COMPUTER NETWORKS

UNIT-5

data link & physical layers

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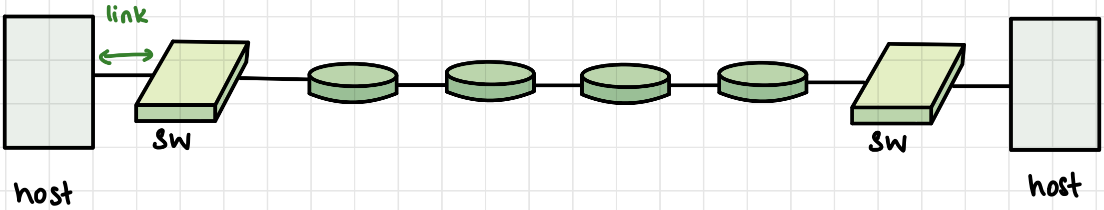
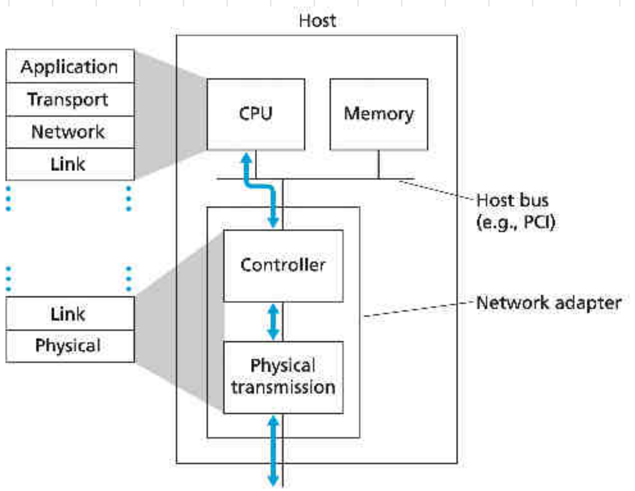
LINK LAYER

- Transport layer: process-to-process (port)
- Network layer: host-to-host (IP address)
- Link layer: node-to-node
- Node: any device that runs link layer protocol
- Broadcast channels & point-to-point (PPP)



- Nodes: hosts, routers, link-layer switches, Wifi access points
- Links: communication channels that connect adjacent nodes
- Datagram encapsulated in link-layer frame

Link Layer Implementation



- In hosts, implemented in network adapter/Network Interface Card (NIC)
- Combination of hw, sw, fw

Link Layer Services

1) Framing

- Encapsulate datagram within link-layer frame
- Data field: datagram + header fields
- Frame structure depends on link layer protocol

2) Link Access

- Medium Access Control (MAC) protocol specifies rules for frame to be transmitted onto link
- Point-to-point & broadcast

3) Reliable Delivery

- Acknowledgements & retransmissions
- Used with links prone to high error rates (wireless)
- Avoid end-to-end retransmission
- Unnecessary overhead for low bit-error links (fiber, coax etc.)
- Not provided by many wired link-layer protocols (Ethernet)

4) Error Detection & Correction

- Bit error detection
- Error-detection bits
- Correction: detects & corrects errors

5) Flow Control

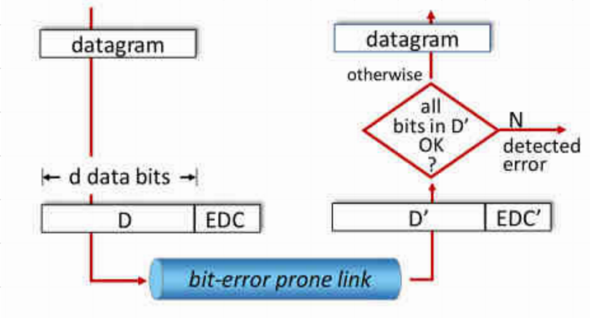
- Pacing between adjacent sending & receiving nodes

6) Half-Duplex & Full-Duplex

- Half: nodes at both ends can transmit, but not simultaneously
- Full: nodes at both ends can transmit simultaneously

Error Detection

- EDC: error detection and correction bits
- D: data protected by error checking



- Error detection techniques: parity checks, checksums, cyclic redundancy checks

1. Parity Checking

- Single Bit Even Parity

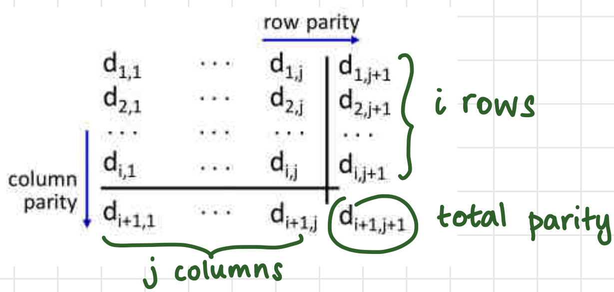
- detect single bit errors
- number of 1's: odd – parity bit 1, even-parity bit 0
- parity bit chosen such that total no. of 1's is even
- can detect if odd no. of bit errors have occurred

0111000110101011	1

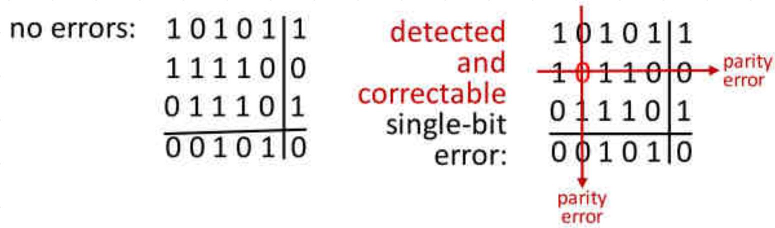
← parity bit

- Two Dimensional Bit Even Parity

- every row & column has parity bits



Example:



- error in parity bits detectable
- can detect (not correct) combination of errors
- forward error correction (FEC)

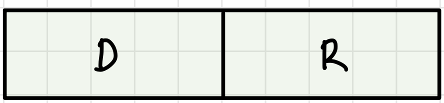
http://gaia.cs.umass.edu/kurose_ross/interactive/

2. Checksum

- UDP: 1's complement of sum passed as checksum (16-bit int)

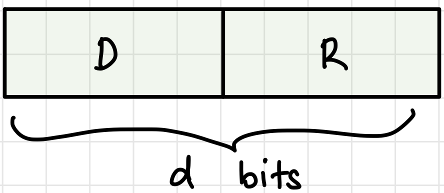
3. Cyclic Redundancy Check (CRC)

- No of data bits: d = D + R



- G: bit pattern known to sender and receiver (key) called generator bits
- $G\overline{)D}$ division; remainder bits appended to end of D to make D divisible by G (perform XOR)
- G is of r+1 bits (must start with 1)

