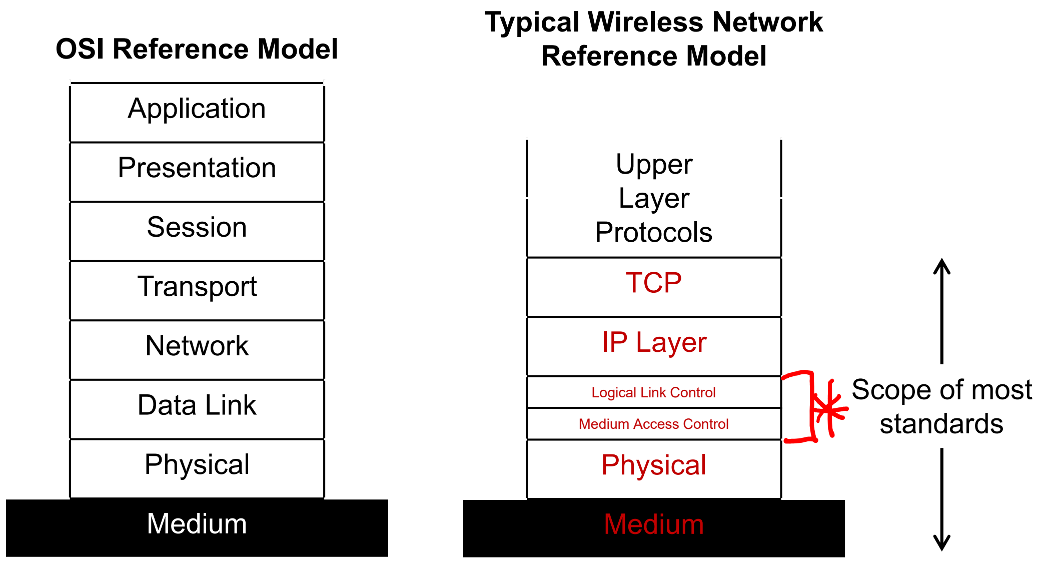
CEG5103 / EE5023

Medium Access Control (MAC) Techniques

Lecture 2

Protocol Layers



Functions of LLC sublayer:
The primary function of LLC is to multiplex protocols over the MAC layer while transmitting and to de-multiplex the protocols while receiving.
LLC provides hop-to-hop flow and error control.

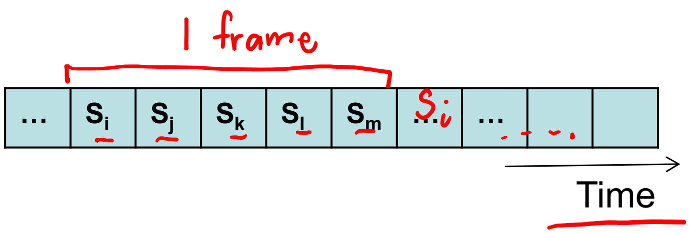
Medium Access Control (MAC)

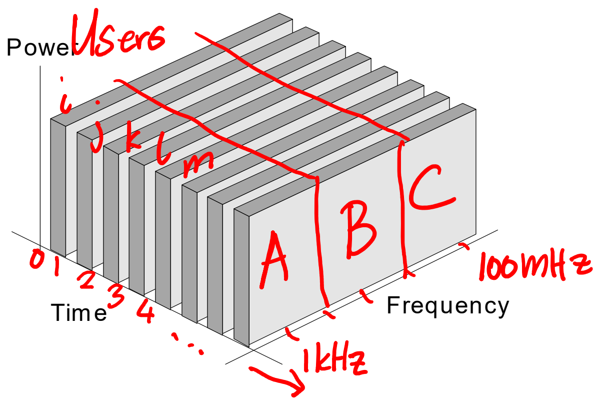
- Medium Access Control techniques
  - I. Conflict-Free
    - Static Allocation (channel-based)
      - TDMA
      - FDMA
      - OFDM
    - Dynamic Allocation
      - Polling (Centralized Control)
  - II. Contention-Based (packet-based)
    - Static Resolution
      - ALOHA
      - CSMA
    - Dynamic Resolution
      - CSMA-CA
  - MAC mechanisms in
    - Wi-Fi (IEEE 802.11xx)
    - Bluetooth (IEEE 802.15.1/3/4)

I. Conflict-Free

Time Division Multiple Access (TDMA)

- TDMA involves organizing communications resource into time slots and slots into frames. Each user is allocated a repetitive time slot to use.
- Guard bands ensure proper separation between slots
- Major disadvantage is that each user must have fixed allocation of channel time regardless of whether it has information to transmit

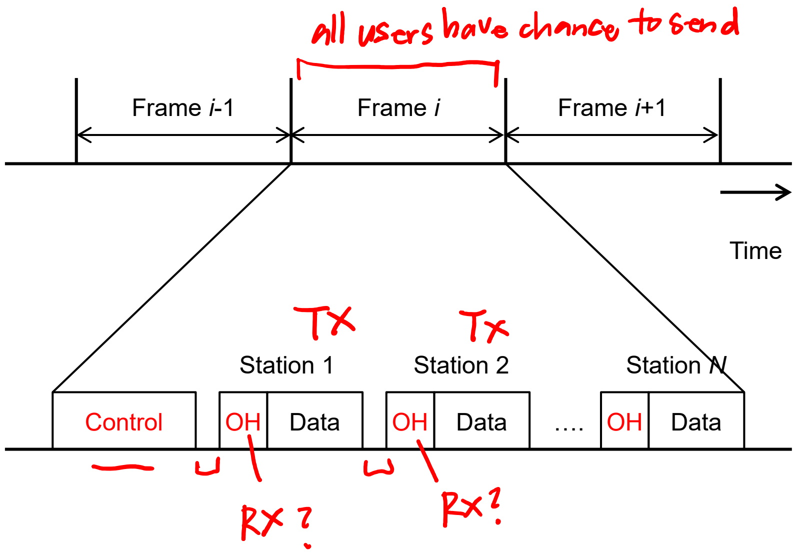




- A variation is called ***narrowband TDMA***, where the allocated frequency spectrum is partitioned into bands, and each band implements a TDMA structure. 2nd generation mobile cellular systems, i.e. GSM, uses this approach.

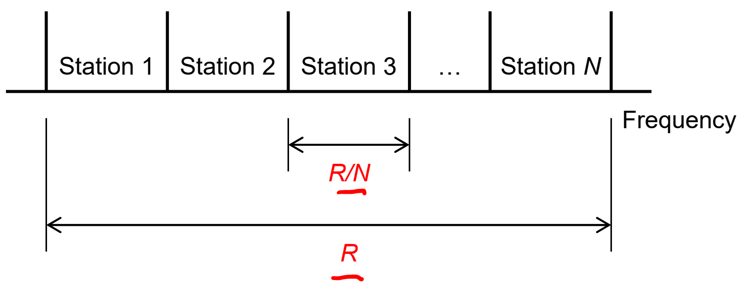
TDMA (cont.)

