multiple access protocol

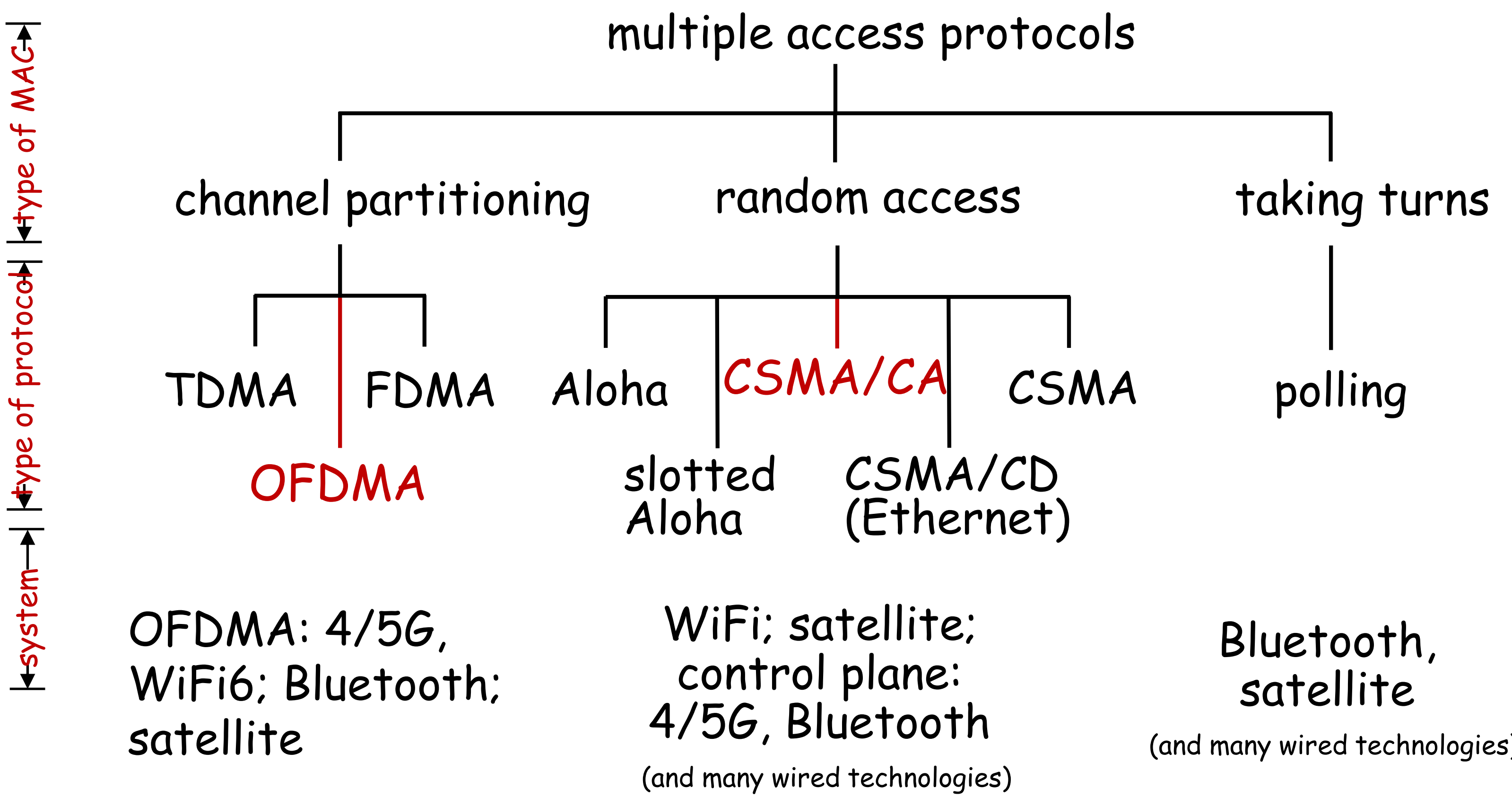
- distributed algorithm that determines how nodes share channel, i.e., determine when node can transmit
- communication about channel sharing must use channel itself!
  - no out-of-band channel for coordination

Ideal Multiple Access Protocol

Broadcast channel of rate R bps

1. when one node wants to transmit, it can send at rate R.
2. when M nodes want to transmit, each can send at average rate R/M
3. fully decentralized:
   - no special node to coordinate transmissions
   - no synchronization of clocks, slots
4. simple

MAC protocols: A taxonomy



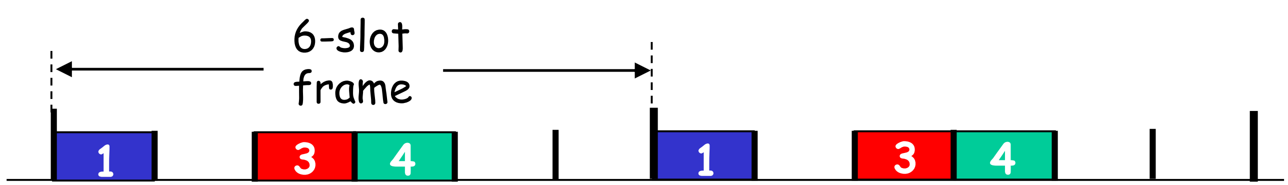
Channel Partitioning MAC protocols: TDMA

TDMA: time division multiple access

- access to channel in "rounds"
- each station gets fixed length slot (length = pkt trans time) in each round
- unused slots go idle

Example 6-station LAN:

- 1,3,4 have pkt, slots 2,5,6 idle



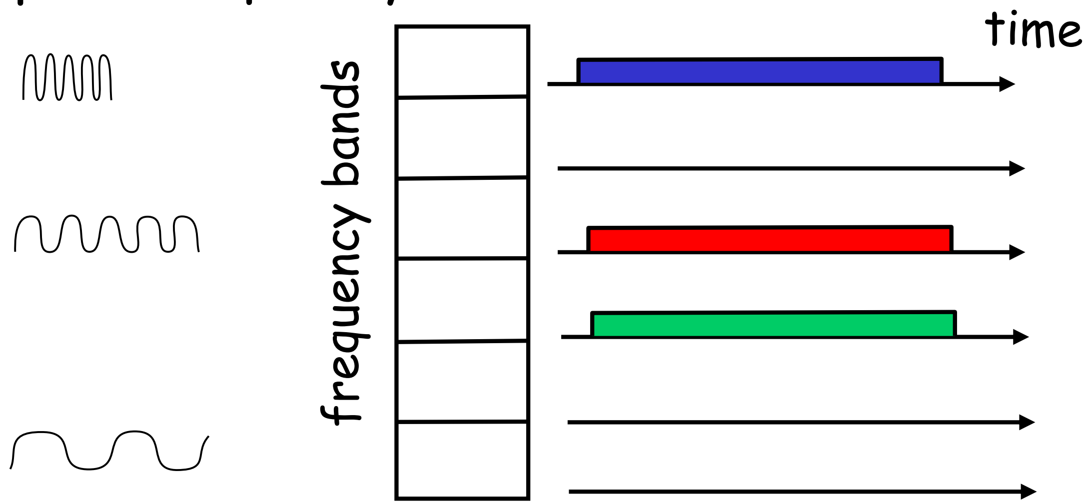
Channel Partitioning MAC protocols: FDMA

FDMA: frequency division multiple access

- channel spectrum divided into frequency bands
- each station assigned fixed frequency band
- unused transmission time in frequency bands go idle

Example 6-station LAN:

- 1,3,4 have pkt, frequency bands 2,5,6 idle

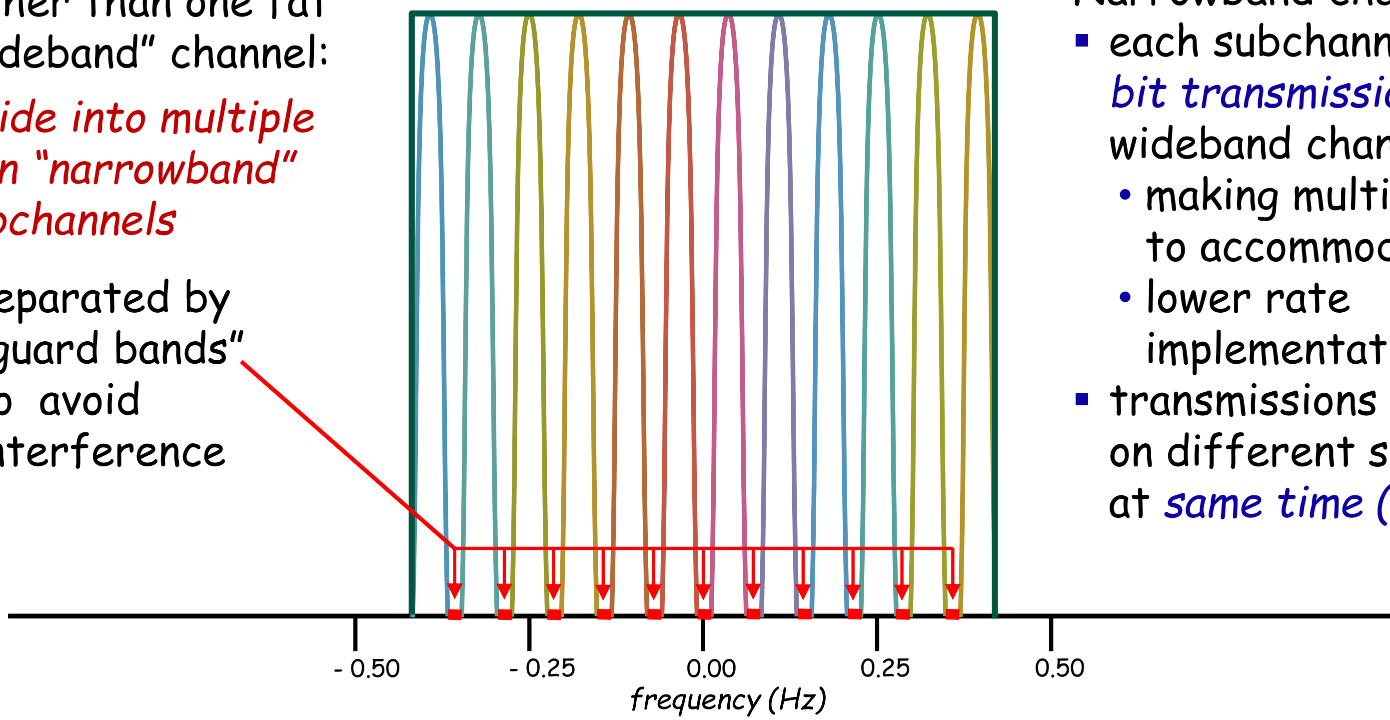


FDM: Frequency Division Multiplexing

rather than one fat "wideband" channel:

divide into multiple thin "narrowband" subchannels

- separated by "guard bands" to avoid interference

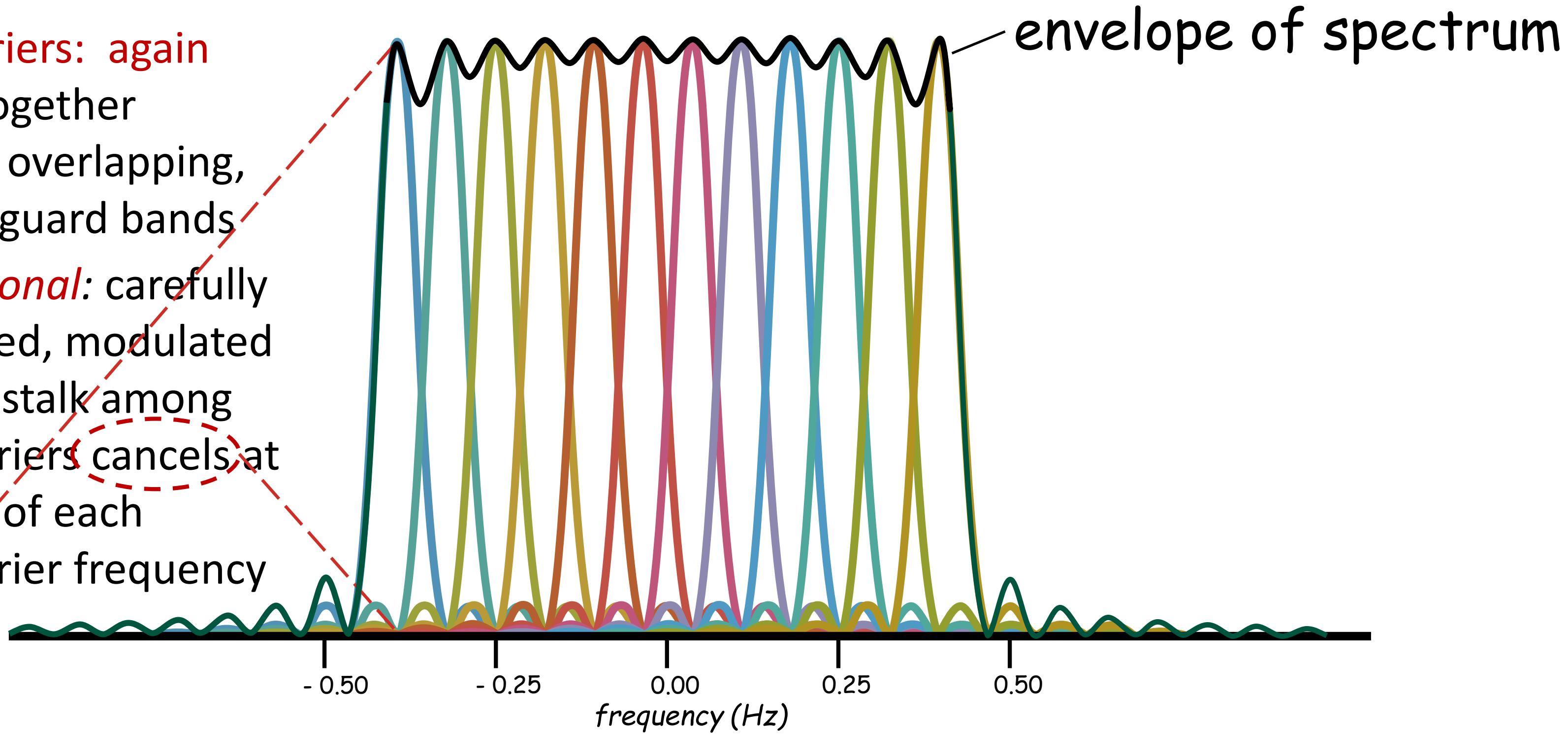


Narrowband channels:

