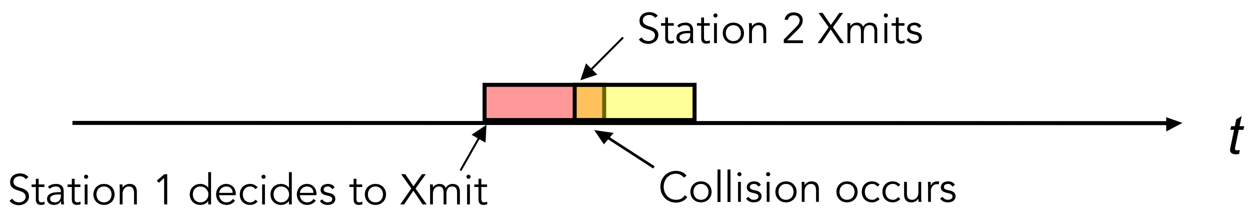
Link Layer

Kyunghan Lee
Networked Computing Lab (NXC Lab)
Department of Electrical and Computer Engineering
Seoul National University
https://nxc.snu.ac.kr
kyunghanlee@snu.ac.kr

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

- *N* stations
  - Each station transmits $\boldsymbol{\lambda}$ (new) packets/sec
  - Arrival of (new) packets from each station is Poisson
  - Fixed Packet lengths with transmission time = $\boldsymbol{m}$

$$\text{Normalized throughput (S)} = \frac{\text{Rate of transmitting new packets}}{\text{Max. channel transmission rate}} = \frac{N\lambda \text{ packets/sec}}{\frac{1}{m} \text{ packets/sec}}$$

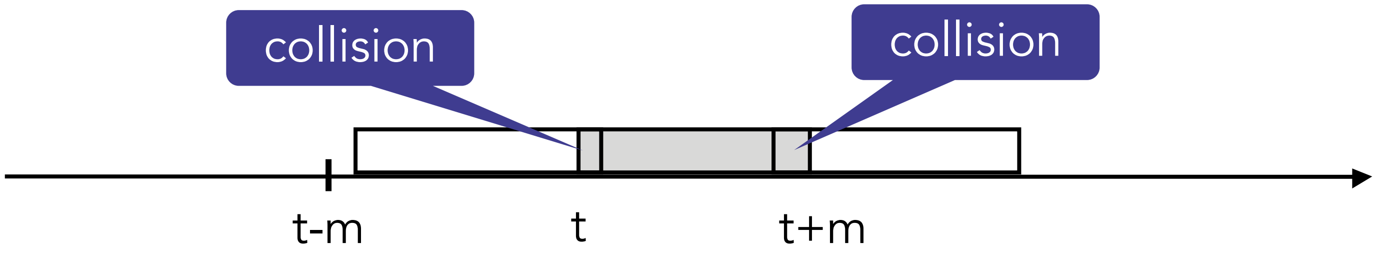
$$\Rightarrow \quad S = N\lambda m$$

- Additional assumption: retransmitted packets are also Poisson distributed
  - Not true: Since retransmissions depend on collision instance
  - Okay if random retransmission delay is long

NXC LAB

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

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

$$
\begin{aligned}
&= \Pr\{\text{No arrivals in } [t-m, t+m] \mid \text{An arrival occurs at } t\} \\
&= \Pr\{\text{No arrivals in } [t-m, t+m]\} \\
&= \Pr\{\text{No arrivals in time interval of } 2m\} \\
&= e^{-N\lambda'(2m)}
\end{aligned}
$$

