Rechnernetze – Computer Networks

Lecture 5: Direct Link Networks
Medium Access Control

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April 29, 2024

Outline

Introduction

Communications channels can be divided into two categories

- point-to-point
- broadcast

So far, we only considered two stations that are connected by a (half-) duplex point-to-point channel.

Broadcast channels

- can be used by more than two stations
- also called multiaccess channels
- resources are typically divided in time, i.e. different stations access the channel at different times

Need to coordinate access to the broadcast channel

- task of medium access control (MAC)
- MAC is a sublayer of the data link layer

An analogy

Telephone conference with several persons

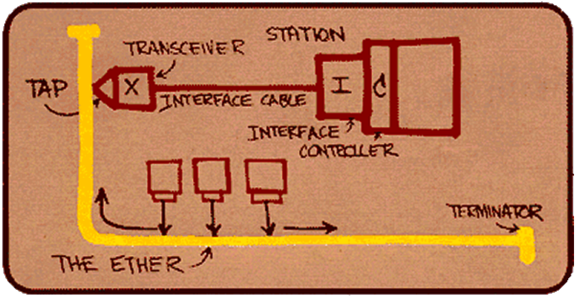
- each participant can hear all other persons and can talk to all other persons, i.e. broadcast channel
- if one participant stops speaking it is likely that more than one participant will start speaking

Face-to-face meeting with several persons

- also uses a broadcast (audio) channel
- but typically also uses a separate (optical) signalling channel
  - raising the hand to express interest to say something
  - central coordinator who resolves conflicts

Medium access control is much harder, if

- only a single channel is available
- channel access is organized completely decentralized

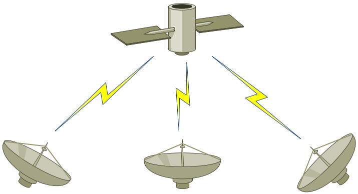


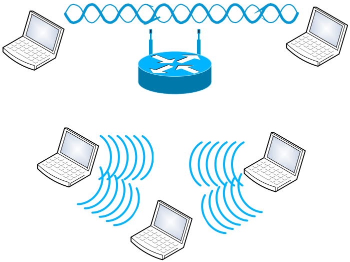
[Original drawing of Ethernet by Metcalfe, 1976]

IEEE 802.3 Ethernet originally

- coaxial cable as broadcast medium (ether)
- vampire taps to connect stations
- stations compete for the medium taking turns in time

Example use cases

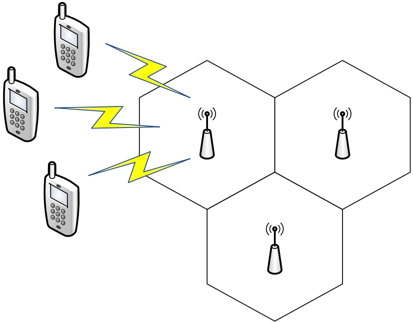




Wireless radio communications generally uses a broadcast medium. Medium access control is essential, e.g., in

- satellite communications
- IEEE 802.11 Wifi
- ad-hoc networks

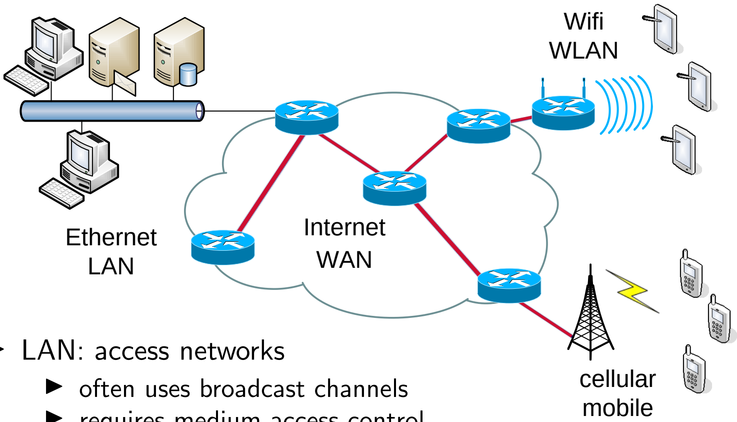
Example use cases



Cellular mobile communications, e.g., GSM, UMTS, LTE

- in brief each basestation/cell is assigned a separate frequency
- stations compete for the medium during 'registration'