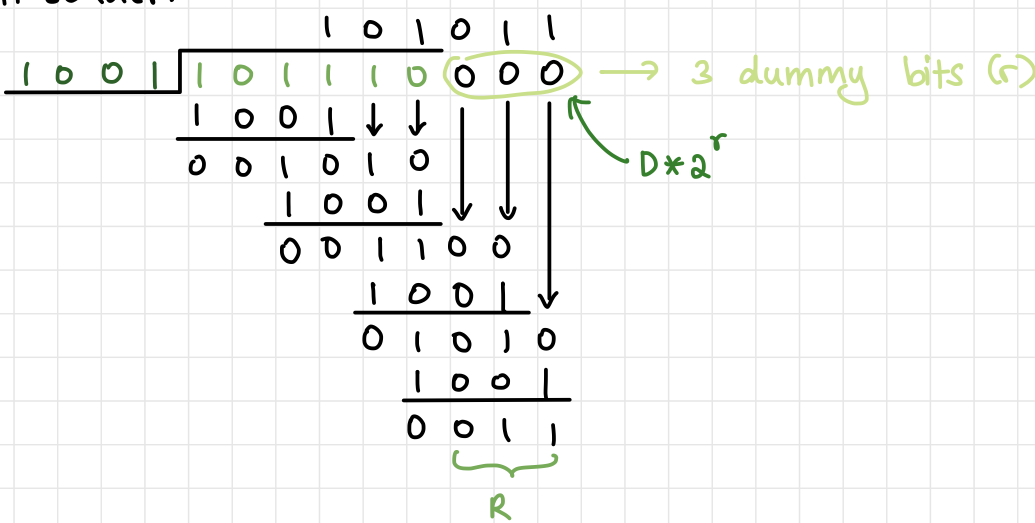
- Modular arithmatic (addition = subraction = XOR); no carries and borrows
- $\langle D, R \rangle$ divided by G at receiver; if remainder is not zero, then error is detected
- Can detect error bursts of fewer than r+1 bits; probability of error burst > r+1 bits = $1 - 0.5^r$



$$\langle D, R \rangle = D * 2^r \text{ XOR } R \quad (\text{same as } D \times 2^r + R)$$

Q: D = 101110 d = 6 bits G = 1001 r = 3

At sender:



sender sends $\langle D, R \rangle$ = 101110011

Link Layer Switching

- Hub & switch : physical & link layer
- Switch broadcasts message with IP address in header
- Hosts will ACK if destination address matches and switch 'learns' the link
- After learning destination IP address, switch no longer broadcasts message
- Hub also broadcasts message initially, like switch ; hub does not maintain state / table (works on bits, not frames) (collision domain)
- Hub does not 'learn' and always broadcasts messages to LAN hosts (does not store MAC addresses)
- Switch: intelligent device ; switch table (broadcast domain)
- Can observe on cisco packet tracer

MULTIPLE ACCESS PROTOCOL

- At any given time, only one host can send data on shared link
- Checks if channel is busy or idle (carrier sense)
- Avoid collisions
- For broadcast links

Ideal Multiple Access Protocol

- Given: Broadcast / Multiple Access channel (MAC) of rate R bps
- If only one node wants to send data, rate of R
- If M nodes want to send data, avg rate of R/M
- Fully decentralised

Three Broad Classes

1. Channel Partitioning Protocols
   - divide channel into time/ frequency slots
   - each slot allocated to node for exclusive use

2. Random Access Protocols
   - collisions allowed ; no divisions
   - Must recover from collisions

3. Taking Turns Protocols
   - nodes take turns
   - longer turns for nodes with more data

Carrier Sense Multiple Access (CSMA) Protocol

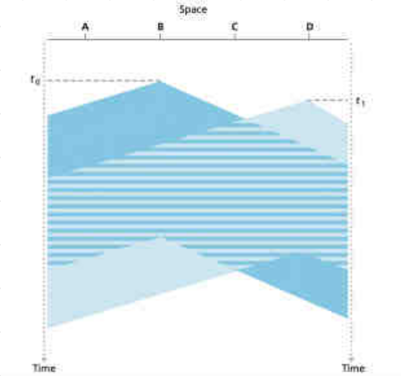
- Listen to channel before transmitting — carrier sensing
- If idle, transmit entire frame
- If not, do not transmit / stop transmitting — collision detection
- No interrupting

- Collisions can still occur if two hosts sense idle channel at the same time or if a host has not yet received broadcast – channel propagation delay

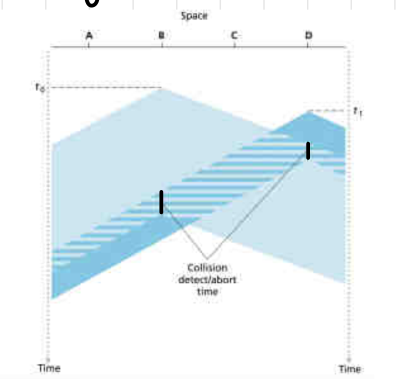
- Collisions waste time and bandwidth; should stop if collision detected

CSMD/CD

- With collision detection; colliding transmissions aborted



CSMA



CSMA/CD

Algorithm

1. NIC/adapter receives datagram from network layer & creates frame

2. If idle: transmit; if busy: waits until it senses no signal energy

3. While transmitting, adapter monitors channel for presence of signal energy

4. If collision detected, abort and send jam signal back to sender. If not, frame transmission complete.

5. Binary (exponential) backoff algorithm – Ethernet, DOCSIS

- After m^{th} collision, NIC chooses k from $\{0, 1, \ldots, 2^m - 1\}$
- NIC waits $k * 512$ bit times (time taken to send 512 bits into the Ethernet $* k$), returns to step 2 (using bps)
- As m increases, backoff increases

Efficiency

- t_{prop} : max prop delay between 2 nodes in LAN
- t_{trans} : time to transmit max frame

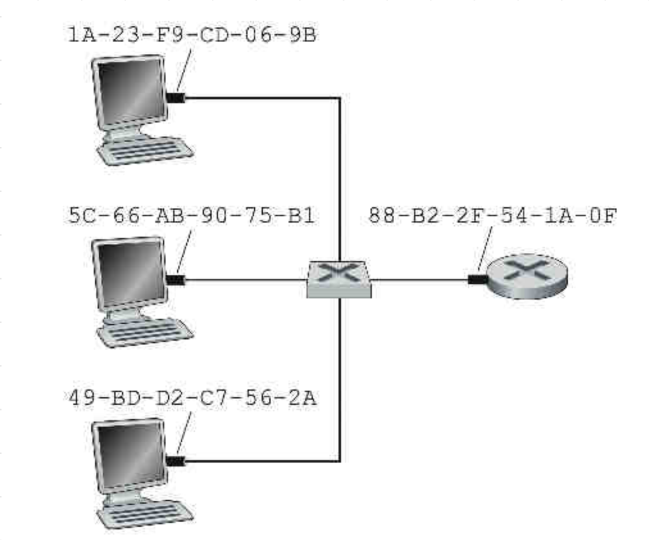
$$\text{efficiency} = \eta = \frac{1}{1 + 5\, t_{prop}/t_{trans}}$$

- As $t_{prop} \longrightarrow 0$, $\eta \rightarrow 1$
- As $t_{trans} \longrightarrow \infty$, $\eta \rightarrow 1$
- Better than ALOHA (decentralised)

LINK LAYER ADDRESSING & ARP

- MAC/LAN/Ethernet address: 48-bit address, usually burned in NIC ROM, sometimes software settable (not advised)
- Unique addresses: managed by IEEE ; manufacturers must buy block of addresses
- MAC: media access control