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

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

Recall that Poisson process gives

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

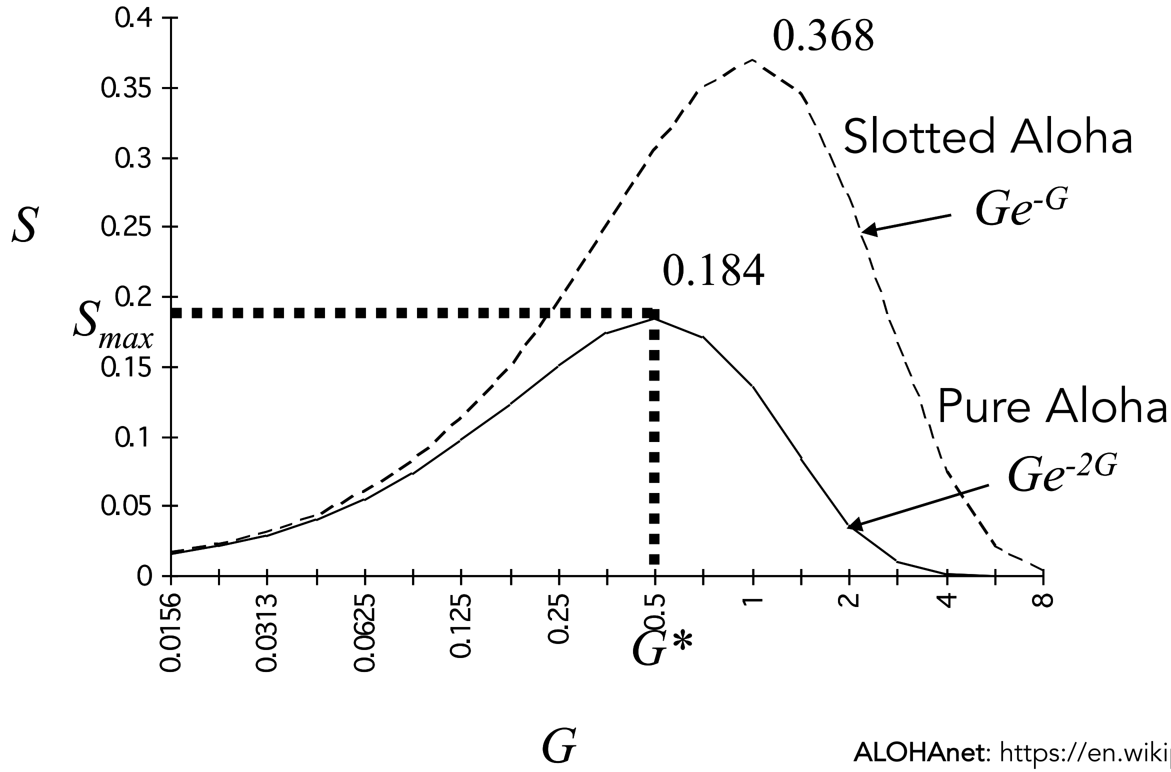
- Also, $P_s = \dfrac{\#\text{ of successfully transmitted packets}}{\#\text{ of totally transmitted packets}}$

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

- 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

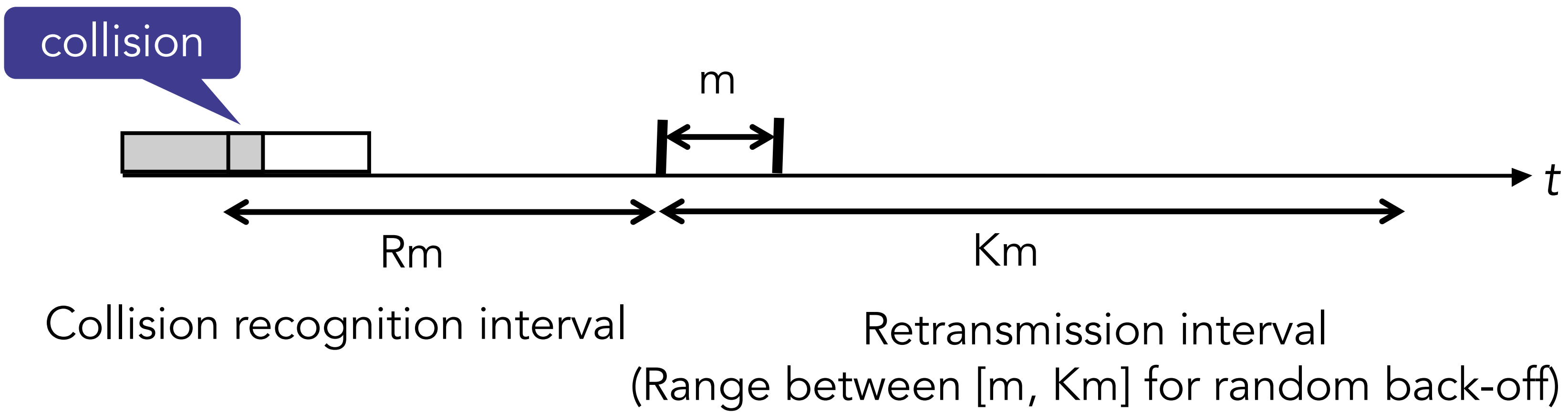
ALOHAnet: https://en.wikipedia.org/wiki/ALOHAnet#ALOHA_protocol