LAN vs. WAN



- LAN: access networks
  - often uses broadcast channels
  - requires medium access control
- WAN: backbone networks
  - typically point-to-point links

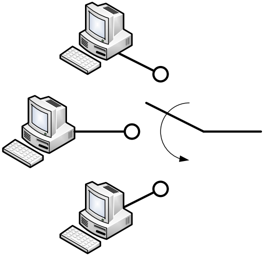
Important parameters

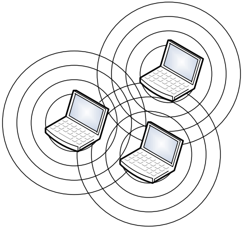
The design of algorithms/methods for medium access control has to consider a number of critical parameters

- distance of stations to each other (power and delay)
- visibility of stations (SNR, signal-to-noise ratio)
- target utilization, overall throughput
- fairness between competing terminals
- capacity of the channel (available time for executing algorithms for medium access)
- burstiness of the traffic (ratio peak to mean rate)
- frame lengths

Basic modes of operation

- coordinated access (contention free)
  - stations ready to send wait until they are scheduled, i.e. until it is their turn
- random access (contention based)
  - stations try to access the medium as soon as they have something to send





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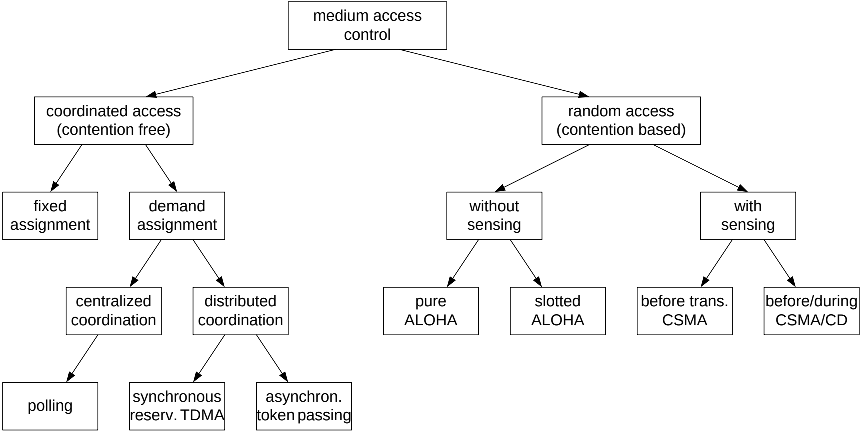

Also, many combined, hybrid methods, e.g., reservation TDMA with ALOHA contention

Outline

Overview

Coordinated access
- Fixed assignment
- Polling
- Reservation TDMA
- Token passing

Random access
- Without carrier sense
  - Pure ALOHA
  - Slotted ALOHA
- With carrier sense
  - CSMA
  - CSMA/CD

Fixed assignment

Fixed assignment, i.e. static channel allocation

- overall service rate of the channel μ
- divided into N sub-channels, e.g., using
  - frequency division multiple access (FDMA)
  - time division multiple access (TDMA)
- each station is assigned a dedicated sub-channel
- divided evenly, each station gets a fixed share of μ/N

Fixed assignment

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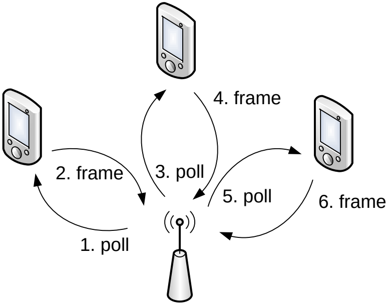
- each station is assigned a dedicated sub-channel
- divided evenly, each station gets a fixed share of μ/N

