EP2210 – FEP3210
Performance analysis of Communication networks

Topic 2
Medium access control
(or multiple access protocols)

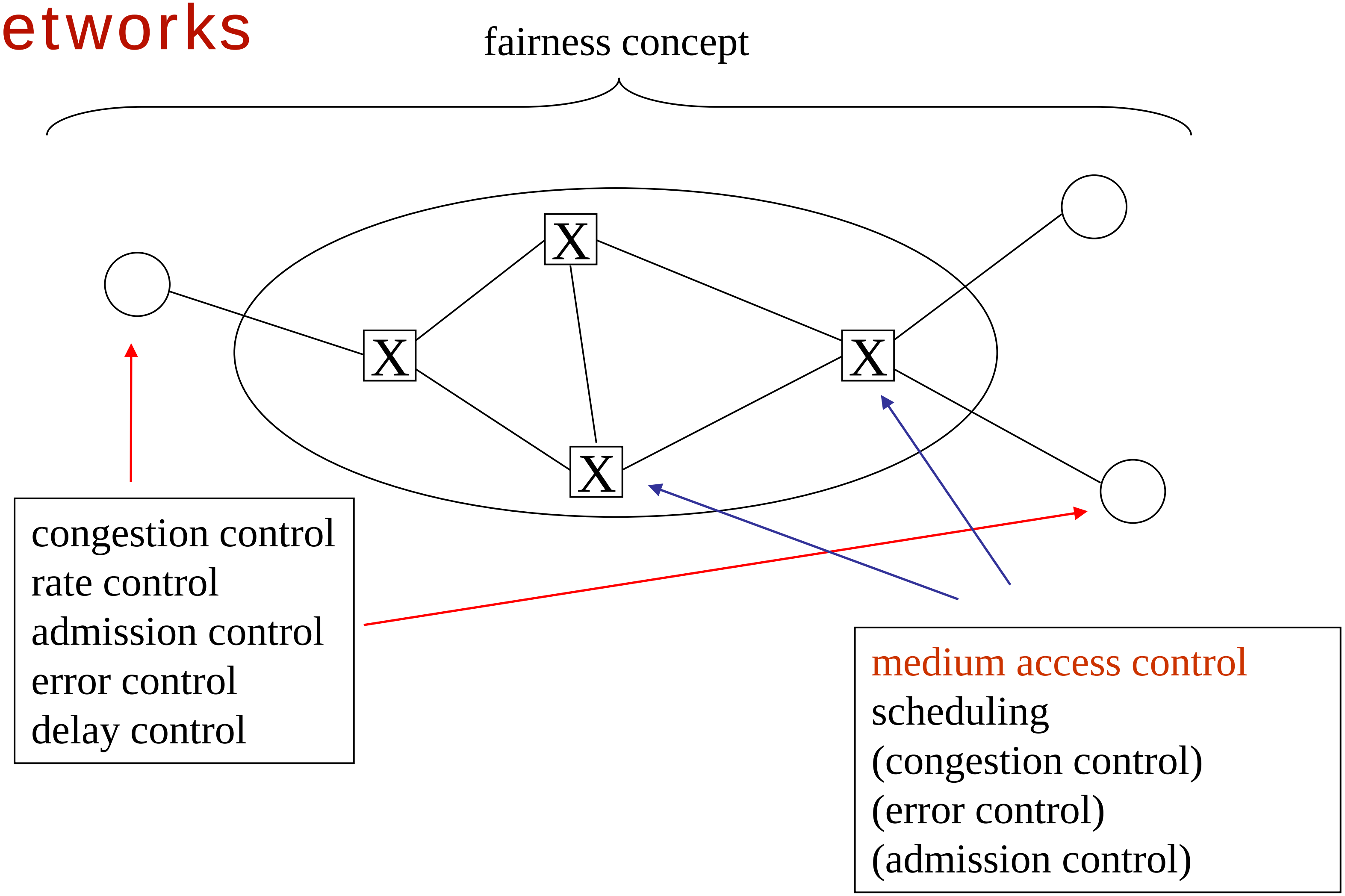
Medium access control

- Lecture material:
  - R. Rom, M. Sidi, Multiple access protocols, Ch. 2-4
  - TDMA, FDMA, Aloha, CSMA
- Reading for next lecture:
  - R. Rom, M. Sidi, Multiple access protocols, Ch. 2-4
  - Slotted Aloha, CSMA/CD main results
  - G. Bianchi, Performance Analysis of the IEEE 802.11 Distributed Coordination Function, IEEE JSAC, 2000 March.
    - Up to equation (16), and numerical 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



fairness concept

congestion control
rate control
admission control
error control
delay control

medium access control
scheduling
(congestion control)
(error control)
(admission control)

Group work

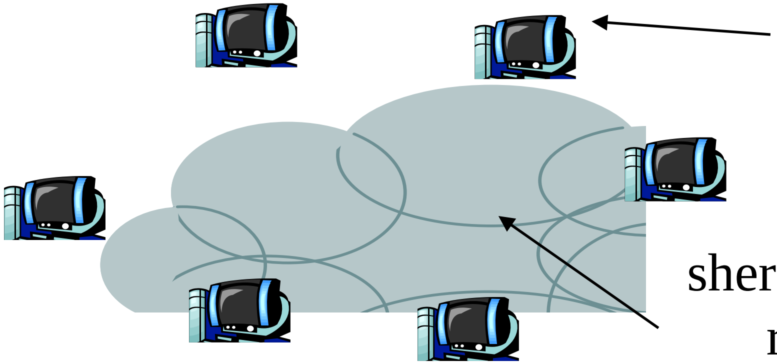
- Give examples of protocols/methods that realize the following control functions.
- Where are these protocols/methods implemented in the network?

Medium access cont.	IEEE 802.x
Error control	IEEE 802.x. TCP, phy, app
Delay control	Playout buffer management
Congestion control	TCP
Admission control	Call process in mobile nw.
Rate control	Service level agreements
Scheduling	Switches with priority function

- End-to-end principle!

