

EP2210 – FEP3210

Performance analysis of Communication networks

Topic 2
Medium access control
(or multiple access protocols)

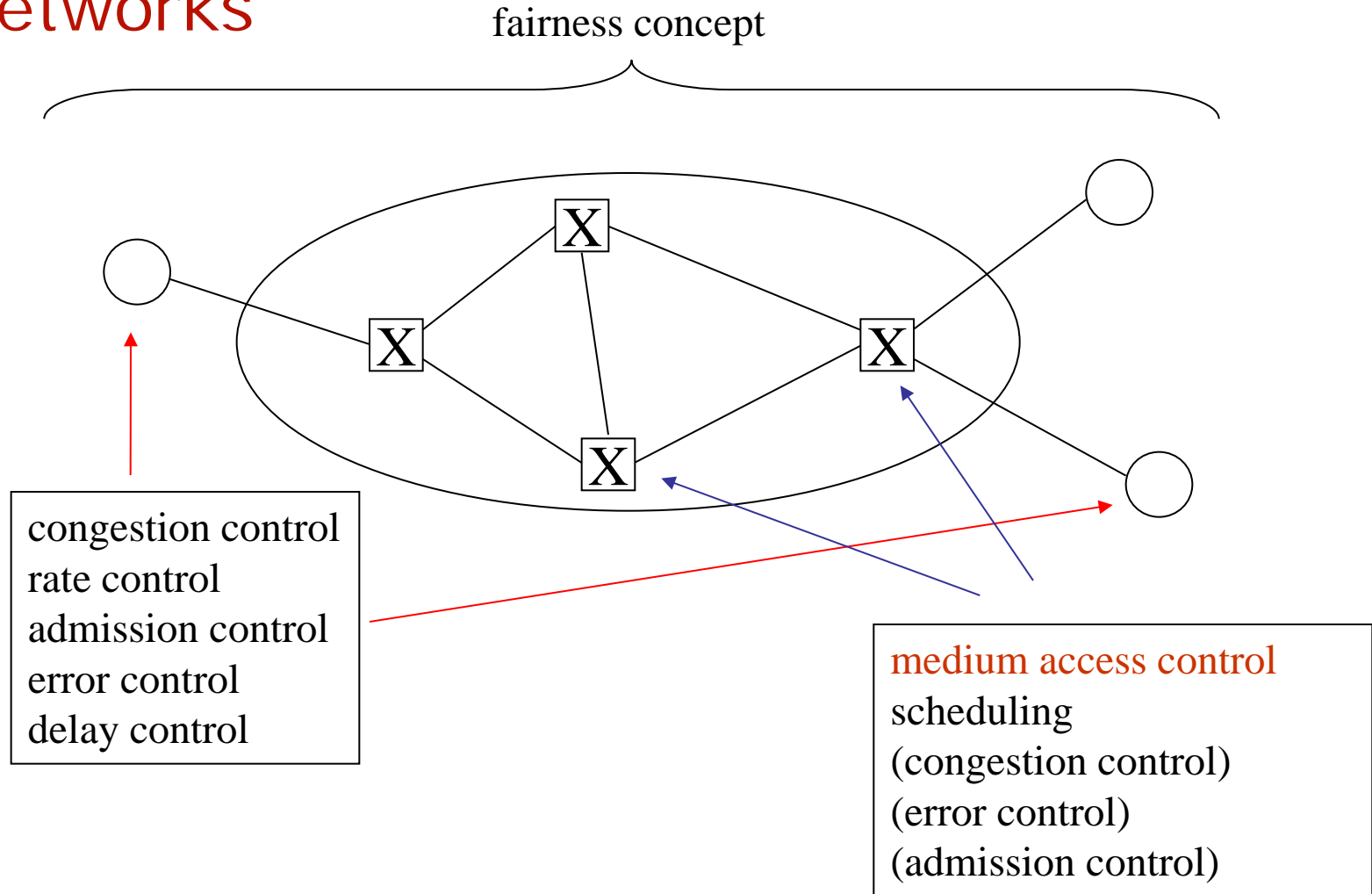
Medium access control

- Lecture material:
 - R. Rom, M. Sidi, Multiple access protocols, Ch. 2-4
 - TDMA, FDMA, Aloha
- Reading for next lecture:
 - R. Rom, M. Sidi, Multiple access protocols, Ch. 2-4
 - Slotted Aloha, CSMA, CSMA/CD main results

Control functions in communication networks

- Protocols or control functions?
- **Control functions** are selected to achieve given objectives (e.g., lossless transmission)
- **Protocols** are realizations of a set of (distributed) control functions, where
- Control functions are coupled in some sensible way (e.g., loss and congestion control in TCP)

