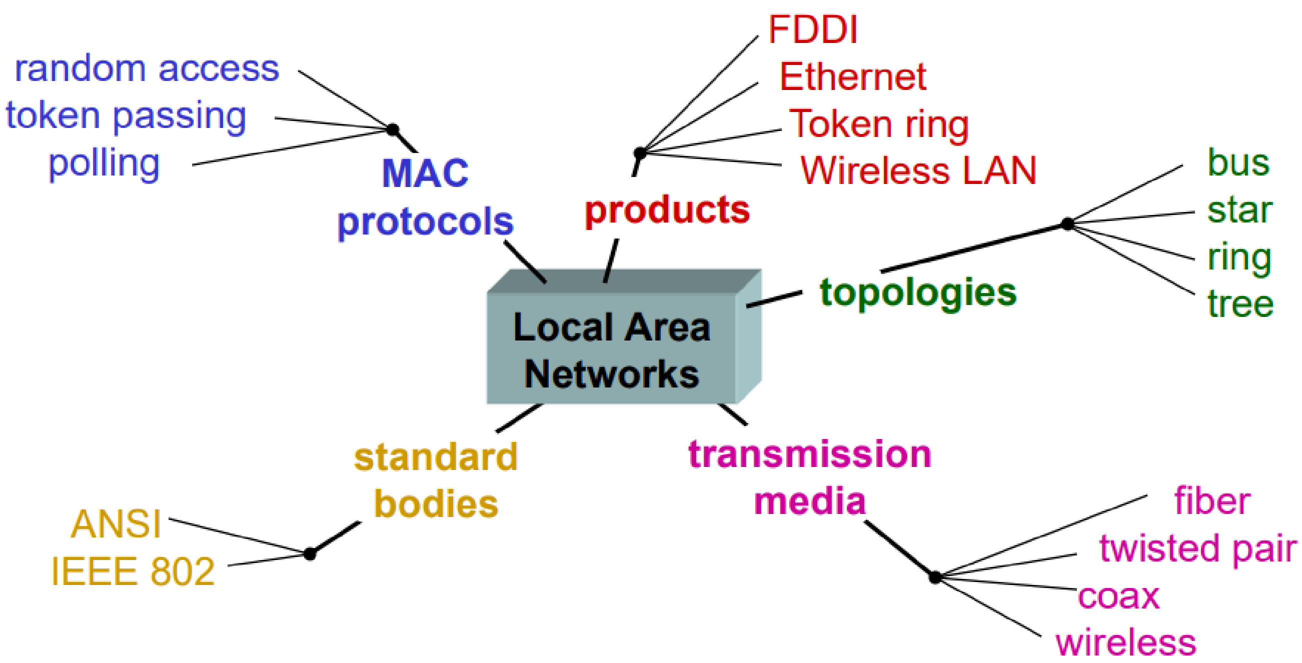
C3 Local Area Network

1. Local Area Network

1.1 Definition and Taxonomy

- Computer network that covers a small area
  - Has higher data rates (10Mbps - 40Mbps) compared to WAN
- Consists of shared transmission medium, regulations for orderly access to the medium, set of hardware and software for interfacing devices

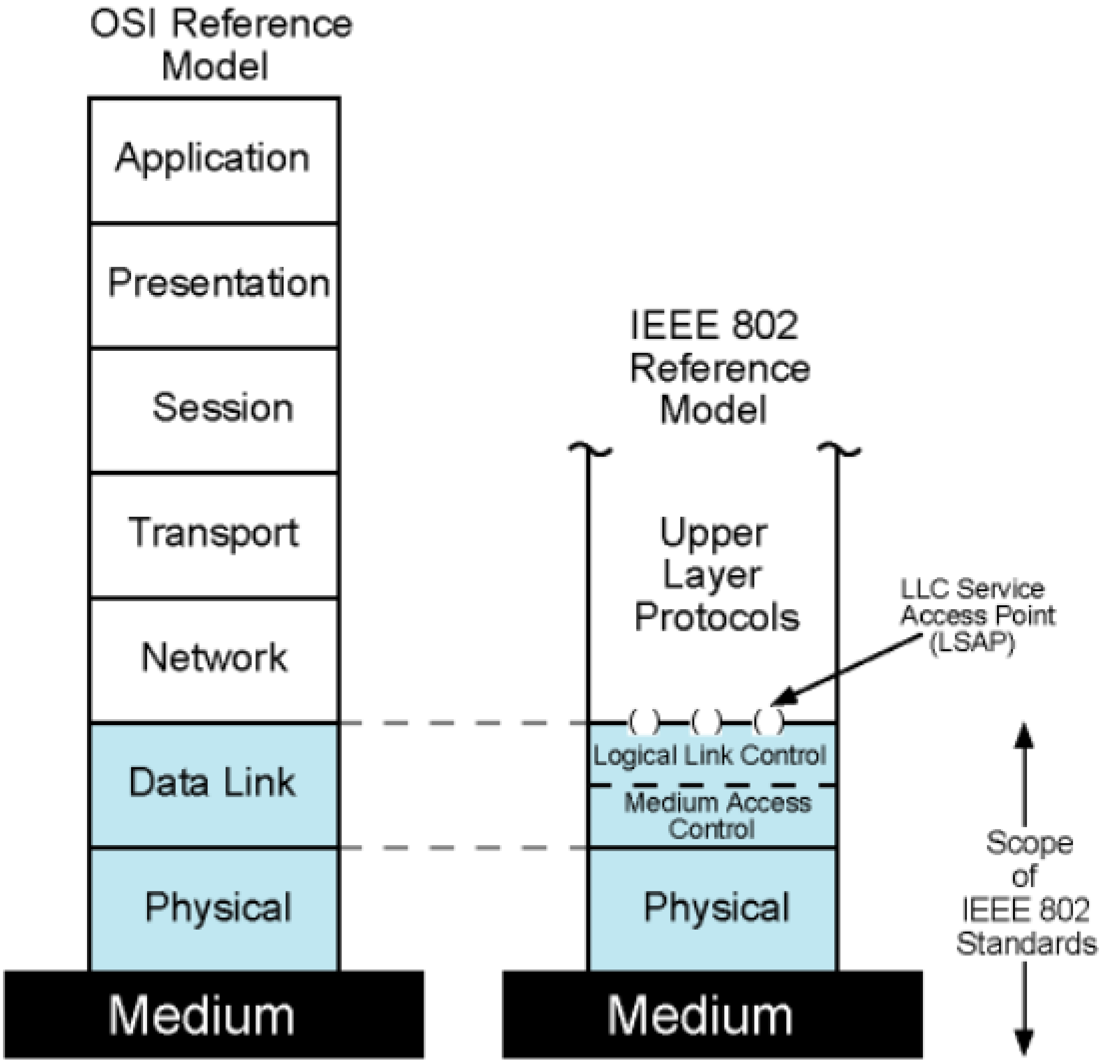
Taxonomy



1.2 Protocol Architecture

- Corresponds to lower two layers of OSI model (usually do not follow OSI)
  - based on ethernet protocols
    - Logical Link Control (LLC) **data layer**
    - Media Access Control (MAC) **data layer**

- Physical



Physical

- Signal encoding / decoding
- Preamble generation / removal (synchronisation purposes)
- Bit transmission / reception
- Specification for topology and transmission medium

LLC

- Interface to higher levels
- Flow control
- Based on Data Link Control Protocols (previous chapter)