- each subchannel has *lower bit transmission rate* than wideband channel:
  - making multipath easier to accommodate
  - lower rate implementations easier
- transmissions can happen on different subchannels at *same time (in parallel)*

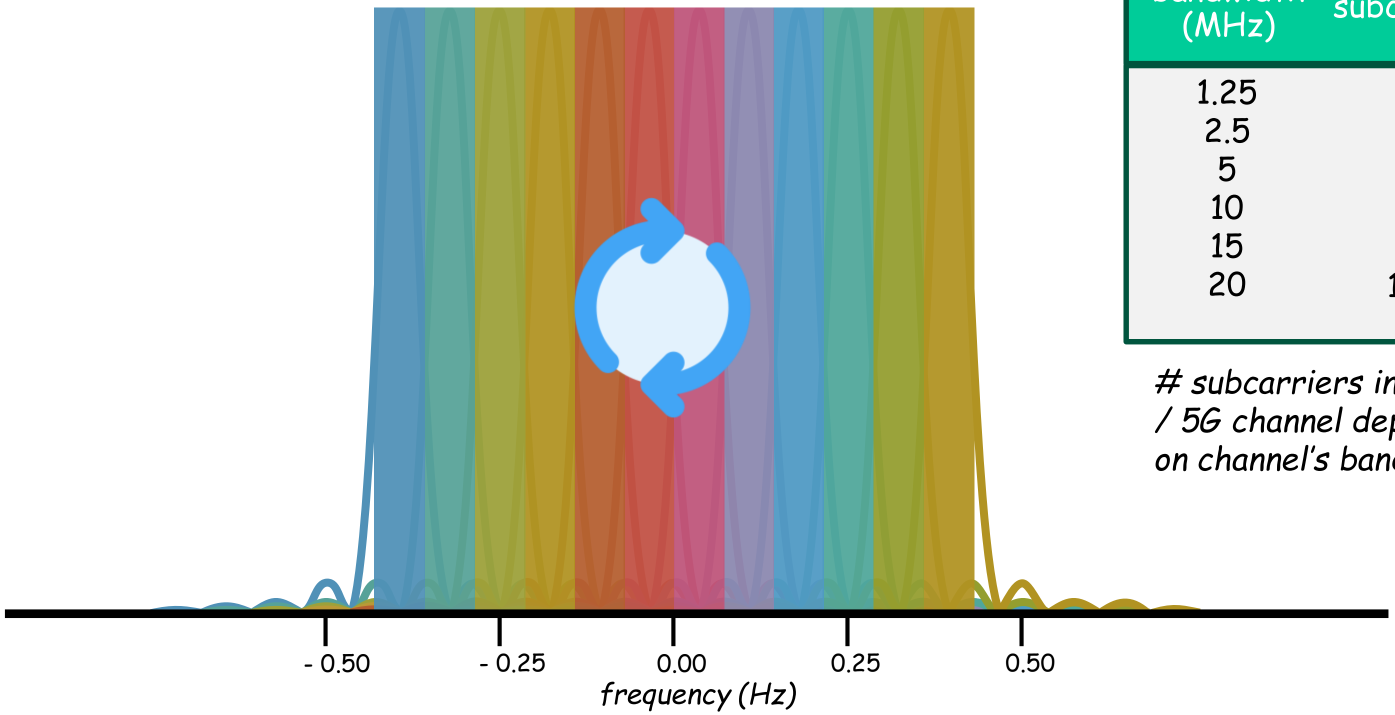
OFDM: *Orthogonal* FDM

- subcarriers: again close together
- slightly overlapping, but no guard bands
- *orthogonal:* carefully designed, modulated so crosstalk among subcarriers cancels at center of each subcarrier frequency



OFDM: Subcarriers

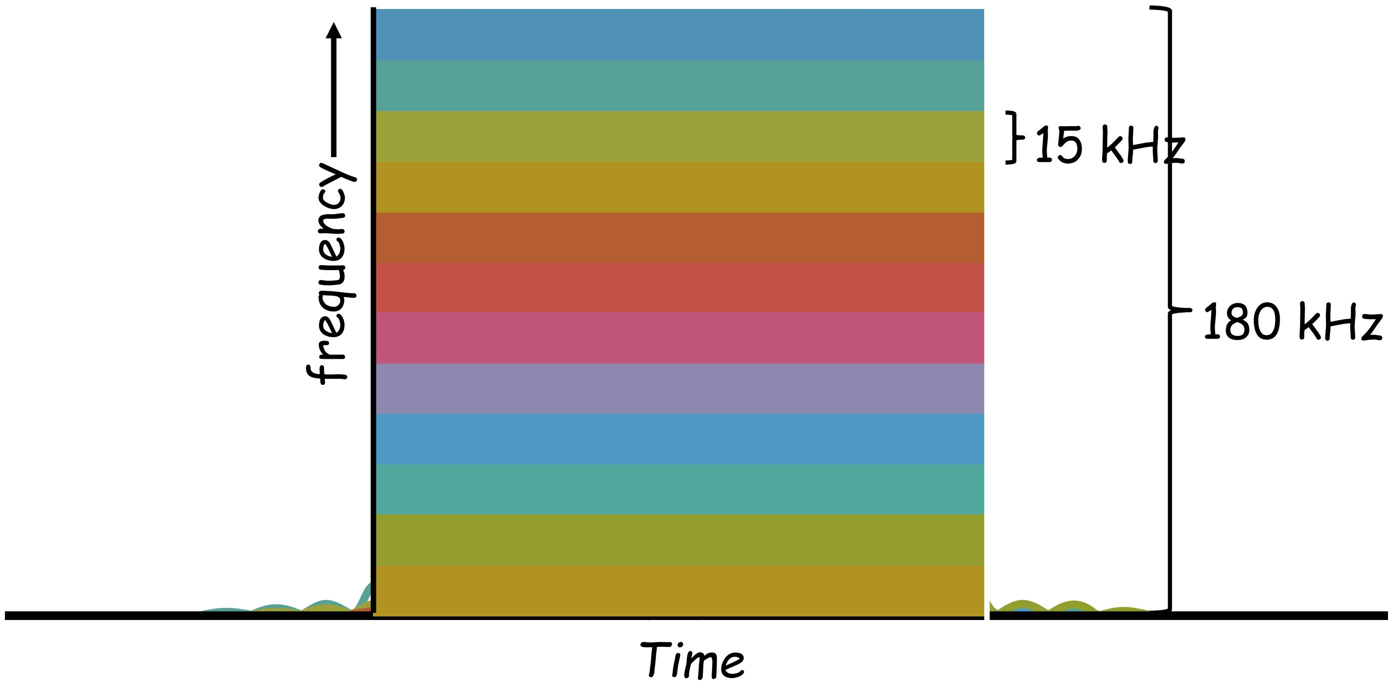
Wireless Jargon:
"carrier" ~ "channel"
"subcarrier" ~ "subchannel"



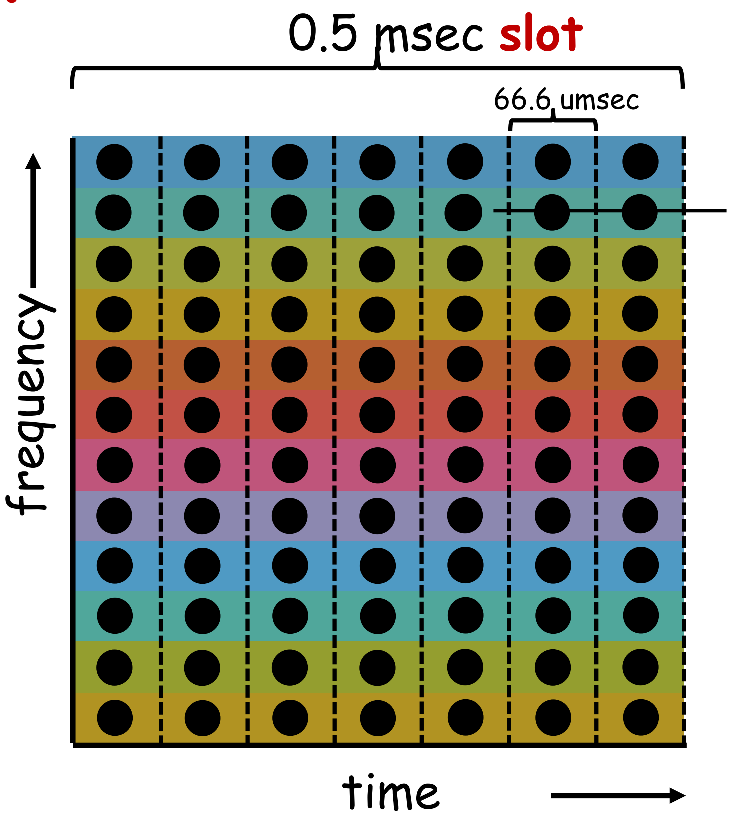
Channel bandwidth (MHz)	Number of subcarriers
1.25	76
2.5	150
5	300
10	600
15	900
20	1200

 # subcarriers in an 4G / 5G channel depends on channel's bandwidth

OFDMA: subcarriers, time



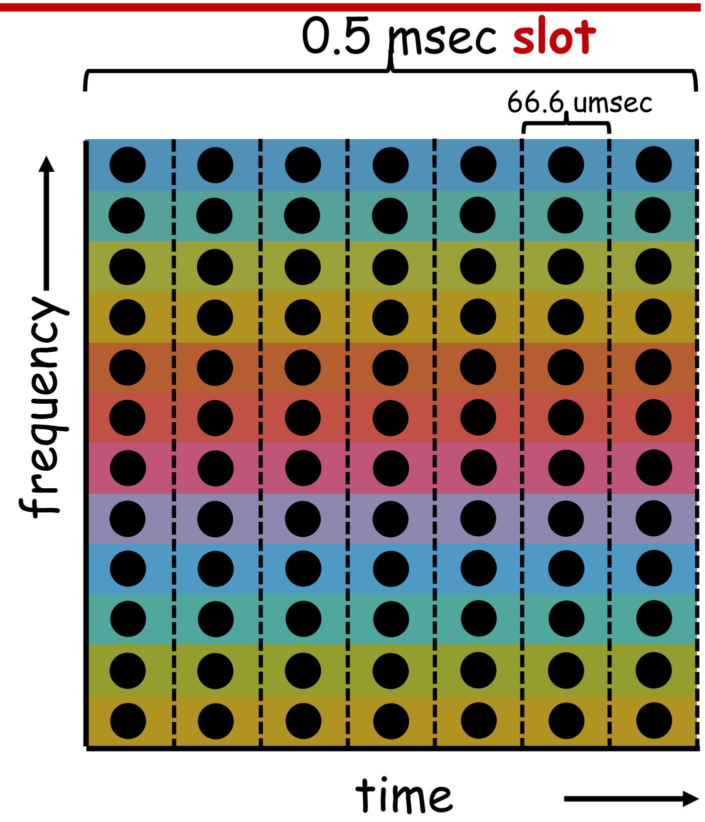
OFDMA: symbols



one "symbol" can be transmitted per 66.6 usec (4G) at given subcarrier frequency

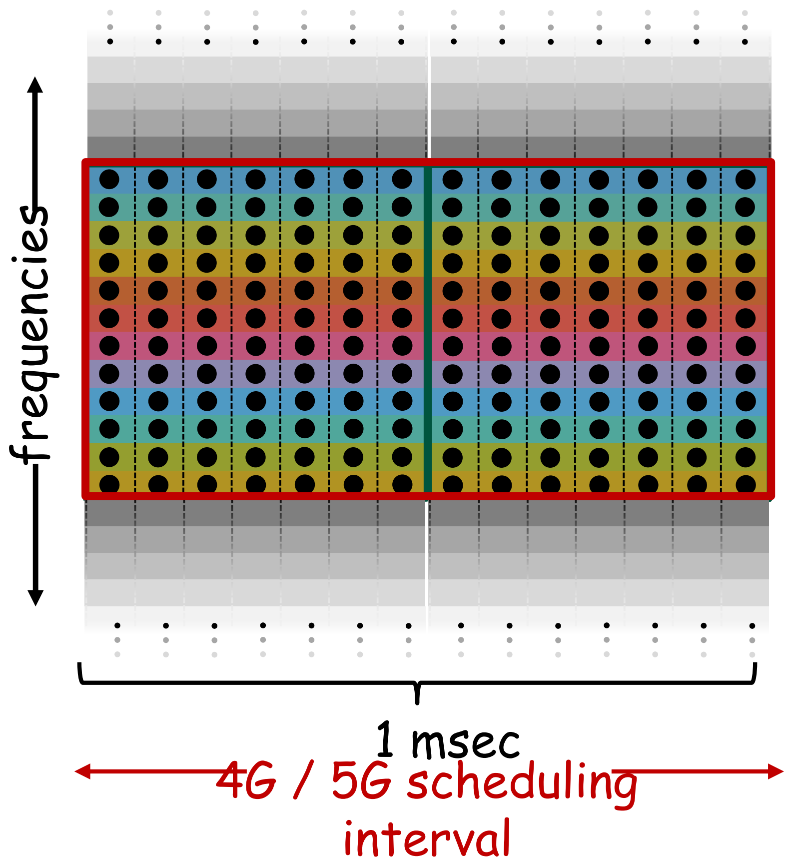
- *number of bits (between 2-8) in symbol depends on modulation technique* chosen (which depends on channel quality)