Control functions in communication networks

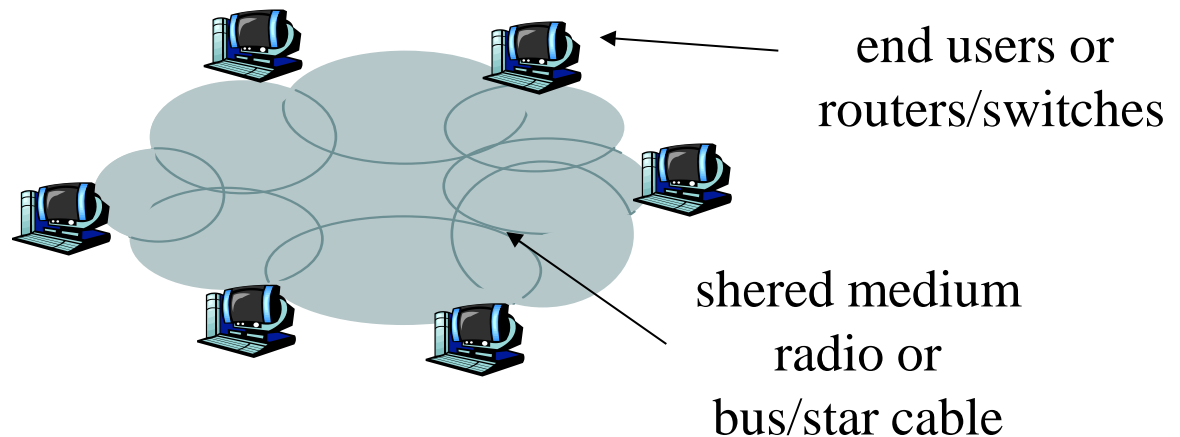


Group work

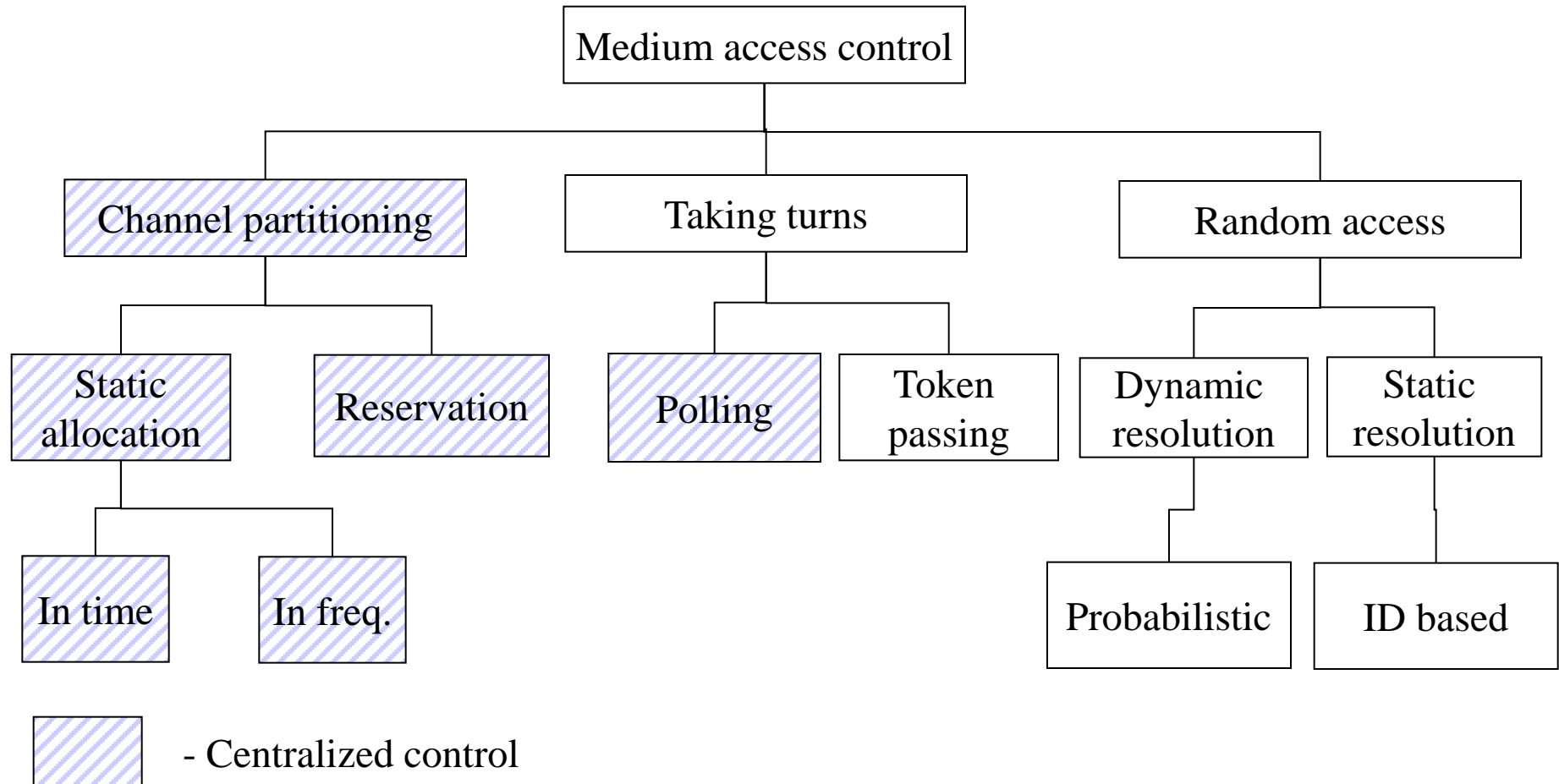
- Give examples of protocols/methods that realize the following control functions.
- Where are these protocols/methods implemented in the network?
 - Medium access cont.
 - Error control
 - Delay control
 - Congestion control
 - Admission control
 - Rate control
 - Scheduling
 - IEEE 802.x
 - IEEE 802.x. TCP, phy, app
 - Playout buffer management
 - TCP
 - Call process in mobile nw.
 - Service level agreements
 - Switches with priority function
- End-to-end principle!

Medium access control

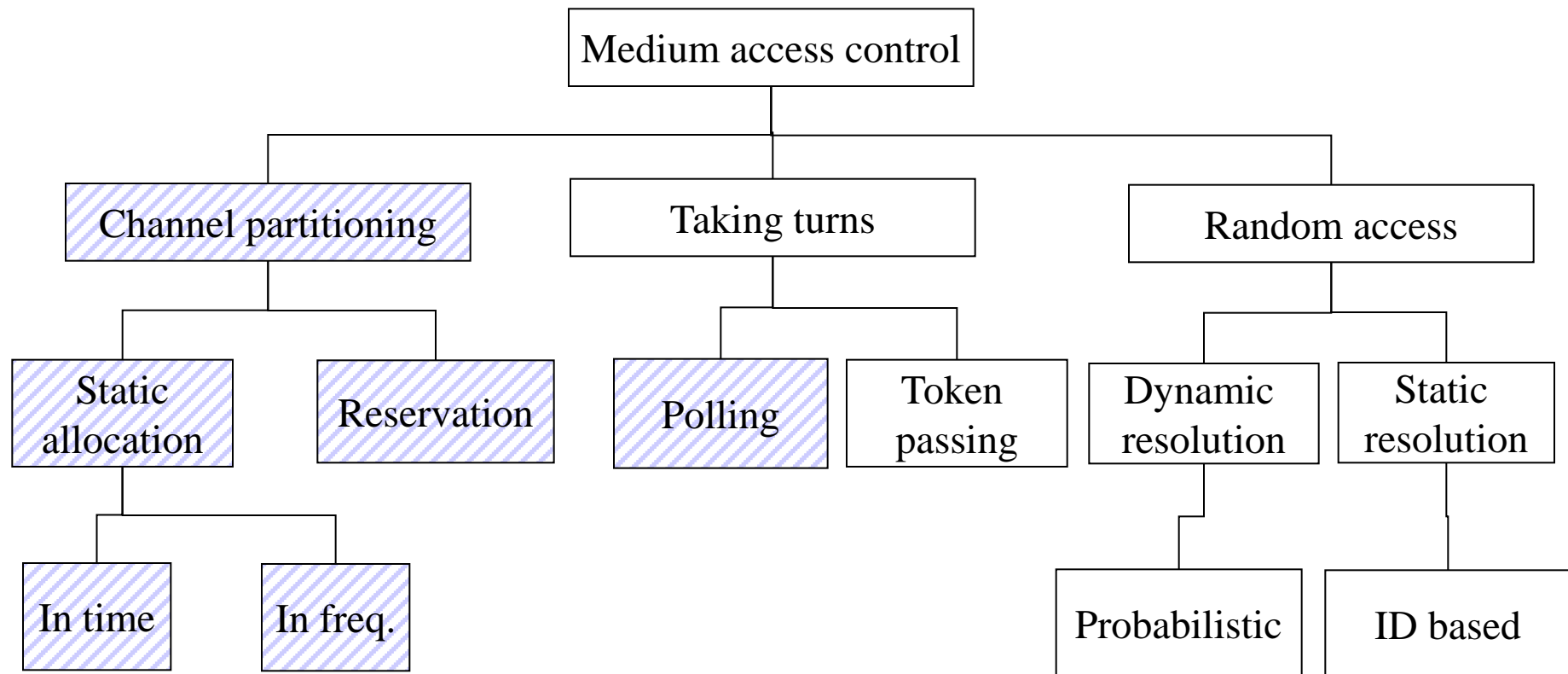
- Medium access control
 - to regulate the access to a shared medium (radio or cable)
 - the main objectives of medium access control
 - Simplicity – have to work at very high speed
 - Efficiency – have to utilize the resources well
 - Fairness – all users should get the similar chances to access the network



Classification



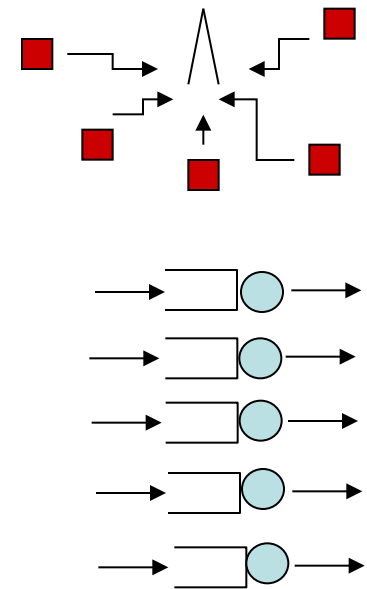
Group work



Classify the followings: FDMA, TDMA, CSMA/CD, Token-ring, Bluetooth, ZigBee, WirelessHART

FDMA performance analysis

- FDMA example:
 - In a cellular system each user (or session) receives a subband of the available spectrum.
 - Each user transmits at the same time, independently from each other.
- Networking scenario:
 - Users receive an equal share of the spectrum.
 - Each user transmits fixed size packets over the FDMA link (deterministic packet size)
 - The packets are generated according to a **Poisson process**, with the same intensity at each user.
 - Queues are infinite
 - We re interested in the **delay** from packet generation to completed transmission



FDMA performance analysis

- Each user served independently: M independent M/D/1 queues
- Average delay as a function of the throughput

R : channel bitrate

M : number of users

→ R/M bitrate per user

λ : packet arrival rate from a single user, Poisson

P : packet size, constant

T : transmission time $T=P/(R/M)$

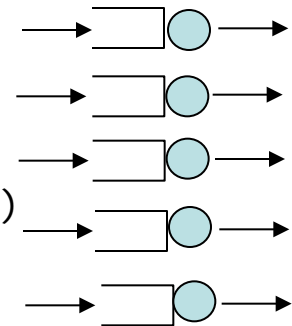
ρ : per channel load ($\rho=\lambda T < 1$)

S : per channel throughput, defined by the fraction of time the channel is busy transmitting useful data, max throughput=1

$S=\rho$: since no losses or unsuccessful transmissions happen

D : average delay including waiting + transmission

D^* : and delay normalized by P/R (packet transmission time for $M=1$)



FDMA performance analysis

- Each user served independently: M independent M/D/1 queues
- Average delay as a function of the throughput