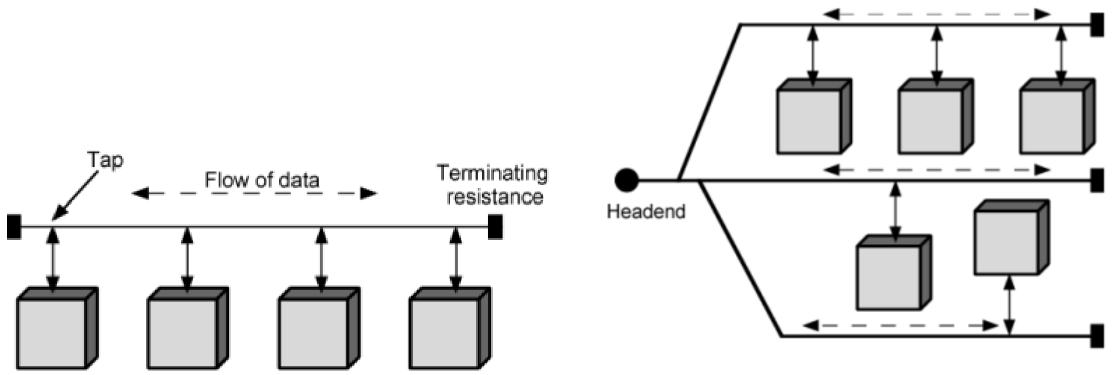
MAC

- Prepare data for transmission
- Error detection
- Address recognition
- Govern access to transmission medium

2. LAN Topologies

2.1 Bus, Tree, Ring, Star

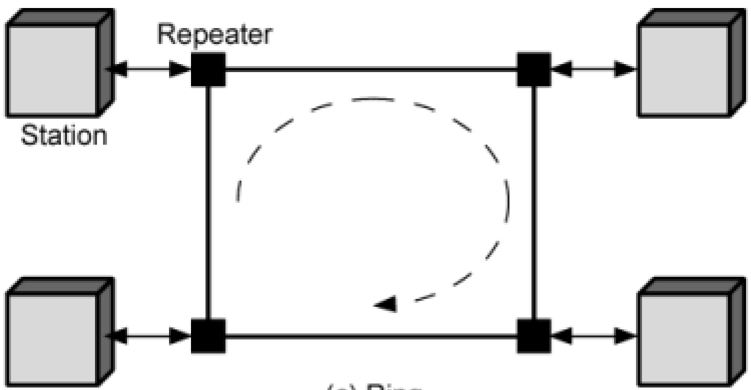
Bus & Tree



(a) Bus
(b) Tree

- Multipoint medium
- Transmission propagates throughout medium and heard by all stations
  - each station has a unique address for identification purposes
- Full duplex (bi-directional) connection between station and tap, allowing for transmission and reception
- Transmissions need to be regulated
  - To avoid collisions (when two stations transmit at the same time)
  - To avoid continuous transmission from a single station
    - data is transmitted in frames
- Terminating resistance absorbs frames at end of medium

Ring

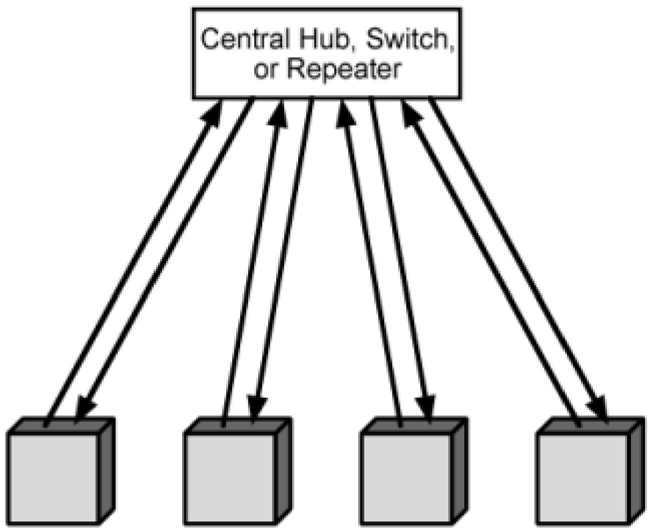


(c) Ring

- Stations are attached to repeaters which are joint by point to point links in closed loop
  - Links are unidirectional
  - Data is received on one link and retransmitted on another

- Data frames circulate past all stations, destination recognises target address in frame and copies the frame, frame circulates back to source to be removed
- Medium access control determines when a station can insert its frame

Star



(d) Star

- Each station connected directly to central node using a full-duplex link
- Central node acts as a hub and can be used for broadcast
  - Each link from central node becomes a bus topology (Star is essentially multiple bus topologies connected to one central node)
  - Only one station can transmit at a time to avoid collision
- Central node can also act as a frame switch by retransmitting down one lane to destination

2.2 How to choose

- Reliability
- Expandability
- Performance
- **Need to consider**
  - Medium
  - Wiring Layout
  - Access Control

3. Transmission Media (not examinable)

Voice grade unshielded twisted pair (UTP)

- Cat 3 / Cheap

- Low data rates

Shielded twisted pair (STP) & baseband coaxial

- More expensive than UTP
- Higher data rates than UTP

Broadband

- More expensive than STP
- Higher data rate than STP

High performance UTP

- Cat 5 above
- High data rate for small number of devices
- Switched star topology for large installations

Optical fiber

- Electromagnetic isolation
- Small size
- High capacity, expensive
- High skill needed to install and maintain

Wireless

- Fading channel

4. Media Access Control

4.1 Functions and Features

- Assembly of data into frame with address and error detection fields
- Disassembly of frame
  - Address recognition
  - Error detection
- Govern access to transmission medium
- Several MAC options may be available for the same LLC

Decision making

- Where
  - Central
    - greater control
    - simple access logic at station

        - avoids problems of co-ordination
        - single point of failure
        - potential bottleneck
    - Distributed
- How
    - Synchronous solutions
        - specific capacity dedicated to connection
    - Asynchronous solutions
        - response to demand

4.2 Static Channel Allocation

Time Division Multiplexing (TDM)

- Each user statically allocated one time slot which is wasted if the user does not have anything to send
- Users may not utilise the whole channel for a time slot

Frequency Division Multiplexing (FDM)

- Channel is divided to carry different signals at different frequencies
- Efficient if there is a constant amount of users with continuous traffic

Code Division Multiplexing

4.3 Dynamic Channel Allocation

Round Robin

- Each station has a turn to transmit
    - can either decline turn or transmit up to certain data limit
    - both cases has overhead of passing the turn
- Good performance if many stations have data to transmit for majority of duration
    - otherwise passing will cause inefficiency since useful work done is less

Reservation

- Used for stream traffic, time on medium is divided into slots (like TDM)
- Reservation can be made in centralised or distributed fashion

Contention

- All stations contend to transmit (no control to determine turn)
- Stations send data by taking risk of collision (by sending at the same time)

    - collisions are made known by listening to channel so stations can retransmit
- Good for bursty traffic (commonly seen)
- Efficient under light / moderate load

5. MAC protocols

5.1 MAC

- Single shared broadcast channel
- ≥ 2 simultaneous transmissions
    - Collisions if node receives two or more signals at the same time
- Distributed algorithm to share the channel, communication about channel sharing must use channel itself

Ideal MAC protocols

- Broadcast Channel of Rate R-bps
    - Average rate is given by R/M, with M being the number of nodes
    - Fully decentralised (No special node to coordinate transmissions)
    - No synchronisation of clocks / slots
    - Simple

Taxonomy

- This module focuses on Random Access Protocols (ALOHA, CSMA, CSMA/CD, CSMA/CA)
- **RA Protocols**
    - Transmits at full channel data rate R and has no a-priori coordination among nodes
    - Has collision when there are two or more transmitting nodes
- Designing random MAC focuses on:
    - Whether to sense channel status
    - How to transmit frames
    - How to detect and react to collision

5.2 ALOHA

Assumptions

- All frames are of the same size
- Time is divided into equal size slots (enough to transmit 1 frame)
- Nodes are synchronised and start to transmit frames only at beginning of slots
- All nodes detect collision if two or more nodes try to transmit in the same slot