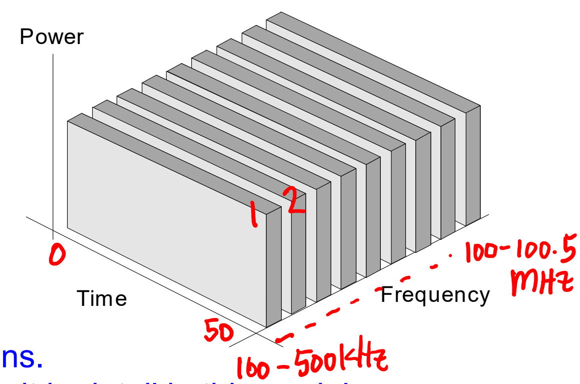
- Each frame has a control frame
- A control segment contains a synchronization pattern to keep stations in sync, as well as other control data
- Guard bands ensure that the time slot assigned to each station are separated
- Each station time slot allows for transmission of both overhead (OH) and data



Frequency Division Multiple Access (FDMA)

- FDMA involves partitioning the available spectrum into smaller frequency bands, and each band or channel is used to support a user.
- Baseband signal is **modulated** onto desired carrier frequency band.
- Since individual bands are disjoint, there is no interference among users.
- Major disadvantage is that each user has fixed allocation of channel bandwidth regardless of whether it has information to transmit
- Used in 1st generation mobile cellular network (AMPS, ETACS, etc.) in 800-900 MHz band

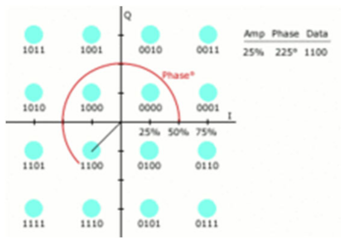




Note: Modulation is a big topic in Digital Communications.
It takes place in the physical layer and we will not cover it in detail in this module.

Orthogonal Frequency Division Multiplexing (OFDM)

- OFDM combines the benefits of **Quadrature Amplitude Modulation (QAM)** and **Frequency Division Multiplexing (FDM)** to produce a high-data-rate communication system.
- Spectrally efficient. Used in Wi-Fi and 5G.
- **QAM** basic concept (16-QAM, can be 64, 256 etc.)



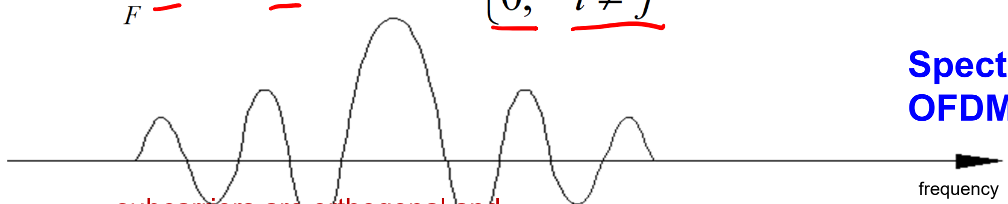
- Next, multi-carrier transmission that requires converting a high-speed data stream to slower parallel bit streams and then employ several channels.
- Chosen subcarrier frequencies are spaced apart by the inverse of the symbol time and the spectrum of each subchannel may overlap to fully utilize the available bandwidth

Orthogonal Frequency Division Multiplexing (OFDM)

Divide a channel into multiple sub-channels and do parallel transmission

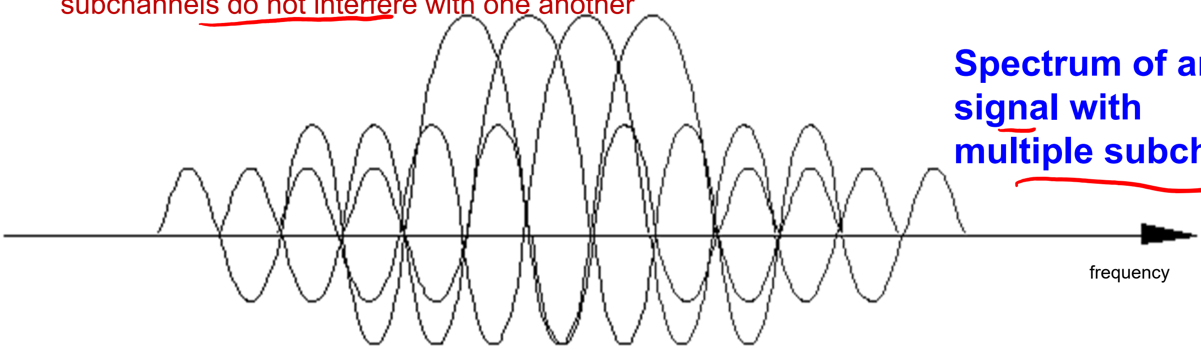
Orthogonality of two signals in OFDM can be given by a complex conjugate relation indicated by *:

$$\int_F s_i(f,t)s^*_j(f,t)dt = \begin{cases} 1, & i=j \\ 0, & i \neq j \end{cases}, \quad i,j = 1,2,\ldots,k$$