R : channel bitrate

M : number of users

λ : packet arrival rate from a single user, Poisson

P : packet size, constant

T : transmission time

$S = \rho$: per channel and system throughputs are equal

D, D^* : average waiting + transmission delay and delay normalized by P/R .

$$T = P / (R / M)$$

$$\rho = \lambda T = S$$

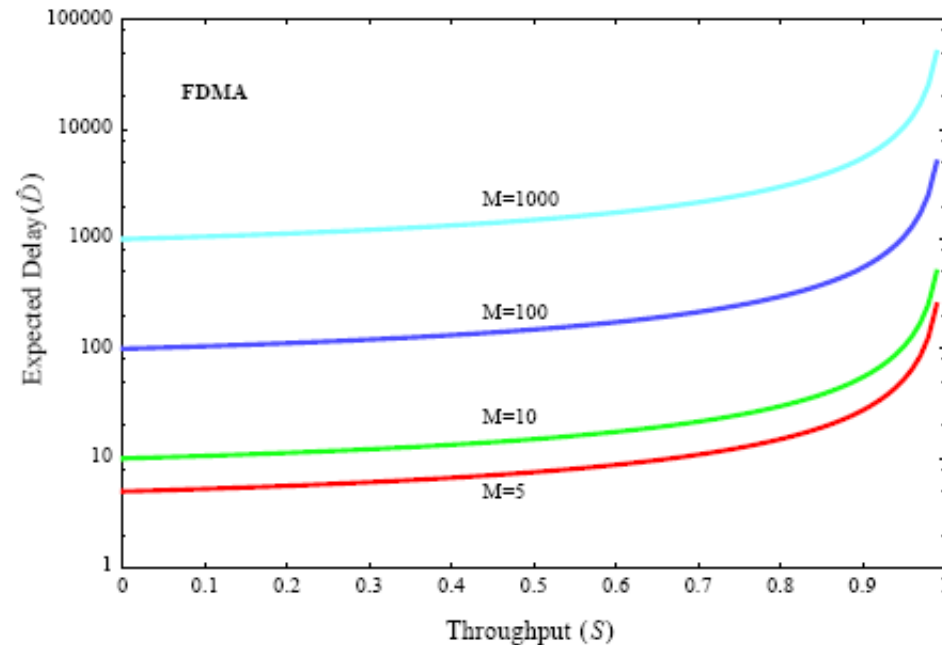
*This depends on the channel bitrate
and the packet size. Normalize!*

$$D = T + W = T + \frac{\lambda T^2}{2(1 - \lambda T)} = T \left[1 + \frac{S}{2(1 - S)} \right] = \frac{MP}{R} \left[1 + \frac{S}{2(1 - S)} \right]$$

$$D^* = \frac{D}{P/R} = M \left[1 + \frac{S}{2(1 - S)} \right] = \frac{M}{2} \left[2 + \frac{S}{1 - S} \right] = \frac{M}{2} \left[1 + \frac{1 - S + S}{1 - S} \right] = \frac{M}{2} \left[1 + \frac{1}{1 - S} \right]$$

FDMA performance analysis

$$D^* = \frac{M}{2} \left[1 + \frac{1}{1-S} \right]$$



- At small load the average delay is determined by the packet transmission time, that is, the number of users: $D^* \sim M$.
- This means, the system uses the resources in an inefficient way if the load is small.
- Simple, fair, but not efficient.

TDMA performance analysis

- Average delay as a function of the throughput

R : channel bitrate

M : number of users

λ : packet arrival rate from a single user, Poisson

P : packet size, constant

$T=P/R$: packet transmission time

$T_c=MT$: frame duration

$S=\rho=\lambda T_c = \lambda MT = \lambda P/(R/M)$:

for the same λ , R and M the same as for FDMA.

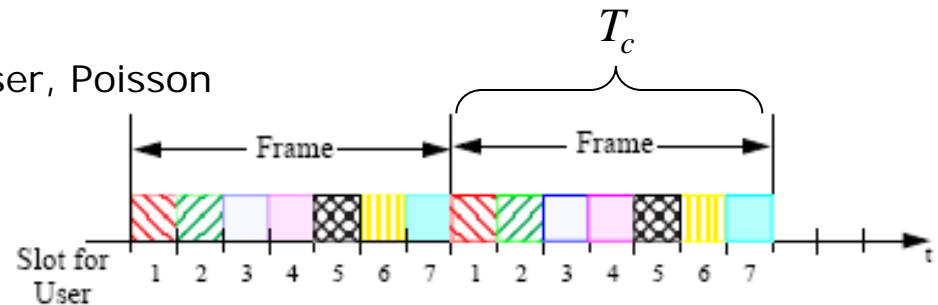
Average delay of a packet:

- packet transmission time: T
- queuing time, 1 packet per frame transmitted: like queuing time in M/D/1 with T_c
- average time until the beginning of a new frame: $0.5T_c$

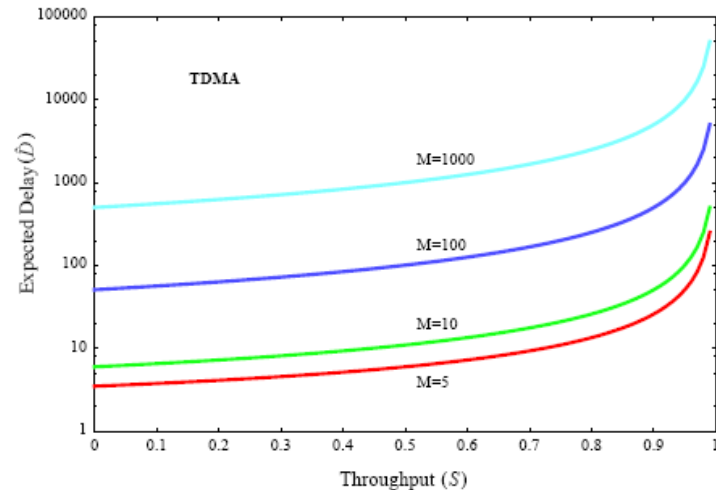
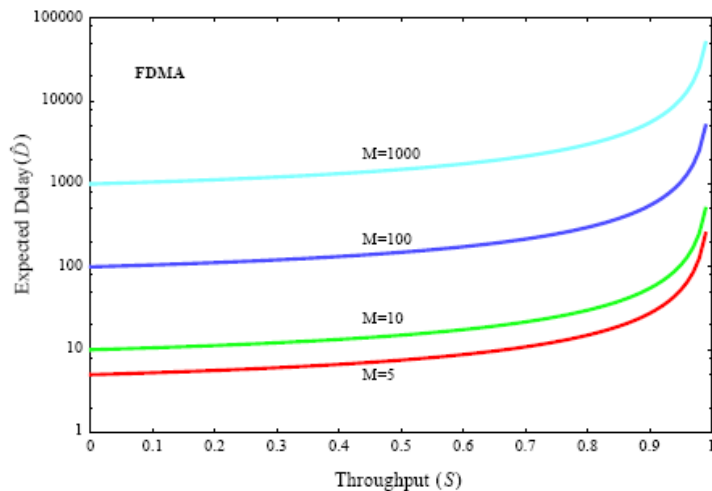
$$D = T + \frac{\lambda T_c^2}{2(1-\lambda T_c)} + 0.5T_c = T + \frac{SMT}{2(1-S)} + 0.5MT = T + \frac{S+1-S}{2(1-S)} MT$$

$$D = T \left[1 + \frac{M}{2(1-S)} \right] = \frac{R}{P} \left[1 + \frac{M}{2(1-S)} \right]$$

$$D^* = \frac{D}{P/R} = 1 + \frac{M}{2(1-S)}$$



TDMA-FDMA performance analysis



$$D^*_{FDMA} = \frac{M}{2} + \frac{M}{2(1-S)}$$

$$D^*_{TDMA} = 1 + \frac{M}{2(1-S)}$$

$$D^*_{FDMA} - D^*_{TDMA} = \frac{M}{2} - 1$$

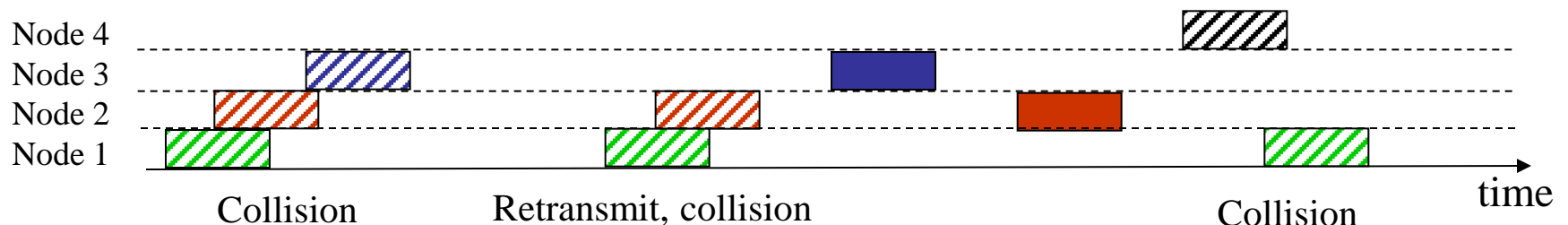
- TDMA is more efficient than FDMA, independently of the load
- However, TDMA is more complex to implement (slot synchronization)