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

E is expected number of retransmissions

- Note that

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

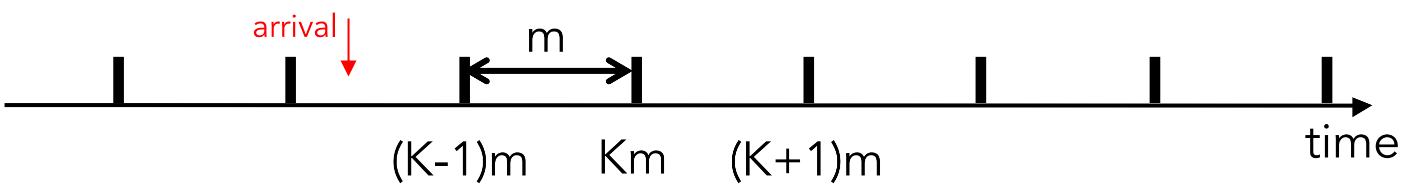
$S = Ge^{-2G}$

- 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 at beginning of time slot
  - 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,

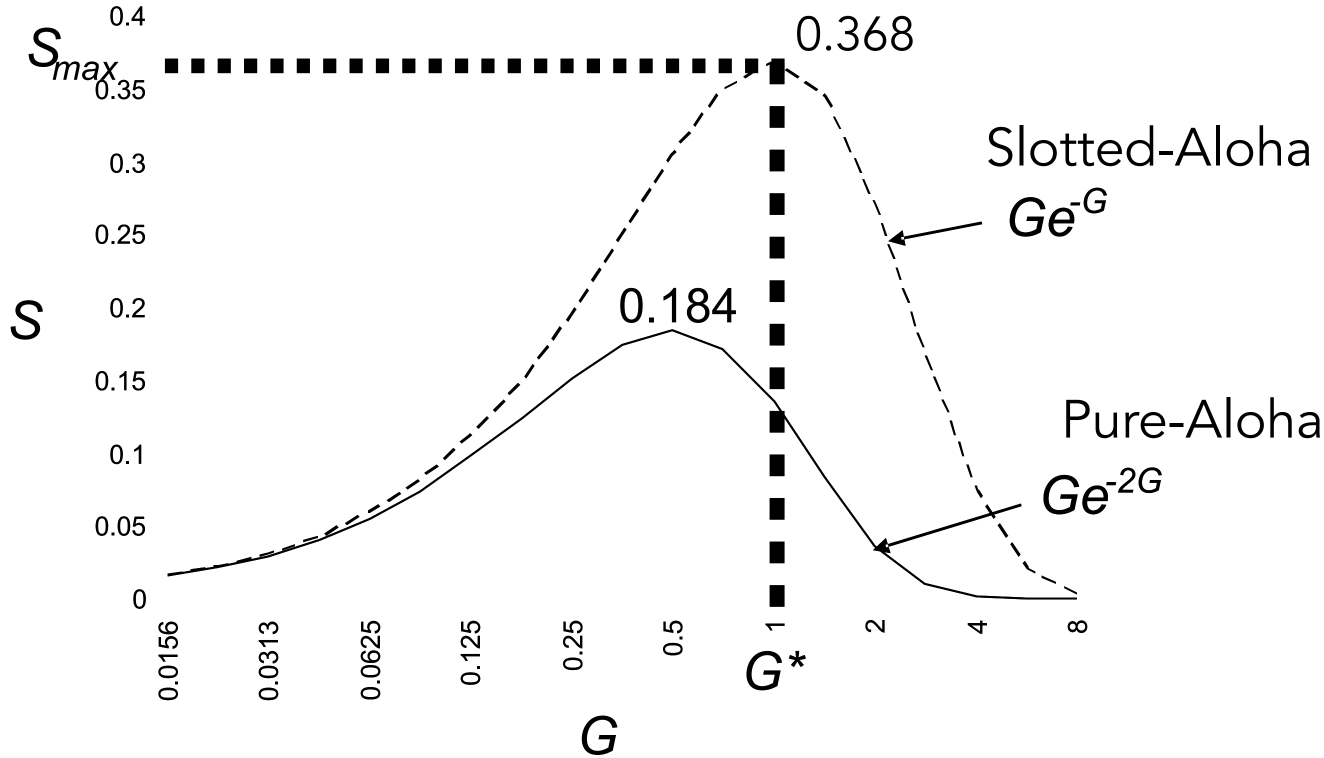
$$\Pr\{\text{Success}\} = e^{-G}, \quad S = Ge^{-G}$$