Slotted ALOHA

- **Efficiency**
  - Success (S): **only one** node transmits
  - Collision (C): 2^+ nodes transmits
  - Empty (E): no transmission
  - If there are N nodes in each slot with probability of transmission p,
    - Probability of node i having a successful transmission is given by $p(1-p)^{N-1}$ (one node transmits, other nodes don't transmit)
    - Probability that a slot is successful is $Np(1-p)^{N-1}$
  - Offered load is the expected total number of transmissions in a slot, given by $G = Np$
- **Pros and Cons**
  - P: Single active node can continuously transmit at full rate of. channel
  - P: Only slots need to be synced (highly decentralised)
  - P: Simple
  - C: Collisions, wasting slot, empty slots
  - C: Clock synchronisation

Pure ALOHA

- Frames are transmitted immediately when they arrive (i.e. at completely arbitrary times) (no synchronisation)
- Probability of collision increases
  - Frame sent at t_0 collides with other frames sent in $[t_0 - 1, t_0 + 1]$ since overlapping occurs
- **Efficiency**
  - $P(S_i) = p(1-p)^{N-1} \times (1-p)^{N-1} = p(1-p)^{2N-2}$
    $\implies P(S) = Np(1-p)^{2N-2}$
  - For very large N, $P(S) = Ge^{-2G}$

5.3 CSMA

- Carrier Sense Multiple Access
- Avoid transmissions that are certain to cause transmission to improve performance
- Based on very small LAN propagation time
  - All stations know if a frame is sent by a station, so they can wait before sending
  - A station with intention to send frames should sense medium for the presence of another transmission before starting transmission

- Reduces collision probability but cannot eliminate it, can still happen when more than one station begin transmitting within a short time (propagation time method)

Non-persistent CSMA

- Station with frames to be sent should sense the medium, two cases
  1. Medium Idle - transmit
  2. Medium Busy - back off, wait a random amount of time and check again
- Stations are deferential
- Performance
  - Random delays between sensing reduces probability of collisions since two stations who senses the medium at the same time will have different delay duration
  - Bandwidth is wasted if back off is large because medium will remain idle following end of transmission

1-persistent CSMA

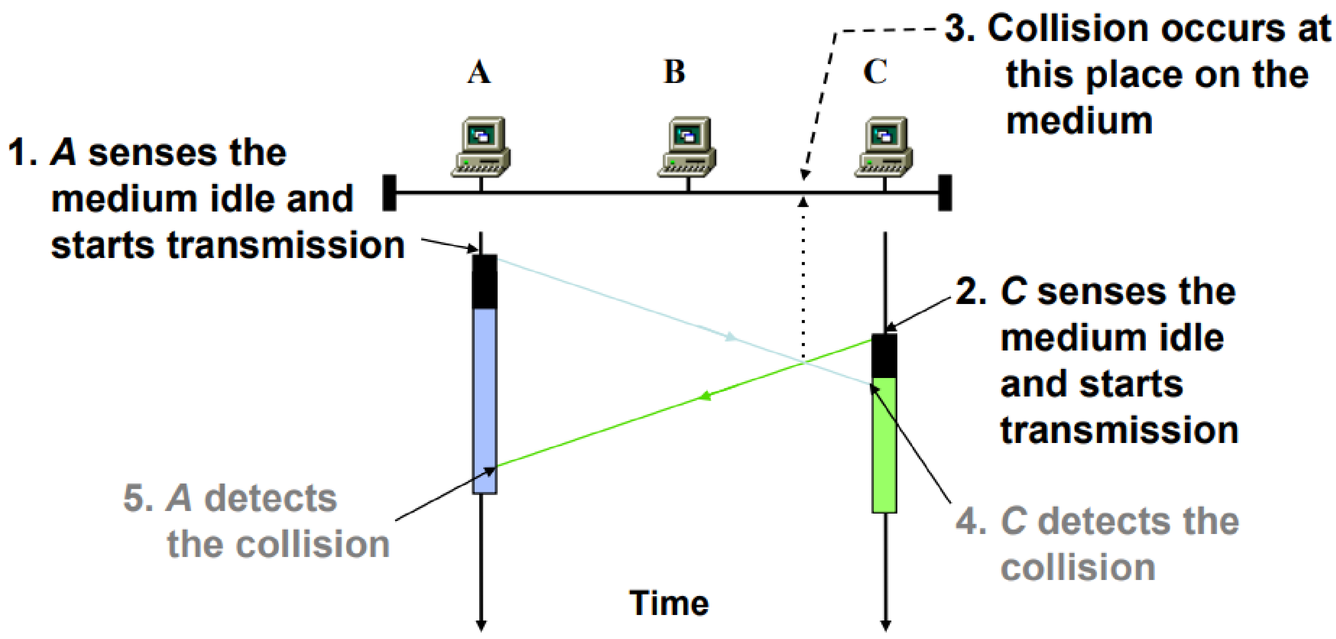
- Used to avoid idle channel time
- Station listens to medium if it wishes to transmit, 2 cases
  1. Medium Idle - transmit immediately
  2. Medium Busy - keep listening until medium becomes idle, then transmit immediately (P(transmission) = 1)
- Stations are selfish (not deferential)
- Performance
  - Collision is guaranteed if two or more stations become ready at the same time

P-persistent CSMA

- Time is divided into slots where each slot equals maximum propagation delay
- Station listens to medium if it wishes to transmit, 2 cases
  1. Medium Idle - transmit with probability p or wait one time slot with probability $(1-p)$ and listen again
  2. Medium Busy - continuously listen until medium becomes idle do case 1
- Performance
  - Reduces possibility of collisions
  - Reduces channel idle time

5.4 CSMA / Collision Detection

Collision in CSMA



Vulnerable time

- Maximum propagation time, larger propagation time means worse performance

CSMA/CD

- Colliding packets are still fully transmitted, leads to channel wastage
- While transmitting, sender listens to medium for collisions, stops transmission if collision is detected, reducing channel wastage
- Widely used for bus topology LANs

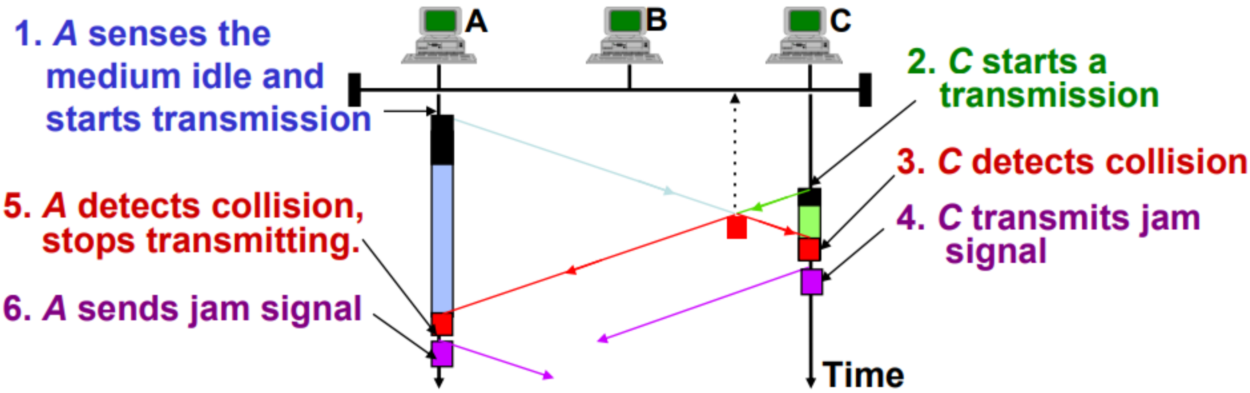
Collision Detection

- **Transceiver**
  - Node monitors medium while transmitting, higher power observed compared to transmitted power of its own signal means collision has occurred
- **Hub**
  - If input occurs simultaneously on two ports, collision has occurred and hub sends a collision presence signal on all ports
- **In the worst case, collision detection takes twice the maximum propagation delay of the medium**