Random access – or contention based protocols

- (Pure) Aloha
- The first contention based medium access protocol
- The naïve approach
 - If you have data → send
 - If the transmission is not successful → wait random amount of time then try again (back-off)
- 1971, Hawaii, communication between islands

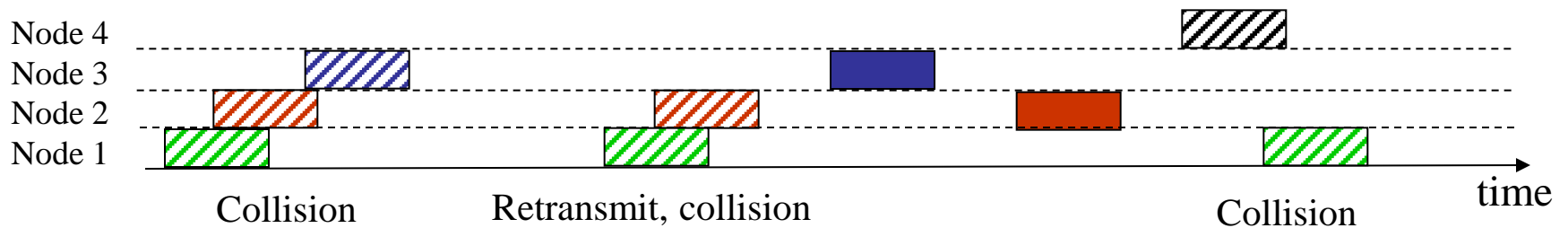
Aloha protocol description

- All nodes share the common transmission medium (radio, bus, star)
- Nodes transmit newly generated packets immediately
- Colliding packets are lost, no bits can be recovered
- If no acknowledgement arrives, nodes retransmit with random delay



Aloha – maximum throughput

- Model assumptions and notation:
 - infinite population
 - transmitted and retransmitted packets from all users form a Poisson arrival process ($g > \lambda$)
 - constant packet transmission time (T)
 - offered load: $G = gT$
 - throughput (collision free): S
- Vulnerable period: packet is lost if other packets arrive within this time interval: $2T$



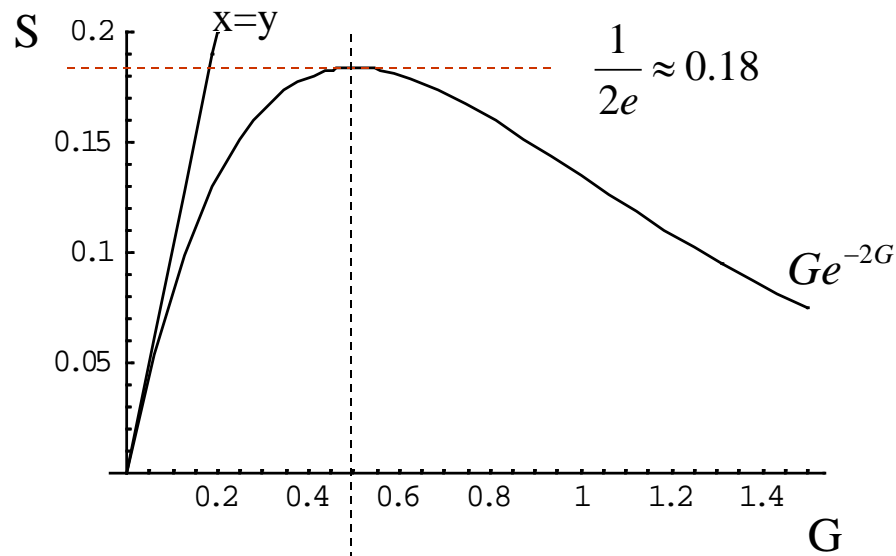
Aloha – maximum throughput

$$p(k) = P\{k \text{ arrivals in } 2T \text{ period}\} = \frac{(g2T)^k}{k!} e^{-g2T}$$

$$P_{succ} = P\{\text{no other arrivals in } 2T \text{ period}\} = e^{-2gT}$$

$$S = P_{succ} gT = gT e^{-2gT}$$

$$S = G e^{-2G}, \quad S' = (1 - 2G) e^{-2G}$$

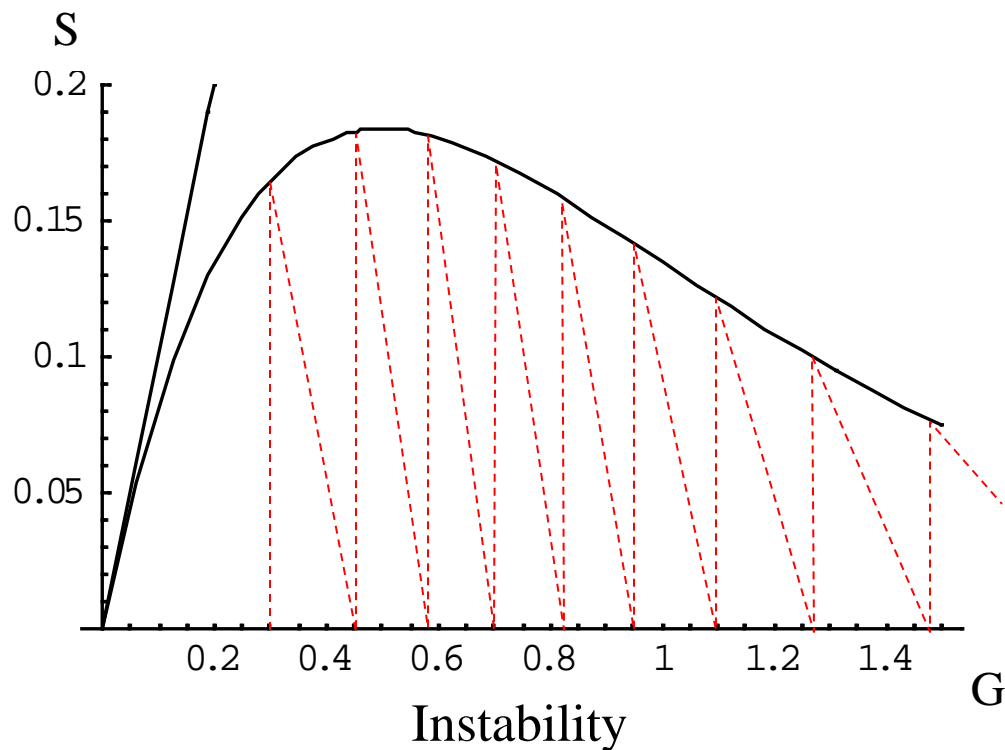


- Poisson arrival with g
- S : throughput defined as useful load (< 1)
- $G = gT$: offered load

- Max throughput of 0.18
- At offered load (first and retransmissions) of 0.5

Aloha instability

- Pure Aloha throughput converges to 0 under Poisson load
 - simple, fair, not efficient
 - Poisson load is not realistic (off hours), so Aloha could work in practice
- It is not a perfect solution – let's look at the modifications



