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Communications and Computer Networks

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Recap of last lecture (1/2)

- Introduction to network characteristics and techniques
  - You know different types of classification of computer networks
  - You know the ISO/OSI reference model and can explain it
  - You know relevant protocols for the different layers
  - You know different network components and the assigned layer
  - You know the problem of fragmentation
  - You understand the process of encapsulation

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Layer 1 – Physical Layer

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Overview

- Data transmission fundamentals
  - Digital signals
  - Channel capacity
  - Interference and noise
- Line encoding
- Multiplexing
- Hardware
- Transmission media

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Learning Objectives

- You know the tasks of the physical layer
- You know fundamentals of data transmission
- You can explain what multiplexing techniques are needed for.
- You know the difference between baseband and broadband transmission
- You can explain the terms channel capacity, Nyquist theorem and Shannon-Hartley theorem
- You know the characteristics of the most important transmission media and hardware on layer 1

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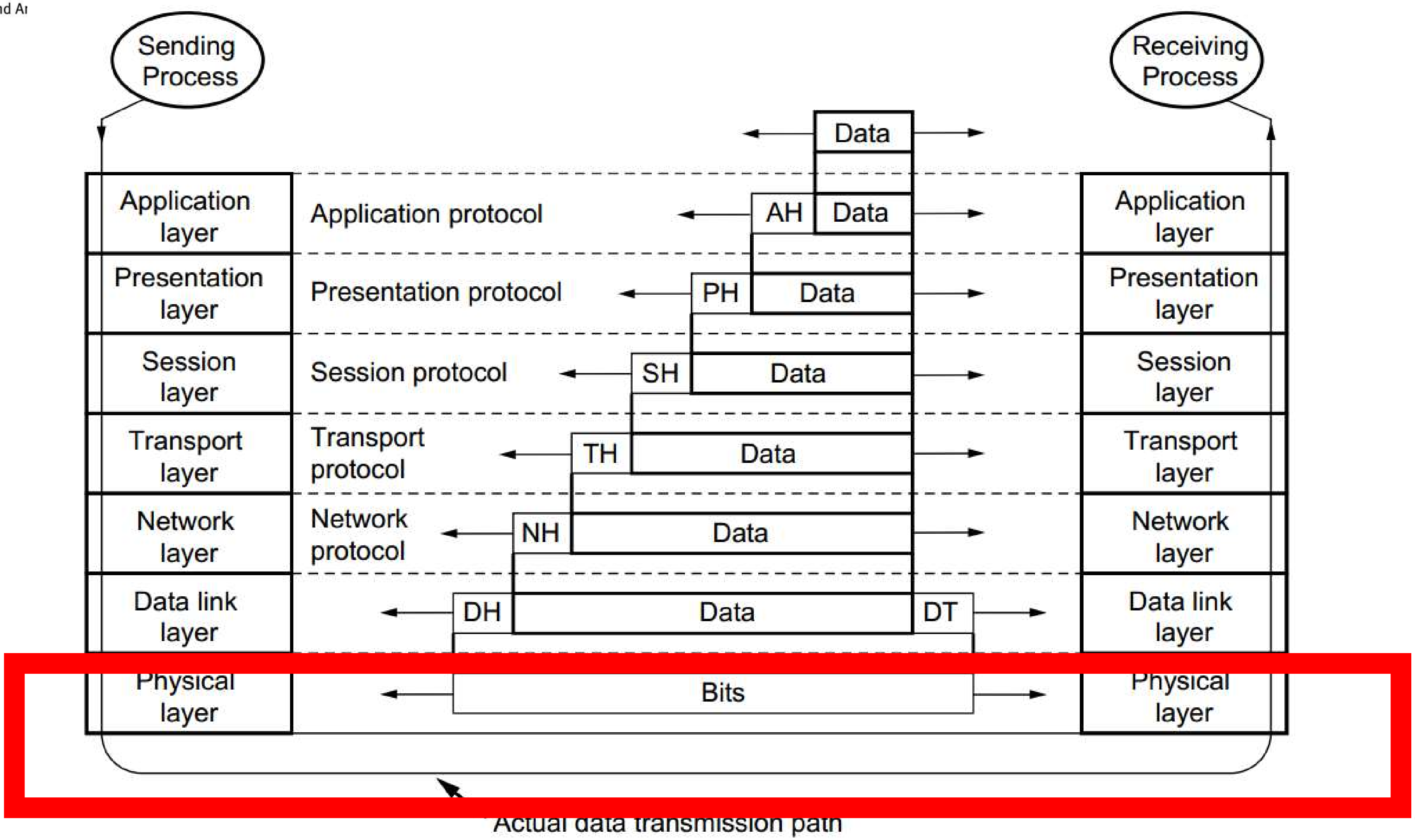
OSI reference model