Medium access control

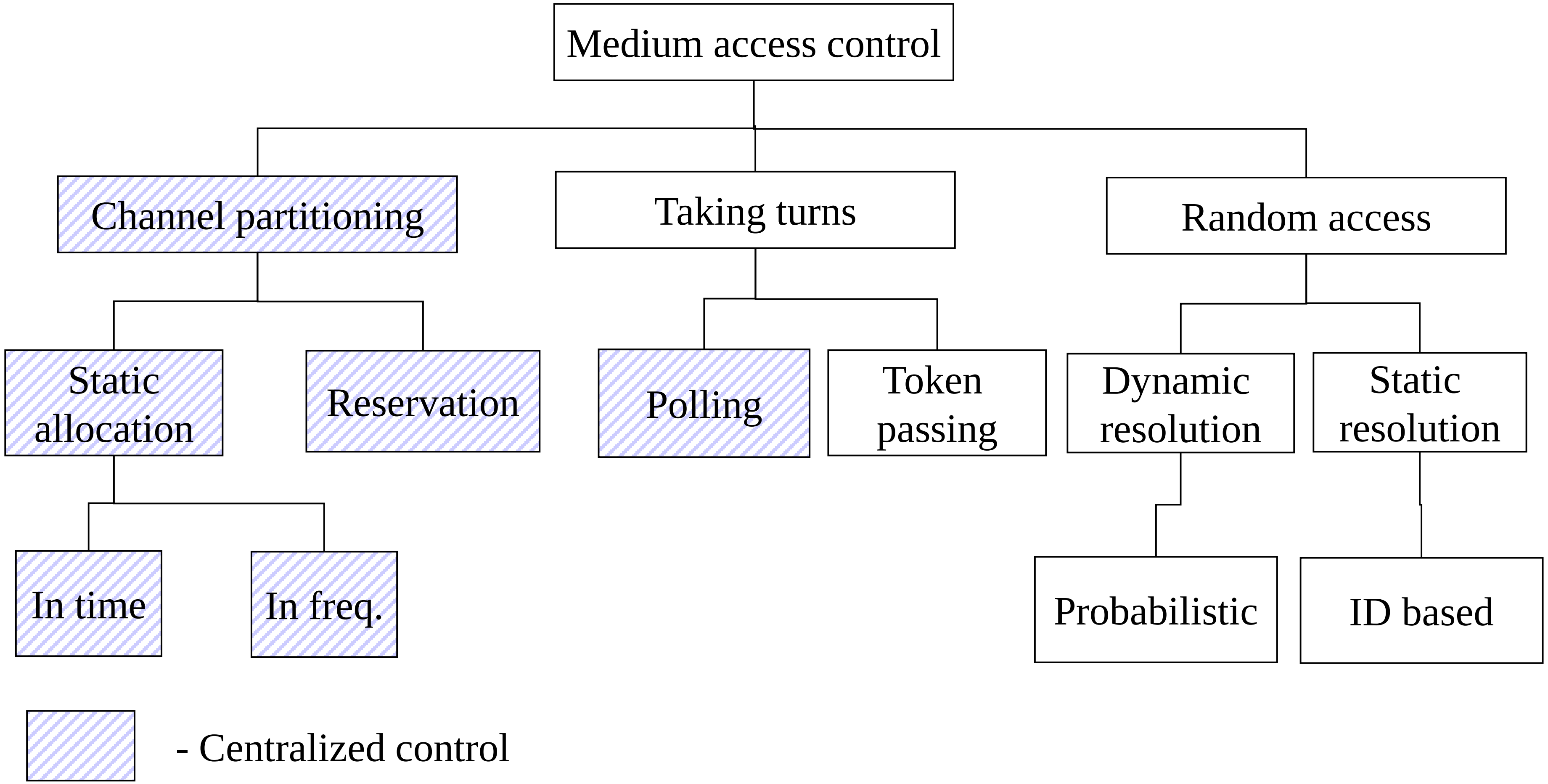
- Medium access control
  - to regulate the access to a shared medium (radio or cable)
  - the main objectives of medium access control
    - Simplicity – have to work at very high speed
    - Efficiency – have to utilize the resources well
    - Fairness – all users should get the similar chances to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



end users or
routers/switches

shered medium
radio or
bus/star cable

Classification


Medium access control

Channel partitioning

Taking turns

Random access

Static allocation

Reservation

Polling

Token passing

Dynamic resolution

Static resolution

In time

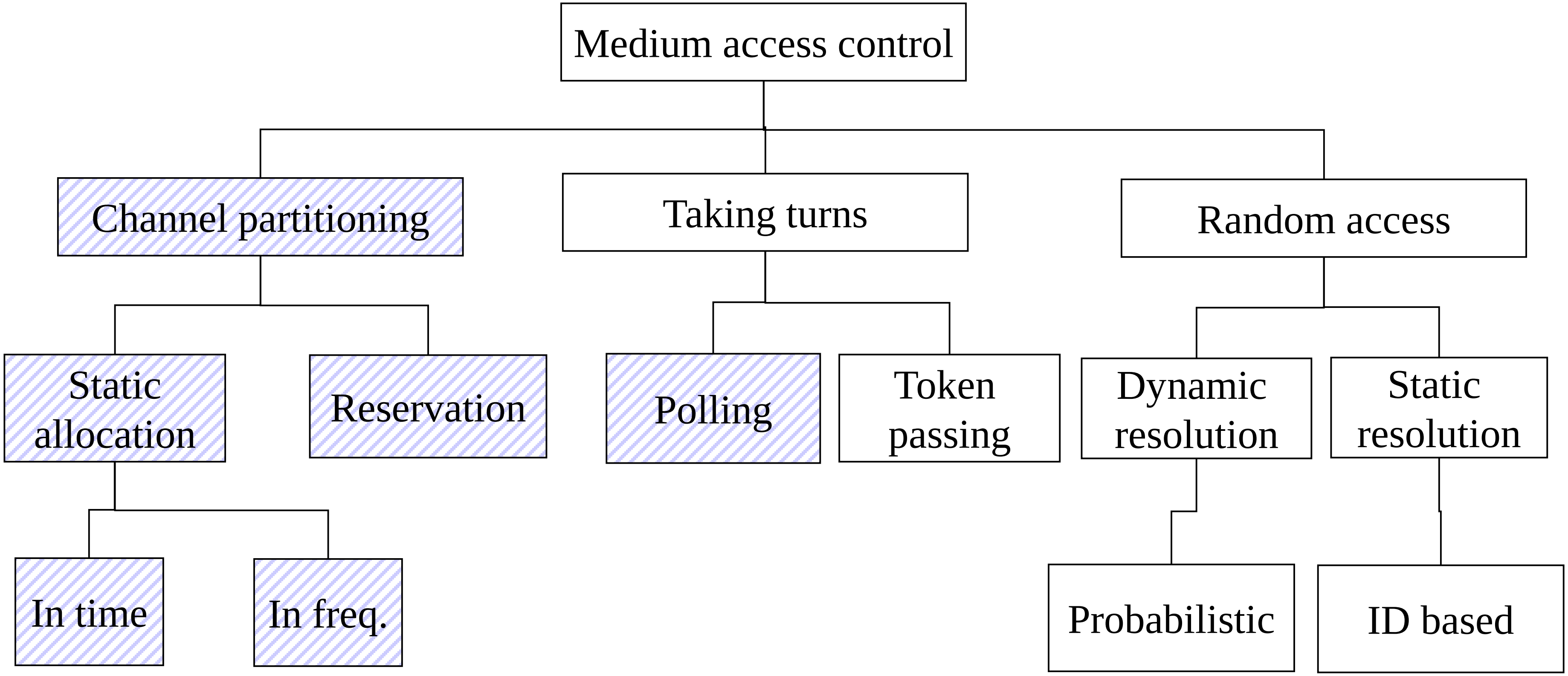
In freq.

Probabilistic

ID based

▨ - Centralized control

Group work


Medium access control

Channel partitioning

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Dynamic resolution

Static resolution

In time

In freq.

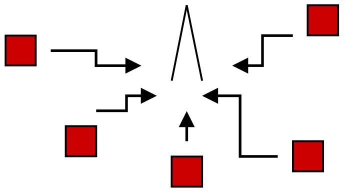
Probabilistic

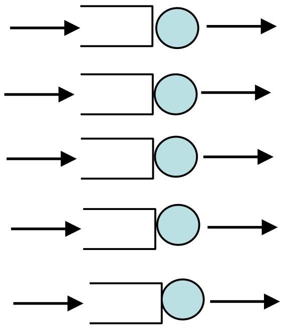
ID based

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

FDMA performance analysis
Not course material, read it if you have never seen it….

- 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.



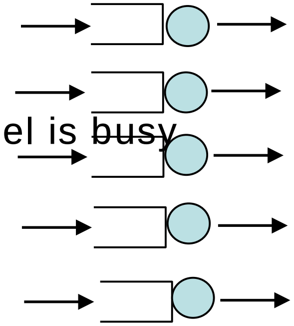


- Networking scenario:
  - Users receive an equal share of the spectrum.
  - Each user transmits fixed size packets over the FDMA link (deterministic packet size)
  - The packets are generated according to a Poisson process, with the same intensity at each user.
  - Queues are infinite
  - We re interested in the delay from packet generation to completed transmission

FDMA performance analysis Not course material, read it if you have never seen it....

