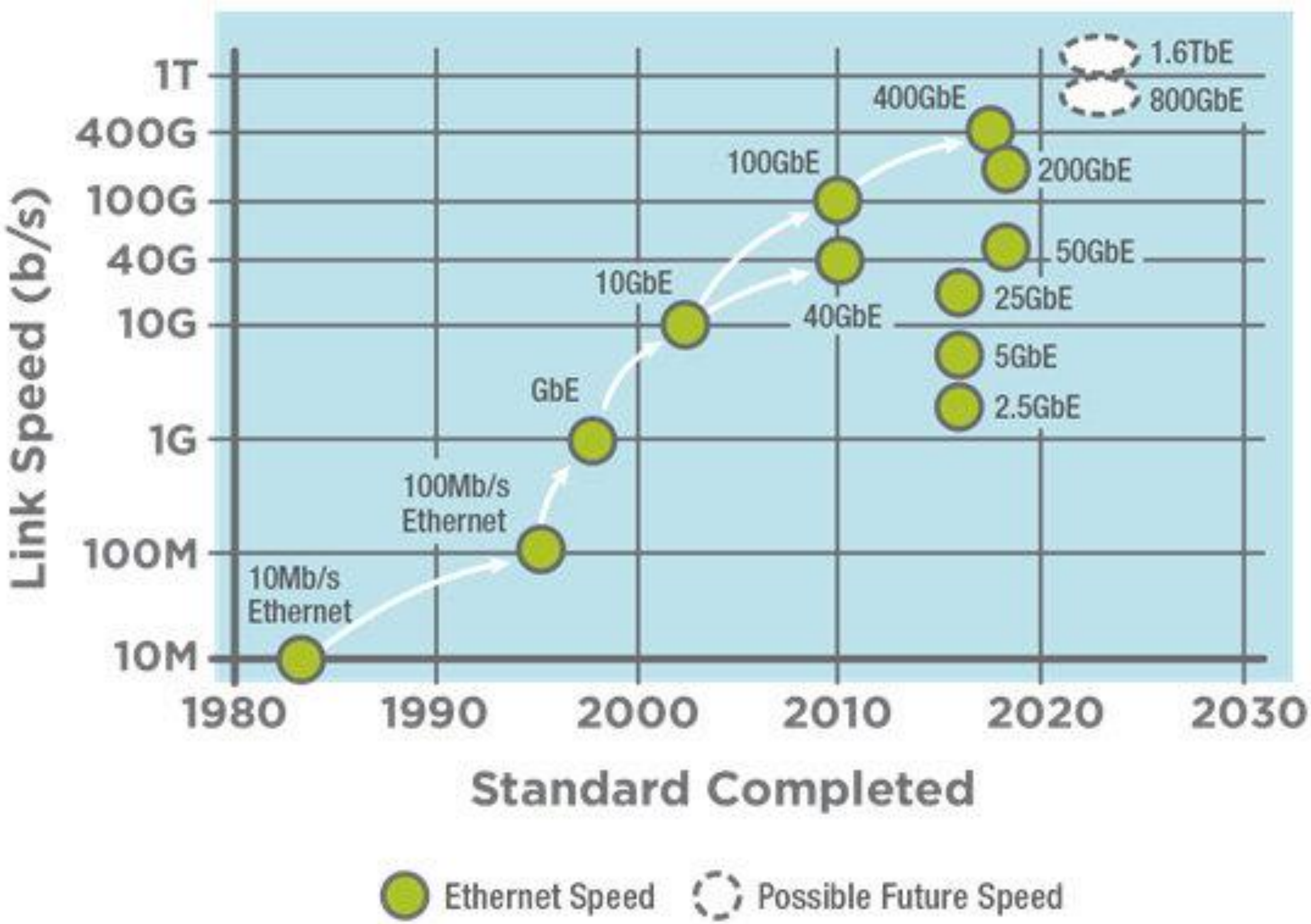
100 Gigabit Ethernet

- Media Transmission Speed: 100 Gbps
- Physical interfaces
  - Copper based backplane:
    - Used in backplane for high-speed communication between cards
    - Distance up 1m
  - Copper based cables:
    - Twin-axial cable
    - Distance up to 7m
  - Fiber-optic based cables:
    - Distance of 125m over multi-mode fiber
    - Distance of 80km over single mode fiber

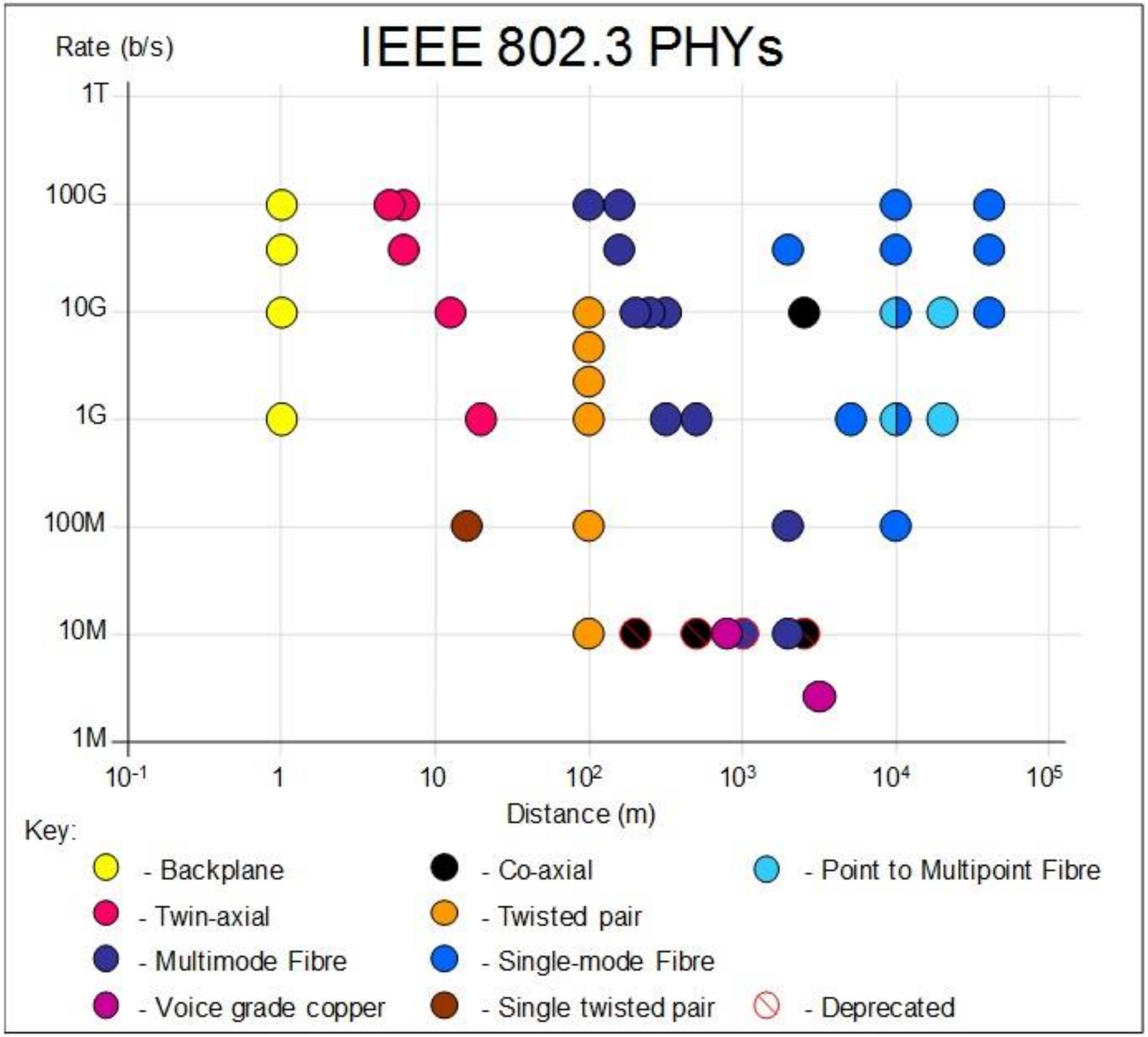
Terabit Ethernet

- Terabit Ethernet or TbE is Ethernet with speeds above 100 Gigabit Ethernet.
- Media Transmission Speed: 200 Gbps and 400 Gbps
- Physical interfaces
  - Copper based backplane
  - Copper based cables: Twin-Axial
  - Fiber-optic based cables: Single Mode and Multi-Mode
  - Chip to Chip Communication
- Standards under development
  - 800 Gbps
  - 1.6 Tbps

Ethernet Standard Trend

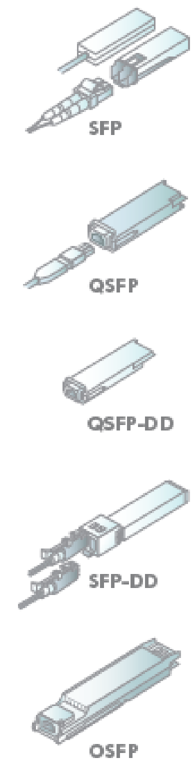


Ethernet Speed and Reach



LATEST INTERFACES AND NOMENCLATURE

	Backplane	Twinax Cable	15-40m(OT) Single Twisted Pair	>100m (OT) Single Twisted Pair	100m (IT) Twisted Pair (2/4 Pair)	MMF	500m PSM4	2km SMF	10km SMF	20km SMF	40km SMF	80km SMF	Electrical Interface	Pluggable Module
10BASE–	T1S		T1S	T1L	T									
100BASE–			T1	T1L*	T									
1000BASE–			T1		T									
2.5GBASE–	KX		T1		T									
5GBASE–	KR		T1		T									
10GBASE–			T1		T				BIDI Access	BIDI Access	BIDI Access			
25GBASE–	KR1 KR	CR1 CR/CR-S	T1		T (30m)	SR			LR EPON BIDI Access	EPON BIDI Access	ER BIDI Access		25GAUI	SFP
40GBASE–	KR4	CR4			T (30m)	SR4/eSR4	PSM4	FR	LR4				XLAUI XLPPI	QSFP
50GBASE–	KR2 KR	CR2 CR	T2			SR		FR	EPON BIDI Access LxR	EPON BIDI Access	BIDI Access ER		LAUI-2/50GAUI-2 50GAUI-1	SFP/QSFP
100GBASE–	KR4 KR2 KR1	CR10 CR4 CR2 CR1	T4			SR10 SR4 SR2 VR1 SR1	PSM4 DR	CWDM4 FR1	LR4 4WDM-10 LR1	4WDM-20	ER4 4WDM-40	ZR	CAUI-10 CPPI CAUI-4/100GAUI-4 100GAUI-2 100GAUI-1	SFP QSFP/QSFP-DD OSFP
200GBASE–	KR4 KR2	CR4 CR2 CR1*				SR4 VR2 SR2	DR4 1pair*	FR4 1 pair*	LR4		ER4		200GAUI-4 200GAUI-2 200GAUI-1*	QSFP/QSFP-DD SFP-DD
400GBASE–	KR4*	CR4 CR2*				SR16 SR8/SR4.2 VR4 SR4	DR4 2 pair*	FR8 FR4 400G-FR4	LR8 LR4-6 400G-LR4-10		ER8	ZR	400GAUI-16 400GAUI-8 400GAUI-4 400GAUI-2*	QSFP/QSFP-DD OSFP
800GBASE-	ETC-KR8 KR8*	ETC-KR8 CR8* CR4*				VR8* SR8*	8 pair* 4 pair*	8 pair* 4 pair* 4 lambda*	TBD*		TBD*		800GAUI-8* 800GAUI-4*	
1.6TBASE-		CR8*					8 pair*	8 pair*					1.6TAUI-16* 1.6TAUI-8*	QSFP/QSFP-DD OSFP/OSFP-XD



Gray Text = IEEE Standard　Red Text = In Task Force　Green Text = In Study Group

Blue Text = Non-IEEE standard but complies to IEEE electrical interfaces　* Note: As of publication, subject to change

Logical Link Control: 802.2

- For some applications, an error-controlled, flow controlled connection is desired
- Data link layer for 802 protocols consists of two parts:
  - LLC logical link control
  - MAC multiple access control
- LLC implements the functionality as discussed in the data link layer section like:
  - Error control
  - Flow control
- LLC offers three services:
  - Unreliable datagram service
  - Acknowledged datagram service
  - Reliable connection-oriented service
- LLC header is based on the HDLC protocol

