S-72.333
Post-graduate course in Radio Communications
2003 - 2004

Principles of WLANs

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Wireless Local Area Networks

- ❒ Definition of WLANs
- ❒ Basic principles and network topologies of LANs and WLANs
- ❒ Motivations for the use of WLANs
- ❒ PACKET RADIO ACCESS METHODS AND PERFORMANCE MEASURES
- ❒ WLAN IMPLEMENTATION ALTERNATIVES
- ❒ WLAN SOLUTIONS
- ❒ SYSTEMS IN THE ISM FREQUENCY BAND
- ❒ IEEE 802.11 WLAN STANDARDS
- ❒ ETSI HIPERLAN STANDARD
- ❒ AVERAGE PATH LOSS MODELS IN WLANs
- ❒ EXAMPLES

Definition of a Local Area Network:

- A LAN is a communication network which covers a limited geographical area with a diameter up to 5 km, e.g . a single building or an entire university campus area.
- A LAN offers a high bit rate link for the traffic between computers, peripherals, and other equipment.
- In a WLAN at least part of the transmission links is implemented with radio connections.
- Typically a locally owned, wide-bandwidth network intended for computer communications
- As computer communication are of bursty nature (large ratio between peak and average data rates), packet transmission protocols will be more efficient than circuit switched protocols

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Basic principles of LANs, 1

- Packet routing:
  - Virtual circuit routing (connection oriented):
    A fixed, specific path through the network is set up in the beginning of the session and maintained throughout the entire session, however, it is used only when required, and can be used by other simultaneous sessions
  - Datagram routing (connectionless):
    Each packet can take a different path through the network than the adjacent packets or any other packet. Datagram packet can thus arrive in any other, and must thus be time-stamped at the transmitting end (more overhead data). Packets can also be completely lost

Basic principles of LANs, 2

- ❒ Medium access control methods
  - Access to the LAN is implemented in the Network Interface Unit, NIU,
    which enables synchronous and asynchronous equipment to communicate which each other
  - Random access
    - ▫ Pure/slotted ALOHA
    - ▫ CSMA, CSMA/CD, CSMA/CA
  - Controlled access
    - ▫ Reservation
    - ▫ Polling
    - ▫ Token passing
  - Channelisation
    - ▫ FDMA
    - ▫ TDMA
    - ▫ CDMA

Basic principles of LANs, 3

❒ Servers

A servers is the heart of a LAN, and it

- distributes the resources to all network users,
- is the network maintainers tool to satisfy the needs of the users, to do network management, etc.
- The server is located in network cards, which typically are inserted in an effective computer
- Software is an essential part of the server

❒ Protocols

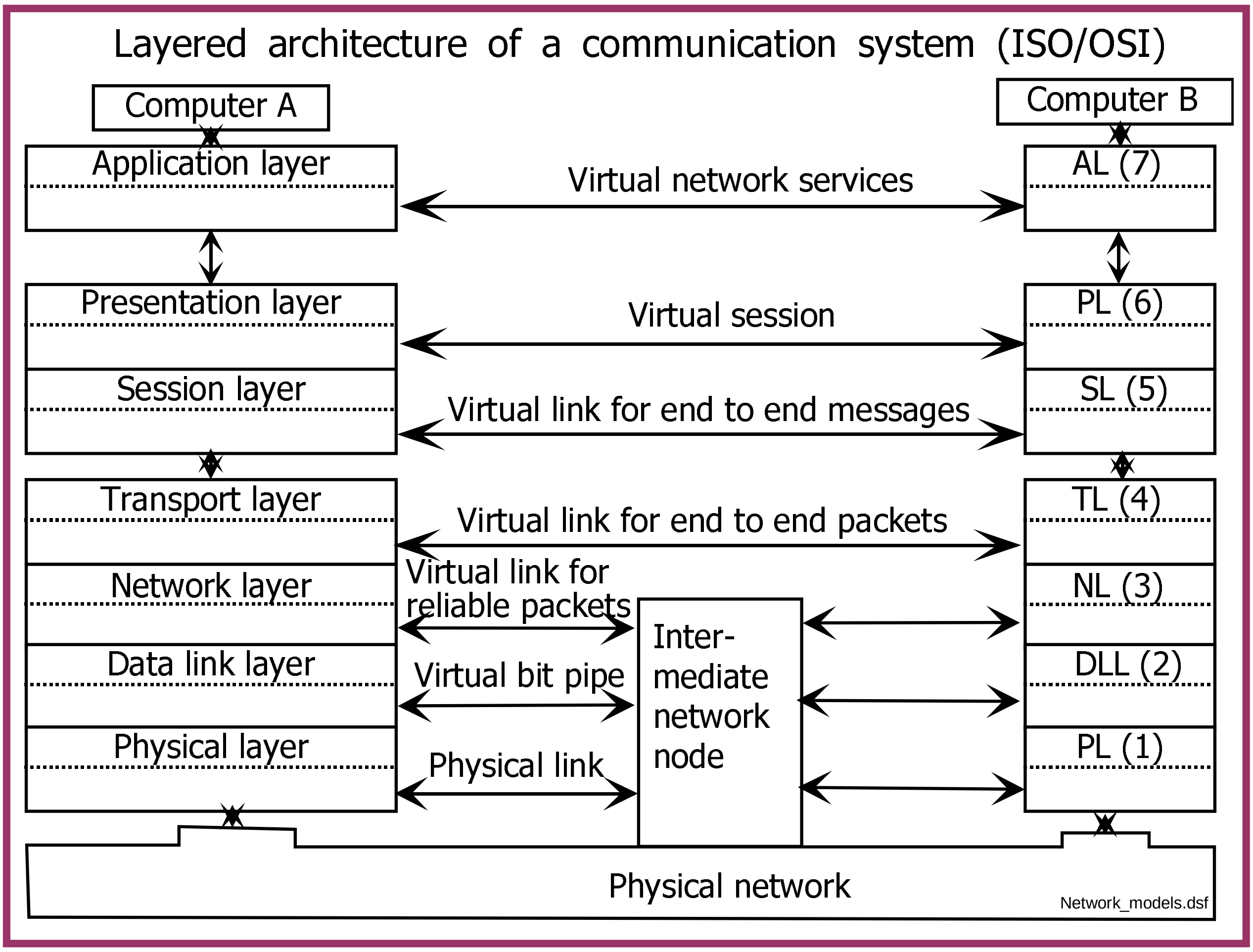
Defines the procedures for e.g. starting, maintaining, and closing connections

- MAP (Manufacturing Automation Protocol/ Technical Office Protocol)
- ISO/OSI 7 layer protocol stack
- TCP/IP (Transmission Control Protocol/ Internet Protocol)

Basic principles of LANs, 4

- Wired LAN topologies
  - bus, (e.g. Ethernet)
  - star, (e.g. StarLAN)
  - ring/loop, (e.g. Token-Ring)
  - mesh
  - hub
  - tree

- Wireless LAN topologies
  - centralised network
  - distributed network
  - multihop network



Layered architecture of a communication system (ISO/OSI)

Computer A

Application layer

Presentation layer

Session layer

Transport layer

Network layer

Data link layer

Physical layer

Computer B

AL (7)

PL (6)

SL (5)

TL (4)

NL (3)

DLL (2)

PL (1)