- 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
$\rightarrow$ 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 .. Not included

- 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=ρ: per channel and system throughputs are equal

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

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

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

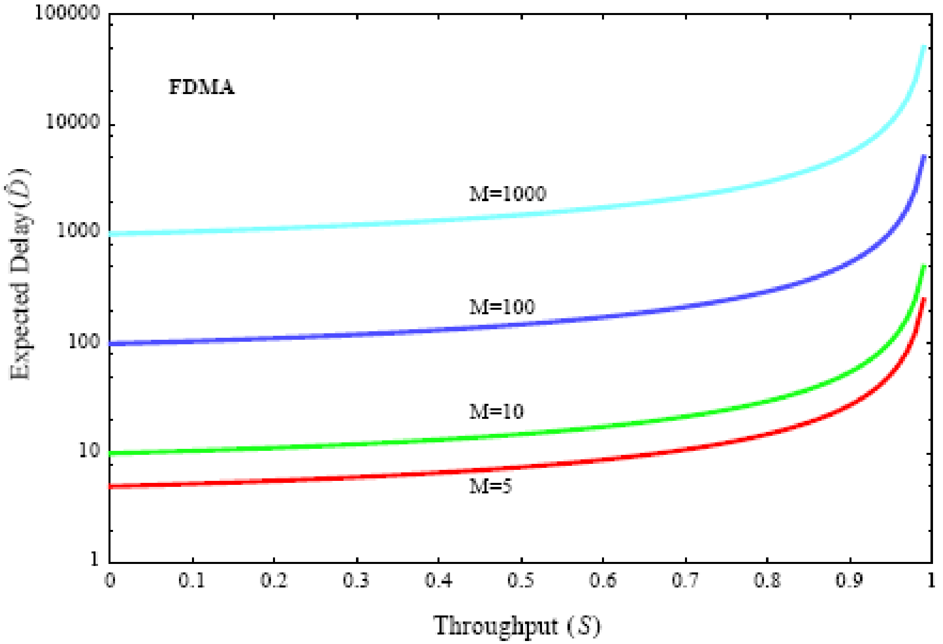
This depends on the channel bitrate and the packet size. Normalize!

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

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

FDMA performance analysis – Not included

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

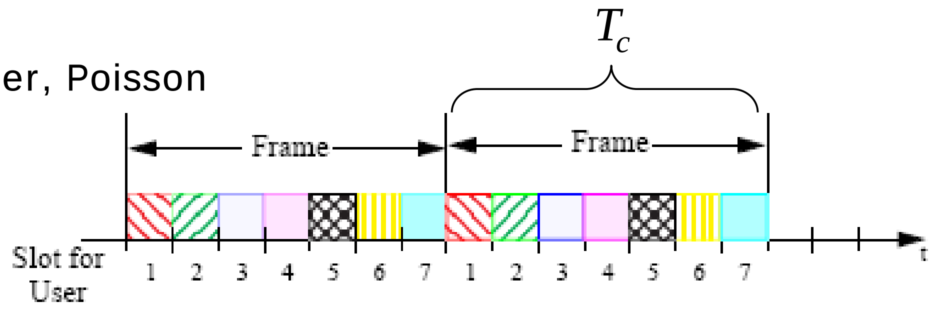


- At small load the average delay is determined by the packet transmission time, that is, the number of users: D*~M.
- This means, the system uses the resources in an inefficient way if the load is small.
- Simple, fair, but not efficient.

TDMA performance analysis – Not included

- 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



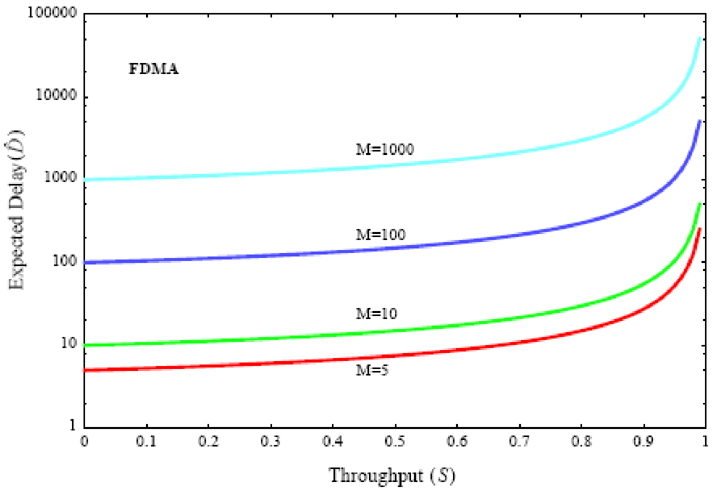
  $T=P/R$: packet transmission time
  $T_c=MT$: frame duration
  $S=\rho=\lambda T_c= \lambda MT= \lambda P/(R/M)$:
  for the same λ, R and M the same as for FDMA.
  Average delay of a packet:
  - packet transmission time: T
  - queuing time, 1 packet per frame transmitted: like queuing time in M/D/1 with T_c
  - average time until the beginning of a new frame: $0.5T_c$

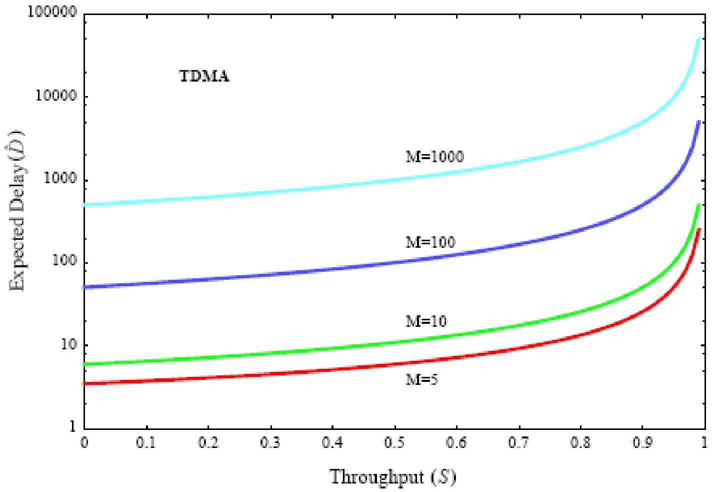
$$D = T + \frac{\lambda T_c^2}{2(1-\lambda T_c)} + 0.5T_c = T + \frac{SMT}{2(1-S)} + 0.5MT = T + \frac{S+1-S}{2(1-S)}MT$$

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

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

TDMA-FDMA performance analysis – Not included





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

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

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

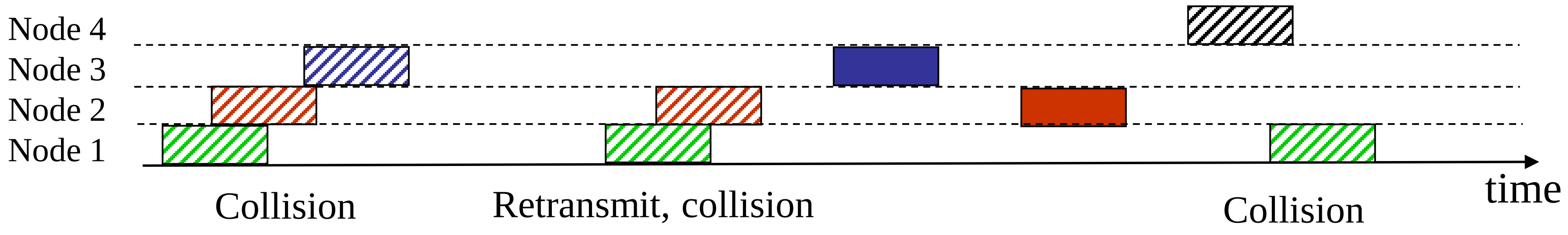
- TDMA is more efficient than FDMA, independently of the load
- However, TDMA is more complex to implement (slot synchronization)

