Data Link Layer
(Sicherungsschicht)
Medium Access Control
(Zugriffsverfahren)

References:
[Bosser99]
[Wa0102]
OSI-model for local networks with partition of the link layer in media access control and logical link control, as defined by IEEE 802.
Multiple Access Protocols
(Vielfachzugriffsprotokolle)

- **MAC**: Medium (Multiple) Access Control
- Influence
  - Medium (Übertragungsmedium)
  - Network Topology (Netztopologie)
- Performance Aspects
## Multiple Access Protocols

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Competitive Methods

- Random Access Schemes (Zufallszugriff)
  - Every station with data to send can principally access the channel
  - Transmission successful, when only one station accesses the medium
  - Concurrent access of more than one station at the same time leads to errors
Scheduling Methods (*Zuteilungsverfahren*)

- Perfectly scheduled
- Centralized:
  - Polling:
    - a master station polls each station in turn
- Decentralized: all stations are equal
  (Token Passing, Register Insertion, DQDB)
Reservation Methods
(Reservierungsverfahren)

- Examples: TDMA, FDMA, CDMA
- Management of a channel by a central station
- Channel with synchronous multiplexing techniques with subchannels
- Assignment of one or more channels on request
- Request in a fixed subchannel through random access or scheduling method
- Combined Methods
Network Topology

- **Polling**: (usually) star topology
  master in the center
- **Ring / Bus**: pairs of fiber channels,
  often separate rings or busses in both directions
  *(dual ring, dual bus)*
- **Mobile Radio Networks**
  usually use random access methods for reservation
- **Reliability (Ausfallsicherheit) and Robustness**:  
  - Polling ?  
  - Random access methods ?
    - Critical: error in central station  
    - Critical: high load
Performance Evaluation of Methods

- Offered Traffic (Verkehrsangebot)
- Transmission Time (Übertragungszeit)
- Throughput (Durchsatz)

- Which methods are to be preferred for high and low traffic?
- How does the offered traffic influence throughput and transmission time?

- Random access methods lead to lower transmission times for low or high traffic?
- Reservation and Scheduling Strategies lead to lower transmission times for low or high traffic?
Aloha Protocols

- Development at the University of Hawaii end of the 60s for the transmission of packet data in a radio network between terminals and a central computer
- Basic method of all random access methods
- Easy to implement, no complex coordination
- Unsuccessful transmissions are repeated
- Robust against transmission errors
- Used in mobile radio networks, e.g.,
  - GSM (Global System for Mobile Communication) or
  - TETRA (Trans-European Trunked Radio, digitaler Bündelfunk) for reservation
- Collisions
Assumptions for the Evaluation of Collision Resolution Methods (Kollisionsauflösungsverfahren) (1)

- \( m \) sending stations and exactly one receiver station
- One jointly used channel from all sending stations to the receiver
- Channel close to error free
- Data packets generated in all stations with Poisson distribution with rate \( \frac{\lambda}{m} \), all packets of equal length, \( X \) transmission time of a packet
- Immediate Transmission for Pure (Unslotted) Aloha
- Transmission in the next time slot for Slotted Aloha
- Transmission successful when only one sender accesses the channel during the transmission
- Collisions for concurrent access
- Immediate feedback: sender knows immediately whether or not the transmission was successful
Assumptions for the Evaluation of Collision Resolution Methods (2)

- No loss: sender retransmits packet until the transmission is successful
- Station is backlogged, as long as the transmission of a packet is repeated
- No buffering assumption: stations in a backlogged state do not generate additional packets
- Infinity assumption: the number $m$ of stations are assumed to be infinite, i.e., $m \to \infty$
- Probability for generating a packet at a specific station in time $T$:

\[ P\{\text{Generate a Packet in time } T\} = \frac{\lambda T}{m} e^{-\frac{\lambda T}{m}} \]

(Poisson Distribution)
Pure Aloha (*unslotted*)