Virtual network services

Virtual session

Virtual link for end to end messages

Virtual link for end to end packets

Virtual link for reliable packets

Virtual bit pipe

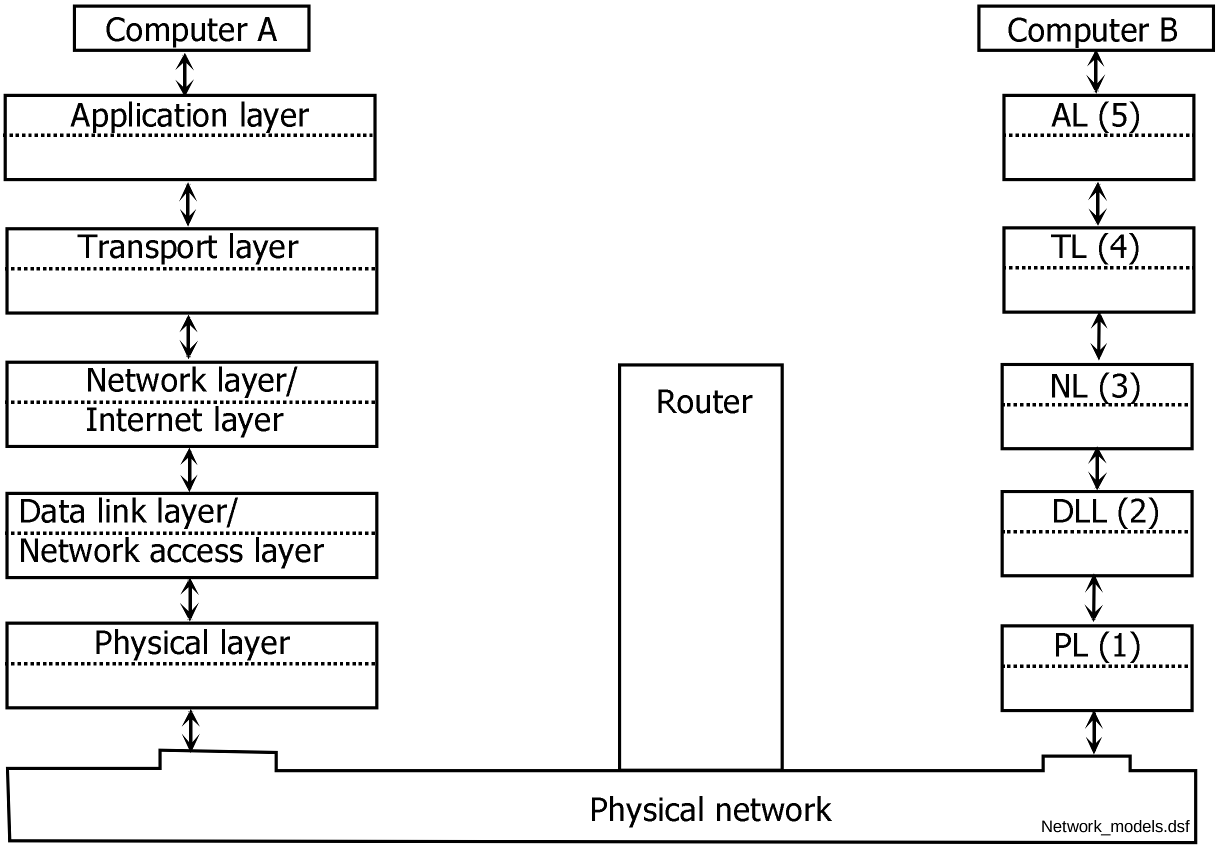
Physical link

Inter-mediate network node

Physical network

Network_models.dsf

Internet TCP/IP layered architecture



Computer A

Application layer

Transport layer

Network layer/
Internet layer

Data link layer/
Network access layer

Physical layer

Router

Computer B

AL (5)

TL (4)

NL (3)

DLL (2)

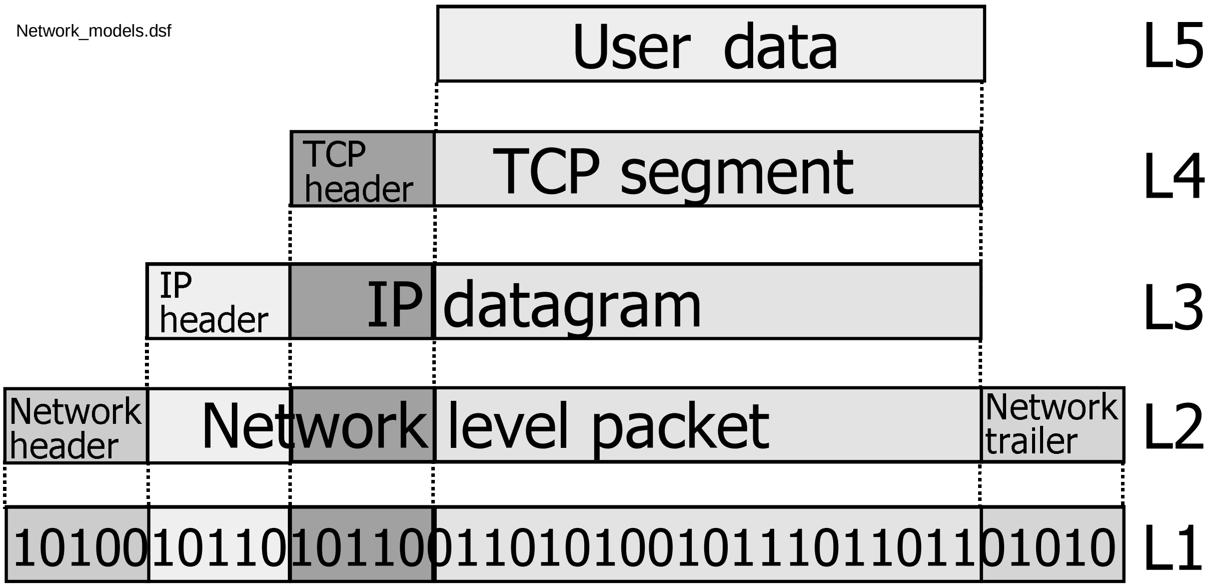
PL (1)

Physical network

Network_models.dsf

Protocol data units (PDUs) in TCP/IP

Network_models.dsf



User data — L5

TCP header | TCP segment — L4

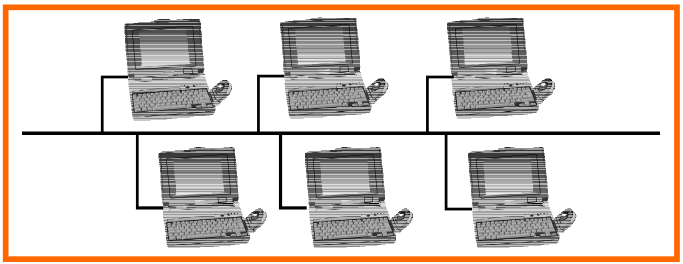
IP header | IP datagram — L3

Network header | Network level packet | Network trailer — L2

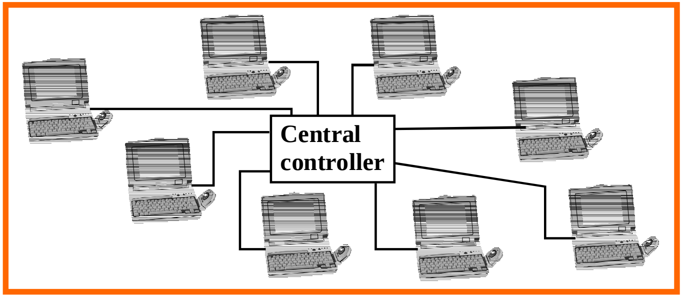
10100 10110 10110 0110101001011101101 01010 — L1