- Eg: 1A-2F-BB-76-09-AD



- MAC: flat address ; can move from one LAN to another unlike IP address (not hierarchical)

- Broadcast address: FF-FF-FF-FF-FF-FF

Address Resolution Protocol (ARP)

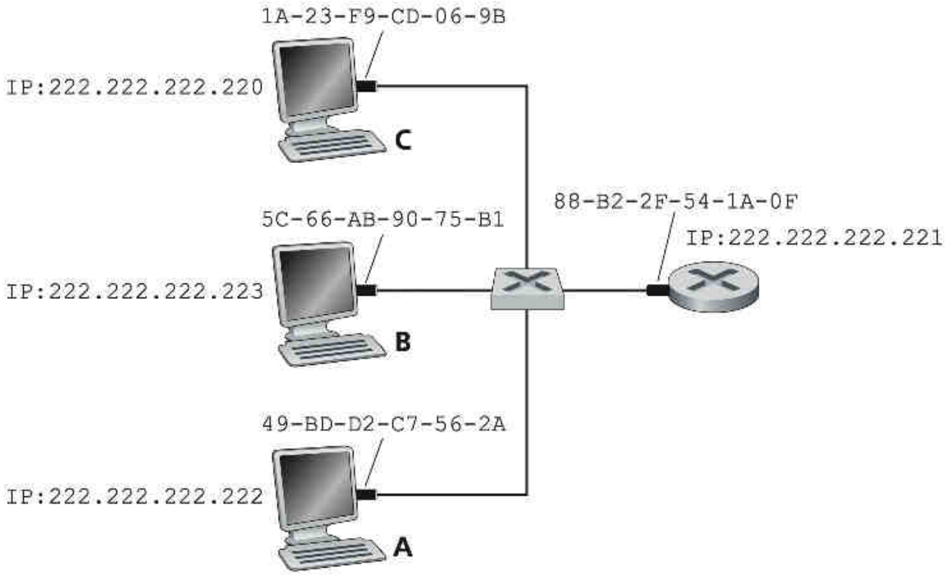
- Link layer: device to device

- ARP table: every IP node (host, router etc) on LAN has its own ARP table

- IP/MAC address mappings for some LAN nodes

- TTL: after which mapping forgotten (~20 mins)

< IP addr; MAC addr; TTL >



Eg: A wants to send datagram to B

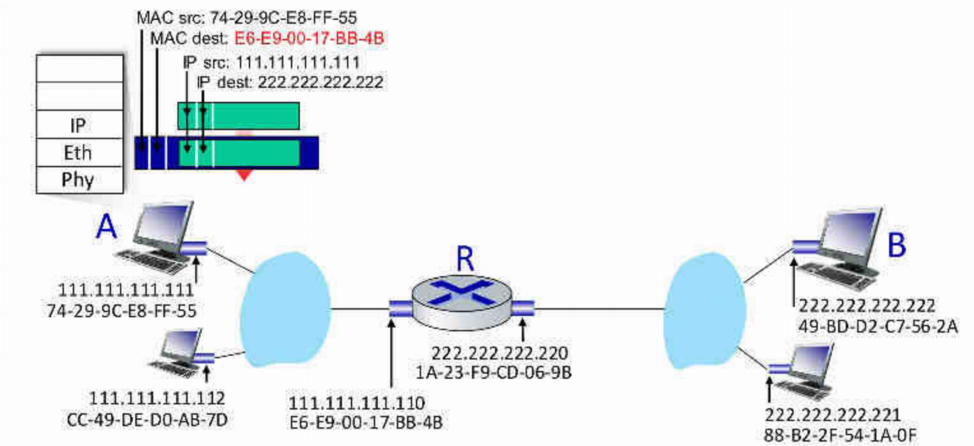
- If B's entry not in ARP table, it is broadcasted
- A broadcasts ARP query containing B's IP addr
- Destination MAC: broadcast FF-FF-FF-FF-FF-FF
- All nodes on LAN receive ARP query
- B sends response with MAC addr to A

ARP Table of A

IP	MAC	TTL (when it will delete mapping)
222.222.222.221	88-B2-2F-54-1A-0F	500

With Router - across subnets

- A knows IP address of first-hop router
- ARP for all router interfaces



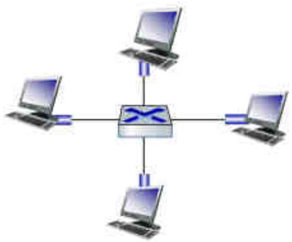
ETHERNET

- LAN technology ; first widely used, dominant
- Cheap, simple, fast (802.3)

Physical Topology

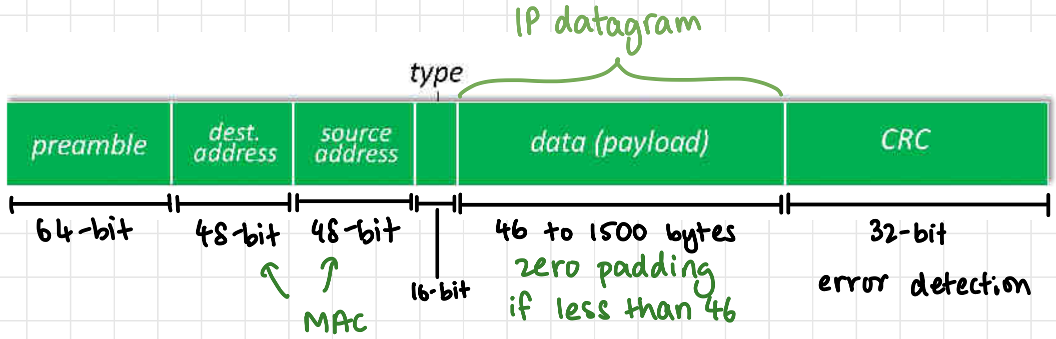
- Bus: all nodes in same collision domain ; 90s
- Switched: active switch in centre (link layer) ; no colliding

bus



switched

Ethernet Frame Structure



Preamble

- synchronises sender & receiver clock rates
- 7 bytes of 10101010 followed by one byte of 10101011 (end of pre)

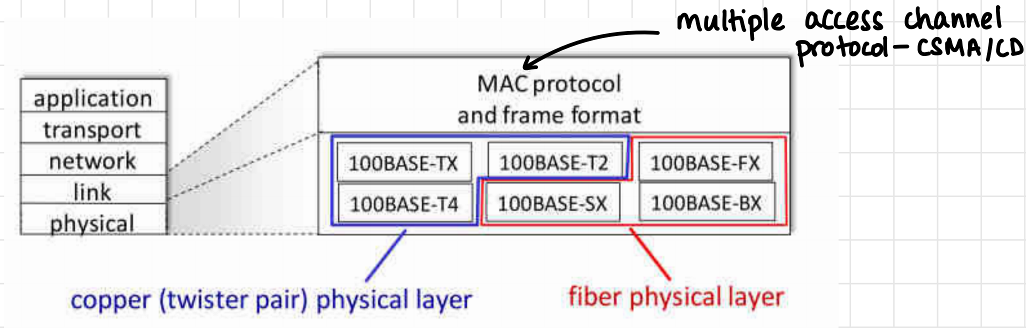
Type

- Higher (network) layer protocol (eg: IP)
- IP, Novell, AppleTalk, ARP
- Demux at receiver