- Basic random access method
- Station sends packet immediately after arrival
- Packet is received successfully when no other station sends during the same time
- Acknowledgement by receiver immediately after transmission
- Collision: two or more stations sending during the same time, no acknowledgement
- Sender sends packet again after a random time until packet is successfully transmitted (Acknowledgement)
Analysis of pure Aloha (1)

- Packet generation rate $\lambda$ [packets/s]
- Packet transmission time $X$
- Maximum packet transmission rate $\mu = 1/X$
- Offered traffic $\rho = \lambda / \mu$
- Channel access rate (incl. repetitions) $g$ [packets/s]
- Ratio to maximum transmission rate $G = g / \mu = gX$
- Rate of successful channel accesses $s$ [packets/s]
- Throughput $S = s / \mu = sX$
- Infinitely many stations in the network $m \rightarrow \infty$
- Simplification: Poisson distribution of the number of channel accesses of newly generated packets and repetitions: $g$
Analysis of pure Aloha (2)

- Average number of channel accesses until packet was transmitted successfully?
- \( P\{\text{successful access}\} = \frac{s}{g} = \frac{S}{G} \)

Channel access: Poisson distribution ⇔ Packet interarrival time: neg. exponential distribution
Formulas for pure Aloha

\[ P\{ T \geq X \} = \int_{X}^{\infty} ge^{-gt} dt = e^{-gX} = e^{-G} \]

\[ P\{ \text{success} \} = P\{ T_{\text{before}} \geq X \} P\{ T_{\text{after}} \geq X \} = e^{-2G} \]

\[ S = Ge^{-2G} \]

\[ S_{\text{max}} = \frac{1}{2e} = 0.184 = \rho_{\text{max}} = 18.4\% \text{ for } G = 0.5 \]
Throughput “Pure Aloha” protocol

\[ S \]

\[ \frac{1}{2e} \]

\[ \rho \]

\[ G_{stab} \]

\[ G_{lab} \]
Slotted Aloha

- Receiver defines pattern of time slots of length $X$ for the channel access
- Stations access the channel synchronously to the predefined slot pattern
- Otherwise: see pure Aloha
- Synchronization leads to complete overlay of packets sent in the same time slot
- $\Rightarrow$ Maximum Throughput relative to Pure Aloha?

**Maximum Throughput is doubled!**
Formulas Slotted Aloha

\[ P\{1 \text{ access}\} = P\{1|X\} = gXe^{-gX} \]

Rate of successfully used time slots:

\[ P\{1 \text{ access}\} \mu = s = S\mu \]

or \( P\{1 \text{ access}\} = S \)

with \( \mu = 1/X \) this results in

\[ S = Ge^{-G} \]

\[ S_{\text{max}} = 1/e = 0.368 \text{ for } G=1 \]
Throughput Slotted Aloha Protocol
Strategies for Collision Resolution

Binary Exponential Backoff

- Channel Access Probability $q_r$
- After $j$ erroneous accesses $q_r$ is set to $2^{-j}$
- Stabilization
- Goal: Region of $G=1$ with high throughput $S$

or other more complex methods see Pseudo-Bayes-Algorithm [Bossert99]
Max. Throughput < 0.587
Tree Method: Throughput < 0.46
Tree Algorithm (1)

- Throughput < 0.43

Example for Tree Algorithm

Time slots of the collision resolution period (Kollisionsauflösungsperiode)
Tree Algorithm (2)

- Throughput < 0.46

Presentation of subsets as trees.

