Mobilkommunikation - Mobile Communications

Lecture 6: IEEE 802.11 DCF

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Outline

- Distributed coordination function (DCF)
- Throughput
  - Single station
  - Multiple stations
- Fairness
  - Inter-transmissions
  - Near and far terminals
  - Hidden and exposed terminals
- Quality of service

Distributed coordination function

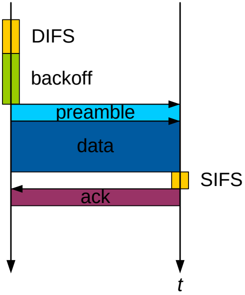
Carrier Sense Multiple Access/Collision Avoidance (CSMA/CA)

Per-packet channel idle times

- Distributed inter-frame space (DIFS)
- Random backoff duration
- Short inter-frame space (SIFS)
  SIFS < DIFS

Per-packet protocol overhead

- preamble
- acknowledgement

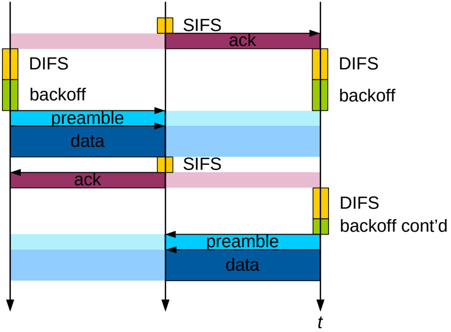


If the channel is idle, the first channel access can be performed without random backoff, i.e. immediately after DIFS waiting.

Multiple access and inter-transmissions

The countdown at different stations is carried out simultaneously

- the station with the smallest backoff value finishes the countdown procedure first and transmits its packet
- other stations pause their countdown procedure and resume it afterwards
- each packet can be assigned one DIFS, SIFS, preamble, and ack.



If two stations transmit at the same time they cause a collision.

Inter-frame spacing

Different inter-frame spaces are used to prioritize channel access.

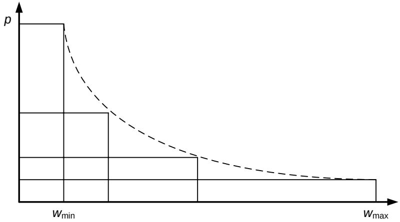
- short inter-frame space (SIFS)
  - high priority
  - for signalling (synchronized), e.g. acknowledgement, CTS
- PCF inter-frame space (PIFS)
  - PIFS = SIFS + 1 slot time
  - medium priority
  - for time-bounded services using the PCF (point coordination function; alternative centralized scheme)
- distributed inter-frame space (DIFS)
  - DIFS = SIFS + 2 slot times
  - low priority
  - for asynchronous data access

Backoff procedure

Collisions are used as an indicator for the unknown number of contending stations to adapt the width of the backoff distribution.

Two rules apply for generation of random backoff values:

- **uniform backoff**: backoff values are uniformly distributed in the window $[0, 1, ..., w - 1] \times \delta$ where δ is the slot time
- **exponential backoff**: in case of a collision the involved stations double their window at most up to $w_{\max}$; they return to $w_{\min}$ after each successful retransmission



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The probability density function of an exponential random variable is

$$f_X(a) = \beta e^{-\beta a}.$$

The cumulative distribution function is

$$F_X(a) = P[X \leq a] = \int_0^a f_X(x)dx = 1 - e^{-\beta a}$$

and the expected value $\mathsf{E}[X] = \int_0^\infty x f_X(x)dx = 1/\beta$.

Memorylessness

Exponential random variables are memoryless, i.e., it holds that $P(X > a + b|X > b) = P(X > a)$ where $P(X > a + b|X > b)$ is the conditional probability that $X > a + b$, given $X > b$ is known.

Example:

Assume the time until an event occurs is exponentially distributed. Given the event has not occurred during the past b units of time. The probability that the event occurs during the next a units of time is independent of b (e.g., Roulette).