Aloha improvements – home reading

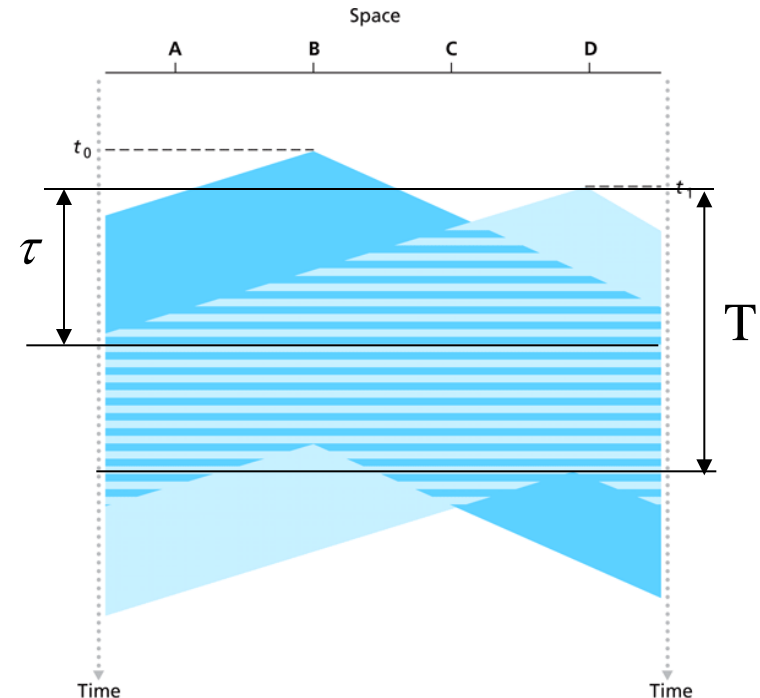
- Slotted version to decrease contention interval
 - home reading, including throughput analysis (R-S 3.2)
- Listen before talk: carrier sense multiple access, CSMA
 - home reading, basic ideas and results, discussed next lecture (R-S 4.3)
- Listen while talking: CSMA with collision detection, CSMA/CD
 - home reading, basic ideas and results (R-S 4.4)
- IEEE 802.11 Markovian model
 - maybe discussed next lecture

Carrier sense multiple access - CSMA

- Pure Aloha throughput converges to 0 under Poisson load
- It is not a good solution – let's look at the modifications
- Idea: **Listen before** you transmit – carrier sense
- If channel is idle → send data
- If channel is busy → back off
 - nonpersistence: packet rescheduled with a random delay
 - 1-persistent: packet transmitted immediately as the channel becomes idle
 - p-persistent one of the two with probability p and $1-p$
- If no acknowledgement received transmit again
- If all nodes listen before transmit, and **all nodes see the channel**, is there collision in CSMA?

CSMA modeling – slotted case

- Collision due to propagation delay
- Efficient only if the packet transmission time (T) is much larger than the propagation time (τ)
- Slotted CSMA
 - time divided into minislots = propagation delay (τ)
 - packets wait until the beginning of next minislot, and sense the channel
 - if idle: transmit
 - if busy: retries according to being persistent or non-persistent

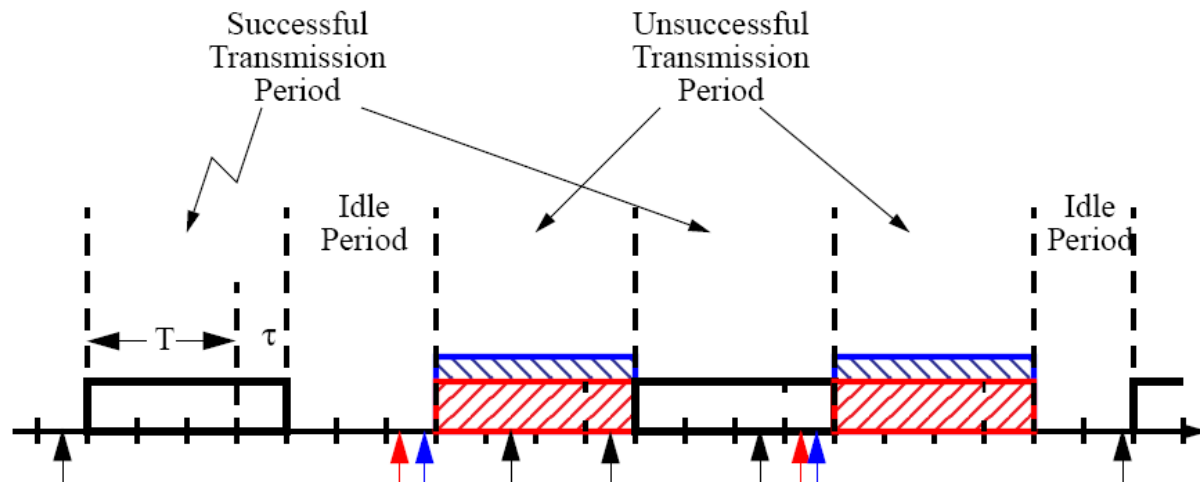


CSMA modeling – slotted case

- Modeling:

- Poisson packet arrival, λ
- fixed packet size, T
- **Throughput (S) = (useful periods)/(idle+busy periods) busy period=useful or collision**
- slotted, nonpersistent (if busy, tries again with random back-off)
- minislot: propagation time (equal for all pair of nodes), τ
- normalized diameter, $a = \tau / T \ll 1$ (Packet transmission time \gg propagation time)
- assume $1/a$ is integer, packets occupy "a" minislots.
- average idle period, I
- average busy period (successful transmission or collision), B
- average useful period (successful transmission), U

$$S = \frac{U}{B + I}$$



CSMA modeling – slotted case

Idle period : $P[\hat{I} = k\tau] = (e^{-g\tau})^{k-1} (1 - e^{-g\tau})$ (geometric distr.)

$$I = \frac{\tau}{1 - e^{-g\tau}}$$

*No arrival in $k-1$ slots,
at least one in slot k*

Transmission periods in busy period : $P[\hat{L} = l] = (1 - e^{-g\tau})^{l-1} e^{-g\tau}$, $L = \frac{1}{e^{-g\tau}}$

Busy period : $B = (T + \tau)L = \frac{T + \tau}{e^{-g\tau}}$

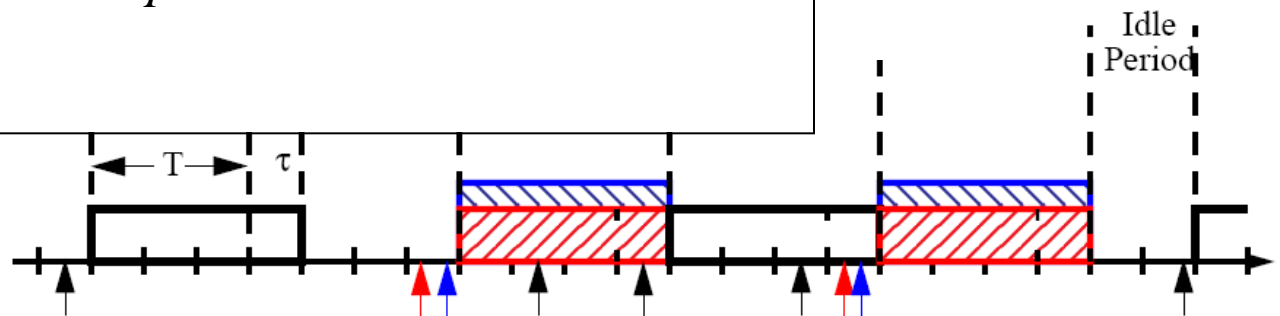
*At least one arrival in $l-1$ slots,
no arrival in the l -th slot*

$$P_{succ} = P[\text{single arrival} \mid \text{some arrivals}] = \frac{P[\text{single arrival}]}{P[\text{some arrivals}]} = \frac{g\tau e^{-g\tau}}{1 - e^{-g\tau}}$$