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

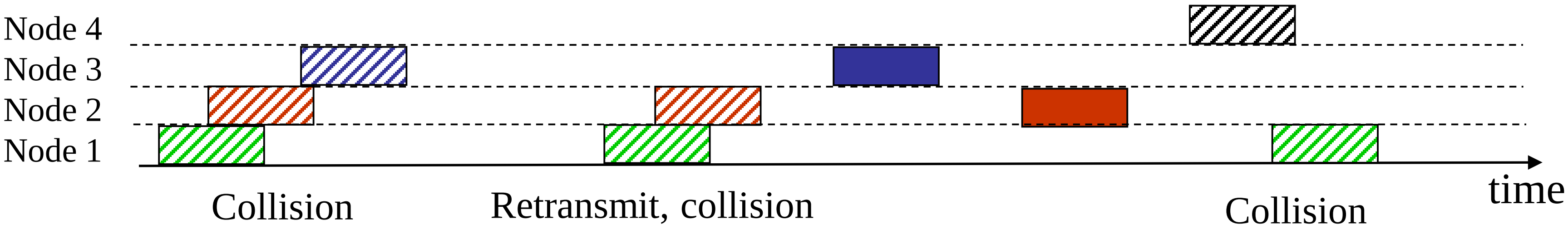
- All nodes share the common transmission medium (radio, bus, star)
- Nodes transmit newly generated packets immediately
- Colliding packets are lost, no bits can be recovered
- If no acknowledgement arrives, nodes retransmit with random delay



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

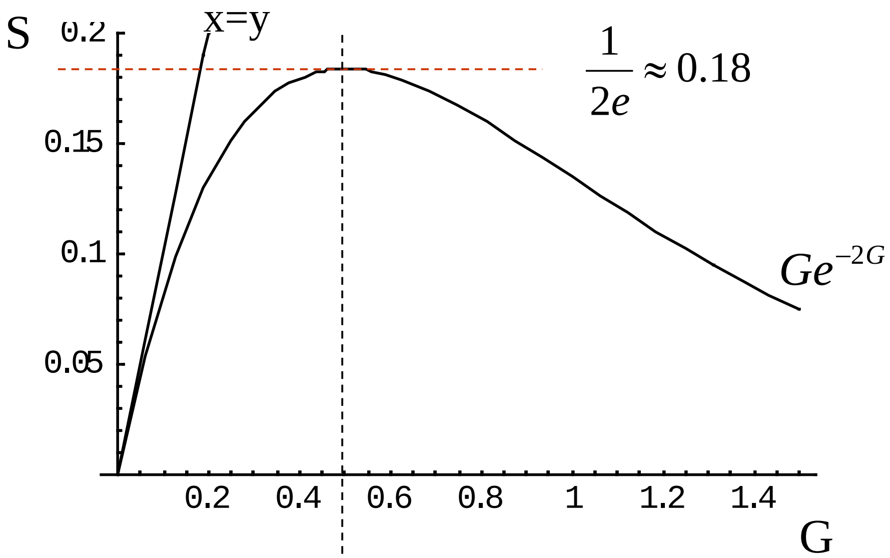
$$p(k) = P\{\text{k arrivals in 2T period}\} = \frac{(g2T)^k}{k!} e^{-g2T}$$

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

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

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

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

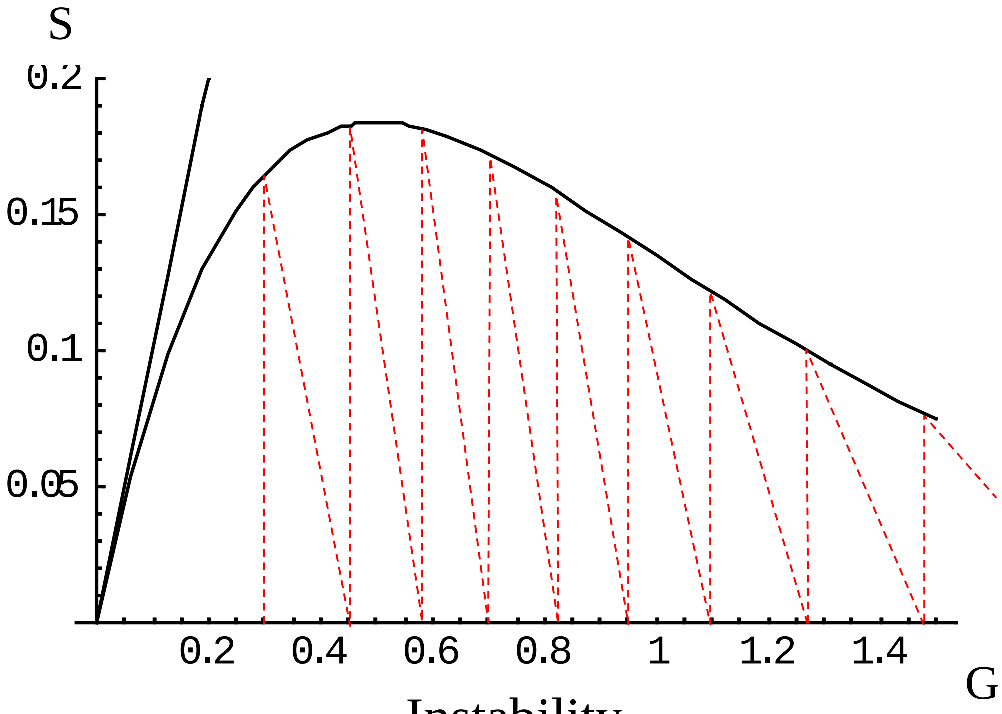


- Max throughput of 0.18
- At offered load (first and retransmissions) of 0.5

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



Instability

Aloha improvements

- Slotted version to decrease contention interval
  - complete derivation (R-S 3.2)
- Listen before talk: carrier sense multiple access, CSMA
  - basic ideas and results (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
  - home reading, discussed next lecture

Slotted Aloha – group work

- Poisson arrival with intensity g
- Slot length = Packet transmission time = T
- S: throughput defined as useful load (<1)
- G=gT: offered load