OFDMA: resource blocks



resource block (RB):
- symbols grouped into resource blocks
- 84 symbols (7 symbols/slot over 12 subcarriers) in 4G
- *smallest unit of data that can be sent to (assigned to) a user*

OFDMA: resource blocks



Base station decides which RBs get assigned (over all frequencies) to which devices at 1 msec intervals

From 4G LTE to 5G New Radio (NR)

Commonalities, differences:

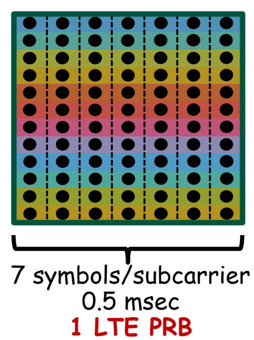
4G, 5G both use OFDMA

- Subcarrier bandwidths:
  - 4G: 15 kHz
  - 5G: 15, 30, 60, 120 kHz
- Max carrier bandwidth:
  - 4G: 20 MHz
  - 5G: 100 MHz

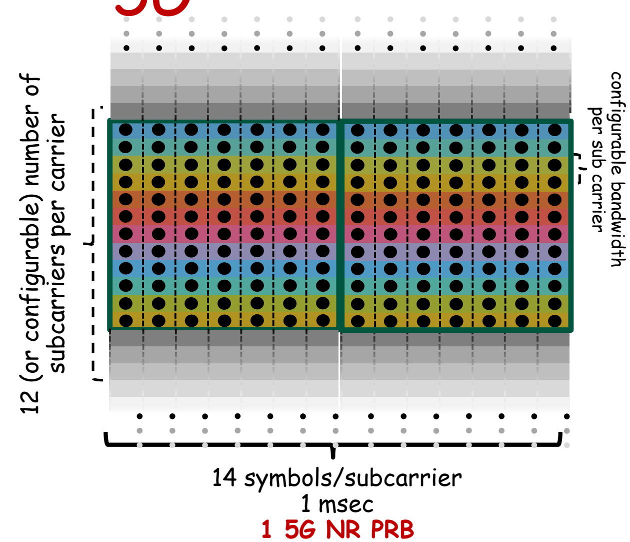
4G, 5G: resource blocks (RB)

- smallest scheduling unit of transmission to device

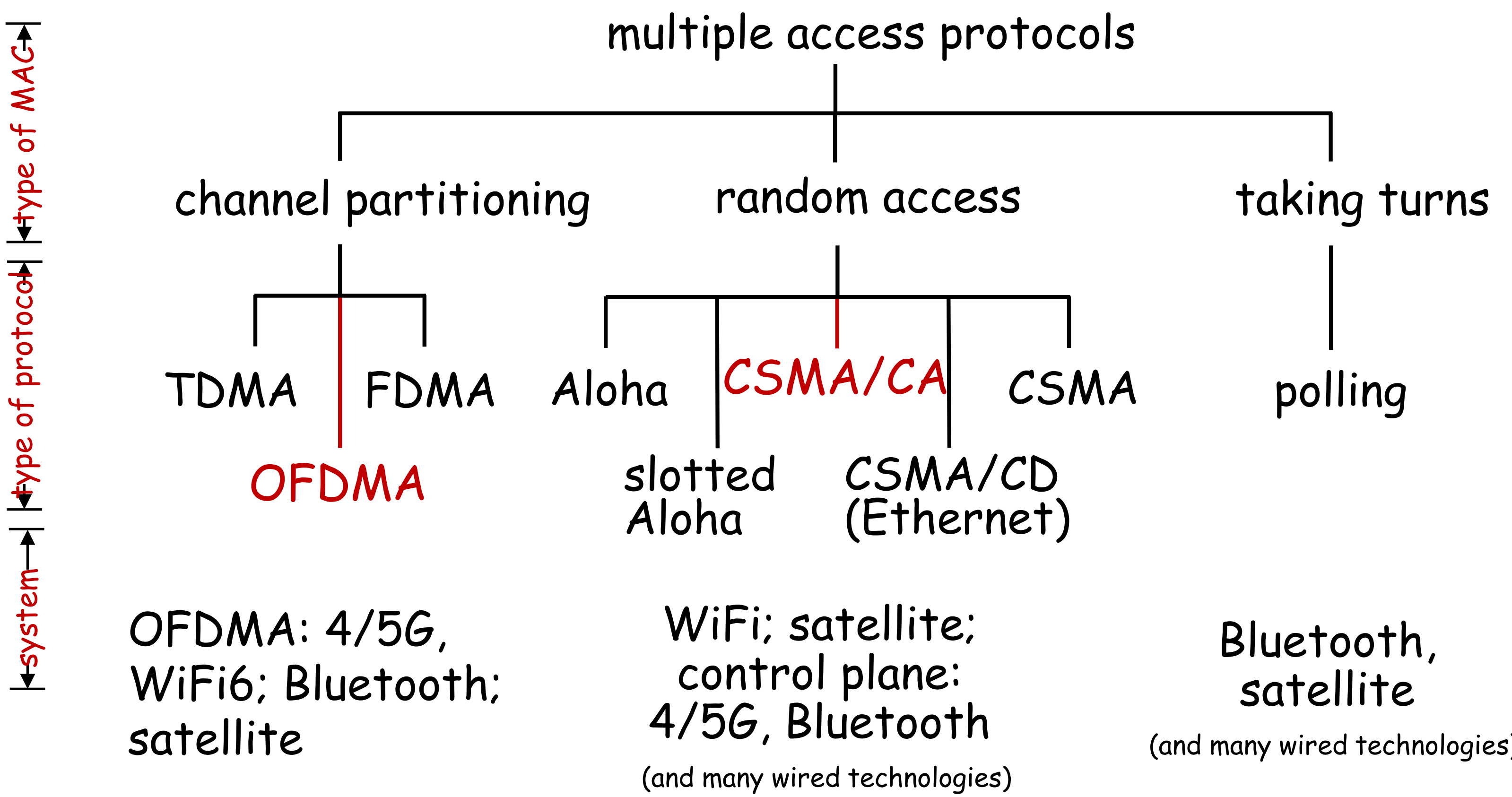
4G



5G



Recall: MAC protocols



Random Access Protocols

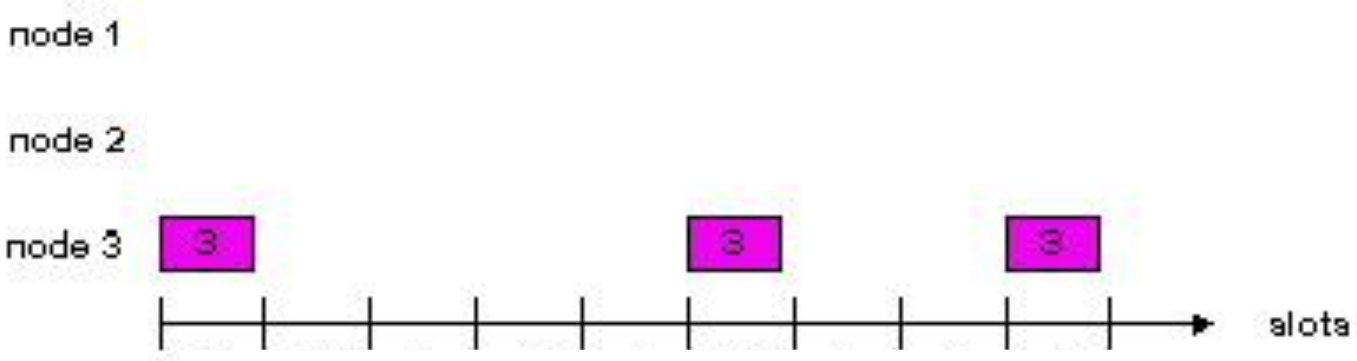
- When node has packet to send
  - transmit at full channel data rate R.
  - no *a priori* coordination among nodes
- two or more transmitting nodes ➜ "collision"
- random access MAC protocol specifies:
  1. how to detect collisions
  2. how to recover from collisions (e.g., via delayed retransmissions)

Examples of random access MAC protocols:
- slotted ALOHA
- ALOHA
- CSMA, CSMA/CD, CSMA/CA

Slotted ALOHA

Assumptions:

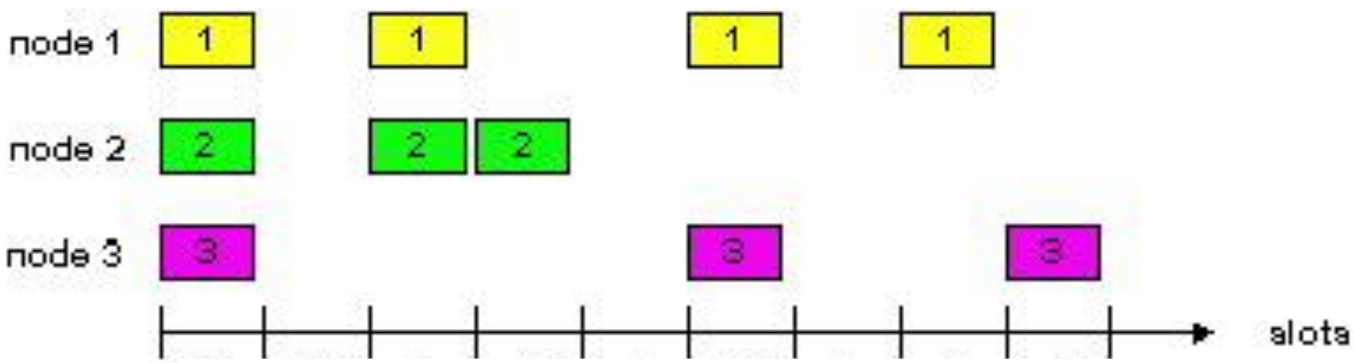
Slotted ALOHA



Assumptions:

- all frames same size
- time divided into equal size slots (time to transmit 1 frame)
- nodes start to transmit only slot beginning
-
-

Slotted ALOHA



Assumptions:

- all frames same size
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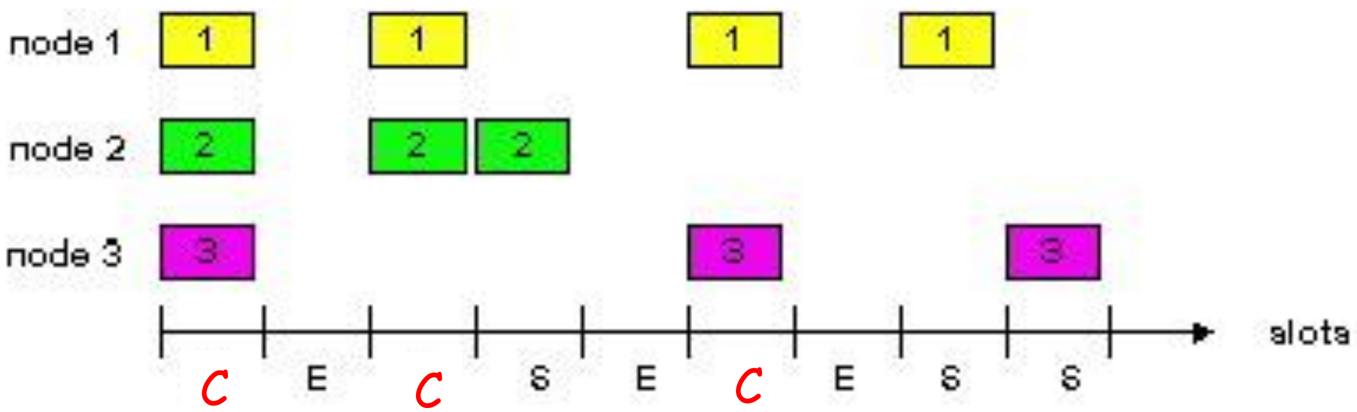
- nodes are synchronized
- if 2 or more nodes transmit in slot, all nodes detect collision

Slotted ALOHA



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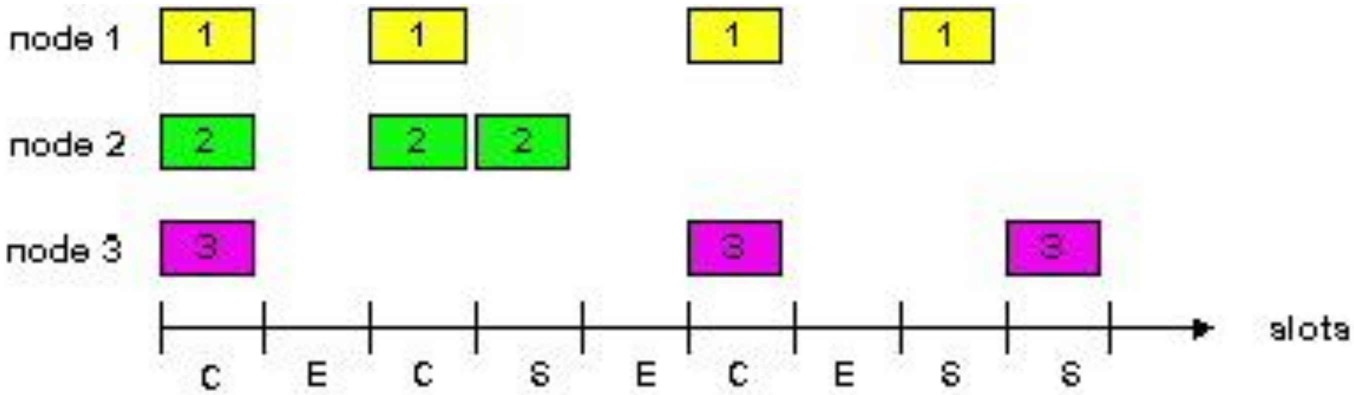