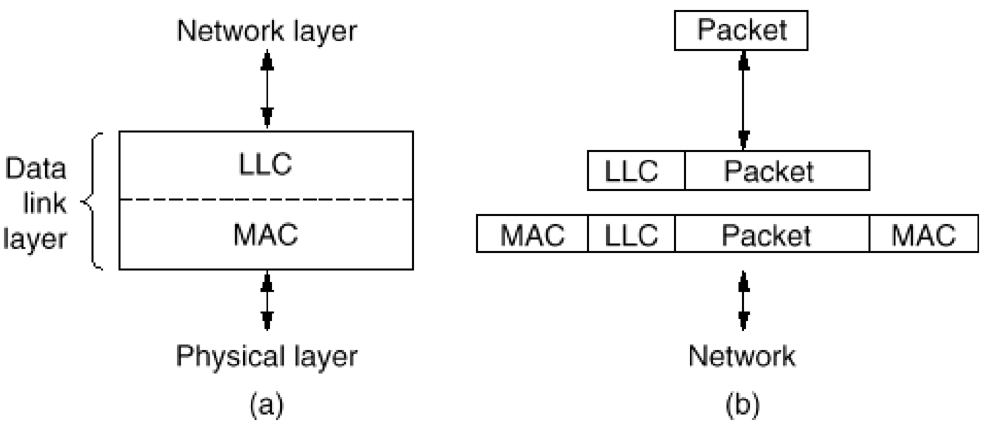
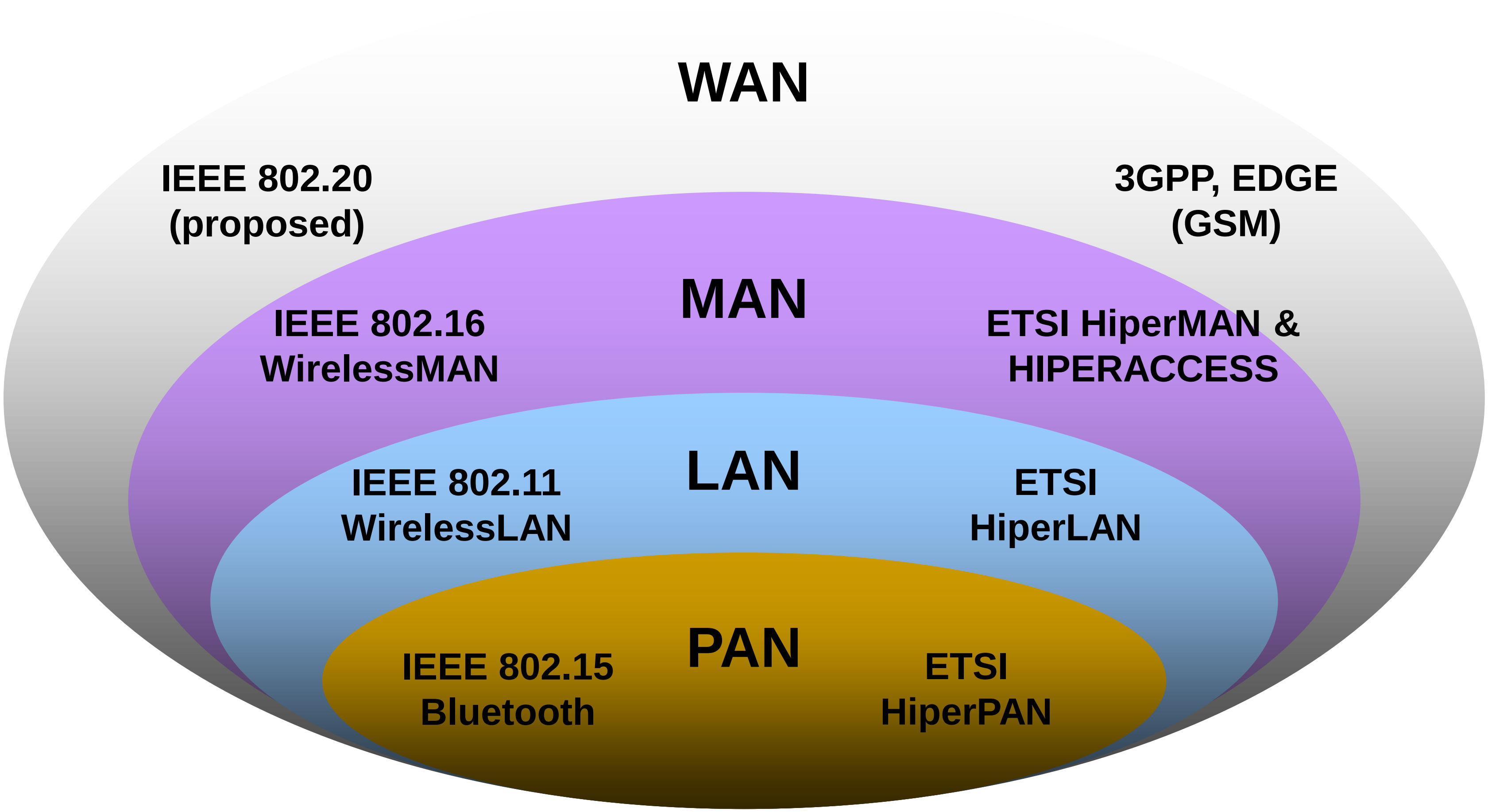
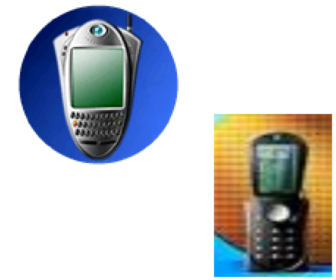


Fig. 4-33. (a) Position of LLC. (b) Protocol formats.

Global Wireless Standards



Wireless Platforms



Fixed

Licensed and Unlicensed
E1/ T1 & DSL level service

Portable

Licensed and Unlicensed
Consumer DSL level service

Mobile

Licensed
Wideband Data Rates

Enterprise / Backhaul → 802.16 HiperMAN

Residential access → 802.16 HiperMAN

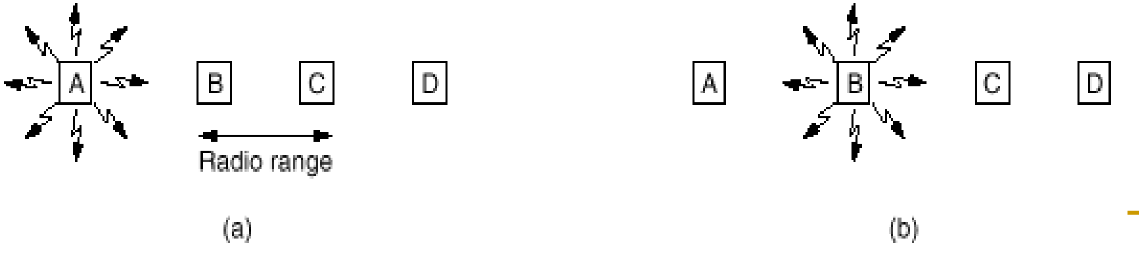
Destination based → 802.11 Hot Spots

Nomadic → 802.16e

Cellular Wideband → 2.5G, 3G

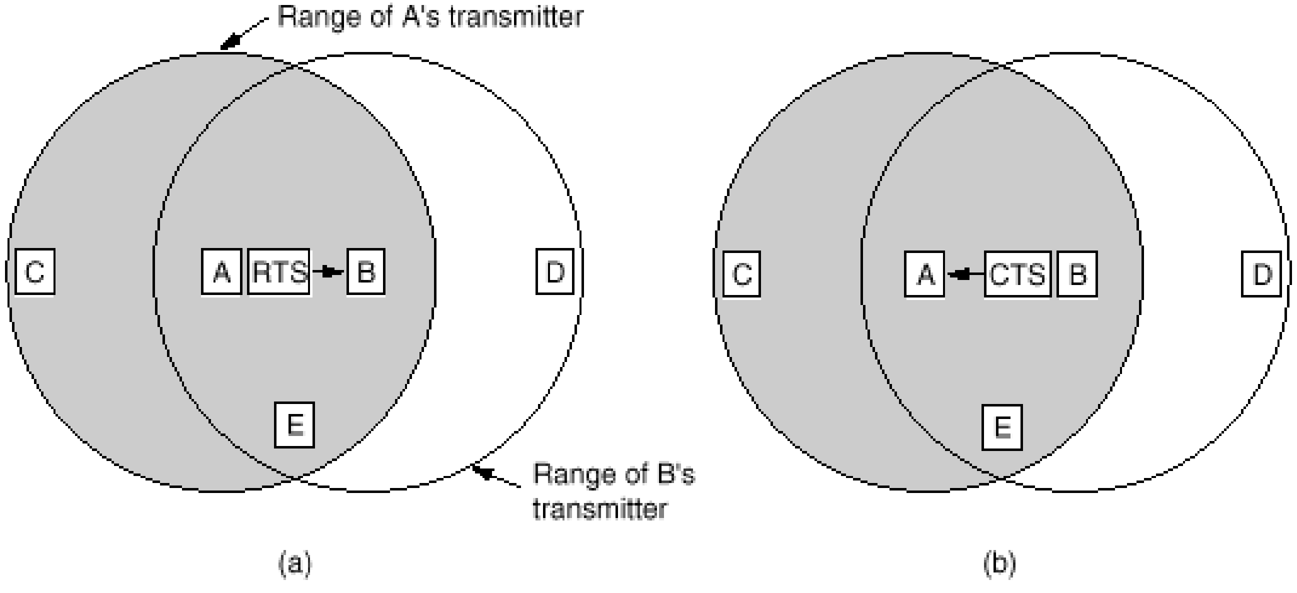
Wireless LAN Protocols

- Wireless protocols are *inherently multiple access* !
- Can we use ***sensing*** ?
  - What matters is collision at Rx
- Hidden station problem:
  - C can not sense A. If both target B, there will be a collision
- Exposed station problem:
  - B sends to A. C senses the medium and concludes that there is activity. So, it does not send to D. The link between C and D is not susceptible to the conversation of A and B.



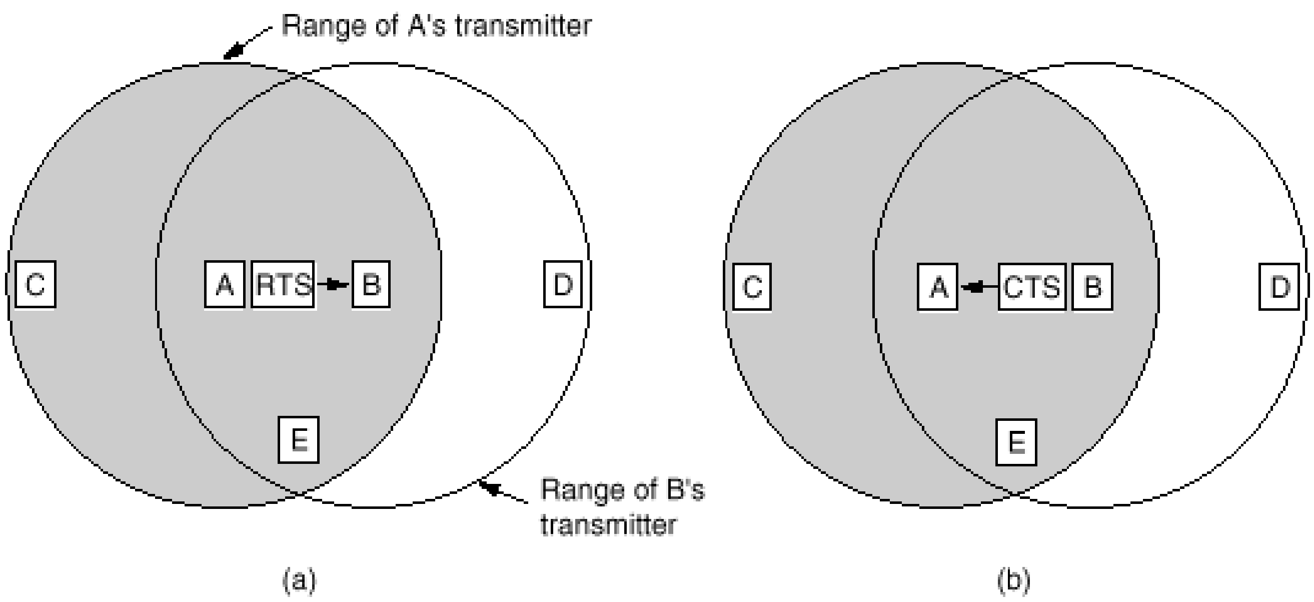
Wireless LAN Protocols

- MACA: ***Multiple Access with Collision Avoidance***
  - Sender: sends RTS (request to send)
  - Receiver: sends CTS (clear to send)
  - RTS and CTS contain length of message to be sent



