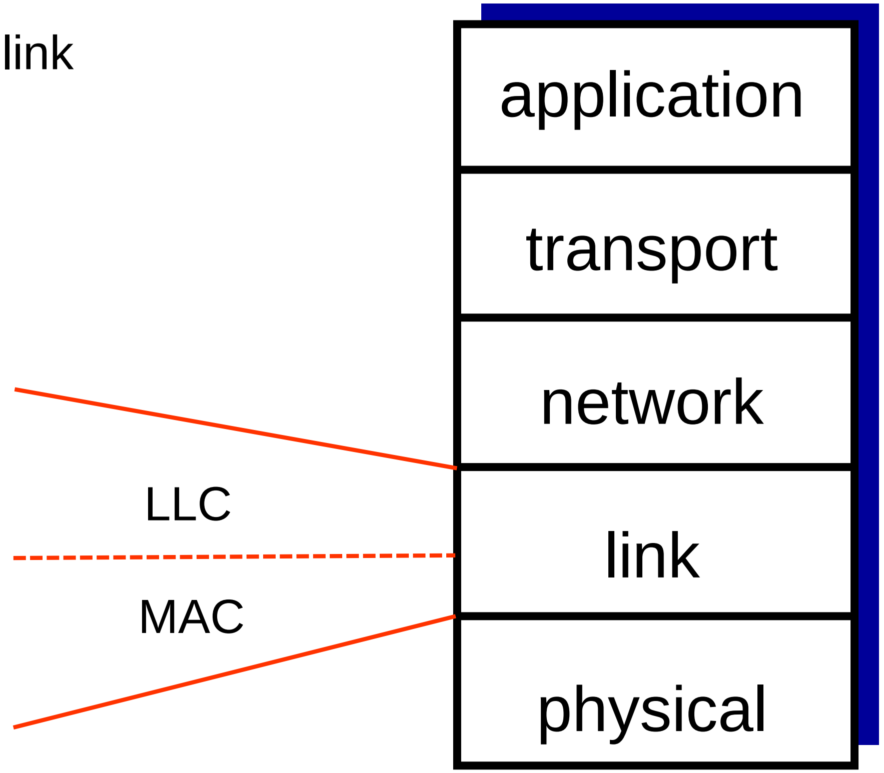
4. Medium Access Control

* multiple access communications
* random access
* scheduling

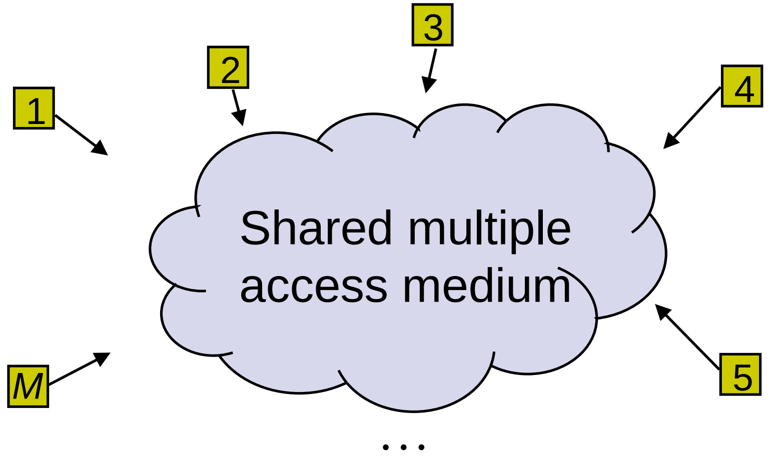
In networks with shared medium, data link layer is divided into two sublayers

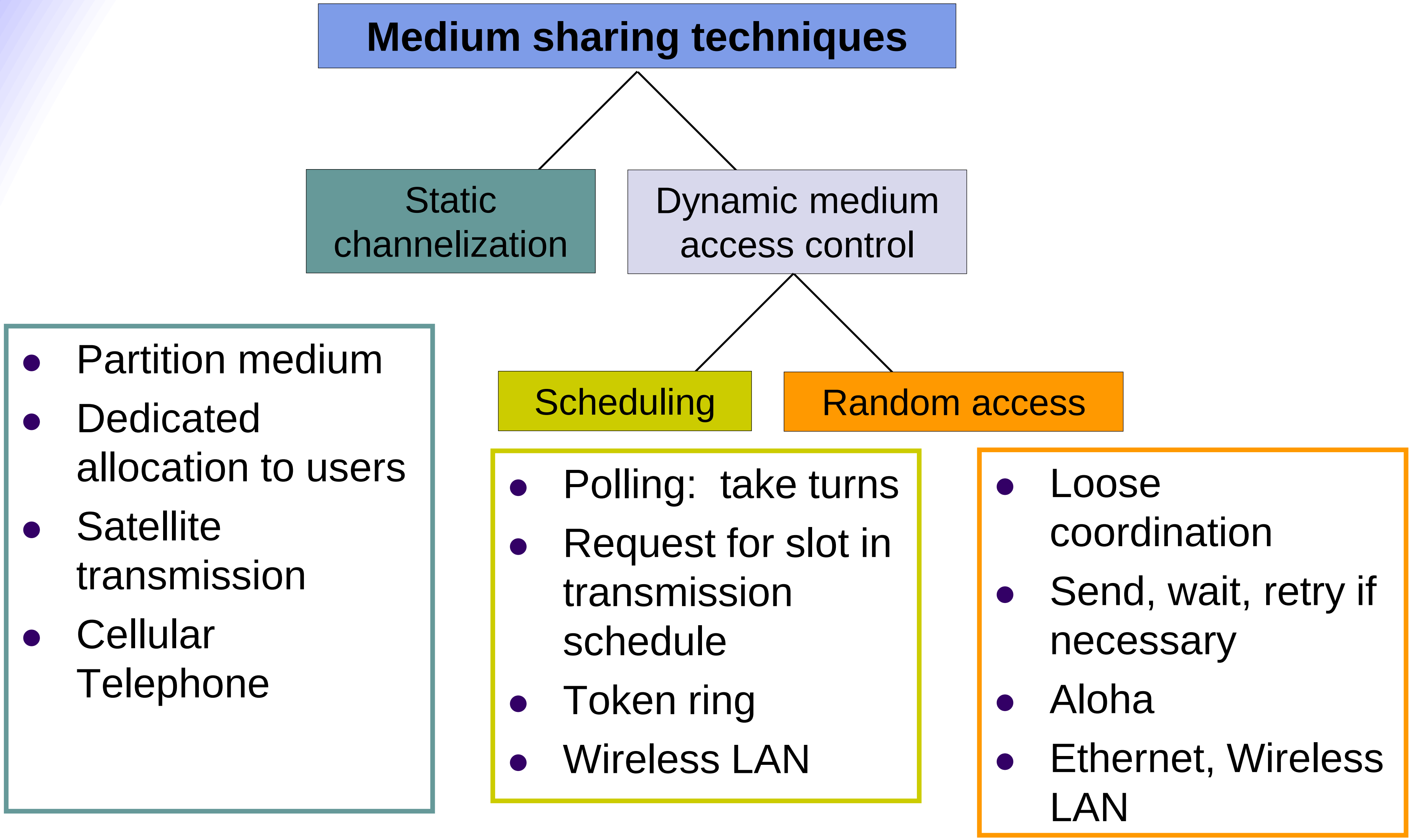
- LLC – Logical link Control
- MAC – Medium Access Control



4.1 multiple access communications

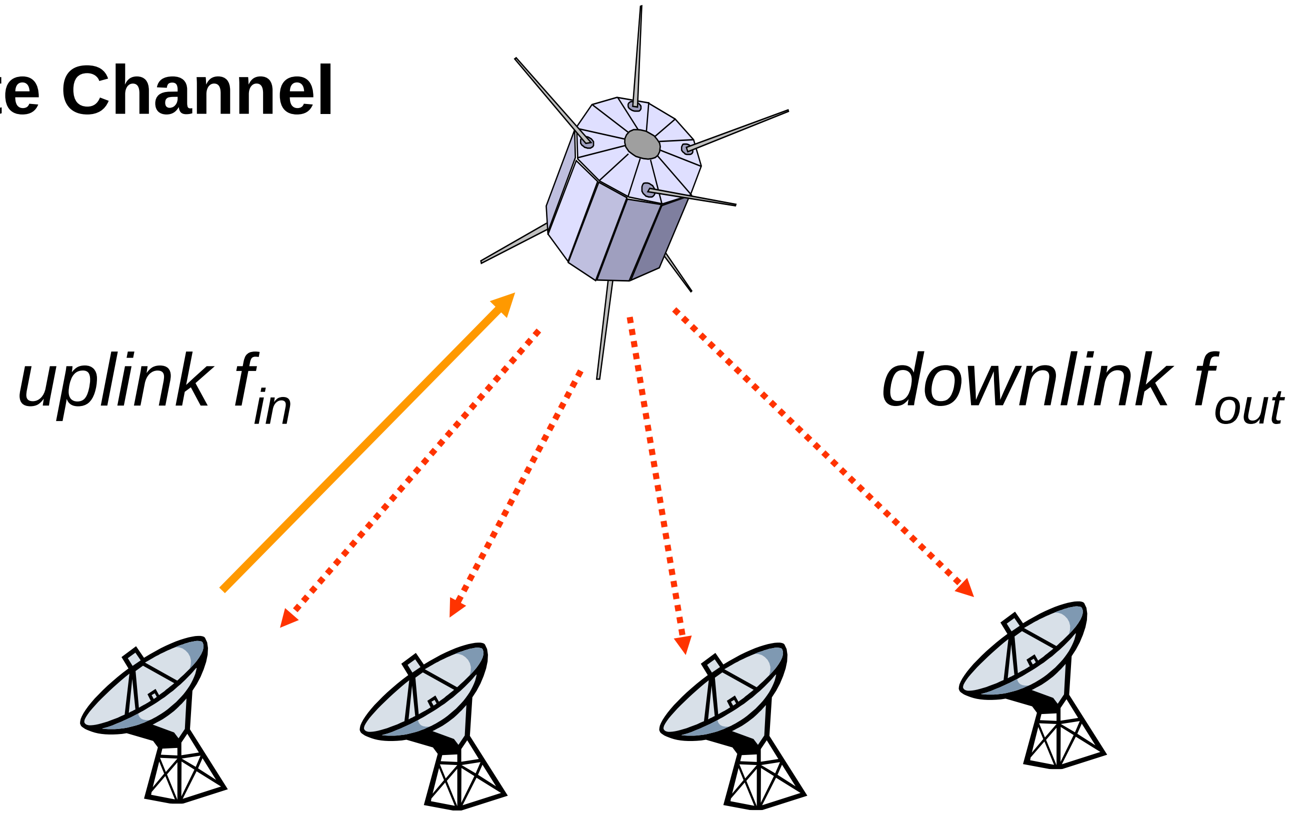
- Shared media basis for broadcast networks
  - Inexpensive: radio over air; copper or coaxial cable
  - M users communicate by broadcasting into medium
- Key issue: How to share the medium?