Basic network topologies in wired LANs

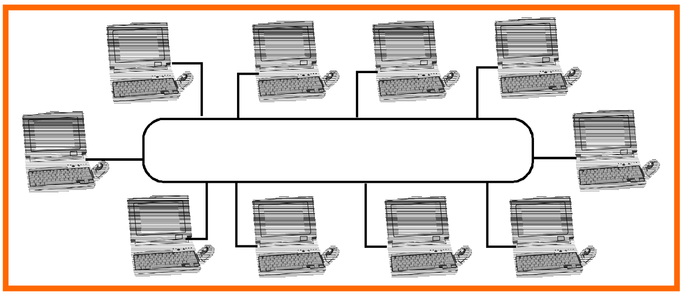
Bus



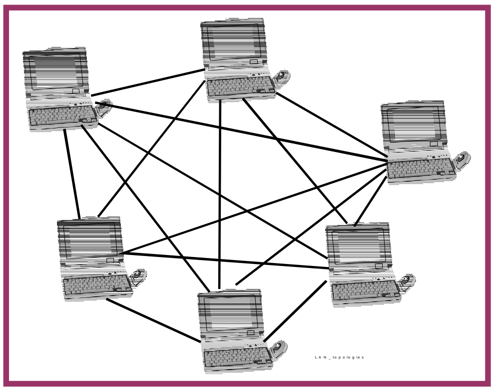
Star



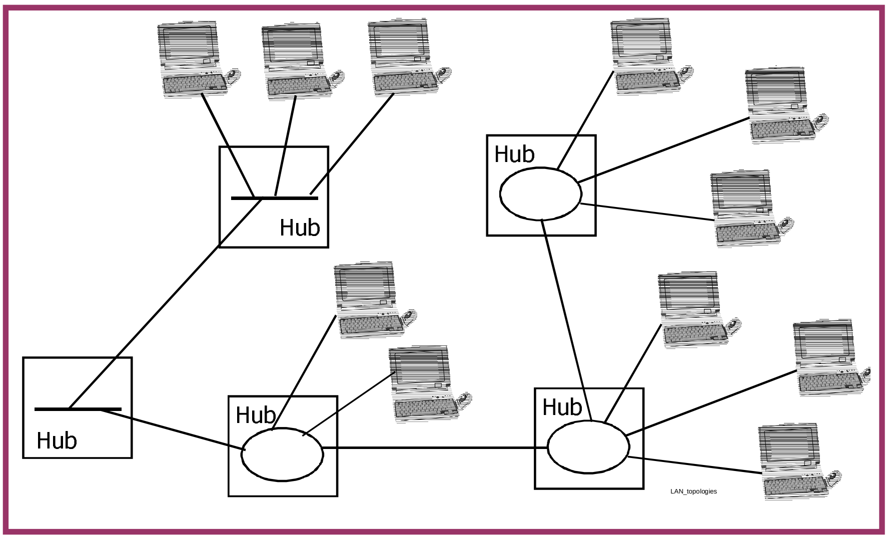
Ring/Loop



Mesh



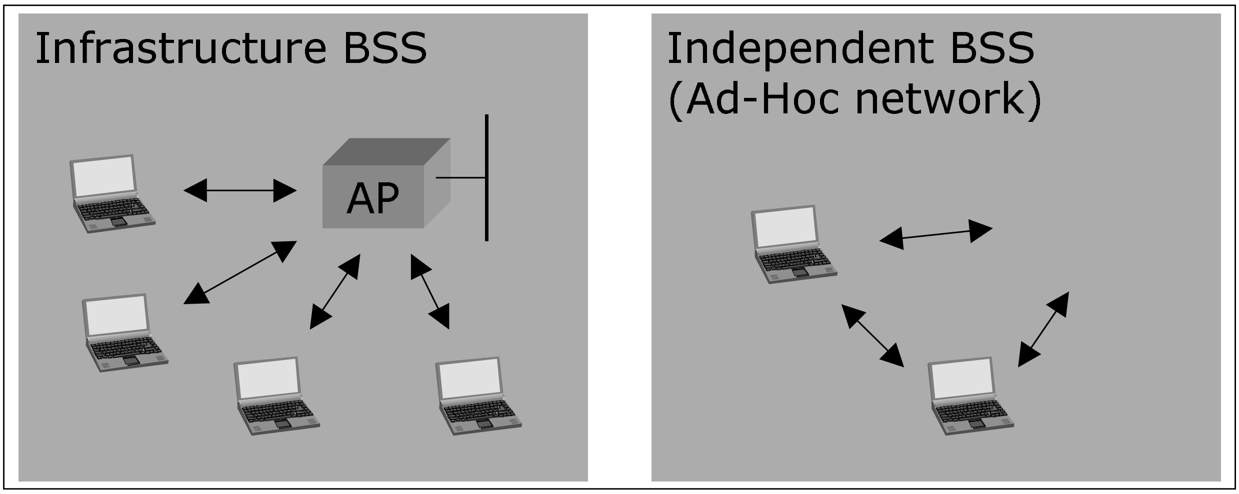
Hub/Tree



Basic network topologies in wireless LANs

- Centralised network based on star topology
- Distributed network e.g. ad-hoc network

In IEEE802.11x context the two topologies correspond to two basic service sets:



Infrastructure BSS

Independent BSS
(Ad-Hoc network)

Motivations for the use of WLANs

- Easy access to computer installations and computer networks
- Collection and dissemination of data over large distributed geographical areas independent of the availability of preexisting wire networks
- Suitability for communications with nomadic and mobile users
- Easily bypassed hostile terrain or limitations in the use of wired solutions (historical buildings etc.)
- Easily adaptable to changing needs and environments
- Appropriate data rates for many applications
- Standardisation enables use of equipment from different vendors (a problem in early WLAN solutions)

Comparison of circuit switched and packet switched transmission

CIRCUIT SWITCHED CONNECTIONS

- A fixed resource (e.g. a radio channel) is allocated to the connection throughout the entire session regardless of whether there is information to be transmitted or not.
- The switching procedure may take rather long time
- Circuit switching is not an efficient use of resources with bursty traffic

PACKET SWITCHED CONNECTIONS

- The information to be transmitted is divided into packets
- Transmission resources are allocated separately for each packet
- Virtual circuit (connection-oriented) routing uses a specific path through the network like a circuit switched connection but is used only when information is transmitted
- Datagram (connectionless) routing is made independently for each packet, packets may arrive with different transmission delays and in different order than transmitted
- Each packet must contain address and be numbered

Typical packet structure

Header			User data	Trailer
Flag	**Address Field**	**Control Field**	**Information Field**	**Frame Check Sequence Field**

packet_frame_structure.dsf

- the flag bits indicate beginning and end of each packet
- the address field contains the source and the destination addresses for transmitting messages and receiving acknowledgements
- the control field defines functions such as transfer of acknowledgements, automatic repeat requests (ARQ), and packet sequencing
- the information field contains user data and can be of variable length
- the frame check sequence field contains cyclic redundance check bits (CRC) and is used for error detection

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Multiple Access Methods in Packet Radio

FIXED-ASSIGNMENT CHANNEL ACCESS METHODS

- TDMA, Time Division Multiple Access
- FDMA, Frequency Division Multiple Access
- CDMA, Code Division Multiple Access

RANDOM ACCESS METHODS

ALOHA
Variations:

- Pure ALOHA
- Slotted ALOHA

CSMA (Carrier Sense Multiple Access)
Variations:

- non-persistent CSMA
- 1-persistent CSMA
- p-persistent CSMA
- CSMA/CD (Collision Detection)
- CSMA/CA (Collision Avoidance)
- CSMA/CE (Collision Elimination)

CONTROLLED RANDOM ACCESS METHODS

- Reservation ALOHA
- Polling methods
- Token passing method

MIXED VOICE AND DATA TRANSMISSION

- CDPD (Cellular Digital Packet Data (overlay in AMPS))
- GPRS (General Packet Radio System (overlay in GSM))
- PRMA (Packet Reservation Multiple Access)

Packet transmission performance measures:

- Throughput: $\rho = N \cdot \lambda = (R/T_p) \cdot \lambda$, the average amount of successfully transmitted data in bits/s
    - N is the packet length in bit/packet
    - λ is the output packet rate = input packet arrival rate (packet/s), when the system is in equilibrium state
    - R is the bit rate in bit/s
    - T_p is the packet duration in seconds

- Normalised throughput: $S = \rho / R$

- Normalised total traffic: $G = N \cdot \lambda_{tot} / R = T_p \cdot \lambda_{tot}$
    - λ_{tot} is the transmitted packet rate (including retransmitted packets)

- Average normalised packet transmission delay:
    - normalisation to packet transmission time

- instantaneous packet transmission delay: $D = 1 + a + \sum_{n=1}^{N_{re}} T_{re}(n)$
- a is the normalised path delay
- N_{re} is the number of retransmissions
- $T_{re}(n)$ is the normalised total retransmission time in the nth retransmission
- $T_{re}(n) = 1 + 2a + T_{ack} + D_r(n)$
- T_{ack} is the normalised transmission time of an acknowledgement message
- $D_r(n)$ is the normalised retransmission delay in the nth retransmission

- The packet delay is a random variable because both the number of retransmissions and the retransmission delay are random
- The delay probability density function would give the best information of the delay properties, and it can in principle be derived if the p.d.f.:s of number of retransmissions and retransmission delay are known.
- E.g. the delay exceeded for 10 % of the packets could be an important parameter.