Unreliable Connectionless

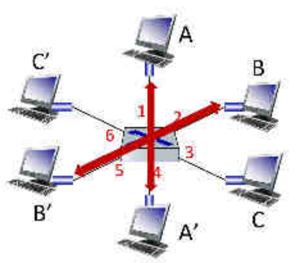
- Connectionless: no handshaking between NICs
- Unreliable: no ACKs/NAKs; only higher layer protocols verify

802.3 Ethernet Standards: Link & Physical Layers



SWITCH

- Link layer device, active
- Store & forward ethernet frames
- No configuration for switches ; transparent to hosts/routers
- Full duplex, no collisions



switch with six interfaces (1,2,3,4,5,6)

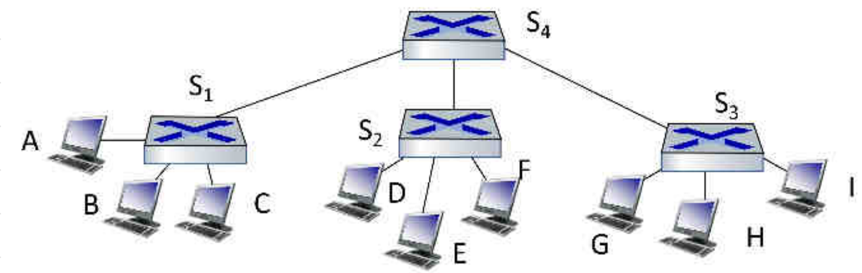
Switch Table

Switch table (initially empty)

MAC addr	interface	TTL
A	1	60

Interconnecting Switches

- All switches in one network ; only routers separate out networks



within single network

Switch Filtering & Forwarding

- Suppose frame with destination address DD-DD-DD-DD-DD-DD arrives via interface x to a switch

- The switch indexes switch table for address DD-DD-DD-DD-DD-DD. Three possibilities

(1) No entry for address DD-DD-DD-DD-DD-DD
- Switch forwards copies of frame to all interfaces except incoming interface x
- Broadcast

(2) Entry for address with interface x
- Frame coming from LAN segment containing adapter DD-DD-DD-DD-DD-DD
- Filter frame out ; discarded

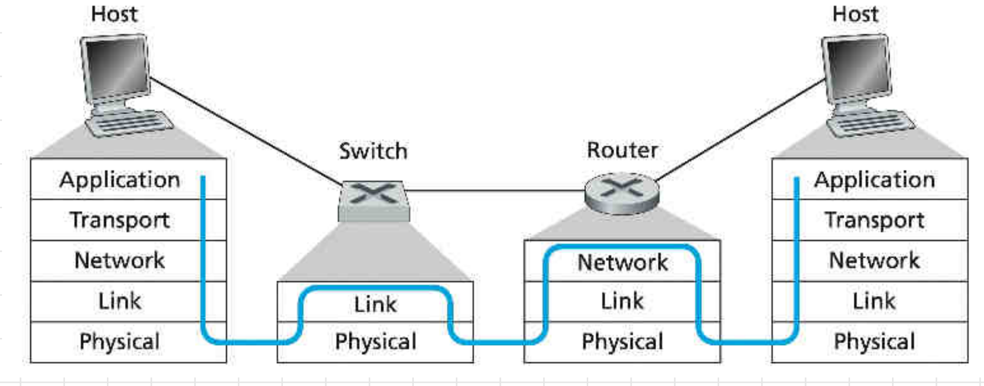
(3) Entry for address with interface $y \neq x$
- Frame forwarded to LAN segment attached to interface y
- Forward frame

SELF-LEARNING SWITCH

- Table constructed automatically
- Table initially empty
- For each incoming frame, entry added to table with MAC Address as frame's source address, interface as incoming interface and the current time
- After a period of time (aging time) switch deletes outdated entries
- Plug & play devices; no configuration required

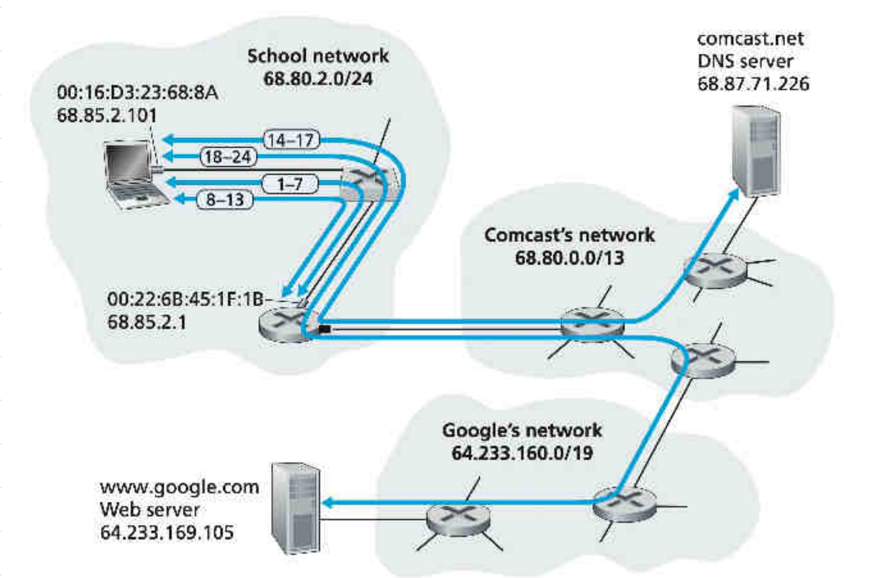
Switch vs Router

Switch	Router
• link layer • connection of devices • switch table: forwarding using flooding, MAC addresses	• network layer • connection of networks • routing table: routing algorithms, IP addresses



A DAY IN THE LIFE OF WEB REQUEST – skim through

- Laptop on institutional network makes request to www.google.com



(i) Laptop runs DHCP protocol to obtain IP address from local DHCP server (assume running within the router)

1. Laptop OS creates DHCP request message and puts message within UDP segment with destination port 67 (DHCP server) and source port 68 (DHCP client)

2. UDP segment placed inside IP datagram with broadcast IP destination address (255.255.255.255) and source IP of 0.0.0.0 as laptop does not have an IP address yet

3. IP datagram placed inside Ethernet frame with destination MAC address FF-FF-FF-FF-FF-FF (so that frame broadcasts to all interfaces) and source MAC address equal to host's MAC address (00-16-D3-23-68-8A)

4. The broadcast Ethernet frame is the first frame sent by the host laptop to the switch and the frames is broadcasted to all outgoing ports of the switch, including the router

5. The frame is received by the router on interface with a specific MAC address (00-22-6B-45-1F-1B) and IP datagram is extracted

6. Datagram's destination IP address is the broadcast address, which indicates that the datagram needs to be processed by DHCP server (upper layer protocols of the router)