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

Try to get this result by yourself

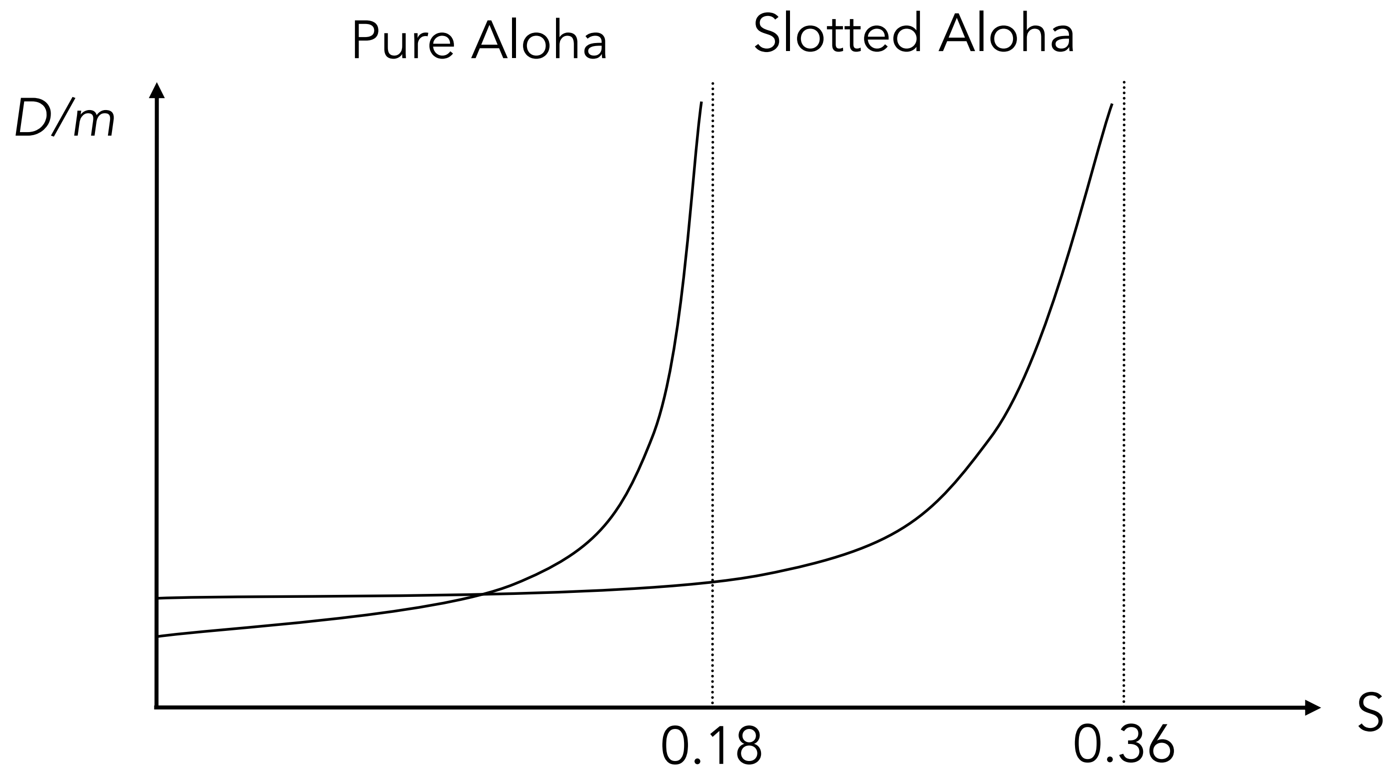
Throughput Analysis of Slotted Aloha

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



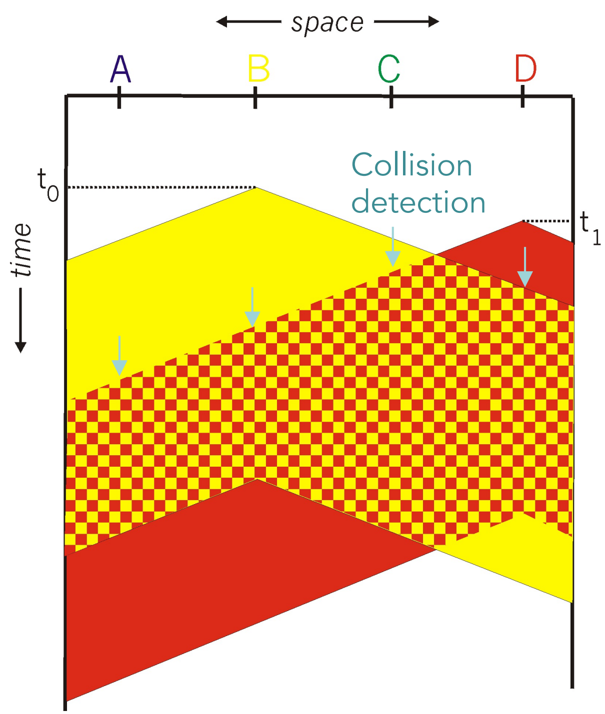
Performance Comparison

- Throughput-delay curve



CSMA/CD

- Carrier Sense Multiple Access with Collision Detection
  - All stations listen for transmissions on the line (carrier sense)