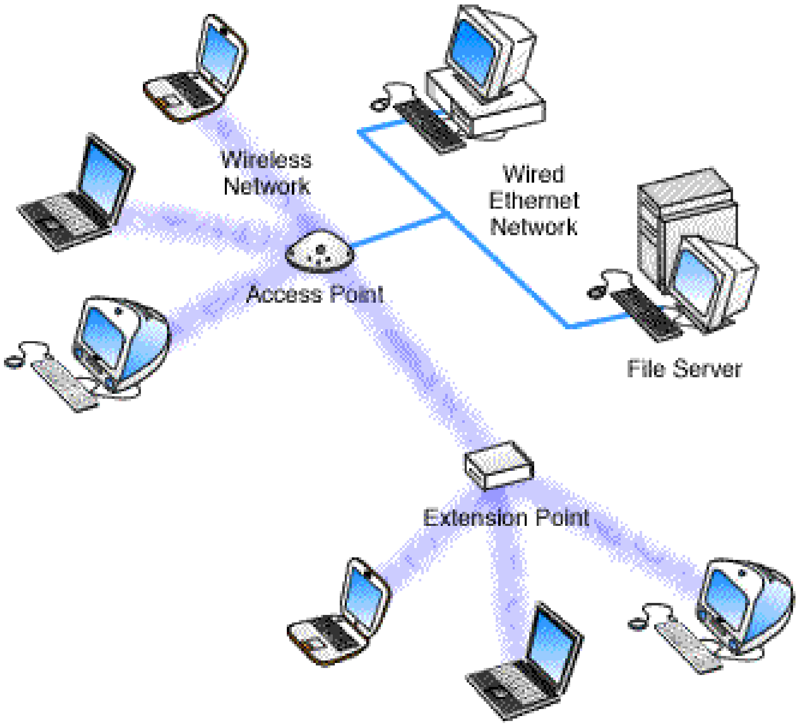
Wireless LAN Protocols

- Key observations:
  - Any station hearing RTS must keep silent during the next phase of data transmission
  - Any station hearing CTS must keep silent during next message



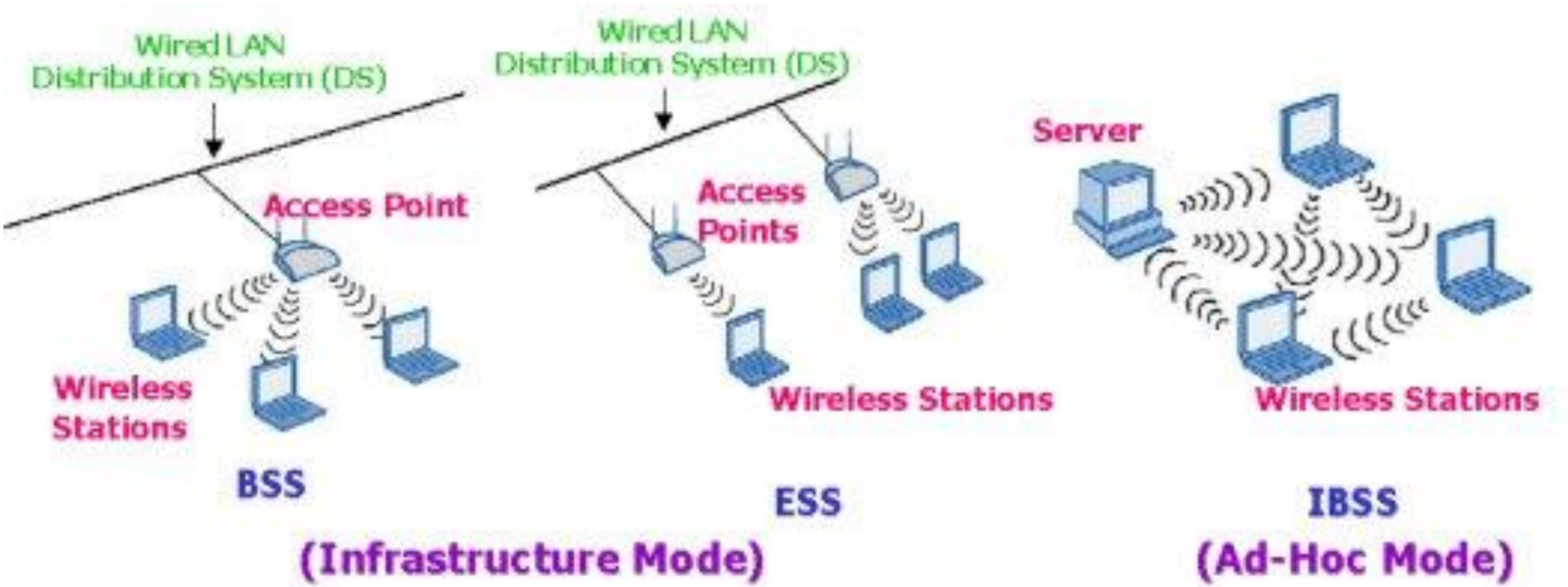
Wireless LANs

- Wireless LANs are becoming increasingly popular due to:
  - Ease of installation
  - Support of mobility
  - Easy connection to back-bone networks in places like airports, shopping centers, conference rooms, etc



Wireless LAN

- Key Architectures
  - Infrastructure Mode: Require Access Point/Base Station
  - Ad-Hoc Mode: On demand networking without infrastructure



Wireless LANs

- Several standards have been developed in the last decade
- One of the hottest areas of telecommunication
- The list of standards keeps growing every year!

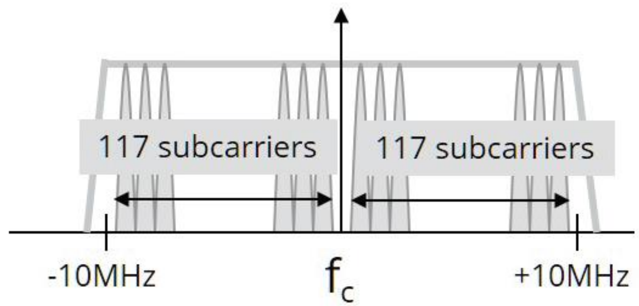
IEEE 802.11 Overview

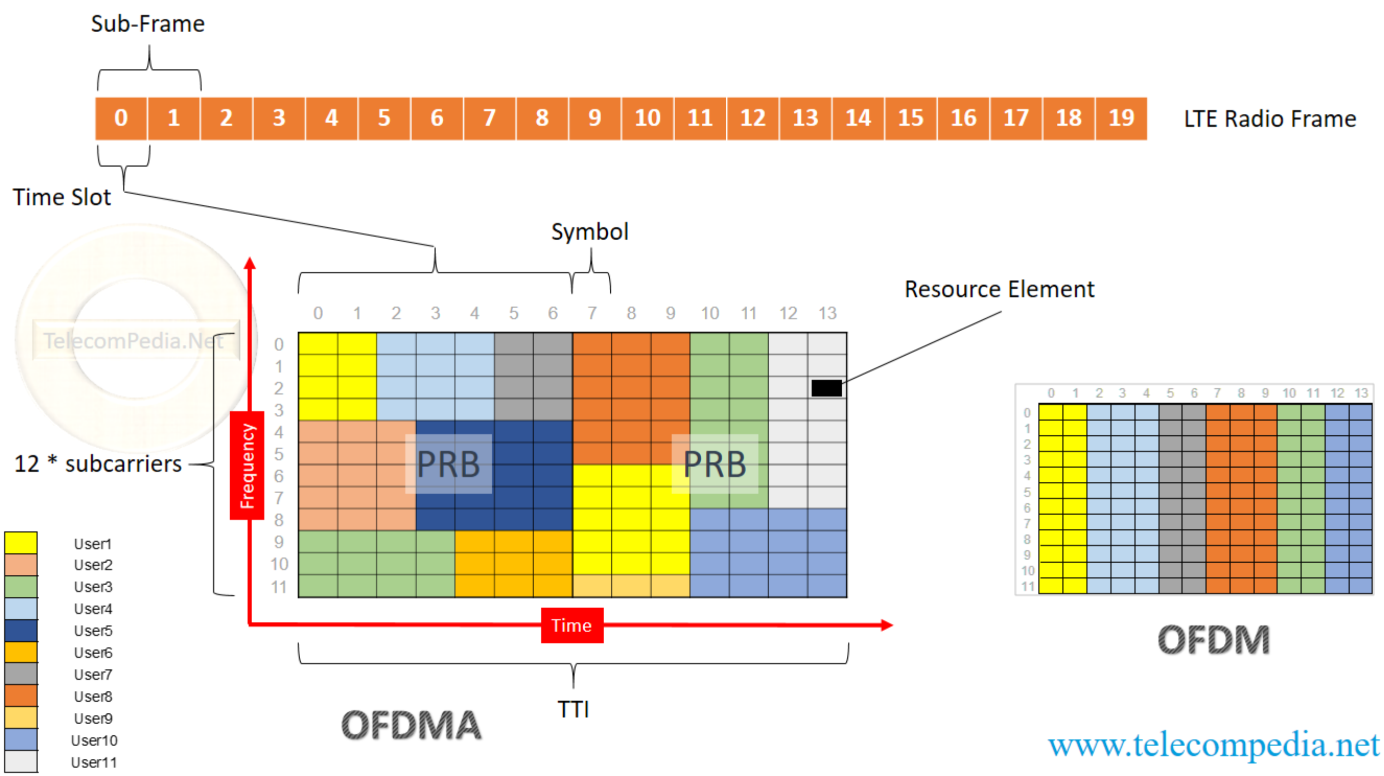
TABLE 1: IEEE 802.11 COMMON WIFI STANDARDS BREAKDOWN							
Standard	Frequency Band	Bandwidth	Modulation Scheme	Channel Arch.	Maximum Data Rate	Range	Max Transmit Power
802.11	2.4 GHz	20 MHz	BPSK to 256-QAM	DSSS, FHSS	2 Mbps	20 m	100 mW
b	2.4 GHz	21 MHz	BPSK to 256-QAM	CCK, DSSS	11 Mbps	35 m	100 mW
a	5 GHz	22 MHz	BPSK to 256-QAM	OFDM	54 Mbps	35 m	100 mW
g	2.4 GHz	23 MHz	BPSK to 256-QAM	DSSS, OFDM	54 Mbps	70 m	100 mW
n	2.4 GHz, 5 GHz	24 MHz and 40 MHz	BPSK to 256-QAM	OFDM	600 Mbps	70 m	100 mW
ac	5 GHz	20, 40, 80, 80+80= 160 MHz	BPSK to 256-QAM	OFDM	6.93 Gbps	35 m	160 mW
ad	60 GHz	2.16 GHz	BPSK to 64-QAM	SC, OFDM	6.76 Gbps	10 m	10 mW
af	54-790 MHz	6, 7, and 8 MHz	BPSK to 256-QAM	SC, OFDM	26.7 Mbps	>1km ?	100 mW
ah	900 MHz	1, 2, 4, 8, and 16 MHz	BPSK to 256-QAM	SC, OFDM	40 Mbps	1 km	100 mW

IEEE 802.11 PHY Review

- 802.11a Orthogonal Frequency Division Multiplexing (OFDM)
  - Variable bit rates up to 54 Mbps
  - Uses 5 GHz ISM band
  - Much more immune to channel variations
  - Short range, mostly used for indoor LANs
- 802.11b High Rate Direct Sequence Spread Spectrum (HR-DSSS)
  - Variable bit rate up to 11 Mbps (1,2,5.5,11)
  - Uses 2.4 GHz ISM band
  - Longer range than 802.11a (Can be used for inter-office LAN connection)
- 802.11g (OFDM)
  - Variable bit rate up to 54 Mbps
  - Uses 2.4 GHz band
- 802.11n
  - OFDM/DSSS Modulation
  - Up to 540 Mbps
  - Uses 2.4 and 5 GHz bands
- 802.11ac (5 GHz)
  - Uses MIMO and OFDM
  - Up to 860 Mbps per stream
  - Up to 8 MIMO streams