- As retransmission is repeated until the receiver assumes a correct packet is received, the number of retransmissions has a geometric distribution, i.e.

$$p(N_{re}) = \sum_{n=0}^{\infty} p^n (1-p)\,\delta(n - N_{re}),$$

where p is the probability of an error packet caused either by collision or bit errors. These two events can be regarded as statistically independent which gives

$$p = P_{coll} + P_{ep} - P_{coll} \cdot P_{ep}$$

P_{coll} is the collision probability which depends on the packet access method and traffic model

P_{ep} is the probability of an error packet due to noise etc. With independent bit errors occurring with probability P_b, this probability is

$$P_{ep} = 1 - (1 - P_b)^N$$

- The retransmission delay p.d.f. can be set by the network operator, one simple model could be a uniform distribution over a given time interval.
- A less informative, but more easily obtainable delay measure is the average packet delay:

$$\mathrm{E}\{T_{re}\} = 1 + a + \mathrm{E}\left\{\sum_{n=1}^{N_{re}} T_{re}(n)\right\} = 1 + a + \mathrm{E}\{N_{re}\}\cdot\mathrm{E}\{T_{re}\}$$

The latter equality requires that the total retransmission times are statistically independent in each retransmission

- Due to the geometric distribution of the number of retransmission the average number of retransmission times is

$$\mathrm{E}\{N_{re}\} = \int_{-\infty}^{\infty} N_{re}\, p(N_{re})\, dN_{re} = (1-p)\sum_{n=0}^{\infty} np^{n} = (1-p)\frac{p}{(1-p)^{2}}$$

$$= \frac{p}{1-p}$$

- On the other hand one can also express the average number of retransmission as

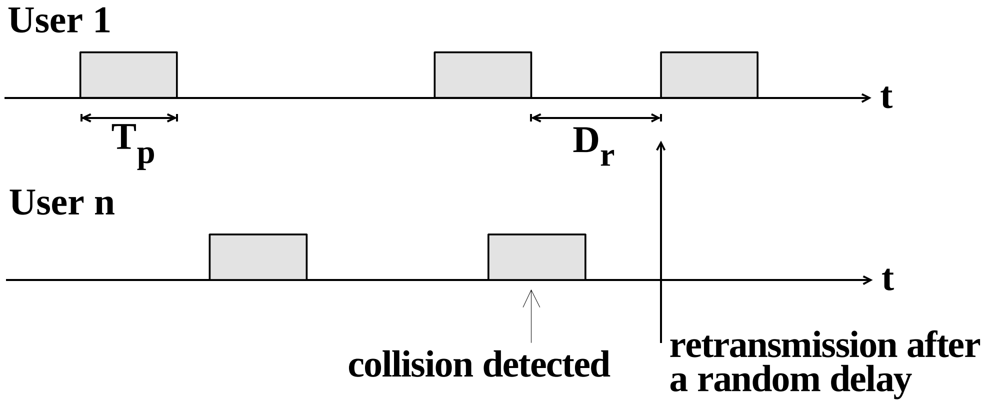
$$\mathrm{E}\{N_{re}\} = G/S - 1$$

- **For real time services (e.g. speech and video) delay variation is a very important quality measure**

ALOHA system modes

1. Transmission mode: Users transmit message at any time
2. Listening mode: After transmission user listens for ACK or NAK
3. Retransmission mode: When NAK is received the message is retransmitted after a random delay
4. Timeout mode: If ACK or NAK is not received within a specified time the message is retransmitted

Functional principle of ALOHA



Collisions are avoided if there are zero packet arrivals during a $2T_p$ period.

Average throughput and delay in ALOHA

Input packet arrival is assumed to be Poisson distributed:

$$P\{n \text{ packet arrivals in a time period of length } t\} = \frac{(\lambda t)^n e^{-\lambda t}}{n!}$$

Transmitted packet arrival is also assumed to be Poisson distributed:

$$P\{n \text{ packet arrivals in a time period of length } t\} = \frac{(\lambda_{tot} t)^n e^{-\lambda_{tot} t}}{n!}$$

- Average normalised throughput

S = Normalised total traffic · Probability of no collisions

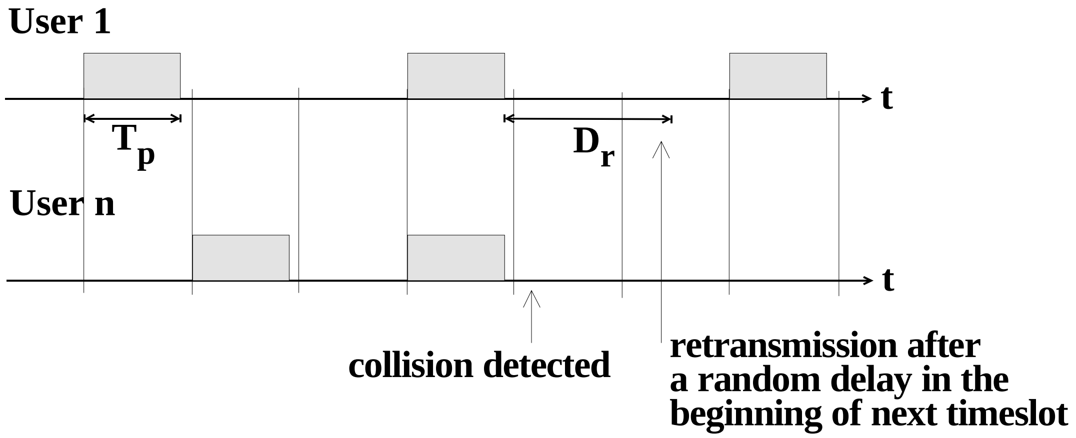
$$= G \cdot \frac{(\lambda \cdot 2T_p)^0 e^{-\lambda_{tot} \cdot 2T_p}}{0!} = Ge^{-2G}$$

- Average packet transmission delay

$$D = 1 + a + \left(e^{2G} - 1\right) D_r$$

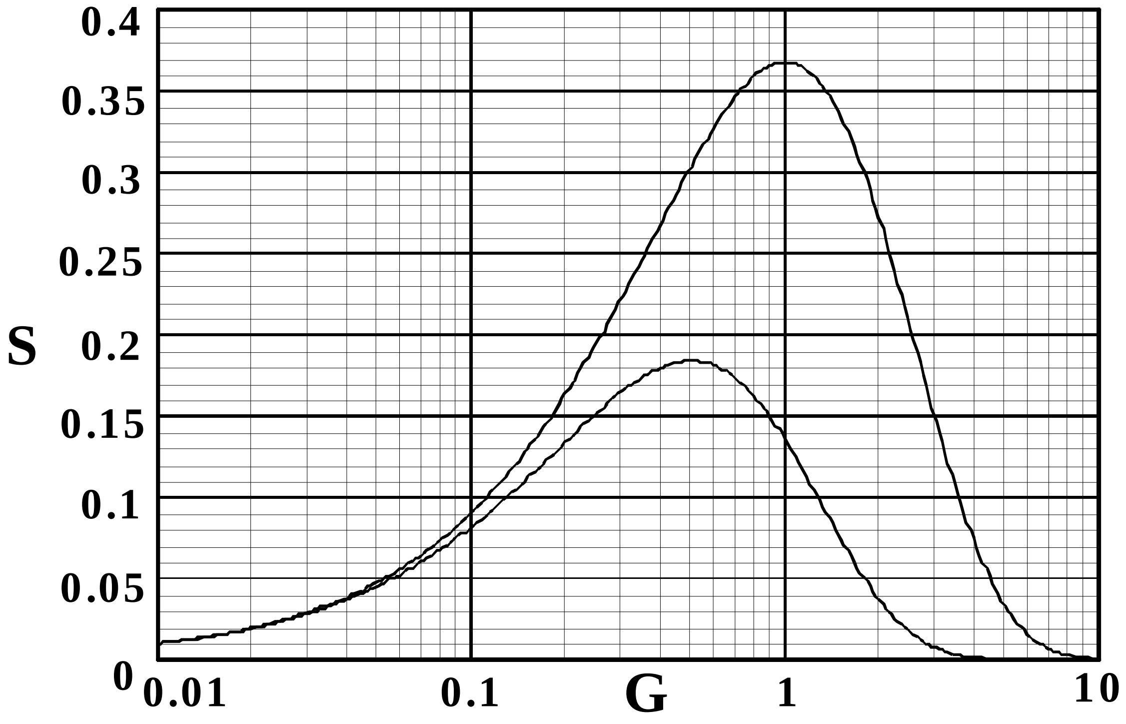
Slotted ALOHA

The performance of ALOHA is improved with the use of slotted ALOHA, where time is divided into time-slots and transmission can be started only at the beginning of a time-slot. The price paid is the need of synchronisation.