- simple scheme: easy to implement
- inflexible allocation: cannot adapt if number of stations varies
- inherently inefficient: even if number of stations is constant
  - if a station is quiescent, its allocated bandwidth is simply lost
  - stations which have more data to send cannot use bandwidth left unused by other stations
  - data traffic typically is very bursty (e.g., peak-to-mean 1000:1)
  - most sub-channels will be idle most of the time

Polling

- coordinated access
- demand assignment (dynamic allocation)
- centralized coordination

If a station has nothing to send the next station is polled



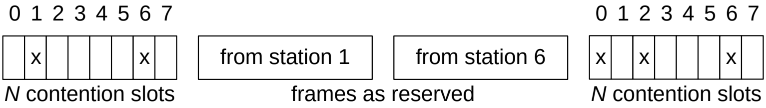
Efficiency

- high, if all stations have frames to send
- low due to overhead, if polled stations have nothing to send

Reservation TDMA

Reservation TDMA

- coordinated access, demand assignment (dynamic allocation)
- distributed coordination, synchronous



Mode of operation

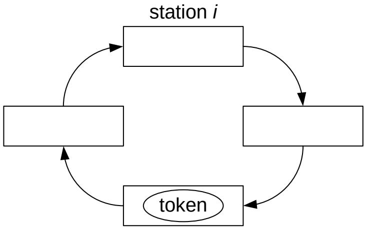
- stations are permitted to transmit frames after reservation
- contention slots for reservation alternate with data frames
- each station has its own unique contention slot
- all stations know exactly which station transmits when
- requires exact timing
- contention slots use part of the capacity

Token passing

Token passing

- coordinated access, demand assignment (dynamic allocation)
- distributed coordination, asynchronous

- stations form a physical or virtual/logical ring
- token circulates on the ring
- token is permission to send
- data frames circulate the entire ring
- after sending the token is passed on



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    - CSMA
    - CSMA/CD

Model/Assumptions

1. stations
   - N independent stations generate frames for transmission
   - station blocks until frame has been successfully transmitted
2. channel
   - single channel for all communication (all can send/receive)
3. collisions
   - simultaneous transmissions cause collisions (garbled signals)
   - stations can detect collisions (e.g., missing acknowledgement)
4. time
   - continuous time: frame transmission can begin at any instant
   - slotted time: time is divided into discrete intervals (slots); frame transmission always begins at the start of a slot
5. sensing
   - carrier sense: stations can detect whether channel is in use or not; if channel sensed as busy, a station will not attempt to transmit until the channel becomes idle
   - no carrier sense: stations cannot sense the channel

ALOHA

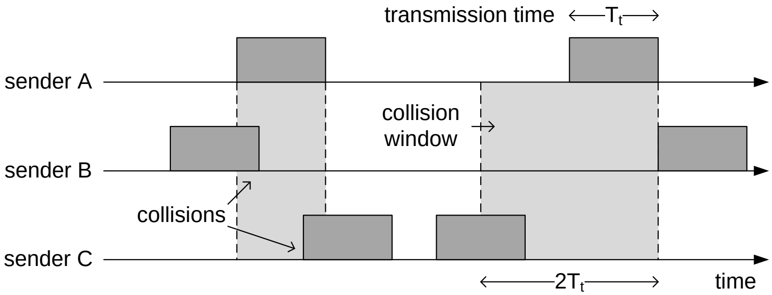
The ALOHA protocol was developed by Abramson for a wireless computer network between the Hawaii islands. It is widely used today, e.g., for the LTE Random Access Channel.

A number of hosts share a wireless channel

- if a host has data for transmission it sends the data immediately
- the hosts do not consider other potentially sending hosts
- if two or more frames are transmitted at the same time they are destroyed
- these frames are retransmitted after a random time (can detect collisions from missing ack)

What is the impact of frame collisions on the performance, i.e. what is the maximally achievable throughput?