Basics of OFDMA





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OFDMA in 802.11

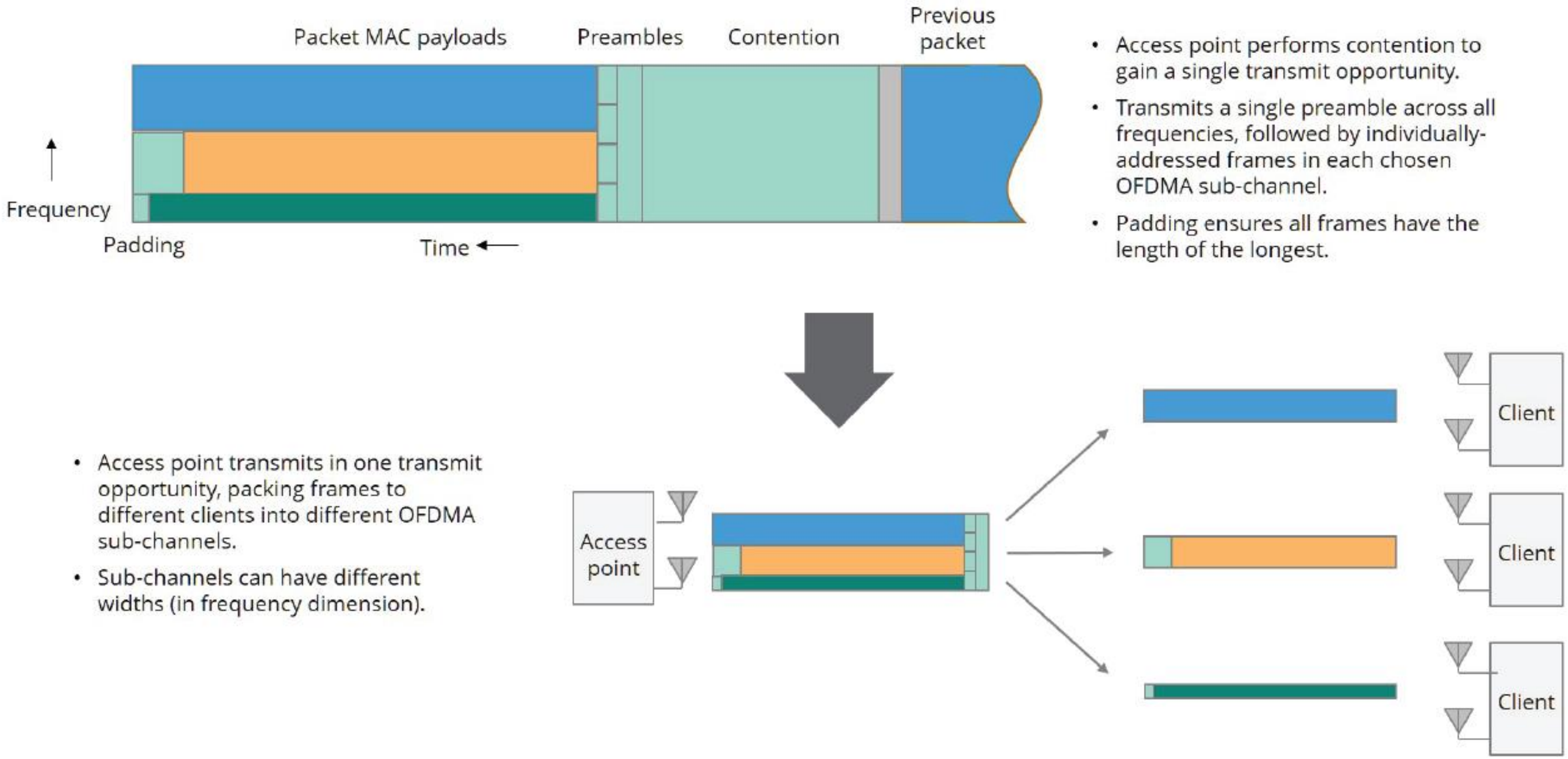


Figure 9: Downlink OFDMA transmission

OFDMA in 802.11

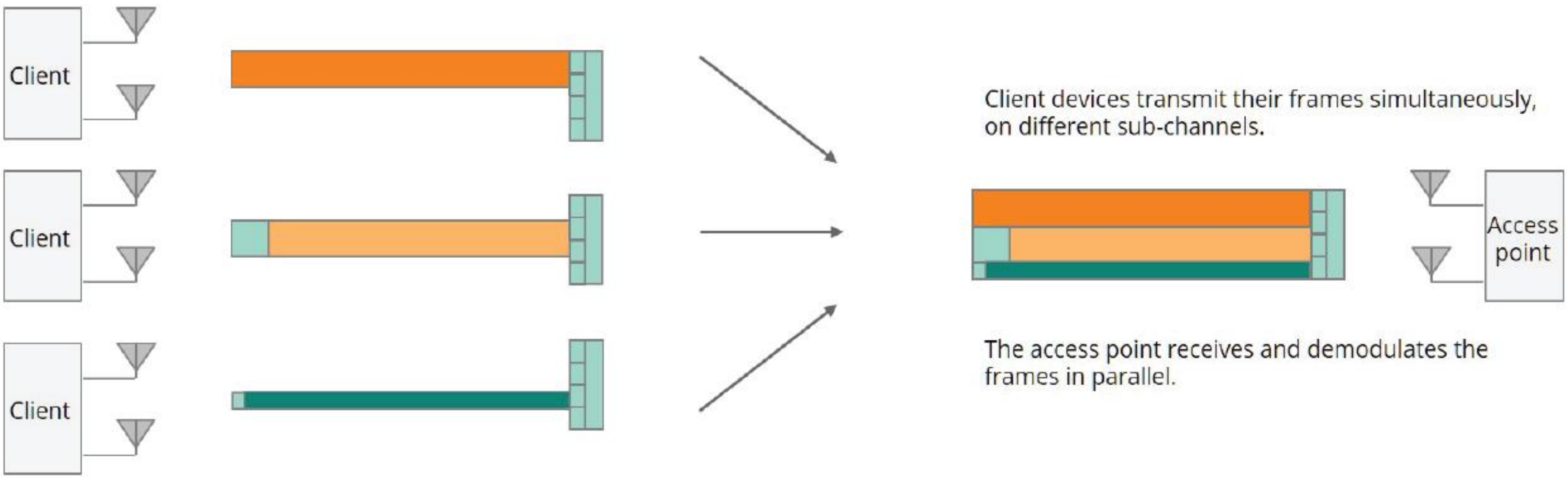


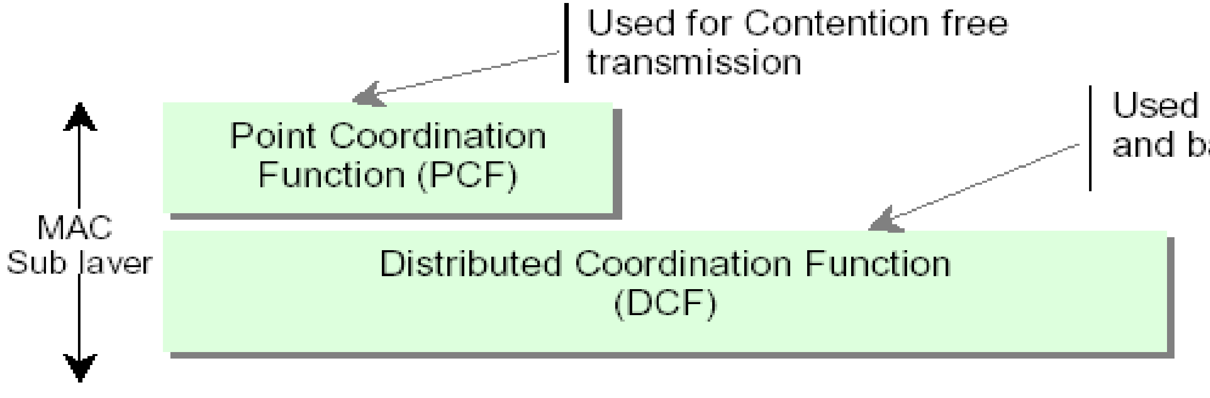
Figure 12: Uplink OFDMA transmission

Overview of 802.11 MAC

- All 802.11 (a,b,g) networks use the same MAC
- MAC supports two modes of operation
  - Distributed Coordination Function: Used for Ad-Hoc connections
  - Point Coordination Function: Used when nodes are connected to an access point

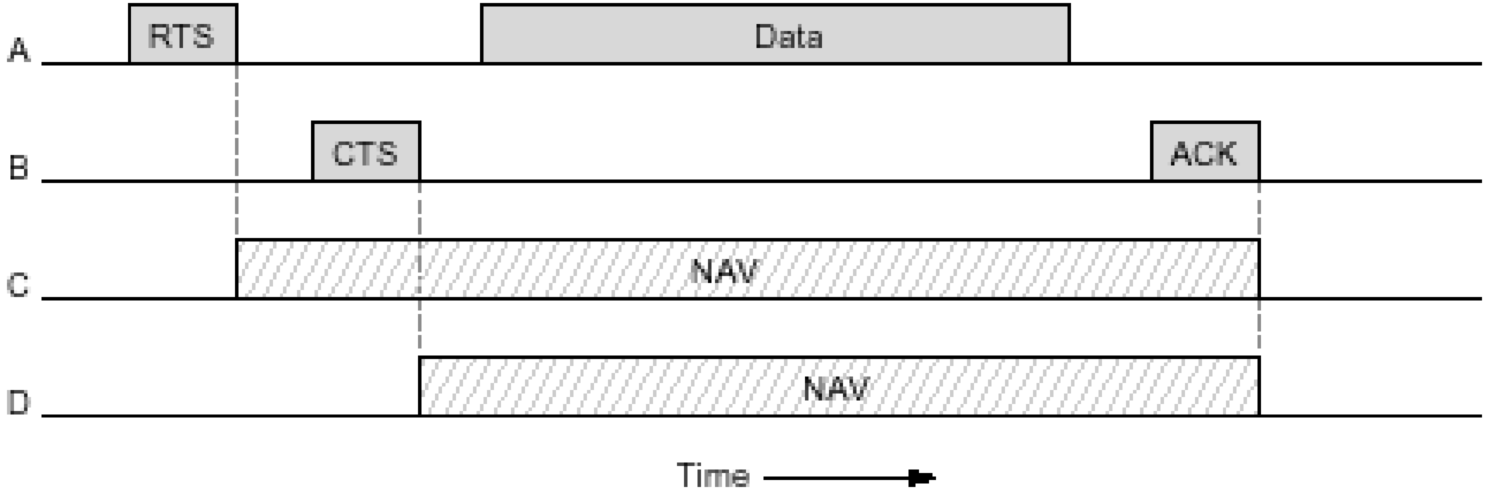
Overview of 802.11 MAC

- PCF Mode:
  - Base station broadcasts a beacon frame that contains frequency hopping, synch and some other information periodically
  - Stations can sign up to the base for receiving services
  - Once base station registers a user, it will assign the necessary resources.
  - Base station can manage the activity of users by putting them in sleep mode to save battery power. It wakes them up when needed.



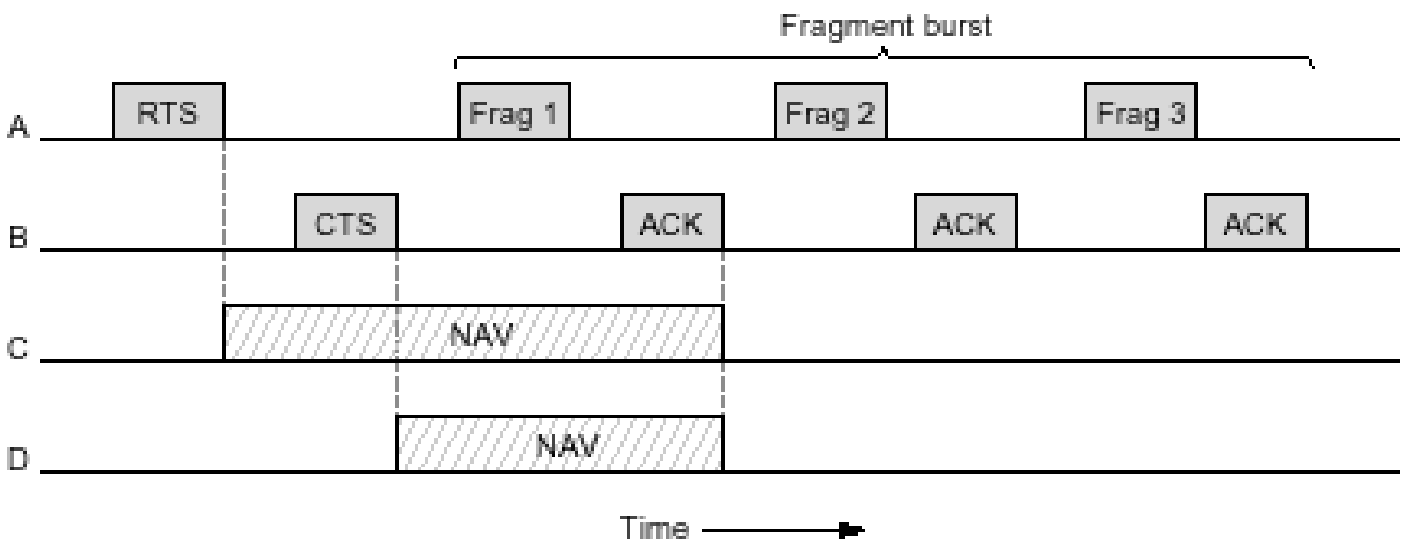
Overview of 802.11 MAC

- DCF employs CSMA/Ca that has two access methods
  - Start transmitting as soon as channel is idle. If a collision, wait a random time (exponential back off) and try again
  - Use MACAW using RTC/CTS
  - Note: RTS and CTS contain data length thereby setting the waiting time (Not Available Vector) in other stations.