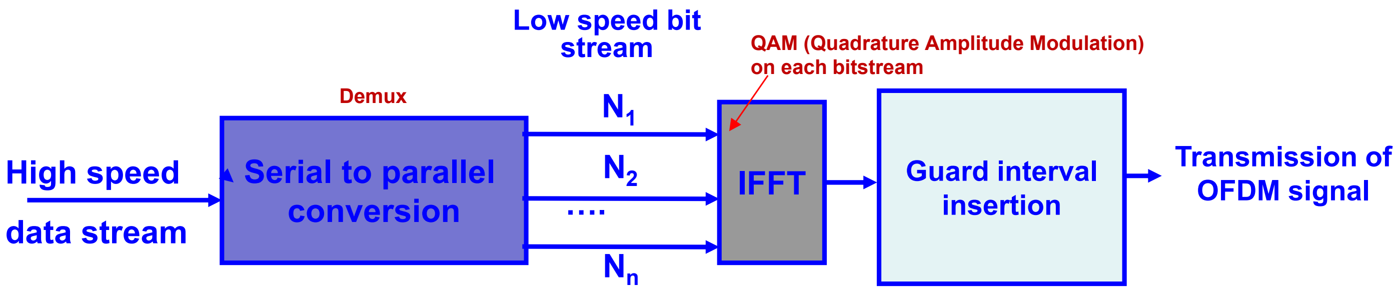
Spectrum of a single OFDM subchannel

subcarriers are orthogonal and
subchannels do not interfere with one another

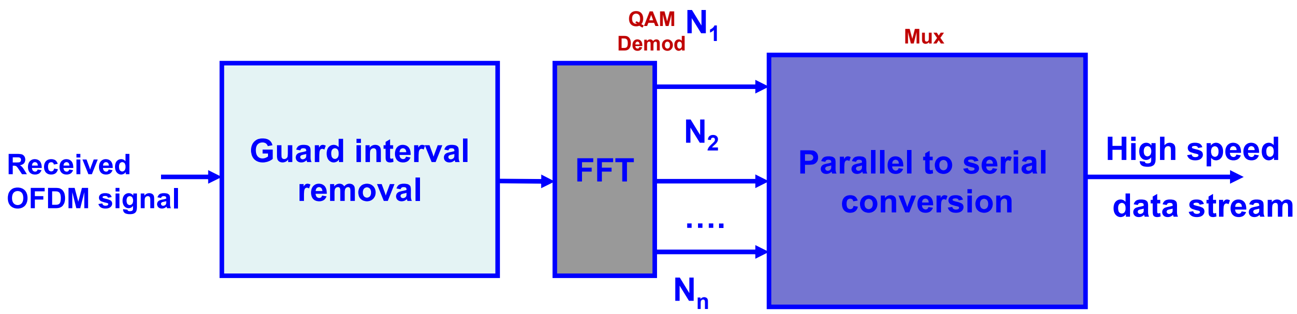


Spectrum of an OFDM signal with multiple subchannels

OFDM Demux - Mod - Demod - Mux

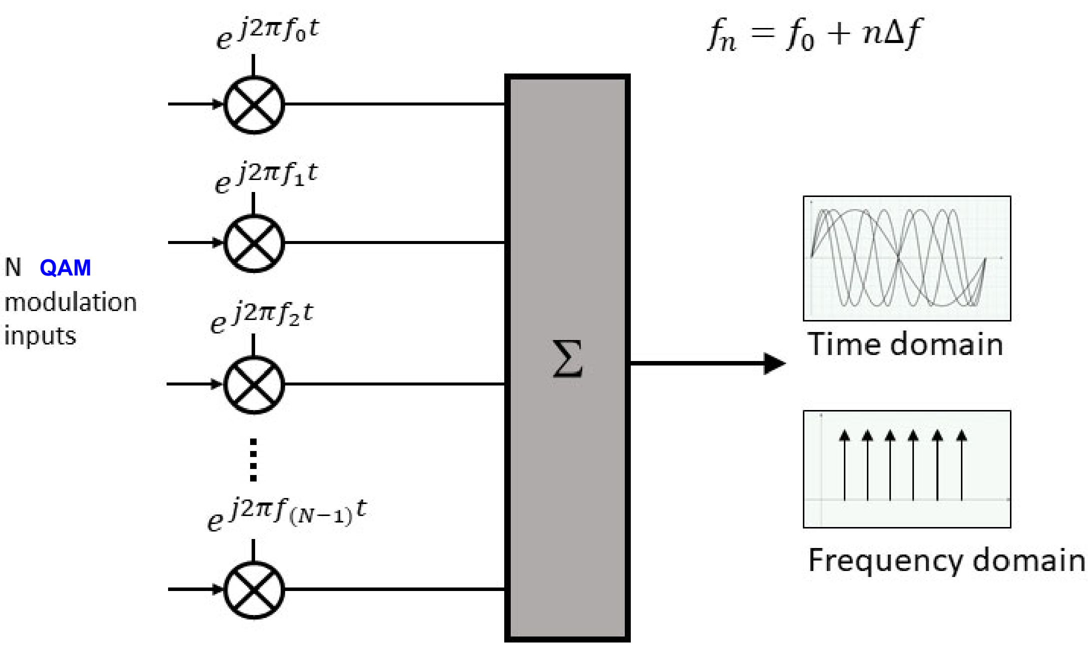


Modulation operations at the OFDM transmitter



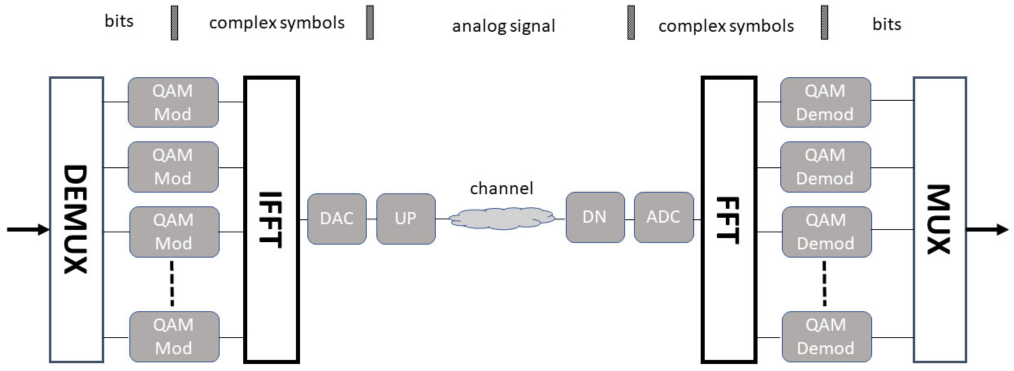
Demodulation operations at the OFDM receiver

Orthogonal Frequency Division Multiplexing (OFDM)



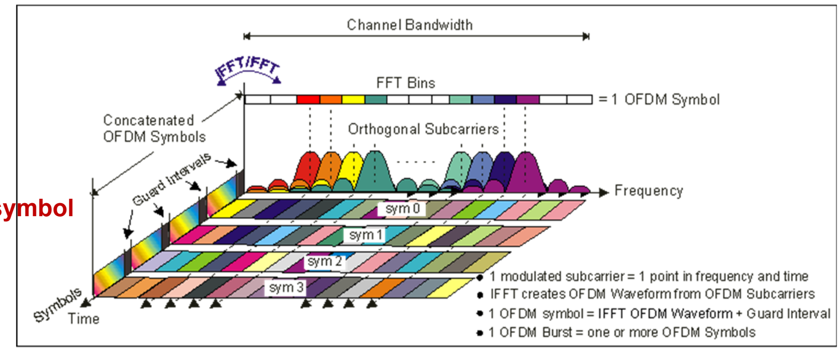
Equivalent to IFFT + DAC

Orthogonal Frequency Division Multiplexing (OFDM)



Transmitter **Complete OFDM System** Receiver

send different OFDM symbol at different time



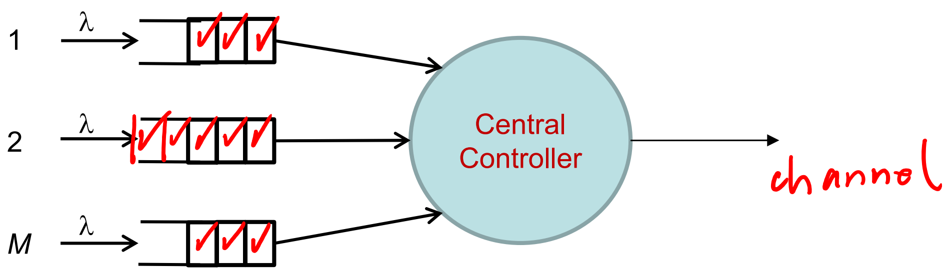
Frequency-Time Representative of an OFDM signal

Dynamic Allocation

Polling

in time

- Central controller sends *polling messages* to each station in a logically arranged sequence.
- When station receives *polling message* addressed to it, then it transmits data to central controller followed by *go-ahead message* to indicate it has completed its transmission.
- Polling sequence is repeated.