7. Datagram's payload demultiplexed to obtain UDP segment and DHCP request message extracted

8. Suppose DHCP server is allowed to allocate addresses within the CIDR block 68.85.2.0/24 and DHCP server allocates address 68.85.2.101 to host laptop

9. Server creates DHCP ACK message containing IP address of host (68.85.2.101), IP address of DNS server (68.87.71.226), IP address of default gateway router (68.85.2.1) and the subnet block/network mask (68.85.2.0/24)

10. DHCP ACK message put inside UDP segment → IP datagram → Ethernet frame with source MAC address equal to router's interface to host's subnet (00-22-6B-45-1F-1B) and destination MAC address equal to host's MAC address (00-16-D3-23-68-8A)

11. Ethernet frame sent to switch and then forwarded to host (self learning)

12. Host receives frame and extracts IP datagram → UDP segment → DHCP ACK message

13. Host's DHCP client (port 68) records its IP address and DNS server's IP address

14. Host installs address of default gateway into its IP forwarding table where all datagrams with destination IP address outside of its subnet will get forwarded to

(ii) DNS protocol to obtain IP address of www.google.com

15. OS creates DNS query message with string www.google.com as question (host)

16. Message placed in UDP segment with destination port 53 → IP datagram with destination address 68.87.71.226 (DNS server address returned in step 9) and source IP address 68.85.2.101 → Ethernet frame

17. Ethernet frame needs to run ARP to find MAC address of gateway router using IP address 68.85.2.1

18. Host creates ARP query message with target IP address 68.85.2.1 of default gateway and places within Ethernet frame with broadcast destination address FF-FF-FF-FF-FF-FF which gets delivered to all connected devices

19. Frame received at gateway router, ARP table checked, ARP reply prepared with MAC-IP mapping → Ethernet frame sent to switch and then host

20. Host receives ARP reply and extracts MAC address

21. Ethernet frame containing DNS query addressed to gateway router's MAC address and sent to switch

(iii) Intra-domain routing

22. Gateway router receives DNS frame → IP datagram and looks up destination IP → checks forwarding table and placed inside link layer frame → sent to next router

23. Forwarded to DNS server over hops

24. IP datagram arrives at DNS server → message and looks up name www.google.com in database, finds resource record, forms DNS reply message → UDP → IP and routed back to host

(iv) Web Client-Server Interaction

25. Host creates TCP socket, performs three-way handshake with TCP in google.com (TCP SYN, port 80, arrives at google port 80, TCP connection socket created, TCP SYNACK sent back)

26. Host creates HTTP GET message with URL www.google.com, written into socket → payload of TCP segment is GET message → IP datagram and sent to www.google.com

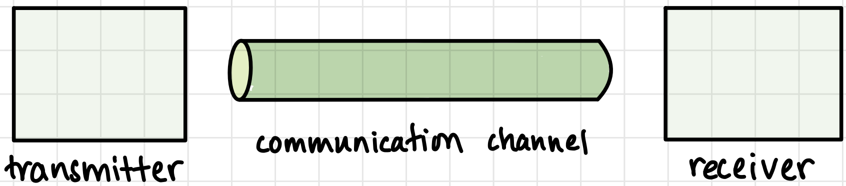
27. Server creates responce, places webpage content in body of HTTP response, sent to TCP socket

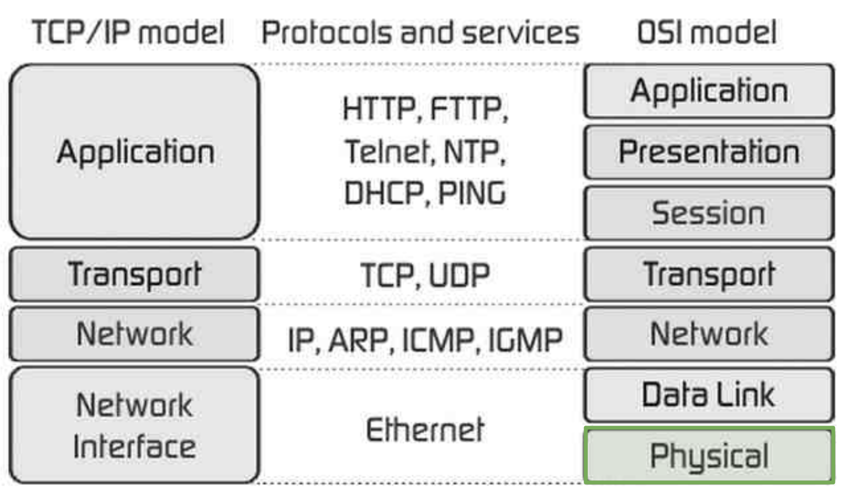
28. Datagram sent to host, web browser reads, extracts html, displays webpage

Skim through slides for images

PHYSICAL LAYER

- Physical circuit; hardware — media, circuitry, connectors
- Converts frames to electrical pulses
- Responsible for specifying physical medium, signal, bits



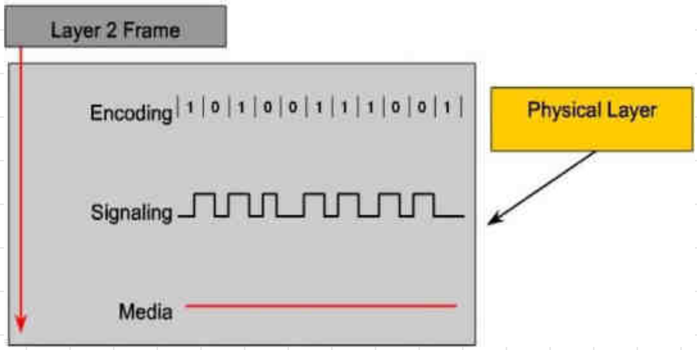


Hardware Components

- Network adapters, network interface cards
- Connectors
- Cable materials

Signalling

- All data in 0's and 1's
- Manchester encoding: 1 — low to high, 0 — high to low (not always at bit boundaries)



Data Carrying Capacity

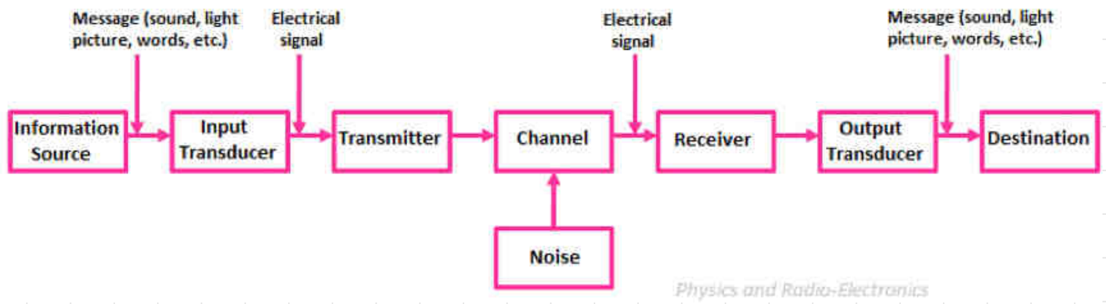
- Bandwidth: capacity of medium to carry data in a given amount of time — physical properties, signalling method (theoretical)
- Throughput: practical transfer rate
- Goodput: transfer rate of usable bits