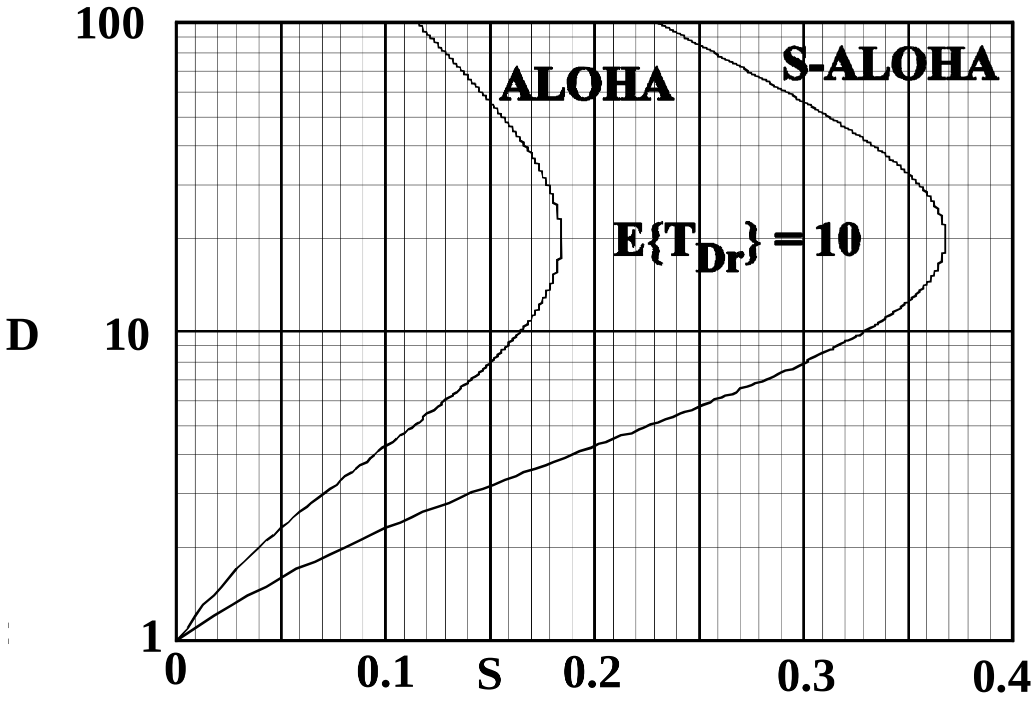


- Average normalized throughput $S = Ge^{-G}$
- Average packet transmission delay $D = 1 + a + \left(e^{G} - 1\right) D_r$

Throughput in pure and slotted ALOHA



Average packet transmission delay in pure and slotted ALOHA



CSMA

The terminal listens if there is a user already using the traffic channel, and starts the transmission when it assumes the channel to be free. If a collision is detected retransmission is started after a randomly chosen time interval

- non-persistent CSMA
  When the channel is sensed busy, this is interpreted as a collision, and next sensing is made after a randomly chosen time interval

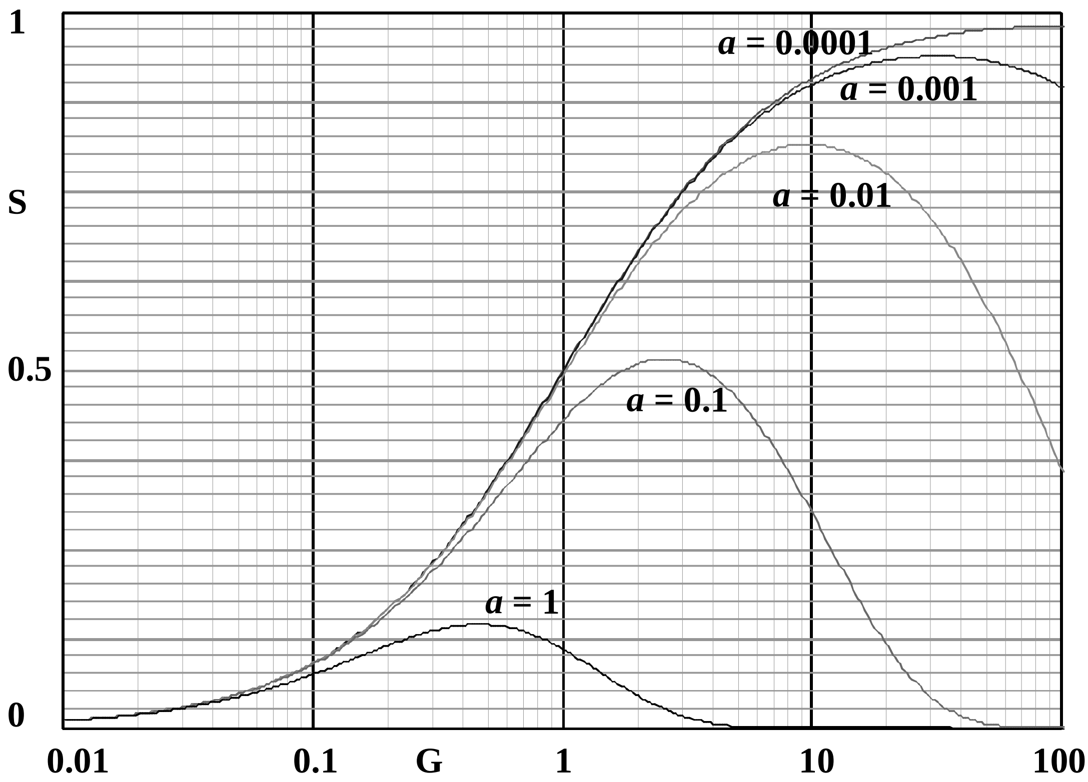
  Throughput in unslotted operation:

$$S = \frac{G\exp\left(-aG\right)}{G(1+2a)+\exp\left(-aG\right)}, \qquad a = \frac{\text{transmission delay } \tau}{\text{packet duration } T_p}$$

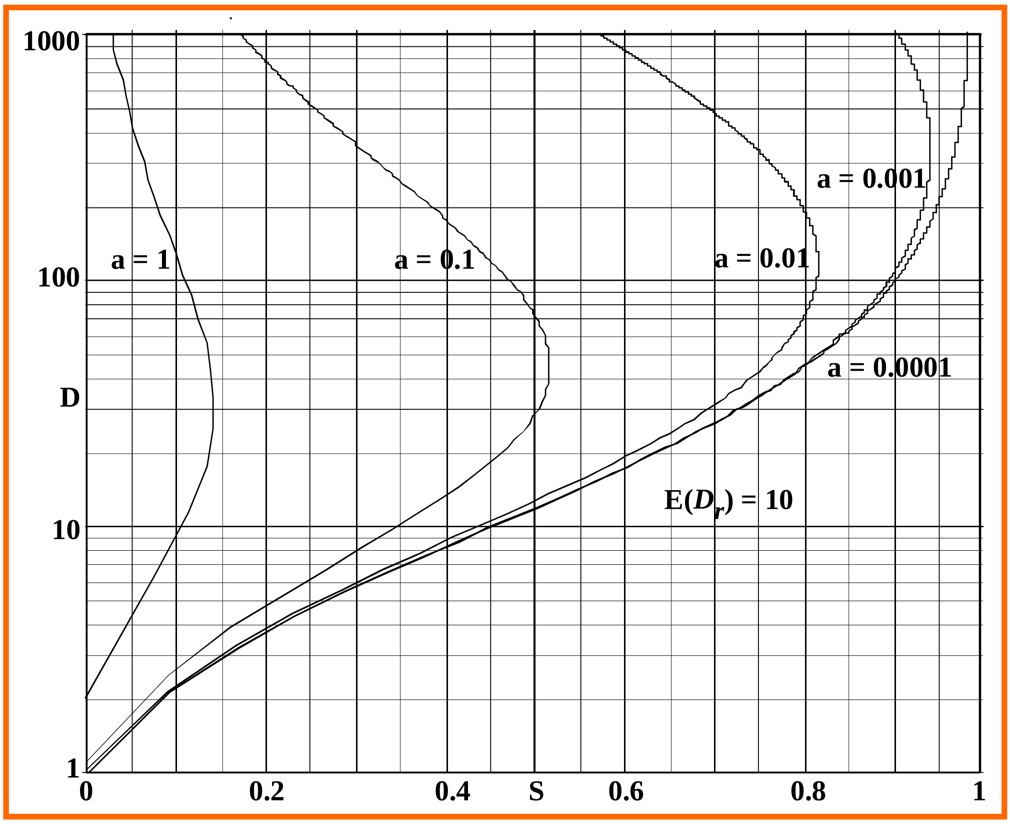
  Average delay in packets in unslotted operation:

$$D = \left(\frac{G}{S}-1\right)\left(1+2a+T_{ack}+D_r\right)+1+a$$

Throughput in non-persistent, unslotted CSMA



Average delay in non-persistent, unslotted CSMA



Throughput in slotted operation:

$$S = \frac{aG\exp(-aG)}{1 + a - \exp(-aG)}$$

Average delay in slotted operation

$$D = \left(\frac{G}{S} - 1\right)\left(1 + 2a + T_{ack} + D_r\right) + 1 + a$$

- 1-persistent CSMA
  Sensing is continued until the on-going transmission disappears, then the terminal starts its transmission immediately (probability = 1)