λ = average packet arrival rate

ALOHA

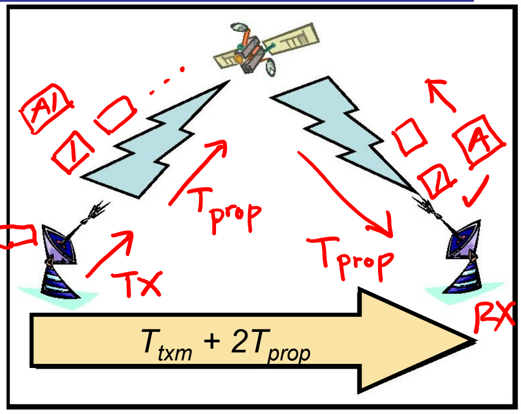
- Developed by University of Hawaii (1971)
- Node sends packet and waits for acknowledgement
- Total delay from Base 1 to Base 2 is:

$$T_{send} = T_{txm} + 2T_{prop}$$

Ttxm Ttxm packet of interest 2Ttxm

where T_{txm} = time to clock out data packet

T_{prop} = propagation delay from base to satellite



- Total delay from sending packet to receiving acknowledgement:

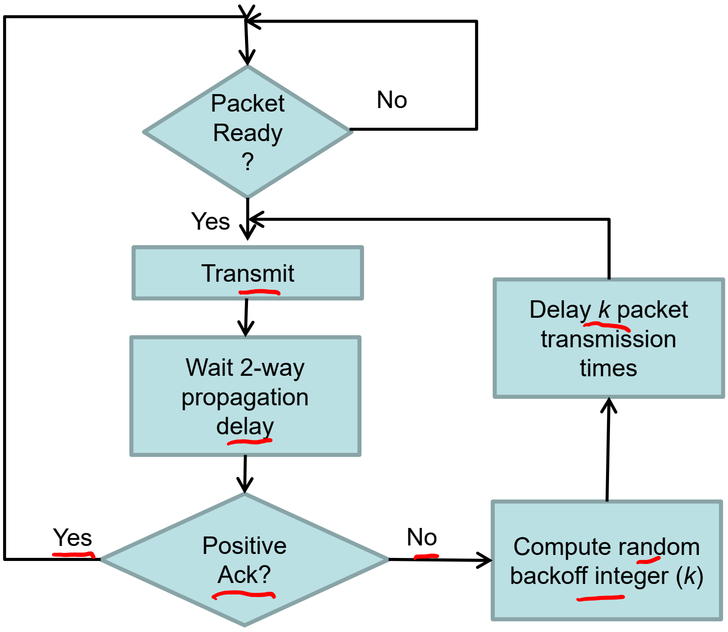
$$T_{send+ack} = \left[T_{txm} + 2T_{prop}\right] + T_{response} + \left[T_{txm} + 2T_{prop}\right] = 2\left[T_{txm} + 2T_{prop}\right] + T_{response}$$

- If no acknowledgement is received, packet is sent again.
- Packet transmission successful only if no other nodes send within T_{txm} seconds before or after it, i.e. vulnerable ***contention window*** is $2T_{txm}$ seconds.
- If collision occurs, affected nodes retransmit after a ***random backoff*** period to reduce further collisions

Geosynchronous orbit : 42,164 km from centre of earth / altitude of 35,786 km

ALOHA (cont.)

- Packet transmission algorithm at each station



ALOHA (cont.)

- System works well for low loading. At high load, frequent collisions and retransmissions cause more collisions, drastically reducing throughput.
- Successful transmission when no other packets transmit in contention window of $2T_{txm}$. Hence, probability of successful transmission, $P(0)$, is:

$$P(0) = e^{-2T_{txm}\lambda}$$

Poisson Distribution

$$P(n) = \frac{(\lambda t)^n e^{-(\lambda t)}}{n!}$$

where λ = arrival rate.

- Rate at which packets are successfully transmitted, S: Throughput

$$S = \lambda . P(0) = \lambda e^{-2T_{txm}\lambda}$$

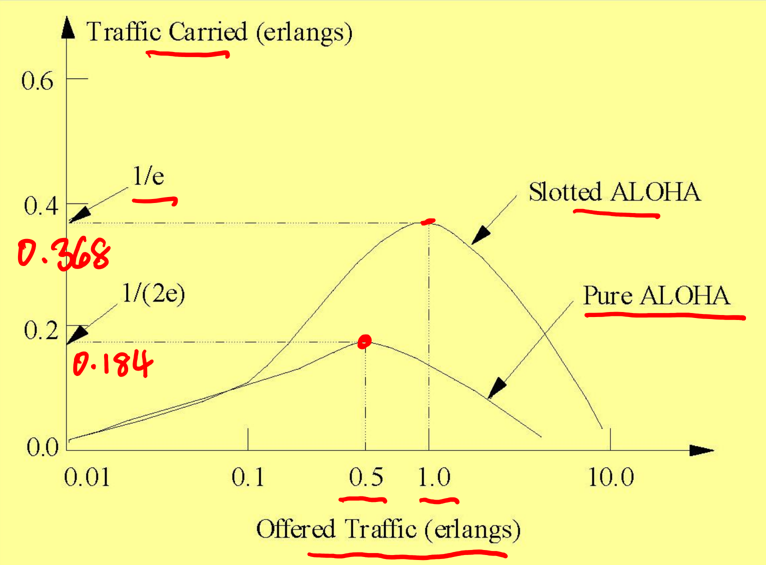
- Differentiating S w.r.t. λ and setting to 0, i.e. $\frac{dS}{d\lambda} = 0$, we obtain:

$$\lambda_{max} = 1/(2T_{txm})$$

$$S_{max} = \frac{1}{2T_{txm}e} \text{ packets/s}$$

ALOHA (cont.)

- Now T_{txm} is packet duration, so:
  Traffic offered $A = \lambda_{max} T_{txm}$
  $= (0.5/T_{txm}).T_{txm}$
  $= 0.5$ erlang
  when max throughput
- Traffic carried $= S_{max}.T_{txm}$
  $= 1/(2e)$
  $= 0.184$ erlang
  Successful
- Retransmission traffic
  = Offered traffic – Actual carried traffic
  = 0.5 - 1/(2e)
  = 0.316 erlang
  not successful needs to retx