Medium sharing techniques
Static channelization
Dynamic medium access control
Scheduling
Random access
Partition medium
Dedicated allocation to users
Satellite transmission
Cellular Telephone
Polling: take turns
Request for slot in transmission schedule
Token ring
Wireless LAN
Loose coordination
Send, wait, retry if necessary
Aloha
Ethernet, Wireless LAN

Channelization: Satellite

Satellite Channel

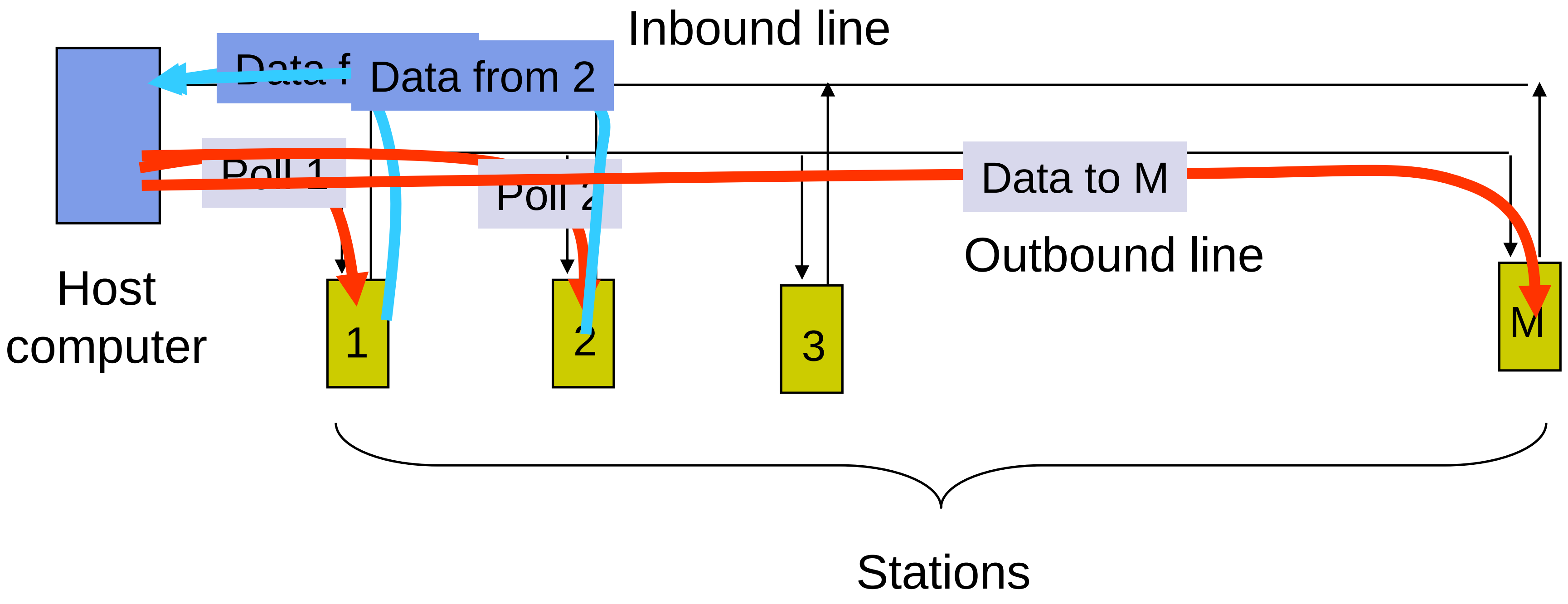


Channelization: Cellular

uplink f_1 ; *downlink* f_2

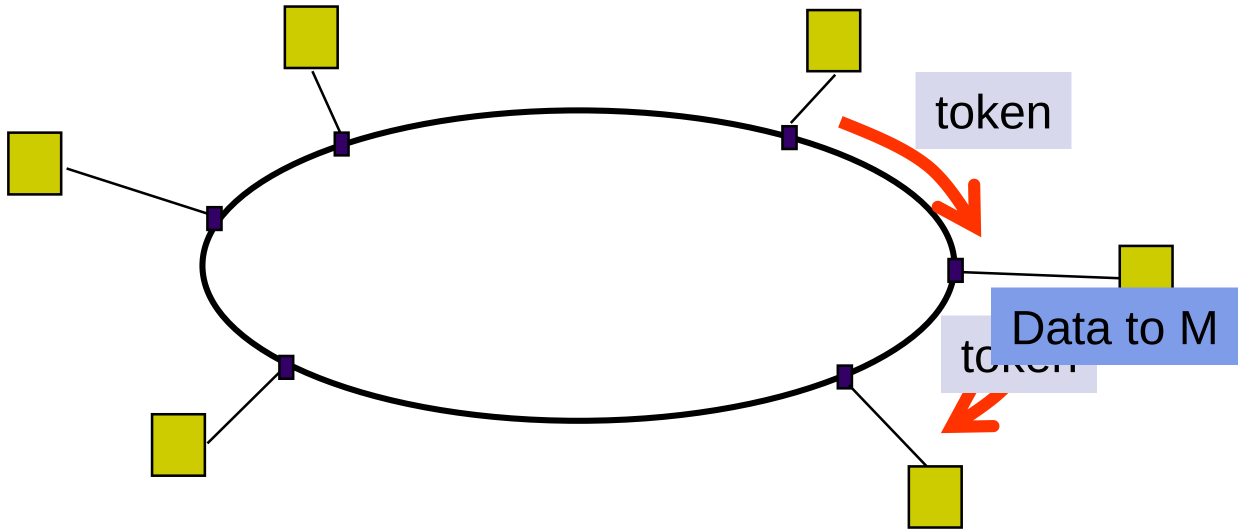
uplink f_3 ; *downlink* f_4

Scheduling: Polling



Scheduling: Token-Passing

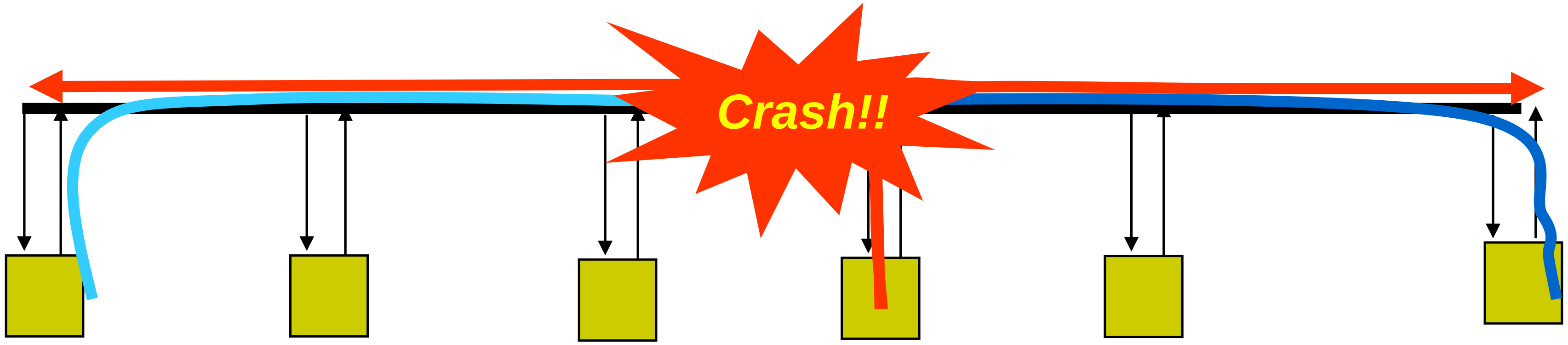
Ring networks



Station that holds token transmits into ring

Random Access

Multitapped Bus

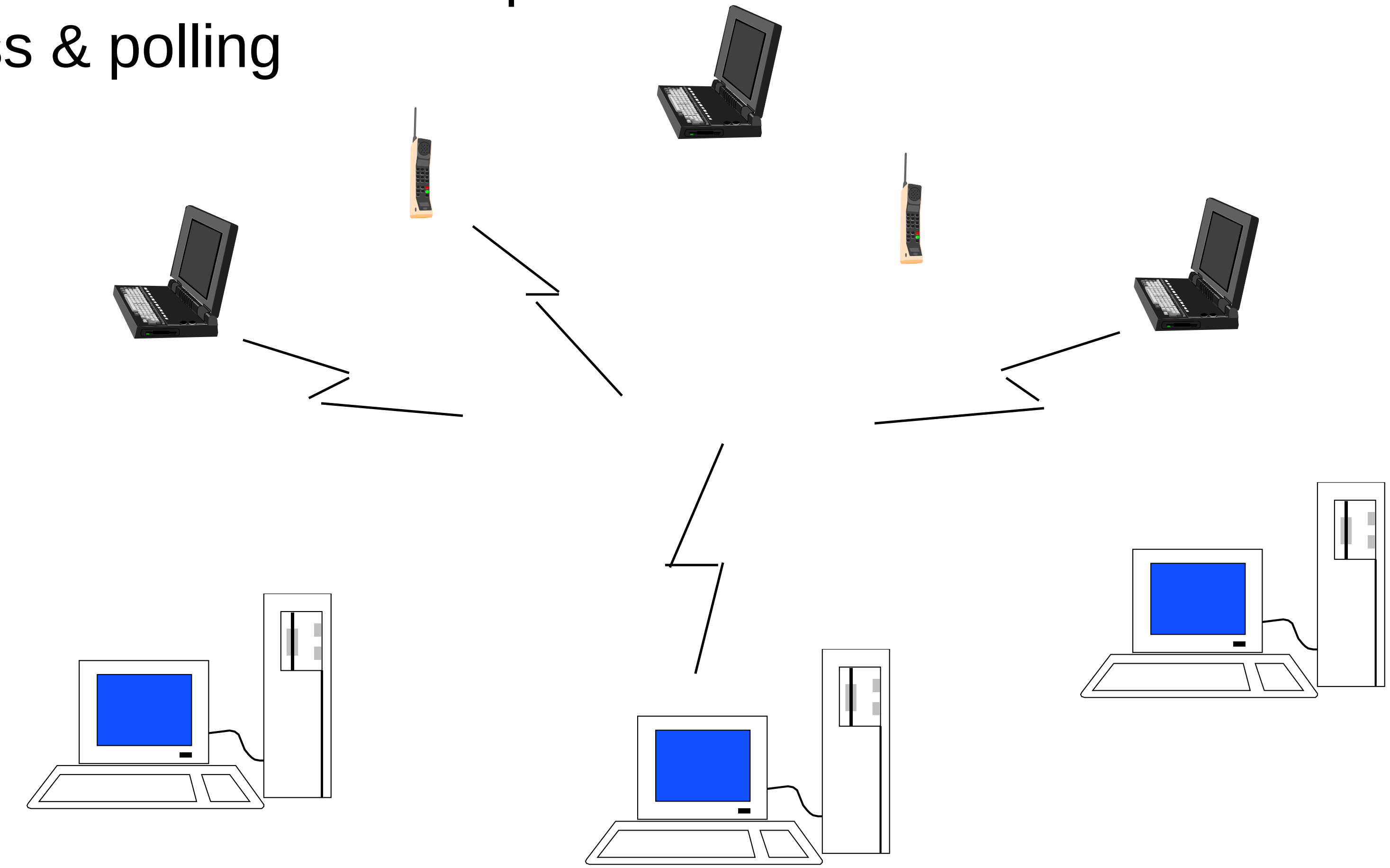


Transmit when ready

Transmissions can occur; need retransmission strategy

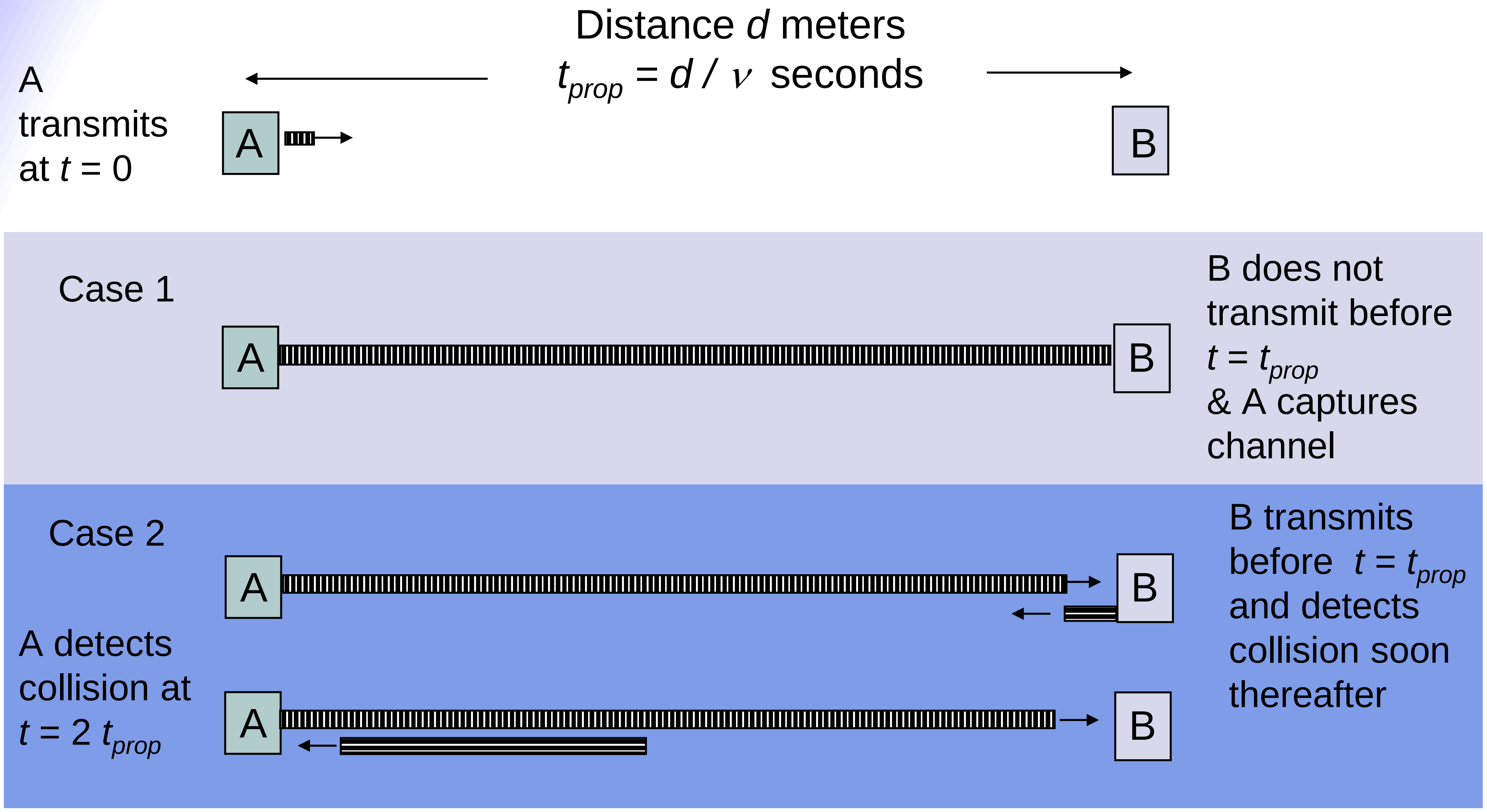
Wireless LAN

AdHoc: station-to-station
Infrastructure: stations to access point
Random access & polling



