Wireless Medium Access Control (MAC)

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Adapted from Prof. Sunghyun Choi's slides

Medium Access Control (MAC)

- Layer 2 in the layered architecture
- Determines when (or which resource to use) to transmit a packet to the channel
  - Resource = time, frequency, code, antenna, etc.
  - Dependent on the multiple access (MA) scheme

- Provides MAC-specific framing
  - Fragmentation
  - Splitting into time/frequency slots

- Provides error control mechanism
  - How to detect the erroneous transmission
  - How to recover from the error if needed
    - ARQ, FEC, ...

Distributed vs. Centralized

- Distributed and contention-based
  - Typically, random access (see Token Passing)
  - Simple, robust to a single point failure
  - Good for bursty traffic in light load → possible lower delay

- Centralized and controlled
  - Controlled by an BS → well fit into cellular
  - More controllable → QoS support
  - Could be more efficient, esp., with many users in heavy load

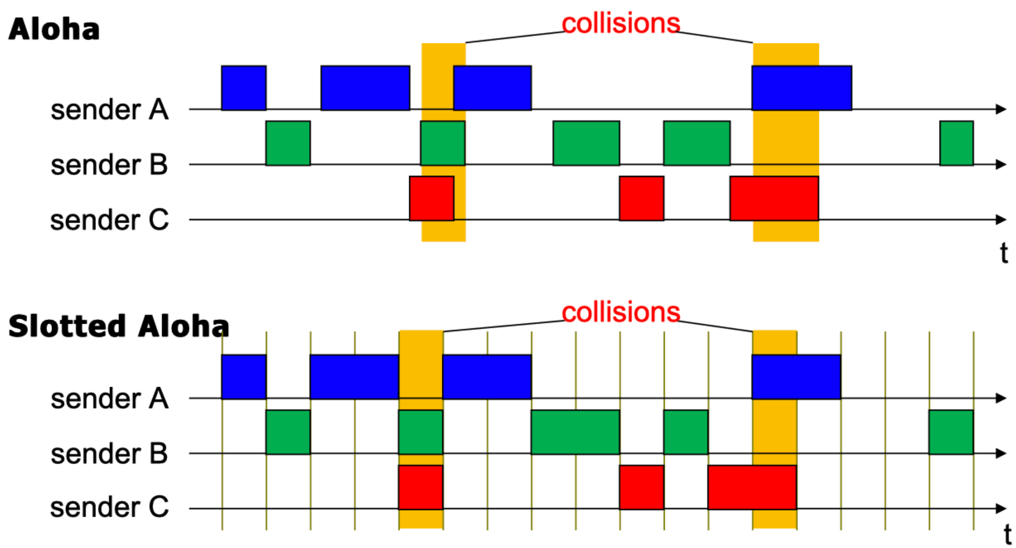
Slotted ALOHA

- Assumptions
  - all frames same size time is divided into equal size slots, time to transmit 1 frame
  - nodes start to transmit frames only at beginning of slots
  - nodes are synchronized
  - collision is detected

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

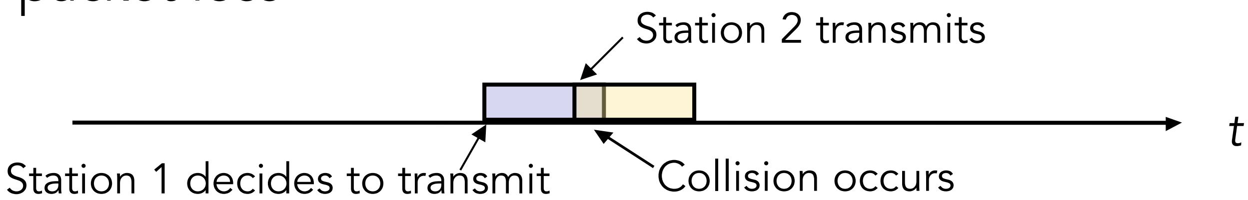
Slotted ALOHA

- Pros
  - single active node can continuously transmit at full rate of channel
  - highly decentralized
  - simple
- Cons
  - collisions, wasting slots
  - idle slots due to probabilistic retransmission



Collision

- **Collision:** Two or more users' transmissions overlap (in time) resulting in packet loss



- Recognition: Some way of recognizing that a collision has occurred and signaling users involved
  - (a) Use a central controller to recognize collisions (signal distortions) and then signal users 🡐 original Aloha
  - (b) Use a positive ACK with timeout
  - (c) Stations listen and detect their own collisions 🡐 bus architectures
- Retransmission: After a collision, attempt again after some random time has elapsed (back-off)
  - The amount of time is specified by a collision resolution protocol.

Throughput Analysis of Pure Aloha

- Assume N stations
  - Each station transmits λ (new) packets/sec
  - Arrival of (new) packets from each station is Poisson
  - Fixed packet lengths with transmission time = m

$$\text{Normalized throughput (S)} = \frac{\text{Rate of transmitting new packets}}{\text{Max. channel transmission rate}}$$

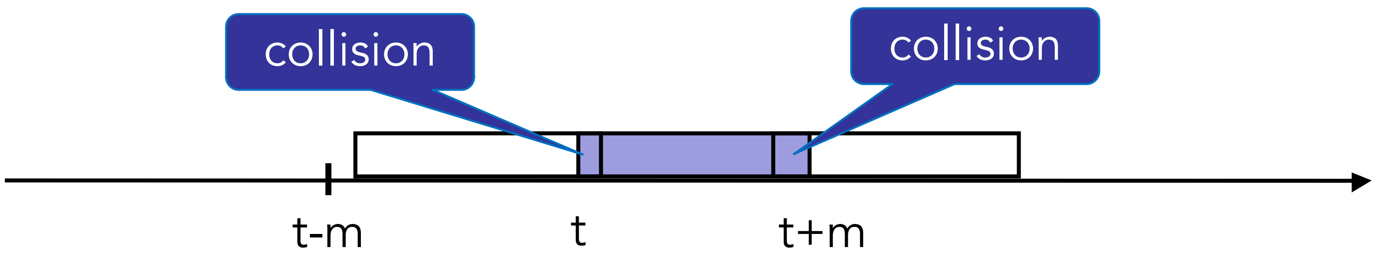
$$= \frac{N\lambda \text{ packets/sec}}{\frac{1}{m} \text{ packets/sec}}$$

$$\Rightarrow \quad S = N\lambda m$$

- Additional assumption: retransmitted packets are also Poisson distributed
  - Not true: Since retransmissions depend on collision instance
    - (Okay if random retransmission delay is long – minor impact to Poisson rate)

Throughput Analysis of Pure Aloha

- Let λ' be total rate of packets attempting transmission, then $\lambda' \geq \lambda$
- Let G be actual traffic intensity or utilization, then $G = N\lambda' m$
- Consider a typical packet transmitted at time t



  - Any transmissions by any station between times $\boldsymbol{t - m}$ and $\boldsymbol{t + m}$ will cause a collision.