Overview of 802.11 MAC

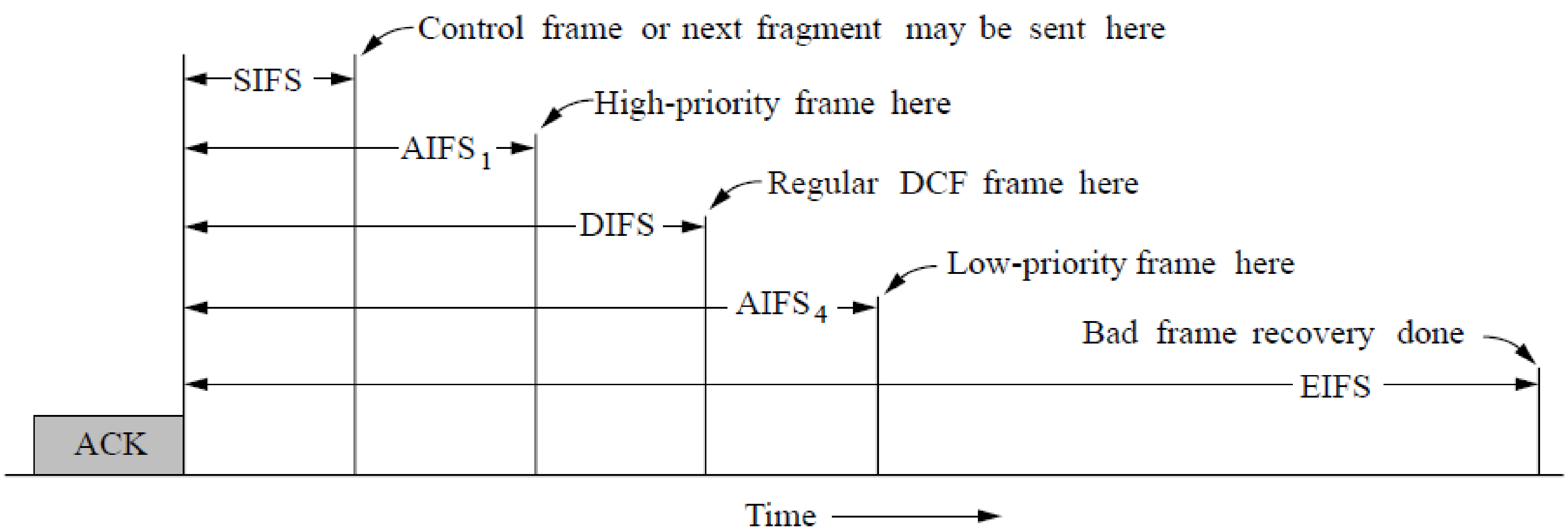
- A long frame has a much higher chance of error than a short frame
- For BER=1e-4, Probability of frame error is more than 70% for a frame of length 12kbit.
- Once channel is acquired, a burst of short frames can also be sent to increase system throughput
- Uses Stop and Wait for each fragment



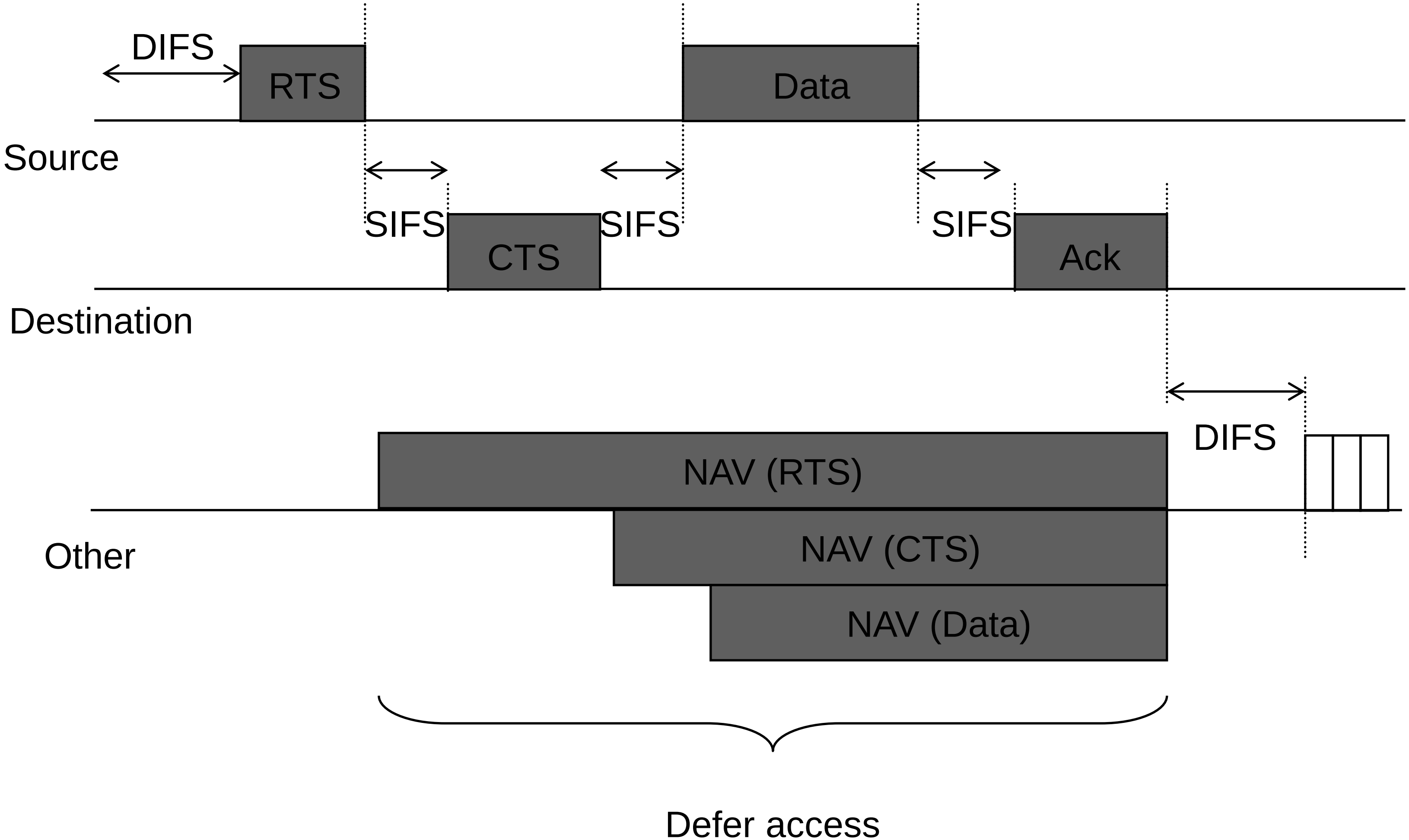
Overview of 802.11 MAC

- All stations should remain quiet for a certain period after a transmission has been completed (Inter Frame Space (IFS)) .
  - Short Interframe Spacing (SIFS):
    - High priority frames (ACK, CTS or fragment burst) only wait for SIFS duration
  - Arbitration Interframe Space (AIFS)
    - Base station can send high priority traffic during AIFS1 and low priority traffic during AIFS4
  - DCF Interframe spacing (DIFS)
    - Any station may attempt to acquire the channel to send a new frame after the medium has been idle for DIFS
  - Extended Interframe spacing (EIFS)
    - A station can report a bad or unknown frame during this time

Overview of 802.11 MAC



Overview of 802.11 MAC



Overview of 802.11 MAC

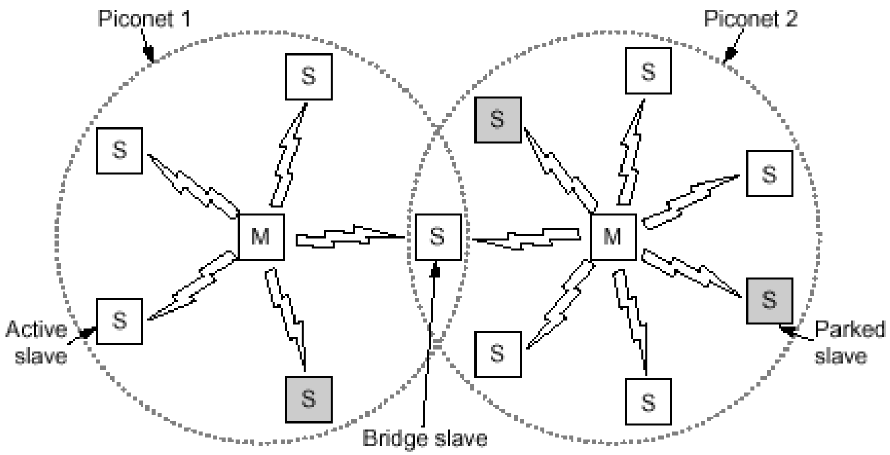
- A station can send if channel is idle for a period of DIFS or longer
- If medium is busy, node starts a random backoff timer
- Station is allowed to transmit when its backoff timer expires during a contention period
- If another station starts transmission during the contention period, the backoff timer is <u>suspended</u> and resumed next time a contention period takes place
- When a station has successfully completed a frame transmission and has another frame to send, the station must first execute the backoff procedure
- Waiting stations tend to have smaller remaining backoff time and can access channel sooner. Therefore, a degree of fairness is provided in the channel access process.

IEEE 802.11 services

- A wireless LAN can provide these services:
  - Distribution Services
    - Association: A mobile can connect to base station using this service.
    - Disassociation: Breaking the relationship between the base and mobile
    - Re-association: Change the preferred base station by moving from one cell to another cell
    - Distribution: A Service that determines how to route frames sent to a base
    - Integration: A service that handles the required translation of frame format for sending a packet to a non-802.11 format
  - Station services
    - Authentication: prove the identity of the mobile
    - De-authentication: cancel the approved identification of a user
    - Privacy: Encryption of messages sent over PHY
    - Data Delivery: Transmission of data from one node to another

Bluetooth (IEEE 802.15)

- A standard for Inexpensive, compact , short range wireless communication.
- Started by Ericsson, IBM, Nokia, Intel and Toshiba in 1994, Version 1.0 finalized in 1999.
- Based on pico-nets connected together by slave bridges
- Each piconet has one master node and seven slaves and up to 255 parked nodes (nodes in power stand-by)
- Each piconet is a centralized TDM system managed by Master. All communications between slaves are done through the master. (No direct slave to slave comm.)



Bluetooth Applications

- Standard specifies the entire protocol stack for various applications.
- Important defined profiles (Important applications which are standardized by the standard):
  - Serial port emulator
  - LAN Access
  - Dial up networking
  - Cordless telephony
  - Intercomm
  - Headset

Name	Description
Generic access	Procedures for link management
Service discovery	Protocol for discovering offered services
Serial port	Replacement for a serial port cable
Generic object exchange	Defines client-server relationship for object movement
LAN access	Protocol between a mobile computer and a fixed LAN
Dial-up networking	Allows a notebook computer to call via a mobile phone
Fax	Allows a mobile fax machine to talk to a mobile phone
Cordless telephony	Connects a handset and its local base station
Intercom	Digital walkie-talkie
Headset	Allows hands-free voice communication
Object push	Provides a way to exchange simple objects
File transfer	Provides a more general file transfer facility
Synchronization	Permits a PDA to synchronize with another computer