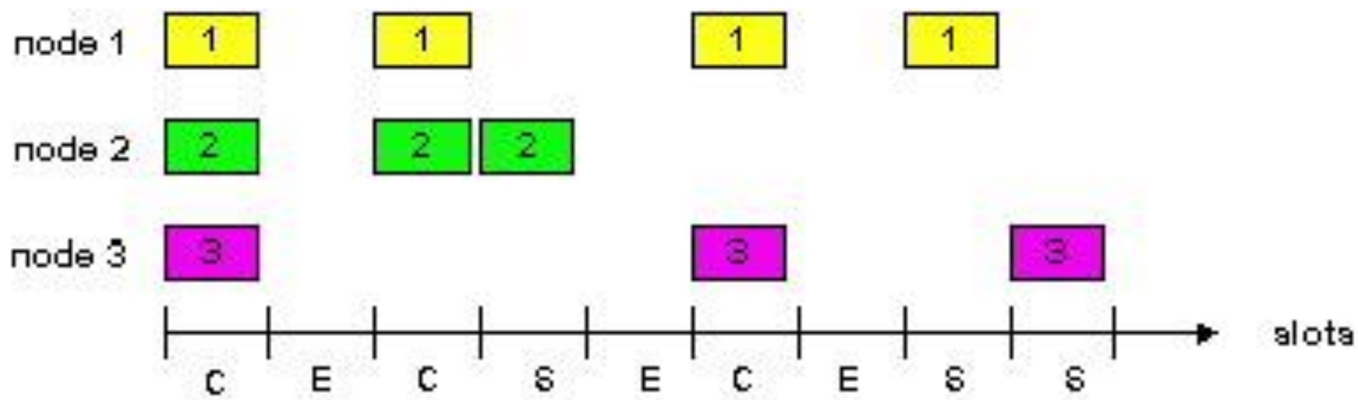
Assumptions:

- all frames same size
- time divided into equal size slots (time to transmit 1 frame)
- nodes start to transmit only slot beginning
- nodes are synchronized
- if 2 or more nodes transmit in slot, all nodes detect collision

Operation:

- when node obtains fresh frame, transmits in next slot
  - ***if no collision***: node can send new frame in next slot
  - ***if collision***: node retransmits frame in each subsequent slot with prob. *p* until success

Slotted ALOHA



Pros

- single active node can continuously transmit at full rate of channel
- highly decentralized: only slots in nodes need to be in sync
- simple

Cons

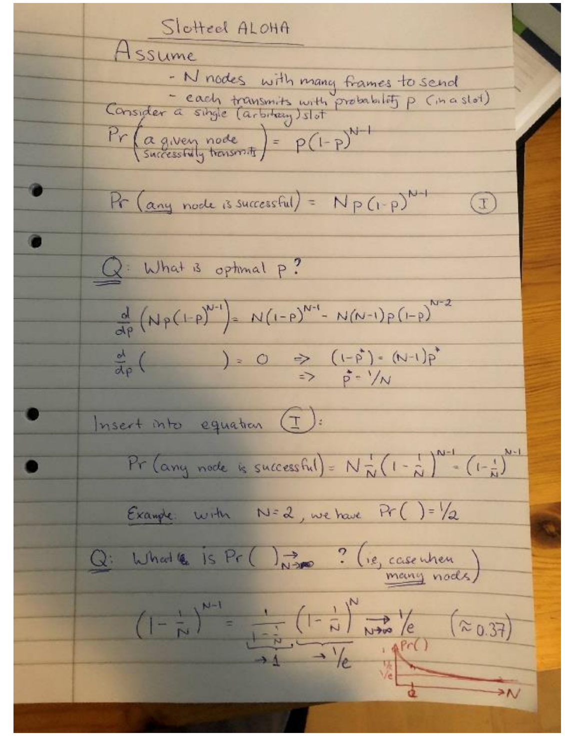
- collisions, wasting slots
- idle slots
- nodes may be able to detect collision in less than time to transmit packet
- clock synchronization

Slotted Aloha efficiency

Efficiency : long-run fraction of successful slots (many nodes, all with many frames to send)

- *suppose:* N nodes with many frames to send, each transmits in slot with probability *p*
- prob that given node has success in a slot = $p(1-p)^{N-1}$
- prob that *any* node has a success = $Np(1-p)^{N-1}$
- max efficiency: find p* that maximizes $Np(1-p)^{N-1}$
- for many nodes, take limit of $Np^*(1-p^*)^{N-1}$ as N goes to infinity, gives:

Max efficiency = 1/e = .37



At best: channel used for useful transmissions 37% of time!

!

Slotted ALOHA

Slotted ALOHA

Assume

- N nodes with many frames to send
- each transmits with probability p (in a slot)

Consider a single (arbitrary) slot

$$Pr\left(\begin{array}{c}\text{a given node}\\ \text{successfully transmits}\end{array}\right) = p(1-p)^{N-1}$$

$$Pr(\underline{\text{any}} \text{ node is successful}) = Np(1-p)^{N-1} \quad \text{(I)}$$

Q: What is optimal p?

Slotted ALOHA

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Slotted ALOHA

$$\Pr(\underline{\text{any}} \text{ node is successful}) = Np(1-p)^{N-1} \qquad \text{(I)}$$

Q: What is optimal p?

$$\frac{d}{dp}\left(Np(1-p)^{N-1}\right) = N(1-p)^{N-1} - N(N-1)p(1-p)^{N-2}$$

$$\frac{d}{dp}\left(\qquad \right) = 0 \Rightarrow (1-p^*) = (N-1)p^*$$

$$\Rightarrow p^* = 1/N$$

Slotted ALOHA

$$\Pr(\underline{\text{any}} \text{ node is successful}) = Np(1-p)^{N-1} \qquad \text{(I)}$$

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$$\frac{d}{dp}\left(\qquad \right) = 0 \quad \Rightarrow \quad (1-p^*) = (N-1)p^*$$

$$\Rightarrow \quad p^* = 1/N$$

Insert into equation (I):

$$\Pr(\text{any node is successful}) = N\frac{1}{N}\left(1-\frac{1}{N}\right)^{N-1} = \left(1-\frac{1}{N}\right)^{N-1}$$

Slotted ALOHA

$$\Pr(\text{any node is successful}) = N \frac{1}{N}\left(1 - \frac{1}{N}\right)^{N-1} = \left(1 - \frac{1}{N}\right)^{N-1}$$

Example: with $N = 2$, we have $\Pr(\ ) = 1/2$

Slotted ALOHA

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Example: with $N = 2$, we have $\Pr(\;) = 1/2$

Q: What is $\Pr(\;) \xrightarrow[N \to \infty]{}$? (i.e., case when many nodes)

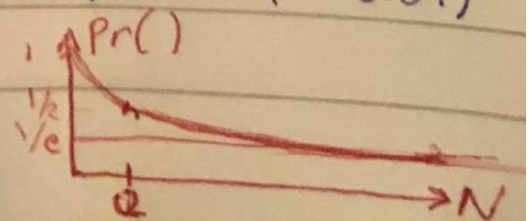
Slotted ALOHA

$$\Pr(\text{any node is successful}) = N \frac{1}{N}\left(1-\frac{1}{N}\right)^{N-1} = \left(1-\frac{1}{N}\right)^{N-1}$$

Example: with $N=2$, we have $\Pr(\ ) = 1/2$

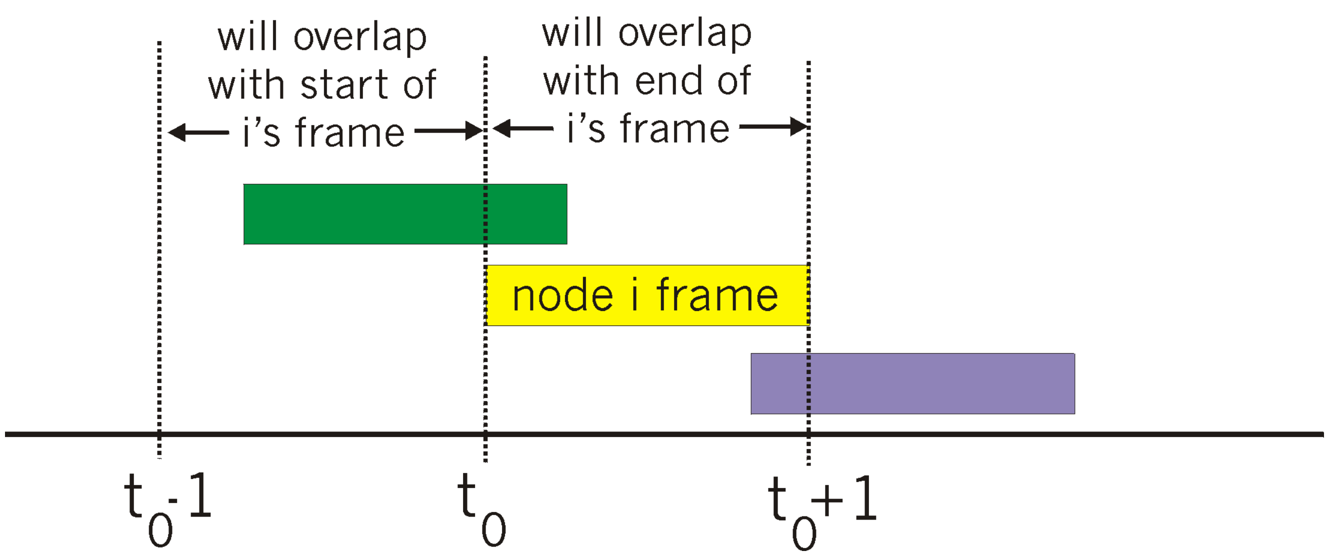
Q: What is $\Pr(\ )\xrightarrow[N\to\infty]{}$? (i.e., case when many nodes)

$$\left(1-\frac{1}{N}\right)^{N-1} = \underbrace{\frac{1}{1-\frac{1}{N}}}_{\to 1}\ \underbrace{\left(1-\frac{1}{N}\right)^{N}}_{\to 1/e} \xrightarrow[N\to\infty]{} 1/e \quad (\approx 0.37)$$



Pure (unslotted) ALOHA

- unslotted Aloha: simpler, no synchronization
- when frame first arrives
  - transmit immediately
- collision probability increases:
  - frame sent at t_0 collides with other frames sent in $[t_0-1, t_0+1]$



Pure Aloha efficiency

P(success by given node) = P(node transmits) ·

P(no other node transmits in $[t_0-1,t_0]$ ·

P(no other node transmits in $[t_0,t_0+1]$

$= p \cdot (1-p)^{N-1} \cdot (1-p)^{N-1}$

$= p \cdot (1-p)^{2(N-1)}$

… choosing optimum p* = 1/(2N) and then letting N -> infinity ...

= 1/(2e) = .18

even worse than slotted Aloha!

Now, let's improve things ...

IEEE 802.11: multiple access

- avoid collisions: 2^+ nodes transmitting at same time
- 802.11: CSMA - sense before transmitting
  - don't collide with ongoing transmission by other node
- 802.11: *no* collision detection!
  - difficult to receive (sense collisions) when transmitting due to weak received signals (fading)
  - can't sense all collisions in any case: hidden terminal, fading
  - goal: *avoid collisions:* CSMA/C(ollision)A(voidance)

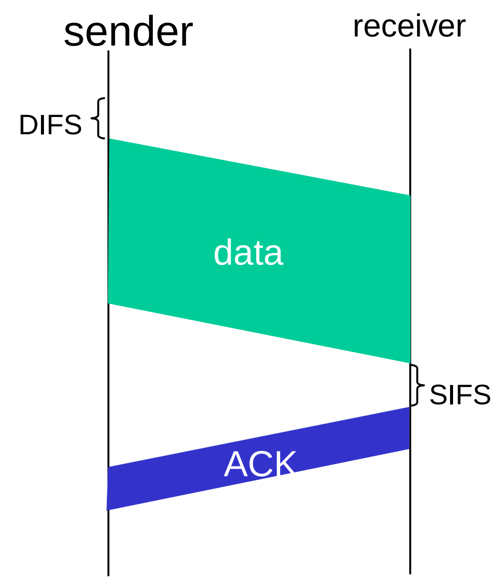
IEEE 802.11 MAC Protocol: CSMA/CA

802.11 sender

1 if sense channel idle for **DIFS** then
  transmit *entire* frame (no collision detection)

2 if sense channel busy then
  start random backoff time
  timer counts down while channel idle
  transmit when timer expires