- *Delay-bandwidth* product key parameter
  - Coordination in sharing medium involves using bandwidth (explicitly or implicitly)
  - Difficulty of coordination commensurate with delay-bandwidth product
- Simple two-station example
  - Station with frame to send listens to medium and transmits if medium found idle
  - Station monitors medium to detect collision
  - If collision occurs, station that begin transmitting earlier retransmits (propagation time is known)

Two stations are trying to share a common medium



- Each frame transmission requires $2t_{prop}$ of quiet time
  - Station B needs to be quiet t_{prop} before *and* after time when Station A transmits
  - R transmission bit rate
  - L bits/frame

$$Efficiency = \rho_{\max} = \frac{L}{L + 2t_{prop}R} = \frac{1}{1 + 2t_{prop}R/L} = \frac{1}{1+2a}$$

$$MaxThroughput = R_{eff} = \frac{L}{L/R + 2t_{prop}} = \frac{1}{1+2a}R \text{ bits/second}$$

Normalized
Delay-Bandwidth
Product

$$\boxed{a = \frac{t_{prop}}{L/R}}$$

Propagation delay

Time to transmit a frame

Two-Station Example:

$$Efficiency = \frac{1}{1+2a}$$

CSMA-CD (Ethernet) protocol:

$$Efficiency = \frac{1}{1+6.44a}$$

Token-ring network

$$Efficiency = \frac{1}{1+a'}$$

a'= latency of the ring (bits)/average frame length

- If $a<<1$, then efficiency close to 100%
- As a approaches 1, the efficiency becomes low

Distance	10 Mbps	100 Mbps	1 Gbps	Network Type
1 m	3.33×10^{-02}	3.33×10^{-01}	3.33×10^{0}	Desk area network
100 m	3.33×10^{01}	3.33×10^{02}	3.33×10^{03}	Local area network
10 km	3.33×10^{02}	3.33×10^{03}	3.33×10^{04}	Metropolitan area network
1,000 km	3.33×10^{04}	3.33×10^{05}	3.33×10^{06}	Wide area network
100,000 km	3.33×10^{06}	3.33×10^{07}	3.33×10^{08}	Global area network

- maximum size Ethernet frame: 1,500 bytes = 12,000 bits
- long and/or fat pipes give large a

MAC protocol features

- Delay-bandwidth product
- Efficiency
- Transfer delay
- Fairness
- Reliability
- Capability to carry different types of traffic
- Quality of service
- Cost

- Frame transfer delay
  - From first bit of frame arrives at source MAC
  - To last bit of frame delivered at destination MAC
- Throughput
  - Actual transfer rate through the shared medium
  - Measured in frames/sec or bits/sec
- Parameters

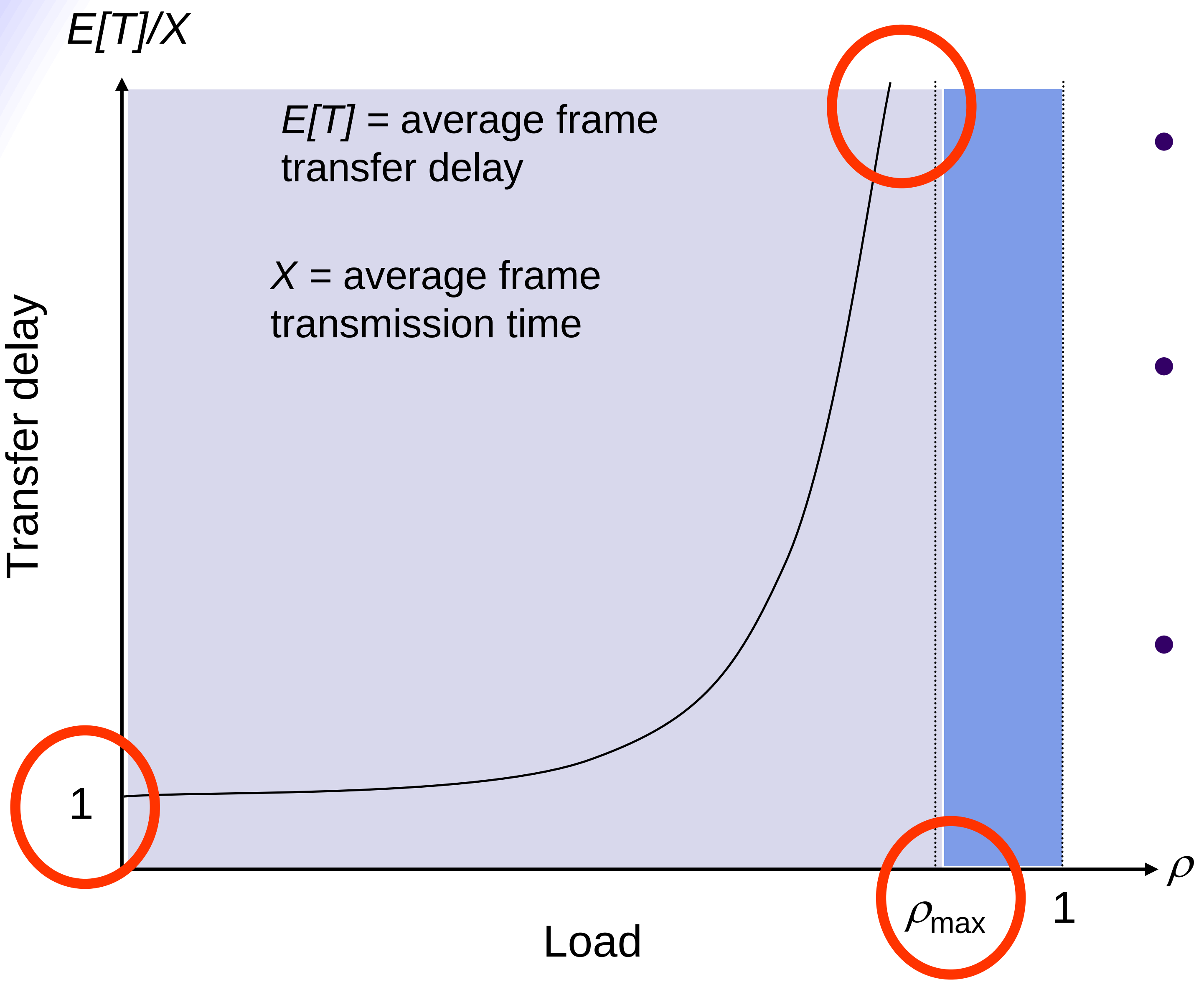
  R bits/sec & *L* bits/frame

  $X=L/R$ seconds/frame

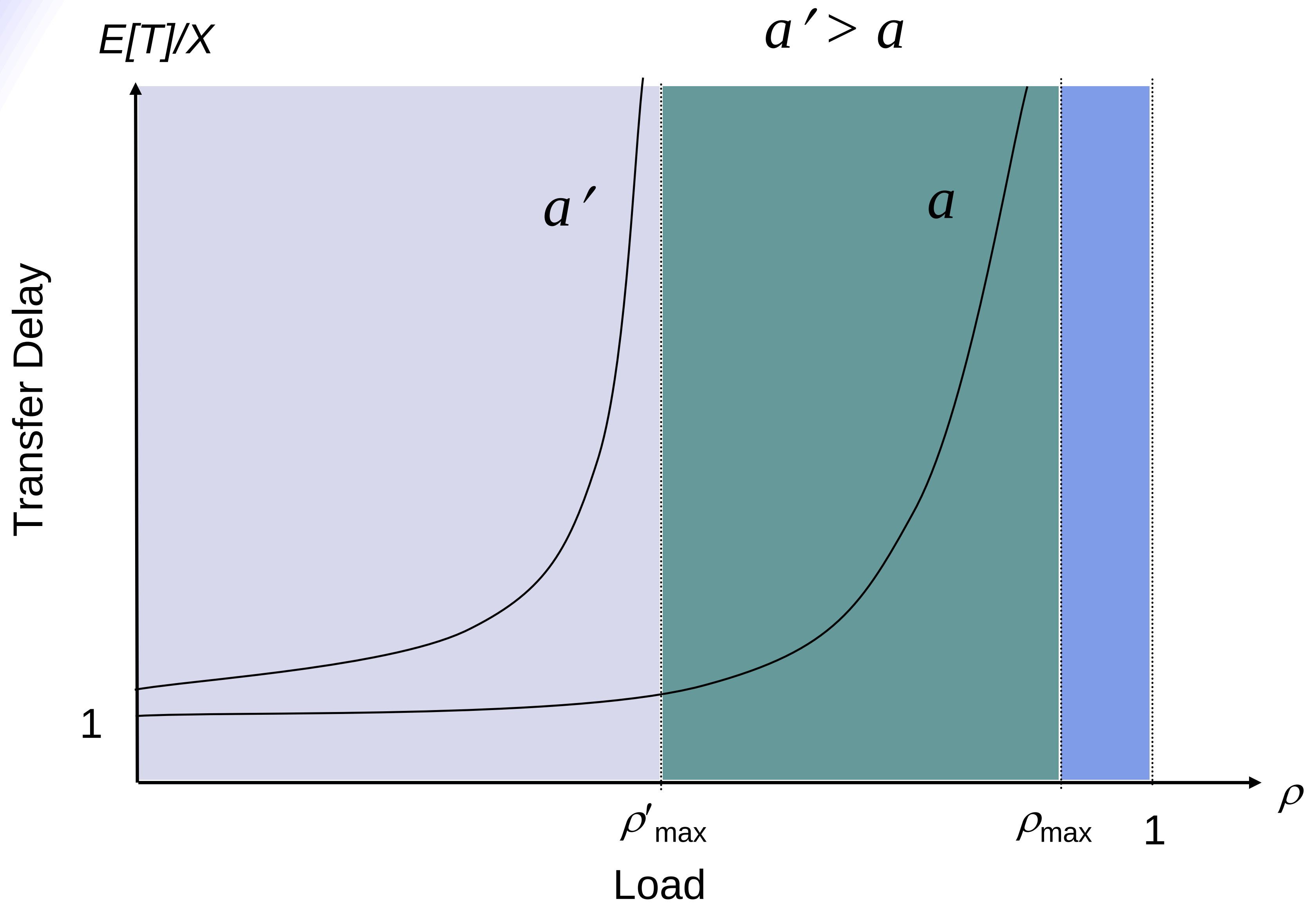
  λ frames/second average arrival rate

  Load $\rho = \lambda X$, rate at which "work" arrives

  Maximum throughput (@100% efficiency): R/L frame/sec



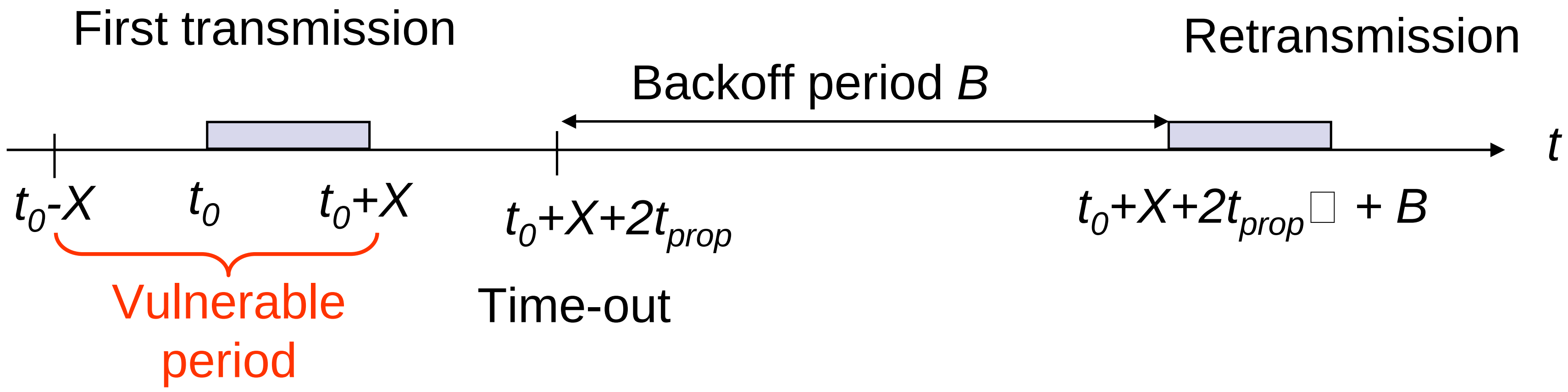
- At low arrival rate, only frame transmission time
- At high arrival rates, increasingly longer waits to access channel
- Max efficiency typically less than 100%