Collision window



- constant sized frames with transmission time T_t
- collision window $2T_t$
- a frame is transmitted without collision if no other frame starts transmission in the collision window

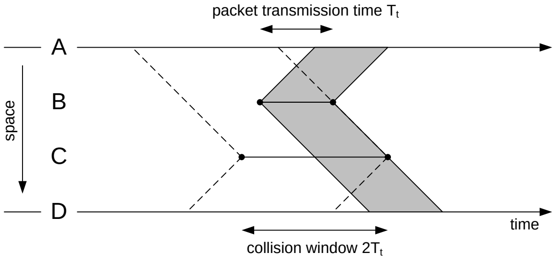
Space time diagram

If distances between stations are large: consider propagation delays

- propagation delay is distance divided by $\approx 2/3$ speed of light
- transmission time T_t

A packet transmission from B to C is error-free if

- C does not transmit a packet within a window of $2T_t$ length
- A, D do not transmit a packet within a window of $2T_t$ length



Poisson arrival process

To analyze the performance of ALOHA we have to model the frame arrivals.

Assumptions:

- the number of stations is large, i.e. $N \to \infty$
- stations generate frames independently of each other
- once generated, a station sends the frame immediately

It can be shown that the number of frame arrivals at the channel is Poisson distributed

$$p(k) = \frac{(\lambda T)^k}{k!} e^{-\lambda T}$$

where

- T is the duration of the observed time interval
- λ is the average rate with which frames are generated
- $p(k)$ is the probability that there are exactly k frames in T

Throughput model

From the Poisson distribution the probability of k arrivals in an interval of length 2 (we normalize time such that $T_t = 1$) is

$$p(k) = \frac{(2\lambda)^k}{k!} e^{-2\lambda}$$

and the probability that there is no arrival is $p(0) = e^{-2\lambda}$.

If a station transmits a frame, $p(0)$ is the probability that no other station starts transmitting in the collision window, i.e., $p(0)$ is the probability of a collision-free, successful transmission.

The average throughput can be computed as the rate of arrivals times the probability that an arrival is transmitted successfully, i.e.

$$S = \lambda p(0) = \lambda e^{-2\lambda}$$

Throughput model continued

Throughput

$$S = \lambda p(0) = \lambda e^{-2\lambda}$$

The maximum throughput is found from

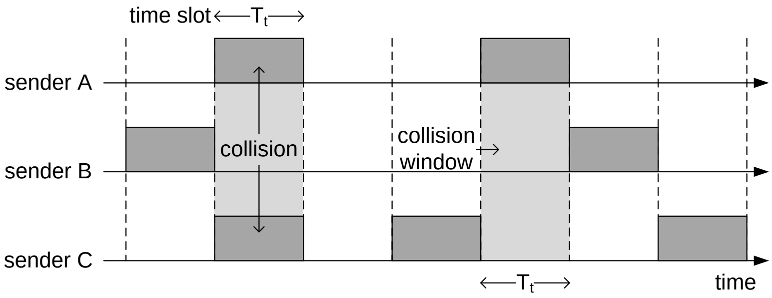
$$\frac{\partial S}{\partial \lambda} = e^{-2\lambda} - 2\lambda e^{-2\lambda} = 0$$

It is attained for an arrival rate (system load) of

$$1 - 2\lambda = 0 \Leftrightarrow \lambda = 0.5$$

and it equals

$$S_{\max} = \frac{1}{2e} \approx 0.18$$



Slotted ALOHA

- TDM scheme with slot time T_t
- requires global time synchronization among all stations
- constant sized frames with transmission time T_t
- the collision window is reduced to T_t

Throughput model

The throughput of slotted ALOHA can be computed in the same way as in case of ALOHA, the only difference is that the collision window is reduced to T_t instead of $2T_t$.