Throughput Analysis of Pure Aloha

- $\Pr\{\text{Successful transmission}\}$

$$= \Pr\{\text{No arrivals in } [t-m, t+m] \mid \text{An arrival occurs at } t\}$$
$$= \Pr\{\text{No arrivals in } [t-m, t+m]\}$$
$$= \Pr\{\text{No arrivals in time interval of } 2m\}$$

- From $G = N\lambda' m$,

$$P_s = \Pr\{\text{Successful transmission}\} = e^{-2G}$$

Recall that Poisson process gives

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

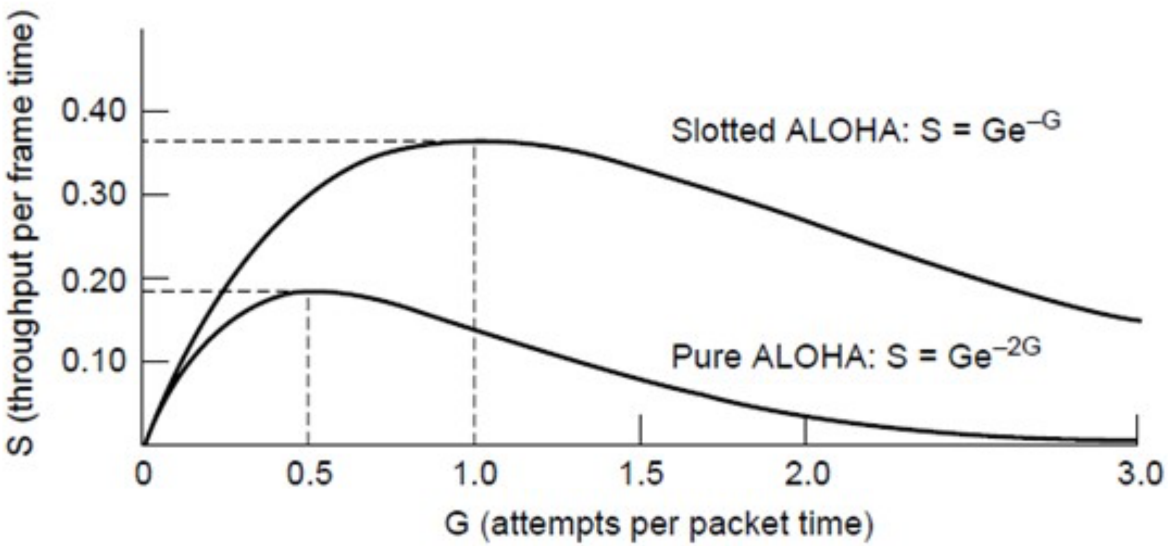
- Also, $P_s = \dfrac{\#\text{ of successfully transmitted packets}}{\#\text{ of totally transmitted packets}}$

$$= \frac{(\text{throughput with new packets})}{(\text{throughput with all packets})} \quad \begin{matrix} \longrightarrow S \\ \longrightarrow G \end{matrix}$$

- Hence, $P_s = \dfrac{S}{G}$

Throughput Analysis of Pure Aloha

- Pure Aloha throughput: $S = Ge^{-2G}$
  - *S* has the peak value $S_{max} = \frac{1}{2e}$, when $G = G^* = \frac{1}{2}$



For Aloha, the max throughput is 18% of channel capacity.

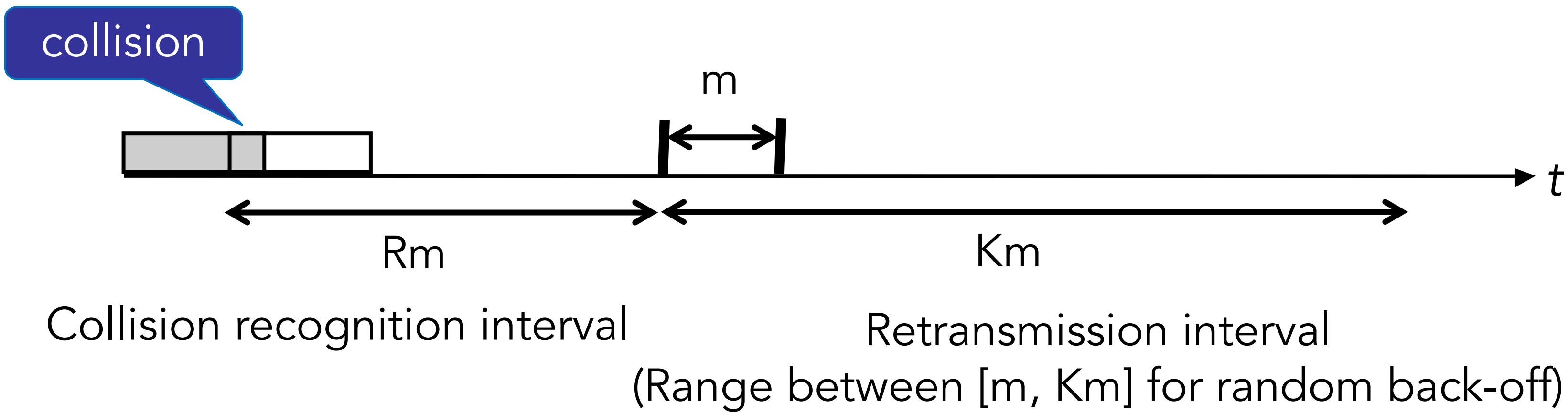
Thus it is suitable for either low traffic rate, or for highly bursty traffic

Time Delay Analysis of Pure Aloha

- Our simple throughput analysis of Pure Aloha is "independent" of the retransmission policy
  - However, for time delay analysis, we need to specify the retransmission policy

- Retransmission Policy:
  - Suppose that each message lengths is of ***m*** seconds
  - If a collision occurs, we choose an arbitrary time interval, whose length is equivalent to ***K***-message unit times ($K \cdot m$)
  - Retransmission randomly occurs in the interval, i.e., following the uniform distribution

Time Delay Analysis of Pure Aloha



- Collision cognition interval:
  - Retransmission will take place, only after the sender noticed that a collision has occurred
  - Let the round-trip delay plus processing time required to obtain the collision information be R intervals (times m)

Time Delay Analysis of Pure Aloha

- Let *D* be average time for a successful transmission

$$D = m + Rm + E\left(Rm + \frac{K+1}{2}m\right)$$

Average delay of random back-off (∈[m, Km])

where m is message transmission time

Rm is recognition time

  - Note that E is expected number of retransmissions

$$1 + E = \frac{\text{avg. \# of attempted transmissions}}{\text{avg. \# of successful transmissions}} = \frac{G}{S}$$

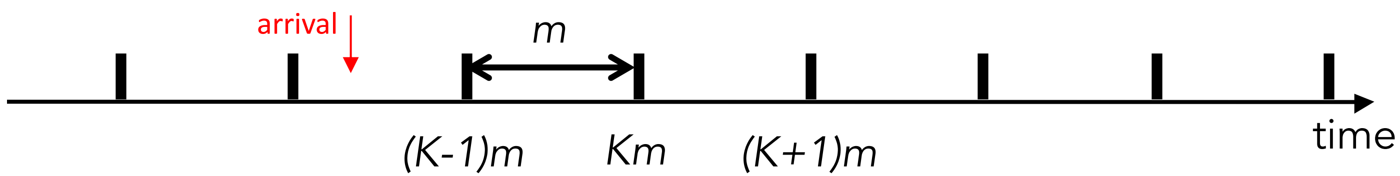
$S = Ge^{-2G}$

- Hence,

$$D = m + Rm + (e^{2G} - 1) \cdot \left(Rm + \frac{K+1}{2}m\right)$$

Slotted Aloha

- Time is slotted into units of message transmission times
  - Messages can only be transmitted <u>at beginning of time slot</u>
  - Collision occurs if another message is transmitted at the same time slot (This message arrives during ((*K*-1)*m*, *Km*))