  Throughput in unslotted operation:

$$S = \frac{G\left[1 + G + aG\left(1 + G + 0.5aG\right)\right]\exp\left(-G(1+2a)\right)}{G(1+2a) - \left(1 - \exp(-aG)\right) + (1 + aG)\exp\left(-G(1+a)\right)}$$

Throughput in slotted operation:

$$S = \frac{G\left[1+a-\exp\left(-aG\right)\right]\exp\left(-G(1+a)\right)}{(1+a)\left(1-\exp\left(-aG\right)\right)+a\exp\left(-G(1+a)\right)}$$

- p-persistent CSMA
  A generalisation of 1-persistent CSMA, applicable to slotted CSMA. When the channel is sensed idle, transmission starts with probability p, and with probability $q = 1 - p$ sensing is repeated in the next slot

❒ CSMA/CD (Collision Detection)

- Before transmission the terminal intending to transmit data senses if the channel is busy.
- If the channel is sensed busy, the terminal is waiting a randomly chosen time period before next attempt
- If the channel is sensed idle, transmission is started
- During and after transmission the terminal listens to the channel to detect collisions (requires a listen-while-talk characteristic, short transmission interruptions)

- If a collision is detected, the transmitting station waits for a randomly chosen time period before retransmission and inserts a jamming signal of duration *b* packets to indicate to other users that a collision has occurred

Throughput in unslotted, non-persistent operation:

$$S = \frac{G\exp\left(-aG\right)}{G\exp\left(-aG\right)+(b+2a)G\left(1-G\exp\left(-aG\right)\right)+2-\exp\left(-aG\right)}$$

❒ CSMA/CA (Collision Avoidance)
This differs from the previous one in that during transmission collisions are not monitored (seldom used)

❒ CSMA/CE (Collision Elimination)
When the terminal senses the channel to be idle, it waits for a pre-defined time period (DST, Deference Slot Time). With a suitable DST estimation algorithm collisions can be totally avoided

- ❒ Reservation ALOHA
- ❒ Polling methods

- ❒ Token passing method
  User authorisation circulates between the stations in the network, an a station can transmit when it gets the authorisation. Collisions are avoided in this method.

- ❒ CDPD (Cellular Digital Packet Data (overlay in AMPS))
- ❒ GPRS (General Packet Radio System (overlay in GSM))
- ❒ PRMA (Packet Reservation Multiple Access)

IMPLEMENTATION ALTERNATIVES FOR WLANs

Wireless LANs can be divided into two classes depending on the physical interface:

- ❒ Radio Local Area Networks, RLAN
  - In RLANs the carrier frequency is below 3000 GHz (definition of radio waves)
  - In practice RLANs use microwave frequencies (1 - 30 GHz)
  - On lower frequencies the radio wave penetrates more easily walls and floors, and is more easily diffracted around obstacles
  - On higher frequencies the significance of line-of-sight increases

- ❒ Infrared Local Area Networks, IR-LAN
  - IR-waves obey ray optic rules,
  - so diffraction is insignificant
  - Many construction materials are rather bad reflectors of IR-waves,
  - and IR-wave wall penetration is very small.
  - As a result the coverage area of an IR-LAN is limited to a single room

Here only RLANs are considered

RLAN SOLUTIONS

TRADITIONALLY USED SOLUTIONS

- Systems in the ISM (Industrial, Scientific, Medical) frequency band
- Systems based on DECT
- Other proprietary systems
  - RadioLAN
  - AMP Wireless

RLANs BASED ON STANDARDS

- HIPERLAN
- HIPERLAN 2
- IEEE 802.11
  - WaveLAN
  - NetWave

SYSTEMS IN THE ISM FREQUENCY BANDS

Radio interface:

- ISM frequency bands: 902 - 928 MHz
  2400 - 2483,5 MHz
  5725 - 5850 MHz
- Frequency license not needed if $P_{tx} \leq 1$ W (FCC) or $\leq 0{,}1$W EIRP (ETS 300 328)
- Radius of coverage area in the order of 250 m
- Radio interface is proprietary solution
- Most commercial systems use the 2.4 GHz band utilising spread spectrum techniques, either frequency hopping or direct sequence spread generally with only one user per carrier frequency
- Transmission rates 1 – 2 Mbit/s

IEEE 802.11 WLAN STANDARD

- Focuses on the Physical Level, Physical Level Interface and Medium Access Control (MAC)
- Frequency band 2400 - 2483,5 MHz (ISM-band) or IR,
  also in 17 and 61 GHz bands
- DSSS PSK- or 4PSK-modulation with 1 and 2 Mbit/s transmission rates, 5 26 MHz sub-bands → 5th order frequency diversity is possible and badly needed due to other users of this band (microwave ovens etc.)
- FHSS with GFSK-modulation, two hopping sequences, 1 and 2 Mbit/s rates, 79 sub-bands with 1 MHz bandwidth, 2.5 hops/s (slow FH)
- DFIR (DifFused IR), OOK-modulation, 1 Mbit/s
- CSMA

- IEEE 802.11b (1999) specifies a higher rate physical layer extension
- 5.5 & 11 Mbit/s, Direct Sequence Spread Spectrum, spreading factor 8
- Modulation: 8-chip Complementary Code Keying (CCK), 4 bits/symbol @ 5.5 Mbit/s, 8 bits/symbol @ 11 Mbit/s

ETSI HIPERLAN-STANDARD

- HIgh Performance European RLAN
- Frequency bands and transmit powers:
  5,15 - 5,25 GHz, 1 W EIRP, common European allocation
  5,25 - 5,30 GHz, 1 W EIRP, additional, national allocation
  17,1 - 17,3 GHz, 0,1 W EIRP, common European allocation
- Transmission rate 20 Mbit/s
- Radius of coverage area 50 m in indoor environment
- System capacity 1000 Mbit/s/hectare/floor
- User mobility ≤ 10 m/s and 360 °/s
- Power consumption a few hundred mW
- Physical size PCMCIA-card (85×54×10,5mm)
- PHY- and MAC-layers are standardised
- Single carrier modulation, GMSK (also spread spectrum methods, multicarrier methods, adaptive antennas have been investigated
- DFE-equaliser proposed (also the applicability of Viterbi-equaliser investigated)
- Channel reservation with distributed load sensing (every station has a list of the active stations)

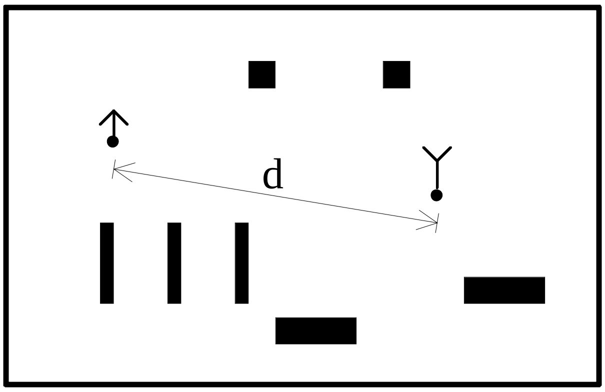
- 1^{st} version of the standard finished in 1995

- HIPERLAN2 standard (1998)
- 64 sub-carrier OFDM is used, 48 data and 4 pilot sub-carriers are actually used
- range up to 150 m
- sub-carrier spacing 312.5 kHz
- channel raster 20 MHz
- Modulation parameters for different data rates

Mode	user data rate	sub-carrier modulation	channel code rate
1	8 Mbit/s	BPSK	1/2
2	9 Mbit/s	BPSK	3/4
3	12 Mbit/s	QPSK	1/2
4	18 Mbit/s	QPSK	3/4
5	27 Mbit/s	16QAM	9/16
6	36 Mbit/s	16QAM	3/4
7	54 Mbit/s	64QAM	3/4