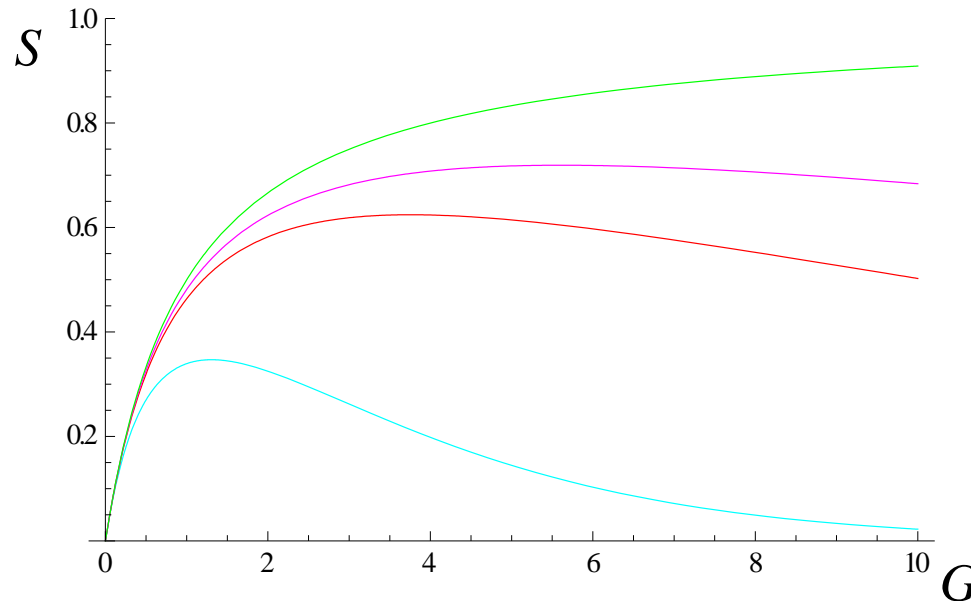
Useful periods within a busy period : $U = \frac{T}{T + \tau} \cdot BP_{succ} = LTP_{succ} = \frac{T}{e^{-g\tau}} P_{succ}$

$$S = \frac{U}{B + I} = \dots = \frac{aGe^{-aG}}{1 + a - e^{-aG}} \quad (a = \frac{\tau}{T})$$

$$S_{a \rightarrow 0} = \frac{G}{1 + G}$$



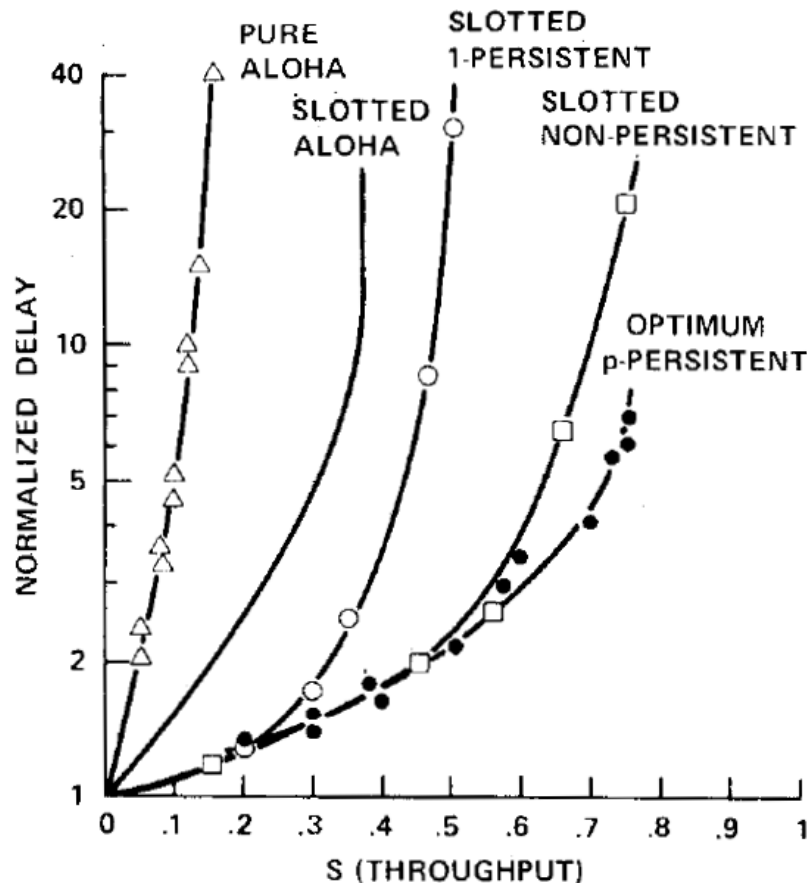
Aloha and CSMA comparison



- **Group work:** find the corresponding curve:
 - slotted Aloha
 - slotted CSMA with $a=0.5$ (packet length = $2 \times$ propagation time)
 - slotted CSMA with $a=0.1$
 - slotted CSMA with $a=0.05$
 - slotted CSMA with $a=0$ (packet length \gg propagation time)

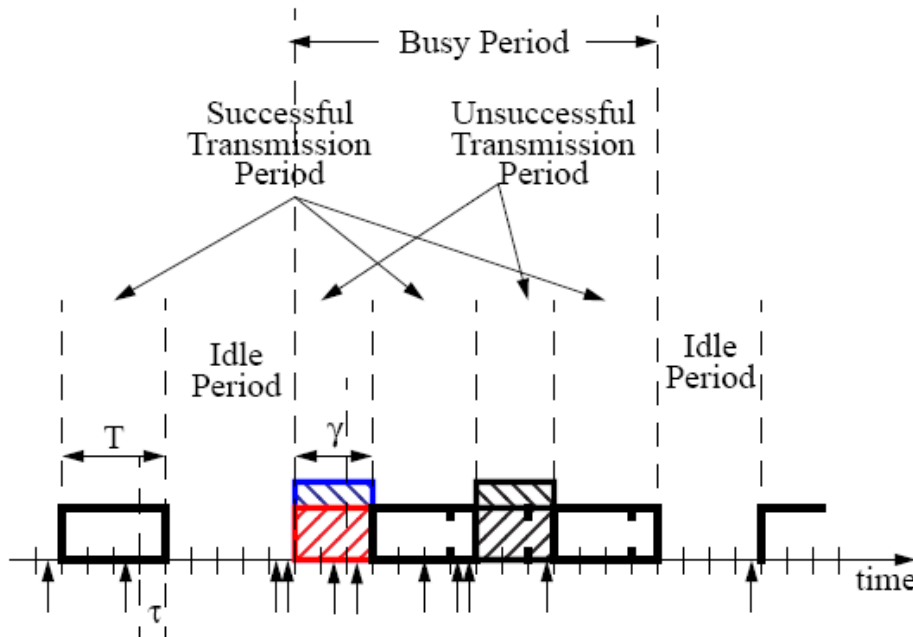
Aloha, CSMA – minimum average delay

Source: Kleinrock, Fuad, Tobagi, "Packet Switching in Radio Channels," 1975



CSMA/CD – slotted case

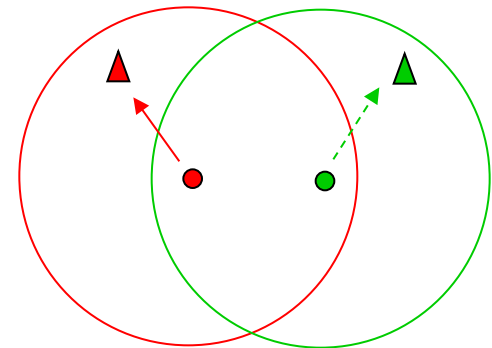
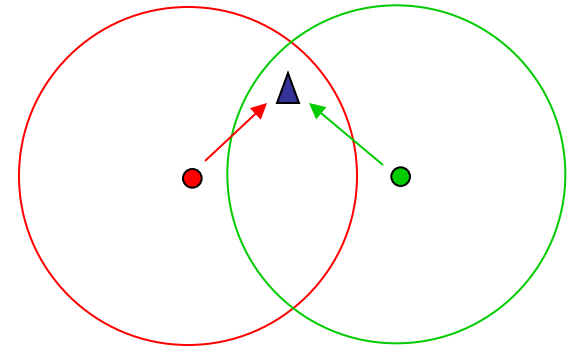
- To increase utilization: shorten busy periods -> shorten unsuccessful periods
- Listen while transmit
 - if collision is detected transmit jamming signal and stop transmission
 - γ : the length of the unsuccessful transmission, $\tau < \gamma < T$



- Modeling:
 - length of idle period
 - transmission periods in busy period
 - probability of success
 - length of busy periods
 - throughput
 - Home reading!