- Following the same line of analysis as Pure Aloha,

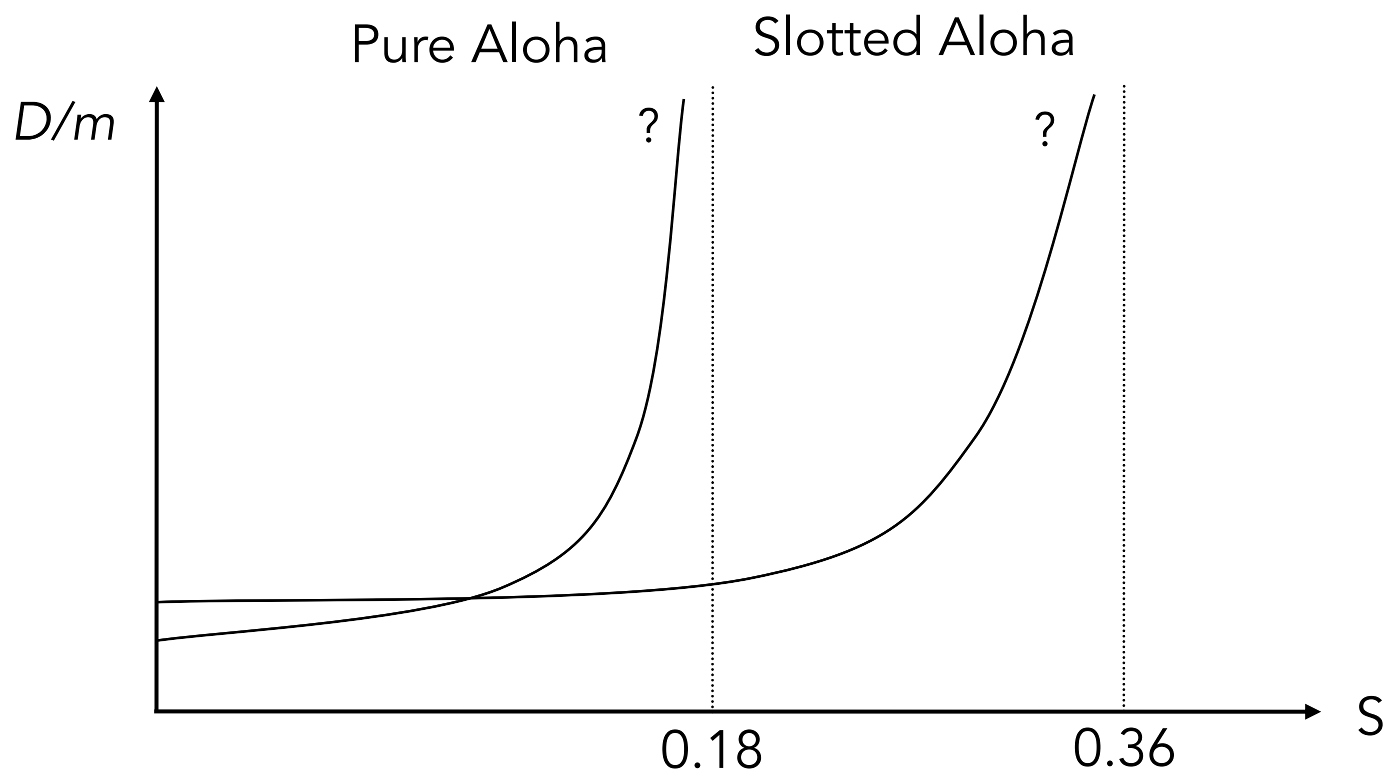
$$\Pr\{\text{Success}\} = e^{-G}, \quad S = Ge^{-G}$$

$$D = 1.5m + Rm + (e^G - 1)\cdot\left(Rm + 0.5m + \frac{K+1}{2}m\right)$$

Try to get this result by yourself

Performance Comparison

- Throughput-delay curve



Comments

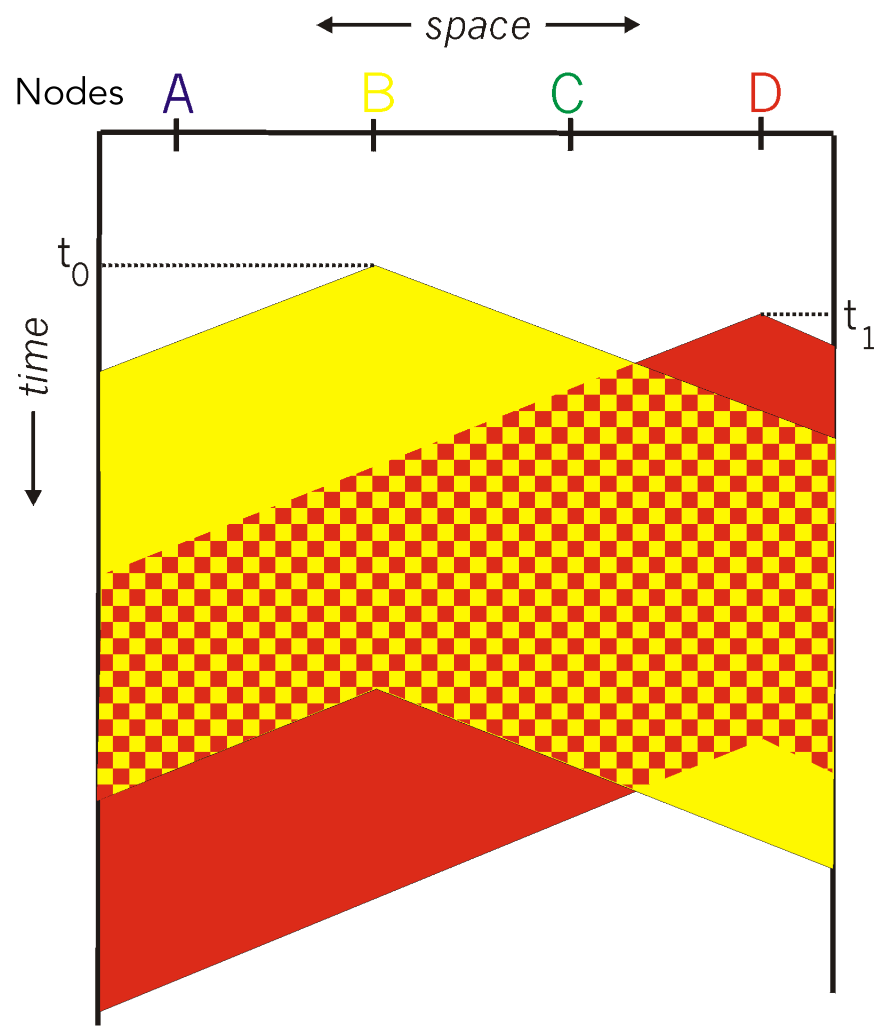
- Slotted ALOHA is often used as part of TDMA and CDMA for random access channel
  - To associate with the BS
  - To send a short message
- For pure distributed wireless systems, more efficient random access schemes are used as follows

CSMA (Carrier Sense Multiple Access)

- Listen before transmit:
- If channel sensed idle: transmit entire frame
- If channel sensed busy, defer transmission
- Human analogy: don't interrupt others!