Time Slots of the Collision Resolution Period
FCFS-Algorithm (1)

- Throughput < 0.4878

Example for the procedure of the FCFS-Algorithm
FCFS-Algorithm (2)

State diagram of the FCFS Algorithm
Carrier-Sensing-Methods

- Prerequisite: all stations can “hear” each other
- Common Topology: Bus
- Collision Avoidance through so-called Carrier Sensing (Abhören des Mediums auf Trägersignal)
- CSMA = Carrier Sense Multiple Access
- “Polite discussion” (höflich geführte Diskussion)
- Persistence:
  - Persistent CSMA: channel is constantly monitored, access as soon as channel is free
  - Non-persistent CSMA: monitor channel, if busy -> random time delay, listen to channel, access as soon as channel is free
  - p-persistent CSMA: Mixture, listen to channel until free, access with probability p, random time delay, listen to channel
\[ \tau = \text{max. signal propagation delay between 2 stations} \]

\[ L = \text{mean packet length [bit]} \]

\[ C = \text{channel transmission rate [bit/s]} \]

\[ X = \text{mean packet transmission delay} \]

\[ X = \frac{L}{C} \]

Parameter \( \alpha = \frac{\tau}{X} = \frac{\tau C}{L} \)
CSMA: Throughput

- Non-persistent CSMA
- \( m \rightarrow \infty \) stations
- States of the channel:
  - free, successful transmission, collision
- \( k \): number of stations ready to send a packet
- Other assumptions: see Aloha Protocol
CSMA: Throughput (1)

CSMA throughput ($\alpha = 0.1$)

\[ S_{\text{max}} \approx \frac{1}{1 + 2\sqrt{\alpha}} \]
CSMA: Throughput (2)

CSMA throughput for different $\alpha$

- $S(k)$
- $G(k)$

$\alpha = 0.0001$
$\alpha = 0.001$
$\alpha = 0.01$
$\alpha = 0.1$
Collision detection by “sensing” the “carrier” while sending

Station 1  Station 2

Start of transmission  

Collision detection  
stop transmission immediately

free channel

Start of transmission

Collision detection
stop transmission immediately

free channel

↓

Time
Ethernet: CSMA/CD System

- **Origin:** Xerox proposal for local networks, coaxial cable, Bus, 10 Mbit/s
- **Standard IEEE 802.3**
  \((\text{IEEE} = \text{Institute of Electric and Electronic Engineers})\)
- **Kilometer range**
- **Collision detection** depends on signal propagation, i.e. configuration of stations in the network
- **Collision resolution:** Binary-Exponential-Backoff
- **Detailed analysis** by simulation
- **Estimation of throughput** \(S\) for max. signal propagation:

\[
S \geq \frac{e^{-\alpha G}}{\alpha + \frac{1}{G} + 2\alpha \left( 1 - e^{-\alpha G} \right) + e^{-\alpha G}}
\]
**CSMA / CA (Collision Avoidance)**

- Collision detection, e.g. in radio networks usually not possible, sent signal conceals external received signal

- **Collision avoidance strategy:**
  - Sequence of access for all stations in the network
  - Segment time into time slots of duration $\delta$
  - $\delta$ slightly larger than max. signal propagation
  - Fixed or Random assignment of slots to stations
  - Station is only allowed to access assigned time slot
  - Time pattern is interrupted, as soon as a station is in sending mode
  - Time slot is an *implicit token*

- **Example:** IEEE 802.11b WLAN
  (installation at University of Bremen / NW1)
Polling

- **Central assignment of sending right**
- **Formerly mainframe access for terminals**
  - Mainframe as master
  - Terminals are polled cyclically
  - Simple implementation
  - Disadvantage: overhead of polling idle terminals results in considerable overhead for a large number of stations

- Improvement by so-called **Binary-Countdown-Protocol**
  - Stations are assigned network IDs
  - Stations broadcast their network IDs simultaneously
  - Stations with highest network ID bit = 1 wins
  - Repeat until station with highest network ID bit ready to send remains
  - In each step the address space is divided by 2: \( k = \lceil \log_2 m \rceil \)
  - Fairness?
Binary-Countdown-Protocol: Example

Station A (0010)
Station B (0100)
Station C (1001)
Station D (1010)
Token-Passing Methods