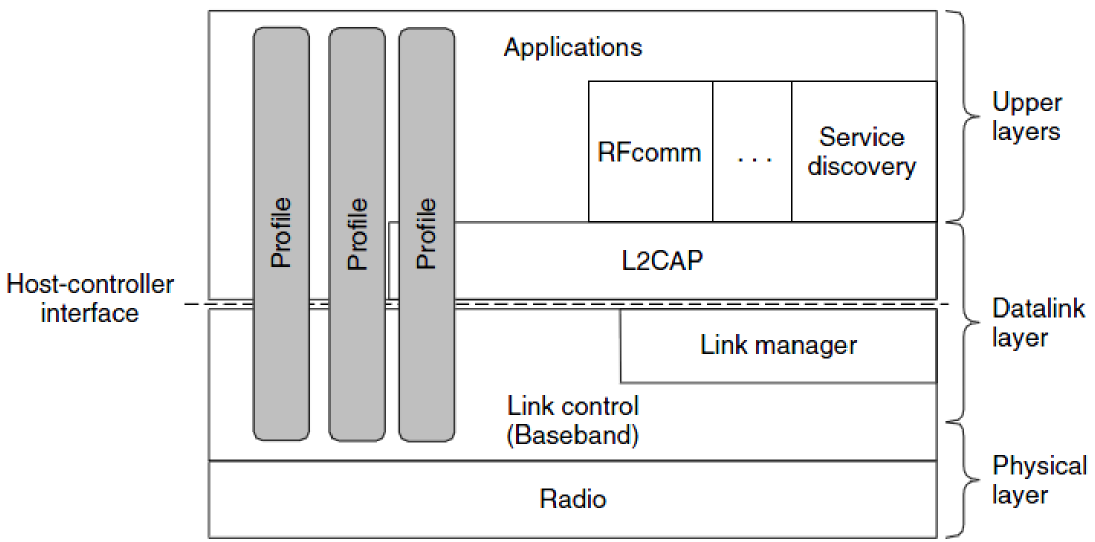
Bluetooth Evolution

Bluetooth Spec. Evolution

Specifications	1.1	1.2	2.0 + EDR	2.1 + EDR	3.0 +HS	4.0
Adopted	2002	2005	2004	2007	2009	2010
Transmission Rate	723.1 kbps	723.1 kbps	2.1 Mbps	3 Mbps	24 Mbps	25 Mbps
Standard PAN Range	10 m	10 m	10 m	10 m	10 m	50 m
Improved Pairing (without a PIN)				Yes	Yes	Yes
Improved Security		Yes	Yes	Yes	Yes	Yes
NFC Support			Yes	Yes	Yes	Yes

Bluetooth Protocol Stack

- Physical Radio:
  - Operates in 2.4 GHz ISM frequency band
- Baseband Layer (MAC)
  - Turns raw bits to frames and defines key formats
  - Each frame is transmitted over a “Link”.
  - Two types of links:
    - Asynchronous Connectionless (ACL) used for packet data
    - Synchronous Connection Oriented (SCO) used for real time data such as voice
- L2CAP:
  - Frame segmentation and re-assembly
  - Mux/Demux of multiple data sources
  - Handles QoS requirements during link establishment and normal operation

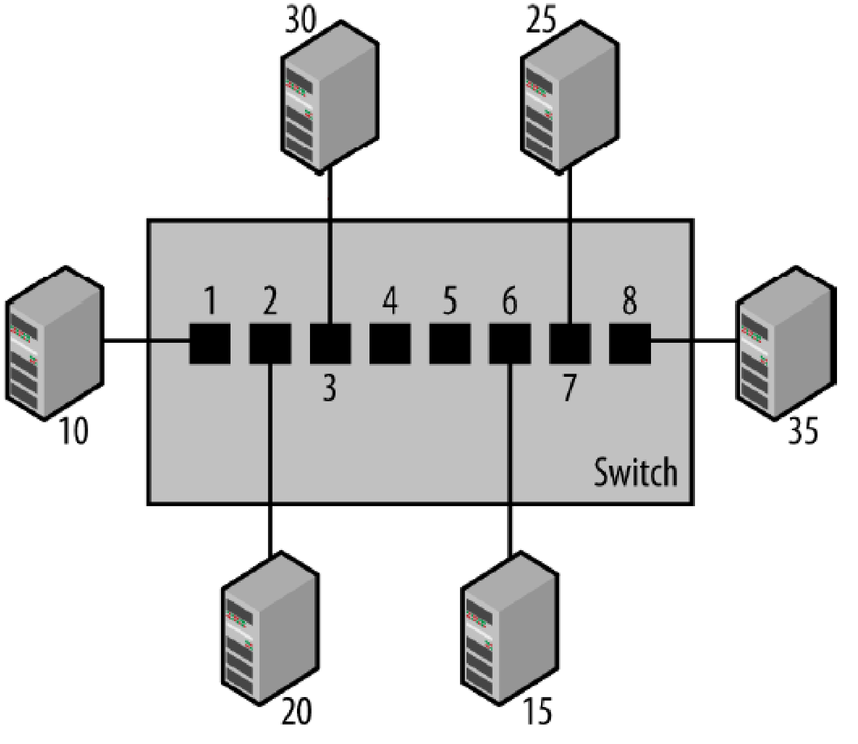


Ethernet Switching

- How to know where to forward frames in an Ethernet Switch?

Forwarding Table

Port	Station
1	10
2	20
3	30
4	No station
5	No station
6	15
7	25
8	35



MAC Address Table

- Switches use MAC address tables to determine how to forward traffic between ports.
  - MAC tables include dynamic and static addresses.
  - The MAC address table was also referred to as content addressable memory (CAM) table.
  - The maximum size of the MAC address table varies with different switches.
    - For example, the Catalyst 2960 series switch can store up to 8,192 MAC addresses

Managing MAC Address Table

```
Mac Address Table
-------------------------------------------
Vlan    Mac Address       Type        Ports
----    -----------       --------    -----
 All    0100.0ccc.cccc    STATIC      CPU
 All    0100.0ccc.cccd    STATIC      CPU
 All    0180.c200.0000    STATIC      CPU
 All    0180.c200.0001    STATIC      CPU
 All    0180.c200.000a    STATIC      CPU
 All    0180.c20000d      STATIC      CPU
 All    0180.c200.000e    STATIC      CPU
 All    0180.c200.000f    STATIC      CPU
 All    0180.c200.0010    STATIC      CPU
 All    ffff.ffff.ffff    STATIC      CPU
   1    000c.7671.7534    DYNAMIC     Fa0/2
   1    0013.e809.7695    DYNAMIC     Fa0/2
   1    0017.9a51.d339    DYNAMIC     Fa0/2
   1    0019.5b0a.a951    DYNAMIC     Fa0/2
   1    0060.b0af.7be4    DYNAMIC     Fa0/2
Total Mac Addresses for this criterion: 25
```

MAC Address Table

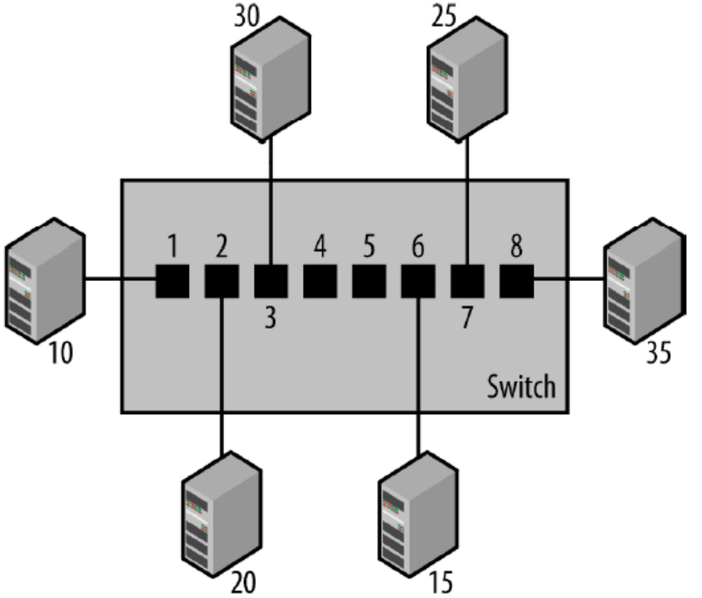
- Static MAC addresses:
  - A network administrator can specifically assign static MAC addresses to certain ports.
  - Static addresses are not aged out.
  - Only those devices that are known to the network administrator can connect to the network.

Managing MAC Address Table

```
Mac Address Table
-------------------------------------------
Vlan    Mac Address       Type        Ports
----    -----------       --------    -----
 All    0100.0ccc.cccc    STATIC      CPU
 All    0100.0ccc.cccd    STATIC      CPU
 All    0180.c200.0000    STATIC      CPU
 All    0180.c200.0001    STATIC      CPU
 All    0180.c200.000a    STATIC      CPU
 All    0180.c20000d      STATIC      CPU
 All    0180.c200.000e    STATIC      CPU
 All    0180.c200.000f    STATIC      CPU
 All    0180.c200.0010    STATIC      CPU
 All    ffff.ffff.ffff    STATIC      CPU
   1    000c.7671.7534    DYNAMIC     Fa0/2
   1    0013.e809.7695    DYNAMIC     Fa0/2
   1    0017.9a51.d339    DYNAMIC     Fa0/2
   1    0019.5b0a.a951    DYNAMIC     Fa0/2
   1    0060.b0af.7be4    DYNAMIC     Fa0/2
Total Mac Addresses for this criterion: 25
```

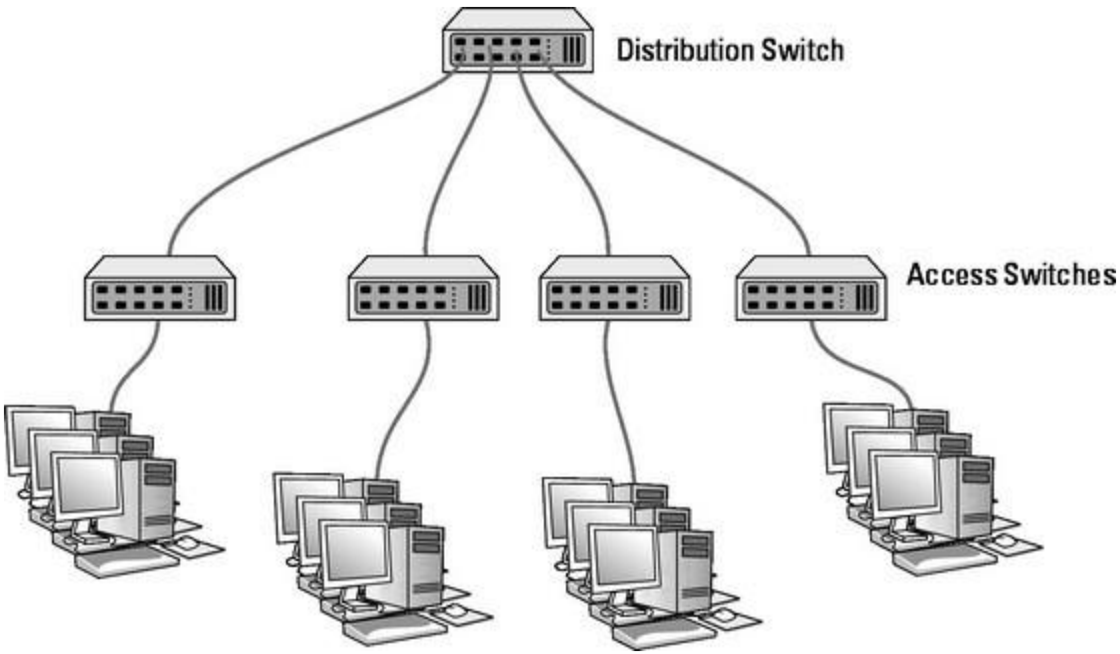
Dynamic MAC Addresses

- Backward Learning is used to dynamically update the MAC address table:
  - If the port for the destination address is the same as the source port, discard the frame.
  - If the port for the destination address and the source port are different, forward the frame on to the destination port.
  - If the destination port is unknown, use flooding and send the frame on all ports except the source port.
  - Remove very old entries (to trace systems going down and other topology changes)