$a' > a$
E[T]/X
Transfer Delay
a'
a
1
ρ
ρ'_{max}
ρ_{max}
1
Load

4.2 random access

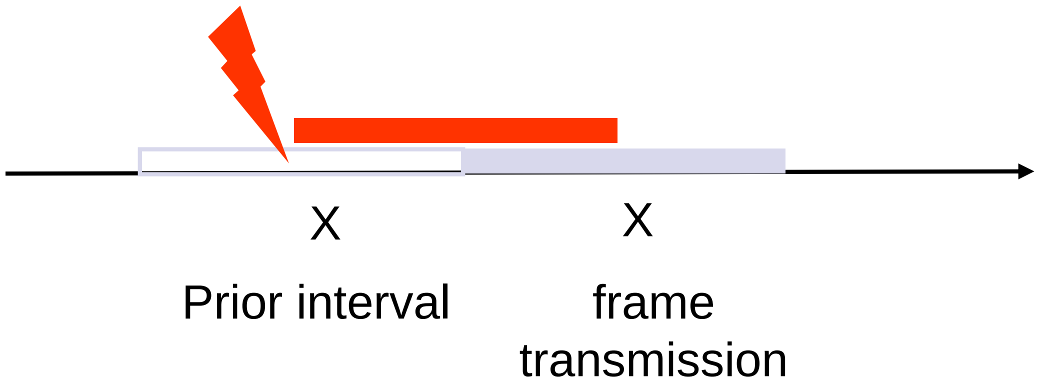
ALOHA

- Wireless link to provide data transfer between main campus & remote campuses of University of Hawaii
- Simplest solution: just do it
  - A station transmits whenever it has data to transmit
  - If more than one frames are transmitted, they interfere with each other (collide) and are lost
  - If ACK not received within timeout, then a station picks random backoff time (to avoid repeated collision)
  - Station retransmits frame after backoff time



- Definitions and assumptions
  - *X* frame transmission time (assume constant)
  - *S*: throughput (average # successful frame transmissions per *X* seconds)
  - *G*: load (average # transmission attempts per X sec.)
  - $P_{success}$: probability a frame transmission is successful

$$S = GP_{success}$$



- Any transmission that begins during vulnerable period leads to collision
- Success if no arrivals during 2X seconds

- *What is probability of no arrivals in vulnerable period?*
- Abramson assumption: Effect of backoff algorithm is that frame arrivals are equally likely to occur at any time interval
- *G* is average number of arrivals per *X* seconds
- Divide *X* into *n* intervals of duration $\Delta = X/n$
- *p* = probability of arrival in Δ interval, then

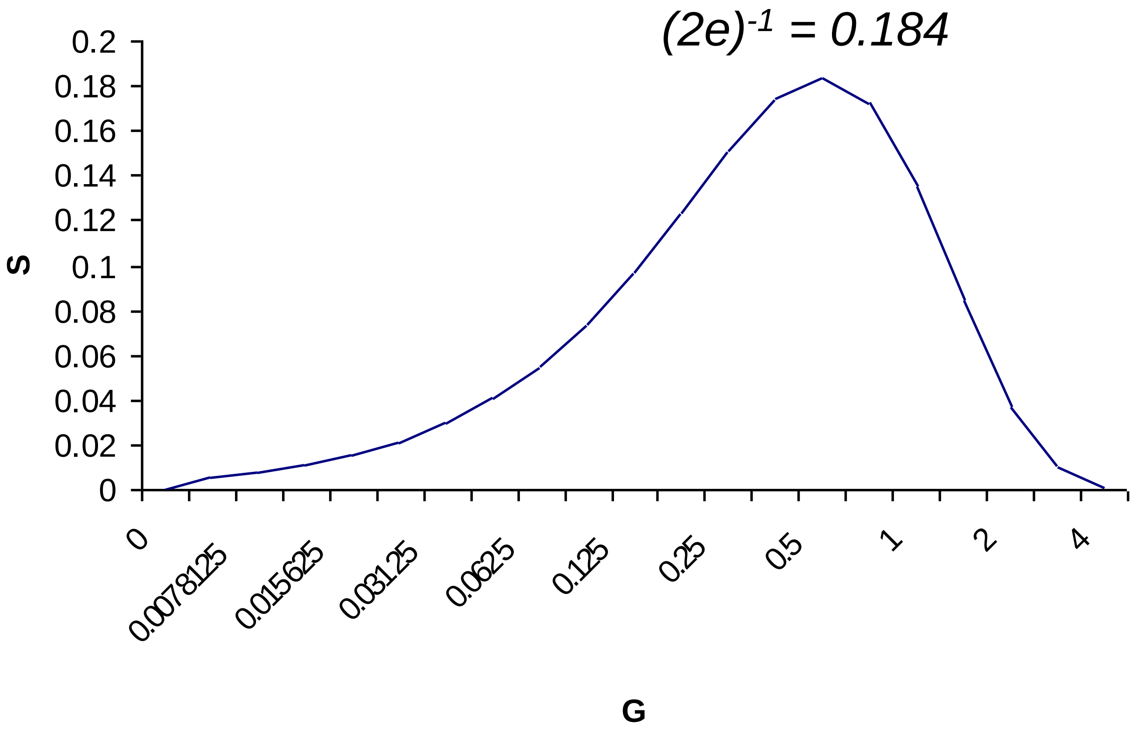
  $G = n\,p$ since there are *n* intervals in *X* seconds

$$P_{success} = P[0 \text{ arrivals in } 2\text{X seconds}] =$$

$$= P[0 \text{ arrivals in } 2\text{n intervals}]$$

$$= (1-\text{p})^{2\text{n}} = (1-\frac{G}{n})^{2n} \rightarrow e^{-2G} \quad \text{as n} \rightarrow \infty$$

$$S = GP_{success} = Ge^{-2G}$$



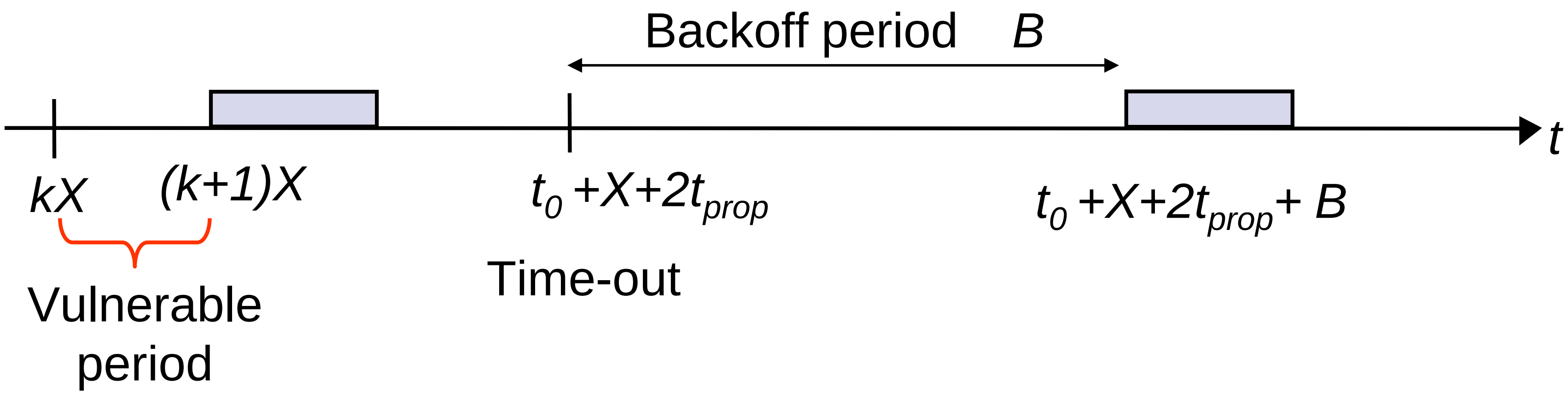
- Collisions are means for coordinating access
- Max throughput is ρ_{max}= 1/2*e (18.4%)*
- Bimodal behavior:

  Small G, S≈G

  Large G, S↓0
- Collisions can snowball and drop throughput to zero

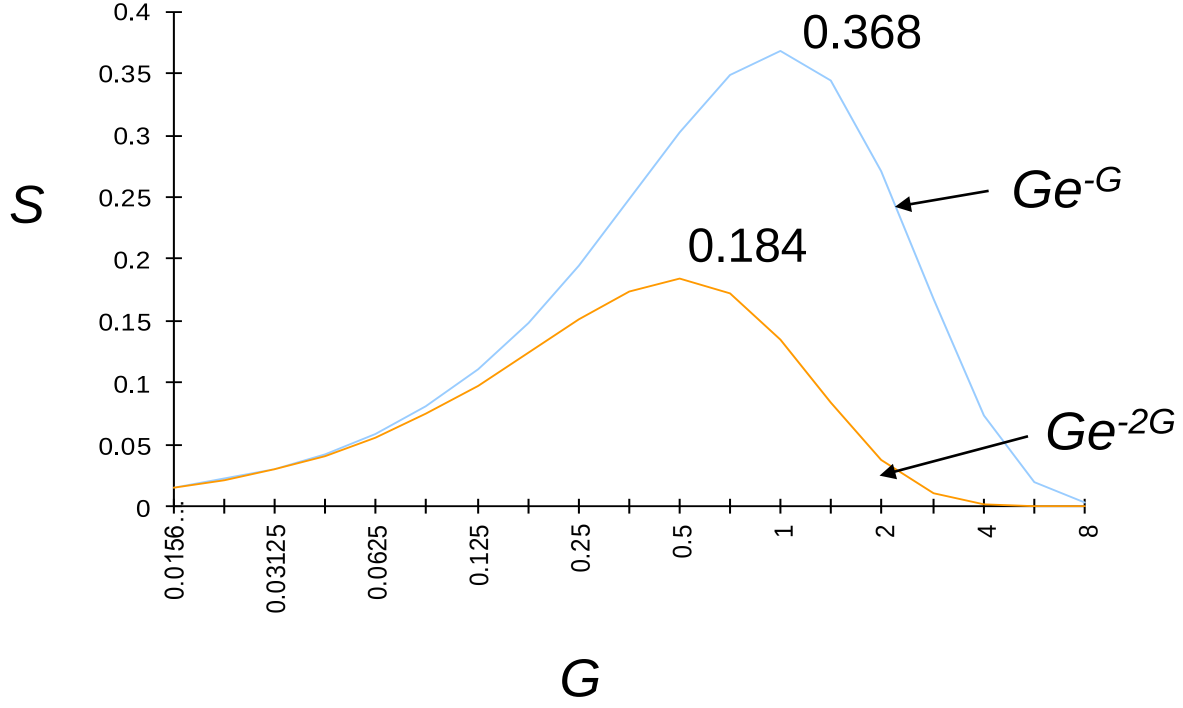
Slotted ALOHA

- Time is slotted in X seconds slots
- Stations synchronized to frame times
- Stations transmit frames in first slot after frame arrival
- Backoff intervals in multiples of slots