The probability of k arrivals in an interval of length $T_t = 1$ is

$$p(k) = \frac{\lambda^k}{k!} e^{-\lambda}$$

and the probability that there is no arrival is $p(0) = e^{-\lambda}$.

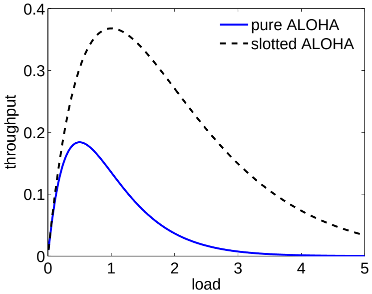
The average throughput can be computed as the rate of arrivals times the probability that an arrival is transmitted successfully, i.e.

$$S = \lambda p(0) = \lambda e^{-\lambda}$$

The maximum is attained at $\lambda = 1$ yielding

$$S_{\max} = \frac{1}{e} \approx 0.37$$

The figures show the throughput of ALOHA for different loads.

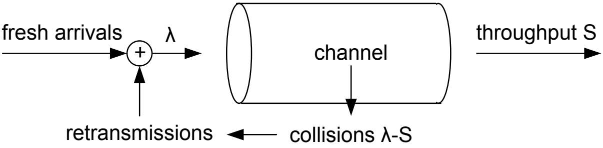


The simple model neglects retransmissions respectively retrials.

Retransmissions

If several stations attempt to send frames at the same time collisions occur. Lost or erroneous frames are retransmitted by the respective stations.

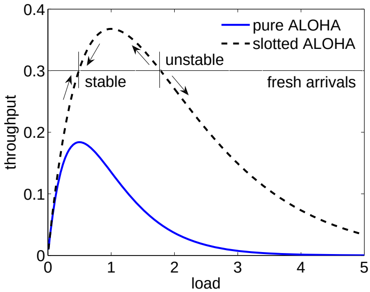
The arrival rate is assumed to be composed of both fresh arrivals and retransmissions due to collisions.



The rate of fresh arrivals matches the throughput, otherwise

- if throughput $>$ rate of fresh arrivals $\Rightarrow$ contradiction
- if throughput $<$ rate of fresh arrivals $\Rightarrow$ instability

The figures show the throughput of ALOHA for different loads.



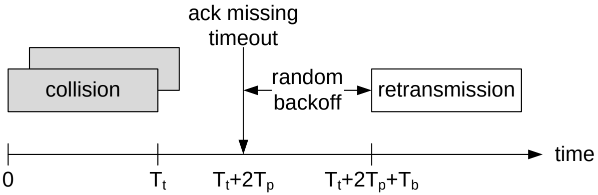
The offered load comprises fresh arrivals and retransmissions.

ALOHA is unstable for loads larger than 0.5 respectively 1.
ALOHA requires a cautious retransmission strategy.

Random backoff

If two or more stations retransmit after a collision the retransmission will inevitably result in a collision, too.

Solution: Retransmission after a random backoff time T_b.



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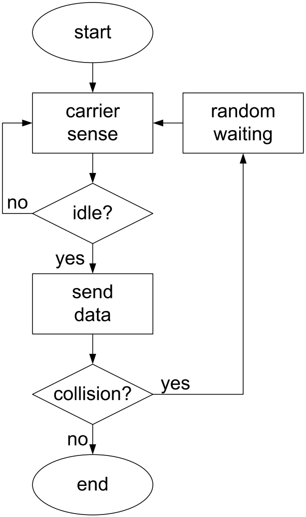
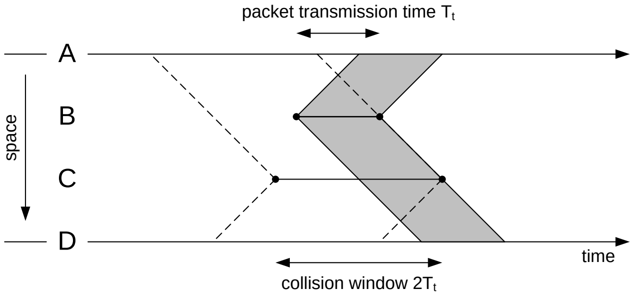
CSMA