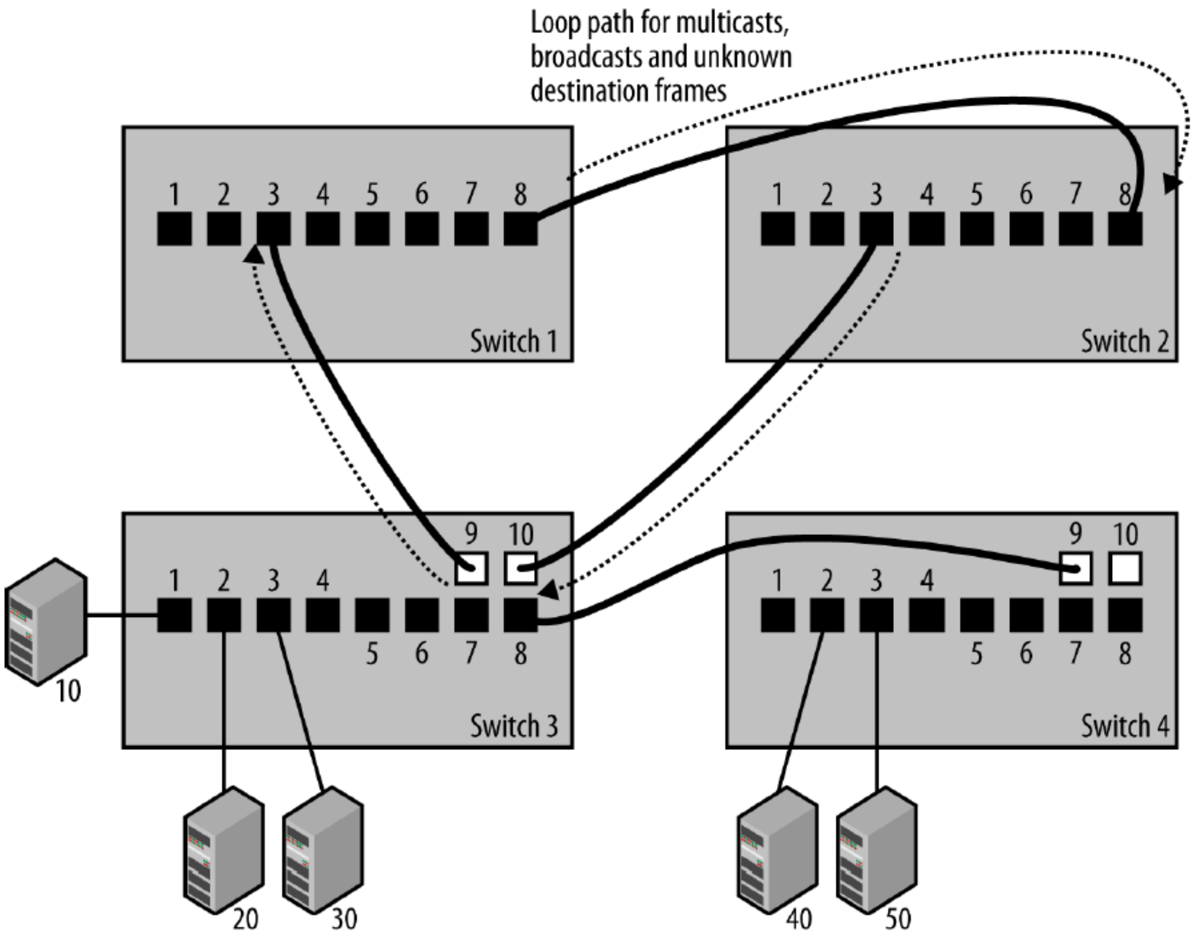


Switching Hierarchy

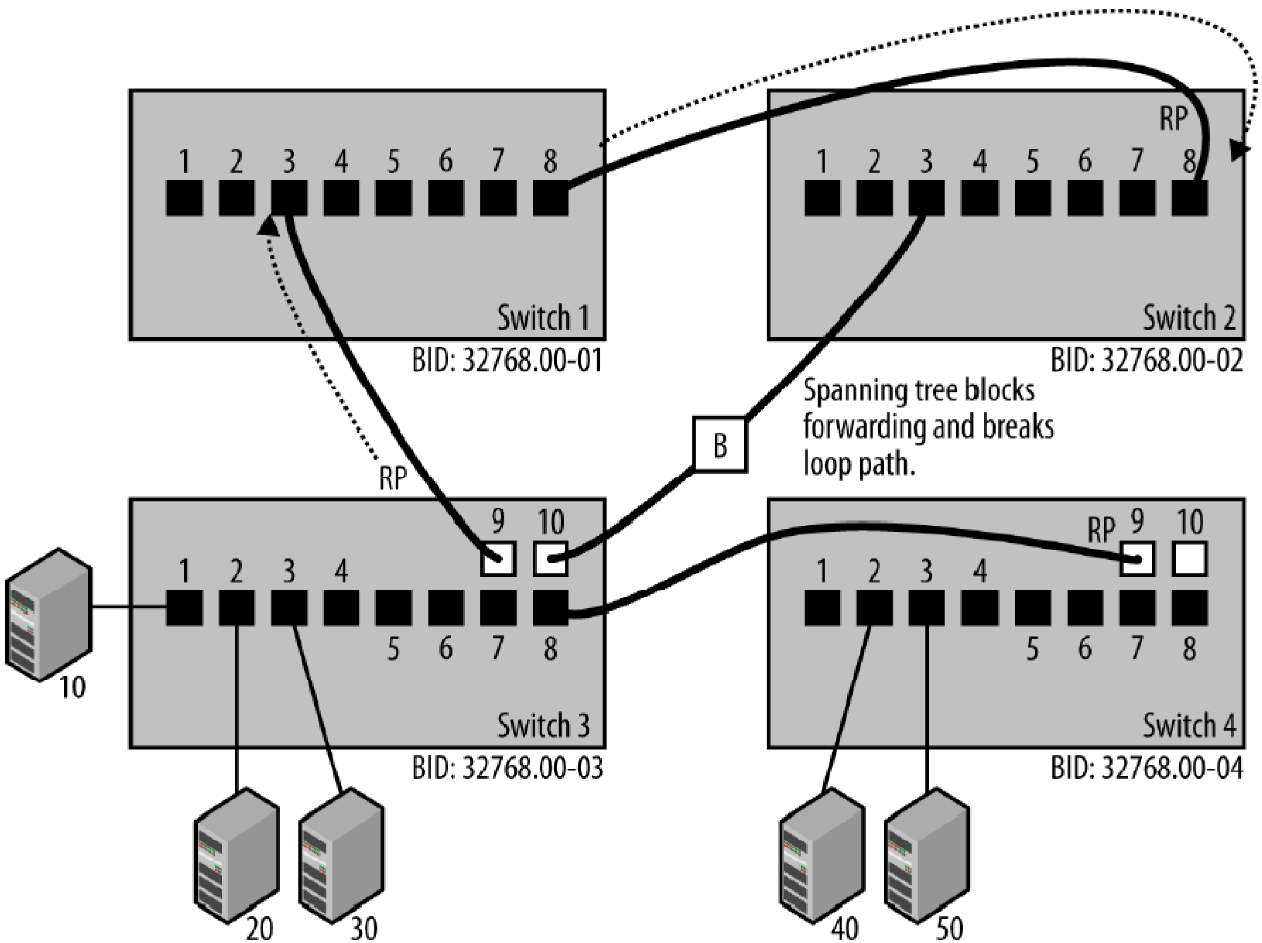
- Ethernet switches can be connected to expand the network
- Backward learning is used to learn addresses in all switches



Backward Learning Loop

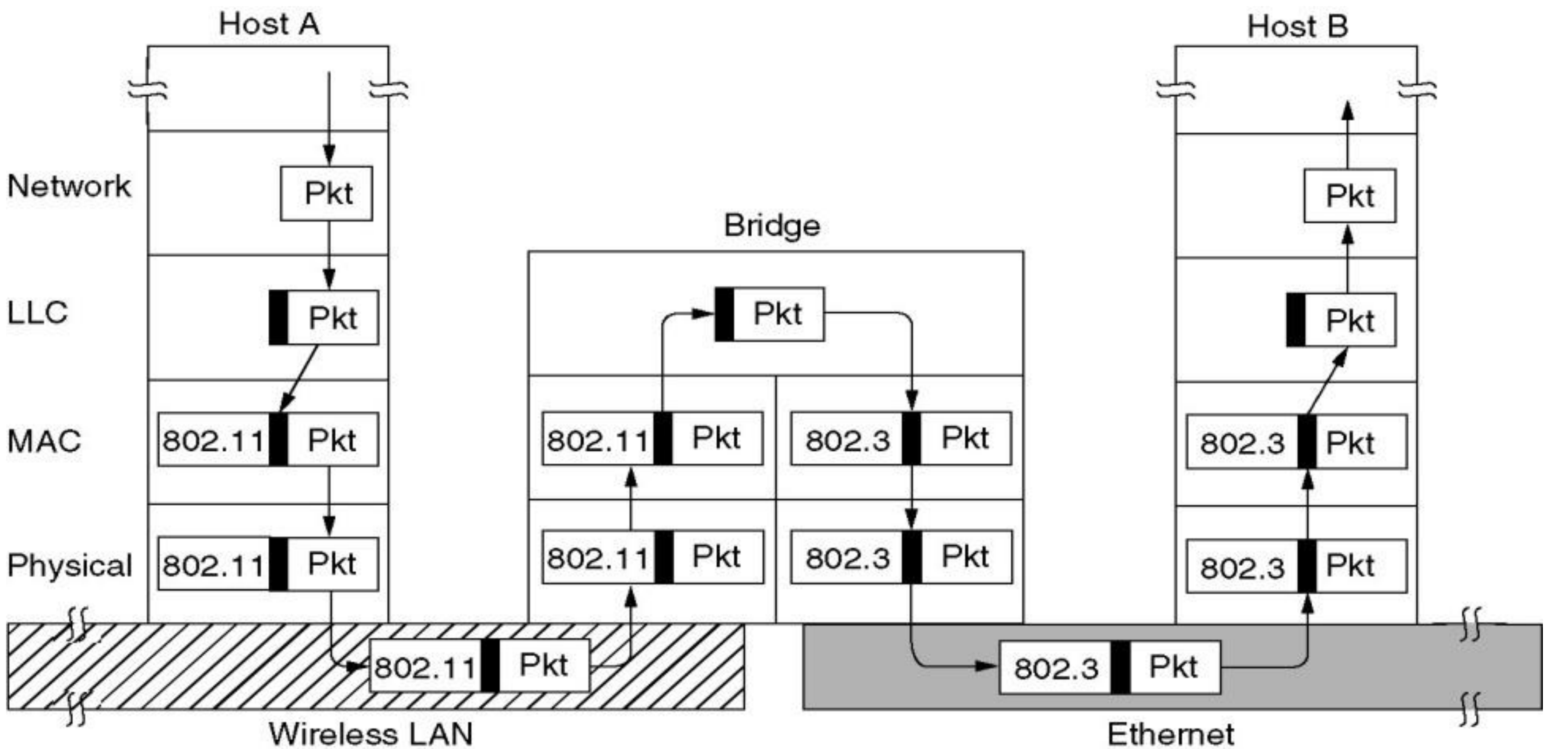


Spanning Tree Protocol



Bridging

- Bridges need to route packets at layer 2 and also do some frame conversions

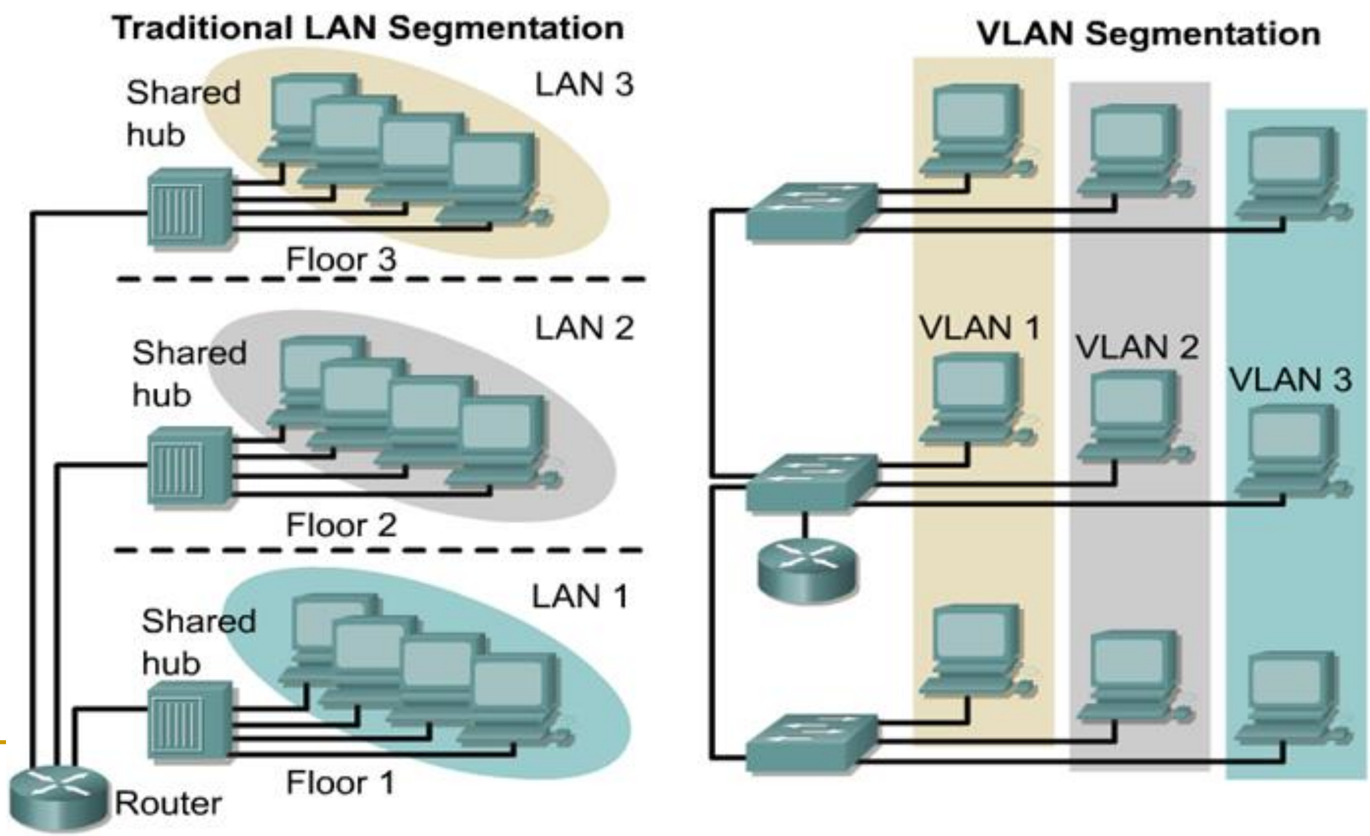


Virtual LAN (VLAN)