Reminder: Aloha, unslotted

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

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

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

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

Carrier sense multiple access - CSMA

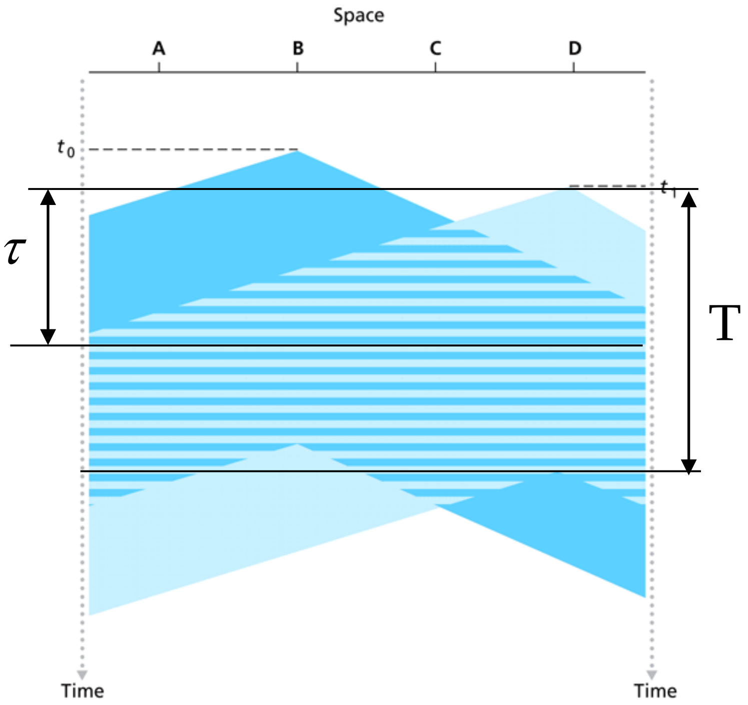
- Pure Aloha throughput converges to 0 under Poisson load
- It is not a good solution – let’s look at the modifications

- Idea: Listen before you transmit – carrier sense
- If channel is idle → send data
- If channel is busy → back off
  - nonpersisten: 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

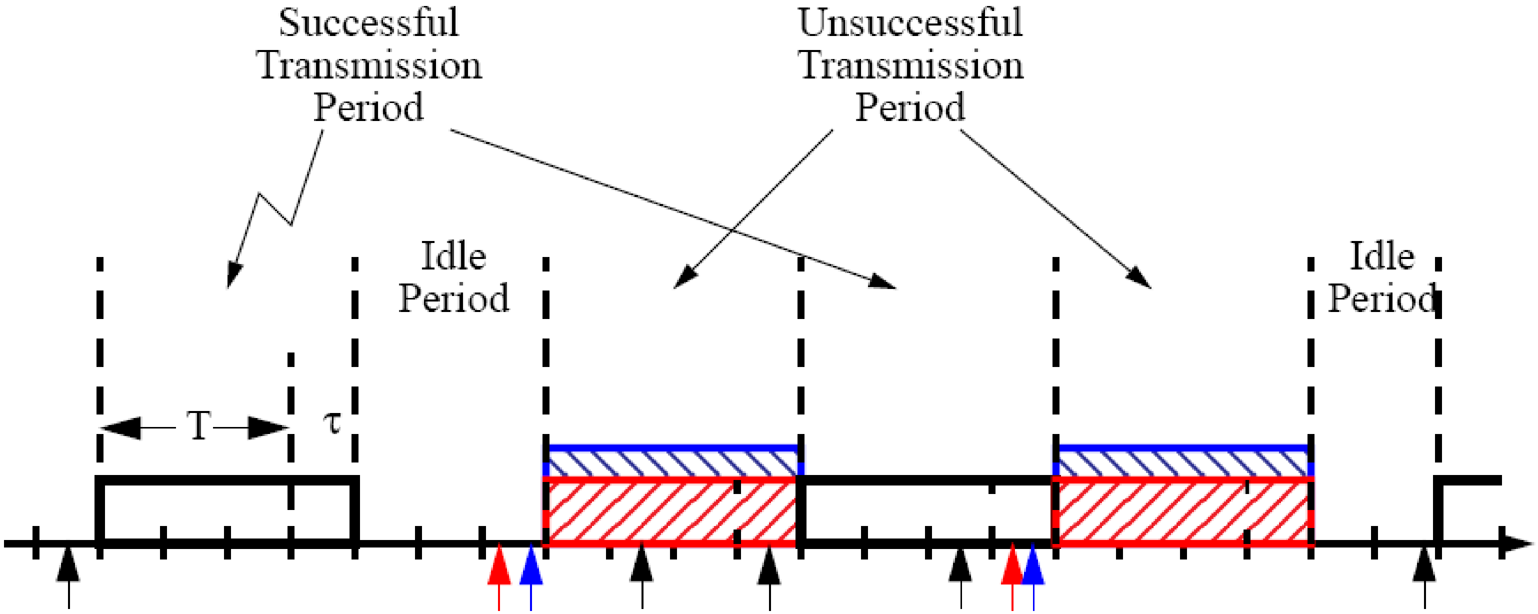
- If all nodes listen before transmit, and all nodes see the channel, is there collision in CSMA?

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



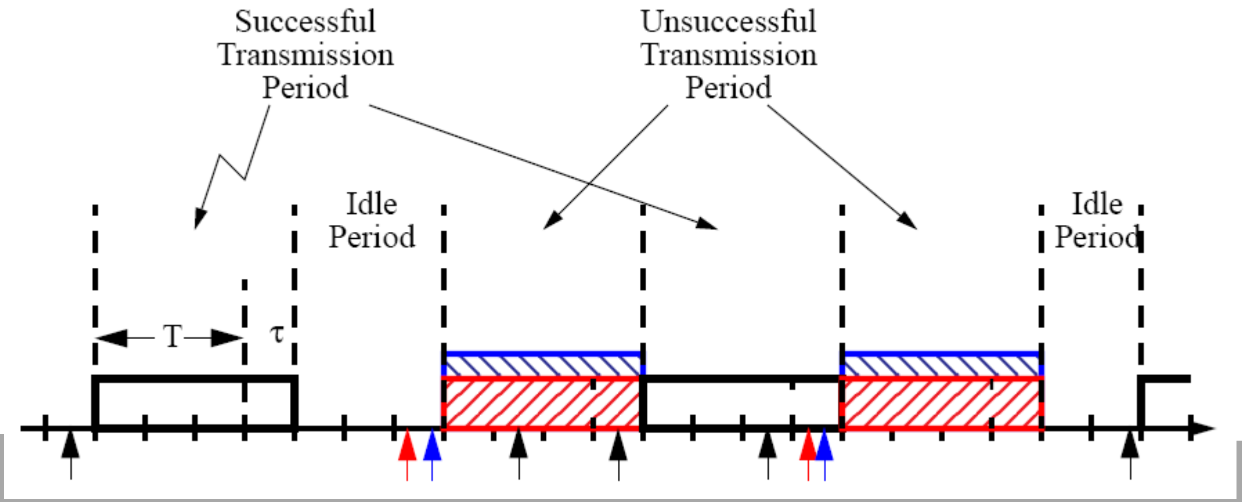
CSMA modeling – slotted case

- 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= τ /T <<1 (Packet transmission time >> 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: $P\left[\hat{I}=k\tau\right]=\left(e^{-g\tau}\right)^{k-1}\left(1-e^{-g\tau}\right)$ (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: $P\left[\hat{L}=l\right]=\left(1-e^{-g\tau}\right)^{l-1}e^{-g\tau}$, $L=\frac{1}{e^{-g\tau}}$

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

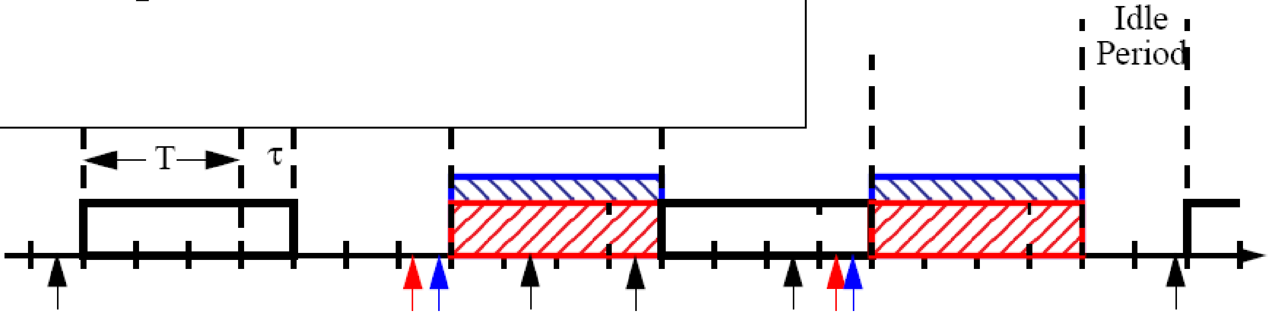
Busy period: $B=(T+\tau)L=\frac{T+\tau}{e^{-g\tau}}$