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Repetition: renewal reward theorem

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Each renewal k may come with a reward (or cost) denoted R_k. Let $K(t)$ be the number of renewals up to time t. The total reward earned by time t is

$$R(t) = \sum_{k=1}^{K(t)} R_k$$

Denote X_k the iid inter-arrival times between subsequent renewals. The long term average reward is

$$\lim_{t\to\infty} \frac{R(t)}{t} = \frac{\mathsf{E}[R]}{\mathsf{E}[X]}$$

i.e. mean reward per renewal divided by mean length of a renewal.

Throughput: single station

The throughput achieved by a single station without contending stations can be easily computed as

$$S = \frac{l}{t_{\mathsf{DIFS}} + t_{\mathsf{backoff}} + t_{\mathsf{preamble}} + t_{\mathsf{data}} + t_{\mathsf{SIFS}} + t_{\mathsf{ack}}}$$

where

- l = packet length, e.g. 1500 Byte = 12000 bit
- $t_{\mathsf{data}} = l/C$
- C = nominal capacity
- t_{backoff} = mean backoff, e.g. window $[0, 31] \cdot$ slot time (9μs)

In case of IEEE 802.11g with 54 Mbps nominal capacity we have $t_{\mathsf{DIFS}} + t_{\mathsf{backoff}} + t_{\mathsf{preamble}} + t_{\mathsf{SIFS}} + t_{\mathsf{ack}} \approx 240\mu$s and $t_{\mathsf{data}} \approx 220\mu$s.
Throughput depends on packet size: 1500 Byte → 26 Mbps!

DCF throughput model for multiple stations

Consider multiple, saturated (greedy) stations, i.e., stations that have a packet to send at any time.

The model assumes that backoff values are exponentially distributed with parameter β respectively mean $1/\beta$. This has been verified in experiments to be a good match.

Required notation: Denote

- n number of stations
- t_0 packet transmission overhead (excluding backoff)
- t_T packet transmission time
- δ slot time
- γ collision probability

A transmission is detected by (silent) stations within one slot time.

Exponential backoff

The exponential backoff model facilitates an elegant analysis

Since the exponential distribution is memoryless all fresh and residual backoff values are exponentially distributed with β. Thus, the start of each DIFS can be viewed as a renewal.

Given n stations each in exponential backoff with parameter β. The time until the first backoff completes is exponentially distributed with parameter $n\beta$

To see this take the exponential distribution $\mathsf{P}[X_i \leq a] = 1 - e^{-\beta a}$ and compute

$$
\begin{aligned}
\mathsf{P}[X_1 \leq a \cup X_2 \leq a] &= \mathsf{P}[X_1 \leq a] + \mathsf{P}[X_2 \leq a] - \mathsf{P}[X_1 \leq a]\mathsf{P}[X_2 \leq a] \\
&= 2(1 - e^{-\beta a}) - (1 - e^{-\beta a})^2 \\
&= 1 - e^{-2\beta a}
\end{aligned}
$$

Throughput: multiple stations

Assume that the vulnerability period is one slot time δ. Consider a station that starts a transmission. A collision occurs, if the backoff at any of the remaining $n-1$ stations is completed within δ.

From the exponential distribution the collision probability γ is

$$\gamma = 1 - e^{-(n-1)\beta\delta}$$

and the reward during each renewal is $(1-\gamma)t_T$

The mean time until the first of n backoffs expires is $1/(n\beta)$ and the mean duration of a renewal follows as $1/(n\beta) + t_0 + t_T$.

From the renewal reward theorem the (normalized) long-term average throughput is

$$S = \frac{e^{-(n-1)\beta\delta} t_T}{\frac{1}{n\beta} + t_0 + t_T}$$

Optimal contention window size

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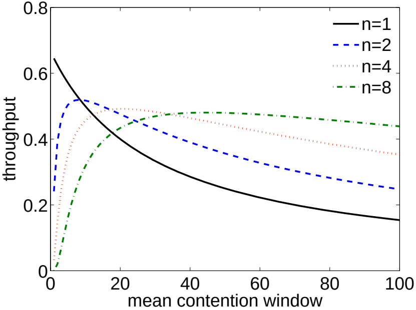

The optimal window size depends on the number of stations n

- a small contention window reduces the countdown time
- a small contention window increases the number of collisions

In practice collisions are used as a rough estimate of the number of contending stations to adapt the contention window accordingly.