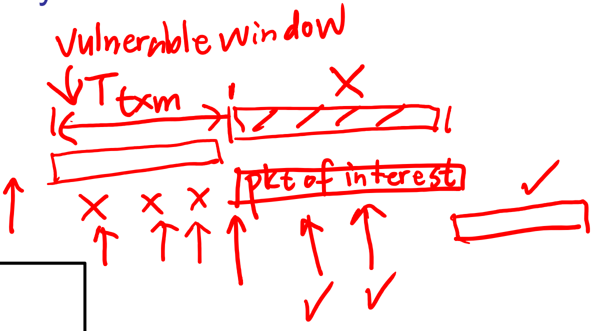


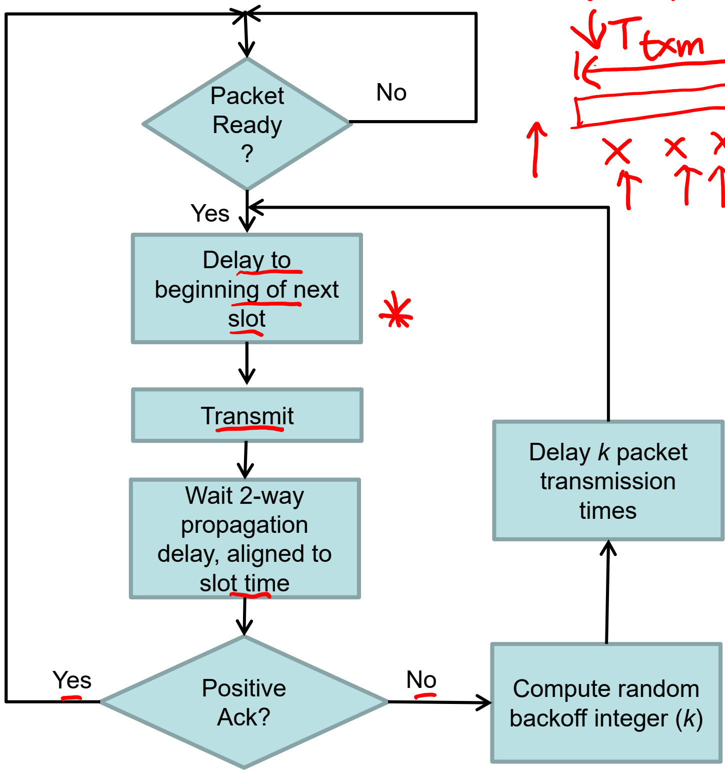
Throughput characteristics for pure and slotted ALOHA

Note: *Traffic Intensity* (erlang) = *Ave. request rate* x *Service holding time*

Slotted ALOHA

- Stations have synchronized time slots and only transmit within slot





Slotted ALOHA (cont.)

- Throughput can be improved significantly if transmissions are ***synchronised***.
- Time is divided into slots of duration T_{txm}.
- A node only starts sending at the beginning of a time slot. This is called ***slotted ALOHA***.
- When collisions occur, packets overlap completely, i.e. no partial overlap as in unslotted ALOHA case.
- Contention window is reduced from $2T_{txm}$ *to* T_{txm}.
- Using the same optimisation procedure, maximum throughput, S_{max} is increased to **1/*e***.

$$S_{S-Aloha} = \lambda e^{-T_{txm}\lambda}$$

$$\frac{dS_{S-Aloha}}{d\lambda} = 0 \quad \Rightarrow \quad S_{S-Aloha,\max} = \frac{1}{eT_{txm}} \text{ and } \lambda_{S-Aloha,\max} = \frac{1}{T_{txm}}$$

$$\therefore \quad \text{Traffic carried} = S_{S-Aloha,\max}.T_{txm} = \frac{1}{e}$$

maximum

(Successful)

Example

1. A pure ALOHA system uses a 56 kbits/s channel. When the traffic carried is maximum, on average, each terminal successfully sends a 1024-bit packet every 30 seconds. What is the number of terminals in the system?
2. How many terminals (with the same effective traffic per terminal) can be in the system if the slotted ALOHA protocol used?

Answers:

1. Duration of packet (T_h) = 1024/56 = 0.0183 = 18.3 ms
   Effective traffic per terminal (A) = (1/30) x 0.0183 = 6.1 x 10^{-4} erlang
   and the total effective traffic is 6.1n x 10^{-4} erlang, where n is the no. of stations.
   The maximum traffic carried for ALOHA is 1/(2e). Hence:

   $6.1n \times 10^{-4} = 1/(2e)$
   $\therefore n = 10^{-4}/(6.1 \times 2e) = 301.54$ $\Rightarrow$ 301 (taking floor value)

   Note that at the maximum throughput condition, the total offered traffic = total carried traffic + retransmission traffic = 0.5 erlang.

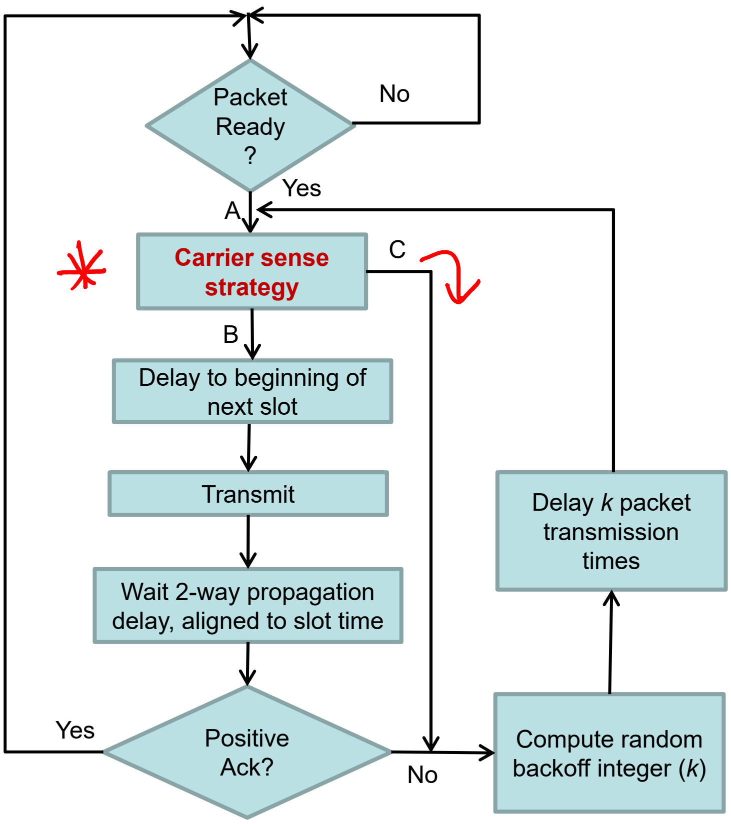
2. For slotted ALOHA, the maximum traffic carried = 1/e erlang. Hence:

   $6.1n \times 10^{-4} = 1/e$
   $\therefore n = 10^{-4}/6.1e = 603.08$ $\Rightarrow$ 603 (taking floor value)

Carrier Sense Multiple Access (CSMA)

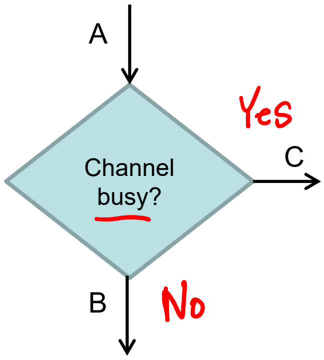
- Carrier-sense information is used to minimize the length of collision interval