  - A station can transmit only if it detects an idle channel
    - Listen-before-talk
  - Two or more stations sensing an idle channel at same time may cause collisions
  - Stations detecting a collision abort their transmission immediately.



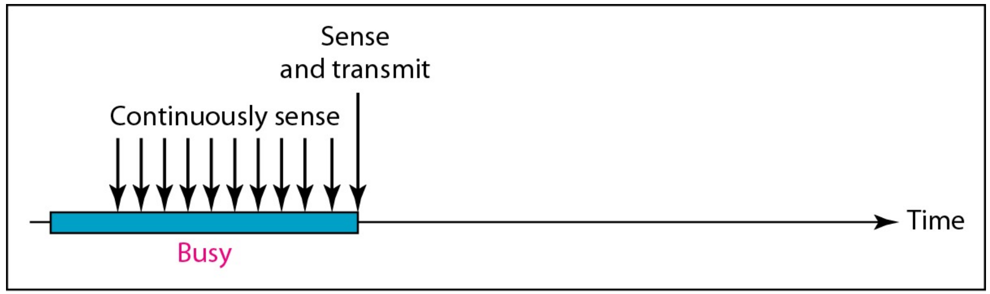
http://www2.ic.uff.br/~michael/kr1999/5-datalink/5_03-LAN.htm

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.