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

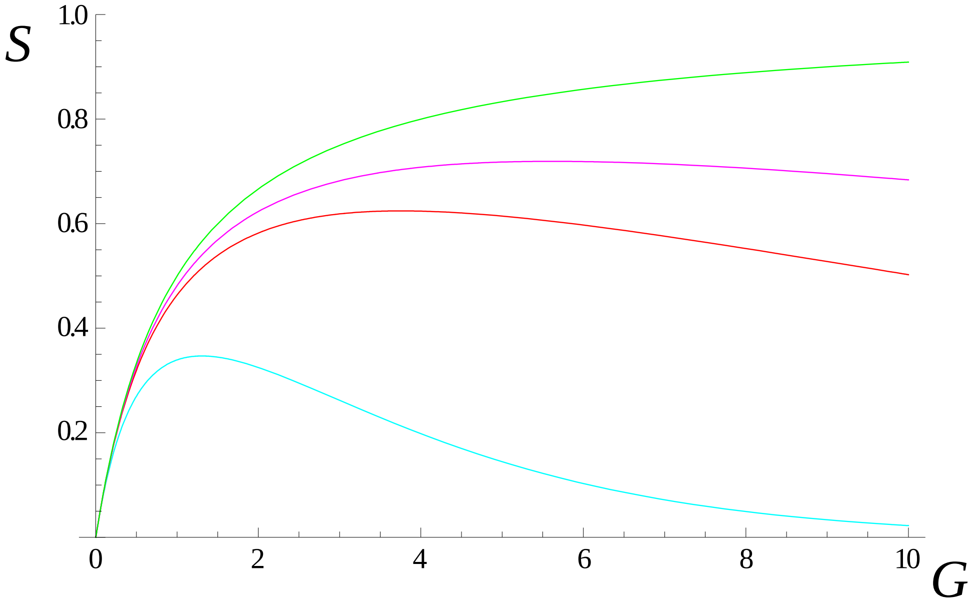
Useful periods within a busy period: $U=\frac{T}{T+\tau}\cdot BP_{succ}=LTP_{succ}=\frac{T}{e^{-g\tau}}P_{succ}$

$$S=\frac{U}{B+I}=\cdots=\frac{aGe^{-aG}}{1+a-e^{-aG}}\qquad\left(a=\frac{\tau}{T}\right)$$

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



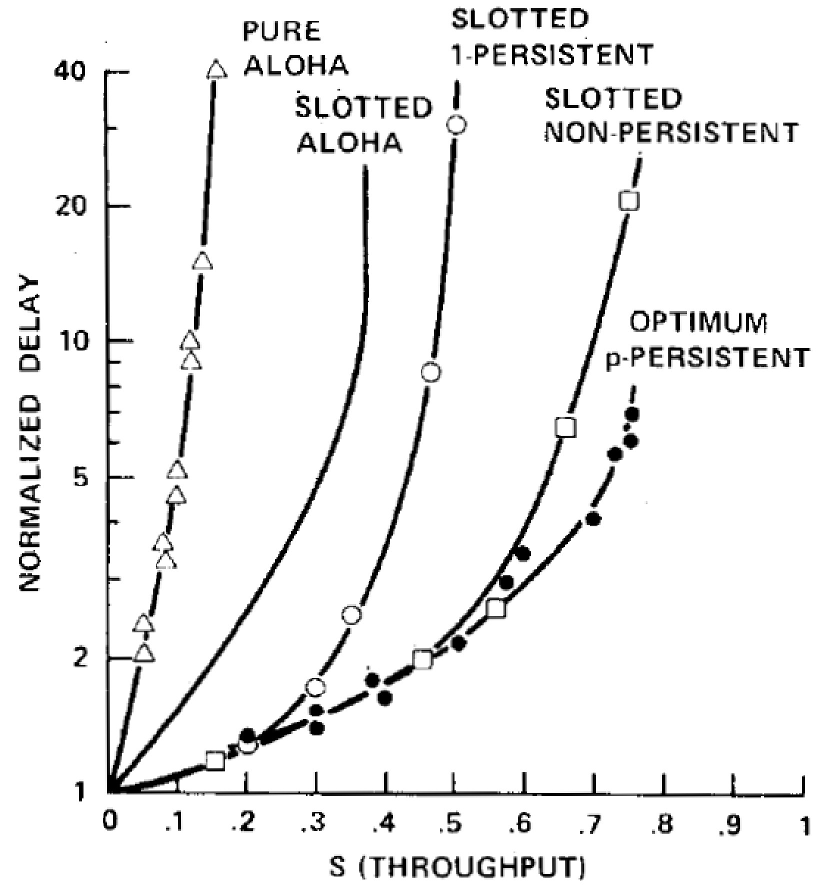
Aloha and CSMA comparison



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

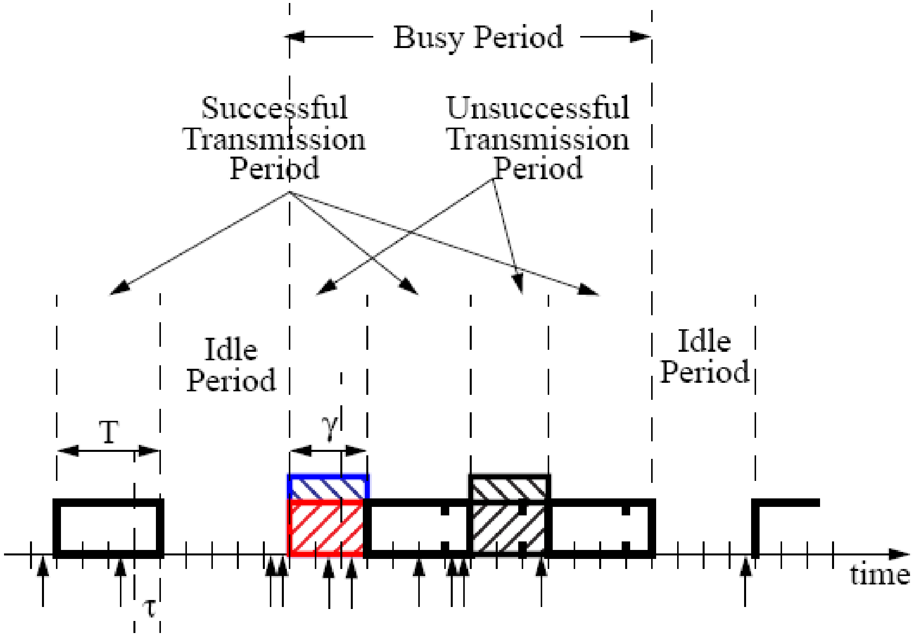
Aloha, CSMA – minimum average delay

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



CSMA/CD – slotted case

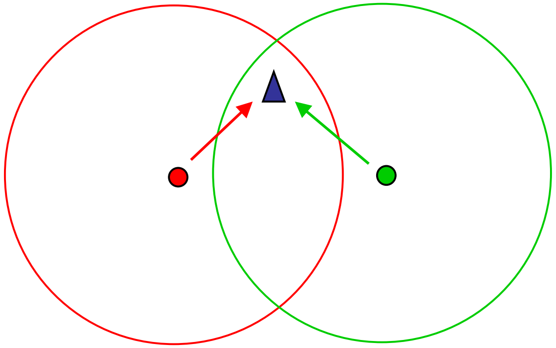
- To increase utilization: shorten busy periods -> shorten unsuccessful periods
- Listen while transmit
  - if collision is detected transmit jamming signal and stop transmission
  - γ: the length of the unsuccessful transmission, $\tau < \gamma < T$