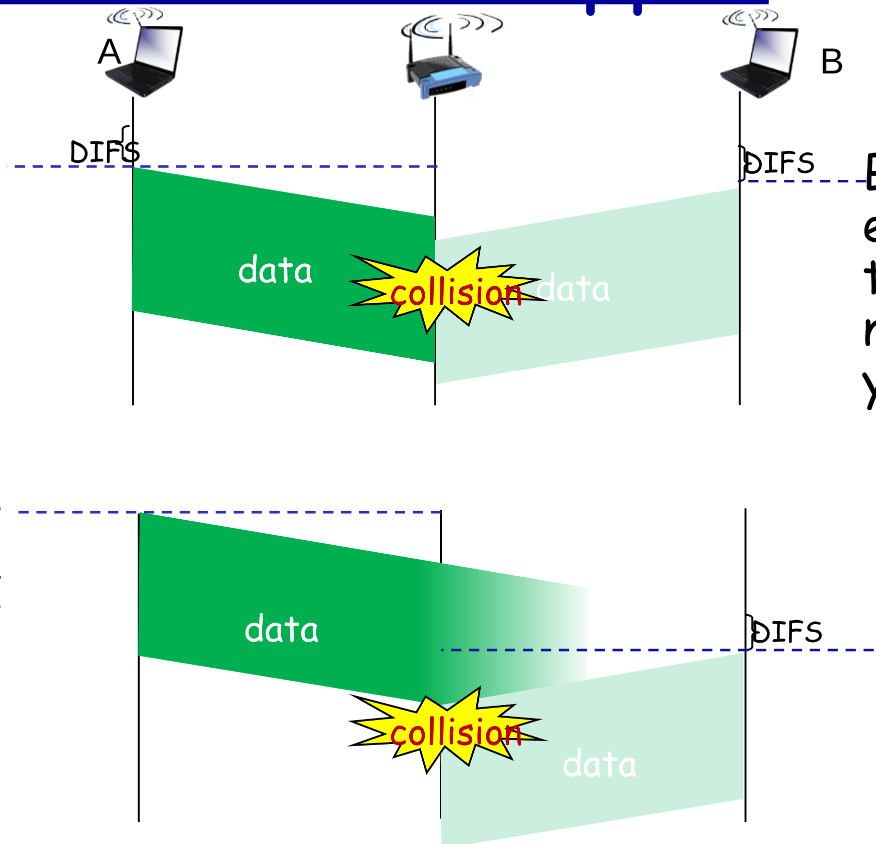
3. if no ACK, increase random backoff interval, repeat 2 (see later slides)



802.11 receiver

if frame received OK
  return ACK after **SIFS** (ACK needed due to hidden terminal problem)

CSMA/CA: collisions happen



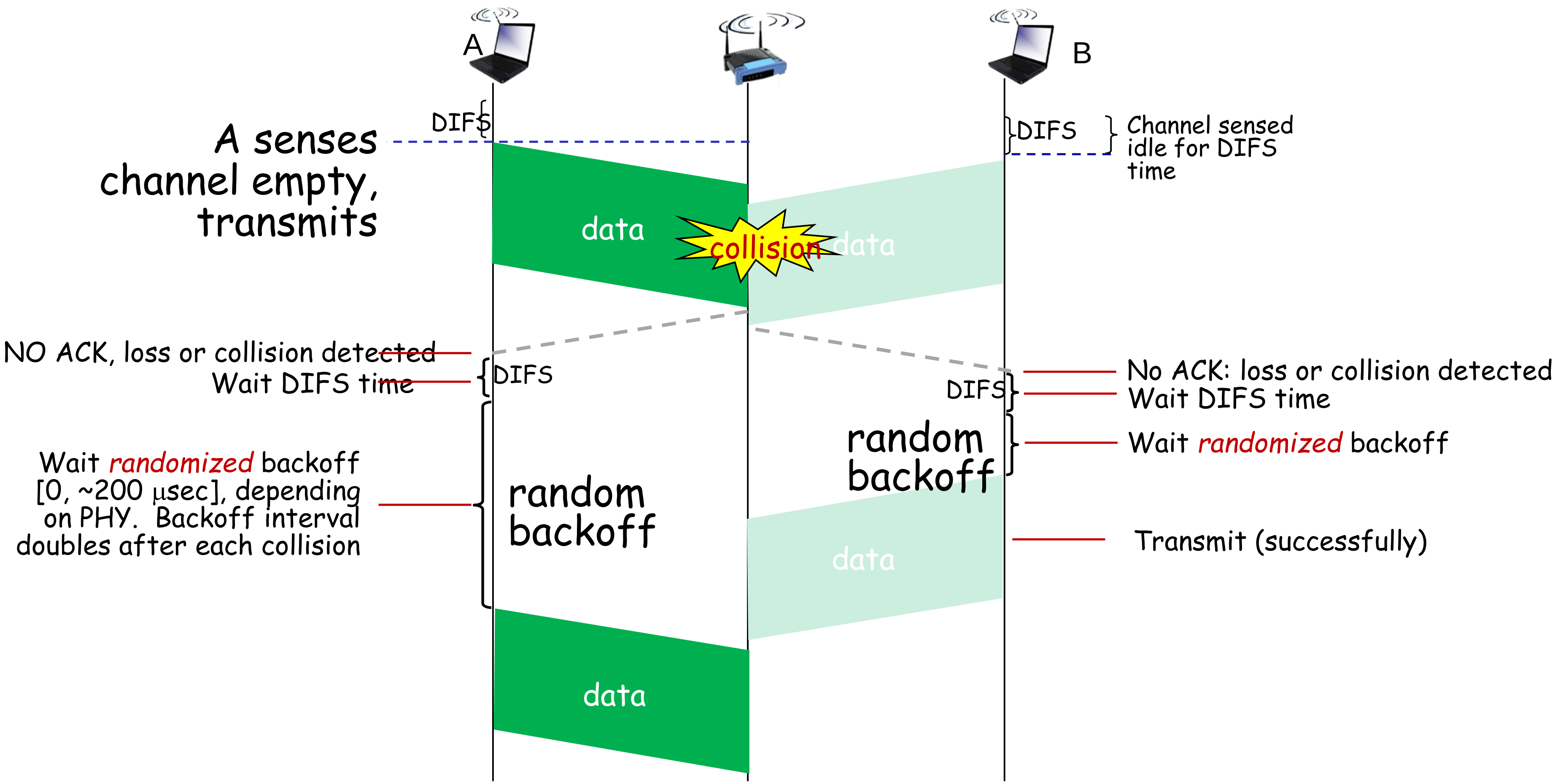
A senses channel empty, transmits

B senses channel empty (A's' transmission has not reached B yet), transmits

A senses channel empty, transmits

B senses channel empty (does not hear A's transmission due to fading), transmits

CSMA/CA: randomization after collision



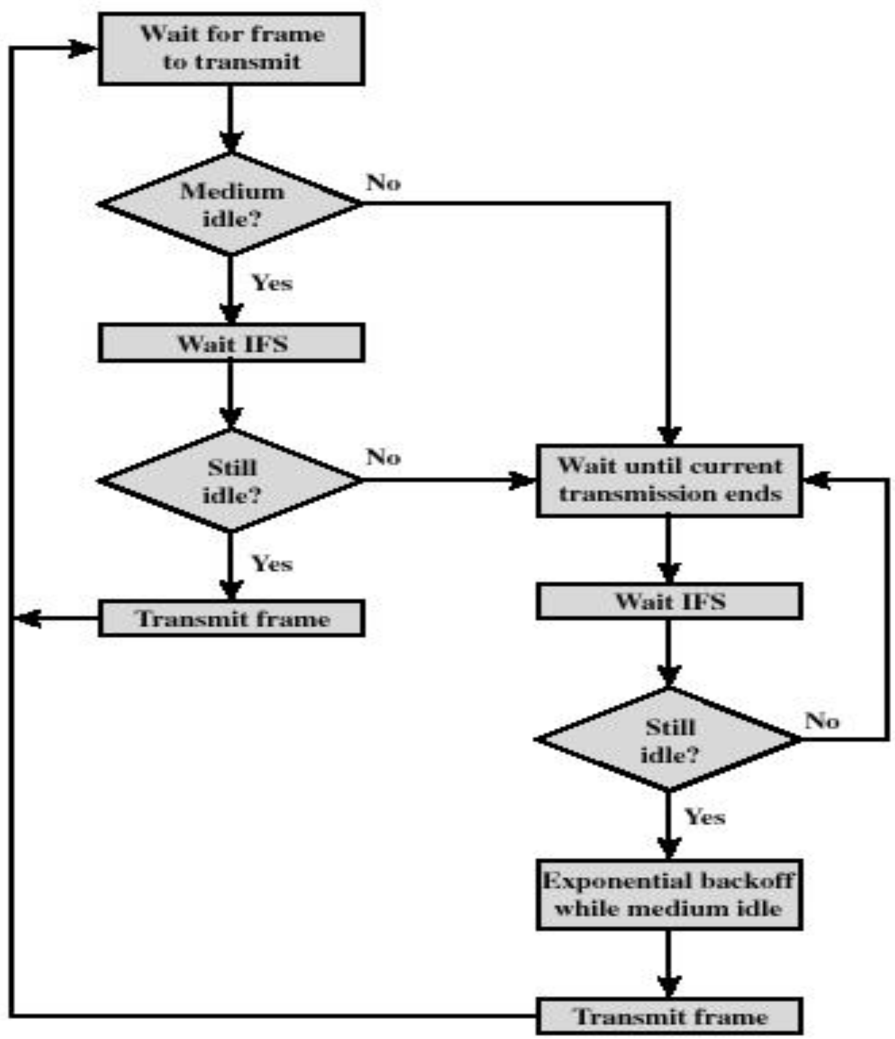
IEEE 802.11 MAC: Distributed Coordination Function (DCF)

- Make use of CSMA (carrier sense multiple access)
- Use set of delays generic called Interframe Space (IFS)

Algorithm Logic:

1. *Station sense the medium*
2. *If medium idle, wait IFS, then if still idle transmit frame*
3. *If medium busy or become busy, defer and monitor the medium until idle*
4. *Then, delay IFS and sense medium*
5. *If medium idle, exponential backoff and if then idle, station transmit*

- Binary exponential backoff -> handle heavy load



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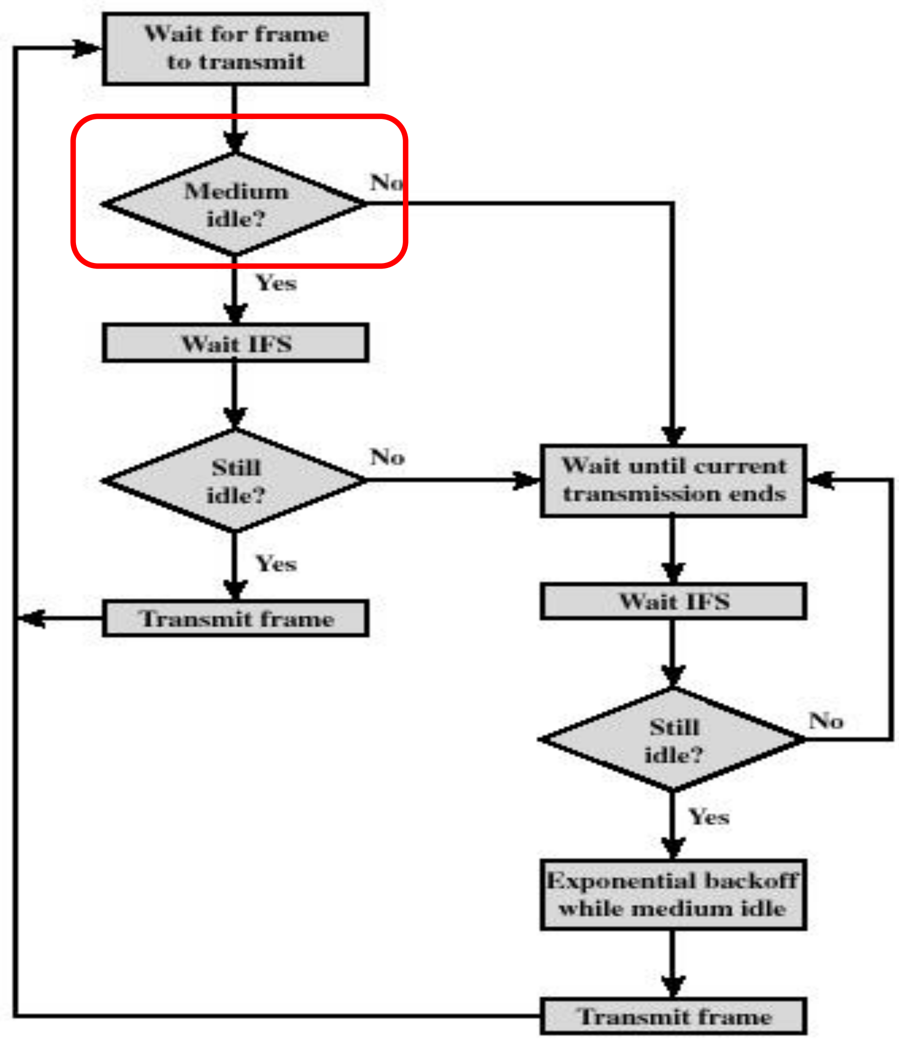