- stations sense the channel before transmitting
  - if the station finds the channel idle it starts sending
  - if the station finds the channel busy it defers sending
    - non-persistent: try again after random waiting time
    - 1-persistent: try again immediately
    - p-persistent: try again, if idle send with probability p, wait one slot with $1-p$
- is used e.g. in LAN and WLAN, i.e. IEEE 802.3 and 802.11



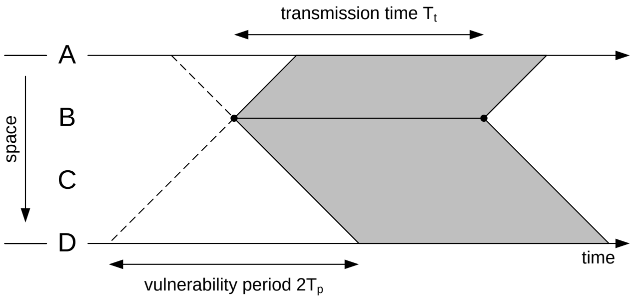
ALOHA space time diagram



Space time diagram

- transmission time T_t
- propagation delay T_p
- collision window $2T_t$ resp. T_t

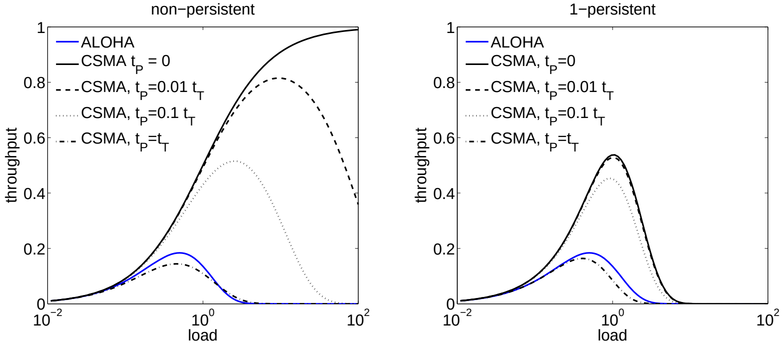
CSMA space time diagram



Space time diagram

- vulnerability period $2T_p$
- CSMA cannot improve ALOHA if propagation delays are large compared to transmission times, i.e. if carrier sensing yields only "old" information

CSMA vs. ALOHA



For small propagation delays T_p e.g. in local area networks CSMA outperforms ALOHA significantly.

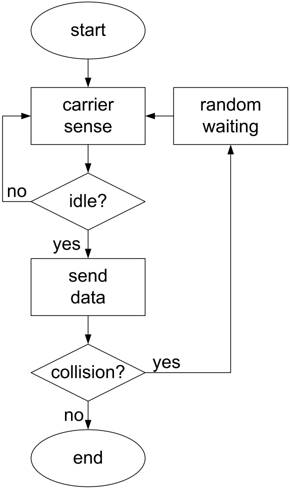
Non-persistent CSMA achieves higher throughput (why?) than 1-persistent CSMA, however, at the cost of additional latencies.

Collision detection

Collision detection during transmission
"listen while talking"

In wired multi access systems a transmitting station can detect other ongoing transmission.

This can be used for collision detection.