CSMA collisions

- Collisions can still occur:
  - propagation delay means two nodes may not hear each other's transmission
- collision:
  - entire packet transmission time wasted
- note:
  - role of distance & propagation delay in determining collision probability



CSMA/CD (Collision Detection)

- Carrier sensing, deferral as in CSMA
  - Collisions detected within short time
  - Colliding transmissions aborted, reducing channel wastage

- Collision detection:
  - Easy in wired LANs: measure signal strengths, compare transmitted, received signals
    - Used in the popular Ethernet
  - Rather impossible in wireless LANs:
    - receiver shut off while transmitting
    - even if not, impossible due to high path loss

CSMA/CD

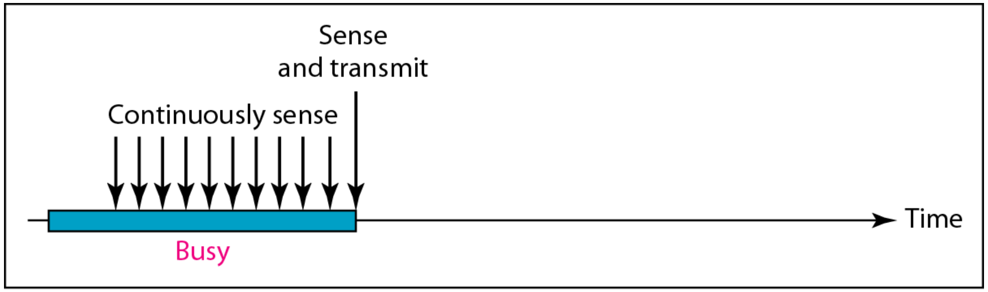
- After a collision is detected
  - Current packet transmission is aborted
  - A retransmission attempt is made at a random time, uniformly chosen within a given time interval (similar to Aloha)
  - Each time a collision occurs (for the same packet), this time interval is "doubled" (up to a maximum value) thereby reducing chance of collisions
  - Known as binary exponential backoff.

CSMA/CD

- In case that the channel is busy
  - There are variants based on what to do when the channel is sensed busy
  - 1-persistent: Attempt transmission as soon as channel is sensed idle (Ethernet)
  - p-persistent: Attempt transmission with probability *p* once channel goes idle. With probability (1-*p*), wait for a propagation delay interval τ and try again!
  - Non-persistent: Reschedule after a random waiting time, sense channel and if idle, transmit, if busy, repeat.