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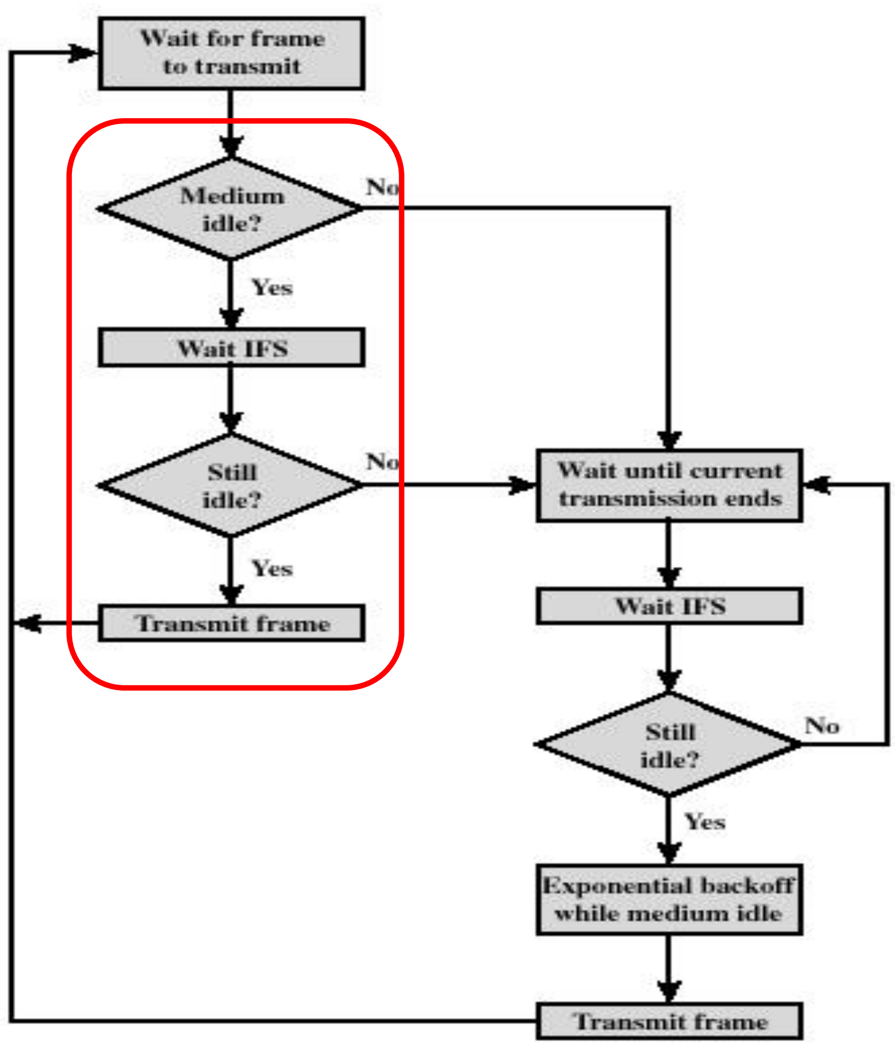

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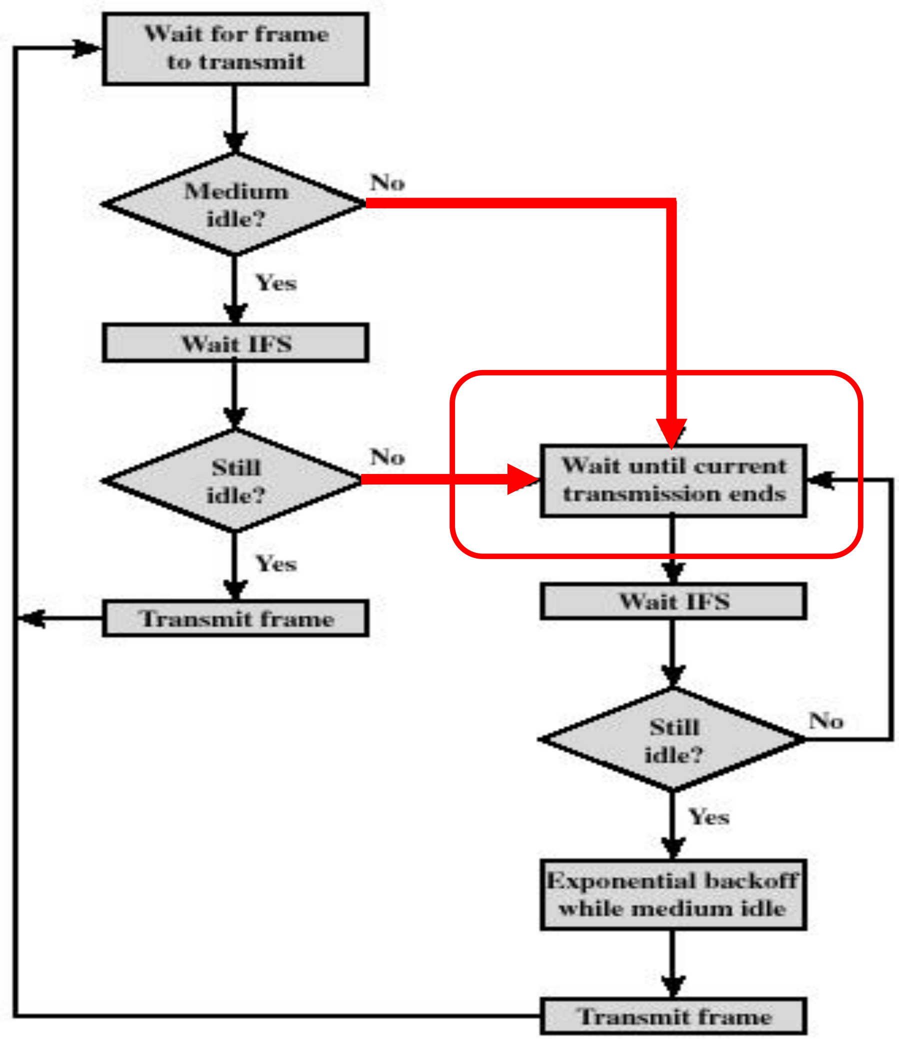

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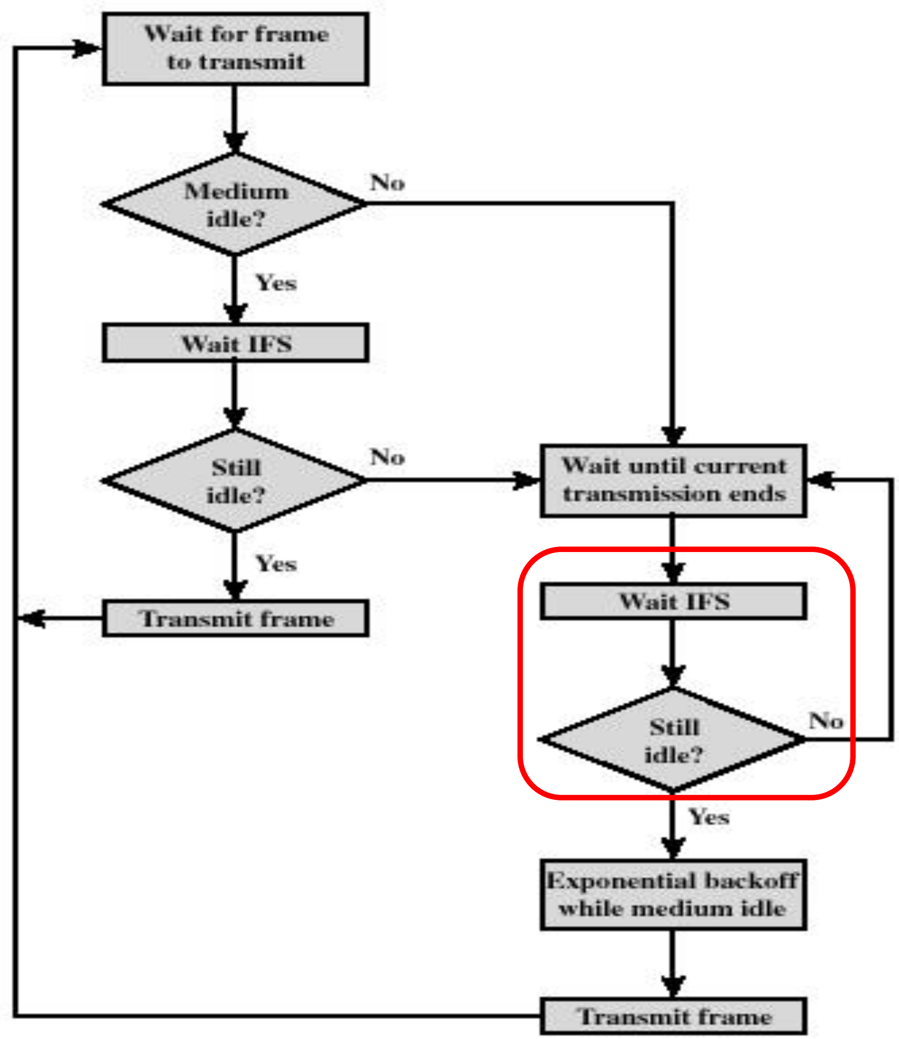

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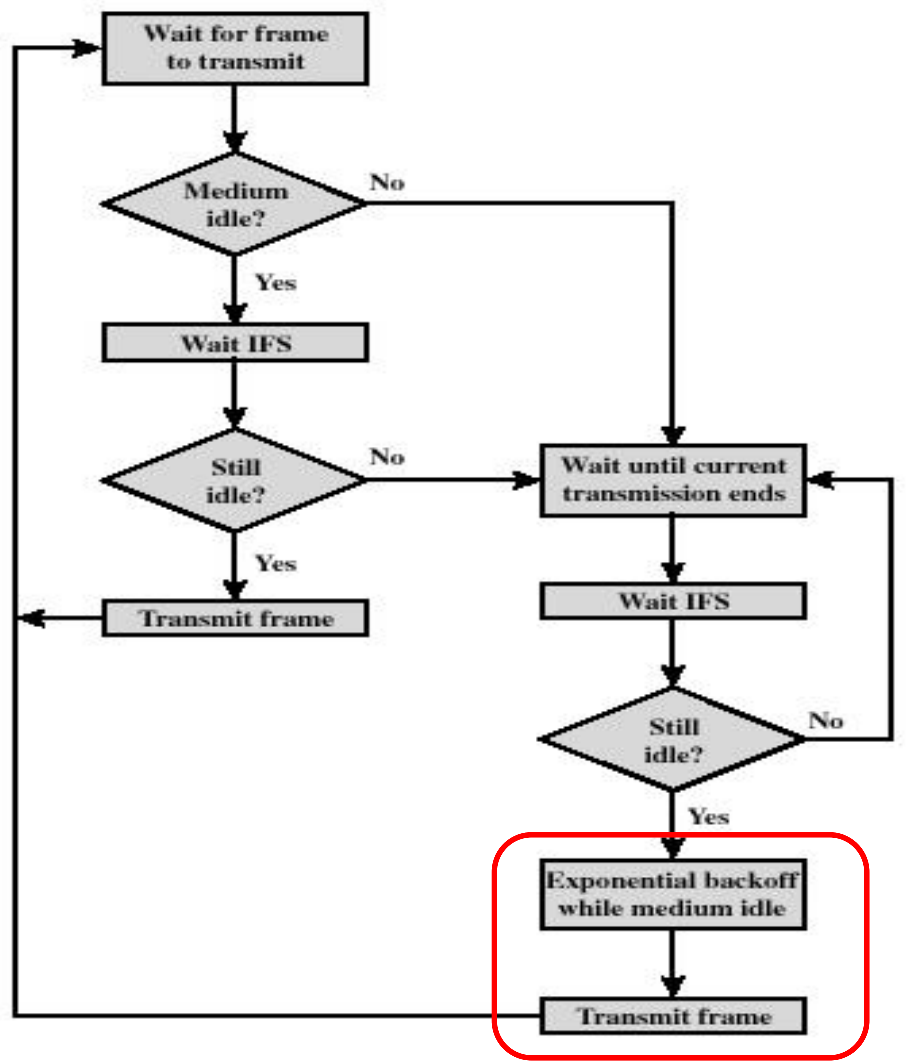


IEEE 802.11 MAC: Distributed Coordination Function (DCF)

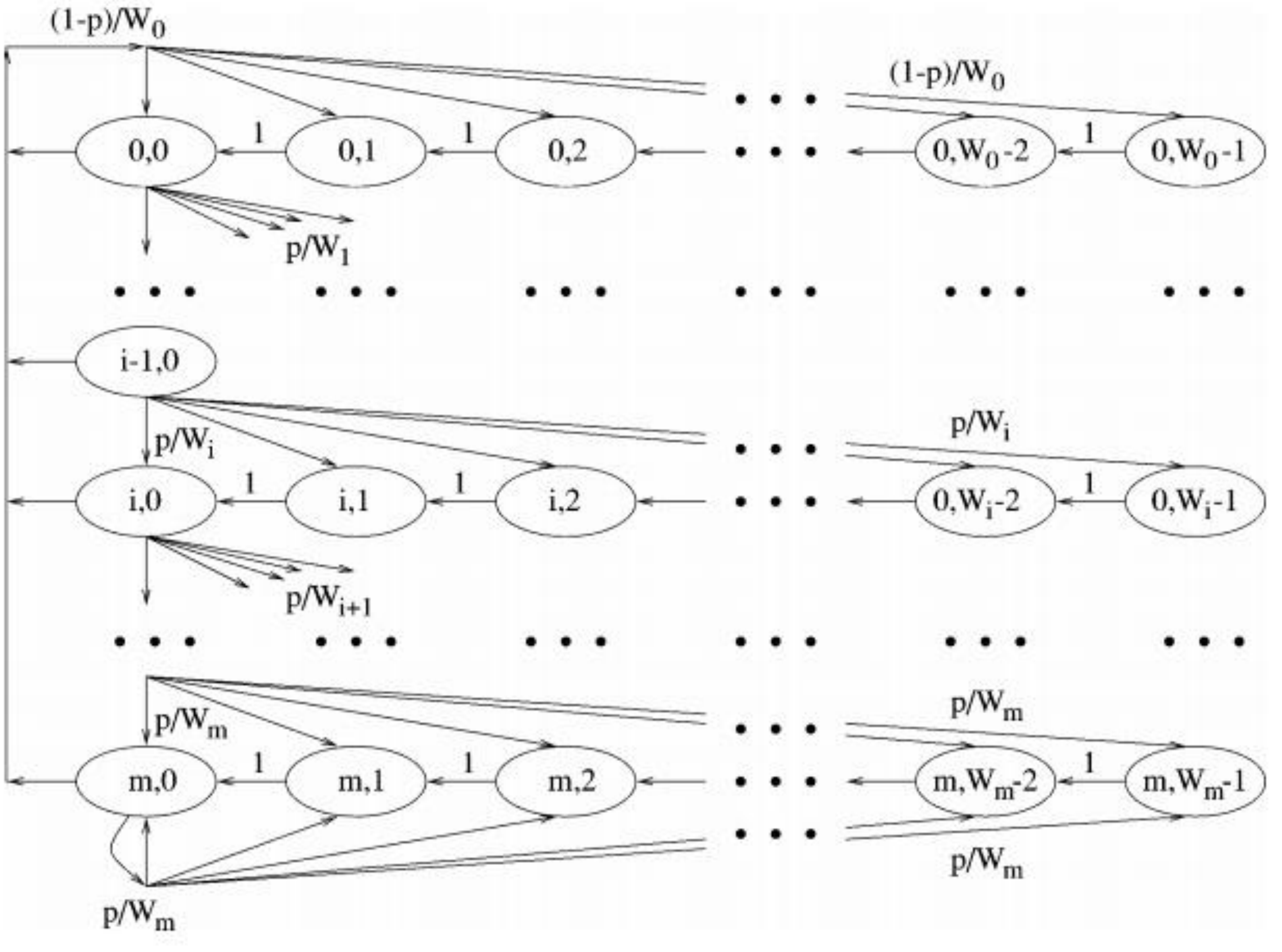


Fig. 4. Markov Chain model for the backoff window size.