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Fairness

Motivation: Consider two (or more) greedy stations that compete for resources. How fair does the DCF distribute the available resources? How can fairness be defined?

Jain defines a basic fairness index. Given n competing users each getting a share x_i of the resources, Jain's index is defined as

$$f = \frac{\left(\sum_{i=1}^{n} x_i\right)^2}{n \sum_{i=1}^{n} x_i^2} = \frac{\mathsf{E}[X]^2}{\mathsf{E}[X^2]}$$

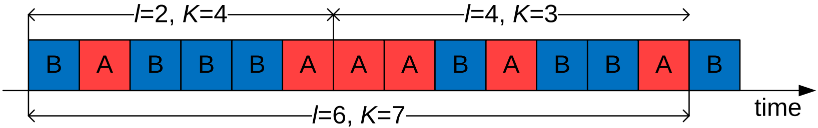
Jain's index is in the interval $[\frac{1}{n}, 1]$ where larger values indicate better fairness.

Inter-transmissions

To analyze the fairness we consider greedy stations and count

- the number of inter-transmissions k of a station
- while a tagged station transmits l packets

Perfect fairness is achieved if $k = l$ always.



Countdown procedure

Countdown procedure

- channel access is determined by the countdown procedure
- the station with the smallest countdown value wins
- if several packets have to be transmitted the countdown procedure is performed several times

What is the probability that station 1 wins k times (transmits k packets) while station 2 wins l times (transmits l packets)?

Countdown procedure

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What is the probability that station 1 wins k times (transmits k packets) while station 2 wins l times (transmits l packets)?

Given $b_i(j)$ is the j-th countdown value of the i-th station we have

$$\mathsf{P}[K = k|l] = \mathsf{P}\left[\sum_{j=1}^{k} b_1(j) \leq \sum_{j=1}^{l} b_2(j) \text{ and } \sum_{j=1}^{k+1} b_1(j) > \sum_{j=1}^{l} b_2(j)\right]$$

- the k-th countdown at station 1 finishes before the l-th countdown at station 2
- the $k+1$-th countdown at station 1 finishes after the l-the countdown at station 2

Exponential model

As before, we assume that the countdown values follow an exponential distribution with parameter β.

Since the exponential distribution is memoryless, it does not matter how long a station has already spent on the countdown procedure.

It follows that at any time each of the two stations has a chance of winning the channel access of $p = 0.5$.

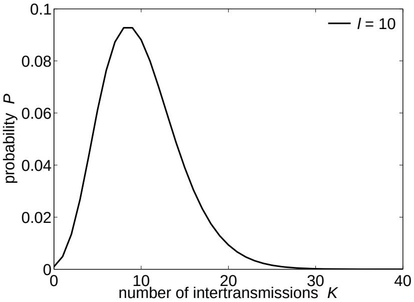
We can thus view each channel access as an independent Bernoulli trial, each with success probability $p = 0.5$.

We seek to find the probability $\mathsf{P}[K = k|l]$ that station 2 wins the channel for the l-th time in the $k + l$-th attempt (ensuring that station 1 has won exactly k times).

The probability to see the l-th success exactly in the $k+l$-th Bernoulli trial is negative binomially distributed:

$$\mathsf{P}[K=k|l] = p^l(1-p)^k \binom{k+l-1}{l-1}$$

where $\binom{k+l-1}{l-1} = \frac{(k+l-1)!}{(l-1)!k!}$ and $p=0.5$ for two contending stations



Computing Jain's fairness index

Negative binomial distribution

- first moment:

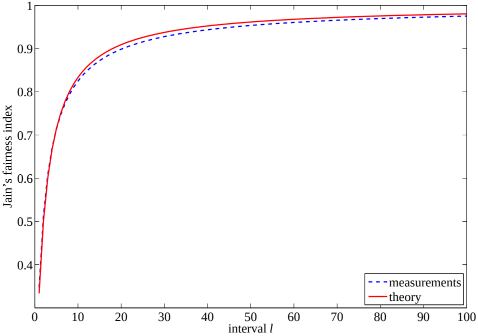
$$\mathsf{E}[K] = l$$

- second moment:

$$\mathsf{E}[K^2] = l^2 + 2l$$

- Jain's index:

$$\frac{\mathsf{E}[K]^2}{\mathsf{E}[K^2]} = \frac{l}{l+2}$$



Packet-size dependent fairness

The DCF seeks to provide fairness in the sense that each station has the same chance to access the medium resulting -on the long run- in the same frequency of accessing the medium.