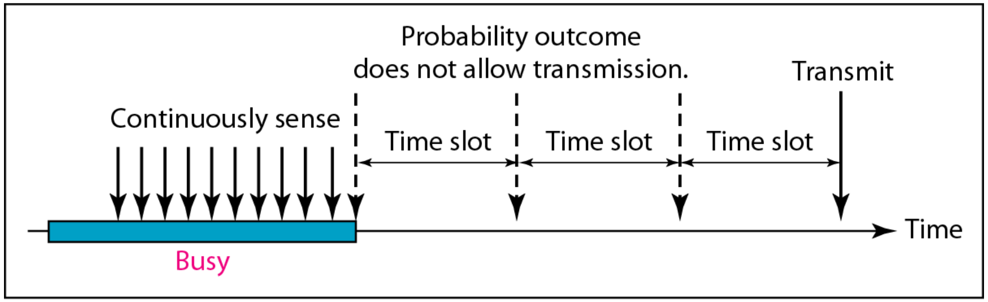
CSMA/CD

1-persistent



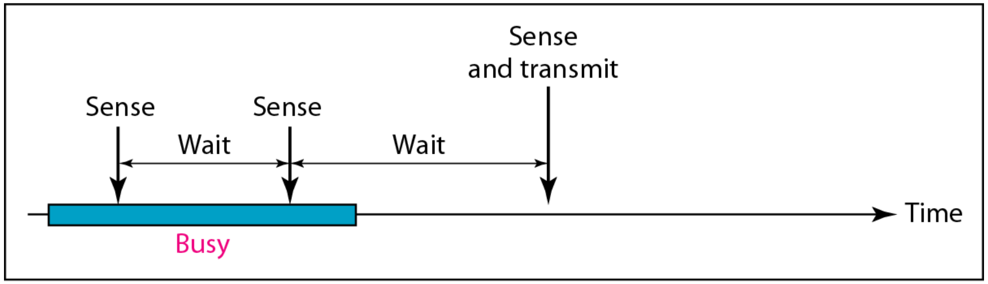
a. 1-persistent

p-persistent



c. p-persistent

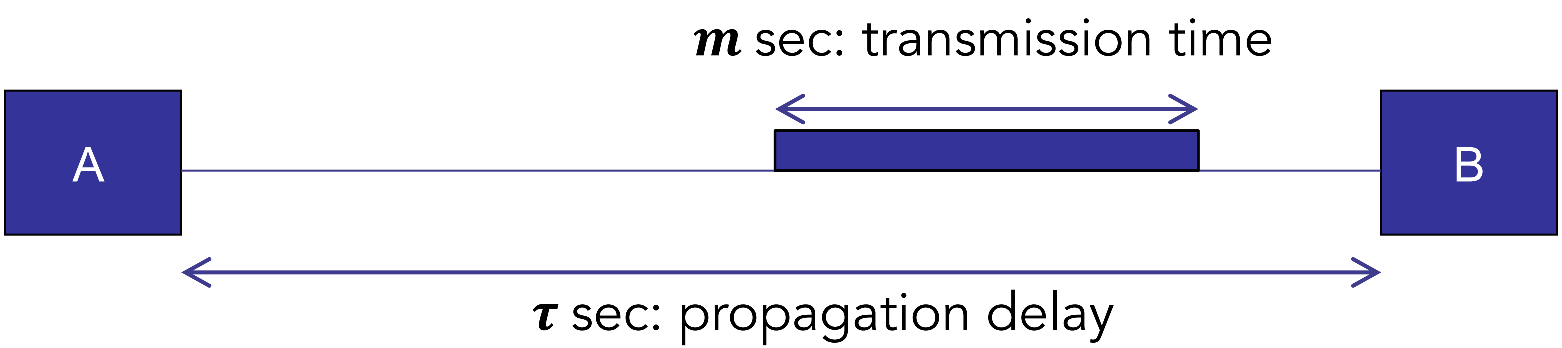
non-persistent



b. Nonpersistent

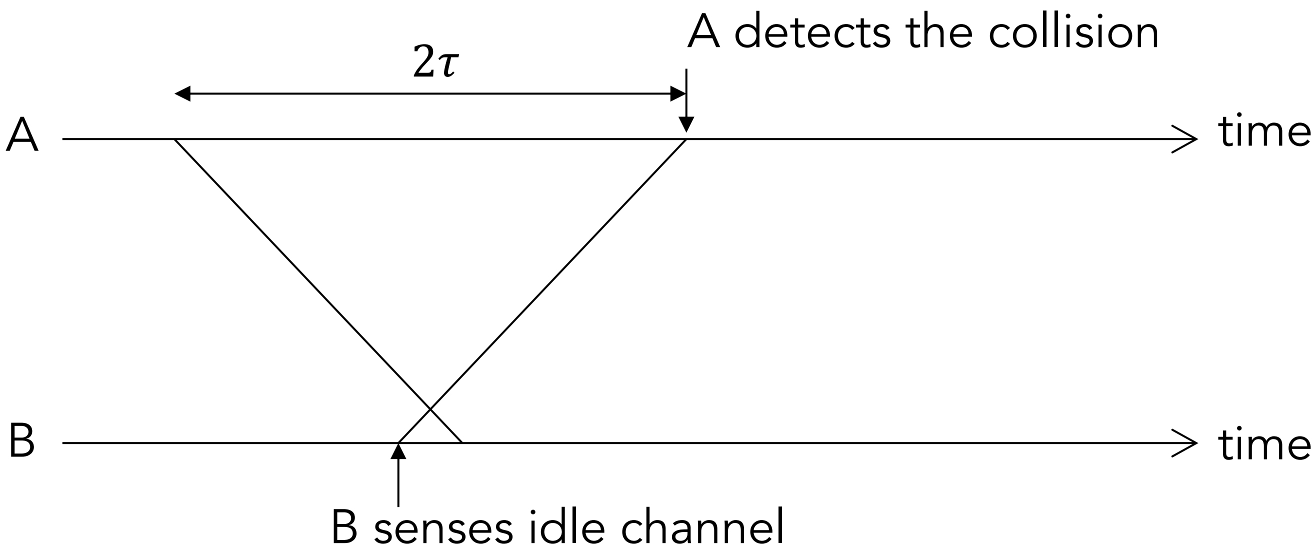
CSMA/CD

- All carrier sense protocols rely on stations being able to
  - Sense that a transmission has ended, soon after its completion
  - Sense that a transmission has started, soon after it begins
  - Need $\boldsymbol{a} = \boldsymbol{\tau}/\boldsymbol{m} \ll 1$ for high throughput
- Suitable for
  - Local Area Network (small $\boldsymbol{\tau}$)
  - Large Networks that are low speed (large **m**)



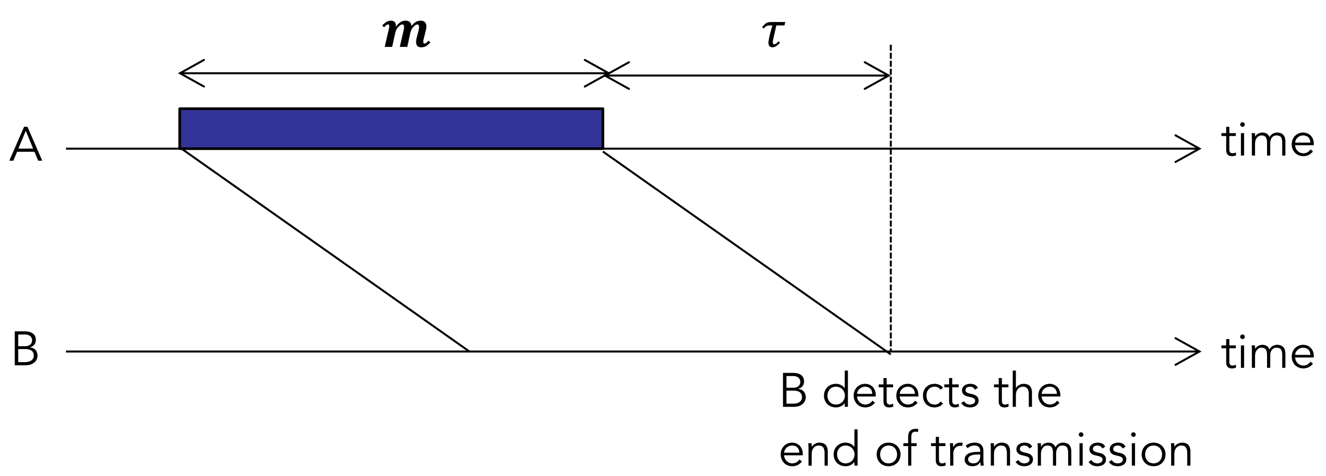
Maximum Throughput of CSMA/CD

- Collision
  - Suppose that a collision takes place between A's & B's transmission
  - In the worst case, it takes 2τ sec for A & B to detect the collision and turn off their transmissions



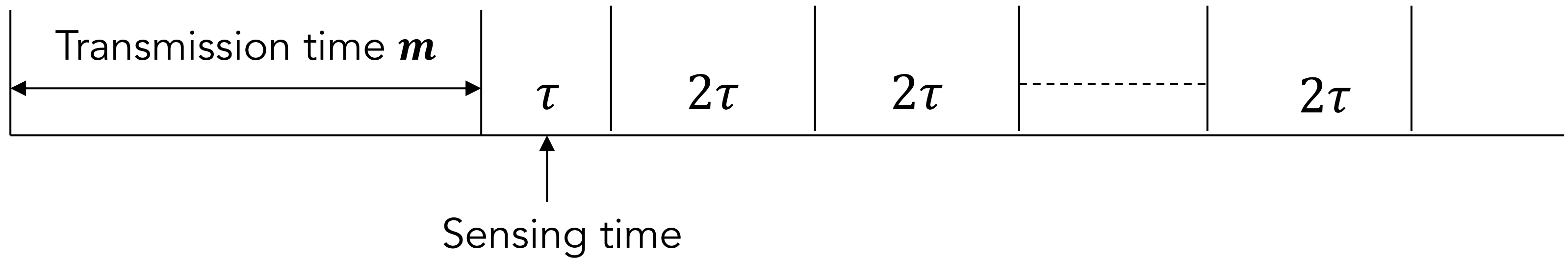
Maximum Throughput of CSMA/CD

- Sensing
  - After A finishes transmission, it takes τ seconds for B to determine that A has finished transmission (idle channel)



Maximum Throughput of CSMA/CD

- Considering intervals for both collision and sensing, we consider τ and 2τ intervals after transmission as follows:



- Let J denote the expected number of 2τ intervals before a successful transmission taking place
  - J depends on the retransmission policy, e.g., binary exponential back-off etc.

Maximum Throughput of CSMA/CD

- Worst-case calculation of transmission time t_v
  - t_v is the time interval between two successful transmissions
  - Given J collisions, it takes $2\tau J$ units of time to resolve it

$$t_v = m + \tau + 2\tau J = m(1 + a(1 + 2J)), \text{ where } a = \tau / m$$

- Use a simple model of retransmissions backed by simulation
  - Assume length of collision interval is geometrically distributed in units of 2τ, with parameter v = Pr{no collision happens}
  - Then $\Pr\{\text{collision interval} = n \cdot 2\tau\} = v(1-v)^{n-1}$

$$J = \sum_{k=1}^{\infty} kv(1-v)^{k-1} = \frac{1}{v}$$

  - So we focus on finding v.