G. Bianchi, **Performance analysis of the IEEE 802.11 distributed coordination function, JSAC 2000**

IEEE 802.11 MAC protocol: parameters

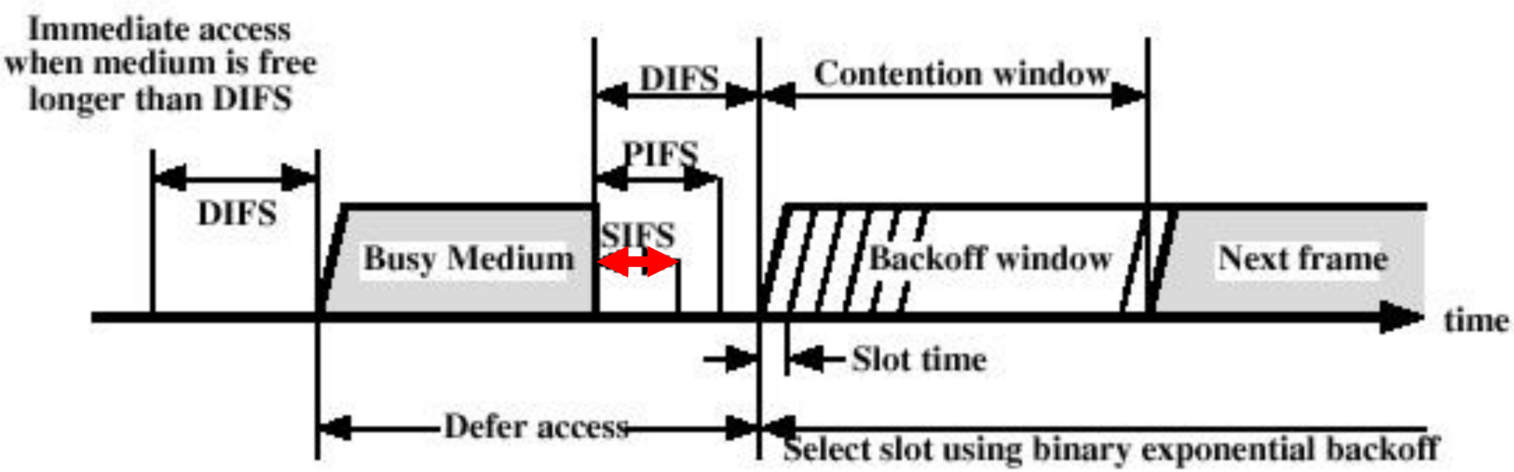
Table 2.1. IEEE 802.11 parameters

Parameter	802.11 (FHSS)	802.11 (DSSS)	802.11 (IR)	802.11b	802.11a
t_{slot}	50 μsec	20 μsec	8 μsec	20 μsec	9 μsec
SIFS	28 μsec	10 μsec	10 μsec	10 μsec	16 μsec
PIFS	SIFS $+t_{slot}$				
DIFS	SIFS$+(2 \times t_{slot})$				
Operating Frequency	2.4 GHz	2.4 GHz	850-950 nm	2.4 GHz	5 GHz
Maximum Data Rate	2 Mbps	2 Mbps	2 Mbps	11 Mbps	54 Mbps
CWmin	15	31	63	31	15
CWmax	1,023	1,023	1,023	1,023	1,023

IEEE 802.11 MAC: DCF, cont'd

Priority-based scheme - use 3 values for IFS:

- SIFS (short IFS): shortest IFS used for immediate responses such as ACK, CTS, poll response
- PIFS (point coordination function IFS): middle length IFS used for issuing polls by a centralized controller
- DIFS (distributed coordination function IFS): longest IFS used for regular asynchronous frames



IEEE 802.11 MAC: DCF, cont'd

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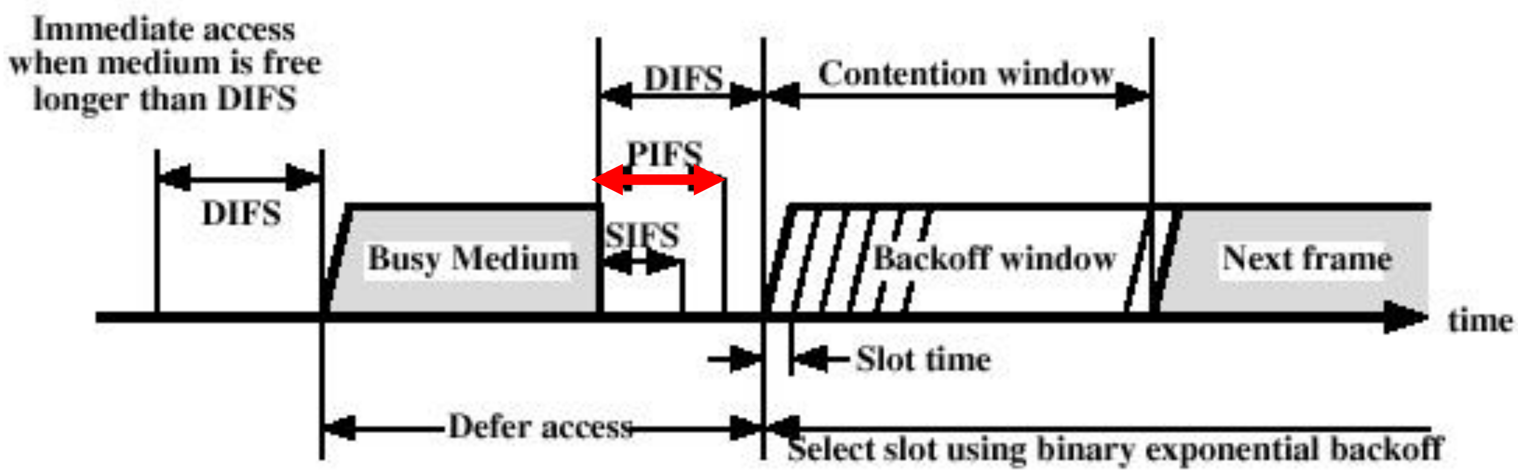

IEEE 802.11 MAC: DCF, cont'd

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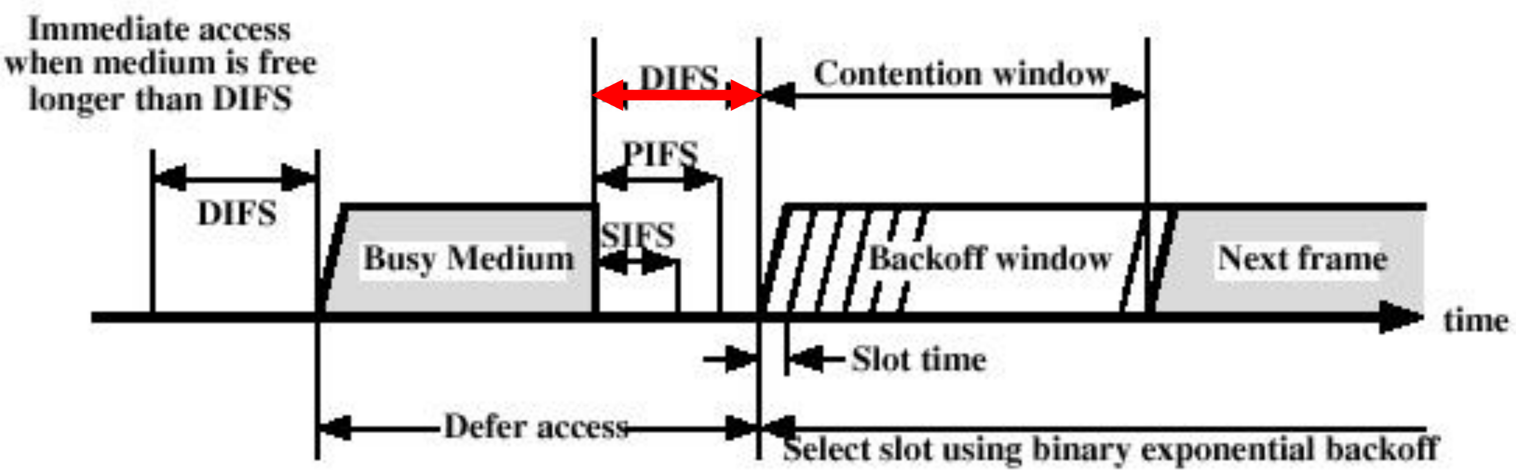
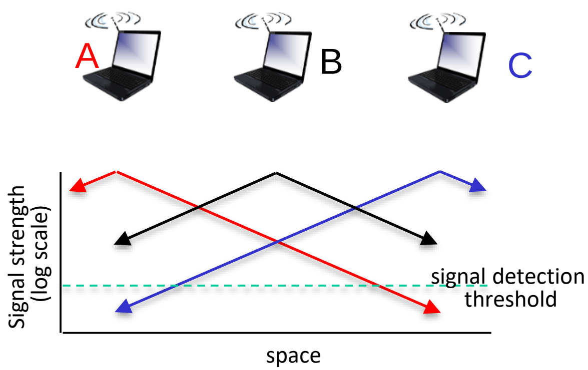


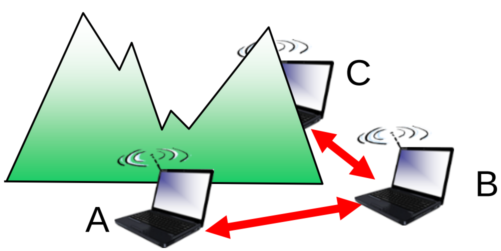
CSMA/CA: addressing the "hidden terminals" problem

Path loss causes "hidden terminals"



- B, A hear each other
- B, C hear each other
- A, C can not hear each other interfering at B

Objects cause "hidden terminals"



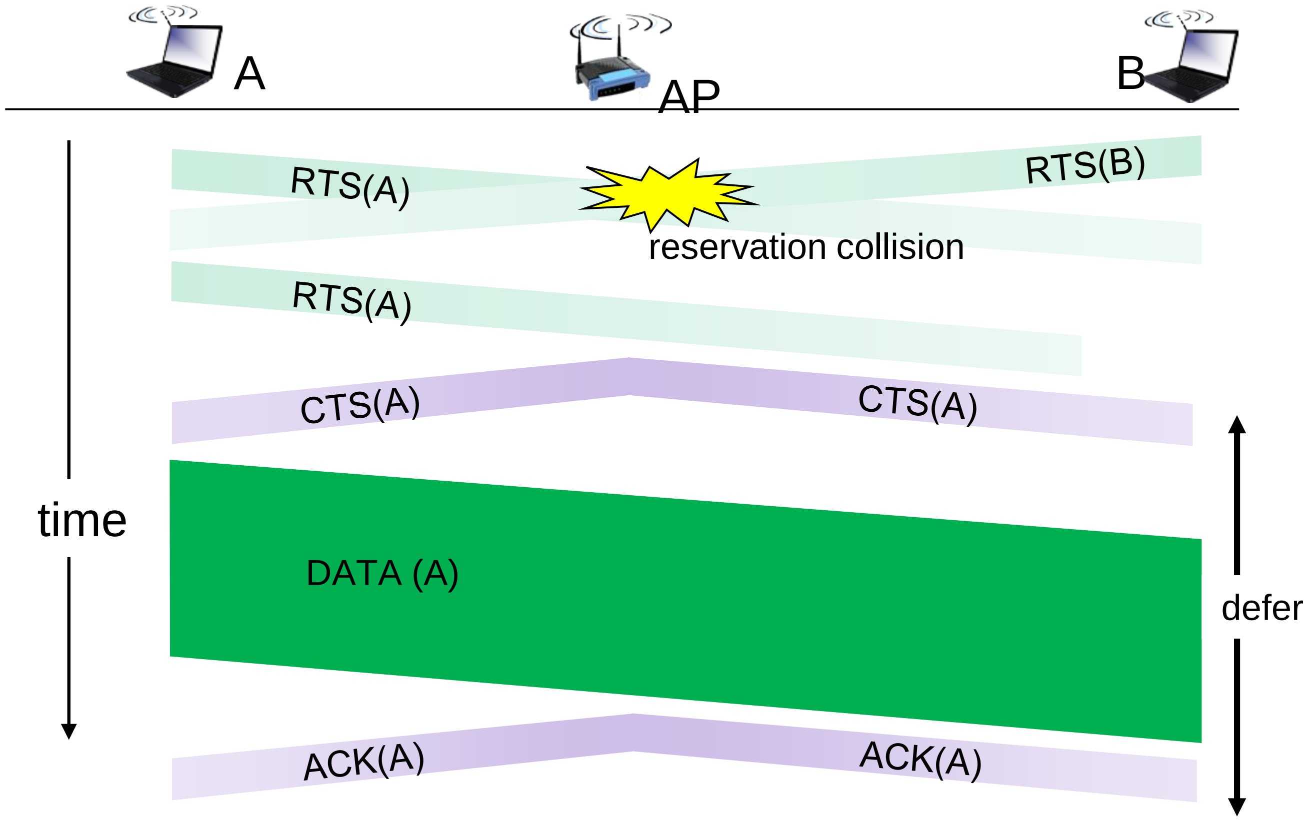
- B, A hear each other
- B, C hear each other
- A, C can not hear each other means A, C unaware of their interference at B