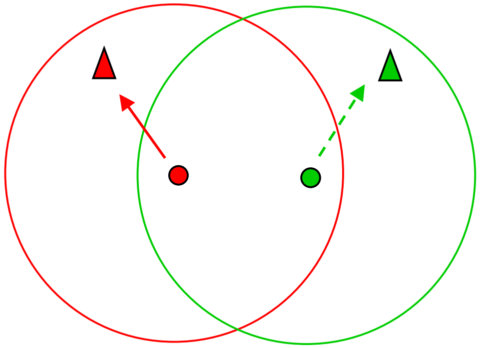
- Modeling:
  - length of idle period
  - transmission periods in busy period
  - probability of success
  - length of busy periods
  - throughput
- Home reading!

CSMA in wireless networks

- Does CSMA/CD work fine in wireless networks?
- Problem 0: Can not sense while transmit -> additional random back-off: 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



Summary

- Medium access control protocols
  - *Static allocation: TDMA, FDMA – not course material*
  - 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)

- Reading assignment:
  - Rom, Sidi, Multiple Access Protocols, excerpts
    - Ch 4: page 79 to 83, 89 to top of 92, 94 to 98 (CSMA variations, slotted non persistent)
  - Bianchi, IEEE 802.11, Sections I-IV, only basic access (no RTS/CTS), this is up to equation (16), maybe numerical results. We will discuss this paper in class. You should understand each step!

CSMA/CA - 802.11

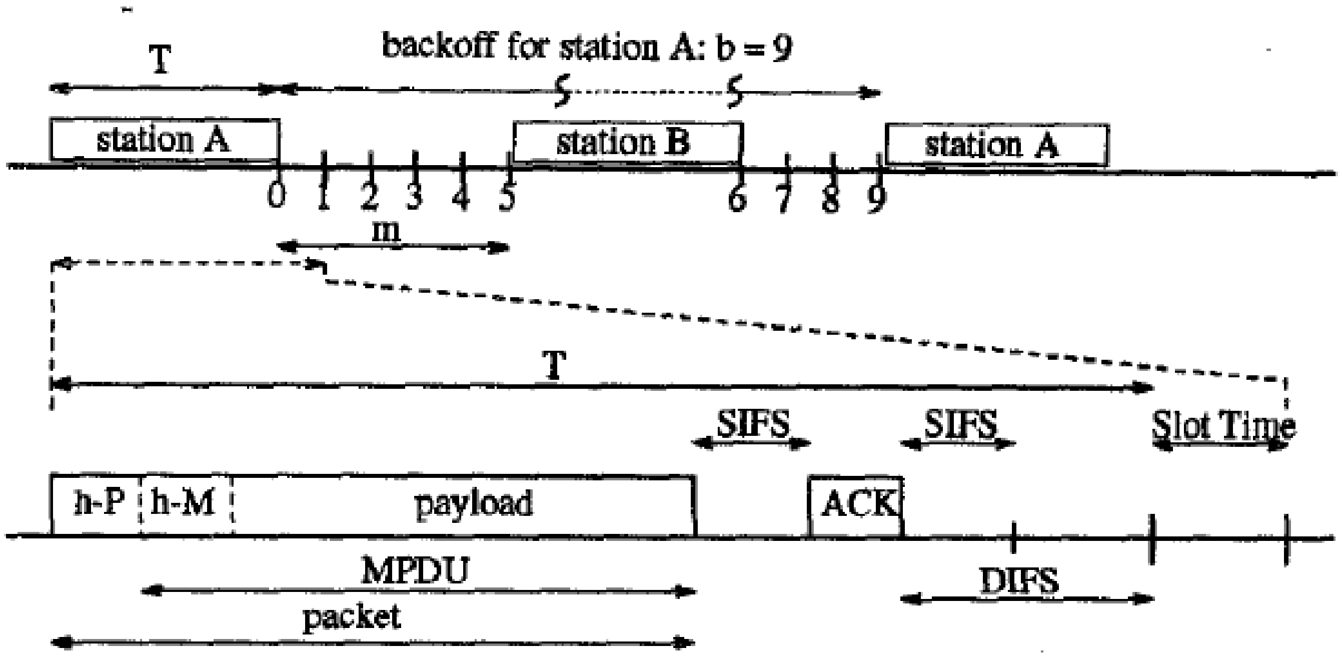
- G. Bianchi, Performance Analysis of the IEEE 802.11 Distributed Coordination Function, IEEE JSAC, 2000 March.
- Objective:
  - Saturation throughput, backlogged transmission queues, fixed number of stations
- Assumption:
  - Collision probability does not depend on history
  - All stations are identical
  - 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:
    - Decremented if channel is idle, freezes if channel busy