AVERAGE RADIO PATH LOSS MODELS, 1

Indoor environment, l.o.s. propagation



$$L = S + 10\cdot n_1\cdot\lg(d)$$

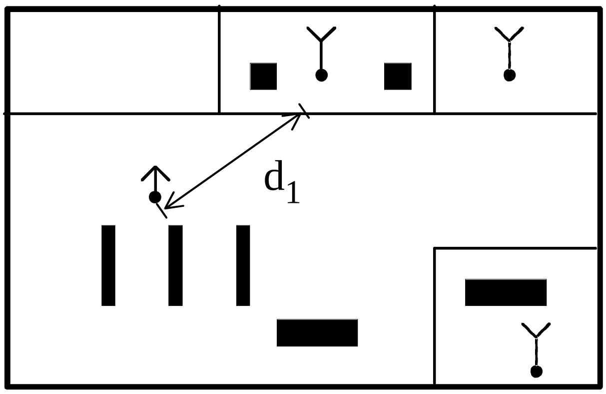
$$S = 20\cdot\lg\left(\frac{4\pi}{\lambda}\right) = 32{,}4 + 20\cdot\lg(f[GHz])$$

n_1 = 2,9 (on short distances)

d is the distance [m] between transmitter and receiver

AVERAGE RADIO PATH LOSS MODELS, 2

2° Indoor environment with internal walls, propagation only through walls



- $L = S + 10 \cdot n_1 \cdot \lg\left(d_1\right) + \sum L_w$
- S and n_1 as in 1°
- d_1 is the distance [m] between transmitter an wall
- L_w is wall penetration loss, which depends on the wall construction and material and on the incidence angle

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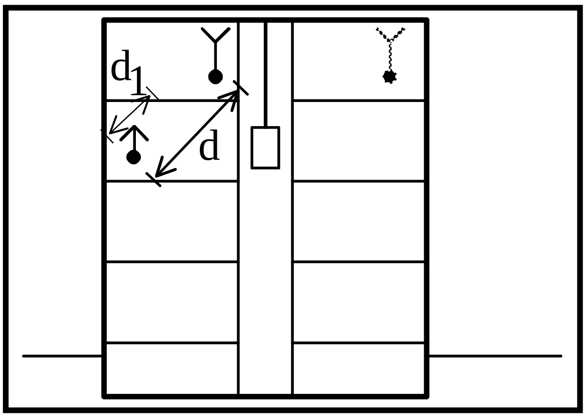
AVERAGE RADIO PATH LOSS MODELS, 3

3° Transmitter and receiver on different floors

$$L = S + 10 \cdot n_1 \cdot \lg\left(d_1\right) + kF + 10 \cdot n_2 \cdot \lg\left(d/d_1\right)$$

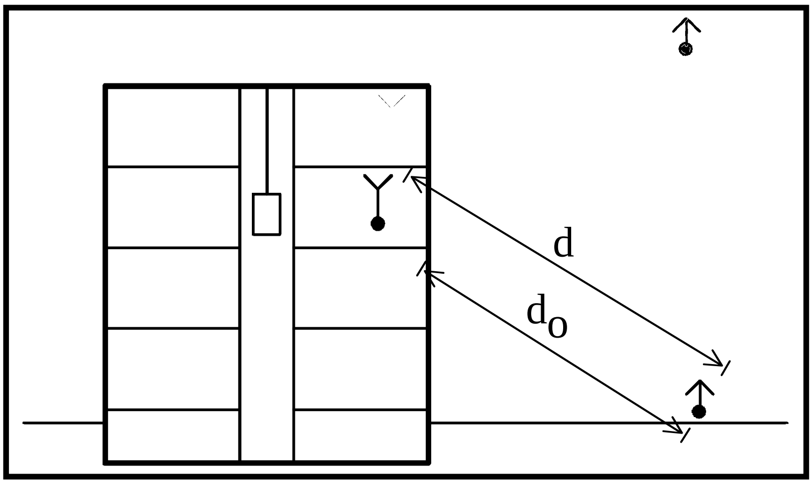


- S as in 1°
- n_1 is the path loss exponent in the transmitter floor, 3.5 in the vertical direction
- d_1 is the distance [m] between transmitter and first penetrated floor
- k is the number of penetrated floors
- F is the floor penetration loss, depends on construction and material
- n_2 is the path loss exponent in the receiver floor, 3.5 in the vertical direction
- d is the distance [m] between transmitter and receiver

AVERAGE RADIO PATH LOSS MODELS, 4

4° Transmitter outdoors above or below roof top level, receiver indoors

$$L = S + 10 \cdot n_o \cdot \lg(d_o) + L_w + 10 \cdot n_1 \cdot \lg(d/d_o) + kM$$



- S as in 1°
- n_0 is the path loss exponent outdoors
- d_0 is the distance [m] between transmitter and outer wall
- n_1 is the path loss exponent indoors
- L_w is the outer wall penetration loss
- d is the distance [m] between transmitter and receiver
- M is the floor penetration loss
- k is the number of penetrated floors

STATISTICAL DESCRIPTION OF RADIO PATH LOSS, 1

For a narrow-band signal is

$$W\Delta\tau << 1$$

- **W** is the signal bandwidth
- $\Delta\tau$ is the radio path delay spread

and when the radio path contains a constant component (e.g. a line-of-sight component), the complex envelope can be represented as

$$r = r_o + r_c + jr_s$$

- r_o is the amplitude of the constant component in a certain location
- $r_c + jr_s$ is the complex envelope of the multipath component in the same location at a given time instant

STATISTICAL DESCRIPTION OF RADIO PATH LOSS, 2

Then the received signal envelope is

$$a = \sqrt{\left(r_o + r_c\right)^2 + r_s^2}$$

and the received power is

$$P = \overline{a^2} = \overline{\left(r_o + r_c\right)^2 + r_s^2} = r_o^2 + \overline{r_c^2} + \overline{r_s^2} = r_o^2 + 2\sigma^2$$

and the power ratio between the constant component and the multipath component is

$$\gamma = \frac{r_o^2}{2\sigma^2}$$

STATISTICAL DESCRIPTION OF RADIO PATH LOSS, 3

then the received signal envelope is Rice-distributed, with the probability density function p.d.f.

$$p_a(a) = e^{-\gamma} \frac{a}{2\sigma^2} e^{-a^2/2\sigma^2} I_o\left(\frac{a}{\sigma}\sqrt{2\gamma}\right) u(a)$$

which in case of no constant component reduces to the Rayleigh distribution with p.d.f.

$$p_a(a) = \frac{a}{2\sigma^2} e^{-a^2/2\sigma^2} u(a)$$

The cumulative distribution for the Rice-distribution can only be obtained by numerical integration of the p.d.f.:

$$F_{\mathrm{a}}(a) = P\left\{\mathrm{a} \le a\right\} = \int_0^a p_{\mathrm{a}}(a)\,da$$

STATISTICAL DESCRIPTION OF RADIO PATH LOSS, 4

APPLICATION: FLAT FADE MARGIN

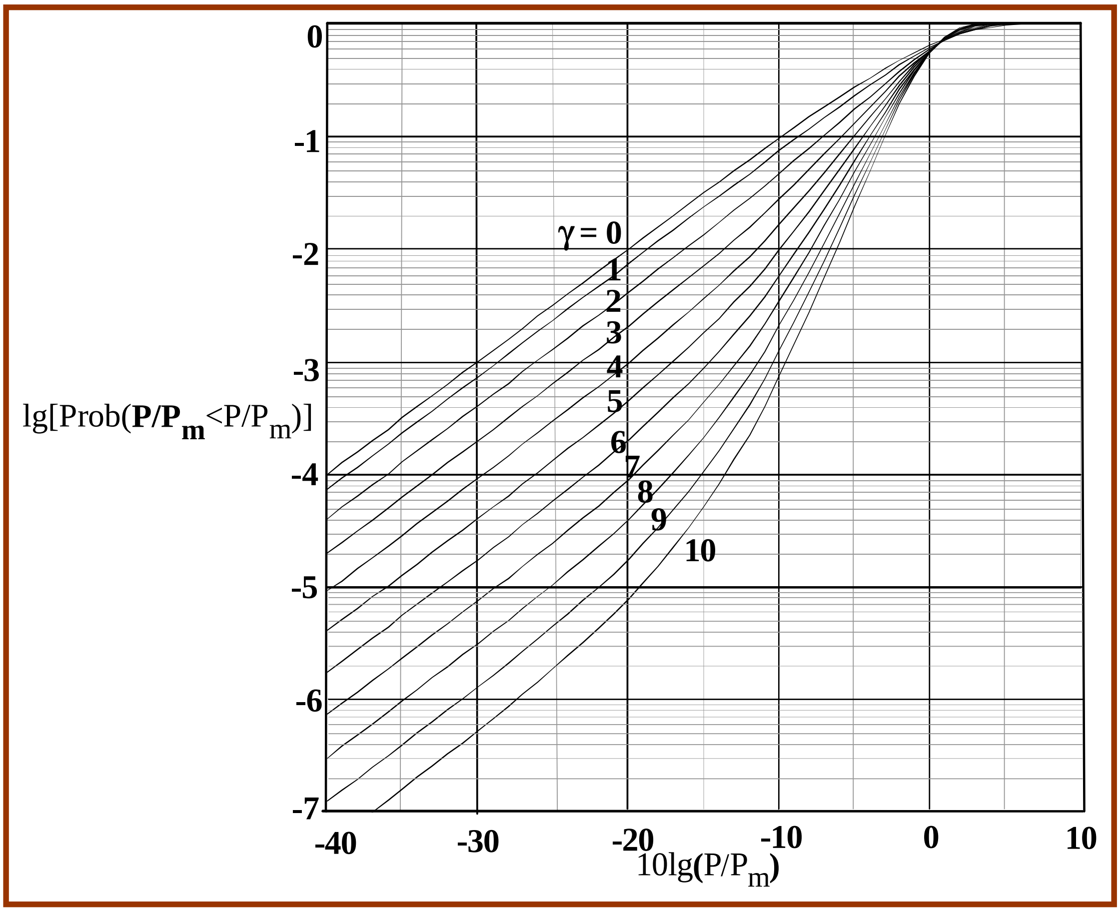
Let's assume that the user terminal in a RLAN is almost stationary, and that 90 % of the users located at the coverage area border will get a sufficient power level