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Maximum Throughput of CSMA/CD

- Assume *n* stations are involved
  - Each station attempts to transmit in a 2τ interval with probability p, independent of others
  - $p = \Pr\{\text{A station wants to transmits in a } 2\tau \text{ interval}\}$

    $$\begin{aligned} v &= \Pr\{\text{no collisions happening}\} \\ &= \Pr\{\text{exactly one station transmits}\} \\ &= np(1-p)^{n-1} \end{aligned}$$

  - $p = \frac{1}{n}$ will maximize v and provides the greatest chances of success

    → maximized v → smallest J

    → max (worst-case) throughput.

Maximum Throughput of CSMA/CD

- Now, by setting $p = \frac{1}{n}$, we obtain that

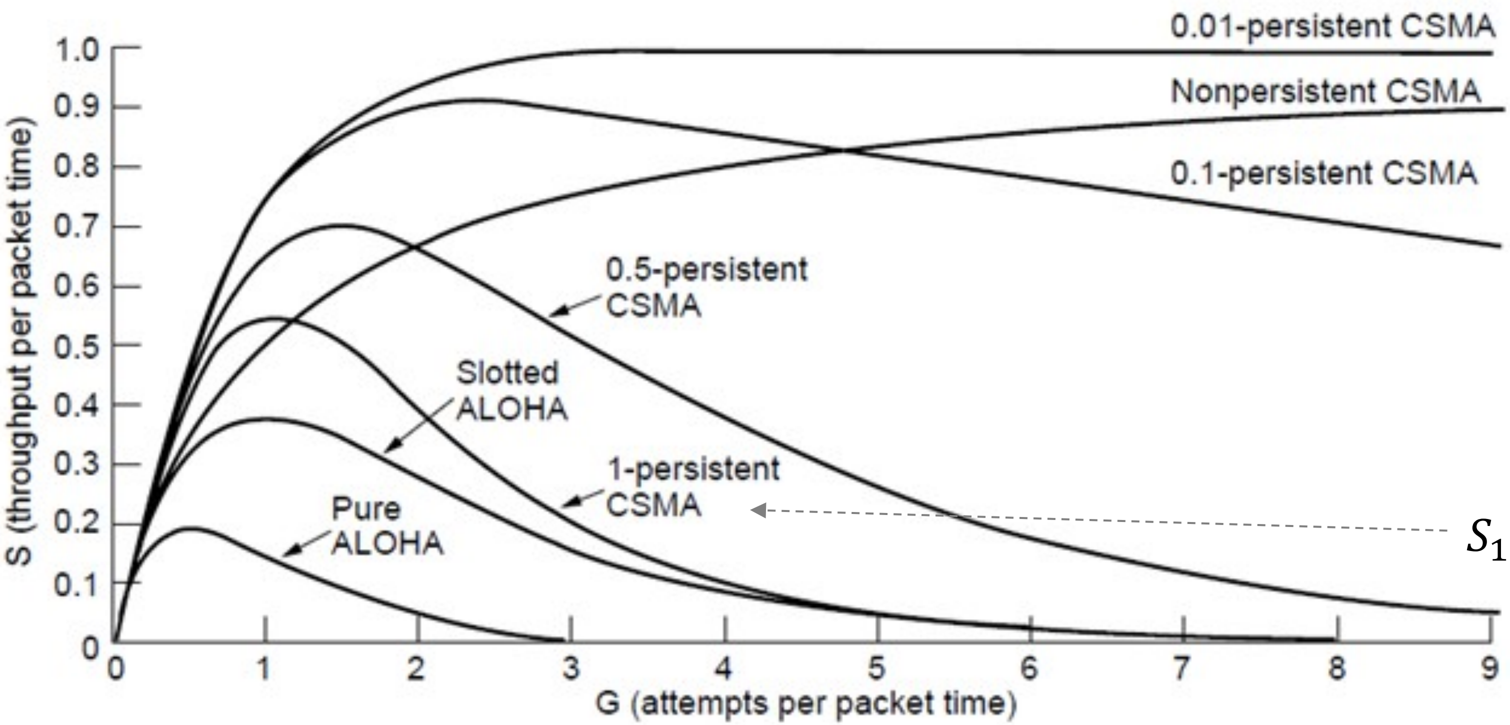
$$v_{\max} = \left(1 - \frac{1}{n}\right)^{n-1} \to e^{-1}, \text{ as } n \to \infty$$

$$t_v = m(1 + a(1 + 2J)) = m(1 + a(1 + 2e))$$

$$\text{max throughput } \lambda_{\max} = \frac{1}{t_v} = \frac{1}{m(1 + a(1 + 2e))}$$

- Let link utilization be $\rho = m\lambda_{\max}$
  - Recall $a = \tau/m$: transmission time (m) must be much larger than the propagation delay (τ) for system to work well
  - If $a = 0.1$, then $\rho < 0.6$
  - If $a = 0.01$, then $\rho < 0.94$

Throughput Comparison



$$S_{\text{non}} = \frac{G}{1+G}$$

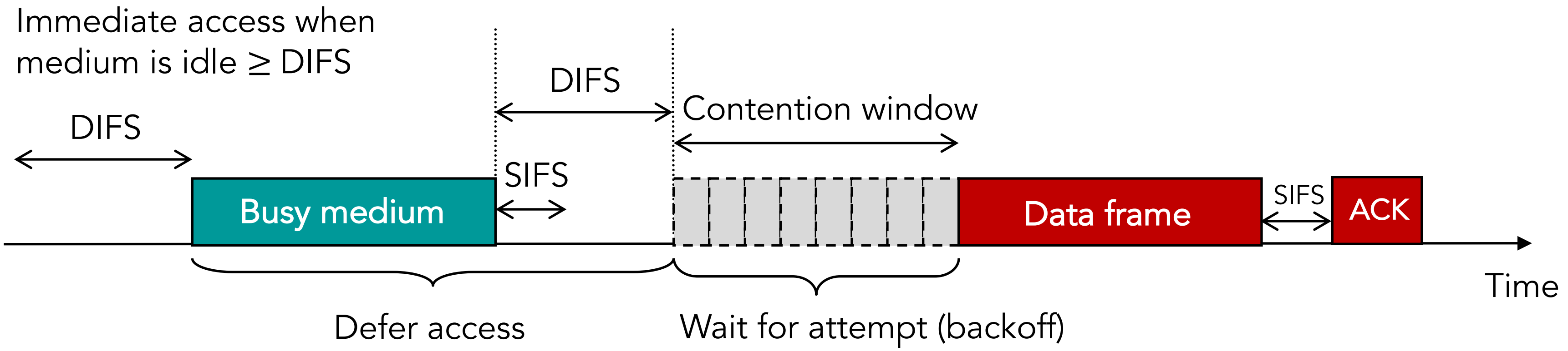
$$S_1 = \frac{Ge^{-G}(1+G)}{G+e^{-G}}$$

Does this graph mean that 0.01-persistent outperforms others? If not, why? Reading this graph correctly is important!

L. Kleinrock and F. Tobagi, "Packet Switching in Radio Channels: Part I - Carrier Sense Multiple-Access Modes and Their Throughput-Delay Characteristics," in *IEEE Transactions on Communications*, vol. 23, no. 12, pp. 1400-1416, December 1975.