Protocol

- Use one of CSMA persistent algorithms
- If collision is detected,
  1. Abort transmission
  2. Transmit jam signal (48 bits) to notify other stations to discard transmitted frame and to make sure collision signal stays until detected by furthest station

3. Back off for random amount of time
4. Attempt to transmit frame again

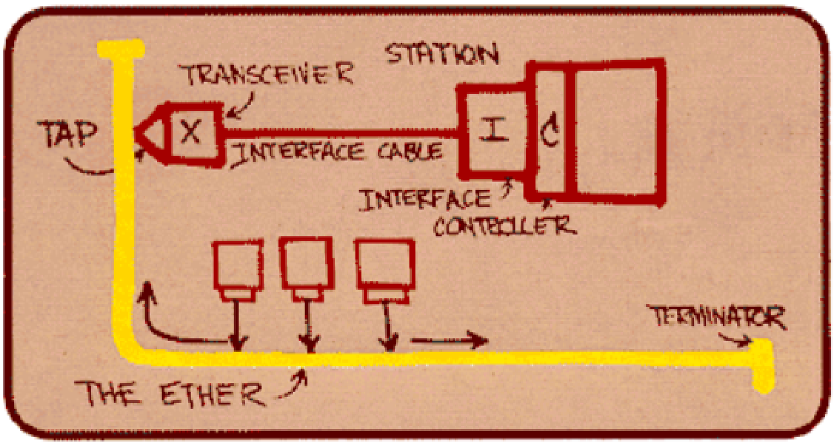


6. Ethernet

6.1 Overview (not examinable)

802.3 Standard

- MAC Protocol: CSMA/CD
- Physical Layer



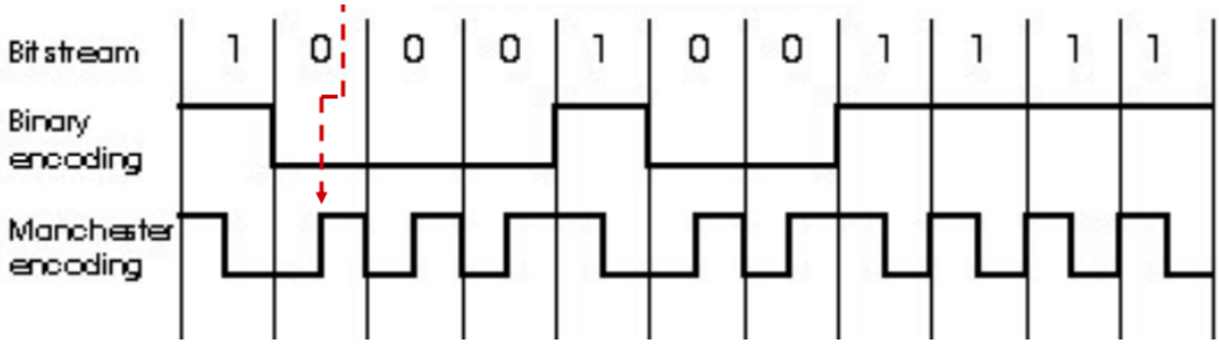
Metcalfe's original Ethernet Sketch: The idea was first documented in a memo that Metcalfe wrote on May 22, 1973, where he named it after the disproven luminiferous ether as an "omnipresent, completely-passive medium for the propagation of electromagnetic waves".

Transmission Media

- Coaxial cable
  - Thick: used by original ethernet (bus topo)
  - Thin: flexible, but shorter network span
- Twisted pair
  - Used with a hub in star topo
- Optical fiber
  - Expensive and difficult to handle but has high data rate
  - Used in backbone

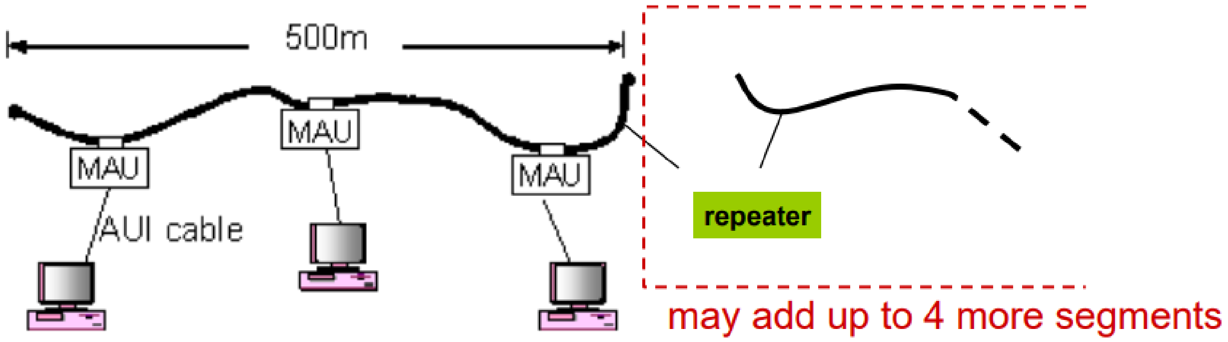
Physical Layer

- Specified in 3 parts
    - Data rate (10 / 100 / 1000 mbps)
    - Signalling method
        - baseband: digital
        - broadband: analog
    - Cabling
        - 2: 200m thin coax
        - 5: 500m thick coax
        - T: Twisted pair
        - F: Optical fiber
        - S: Short wave laser over multimode fiber
        - L: Long wave laser over singlemode fiber
- **Baseband Manchester Encoding**
    - no carrier is modulated; bits are encoded using Manchester encoding and transmitted directly by modifying voltage of a DC signal
    - Ensures that voltage transition occurs in each bit time



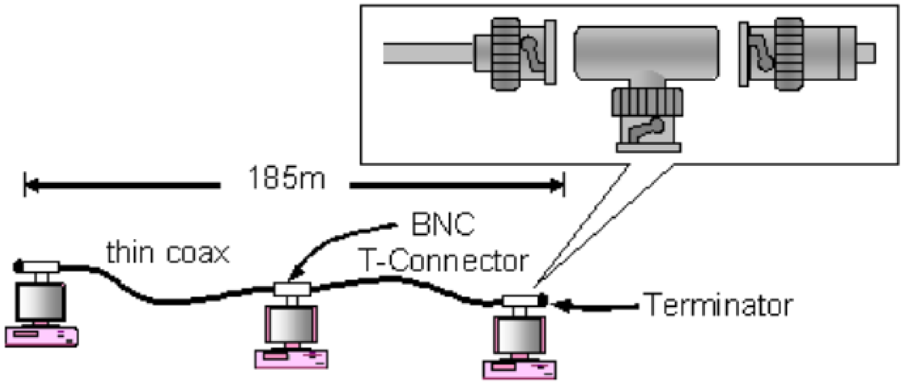
Ethernet versions

- 10BASE-5



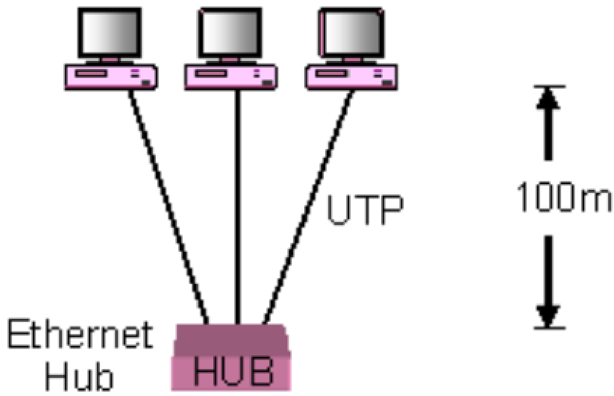
    - Each segment has a maximum length of 500m
    - Maximum of 4 repeaters can be used to connect 5 segments