Collision detection

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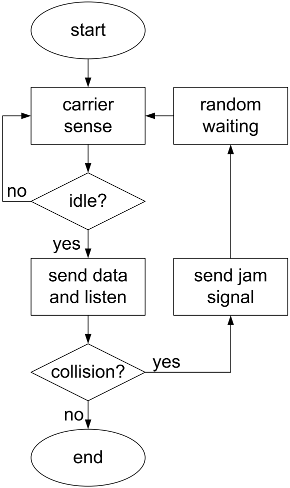
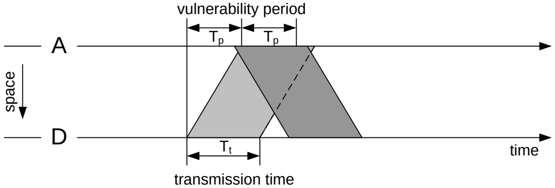
In case of a collision

- immediately stop sending data
- send jam signal to notify others

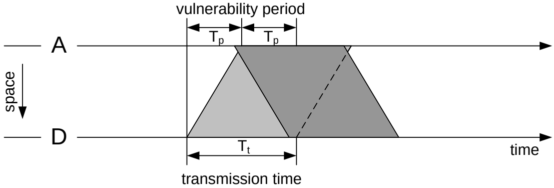


Required frame length

The frame length i.e. transmission time can be too short to detect collisions, e.g. at station D.

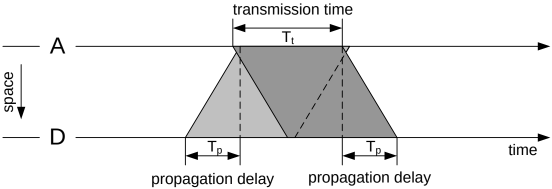


A transmission time of $T_t > 2T_p$ enables reliable collision detection.

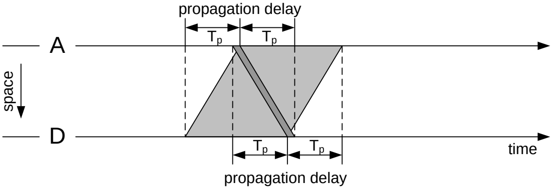


CSMA vs. CSMA/CD

Without collision detection the duration of an unsuccessful busy period can be up to $T_t + 2T_p$.



With collision detection the busy period is bounded by $3T_p$ respectively $2T_p$ at each station.



Backoff procedure

E.g. in case of 1-persistent CSMA/CD

- stations transmit immediately after the medium becomes idle
- if a collision occurs immediate retransmissions will cause further collisions
- need an efficient procedure to schedule retransmissions

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Binary exponential backoff

- random waiting after a collision, waiting time is uniformly in $[0, w-1]$ slot times (slot time = transmission time T_t of the smallest frame allowed, i.e. $2T_p$)
- the contention window w is doubled up to at most $w_{\max}$ (retry limit) after each collision
- w returns to $w_{\min}$ after each successful transmission

Adaptive window since the number of contending stations is unknown.

Comparison of random access methods

<table>
<tr><th rowspan="2" colspan="2"></th><th colspan="2">sensing wrt. sending</th><th colspan="3">behavior if station has something to send and medium is in state</th><th rowspan="2">time slots</th></tr>
<tr><th>before</th><th>during</th><th>busy</th><th>available</th><th>collision</th></tr>
<tr><td rowspan="2">ALOHA</td><td>pure</td><td></td><td></td><td colspan="2" rowspan="2">not known to sender</td><td rowspan="2">retransmission after random time interval</td><td></td></tr>
<tr><td>slotted</td><td></td><td></td><td>X</td></tr>
<tr><td rowspan="3">CSMA</td><td>nonpersist</td><td>X</td><td></td><td>re-check after random time interval</td><td rowspan="2">send immediately</td><td rowspan="3">wait random time interval then perform channel access for retransmission</td><td></td></tr>
<tr><td>1-persist</td><td>X</td><td></td><td rowspan="2">re-check immediately active waiting until channel is available</td><td></td></tr>
<tr><td>p-persist</td><td>X</td><td></td><td>send with probability p
wait with probability 1-p</td><td>X</td></tr>
<tr><td colspan="2">CSMA CD</td><td>X</td><td>X</td><td colspan="2">any of the CSMA procedures above
1-persistent CSMA/CD is used for Ethernet</td><td>stop immediately retransmission after random time interval</td><td></td></tr>
</table>