- Examples:
  - Token-Bus IEEE 802.4
  - Token-Ring IEEE 802.5
  - FDDI (Fiber Distributed Data Interface)

- General Token-Passing Characteristics:
  - Scheduling Method:
    - Station receives sending right through a so-called *token*
  - Transfer of the sending right by sending the short token to the next station
  - No Collisions
  - Limit of max. time until sending right is acquired is possible (e.g. by limiting time or number of packets), suitable for real time services, priorities
Token-Bus (IEEE 802.4)

- Token release after a max. of 10 ms
- Logical Ring implemented on bus topology
- Can handle hardware failures
- Changes of the logical ring structure

- **Deleting stations:**
  - Controlled: Station informs predecessor
  - Uncontrolled, e.g. by error: after releasing a token, Station watches if successor releases token itself, otherwise a message is sent to all stations, successor (of successor) answers or logical ring is newly established.

- **Adding stations:** Stations regularly ask new stations to send a notification.

- **Establishing new logical ring:** if a station has not noticed any access to the bus over a sufficiently long period of time, the station defines itself as the first station and stations are added with the same procedure as above.

- This standard has been withdrawn by the IEEE
Token-Ring (IEEE 802.5)

- Point-to-point connections of neighbouring stations
- Unidirectional mode of operation
- Data is passed on until it reaches the sender again
- Stations that are switched off or damaged are bridged (switch in the interface)
- Tokens are 3 bytes in length and consist of a start delimiter, an access control byte, and an end delimiter.

- Lost token, duplicate token:
  Monitor Station (arbitrary but fixed station) generates new token after max. token rotation time
FDDI - Fiber Distributed Data Interface

- ISO Standard ISO-9314 (ANSI)
- Fiber with 100 Mbit/s
- Copper cables can also be used (CDDI)
- Range is up to 200 km
- Logical topology is ring-based token network
- Timed Token Protocol based on 802.4
- FDDI network usually contains two rings
  - Primary ring
  - Secondary ring (for backup purpose)
- Deployed as backbone network in 90s
FDDI - Fiber Distributed Data Interface

😊 Standard
😊 High throughput

😊 Not developed further
😊 Only one data rate
😊 More expensive than Fast Ethernet and Gigabit Ethernet
DQDB (Distributed Queue Dual Bus)

- IEEE 802.6 Standard (1991)
- 155 Mbit/s, Data and Voice
- Scheduling Method
- Decentralized organization, synchronized system, priorities
- ATM-like cell structure with 48 byte payload
  (ATM: Asynchronous Transfer Mode)
  PLT (Payload Type) only 2 bit,
  SPR=Segment Priority
- MAN = Metropolitan Area Network
  or HSLAN = High Speed Local Area Network
- 2 unidirectional busses, reverse direction of transmission,
  not limited in range/distance
DQDB Topology

Cell Generator

Terminator

Cells

Terminator

Cell Generator

Cells

....
DQDB Cell Format

1 octet

ACF - Access Control Field

VCI - Virtual Channel Identifier
20 bit

PLT | SPR

HEC - Header Error Control

Information Field
48 Octets

Bit 1: Busy
Bit 2: Slot Type
Bit 3: PSR
Bit 4-5: RES
Bit 6: Req 2
Bit 7: Req 1
Bit 8: Req 0
DQDB Mode of Operation

- Cell Generator generates empty cells (Slots, busy bit = 0)
- Transmission of cells from generator to terminator
- Reservation Mechanisms:
  - on the other bus, by setting the request bit of a cell
- Stations: Counter for request bits, a number of empty cells corresponding to this counter are not used
- Is DQDB fair?
- Example: 30 km fiber cable, 155 Mbit/s, how many cells are in transit? What is the effect of a very active node upstream?
- Bandwidth balancing:
  - each node has to let a certain percentage $0 < f < 1$ of empty cells pass without using them