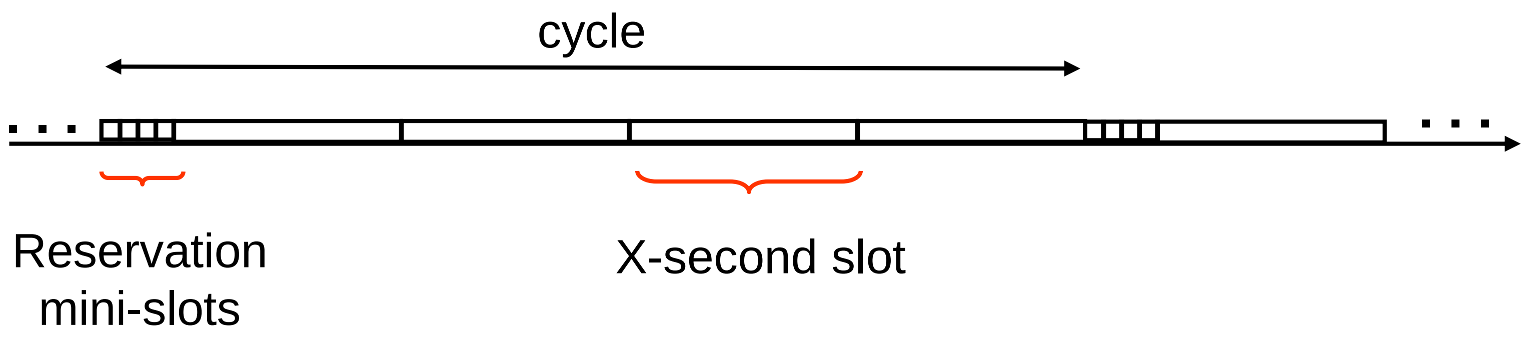


Only frames that arrive during prior X seconds collide

$$S = GP_{success} = GP[\text{no arrivals in X seconds}]$$
$$= GP[\text{no arrivals in n intervals}]$$
$$= G(1-p)^n = G\left(1-\frac{G}{n}\right)^n \rightarrow Ge^{-G}$$



- Max throughput is ρ_{max}= 36.8%
- This occurs at G = 1, i.e. 1 frame per vulnerable period



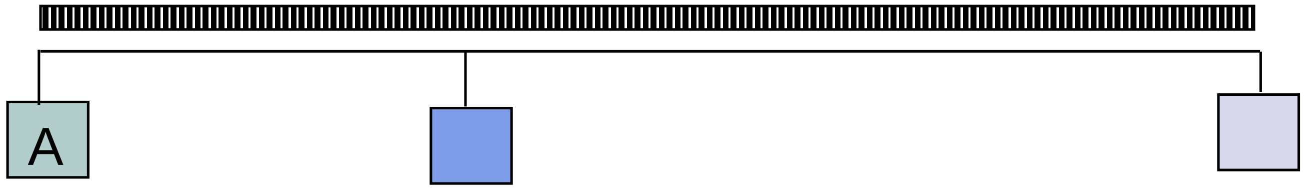
- Reservation protocol allows a large number of stations with infrequent traffic to reserve slots to transmit their frames in future cycles
- Each cycle has mini-slots allocated for making reservations
- Stations use slotted Aloha during mini-slots to request slots

Carrier Sensing Multiple Access (CSMA)

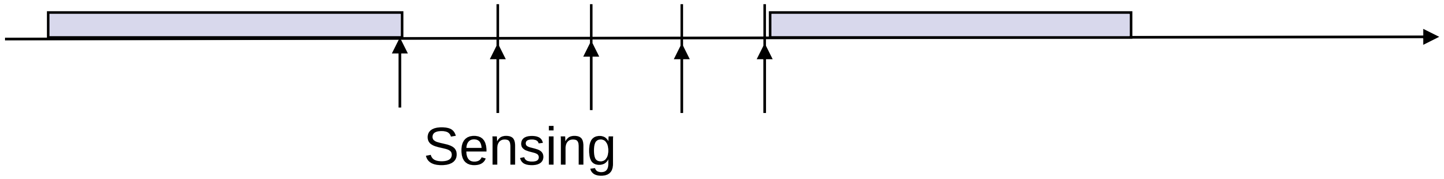
- A station senses the channel before it starts transmission
  - If busy, either wait or schedule backoff (different options)
  - If idle, start transmission
  - Vulnerable period is reduced to t_{prop} (due to *channel capture* effect)
  - When collisions occur they involve entire frame transmission times
  - If t_{prop} >X (or if a>1), no gain compared to ALOHA or slotted ALOHA

Station A begins transmission at $t = 0$

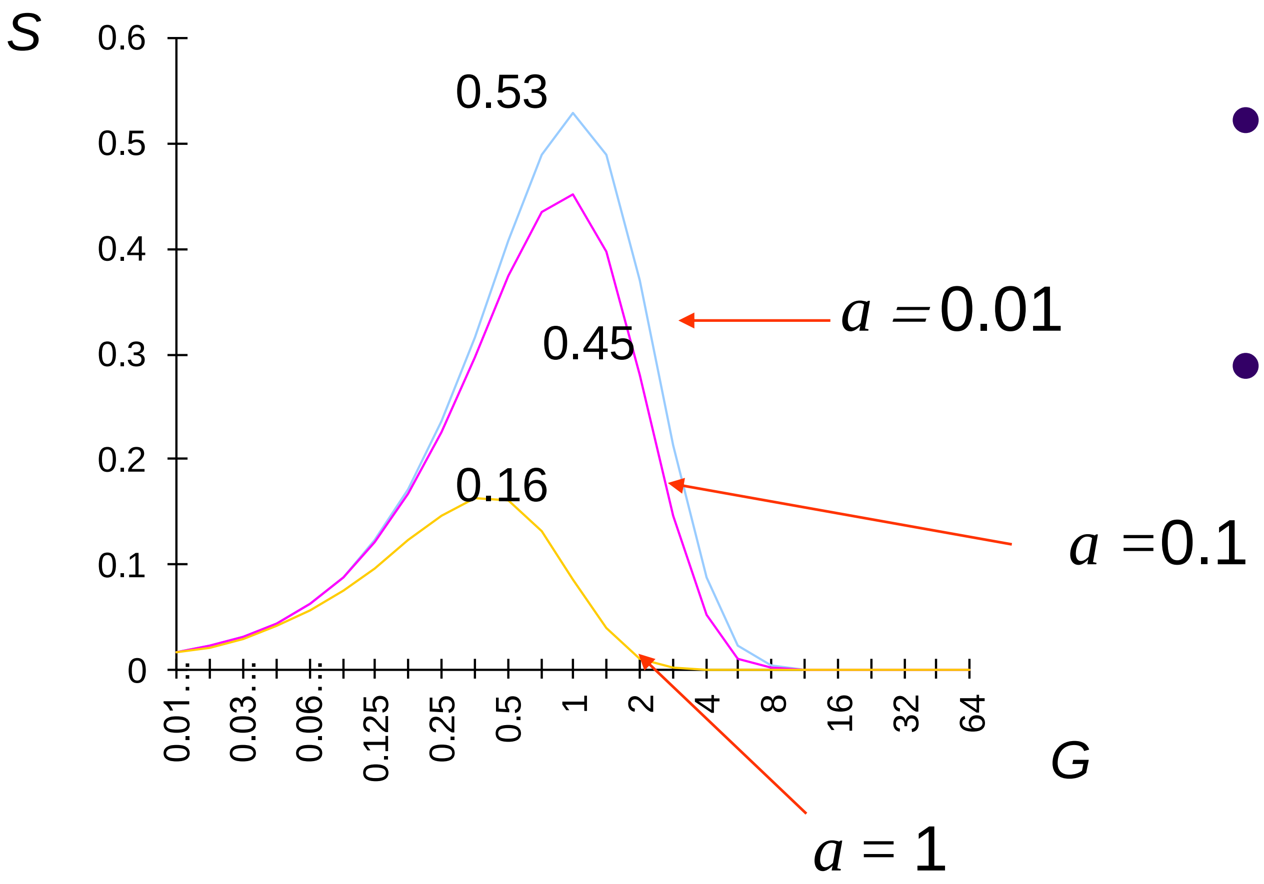
Station A captures channel at $t = t_{prop}$



- Transmitter behavior when busy channel is sensed
  - 1-persistent CSMA (most greedy)
    - Start transmission as soon as the channel becomes idle
    - Low delay and low efficiency
  - Non-persistent CSMA (least greedy)
    - Wait a backoff period, then sense carrier again
    - High delay and high efficiency
  - p-persistent CSMA (adjustable greedy)
    - Wait till channel becomes idle, transmit with probability *p*; or wait one mini-slot time & re-sense with probability 1-*p*
    - Delay and efficiency can be balanced

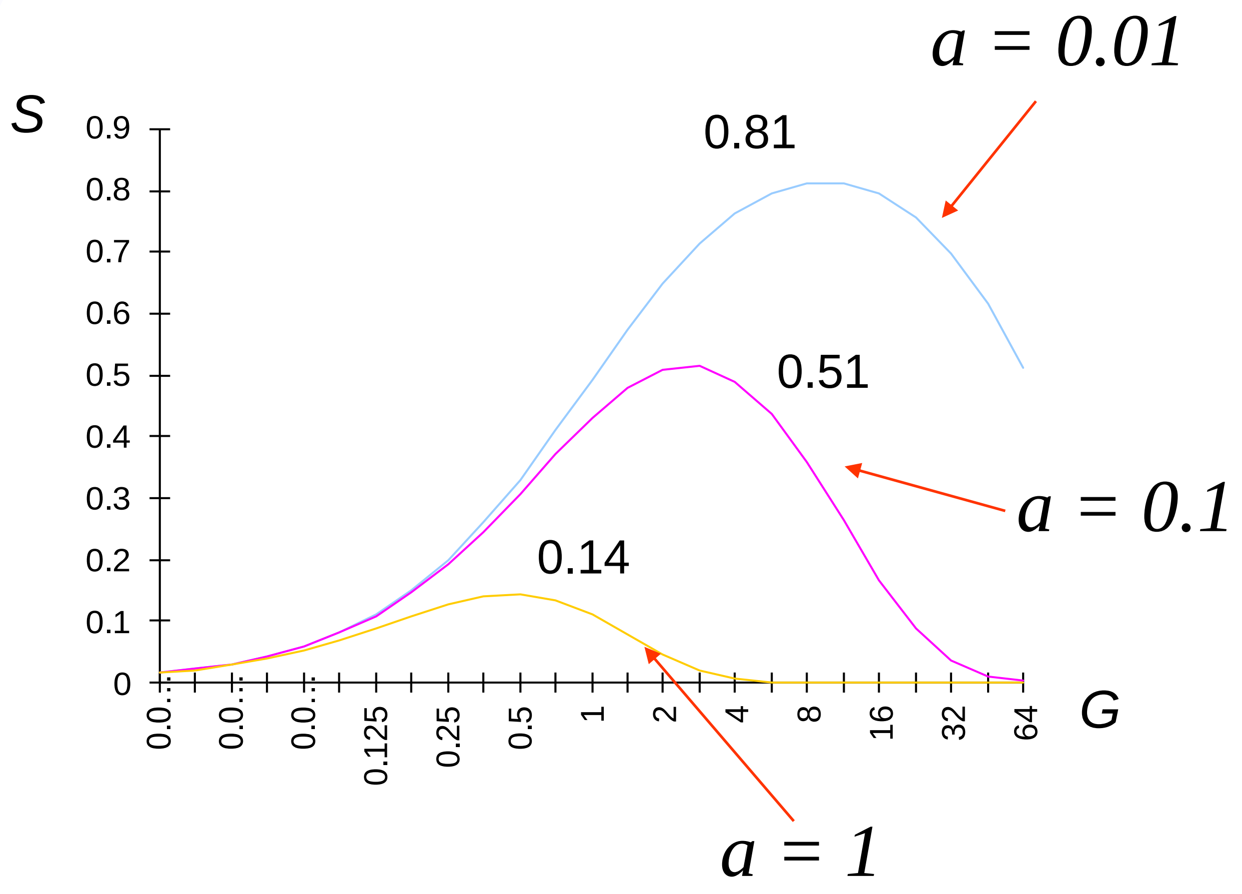


1-Persistent CSMA throughput



- Better than ALOHA & slotted ALOHA for small *a*
- Worse than ALOHA for *a* > 1

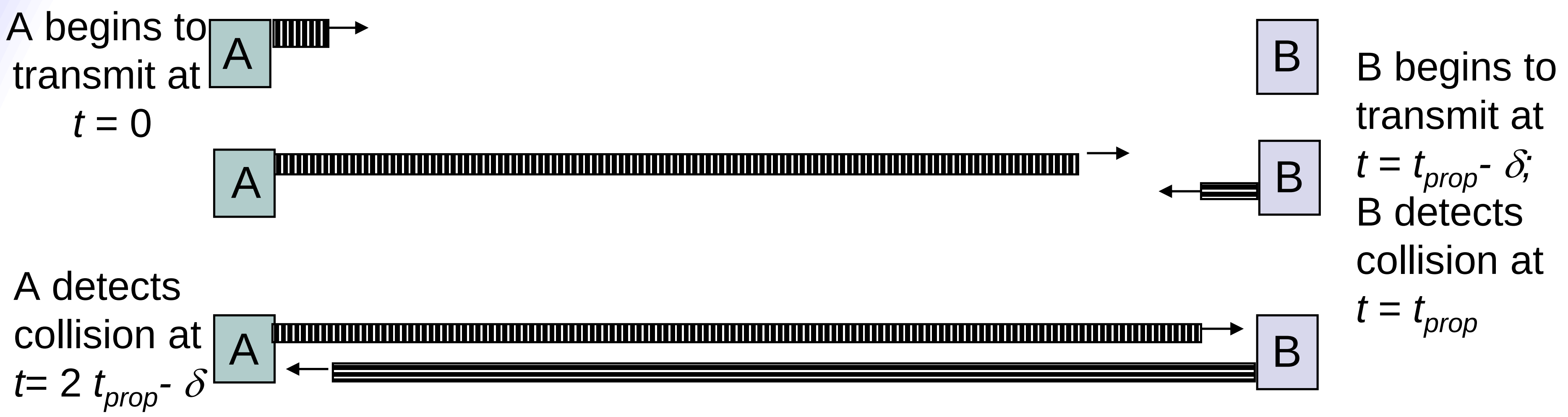
Non-Persistent CSMA throughput



- Higher maximum throughput than 1-persistent for small a
- Worse than ALOHA for $a > 1$