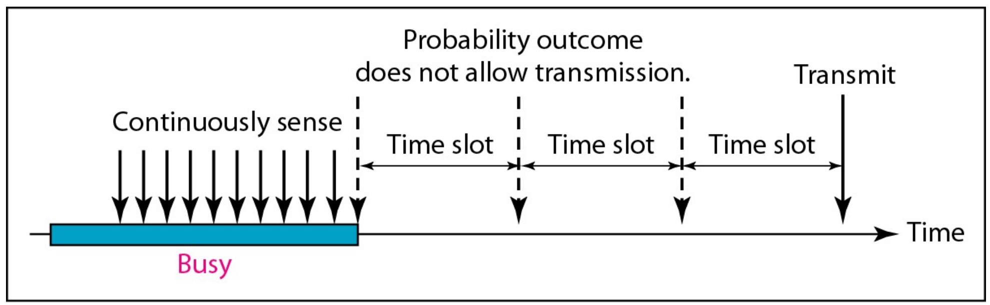
CSMA/CD

1-persistent



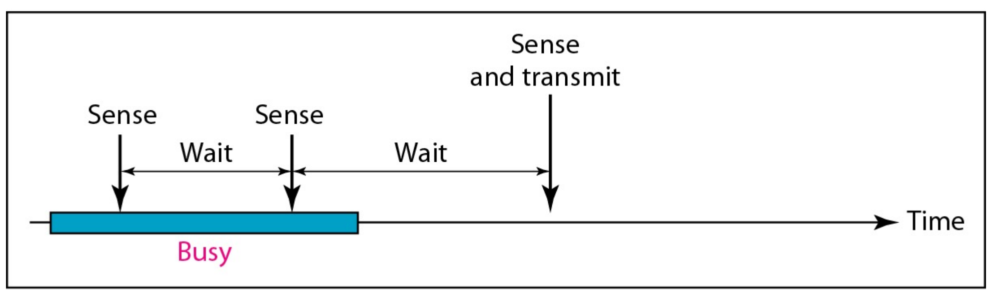
a. 1-persistent

p-persistent



c. p-persistent

non-persistent



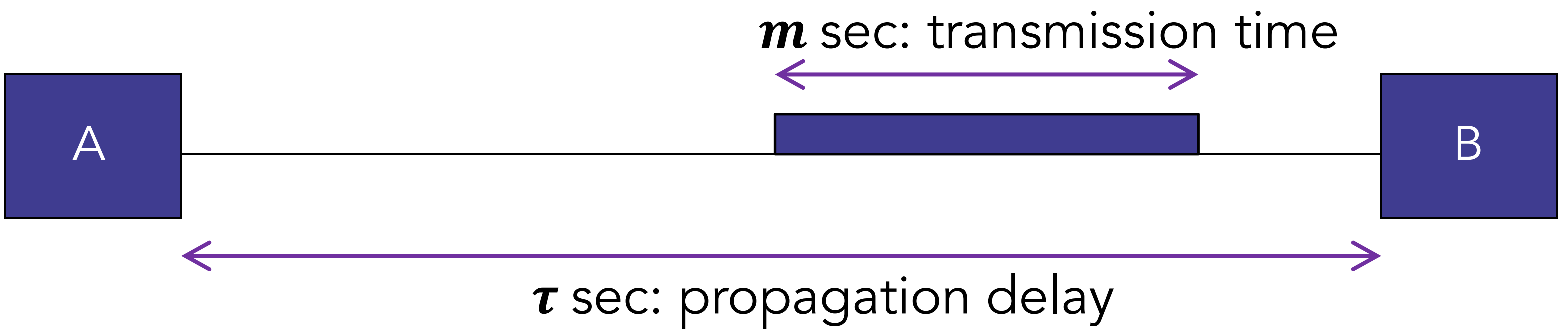
b. Nonpersistent

CSMA/CD

- 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.

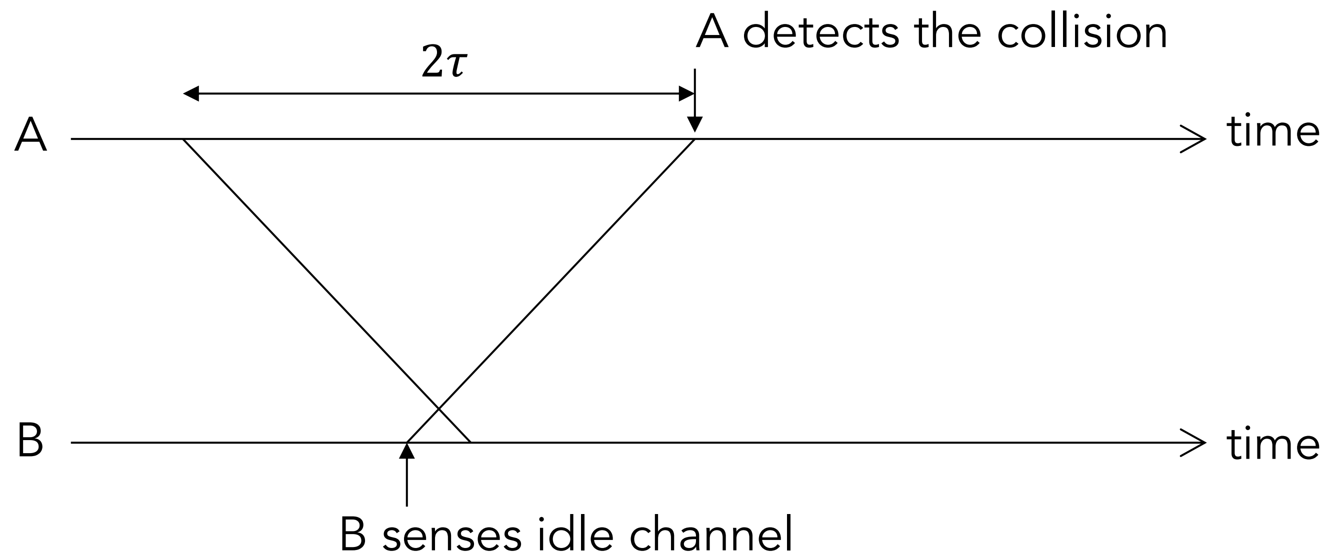
CSMA/CD

- 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**)