- 10BASE-2

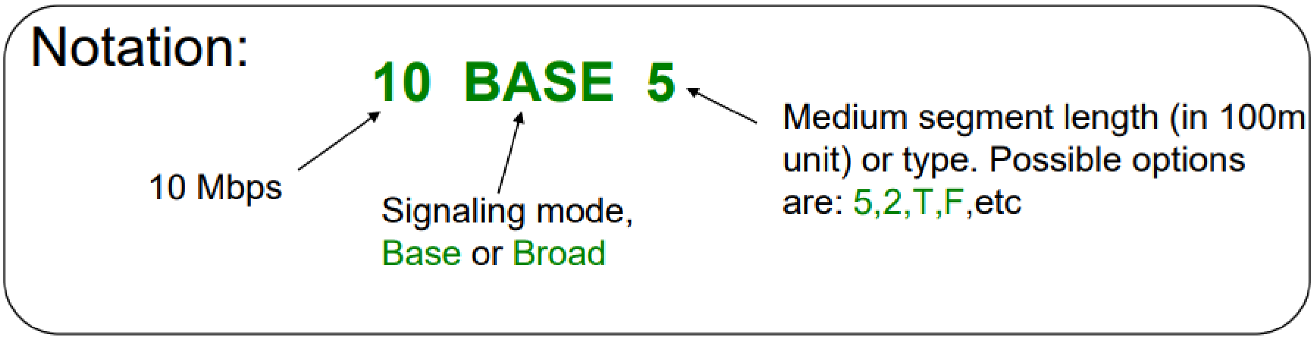


  - Each segment has a maximum length of 185m and a minimum cable length of 0.5m between two nodes, 30 nodes in total maximum

- 10BASE-T

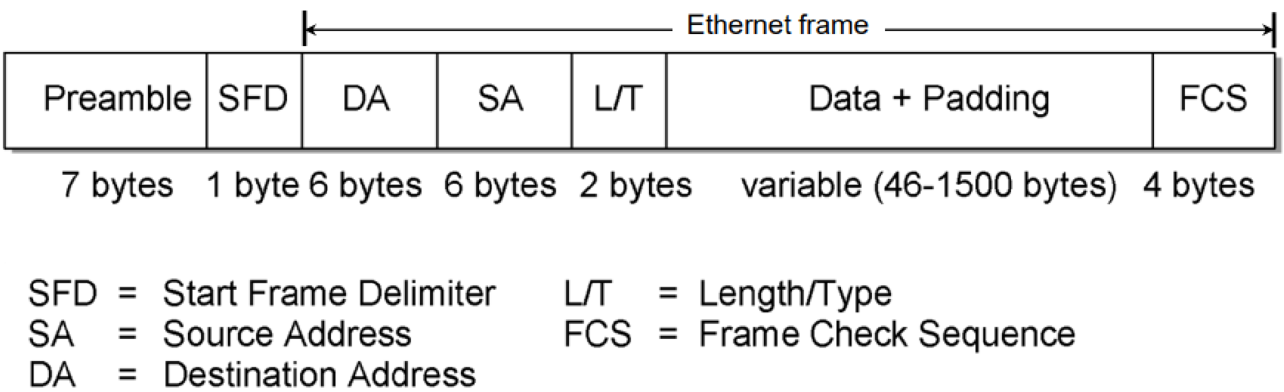


  - At least 2 pairs of wires, with cable length between hub and computer 100m



6.2 Ethernet Frame Format

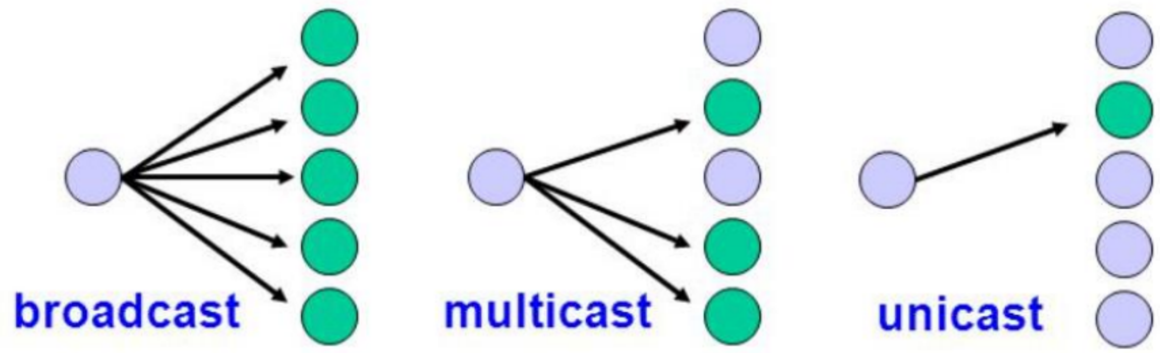
Frame Format



- Preamble and SFD (bytes 0-7, 7 * 10101010, 1 * 10101011) used for synchronising receiver to sender clock before data is sent
- Pad field allows additional dummy data to be included to a frame to meet minimum frame size requirements
- FCS enables error detection using CRC and covers between SA and Pad fields

MAC Address

- Each address has a unique 48-bit unicast address assigned to each adapter (e.g. `08:00:e4:b1:02:a2`)
  - broadcast: all 1s (address = `FF:FF:FF:FF`)
  - multicast: first bit (from the right) of the first byte is 1 (odd byte)
  - unicast: first bit (from the right) of the first byte is 0 (even byte)



- Type field is a demultiplexing key used to determine which higher level protocol the frame should be delivered to

6.3 MAC Protocol

- Ethernet uses CSMA/CD

Minimum Frame Size

- Sender must keep its transmission until it is sure that there are no other transmissions on the medium before ending its transmission
- A transmission requires an e2e signal propagation time T to reach all stations and a potential collision requires T time to return to the sender
  - frame transmission $\geq 2T$
- **Collision Detection**
  - System A knows a collision has taken place when its message reaches B at time T and B's message reaches A at time $2T$, this means A's message is either still transmitting or has collided
  - Standard specifies max value of $2T = 51.2\mu s$ which is given by maximum distance of 2000m between both hosts

        - At 10Mbps it takes $0.1\mu s$ to transmit one bit so $51.2\mu s$ is taken to transmit 512 bits (64Bytes)
        - Frames must be at least 64Bytes long (14Byte header, 46Byte data, 4byte CRC)
        - Padding is used if data < 46Bytes

Binary Exponential Back off

- When a collision is detected, stations can choose a future slot randomly to retransmit based on BEB
- Delay time is selected using BEB
    - n^{th} time: choose K from $\{0, 1, ..., 2^n - 1\}$ then delay = K $\times 51.2\mu s$
    - Maximum value of K is 1023 (n = 10), even though transmission attempt is given up after (usually) 16 times
        - if K is too small, then having a large number of nodes would result in more collisions
- If delays were not random, then there is a chance that stations would retransmit in lock step

MAC Algorithm from Receiver

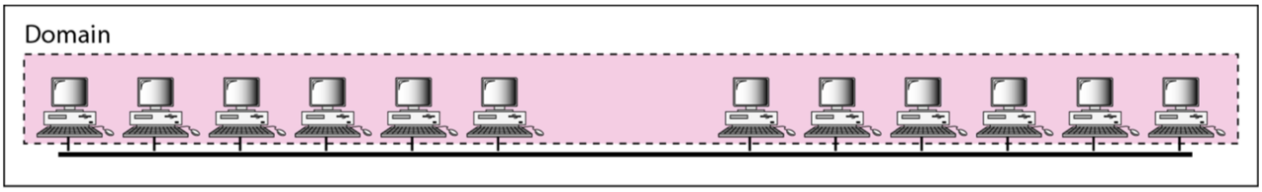
- Sender handles all access control
- Receiver reads frames with acceptable address
    - unacceptable addresses will be discarded by receiver
    - host, broadcast, multicast to which host belongs
    - all frames if host is in promiscuous mode (does not reject frames from unacceptable addresses)
- https://www.youtube.com/watch?v=YVcBShtWFmo (promiscuous mode meaning)