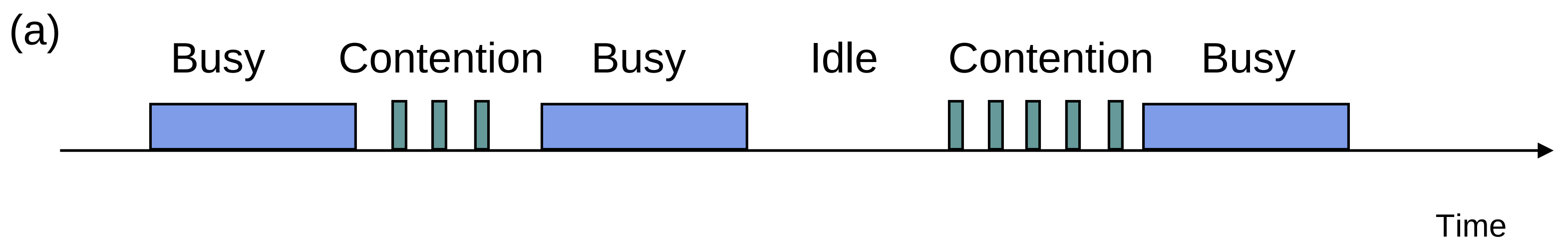
CSMA with Collision Detection (CSMA-CD)

- Monitor for collisions & abort transmission
  - Stations with frames to send, first do carrier sensing
  - After beginning transmissions, stations continue listening to the medium to detect collisions
  - If collisions detected, all stations involved stop transmission, reschedule random backoff times, and try again at scheduled times
- In CSMA collisions result in wastage of X seconds spent transmitting an entire frame
- CSMA-CD reduces wastage to time to detect collision and abort transmission



It takes 2 t_{prop} to find out if channel has been captured

- Assumptions
  - Collisions can be detected and resolved in $2t_{prop}$
  - Time slotted in $2t_{prop}$ slots during contention periods
  - Assume n busy stations, and each may transmit with probability p in each contention time slot
  - Once the contention period is over (a station successfully occupies the channel), it takes X seconds for a frame to be transmitted
  - It takes t_{prop} before the next contention period starts.



- How long does it take to resolve contention?
- Contention is resolved ("success') if exactly 1 station transmits in a slot:

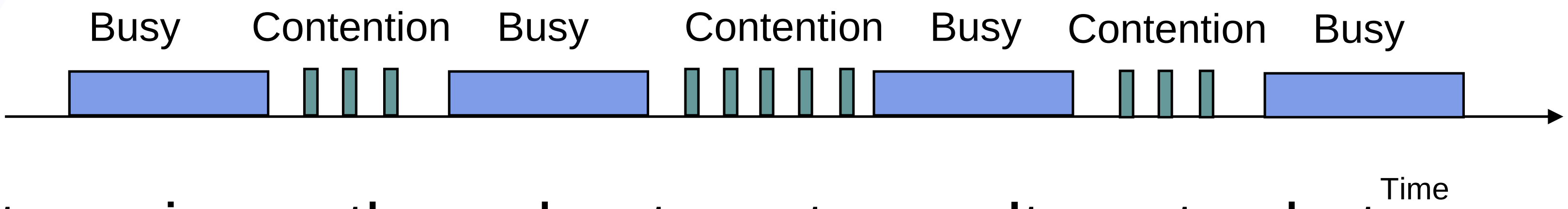
$$P_{success} = np(1-p)^{n-1}$$

- By taking derivative of $P_{success}$ we find max occurs at p=1/n

$$P_{success}^{\max} = n\frac{1}{n}(1-\frac{1}{n})^{n-1} = (1-\frac{1}{n})^{n-1} \to \frac{1}{e}$$

- On average, $1/P^{max} = e = 2.718$ time slots to resolve contention

$$Average\ Contention\ Period = 2t_{prop}e\ seconds$$



- At maximum throughput, systems alternates between contention periods and frame transmission times

$$\rho_{\max} = \frac{X}{X + t_{prop} + 2et_{prop}} = \frac{1}{1 + (2e+1)a} = \frac{1}{1 + (2e+1)Rd/\nu L}$$

- where:

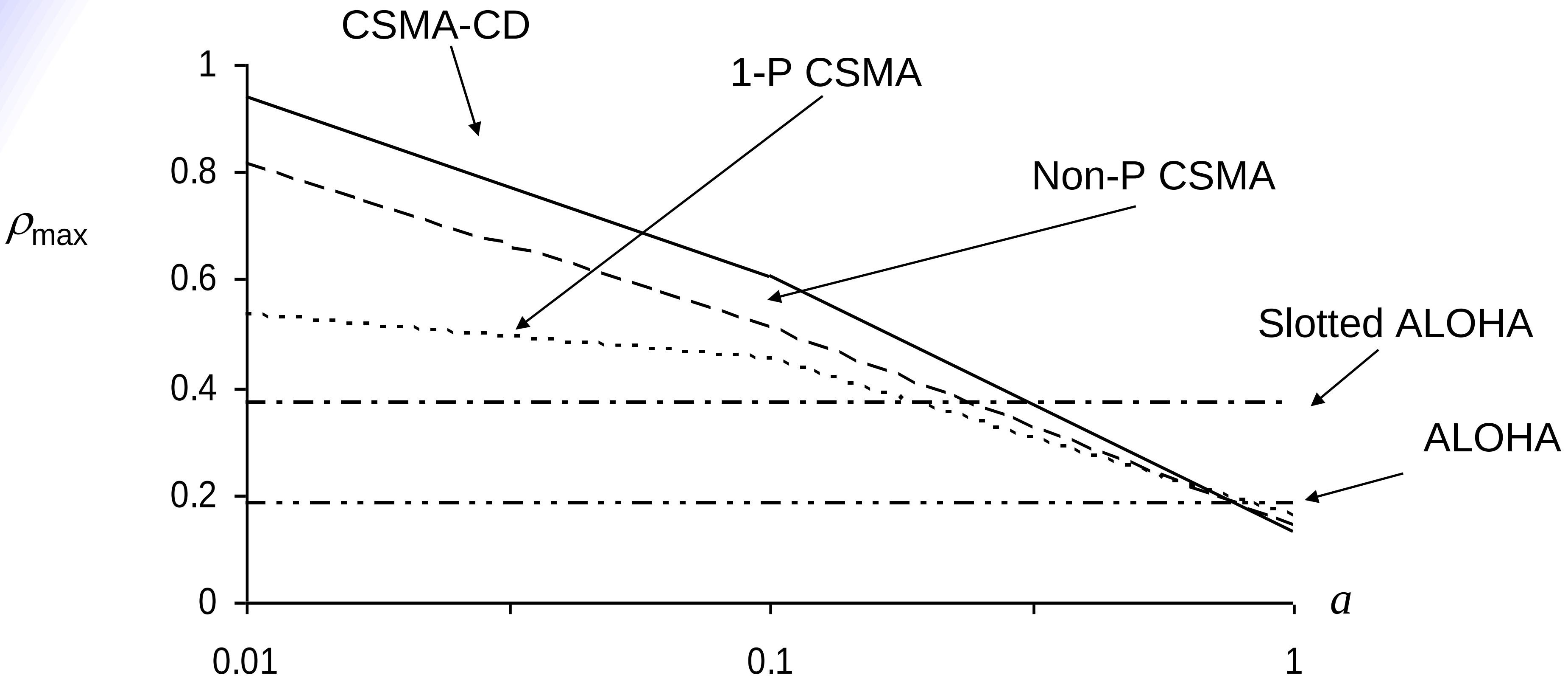
  R bits/sec, L bits/frame, $X=L/R$ seconds/frame

  $a = t_{prop}/X$

  ν meters/sec. speed of light in medium

  d meters is diameter of system

  $2e+1 = 6.44$



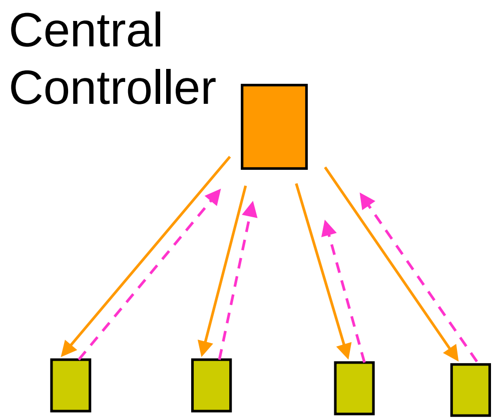
- For small a: CSMA-CD has best throughput
- For larger a: ALOHA & slotted ALOHA better throughput

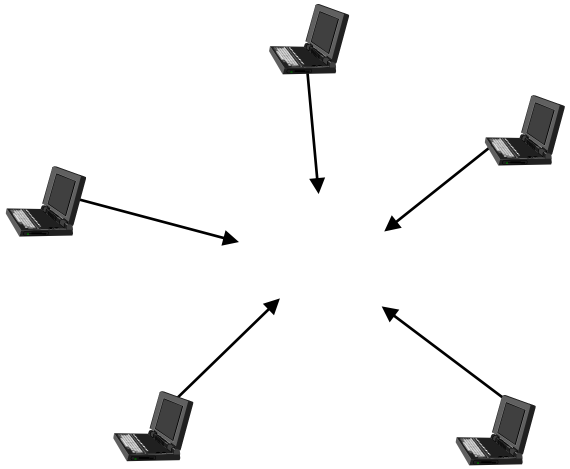
4.3 scheduling

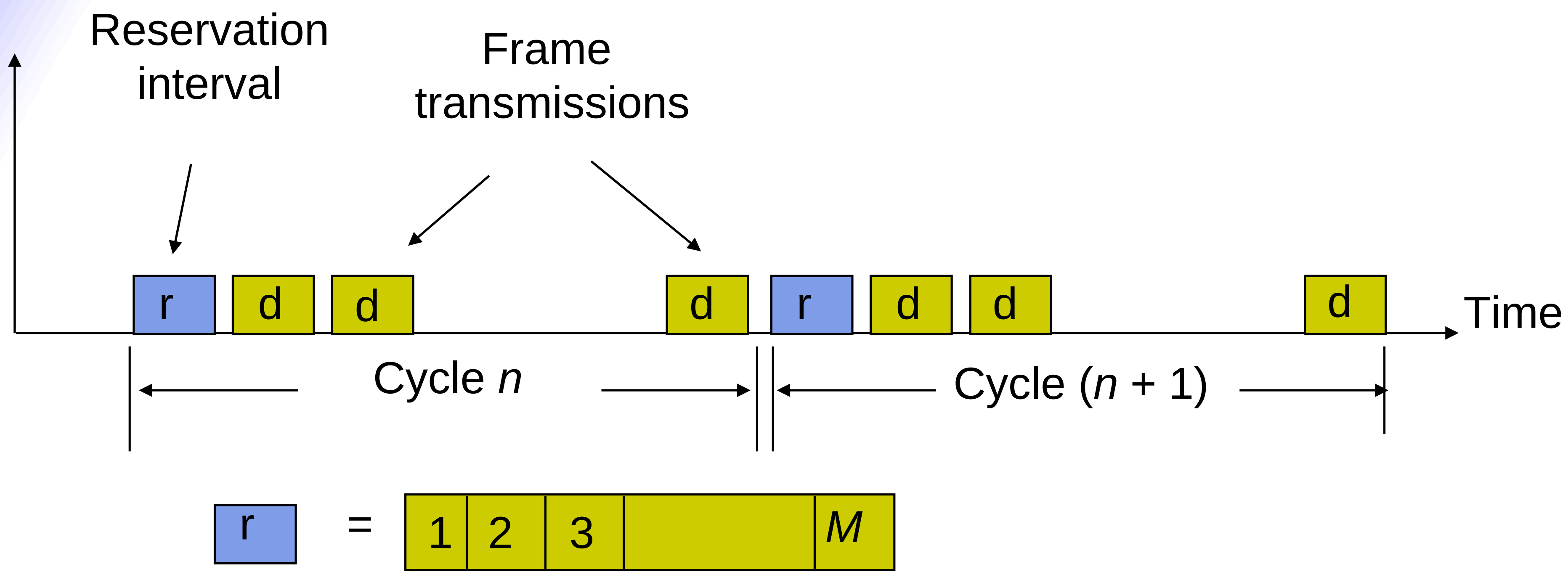
- schedule frame transmissions to avoid collision in shared medium
  - ✓ more efficient channel utilization
  - ✓ less variability in delays
  - ✓ can provide fairness to stations
  - ✗ increased computational or procedural complexity
- two main approaches
  - Reservation Systems
  - Polling