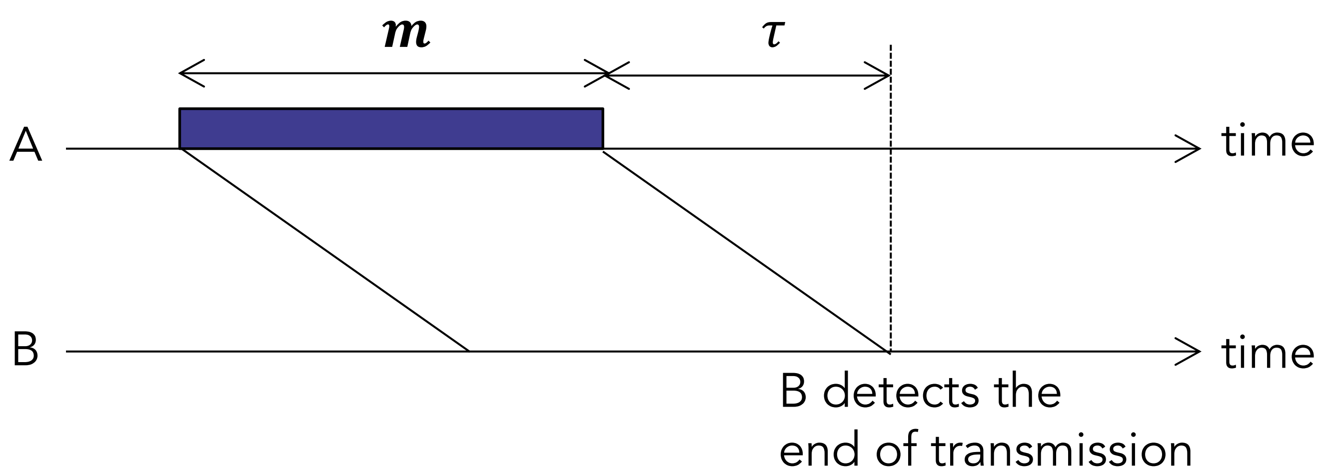
Maximum Throughput of CSMA/CD

- 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



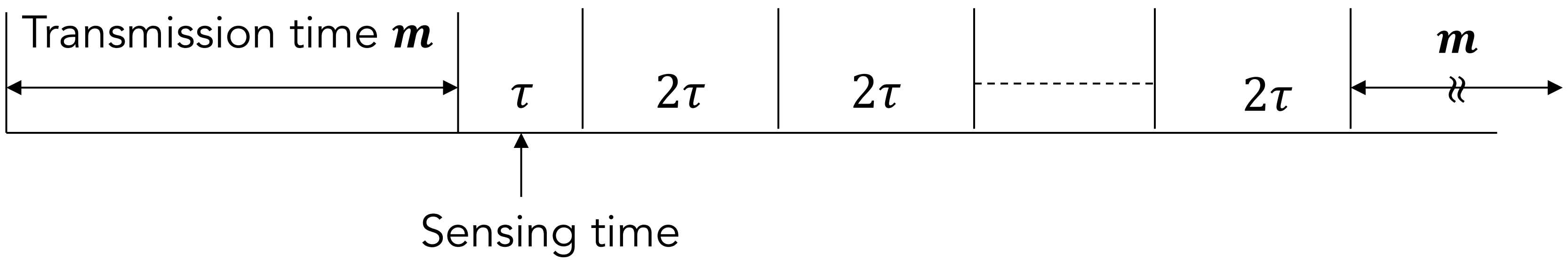
Maximum Throughput of CSMA/CD

- 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.