Each medium access gives the opportunity to transmit one packet

- on the long run the number of transmitted packets is evenly divided among the stations
- packets may have different size
- stations that send larger packets get more resources compared to stations that send small packets

$\Rightarrow$ the DCF does not achieve air-time fairness

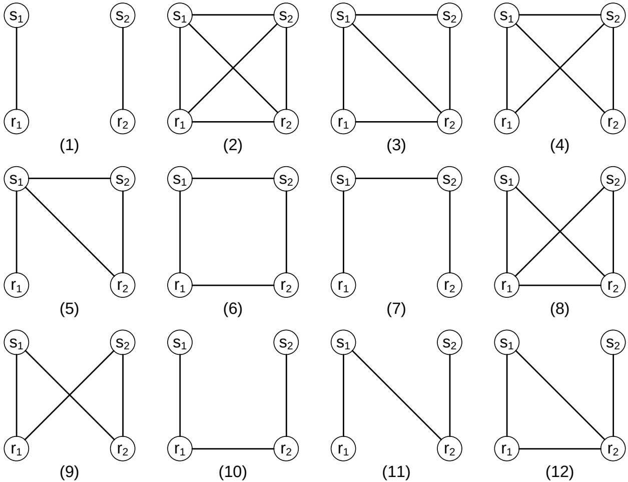
Near and far terminals

Near-far effect

- terminals close to the receiver can drown the signal of terminals that are far away from the receiver
- consider two stations, near and far, that send simultaneously
  - it is more likely that the receiver can decode the signal of the station that is close by
  - in this case the receiver acknowledges the packet from the station that is close by
  - the station that is far away does not receive an acknowledgement
    - it (correctly) assumes a collision occurred and
    - performs exponential backoff (doubles the contention window)
    - hence, it accesses the channel more cautiously
  - only the station that is far away performs backoff!

The DCF increases unfairness due to the near-far effect!

Topologies with pairs of sender and receiver (s_1, r_1) and (s_2, r_2)



Two-flow topologies

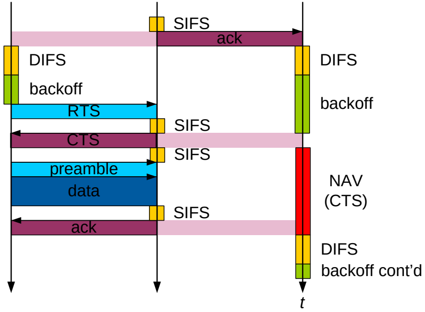
scenarios	type	fairness	throughput
1	disconnected	trivial	perfect
2-7	senders connected	medium-term	good
8-10	symmetric incomplete state	long-term	poor
11-12	asymmetric incomplete state	no	only s_1, r_1

- hidden terminal, e.g. scenario 8, 9, 11, 12
- exposed terminal, e.g. scenario 6, 7

4-way handshake: RTS/CTS

RTS/CTS to address hidden and exposed terminal problems

- 4-way handshake
  - RTS/CTS
  - data/ack
- network allocation vector (NAV) reserves medium
- both RTS and CTS contain NAV
- RTSs may collide
- data does not collide



RTS/CTS adds overhead. It does only eliminate collisions of data!

Quality of service (QoS)

Enhanced DCF (EDCF) adapts parameters of the DCF to give selected stations higher probability of channel access

- adapt contention window size $w_{\min}$ and $w_{\max}$
  - probabilistic method
  - basically dislocates fairness
    - stations with smaller window size achieve higher throughput
    - stations with smaller window size achieve smaller access delays
- arbitration inter-frame space (AIFS) replaces DIFS
  - deterministic but also linked to random backoff
  - gives an advantage to a prioritized station each time an inter-transmission occurs

The idea is simple and effective considering average behavior. Computing the actual QoS that is achieved is, however, difficult.

Literature

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