consider slotted case



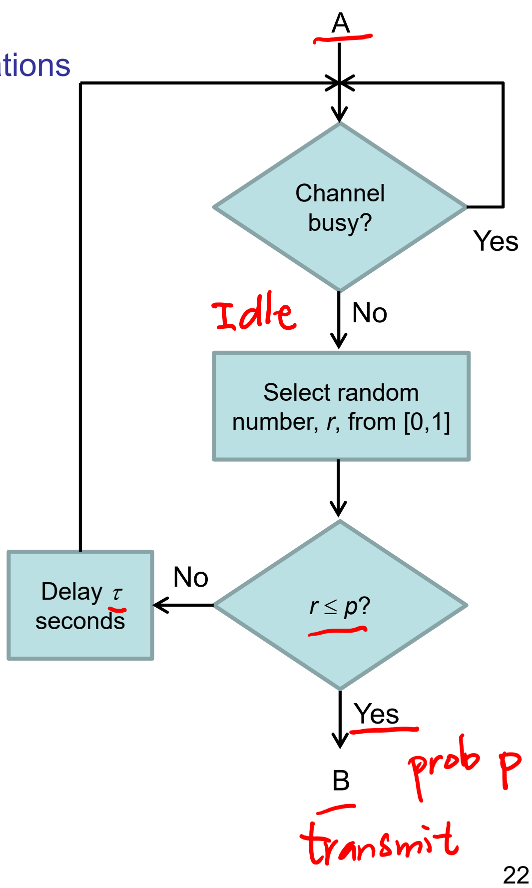
Non-Persistent CSMA

- When station has a ready packet to send, it senses the channel and carries out the following:
  - If channel is idle, packet is transmitted
  - If channel is busy, station uses a backoff algorithm, following path through C to reschedule the transmission
  - At the time of retransmission, channel is sensed again and the algorithm is repeated



p-Persistent CSMA

- 2 constants used for this algorithm
  - τ = maximum propagation delay between 2 stations
  - p = specified probability
- No "C" connection used
- *p*-persistence algorithm works as follows:
  - If channel is sensed idle, a random number uniformly distributed on [0,1] is chosen. If selected number is less than or equal to p, the packet is transmitted; if not, station waits τ seconds and repeats the algorithm
  - If channel is busy, station persists in sensing the channel until it is found to be idle and then proceeds as described above



Carrier Sense Multiple Access with Collision Avoidance (CSMA-CA)

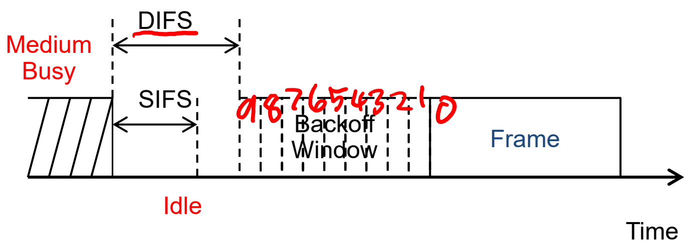
- Wireless nodes cannot receive while transmitting (full duplex mode more costly), so collision detection is an issue
- How to improve CSMA for wireless communication?
  - Nodes need to be less greedy
  - Use collision avoidance scheme
  - Use ACK
  - Augment with robust handshaking

CSMA-CA (cont.)

The CSMA-CA MAC works as follows:

Part 1 – Before Transmitting

- If channel is idle for more than a Distributed coordination function Inter-Frame Space (DIFS) time and the backoff counter is zero, a station can transmit immediately
- If channel is busy, the station generates a random backoff period that is uniformly distributed from [0 to current Contention Window (CW) size.]
- At the initial backoff stage, the current CW is set at the minimum contention window (CW_{min}) size.
- Backoff counter decrements by 1 if channel is idle for each time slot and freezes if channel is sensed busy.
- Backoff counter is re-activated to count down when channel is sensed idle for more than DIFS time.
- If backoff counter reaches 0, station will attempt to transmit.



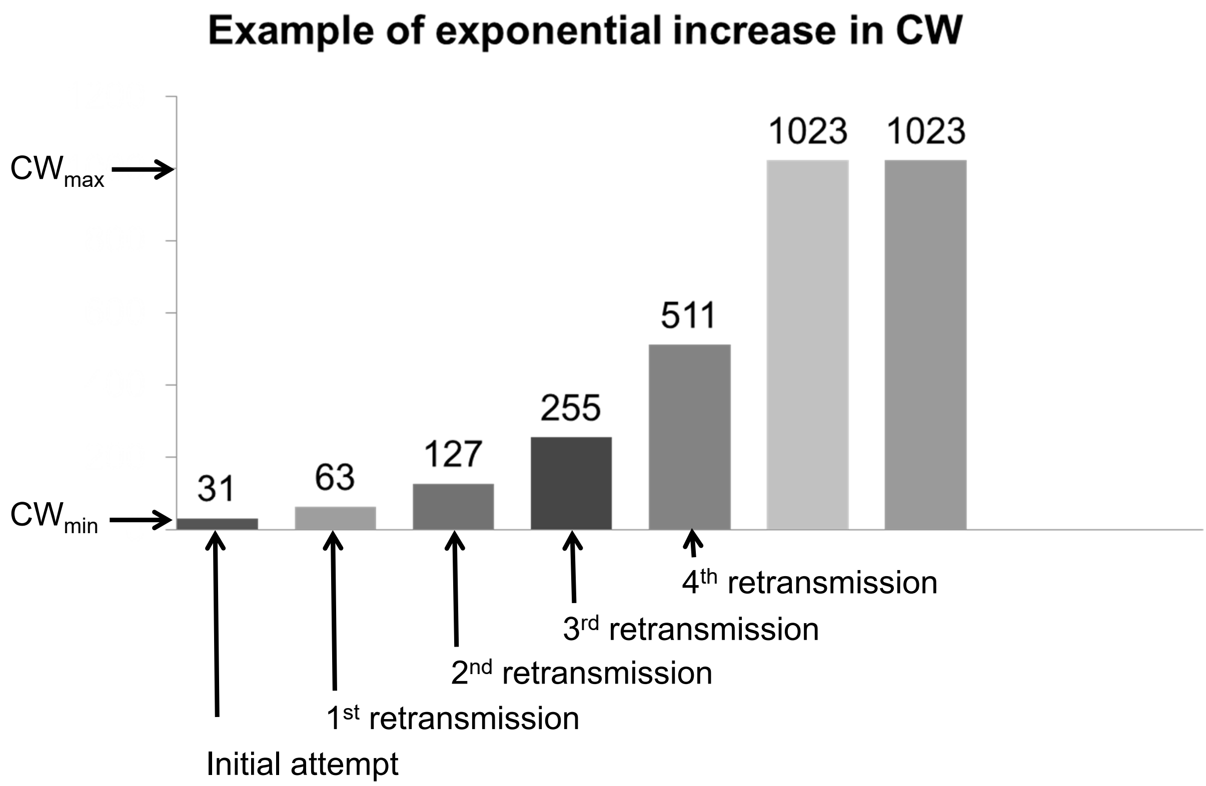
CSMA-CA (cont.)