CSMA in wireless networks

- Does CSMA/CD work fine in wireless networks?
- Problem 0: Can not sense while transmit -> CSMA/CA
- Problem 1: **Hidden terminal problem**
 - the two terminals can not hear each others transmission
 - carrier sense does not work
- Solution: CSMA/CA with RTS/CTS
 - request to send (RTS)
 - clear to send (CTS)
 - both terminals can hear the CTS
- Problem 2: **Exposed terminal problem**
 - B could transmit, but backs off, as it assumes that the channel to its receiver is busy



CSMA/CA - 802.11

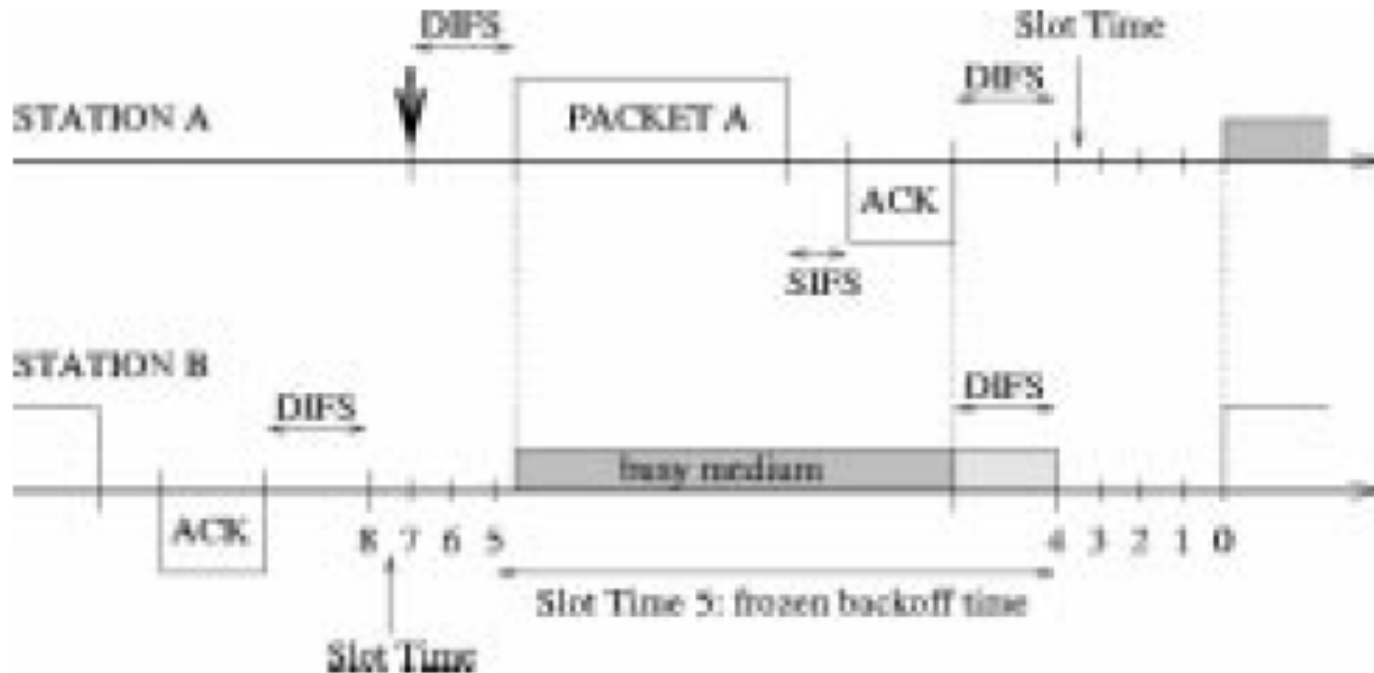
- G. Bianchi, Performance Analysis of the IEEE 802.11 Distributed Coordination Function, IEEE JSAC, 2000 March.
- Objective:
 - Saturation throughput, backlogged transmission queues, fixed number of stations
- Assumption:
 - Collision probability does not depend on history
 - All stations are identical
 - Each stations hear each other immediately
 - All colliding packets are lost

CSMA/CA - 802.11

- CSMA/CA recall
 - Station with a new packet:
 - Monitors the channel, keeps monitoring, until idle
 - Then waits for DIFS, then waits for a random back-off time (this is collision avoidance)
 - Station with retransmission:
 - Doubles the interval for the random back off $[0, 2^i W_0 - 1]$
 - Keeps interval constant after m retries.
 - Back-off counter:
 - Decrement if channel is idle, freezes if channel busy

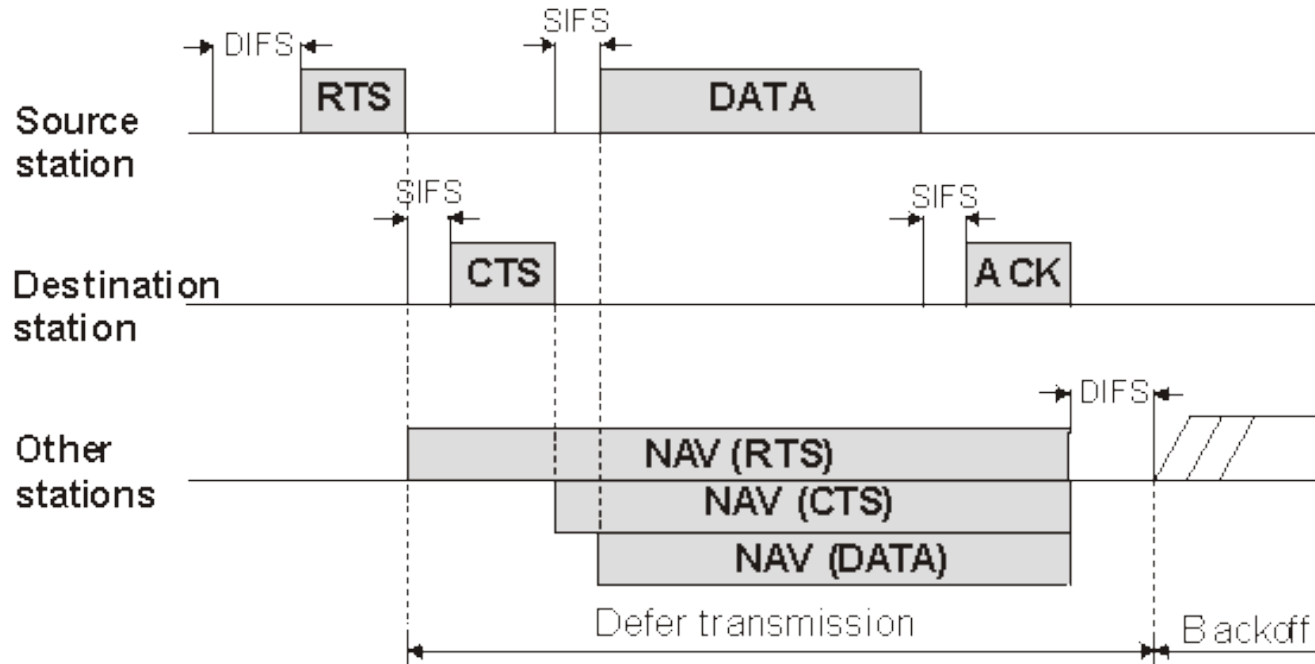
CSMA/CA - 802.11

- CSMA/CA recall – back off schemes



CSMA/CA - 802.11

- CSMA/CA recall – RTS/CTS to avoid hidden terminal problem
 - RTS and CTS carries information on packet length
 - Even hidden terminals can estimate the end of the packet transmission + ACK time