6.4 Evolution

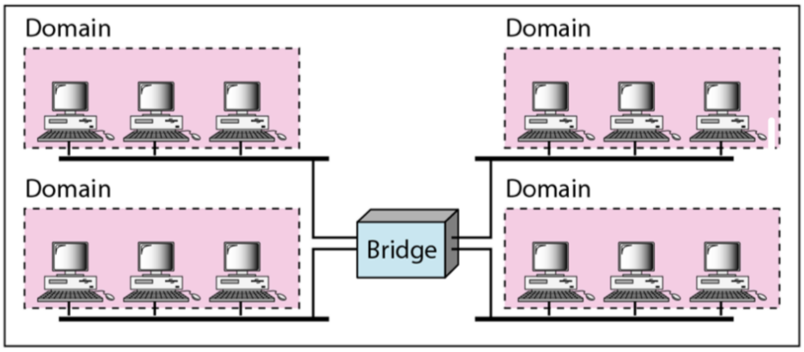
- **Collision Domain**
    - Network region in which collisions are propagated
    - Repeaters and hubs propagate collisions
    - Bridges, routers and switches do not (separates domains); can be used to keep collision frequency low by breaking network into segments
- **Broadcast Domain**
    - Network region in which broadcast frames are propagated
    - Repeaters, hubs, bridges, switches propagate broadcasts (Layer 2)
    - Routers either do or do not depending on configuration (Layer 3)

Bridged vs Switched

- **Bridged**



a. Without bridging



b. With bridging

- A repeater / hub forwards received signals to all output ports except the incoming port. When two computers transmit at the same time, the channel carries no useful information (collision)
- A switch (switching hub) forwards the received signals only to the destination, when two transmission arrive at the same time, they will be stored in different buffers on the switch so that their frames can be forwarded later, this removes collision

7. WLAN

7.1 WLAN Overview

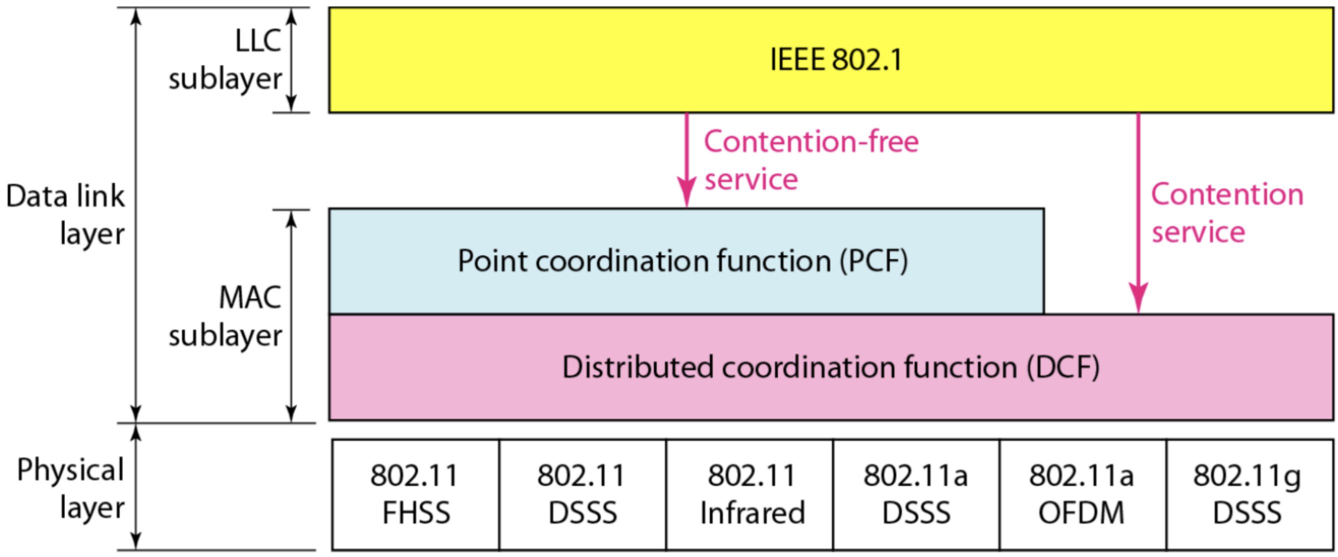
Characteristics

- Decreased signal strength compared to wired link
- More interference from other sources compared to wired link
- Multipath propagation
  - Radio signal reflects off objects, arriving at destination at slightly different times

Architecture

- Building Modules
  - Station (STA)
    - Mobile node, smartphone, tablets, laptops
  - Access Point (AP)
    - Connected to stations
- Infrastructure / centralised
- Ad Hoc / distributed

Protocol Stack



7.2 802.11 Physical layer (not examinable)

Channels

- 2.4GHz - 2.485Ghz spectrum is divided into 11 channels at different frequencies which the AP admin will choose for the AP. However, channel chosen can be the same as that chosen by a neighbouring AP, which may cause interference
- Each host must associate with an AP
  - Scans channels, listening for beacon frames containing AP's name and MAC address
  - Selects AP to associate with
  - May perform authentication for security purposes and will run DHCP to get IP address in AP's subnet

Passive / Active scanning

- Passive Scanning
  1. Beacon frames sent from AP
  2. Association req frame sent : H1 to selected AP
  3. Association res frame sent: selected AP to H1
- Active Scanning
  1. Probe req frame broadcast from H1
  2. Probe res frame sent from APs
  3. Association req frame sent: H1 to selected AP
  4. Association res frame sent: selected AP to H1