CSMA/CA (Collision Avoidance)

- Used in IEEE 802.11 mandatory MAC
- Transmit after a backoff even if an idle channel is detected
- Interframe spacing (in 802.11)
  - Short IFS (SIFS): Typically to complete exchange in progress
    - i.e., between data frame and ACK
  - DCF IFS (DIFS): Time to detect idle medium

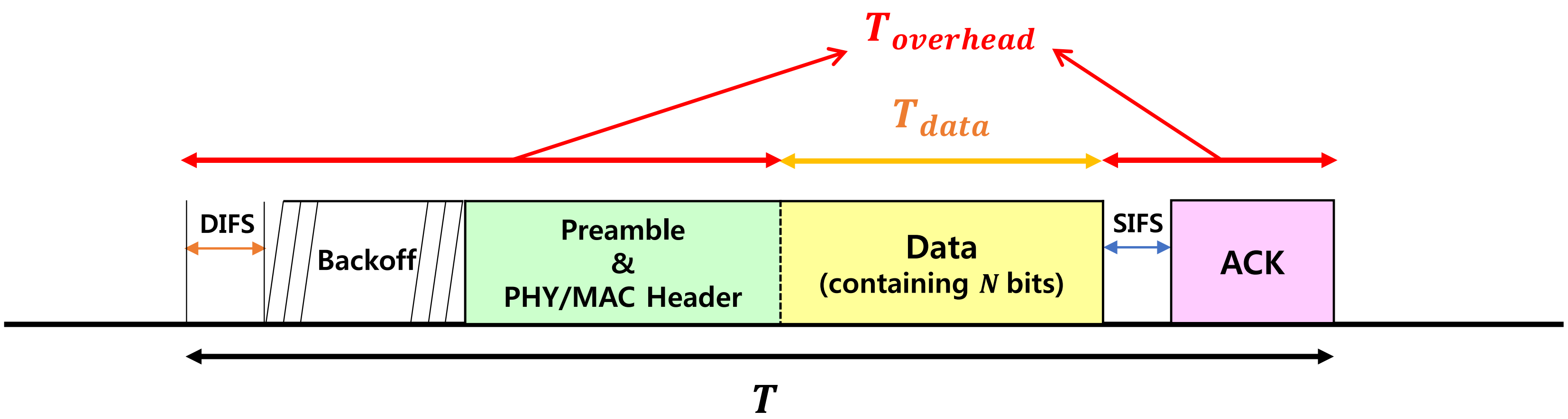


CSMA/CA Throughput

- Average throughput with a single transmitter

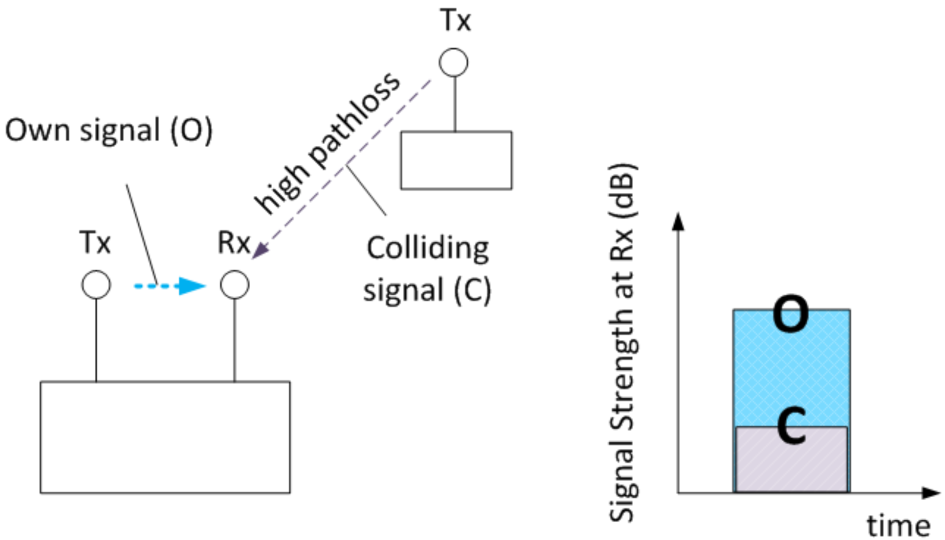
$$Th(\text{bits/sec}) = \frac{N}{T} = \frac{N}{T_{\text{data}} + T_{\text{overhead}}} = \frac{N}{(N/\text{PHY\_rate}) + T_{\text{overhead}}}$$
$$= \frac{1}{(1/\text{PHY\_rate}) + (T_{\text{overhead}}/N)}$$

- Protocol overhead for a single transmission is independent of frame length
- Even with extremely high PHY rate, throughput is bounded by (N/T_{overhead})
- As N becomes larger, throughput can approach the PHY rate



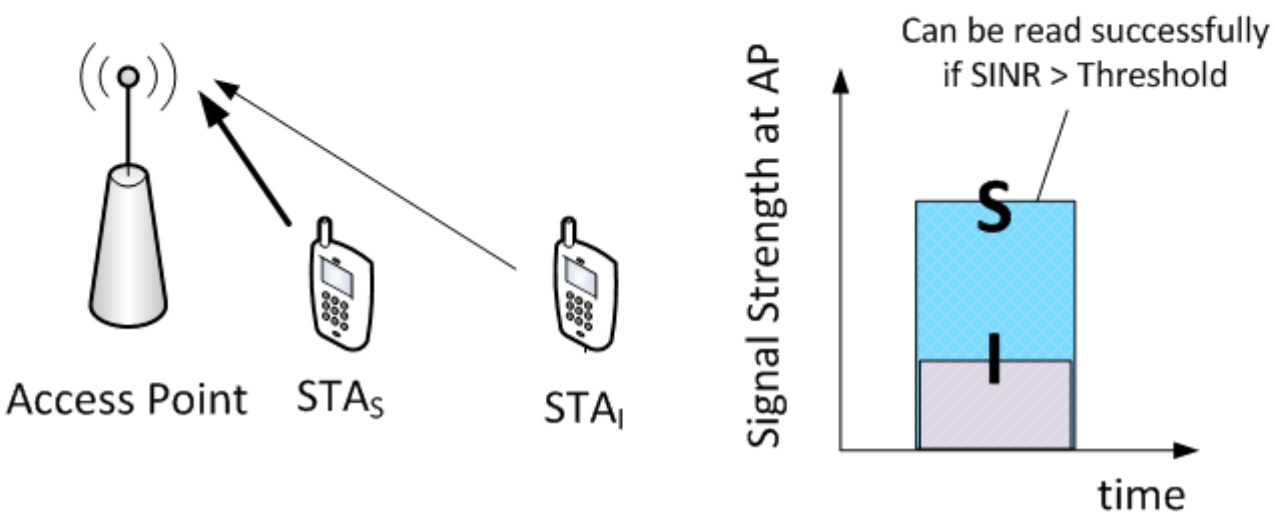
Collision Detection Impossible in Wireless?