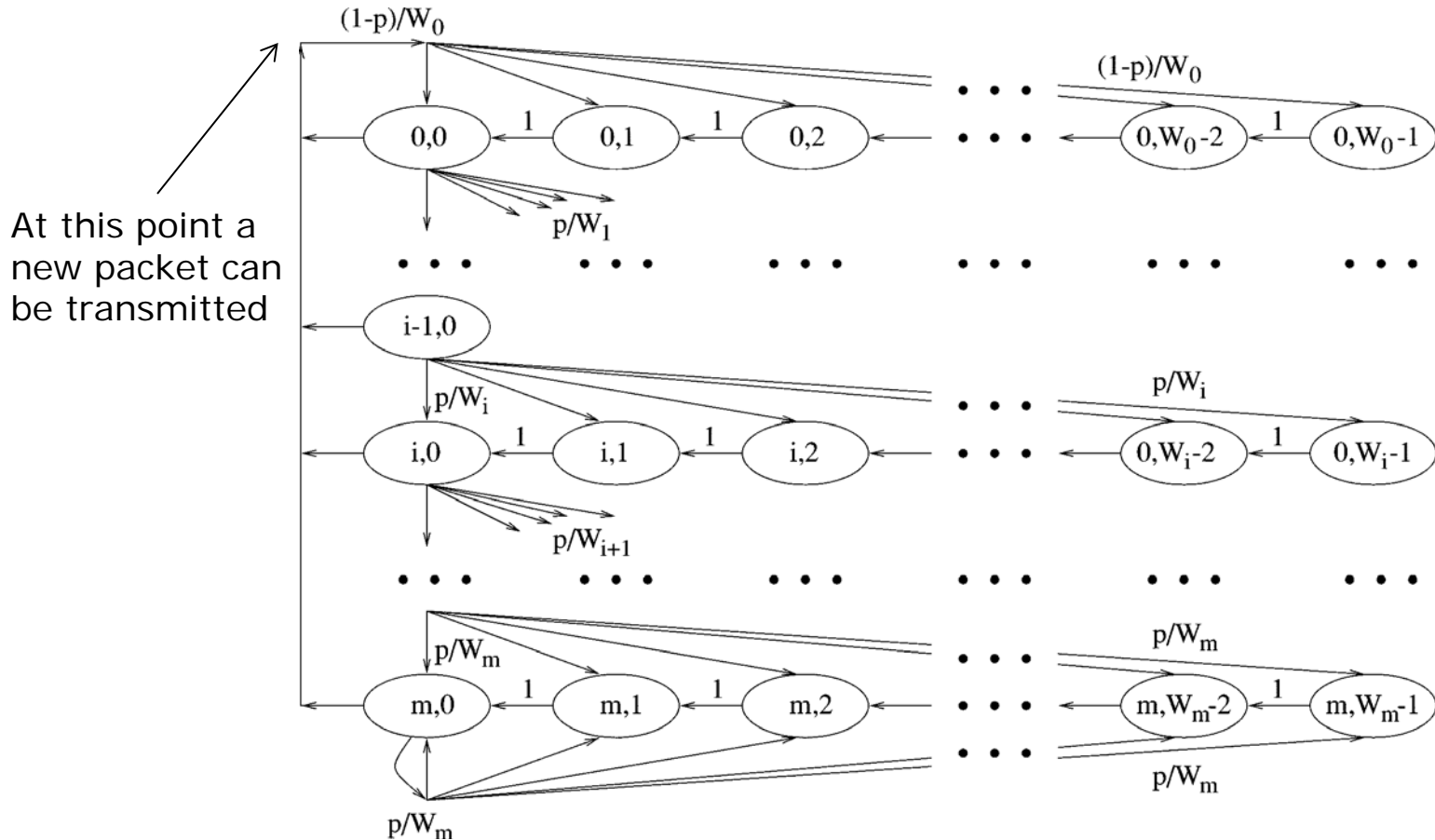


CSMA/CA - 802.11

- Modeling steps:
 - Model the transmission of a single packet – large discrete time Markov chain
 - Using and “abstract time, when frozen periods count as one time slot
 - Calculate the probability of successful packet transmission
 - *Calculate throughput, now counting for the frozen periods*
 - *Done*

CSMA/CA

- Markov chain describing transmissions from saturated queue



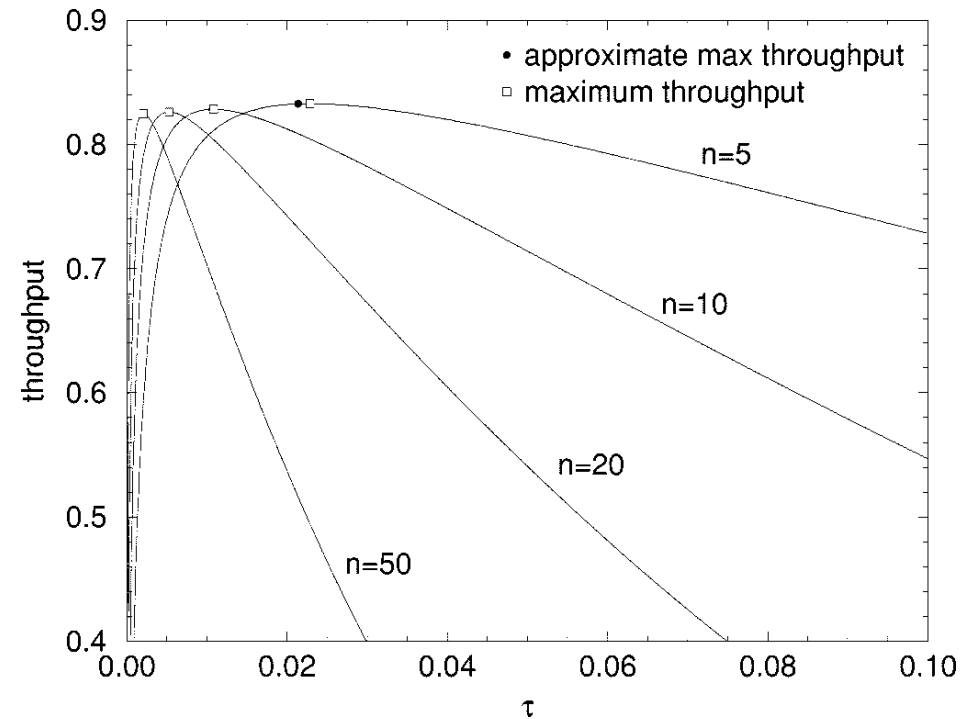
CSMA/CA

- Answer the following questions:
 - What are the two dimensions of the chain?
 - What is W_0 ?
 - Some transitions do not have transition probability given. Extend the figure with these.
 - In which states do transmissions happen?
 - Which of the transitions represent the successful packet transmission?
 - Which of the transitions represent what happens after collision?

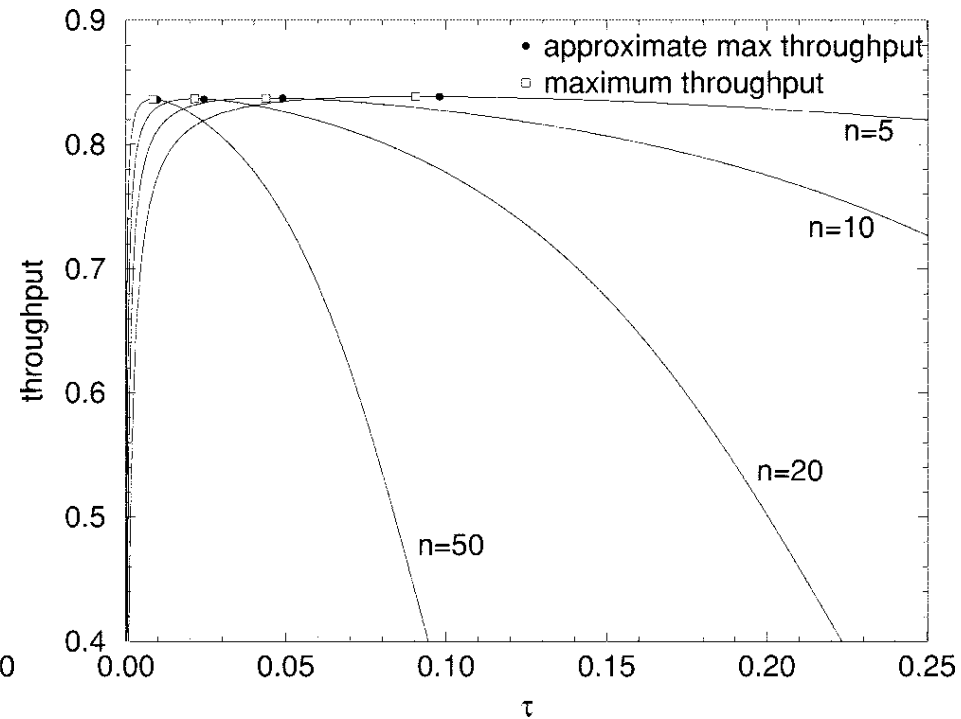
 - Let the steady state probability be $b_{i,j}$. (What is i and what is j ?)
 - Express the probability of packet transmission in a slot (τ).
 - Express the probability of collision (p), if n stations are present. (Remember, stations are assumed to be independent.)

(expressions τ and p form a non-linear system of equations, that can be solved...)

CSMA/CA



without RTS/CTS



with RTS/CTS

Access probability τ changed by changing the window size regions
 n : number of stations

Summary

- Medium access control protocols
 - Static allocation: TDMA, FDMA
 - Random access: Aloha, CSMA, CSMA/CD, CSMA/CA
- Simple models for general conclusions and comparison
 - Packet level models
 - Poisson arrival
 - Simplified network (e.g., equal distances, no hidden terminals)
- Bianchi model for CSMA/CA for saturated buffers
- Reading assignment:
 - Rom, Sidi, Multiple Access Protocols, excerpts
 - Ch.2: page 9 to top of 15 (FDMA, TDMA)
 - Ch.3: page 47 to 52 (ALOHA)
 - Ch 4: page 79 to 83, 89 to top of 92, 94 to 98 (CSMA variations)