7.3 802.11 MAC layer

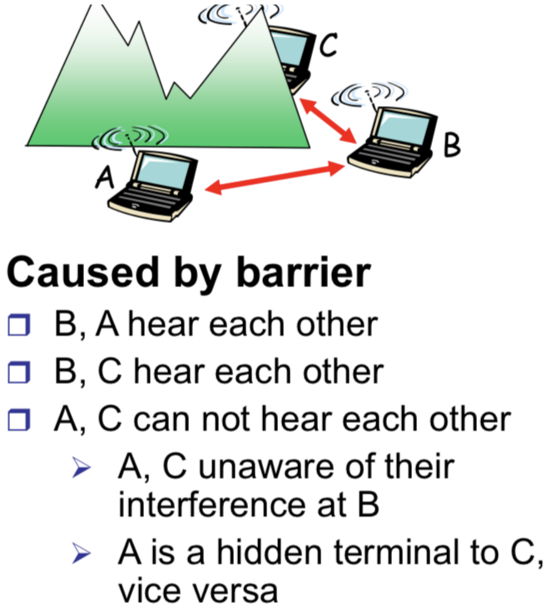
Access Control

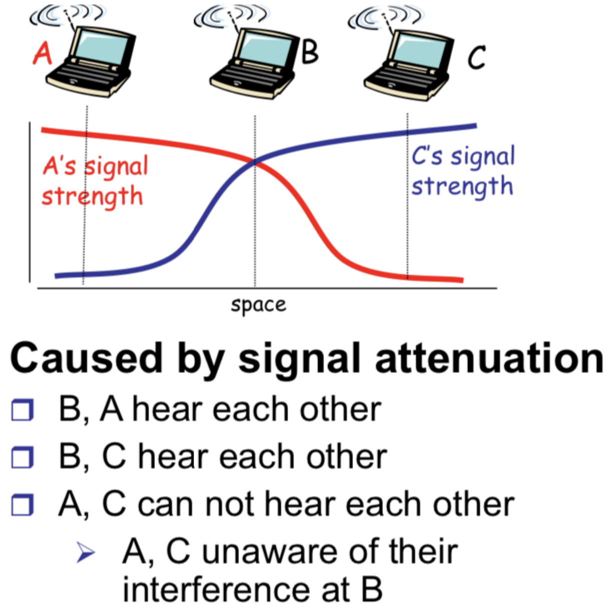
- Distributed Coordination Function (DCF)
  - Distributed Access protocol
  - Contention-based
  - Makes use of CSMA/CA
  - Suited for ad-hoc network and asynchronous traffic
- Point Coordination Function (PCF)
  - Alternative access method
  - Centralised access control
  - Contention-free, works like polling
  - Suited for time-bound services like voice and multimedia
- **Frame Access Protocol**
  - Sender broadcasts data, receiver responds with `ACK`, Sender retransmits frame if `ACK` was not received by them
  - **Enhanced reliability in WLAN**
    1. Sender issues request-to-send (RTS)
    2. Receiver responds with clear-to-send (CTS)
    3. Sender transmits data
    4. Receiver responds with ACK
    - Solves the hidden terminal problem, but does not solve the exposed terminal problem
    - Avoids data frame (data packet) collision completely
      - **RTS** is not free of collision
- **Multi-Access**
  - When collision occurs, receiver hears transmissions from 2 or more nodes at the same time
  - 802.11 CSMA - sense before transmission so as to not collide with ongoing transmission by another node
  - 802.11 No collision detection due to difficulty in sensing collisions with transmitting caused by weak received signals; Cannot sense all carriers and collisions, hidden terminal problem
  - Instead of using collision detection, choose to avoid collision

Hidden and Exposed Terminal Problems

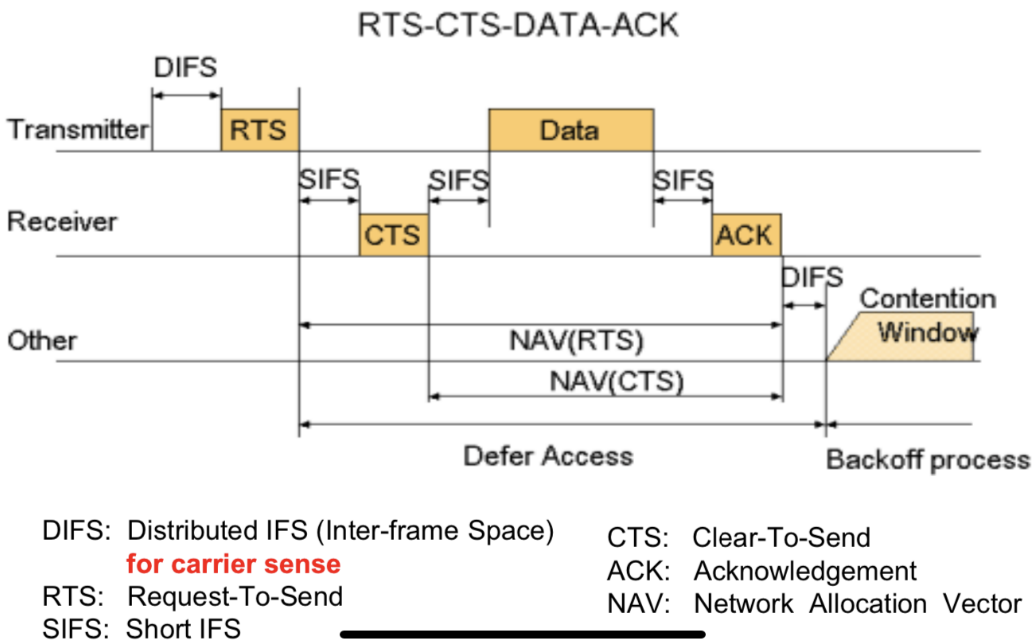
- **Hidden Terminals**

- Hidden terminals can either be caused by a barrier or by signal attenuation





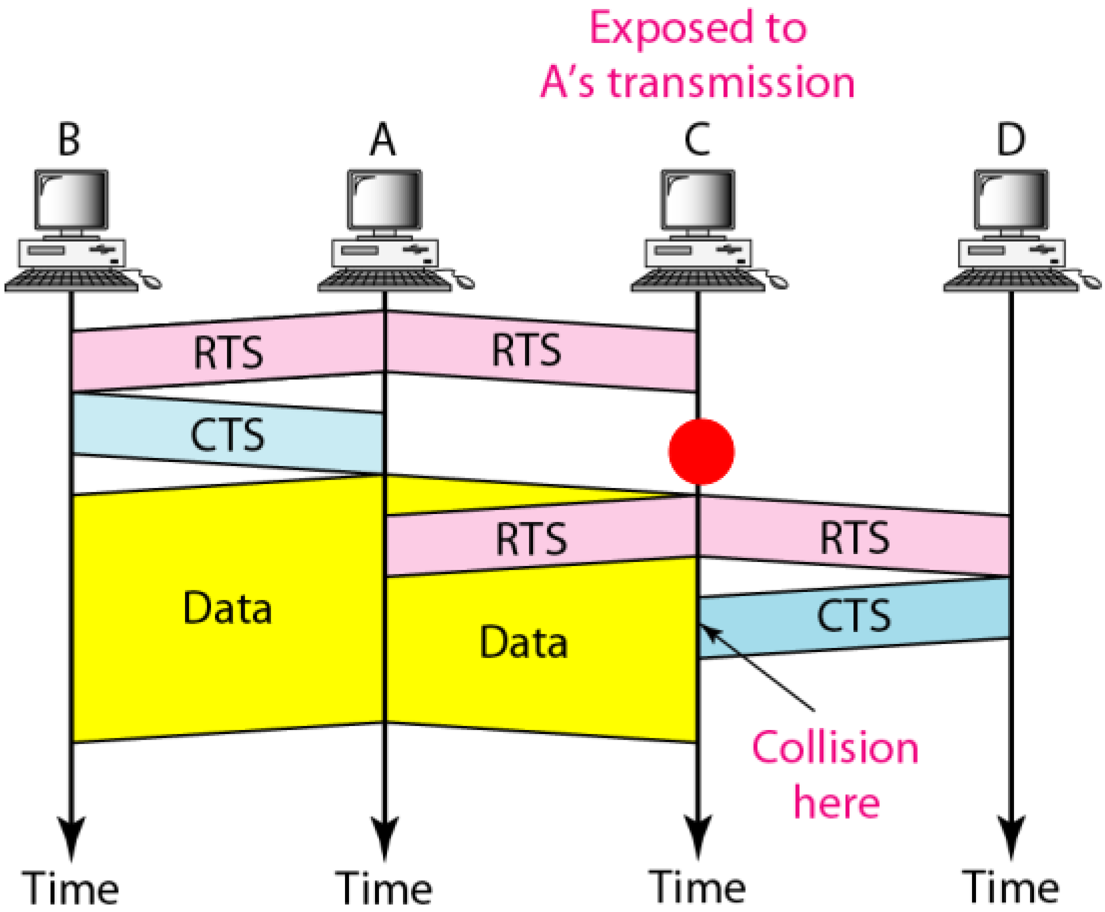
- Collision Avoidance: Sender to 'reserve' channel for a long data frame
    - S first transmits a small req to send (RTS) packet to R using CSMA. RTSs can still collide with each other or collide with an ongoing data frame but they're short
    - Receiver broadcasts clear to send (CTS) in response to S's RTS, which is heard by all nodes. S can then transmit data frame while other stations defer transmissions



    - If there is an RTS collision, after a while, S will send RTS again 'hoping' another terminal S' will not send an RTS. R will then broadcast CTS signalling S to send data. S' receives broadcast and defers sending RTS to R.

- **Exposed Terminal**
    - In exposed terminal problem, lets say terminals are laid in order (B, A, C, D) and assuming range of A covers B and C, range of C covers A and D, i.e. (B {A C) D}, we can see that C is exposed to transmission from A to B.