Reservations Systems

- *Centralized systems*: A central controller accepts requests from stations and issues grants to transmit
  - Frequency-Division Duplex (FDD): Separate frequency bands for uplink & downlink
  - Time-Division Duplex (TDD): Uplink & downlink time-share the same channel
- *Distributed systems*: Stations implement a decentralized algorithm to determine transmission order







- Transmissions organized into cycles
- Cycle: reservation interval + frame transmissions
- Reservation interval has a minislot for ***each*** station to request reservations for frame transmissions

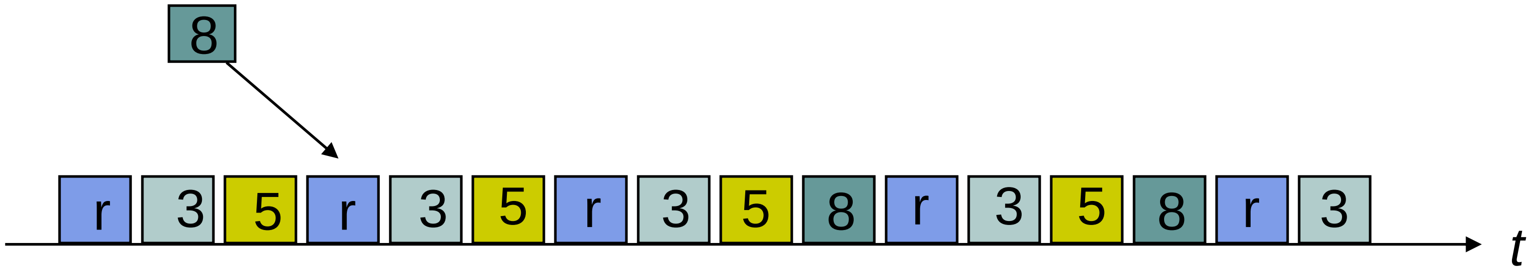
- Centralized or distributed system
  - *Centralized systems*: A central controller listens to reservation information, decides order of transmission, issues grants
  - *Distributed systems*: Each station determines its slot for transmission from the reservation information
- Single or Multiple Frames
  - *Single frame reservation*: Only one frame transmission can be reserved within a reservation cycle
  - *Multiple frame reservation*: More than one frame transmission can be reserved within a frame
- Channelized or Random Access Reservations
  - *Channelized (typically TDMA) reservation*: Reservation messages from different stations are multiplexed without any risk of collision
  - *Random access reservation*: Each station transmits its reservation message randomly until the message goes through

- Initially stations 3 & 5 have reservations to transmit frames

(a)

- Station 8 becomes active and makes reservation
- Cycle now also includes frame transmissions from station 8
- Reservation may take effect with some delay

(b)



- Assume minislot duration = *vX*
- TDM single frame reservation scheme
  - If propagation delay is negligible, a single frame transmission requires *(1+v)X* seconds
  - Link is fully loaded when all stations transmit, maximum efficiency is:

$$\rho_{\max} = \frac{MX}{M\nu X + MX} = \frac{1}{1+\nu}$$

- TDM *k* frame reservation scheme
  - If *k* frame transmissions can be reserved with a reservation message and if there are *M* stations, as many as *Mk* frames can be transmitted in *XM(k+v)* seconds
  - Maximum efficiency is:

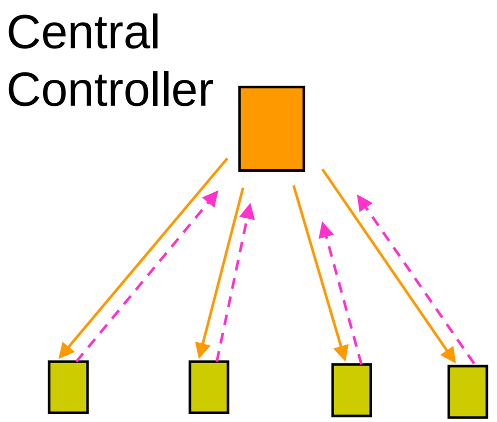
$$\rho_{\max} = \frac{MkX}{M\nu X + MkX} = \frac{1}{1+\frac{\nu}{k}}$$

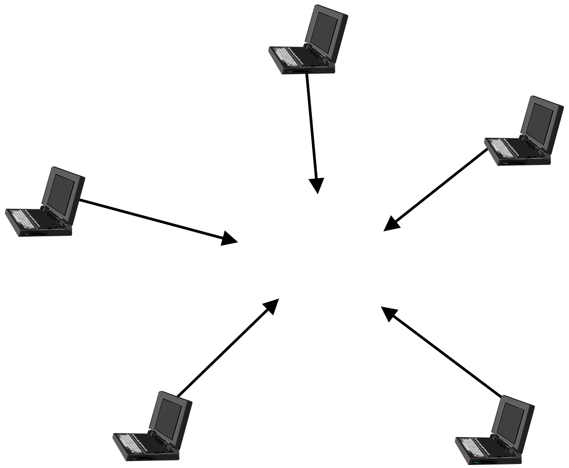
- *Large number of light traffic stations*
  - Dedicating a minislot to each station is inefficient
- Slotted ALOHA reservation scheme
  - Stations use slotted Aloha on reservation minislots
  - On average, each reservation takes at least *e* minislot attempts
  - Effective time required for the reservation is 2.71vX

$$\rho_{\max} = \frac{X}{X(1+ev)} = \frac{1}{1 + 2.71v}$$

Polling Systems

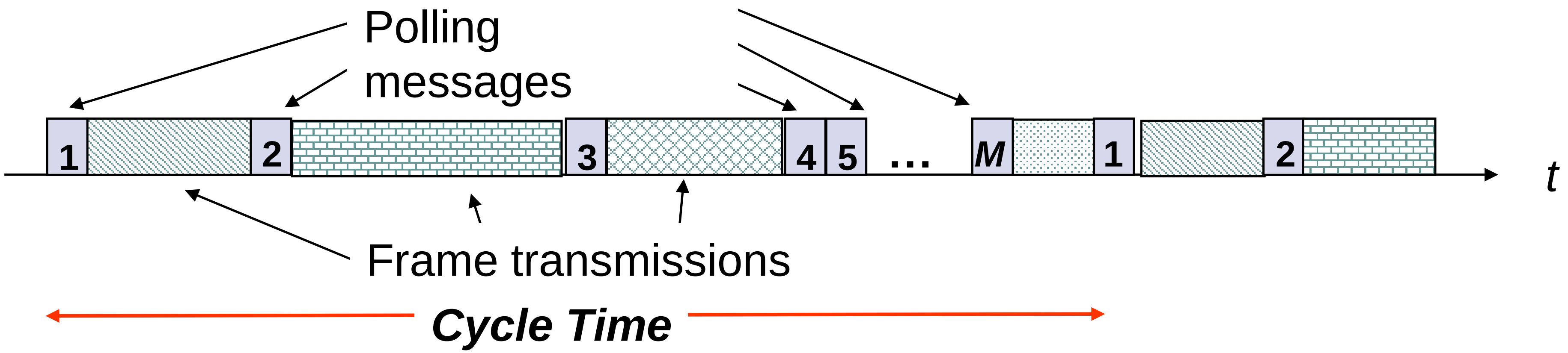
- *Centralized polling systems*: A central controller transmits polling messages to stations according to a certain order
- *Distributed polling systems*: A permit for frame transmission is passed from station to station according to a certain order
- A signaling procedure exists for setting up order

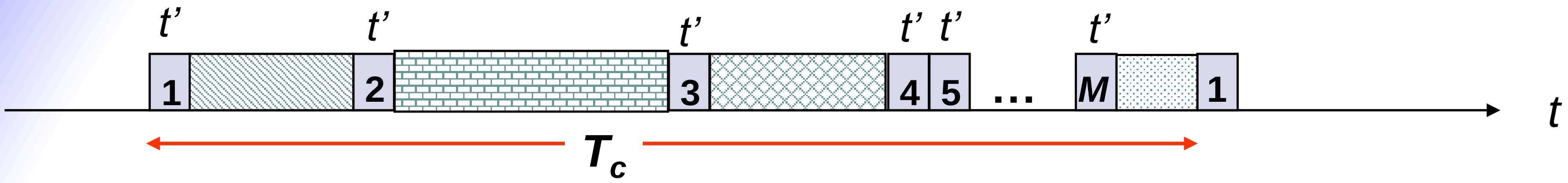




- Service Limits: How much is a station allowed to transmit per poll?
  - *Exhaustive*: until station's data buffer is empty (including new frame arrivals)
  - *Gated*: all data in buffer when poll arrives
  - *Frame-Limited*: one frame per poll
  - *Time-Limited*: up to some maximum time
- Priority mechanisms
  - More bandwidth & lower delay for stations that appear multiple times in the polling list
  - Issue polls for stations with message of priority *k* or higher

- Assume polling order is round robin
- Time is “wasted” polling stations
  - Time to prepare & send polling message
  - Time for station to respond
- *Walk time:* from when a station completes transmission to when next station begins transmission
- *Cycle time* is between consecutive polls of a station
- Overhead/cycle = total walk time/cycle time





- Assume walk times all equal to *t’*
- Exhaustive Service: stations empty their buffers
- Cycle time = *Mt’* + time to empty *M* station buffers
- λ/M be frame arrival rate at a station
- N_C average number of frames transmitted from a station
- Time to empty one station buffer:

$$T_{station} = N_c X = (\frac{\lambda}{M} T_c) X = \frac{\rho T_c}{M} \qquad \rho = \lambda X$$

- Average Cycle Time:

$$T_c = Mt' + MT_{station} = Mt' + \rho T_c \quad \Rightarrow \boxed{T_c = \frac{Mt'}{1-\rho}}$$

- Exhaustive Service
  - Cycle time increases as traffic increases, so delays become very large
  - Walk time per cycle becomes negligible compared to cycle time:

$$Efficiency = \frac{T_c - Mt'}{T_c} \Rightarrow 1$$

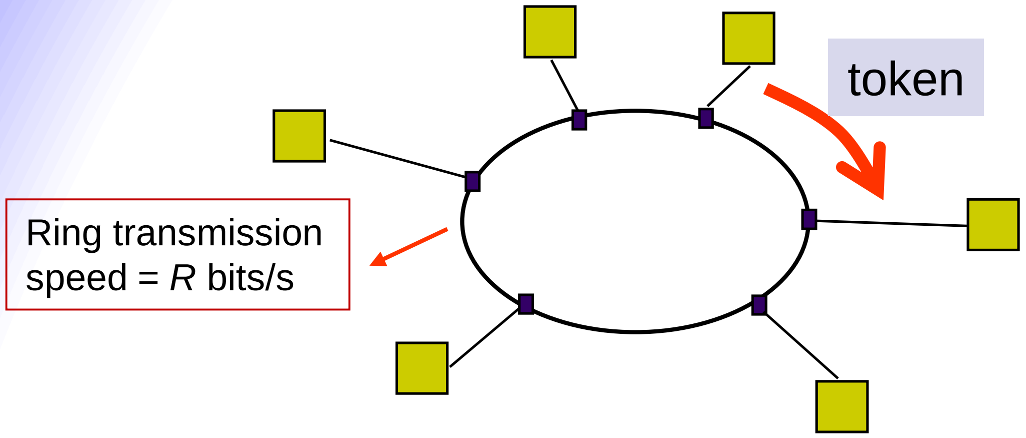
Can approach 100%

- Limited Service
  - Many applications cannot tolerate extremely long delays
  - Time or transmissions per station are limited
  - This limits the cycle time and hence delay
  - Efficiency of 100% is not possible