From the figure can be determined that for

$$\begin{aligned}
&\gamma = 0 && \Rightarrow\ FFM \cong 8{,}8dB\\
&\gamma = 4 \leftrightarrow 6dB && \Rightarrow\ FFM \cong 4{,}4dB\\
&\gamma = 15 \leftrightarrow 12dB && \Rightarrow\ FFM \cong 1{,}9dB
\end{aligned}$$

FFM, Flat Fade Margin is added to the average path loss in the radio link budget

It can be noted that the larger constant component the smaller FFM is needed. In worst case planning the radio channel is assumed to be Rayleigh-fading.



WLAN examples

Example 1.

In a packet radio system the average rate of *transmitted* packets is 10 packets/s. What is the optimum packet length in seconds which maximizes the throughput:

a) in basic ALOHA,
b) in slotted ALOHA?

Solution: a) In basic ALOHA the throughput is given by

$$S = G\exp(-2G)$$

The maximum value is obtained by standard methods

$$\frac{dS}{dG} = \exp(-2G) - 2G\exp(-2G) = 0 \Rightarrow G = 0.5$$

$$\Rightarrow S_{\max} = 0.5\exp(-1) = 0.184 = \lambda T_p = \frac{S_{\max}}{G(S_{\max})}\lambda_{tot} T_p$$

$$\Rightarrow T_P = \frac{G(S_{\max})}{\lambda_{tot}} = \frac{0.5}{10}s = 50.0ms$$

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b) In slotted ALOHA the throughput is given by

$$S = G\exp(-G)$$

The maximum value is again obtained by differentiation

$$\frac{dS}{dG} = \exp(-G) - G\exp(-G) = 0 \Rightarrow G(S_{\max}) = 1$$

$$\Rightarrow S_{\max} = \exp(-1) = 0.368 = \lambda T_p$$

$$= \frac{S_{\max}}{G(S_{\max})}\lambda_{tot} T_p$$

$$\Rightarrow T_P = \frac{G(S_{\max})}{\lambda_{tot}} = \frac{1}{10}s = 100.0ms$$

Example 2.

A packet radio system for 100 identical users is constructed. he packet length is 1000 bit and the radio channel transmission rate is 100 kbit/s. Slotted ALOHA is used.

a) Calculate the maximum throughput in bit/s.
b) Each user receives in average 0,05 packets/s. Estimate the average transmission delay (s) when the average retransmission delay is 50 packets.

Solution:

a) $S_{\max} = \frac{\rho_{\max}}{R} = 0.368 \Rightarrow \rho_{\max} = 0.368R = 36.8\ \text{kbit/s}$

b) The normalized total traffic and the average delay are

$$G = \frac{N\lambda_{tot}}{R} = \frac{1000 \cdot 100 \cdot 0.05}{100000} = 0.05$$

$$D = 1 + \left(\exp(G) - 1\right)\left(1 + E\{D_r\}\right) = 1 + \left(\exp(0.05) - 1\right)(1 + 50)\, packets$$

$$= 3.61\, packets \Leftrightarrow 3.61 \cdot \frac{N}{R} = 3.61 \cdot \frac{1000}{100000} s = 36.1 ms$$

Example 3.

In a taxi communication system the radio channel data rate is 1200 bit/s. A message (packet) contains 30 bytes of information. The system will use either basic ALOHA or slotted ALOHA.

a) How many taxis can be served with these access methods if every taxi produces a message once in two minutes on average (Poisson-distributed)?
b) Estimate the expected transmission delay in seconds when 100 taxis are served and the average retransmission delay is 3 s.

Solution:

a) In standard ALOHA is

$$S_{\max} = \frac{N\lambda}{R} \Rightarrow \lambda = \lambda_{user} N_{user} = \frac{S_{\max} R}{N}$$

$$\Rightarrow N_{user} = \frac{S_{\max} R}{N\lambda_{user}} = \frac{0.184 \cdot 1200}{30 \cdot 8 \cdot 1/120} = 110.4 \rightarrow 110$$

In slotted ALOHA the treatment is the same but $S_{\max}$ is the double and

$$N_{user} = 220$$

b) $S = \dfrac{N\lambda_{in}}{R} = \dfrac{240 \cdot 100 \cdot {}^{1}\!/_{120}}{1200} = 0.167$

Trial and error or iteration of $S = G\exp(-2G)$ gives:

$G = 0.310$ in standard ALOHA

and of $S = G\exp(-G)$ gives G = 0.205 in slotted ALOHA

In standard ALOHA

$$\begin{aligned}
D &= 1 + \left(\exp\left(2G\right) - 1\right)\left(1 + E\left\{D_r\right\}\right) \\
&= 1 + \left(\exp\left(0.620\right) - 1\right)\left(1 + \frac{3}{240/1200}\right) packets \\
&= 14.74\, packets \Leftrightarrow 14.74 \cdot \frac{N}{R} = 14.74 \cdot \frac{240}{1200} s = 2.95 s
\end{aligned}$$

In slotted ALOHA

$$\begin{aligned}
D &= 1 + \left(\exp\left(G\right) - 1\right)\left(1 + E\left\{D_r\right\}\right) \\
&= 1 + \left(\exp\left(0.205\right) - 1\right)\left(1 + \frac{3}{240/1200}\right) packets \\
&= 4.64\, packets \Leftrightarrow 4.64 \cdot \frac{N}{R} = 4.64 \cdot \frac{240}{1200} s = 0.93 s
\end{aligned}$$

Homeworks:

1. A RLAN with a 2 Mbit/s nominal transmission rate and utilising slotted ALOHA with a packet length of 1000 bits and a average transmission delay of 50 packets shall be used for voice transmission. The data rate of a voice signal is 8 kbit/s and the average transmission delay T_d should be ≤ 40 ms. Slotted ALOHA basic formulas are:
   - Throughput $S = G\exp(-G) = \lambda T_p$, λ is the number of arriving packets in the time unit, T_p is the packet duration in same time units,
   - Average delay in packets $D = 1 + (\exp(G) - 1)D_r$

a) Determine T_p and the allowed average delay in packets

b) Determine the normalised total traffic G and throughput S corresponding to the allowed average delay.

c) Determine the number of voice signals that can be transmitted with the defined Grade of Service.

2. If both packet collisions and errored packets due to noise are considered in slotted-ALOHA, the normalised throughput is given by ***S* = Normalised total traffic** · **Probability of no collisions and no error packets** = $G\cdot\left(e^{-2G}\cdot\left(1-P_{ep}\right)\right)$**.** The packet error probability P_{ep} in case of independent bit errors is given by $P_{ep} = 1-(1-p)^N$, where p is the bit error probability and N is the packet length.

a) How large packet error probability can be allowed before the throughput based on collisions only is reduced by 10 %?

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b) What is the maximum packet length under the conditions in part a), if the bit error probability is i) 10^{-2}, ii) 10^{-4}?

3. Slotted-ALOHA is used in a radio local area network, where new packet arrival rate is 100 packet/s, the channel rate 2 Mbit/s, and packet length 1024 bits.

b) Determine normalised throughput with the given traffic.

c) Determine the maximum normalised throughput possible in this system.

c) Calculate the average delay ratio in case b) and case a) when the average retransmission delay is 20 packets. Transmission delay is not considered.