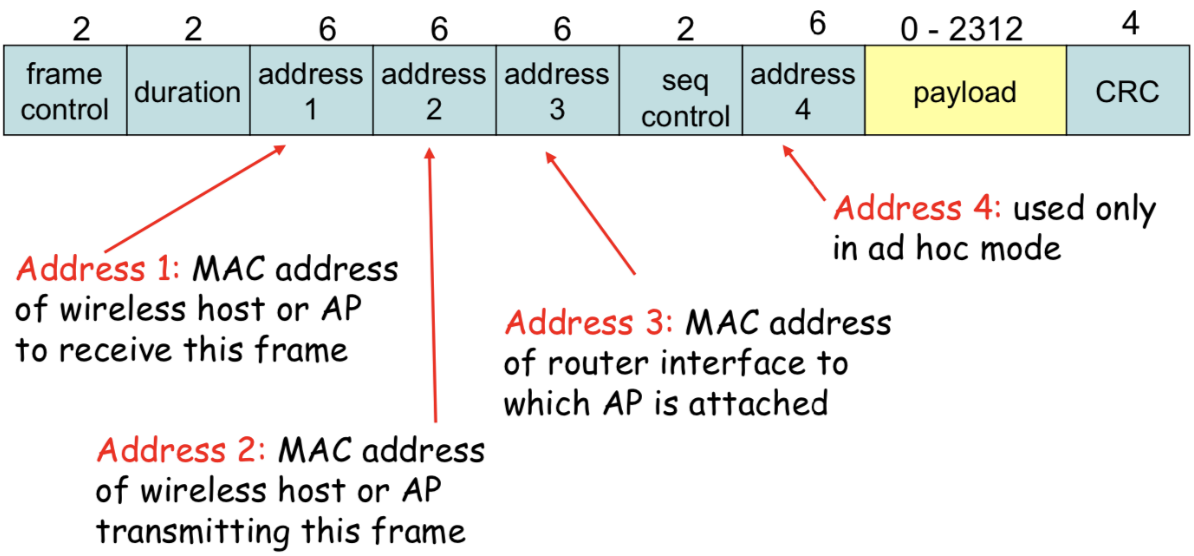
- Because of the close proximity of A and C, when A intends to transmit data to B and C intends to transmit data to D, C is able to detect the transmission of data from A, but is unsure whether it is intended for D. So C will defer transmission of data to D from CSMA principle.



- A sends RTS(B), but because C knows it is intended for B, it does not send CTS to A.
- B sends CTS to A and A prepares to send data.
- At the same time, C sends RTS(D)
- When A is transmitting data, D sends CTS to C, which gets collided with signal from A

MAC management (not examinable)

- **Frame**



7.4 Multi-Access Reservation Protocol

Scheme

- 2 Phase protocol
  1. Channel Reservation, time = s x v units of time, where s = number of tries
  2. Data Transmission, time = u units of time
  - Assume that channel utilisation in reservation phase = S_r
  - Number of reservation trial frames to reserve the channel = x
    - $x = 1$ with probability of S_r
    - $x = k$ with probability of $S_r(1 - S_r)^{k-1}$, first k-1 trials fail
    - Expected value of $x, E[x] = 1/S_r$
      $\therefore$ average transmission window $= u + v/S_r$

Throughput Calculation

Throughput $S = \frac{\text{Time for message transmission}}{\text{Transmission Window}}$

Case	Message Length	Reservation Phase Length	Throughput
Reservation frame not used for message data bits	u	v/S_r	$S = \frac{u}{u + {}^{v}/_{S_r}}$
Reservation frame used for message data bits	u	v/S_r	$S = \frac{u}{(u-v) + {}^{v}/_{S_r}}$
Reservation frame used for message data bits	$u + v$	v/S_r	$S = \frac{u+v}{u + {}^{v}/_{S_r}}$

(case 3 not considered)

- Example

  Consider an experimental LAN using an MARP for data transmission. The protocol consists of two phases. In phase 1, it adopts some MAC protocol for transmission stations to reserve the channel. In phase 2, when one station reserves the channel, it transmits one frame. The length of reservation frame is 5ms, and the length of the data frame is 1s. No information bit is carried in the reservation frame. If the MAC protocol used in phase 1 has a utilization of 0.5, what is the throughput of the multi-access reservation protocol?

  CRACK Framework:
  Context: MARP with no data bits in reservation
  fRamwork: the throughput of MARP is S=1/(1+v/S_r)
  Apply: *v*=5ms, *S_r*=0.5
  Calculation: S = 1/(1+0.005/0.5)=1/1.01=0.99
  checK: S<=1

8. Summary Table

<table>
<tr><th colspan="2" rowspan="2">MAC Protocols</th><th colspan="3">Transmission Protocol</th><th rowspan="2">Throughput/
Utilization</th><th rowspan="2">Note</th></tr>
<tr><th>Carrier Sensing</th><th>Frame Transmission</th><th>Collision Detection</th></tr>
<tr><td rowspan="2">Aloha</td><td>Slotted</td><td rowspan="2">• None</td><td>• Each transmits in a slot immediately with probability p</td><td rowspan="5">• When a collision is detected, the colliding frames are transmitted up to their last bits.</td><td>$S = Np(1-p)^{(N-1)}$
$= Ge^{-G}$</td><td rowspan="2">Number of Stations: N
Probability of Attempt: p
Attempt Rate: $G = Np$</td></tr>
<tr><td>Pure</td><td>• Each transmits immediately with probability p</td><td>$S = Np(1-p)^{2(N-1)}$
$= Ge^{-2G}$</td></tr>
<tr><td rowspan="3">CSMA</td><td>Non-Persistent</td><td rowspan="3">• Must sense channel before transmission</td><td>• When a busy channel is sensed, a station defers for a random period of time before next sense</td><td rowspan="3"></td><td rowspan="3"></td></tr>
<tr><td>P-Persistent</td><td>• When a busy channel is sensed, a station continues to sense until the channel turns idle. Then, with probability p, it transmits, and with probability $1-p$, it defers to next time slot.</td></tr>
<tr><td>1-Persistent</td><td>• A special case of P-Persistent where $p = 1$</td></tr>
<tr><td colspan="2">CSMA/CD
(Ethernet)</td><td>• Must sense channel before transmission</td><td>• The same as CSMA</td><td>• When a collision is detected, transmissions are aborted to reduce the channel wastage.</td><td>$S = \frac{1}{1 + 6.44a}$
$a = \frac{T_{Prop}}{T_{frame}}$
(not covered in lecture)</td><td>Minimum Frame Size
• $T_{frame} \geq 2\tau$
Binary Exponential Backoff
• In i-th retransmission, the slot is chosen from a uniformly distributed random variable R, in the range of $[0, 2^K - 1]$, where $K = \min(i, 10)$.</td></tr>
<tr><td colspan="2">CSMA/CA
(802.11)</td><td>• Must sense channel before transmission</td><td>Sender:
• If sense channel idle for DIFS, then transmit entire frame (no CD).
• If sense channel busy, then start random backoff time. Transmits when timer expires.
• If no ACK, increase random backoff interval
Receiver:
• If frame received OK, return ACK after SIFS</td><td>• No collision detection due to hidden terminal</td><td colspan="2">Multi-Access Reservation
• Use random-access with mini-frame (v unit of time) to reserve the channel
• If reservation successful, transmit u unit of data frame
<table>
<tr><th></th><th>$\frac{u}{u + v/S_r}$</th><th>$\frac{u}{(u-v) + \frac{v}{S_r}}$</th><th>$\frac{u+v}{u + v/S_r}$</th></tr>
<tr><td>Total data length</td><td>u</td><td>u</td><td>$u + v$</td></tr>
<tr><td>Data bit in mini-frame</td><td>No</td><td>Yes</td><td>Yes</td></tr>
</table></td></tr>
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