- It is desirable to group users on LANs based on policy (For example based on organizational structure) rather than the physical layout of the building
  - Security and access control
  - Network Load Control
  - Broadcast Traffic (ARP)
  - Limiting scope of unwanted events such as broadcast storms

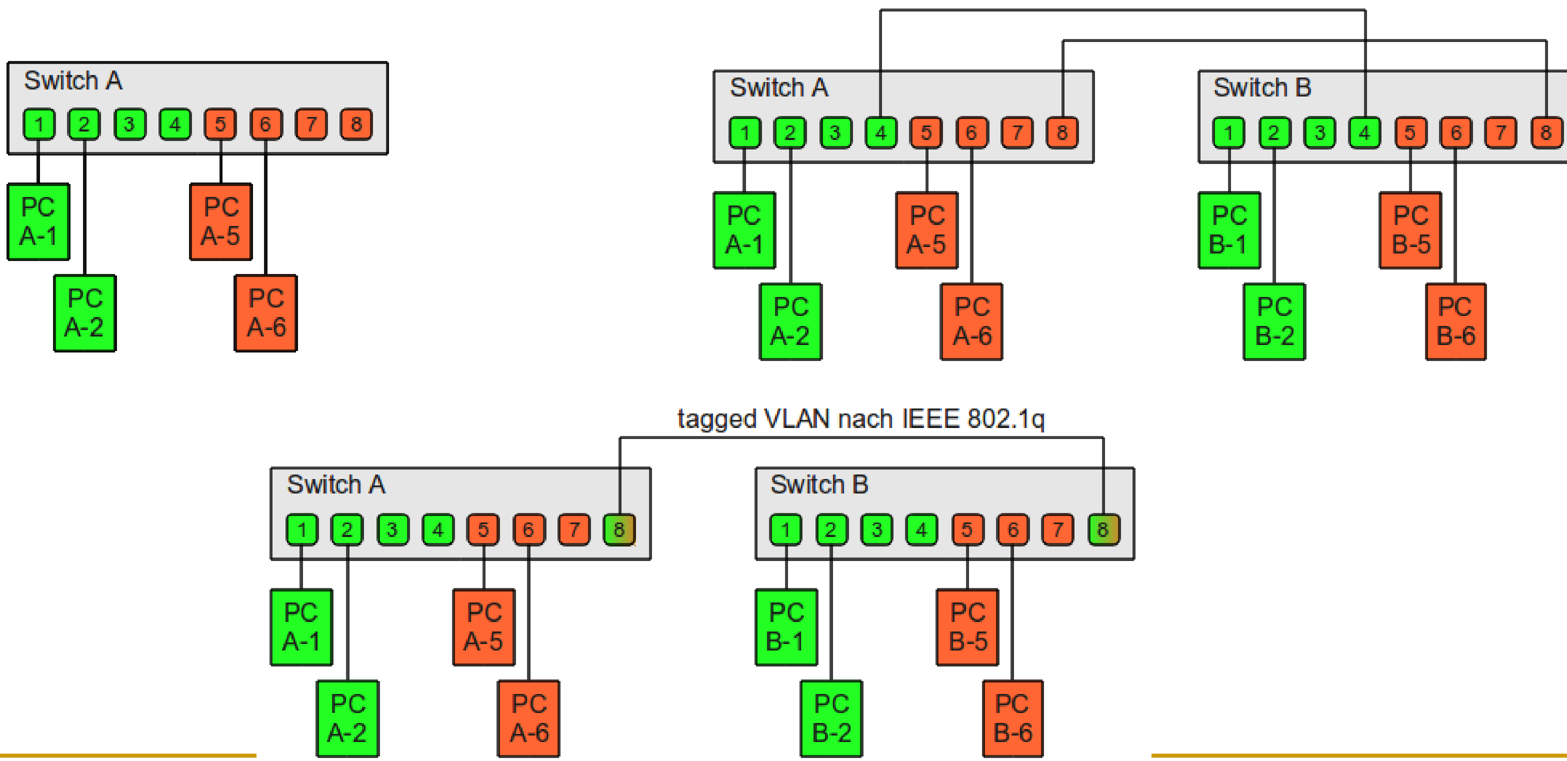
Virtual LAN (VLAN)

- Network partitioning in Layer 2 can be done by proper management of switch learning process.



VLAN

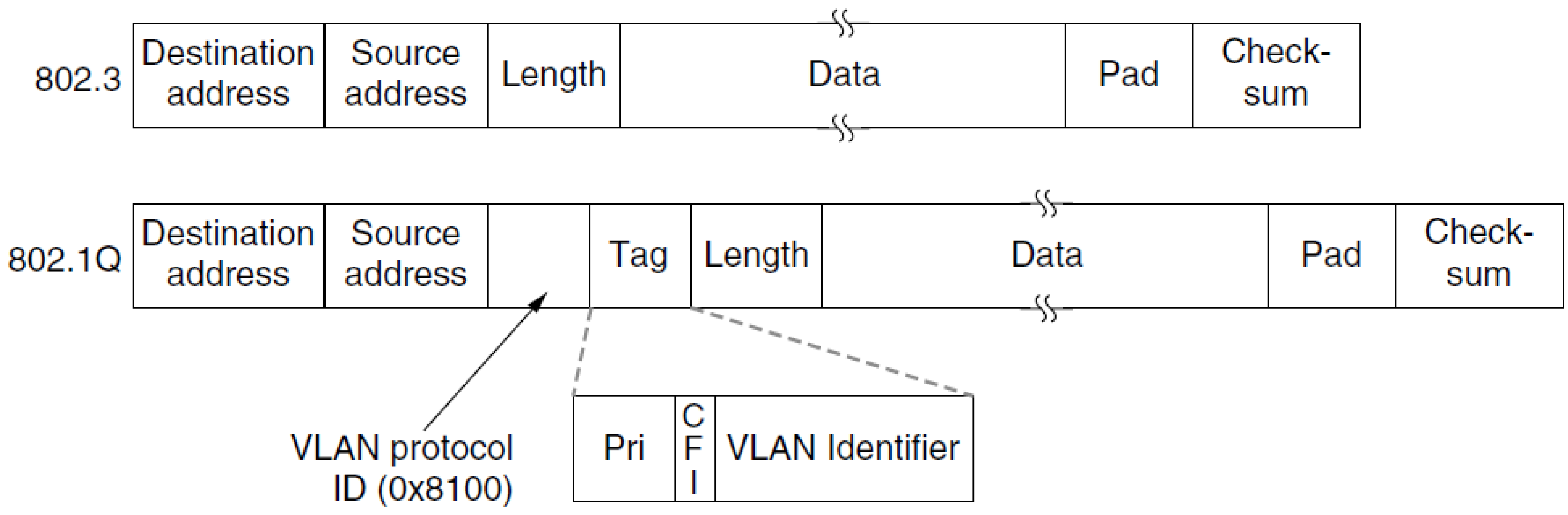
- Partition a switch into different switches
- Use tags to identify VLANs



Pictures: https://www.thomas-krenn.com/en/wiki/VLAN_Basics

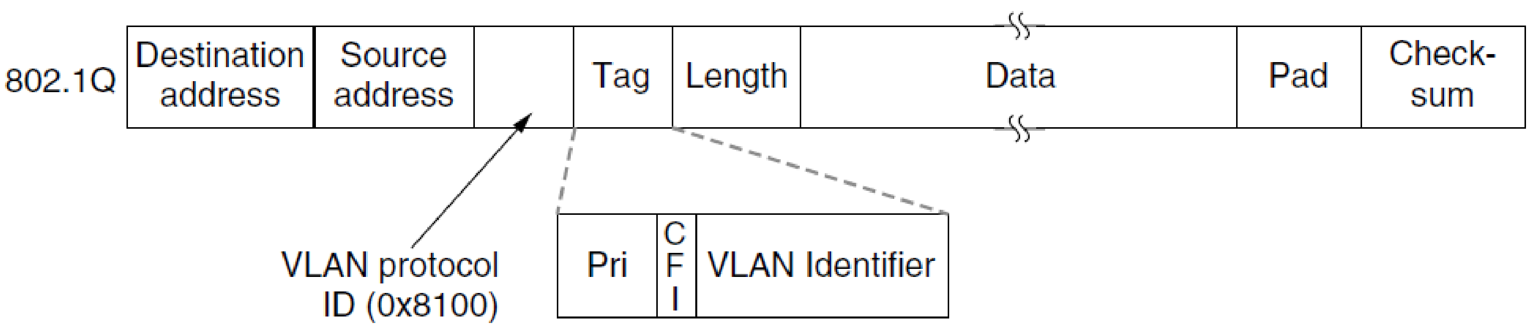
IEEE 802.1Q

- Tag protocol identifier (TPID): a 16-bit field set to a value of 0x8100 in order to identify the frame as an IEEE 802.1Q-tagged frame. This field is located at the same position as the EtherType/length field in untagged frames, and is thus used to distinguish the frame from untagged frames.



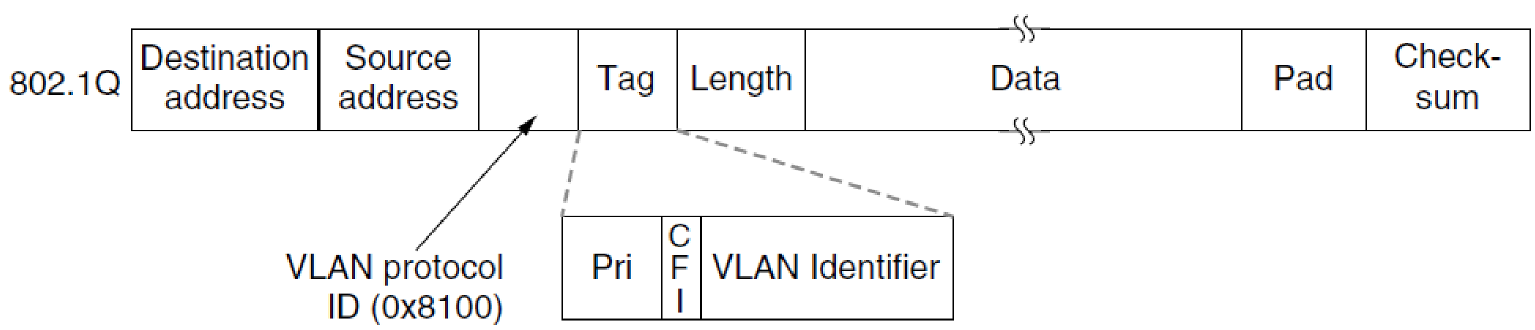
IEEE 802.1Q

- Tag control information (TCI)
  - Priority code point (PCP): a 3-bit field which refers to the IEEE 802.1p class of service and maps to the frame priority level.
  - Values in order of priority are: 1 (background), 0 (best effort), 2 (excellent effort), 3 (critical application), ..., 7 (network control).
  - These values can be used to prioritize different classes of traffic (voice, video, data, etc.).
  - Drop eligible indicator (DEI): a 1-bit field. (formerly CFI) May be used separately or in conjunction with PCP to indicate frames eligible to be dropped in the presence of congestion.



IEEE 802.1Q

- Tag control information (TCI)
  - VLAN identifier (VID): a 12-bit field specifying the VLAN to which the frame belongs.
  - The hexadecimal values of 0x000 and 0xFFF are reserved.
  - All other values may be used as VLAN identifiers, allowing up to 4,094 VLANs.
  - The reserved value 0x000 indicates that the frame does not belong to any VLAN; in this case, the 802.1Q tag specifies only a priority and is referred to as a priority tag



IEEE 802.1Q

- The VLAN fields are only actually used by the bridges and switches and not by the user machines.
- There can be computers (and switches) that are not VLAN aware.
- The first VLAN-aware bridge to touch a frame adds VLAN fields and the last one down the road removes them.
- Frames can be tagged depending on the port on which they are received.