ANALOG & DIGITAL SIGNALS

- Signal: electromagnetic waves or electrical current carrying data

Analog

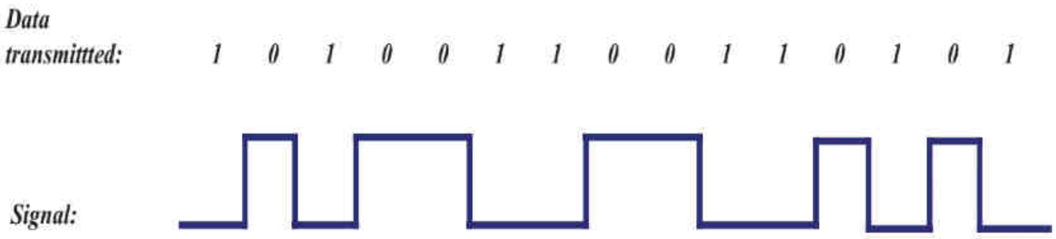
- Transducer converts physical signal to analog signal



- Infinite number of values ; more interference and errors

Digital

- Discrete values (0s and 1s)
- Sequence of voltage pulses
- Cheaper, less interference
- More attenuation than analog



Transmission Media

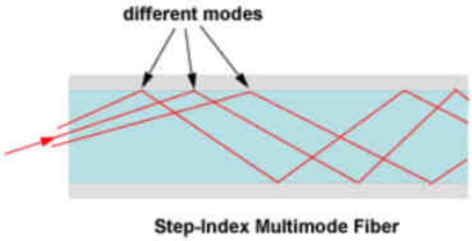
- Guided and unguided (see unit 1)
- Repeaters, amplifiers used
- Twisted pair, coaxial cable, fibre optics, wireless

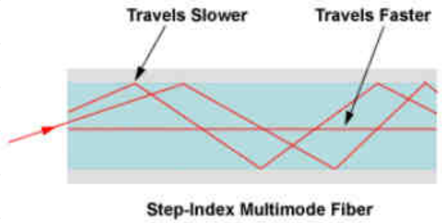
Specification	Media	Maximum Segment Length	Connector
10BASE-T	CAT 3,4 or 5 UTP (4 pair)	100m	RJ-45
100BASE-TX	CAT 5 UTP (2 pair)	100m	RJ-45
100BASE-FX	62.5/125 multimode fiber	2km	
1000BASE-CX	STP	25m	RJ-45
1000BASE-T	CAT 5 UTP (4 pair)	100m	RJ-45
1000BASE-SX	62.5/50 multimode fiber	62.5 – 275m 50 – 550m	
1000BASE-LX	62.5/50 multimode 9-micron single-mode fiber	62.5/50 – 550m 9 –10 km	
1000BASE-ZX	9-micron single-mode fiber	70km	
10GBASE-ZR	9-micron single-mode fiber	80km	

Optical Fibre

1) Multimode step index

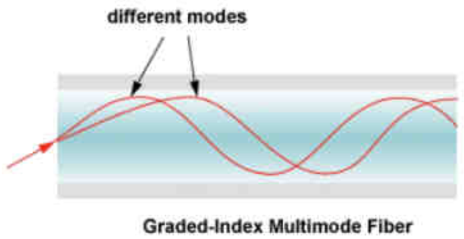
- total internal reflection of light within cable
- zig-zag
- path function of angle of incidence
- distance: few kms

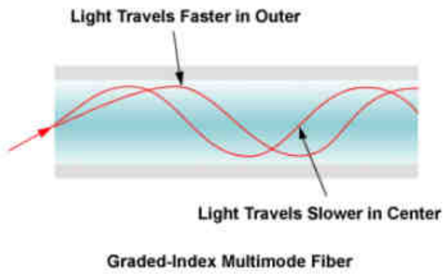




2) Multimode graded index

- sinusoidal oscillations
- better performance
- distance: 10-12 kms

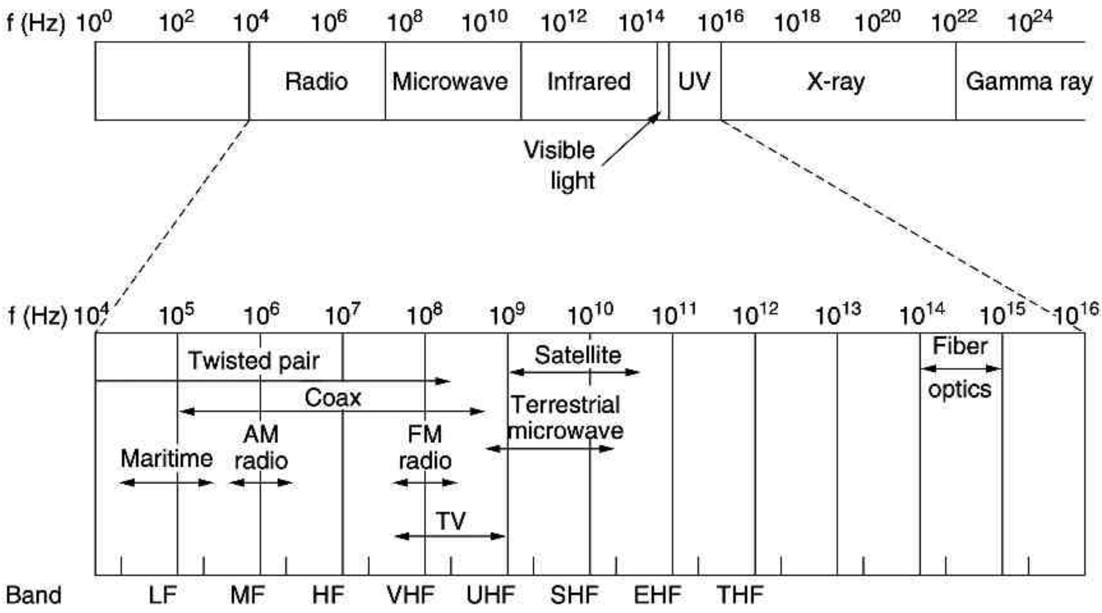




3) single mode step index

- propagation of one transverse EM mode
- core diameter: 2μm to 10μm
- high capacity
- modes - solutions of Helmholtz equation ($\nabla^2 f = -k^2 f$) for waves
- 2009 Nobel Prize

Unguided Media : EM Spectrum



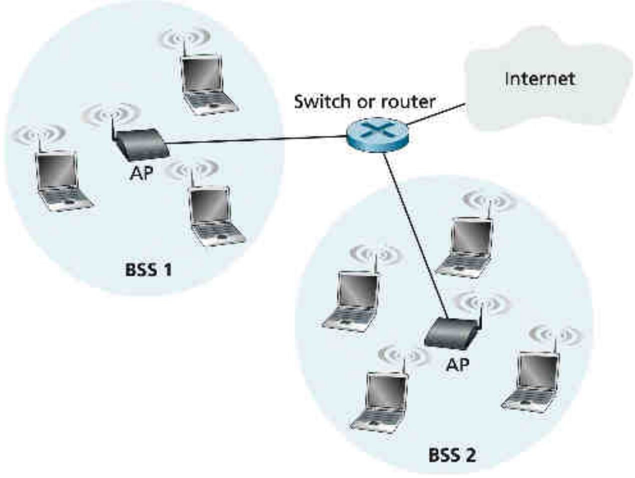
Wireless LAN

- 802.11 — IEEE standard
- Wireless connectivity to router
- Access point (AP): bridge between wireless and wired network
- AP connected to wired network and equipped with antennae for wireless
- Range depends on hindrances ; multiple APs with overlaps
- Hand off of clients from one AP to another