$$Efficiency = \frac{MX}{MX + Mt'} = \frac{1}{1 + t'/X}$$

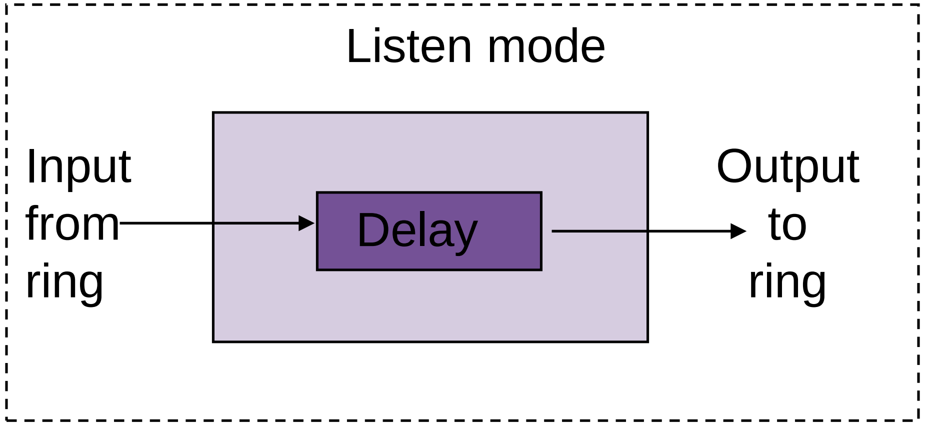
Single frame per poll

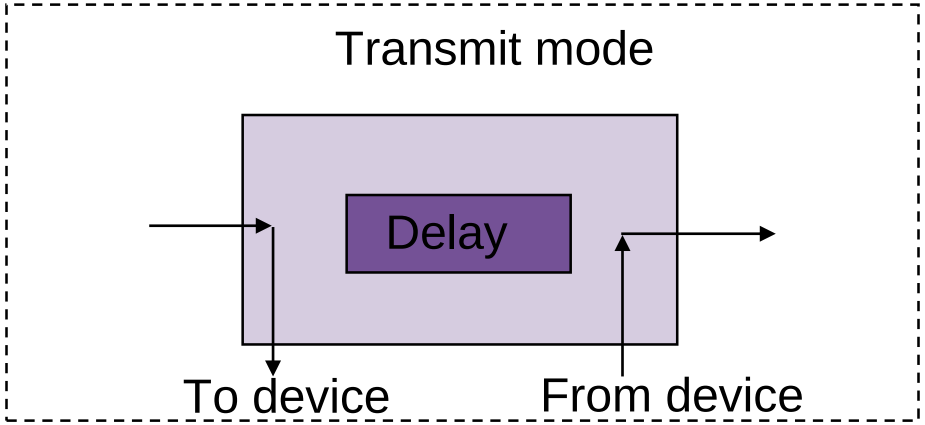
Token-Passing Rings



Free Token = Poll

Frame Delimiter is Token
Free = 01111110
Busy = 01111111



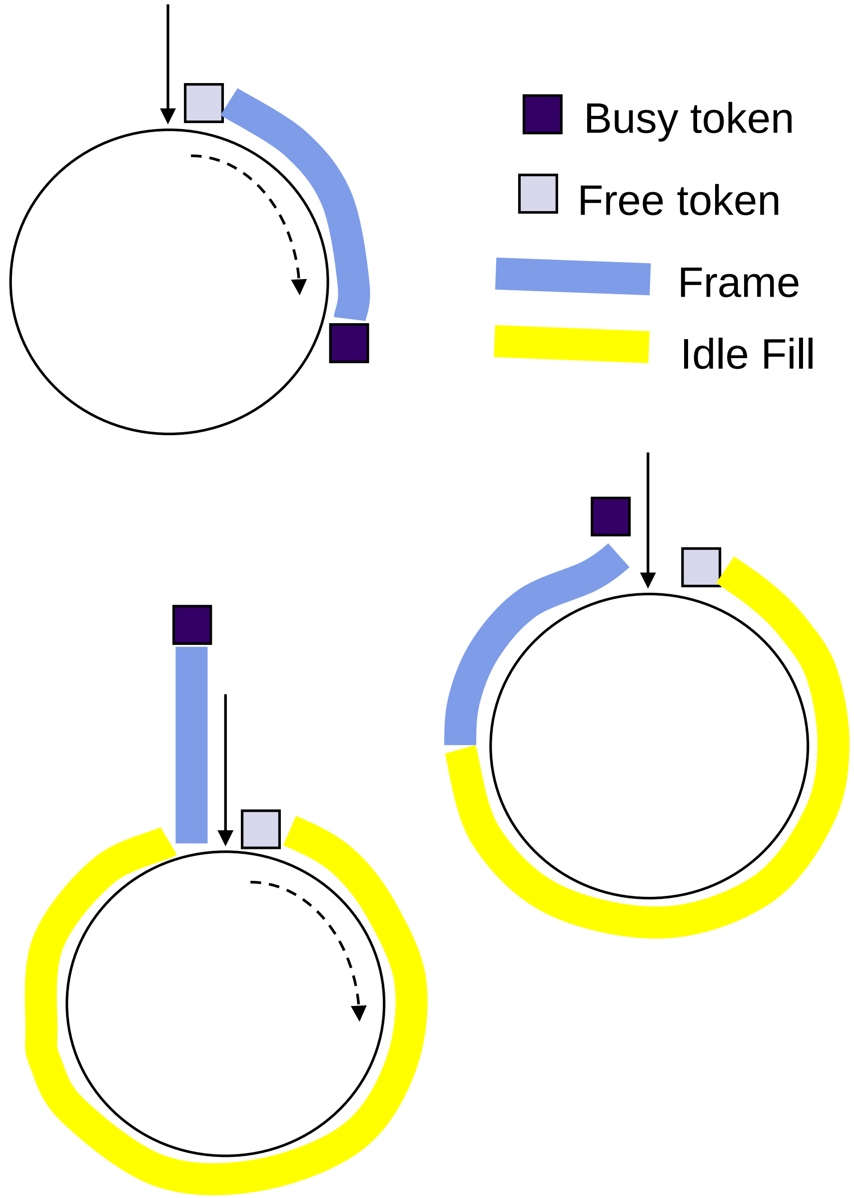


Ready station looks for free token
Flips bit to change free token to busy

Ready station inserts its frames
Reinserts free token when done

output in each station is delayed by b bits $\rightarrow$ delay in each station = b/R

- Multi-token operation
  - Free token transmitted immediately after last bit of data frame
- Single-token operation
  - Free token inserted after last bit of the busy token is received back, and the last bit of the frame is transmitted
  - Transmission time at least ring latency
  - If frame is longer than ring latency, equivalent to multi-token operation
- Single-Frame operation
  - Free token inserted after transmitting station has received last bit of its frame
  - Equivalent to attaching trailer equal to ring latency
  - Can check the return frame for errors



Definition:

τ': ring latency => $\tau + \frac{Mb}{R}$

- τ is the propagation delay around the ring
- M is the number stations
- R is bandwidth of the ring
- ρ_{max} is the maximum normalized throughput

b is number of bit delays in an interface

Assuming only one frame can be transmitted per token:

- **Multi-token operation**

$$\rho_{\max} = \frac{MX}{\tau' + MX} = \frac{1}{1 + \tau'/MX} = \frac{1}{1 + a'/M}$$

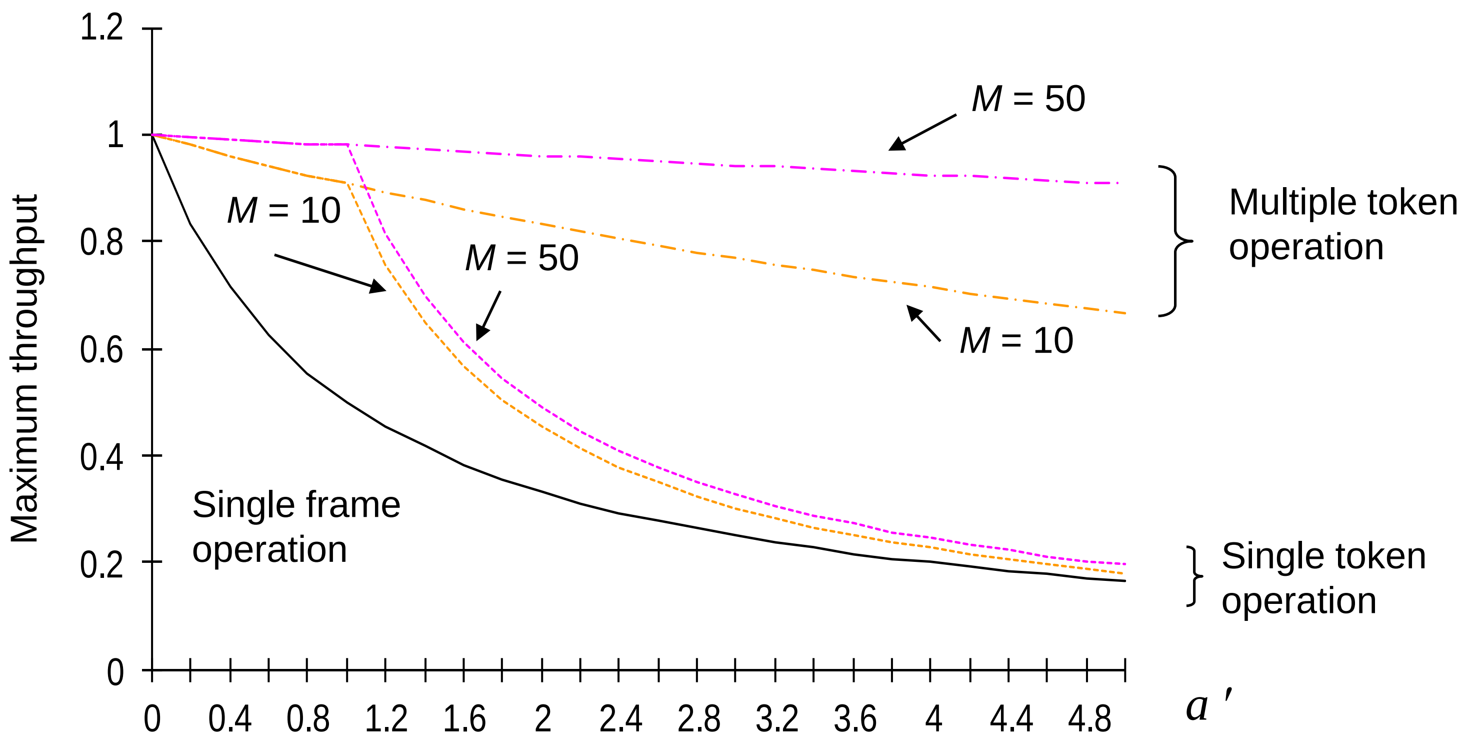
$$a' = \frac{\tau'}{X} \text{ is the normalized ring latency}$$

- *Single-token operation*
  - Effective frame transmission time is maximum of X and τ', therefore

$$\rho_{max} = \frac{MX}{\tau' + M \max\{X, \tau'\}} = \frac{1}{\max\{1, a'\} + a'/M}$$

- *Single-frame operation*
  - Effective frame transmission time is X+ τ' ,therefore

$$\rho_{max} = \frac{MX}{\tau' + M(X + \tau')} = \frac{1}{1 + a'(1 + 1/M)}$$



- $a' \ll 1$, any token reinsertion strategy acceptable
- $a' \approx 1$, single token reinsertion strategy acceptable
- $a' > 1$, multitoken reinsertion strategy necessary

- Single-frame reinsertion
  - IEEE 802.5 Token Ring LAN @ 4 Mbps
- Single token reinsertion
  - IBM Token Ring @ 4 Mbps
- Multitoken reinsertion
  - IEEE 802.5 and IBM Ring LANs @ 16 Mbps
  - FDDI Ring @ 50 Mbps
- All of these LANs incorporate token priority mechanisms

Comparison of MAC approaches

- ALOHA & slotted ALOHA
  - Simple & quick transfer at very low load
  - Accommodates large number of low-traffic bursty users
  - Highly variable delay at moderate loads
  - Efficiency does not depend on a
- CSMA-CD
  - Quick transfer and high efficiency for low delay-bandwidth product
  - Can accommodate large number of bursty users
  - Variable and unpredictable delay

- Reservation
  - On-demand transmission of bursty or steady streams
  - Accommodates large number of low-traffic users with slotted Aloha reservations
  - Can incorporate QoS
  - Handles large delay-bandwidth product via delayed grants
- Polling
  - Generalization of time-division multiplexing
  - Provides fairness through regular access opportunities
  - Can provide bounds on access delay
  - Performance deteriorates with large delay-bandwidth product

Chapter Summary

- multiple access communications
- random access
  - ALOHA
  - slotted ALOHA
  - Carrier Sense Multiple Access (CSMA)
- scheduling
  - Reservation Systems
  - Polling
  - Token-Passing Rings

Reference

Chapter 6, Communication Networks: Fundamental Concepts and Key Architectures