- With a single radio, Tx and Rx cannot occur simultaneously
- Even with two radios, compared with its own signal, strength of the received signal from another station is typically much smaller
  - Collision does not make much difference
    - $P_O \approx P_O + P_C$
  - cf. CD is possible with Full Duplex



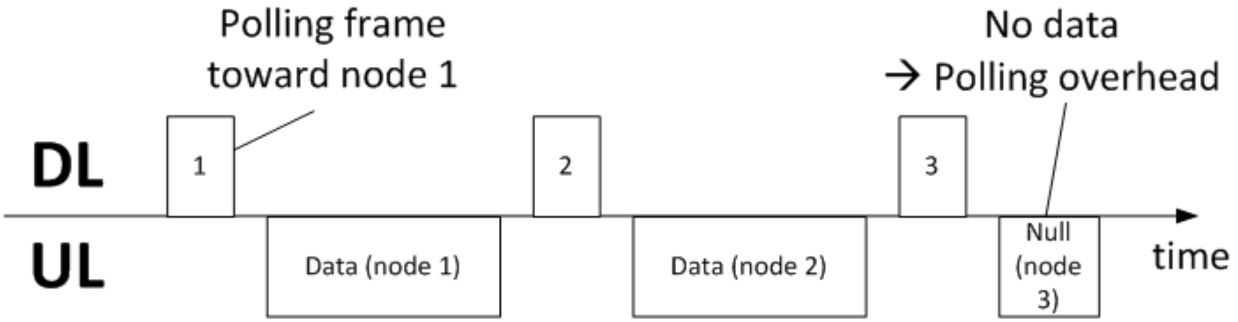
Capture Effect

- Even when a collision occurs, a packet (not all) can be successfully received if SINR (Signal-to-Interference and Noise Ratio) is above threshold
- Threshold is a function of MCS (Modulation and Coding Scheme)
- In practice, there are a lot of captures



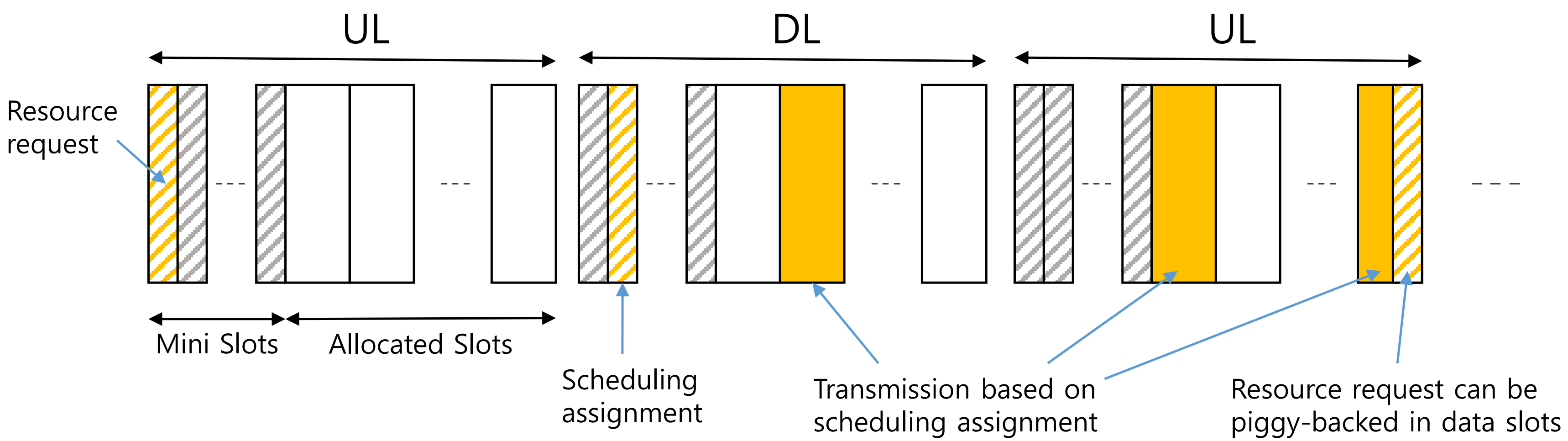
Polling MAC

- A master polls a slave station for the transmission
  - based on the polling order scheduling
  - TDD inherently
- Used in IEEE 802.11 MAC as an optional mode
- Concern:
  - Polling overhead
  - Latency, esp. when lightly loaded
  - Single point of failure (master)



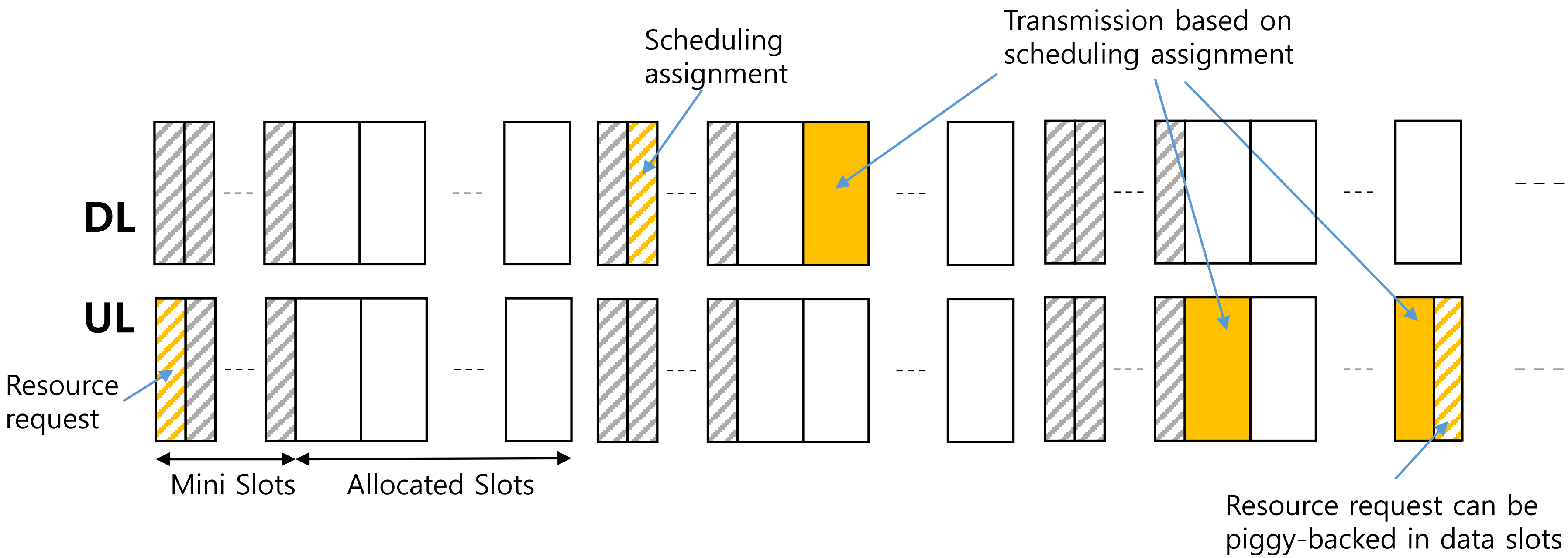
Dynamic TDMA

- Frames divided into resource request (in mini slots) and data slots
  - ALOHA variation be used for request
  - Data slots are allocated based on requests and scheduling
- Example, for TDD



Dynamic TDMA

- Frames divided into resource request (in mini slots) and data slots
  - ALOHA variation be used for request
  - Data slots are allocated based on requests and scheduling
- Example, for FDD



Comments

- Different MAC approaches should be used depending on the system requirements
  - Target application
  - Target environment, e.g., licensed or unlicensed bands
- Many detailed features should be considered
  - QoS provisioning, power consumption, …