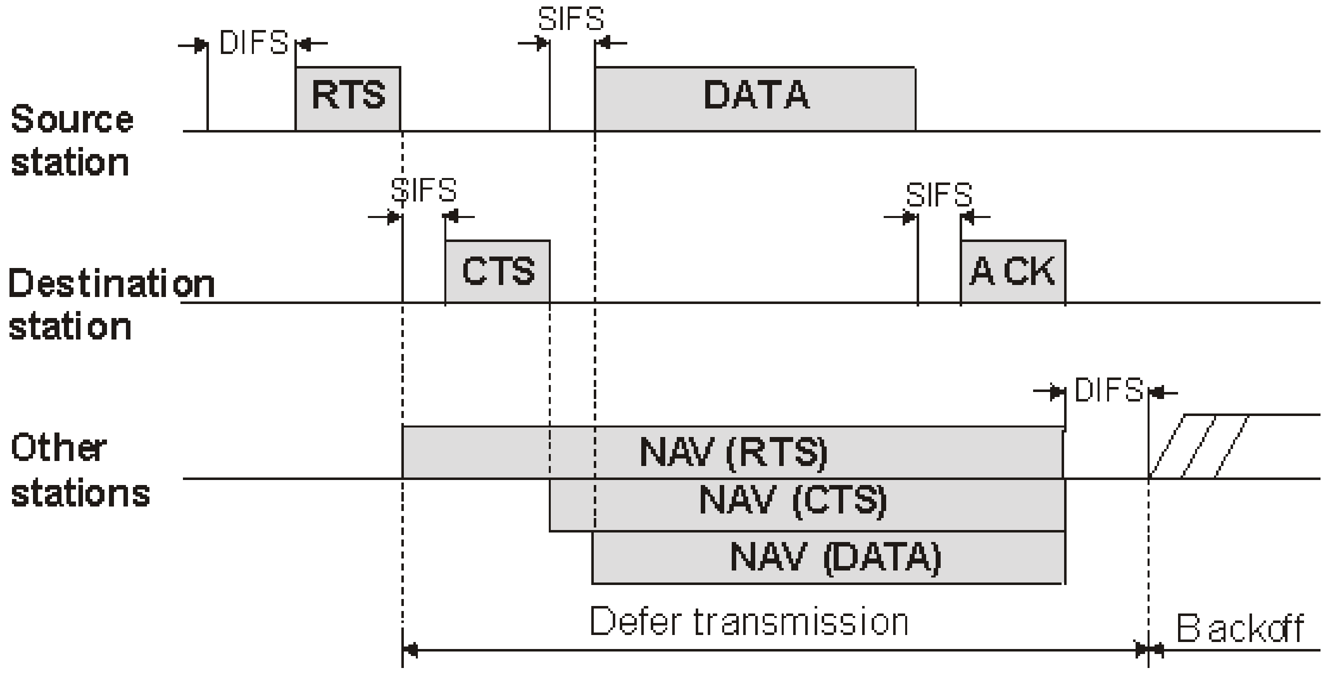
CSMA/CA - 802.11

- 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

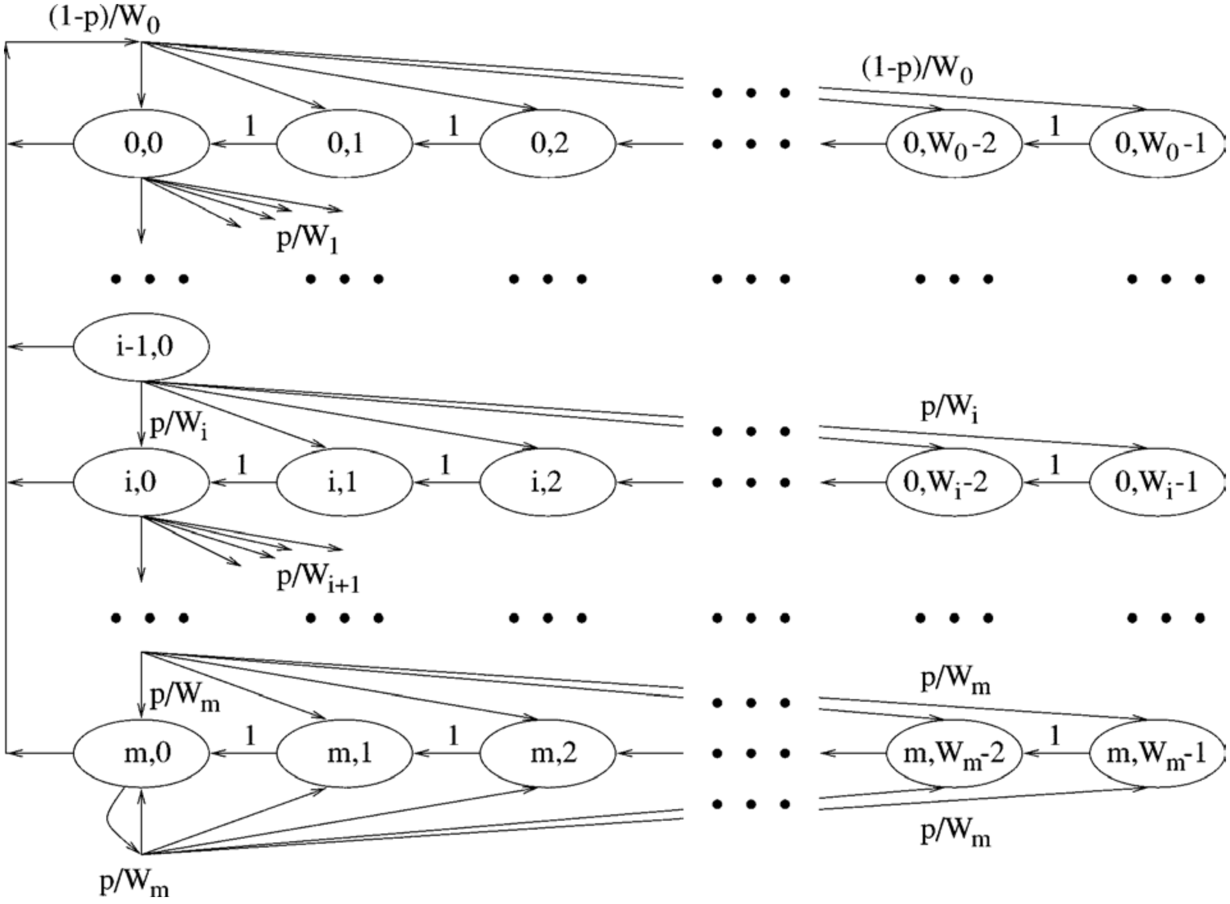


CSMA/CA - 802.11

- 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



At this point a new packet can be transmitted

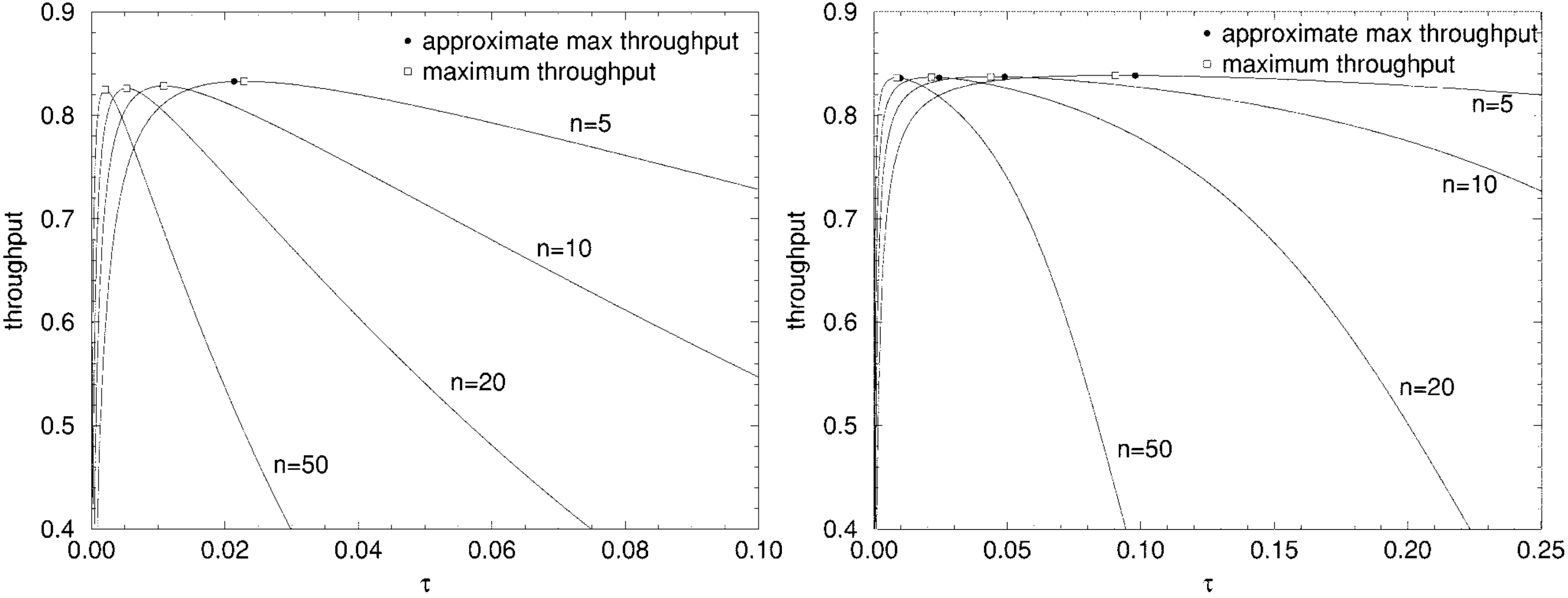
CSMA/CA

- 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, slotted non persistent)
  - Bianchi, IEEE 802.11, Sections I-IV.