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
  - $p = \Pr\{\text{A station wants to transmits in a } 2\tau \text{ interval}\}$

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

  - $p = \frac{1}{n}$ 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

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

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

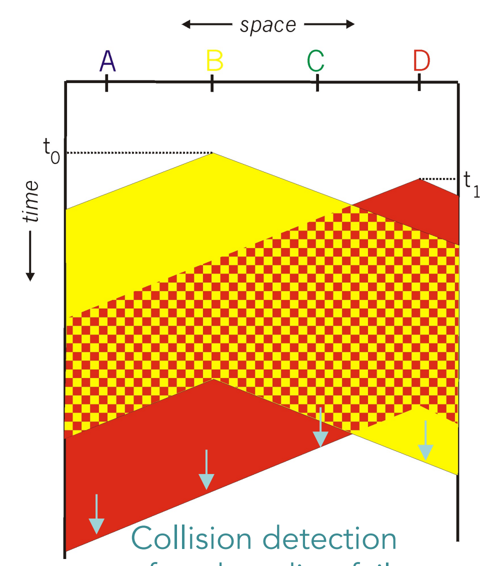
$$\text{max throughput } \lambda_{\max} = \frac{1}{t_v} = \frac{1}{m(1 + a(1 + 2e))}$$

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

CSMA/CA

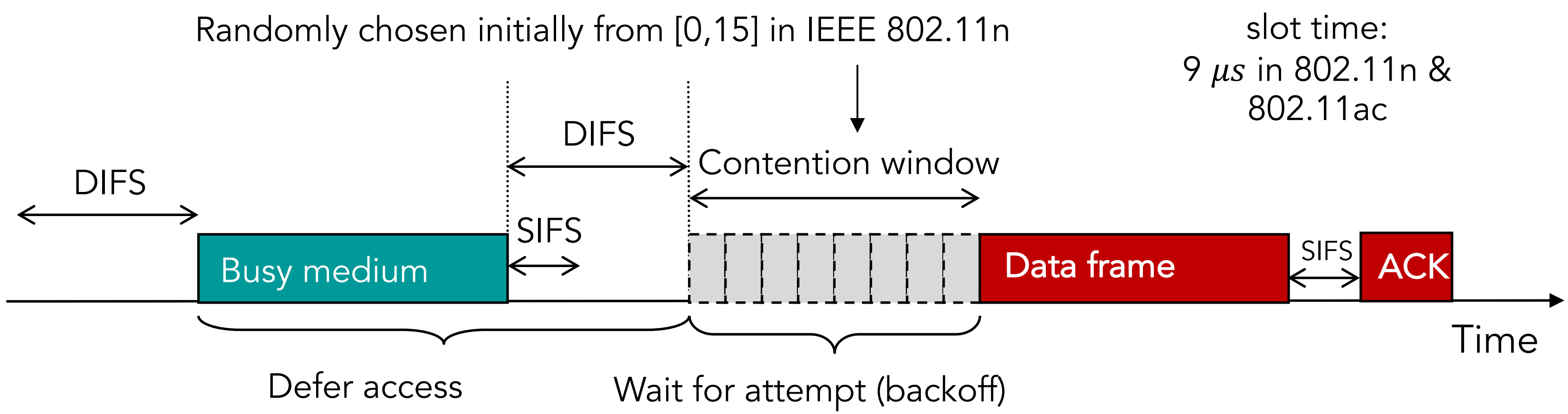
- Carrier Sense Multiple Access with Collision Avoidance
  - Wireless MAC protocols (like Wi-Fi) often use Collision Avoidance with carrier-sense mechanism
  - **Carrier Sense:** When a node wishes to transmit a packet, it first waits until the channel is idle
  - **Collision avoidance:** Use of a random backoff number within the maximum congestion window size

- Why not CSMA/CD?
  - A wireless station may NOT send data and receive collision signals at the same time
  - Collision may NOT be detected in wireless networks
    - Signal fading often prevents a station of one end from hearing a collision at the other end.



CSMA/CA (802.11 DCF (distributed coordinate function))

- Interframe spacing (of Wi-Fi; IEEE 802.11)
  - Short IFS (SIFS): Typically to complete exchange in progress (i.e., between data frame and ACK), SIFS is less than DIFS
  - DCF IFS (DIFS): Time to detect idle medium
  - Backoff time is (contention window) x (slot time)
    - Contention window (cw_i) at time slot i is chosen randomly from [0, CW[i]-1].
    - CW[i] starts from CW_{min} (e.g., 16) and is doubled when collision happens until it grows to Cw_{max} (e.g., 256, 512, 1024)
    - CW[i] resets to CW_{min} when a packet transmission is successful



Example of CSMA/CA Backoff