802.11

Standard	Frequency Range	Data Rate
802.11b	2.4 GHz	up to 11 Mbps
802.11a	5 GHz	up to 54 Mbps
802.11g	2.4 GHz	up to 54 Mbps
802.11n	2.5 GHz and 5 GHz	up to 450 Mbps
802.11ac	5 GHz	up to 1300 Mbps

- Defines MAC protocol
- Physical medium specification for wireless LAN (wifi)
- 2.4 GHz : unlicensed band; microwave oven & 2.4 GHz phones compete
- 5 GHz band: shorter transmission distance, multipath propagation (portions of EM wave reflect & take diff path lengths)
- 802.11n & 802.11ac use multiple input, multiple output (MIMO) antennas (different signals)



Terminology

Base Station

- relay
- sends packets between wireless hosts and wired network
- eg: cell towers, 802.11 access points

Wireless Links

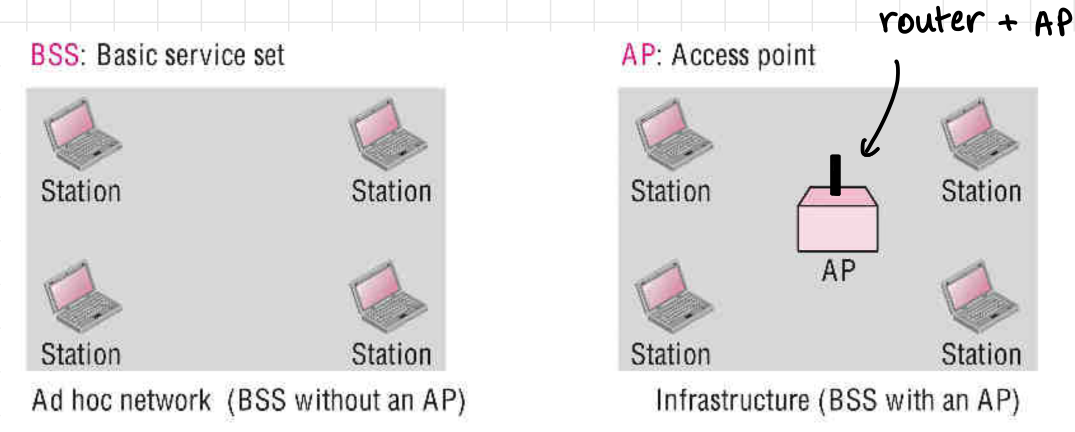
- connect mobile phones to base station
- backbone link
- multiple access protocol coordinates link access

Access Point

- Central base station of basic service set (BSS)
- In most home networks, AP & router combined in single device
- MAC addresses: stored in firmware of wireless NIC
- Service Set Identifier (SSID) assigned to AP (when browsing wifi networks, SSIDs shown)
- Periodically sends beacon frames (containing SSID & MAC of AP) to device

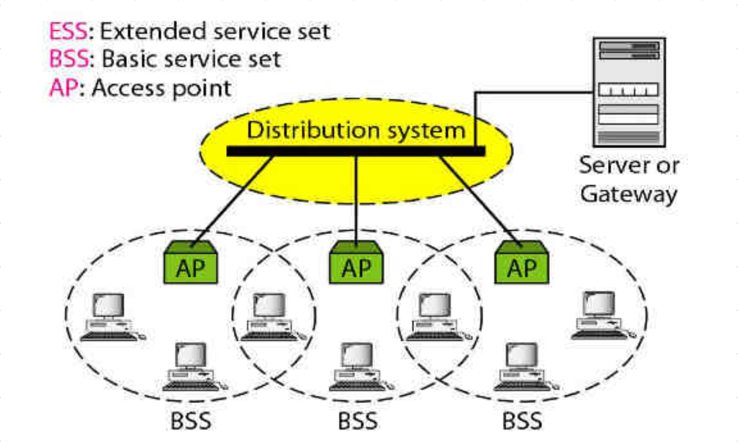
Access point (AP)	Any entity that has station functionality and provides access to the distribution system via the wireless medium for associated stations
Basic service set (BSS)	A set of stations controlled by a single coordination function.
Coordination function	The logical function that determines when a station operating within a BSS is permitted to transmit and may be able to receive PDUs.
Distribution System (DS)	A system used to interconnect a set of BSSs and integrated LANs to create an ESS.
Extended service set (ESS)	A set of one or more interconnected BSSs and integrated LANs that appear as a single BSS to the LLC layer at any station associated with one of these BSSs.
MAC protocol data unit (MPDU)	The unit of data exchanged between two peer MAC entites using the services of the physical layer.
MAC service data unit (MSDU)	Information that is delivered as a unit between MAC users.
Station	Any device that contains an IEEE 802.11 conformant MAC and physical layer.

Basic Service Set (BSS)

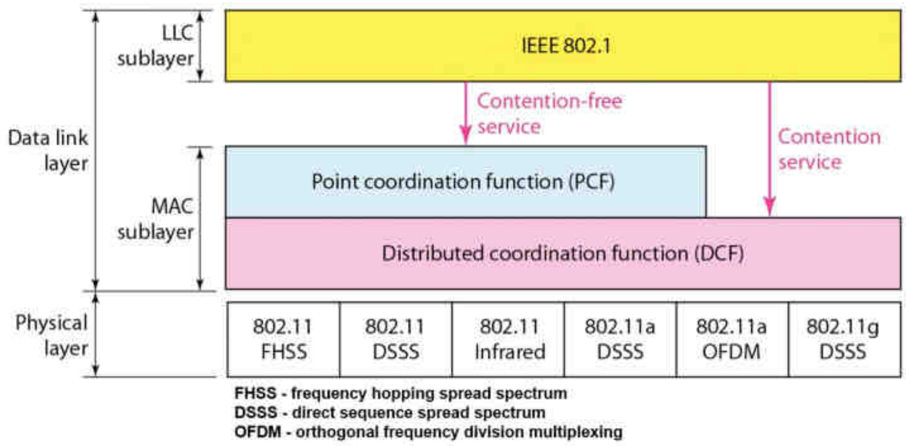


- smallest building block
- AP: central base station

Extended Service Set



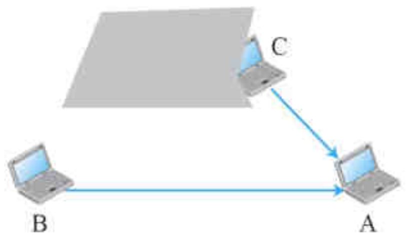
802.11 Architecture



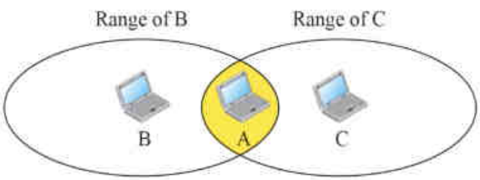
- PCF: collision prevention (optional)
- DCF: CSMA algorithm - exponential

Access Control

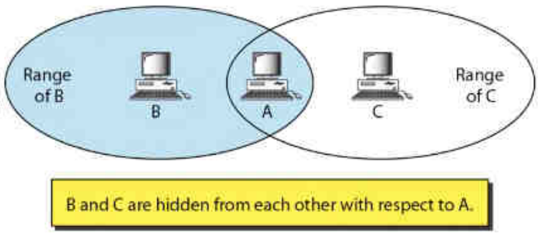
- Shared medium is air; more collisions
- CSMA/CD does not work (detection prevented by hidden stations)



b. Stations B and C are hidden from each other.