Part 2 – After Transmitting

ACK

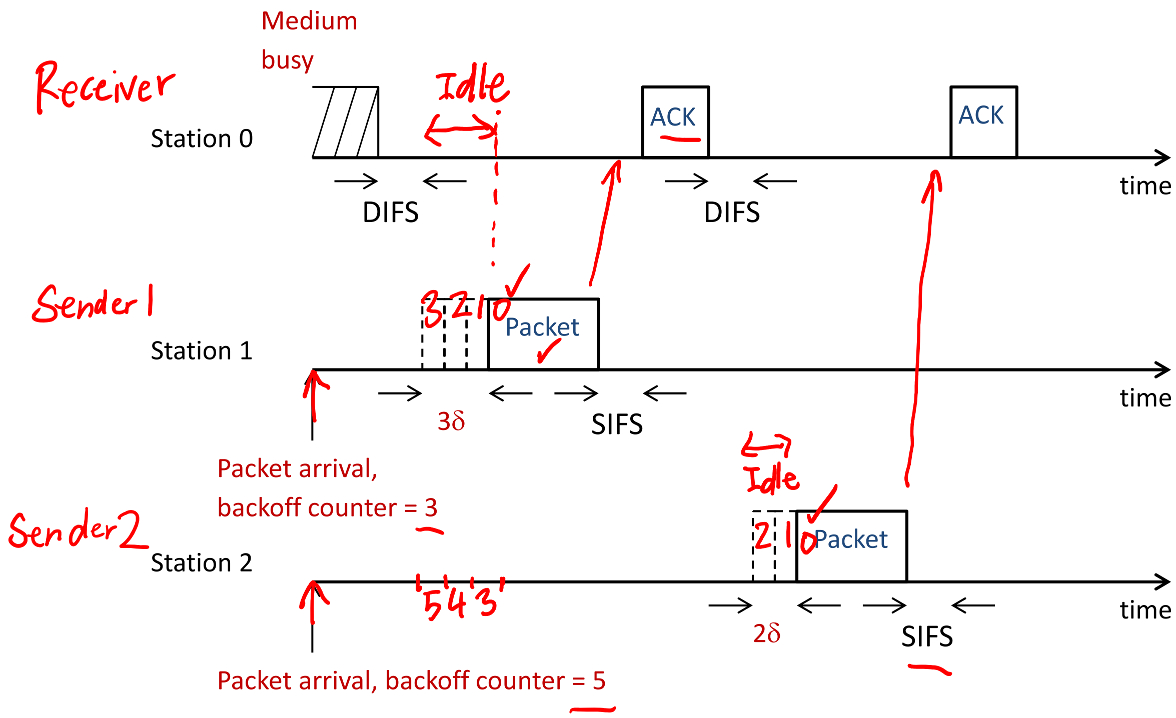
- If successful, the destination station sends an acknowledgement after a Short Inter-Frame Space (SIFS) time and the current CW size is reset to CW_{min}.
- If a station does not receive an acknowledgement within an acknowledgement timeout period after a frame is transmitted, i.e. it is not successful, it will increase the current contention window CW size by doubling it plus one (until a maximum contention window (CW_{max}) size is reached) in the next backoff stage and a new random backoff period is selected as before.
- This process repeats itself until the packet is successfully transmitted or until the maximum retry limit is reached. If the packet is still not successfully transmitted, then it is dropped.

CSMA-CA (cont.)



CSMA-CA (cont.)

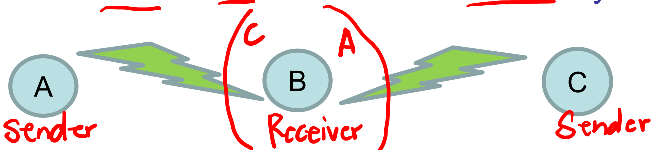
- Example of CSMA-CA MAC data packet transmissions



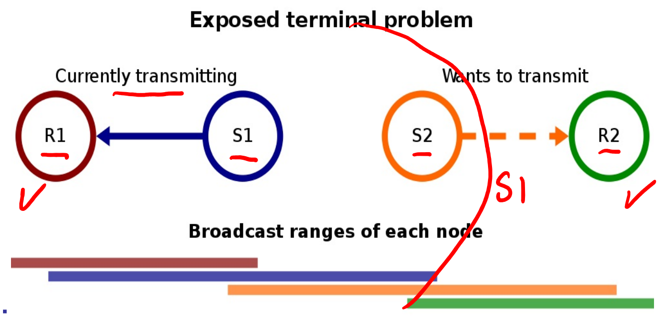
Hidden /Exposed Node Problems

Note: Limited transmission range for wireless communications

- Carrier sense protocols are susceptible to hidden/exposed node problems
  - ***Hidden node*** problem: Node A out of range of Node C. So collision occurs at Node B if both Nodes A and C transmit simultaneously



  - ***Exposed node*** problem: Occurs when a node is prevented from sending packets to other nodes due to a neighbouring transmitter.



- 2 main methods to overcome these:
  - Busy tone
  - RTS-CTS mechanism (from Multiple Access with Collision Avoidance for Wireless (MACAW), then adopted in Wi-Fi)

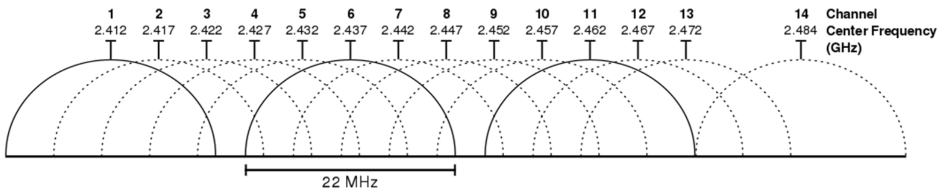
Busy Tone

- Use 2 channels: *Data packet channel* & *Control channel*
- When a node starts to receive packet destined for it, it emits an unmodulated tone on the control channel, and ends when packet reception is finished
- A node that wishes to transmit a packet first senses the control channel for presence of busy tone. If heard, the node backs off. If not, the node starts packet transmission on the data channel.
- Solves both hidden node and exposed node problems
- Busy tone coverage range should be same as data transmission range
- If busy tone range is shorter, then a node within radio range of receiver might start data transmission and interferes with receiver's signal
- If busy tone range is longer, then more nodes than necessary suppress transmission
- Control channel needs narrow bandwidth
- Variants:
  - 2 busy tones, one used by receiver, another used by transmitter
  - Control channel has busy tone and RTS/CTS

F Tobagi and L Kleinrock, "Packet Switching in Radio Channels: Part II – The Hidden Terminal Problem in Carrier Sense Multiple-Access and the Busy-Tone Solution", IEEE Trans. Commun., Vol. 23, No. 12, Dec 1975, pp 1417-1433

Wi-Fi (IEEE 802.11xx)

- [PHY] Wi-Fi operates in the 2.4 and/or 5 GHz frequency bands, sub-divided into 14 channels.

