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 control functions, where
- Control functions are coupled in some sensible way (e.g., loss and congestion control in TCP)
Control functions in communication networks

- congestion control
- rate control
- admission control
- error control
- delay control

fairness concept

- 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.
• Error control
• Delay control
• Congestion control
• Admission control
• Rate control
• Scheduling

• IEEE 802.x
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

Medium access control

Channel partitioning
- Static allocation
  - In time
- Reservation
  - In freq.

Taking turns
- Polling
- Token passing

Random access
- Dynamic resolution
  - Probabilistic
- Static resolution
  - ID based

- Centralized control
Group work

Medium access control

Channel partitioning
- Static allocation
  - In time
  - In freq.
- Reservation

Taking turns
- Polling
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Random access
- Dynamic resolution
  - Probabilistic
  - ID based
- Static resolution

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.
  - The packets are generated according to a Poisson process, with the same intensity at each user.
  - Packet sizes are deterministic (and equal for all users.)
  - Queues are infinite
  - We are 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
$\lambda$: packet arrival rate from a single user, Poisson
$P$: packet size, constant
$\rho$: per channel load ($\rho = \lambda T < 1$)

$T$: transmission time $T = P/(R/M)$
$S$: per channel and system throughput, defined by the fraction of time the server 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 $P/R$
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
  \( \lambda \): packet arrival rate from a single user, Poisson
  \( P \): packet size, constant
  \( T \): transmission time
  \( \rho = S \): 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!

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

\[
D^* = \frac{D}{P / R} = M \left[ 1 + \frac{S}{2(1 - S)} \right] = M \left[ 2 + \frac{S}{1 - S} \right] = M \left[ 1 + \frac{1 - S + S}{1 - S} \right] = M \left[ 1 + \frac{1}{1 - S} \right]
\]
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
  - $\lambda$: packet arrival rate from a single user, Poisson
  - $P$: packet size, constant

  $T = \frac{P}{R}$: packet transmission time
  $T_c = MT$: frame duration

  $S = \rho = \lambda T_c = \lambda MT = \lambda \frac{P}{(R/M)}$:
  for the same $\lambda$, $R$ 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: $0.5 T_c$

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

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

  \[
  D^* = \frac{D}{P/R} = 1 + \frac{M}{2(1-S)}
  \]
TDMA-FDMA performance analysis

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

\[
D_{FDMA}^* = \frac{M}{2} + \frac{M}{2(1-S)}
\]

\[
D_{TDMA}^* = 1 + \frac{M}{2(1-S)}
\]

\[
D_{FDMA}^* - D_{TDMA}^* = \frac{M}{2} - 1
\]
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 protocol diagram](image-url)
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

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

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

\[ S = P_{\text{succ}} gT = gTe^{-2gT} \]

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

- 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
  - nonpersistent: 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 \( \tau \)

- Slotted CSMA
  - time divided into minislots = propagation delay \( \tau \)
  - 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, $\lambda$
  - fixed packet size, $T$
  - Throughput=$(\text{useful periods})/(\text{idle+busy periods})$  \text{busy period=useful or collision}
  - slotted, nonpersistent (if busy, tries again with random back-off)
  - minislot: propagation time (equal for all pair of nodes), $\tau$
  - 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). $U$
CSMA modeling – slotted case

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

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

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

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

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

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

\[
S = \frac{U}{B + I} = \frac{aG e^{-aG}}{1 + a - e^{-aG}}
\]

\[
S_{a \to 0} = \frac{G}{1 + G}
\]
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)
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
  - $\gamma$: 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
Summary

- Medium access control protocols
  - Static allocation: TDMA, FDMA
  - Random access: Aloha, CSMA, CSMA/CD

- 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.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)