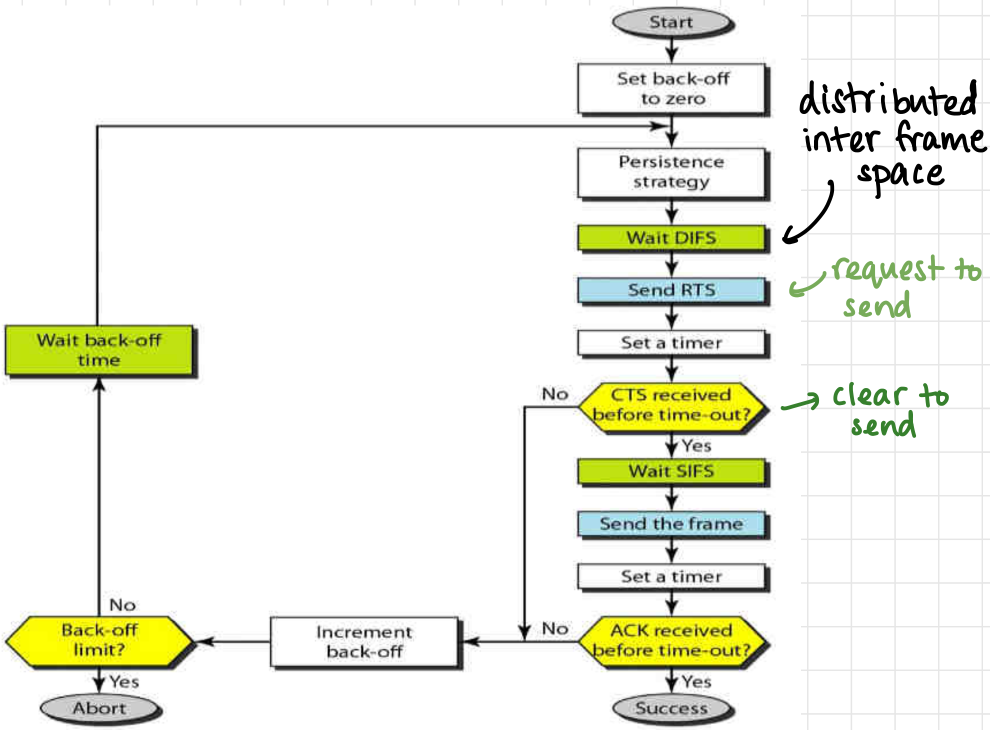


a. Stations B and C are not in each other's range.

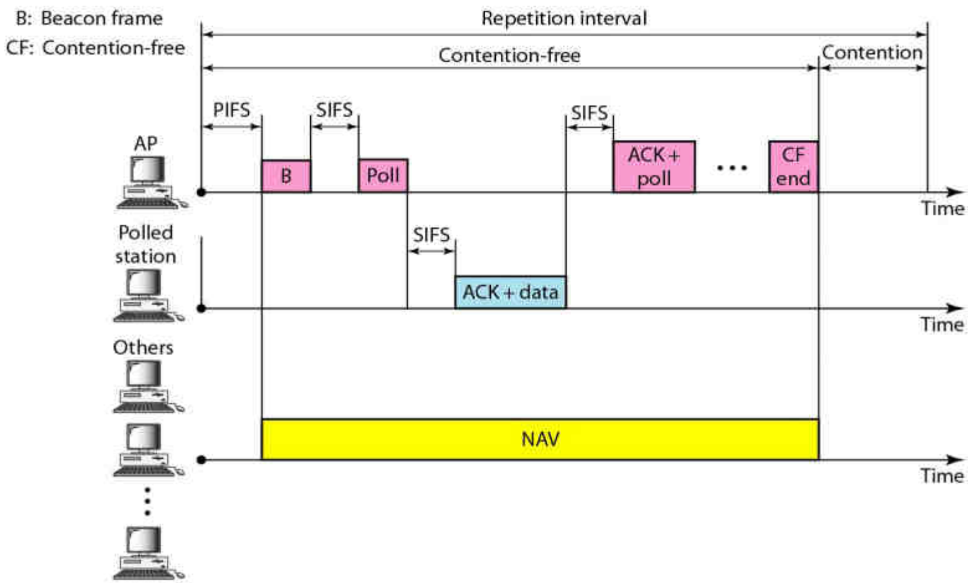


CSMA/CA

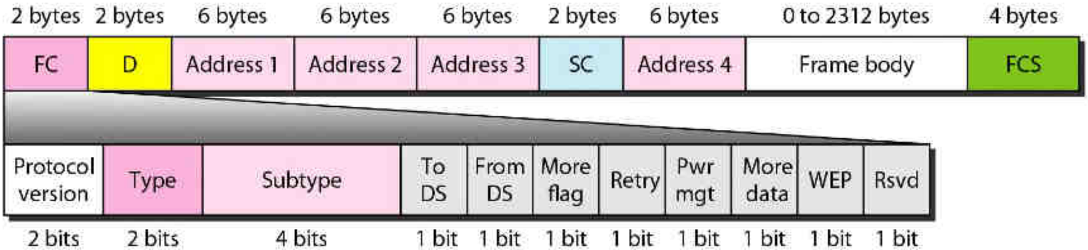
- proposed as solution - collision avoidance
- link layer acknowledgement - retransmission scheme (ARQ)



Repetition Interval



FRAME FORMAT



- FC: frame control
- FCS: frame check sequence (CRC)
- D: duration of transmission used to set NAV

- SC: sequence control (sequence # of the frame used in flow control)

- Four address fields —— first 3 address fields for internetworking

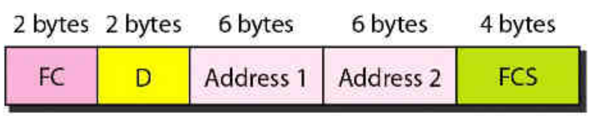
Address 1: MAC address of station that receives frame (next device)

Address 2: MAC address of station that transmits frame (previous device)

Address 3: MAC address of final destination if not defined by Address 1

Address 4: MAC address of original source if not defined by Address 2

Control Frames



RTS

CTS or ACK