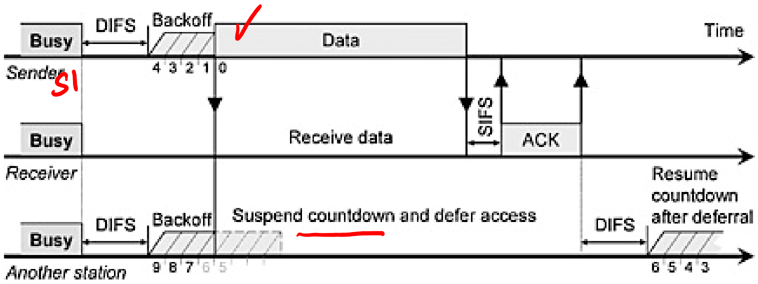


- The modulation scheme in IEEE 802.11a/g/p is OFDM
- Wi-Fi 4: IEEE 802.11n – MIMO-OFDM (HT-OFDM)
- Wi-Fi 5: IEEE 802.11ac – MIMO-OFDM (VHT-OFDM)
- Wi-Fi 6 (Sept 2019): IEEE 802.11ax – MIMO-OFDM (HE-OFDM)

- [MAC] Wi-Fi uses CSMA-CA and (optional) RTS-CTS mechanism
  - Distributed Coordination Function (DCF)

Distributed Coordination Function (DCF): 1. Basic Access method

Similar to CSMA-CA



S2

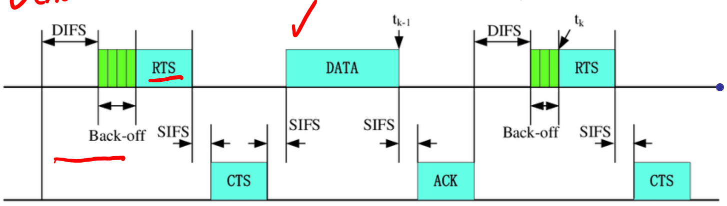
- Stations with a frame to transmit perform carrier sensing for DIFS (Distributed Inter-Frame Space) time after the previous busy period and then count down their backoff timers.
- The station whose backoff timer reaches 0 transmits its data.
- The transmitting station waits for a time equal to SIFS (Short Inter-Frame Space) for the acknowledgement (ACK) from the receiver.
- Other stations that sense that the channel is busy during the contention period pause their timers until the channel is clear.
- After the ACK, the process is repeated for stations with a frame to transmit.

Distributed Coordination Function (DCF): 2. Four-Way Handshaking access method

Busy

new cycle

Sender

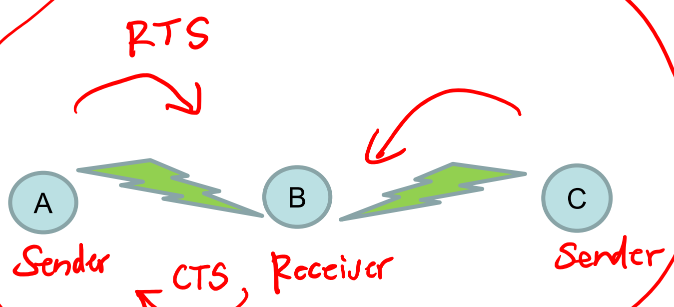


Receiver

S2

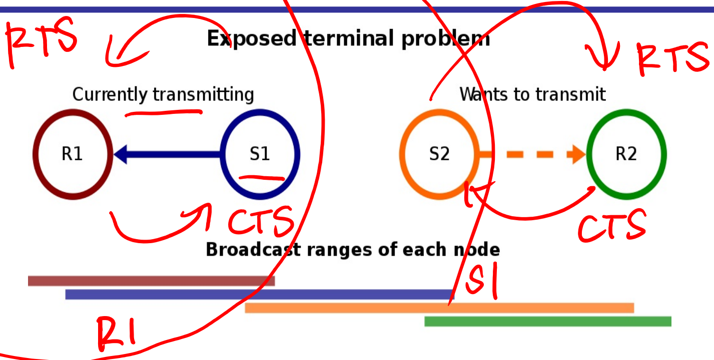
- Stations with a frame to transmit perform carrier sensing for DIFS time after the previous busy period and then count down their backoff timers.
- The station whose backoff timer reaches 0 transmits a RTS (request to send) frame.
- The receiver waits for a time equal to SIFS and responds using a CTS (clear to send) frame if it is available.
- The transmitting station waits for a time equal to SIFS and transmits its data.
- The transmitting station waits for a time equal to SIFS for the acknowledgement (ACK) from the receiver.
- After the ACK, the process is repeated for stations with a frame to transmit.

Hidden Node scenario



- IEEE 802.11 solves the hidden node problem by using the RTS/CTS mechanism found in the four-way handshaking access method.
- In the figure, B may receive RTSs from both A and C, and decides to respond only to A by sending a CTS to A.
- C will also receive the CTS meant for A, which it will take to mean that B is currently busy with a hidden node.
- C will continue to sense B until it becomes idle again.

Exposed Node scenario



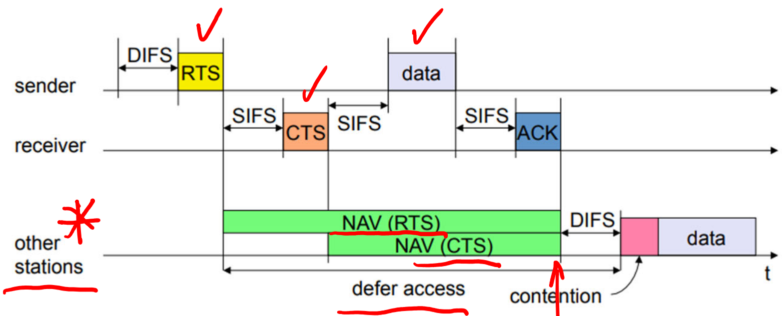
- In the figure, S1 is currently transmitting to R1 and S2 wants to transmit to R2.
- Due to CSMA/CA, S2 will be prevented from transmitting to R2 as it thinks it will interfere with S1's transmission even though it should not happen as R2 is out of S1's range.
- Unlike in the hidden node scenario, the RTS/CTS mechanism only works in this scenario if the nodes are in sync, and that the transmitting nodes are sending packets of the same size at the same rate.
- In this case, if S2 senses a RTS from S1, but without a corresponding CTS, S2 (an exposed note) can safely assume that the receiving node (of S1) is out of its range and it can thus transmit to other nodes within its own range (e.g. R2).

Virtual Channel Sensing in CSMA/CA

- Virtual channel sense or virtual carrier sense is a mechanism to predict future traffic in wireless networks that uses carrier sense multiple access with collision avoidance (CSMA/CA).
  - saves power since no need to do physical carrier sensing
- It is implemented in wireless network protocols, IEEE 802.11 and IEEE 802.16, and operates in the medium access control (MAC) layer.

- In virtual channel sensing, a timer mechanism is used that is based on information of durations of previous frame transmissions in order to predict future traffic in the channel.
- It uses network allocation vector (NAV), which can be considered as a counter that counts down to zero.

Virtual Channel Sensing in CSMA/CA



e.g. S2

NAV reach 0

- The steps are:
  - The transmitting station waits for a time equal to DIFS and issues a request to send (RTS) if the channel is clear.
  - After sending RTS, the *Duration* field is read and a NAV (RTS) is initialized at other stations, so they do not attempt to transmit until the end of the NAV.
  - The receiving station waits for SIFS time and issues a clear to send (CTS).
  - With the CTS, the *Duration* field is read and a NAV (CTS) is initialized at other stations.
  - The sender waits for SIFS time and transmits its data frame.
  - On receiving the data frame, the receiver waits for SIFS time and sends an acknowledgement frame (ACK).
  - Both the NAV values decrement to 0 during this time period.
  - The other stations wait for a DIFS before contending for the channel.