Avoiding collisions: using RTS/CTS

idea: sender "reserves" channel use for data frames using small reservation packets

- sender first transmits *small* request-to-send (RTS) packet to BS using CSMA
  - RTSs may still collide with each other (but they're short)
  - contains duration for following data transmission
- BS broadcasts clear-to-send (CTS) packet in response to RTS
  - contains duration for following data transmission
- RTS and/or CTS heard by all nodes
  - All nodes except transmitter defer transmissions
  - transmits data frame

Collision Avoidance: RTS-CTS exchange



Hidden Terminal Problem [2]

Problems with RTS-CTS solution:

- possible collisions between CTS and RTS
- collisions between data packets due to multiple different CTS granted to different neighboring nodes

- Also, adds delay and overhead …
  - Only beneficial used for very large packets
  - Typically, not used in practice (unless very large packets)…

802.11 frame: addressing

frame control	duration	address 1	address 2	address 3	seq control	address 4	payload	CRC
2	2	6	6	6	2	6	0 - 2312	4

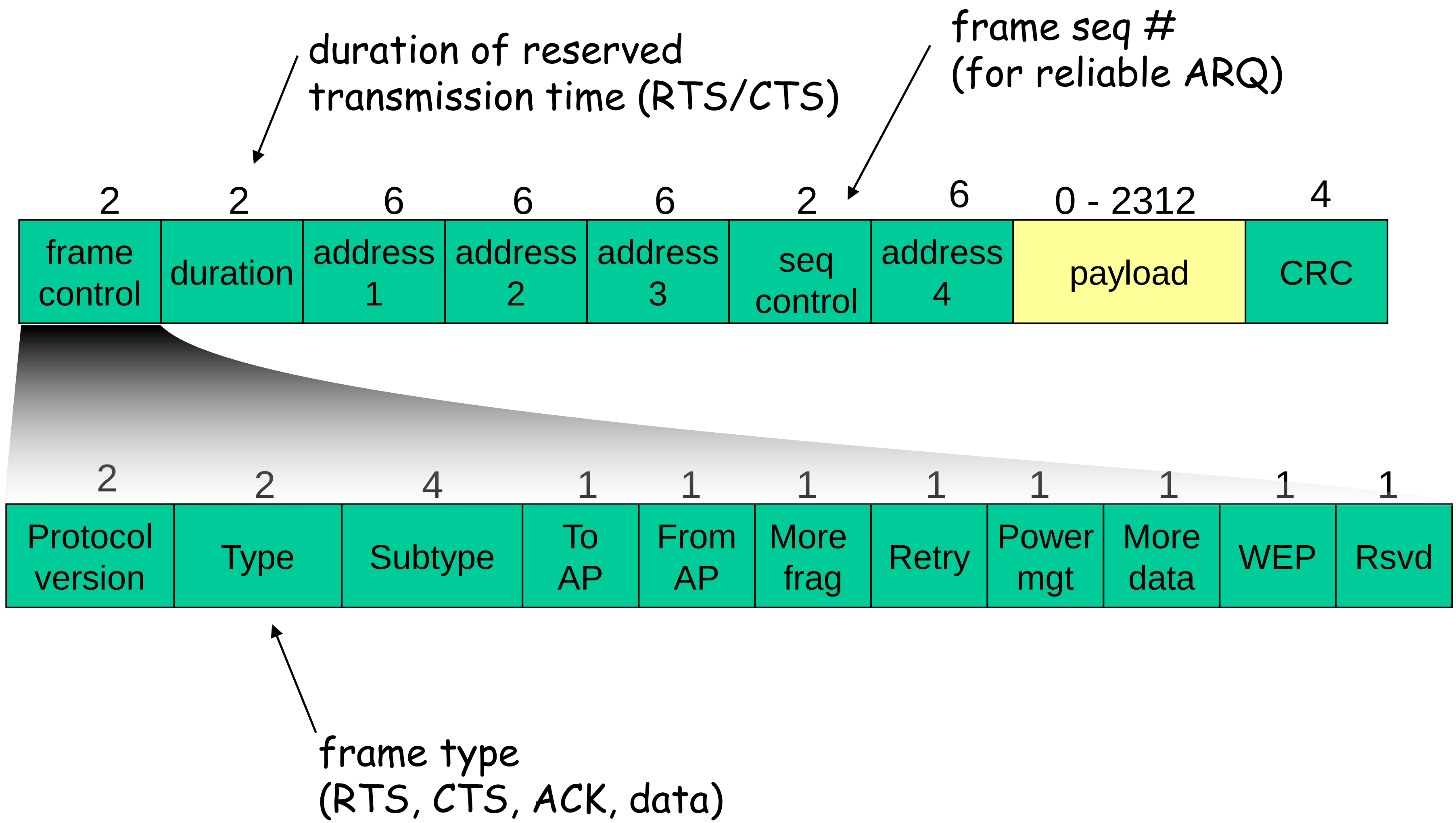
Address 1: MAC address of wireless host or AP to receive this frame

Address 2: MAC address of wireless host or AP transmitting this frame

Address 3: MAC address of router interface to which AP is attached

Address 4: used only in ad hoc mode

802.11 frame: more



More slides …

Exposed Terminal Problems

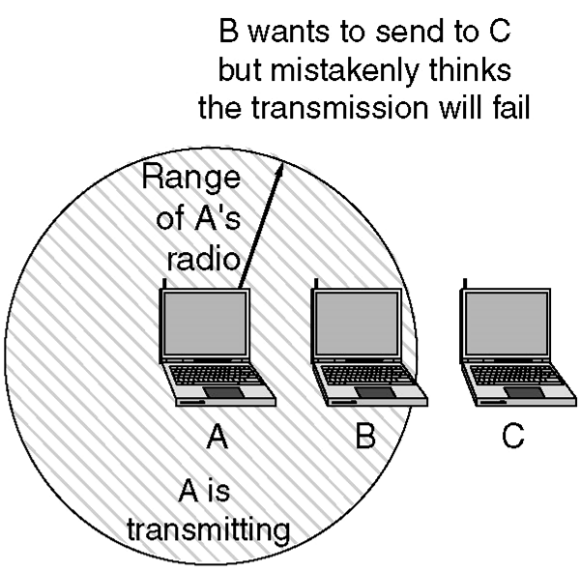
Exposed terminal problem (ad-hoc and WLAN)

- medium free near the receiver
- medium busy near the transmitter

  => *Waist of bandwidth*

Possible solutions:

- directional antennas
- separate channels for control and data



Issues, medium access schemes

- Distributed operation
- Synchronization
- Hidden terminals
- Exposed terminals
- Throughput
- Access delay
- Fairness
- Real-time traffic support
- Resource reservation
- Ability to measure resource availability
- Capability for power control
- Adaptive rate control
- Use of directional antennas

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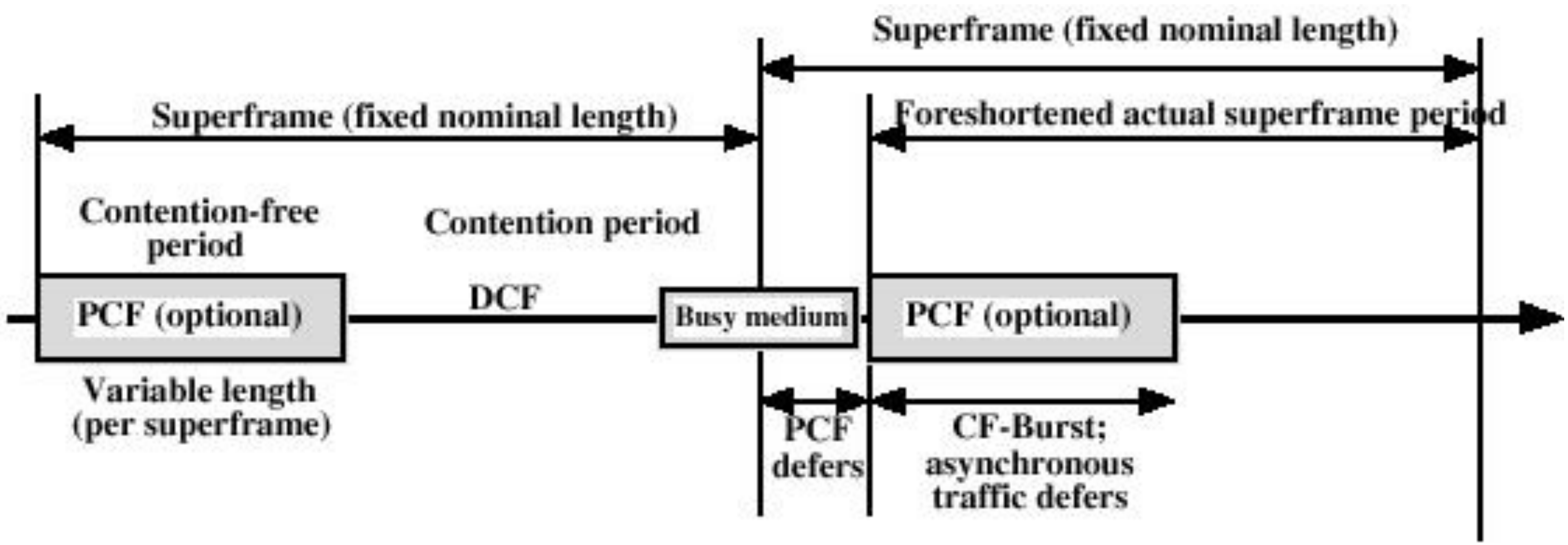
A few more words about QoS

IEEE 802.11 MAC: Point Coordination Function (PCF)

- Alternative access method on top of DCF
- Polling operation by a centralized master
- Use PIFS when issuing polls
- To avoid locking out the asynchronous traffic the superframe is used



IEEE 802.11e: Enhanced Distribution Coordination Function (EDCF)

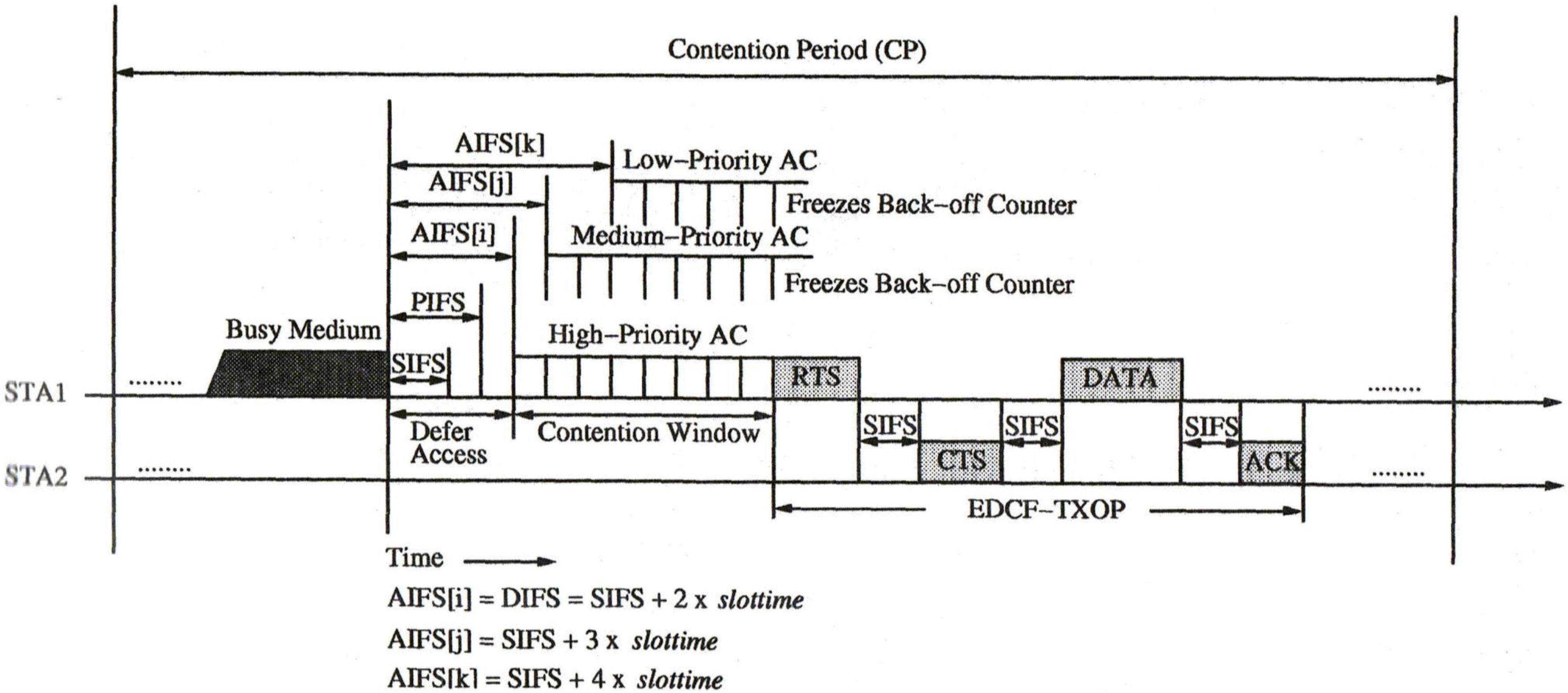


Figure 10.5. An example of EDCF access mechanism.