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Tasks of the physical layer

- Transmission of raw bits over a communication channel (stream of bits)
  - Encoding and sending
  - Reception and decoding
  - Timing
- Information of the data link layer are “translated” into hw-specific operations regarding the underlying media
- Definition of mechanical and electrical interfaces:
  - Plugs, assignments
  - Duration of a symbol, baud rate
  - Full duplex, half duplex
- Physical representation of bit sequences (symbols)

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Physical layer – Transmission fundamentals

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Transmission

- Transmission between sender S and receiver R needs a carrier
- Each carrier has different trade-offs in frequency, cost, capacity, bandwidth, delay or installation „comfort“
- These trade-offs affect the transmission of the information
- Additionally, most of the time, multiple communications run in parallel

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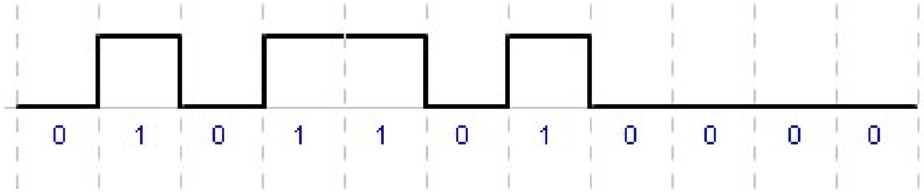
Digital signals



- Upper layers provide data to be transferred to the receiver
- Data is transferred as a sequence of bits
- **Bit** ("binary information unit" or "binary digit") is the smallest unit of information.
- This bitstream results in a **digital signal** send over the network
- A **digital signal** is a continuous-time physical signal, alternating between a discrete number of waveforms, representing a bitstream.
- The waveform consist of different symbols
- A **symbol** is one of several voltage, frequency or phase changes of the digital signal and may consist of **one or more bits** as determined by the modulation/coding scheme. (bit rate >= baud rate)

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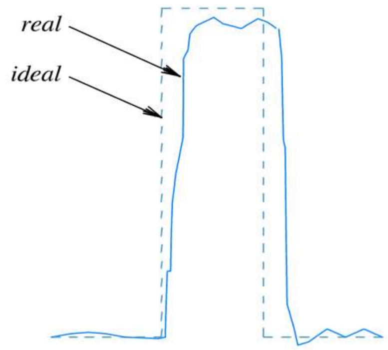
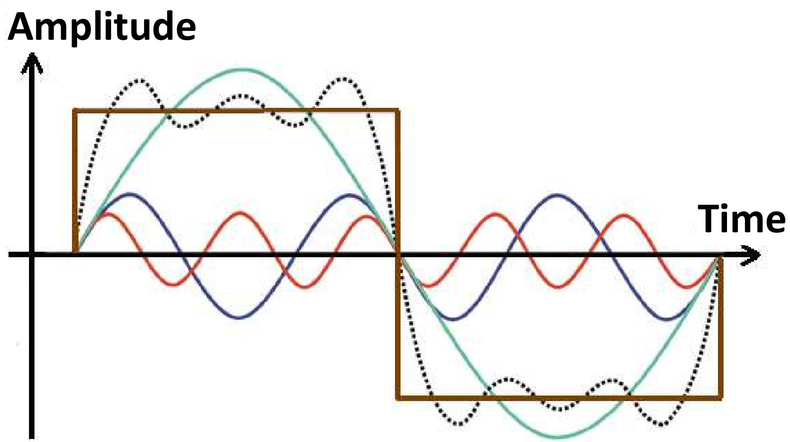
Digital signals and frequency



- The amount of information or data that can be transmitted from one end of the medium to the other end is defined as the bandwidth
  - More precise: bandwidth is the range of frequencies that can be passed
- „Outside“ this range the attenuation increases



- The attenuation of a signal depends on the frequency
- The bandwidth of a transmission medium is a physical property

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Baud rate and transfer rate

- Digital signals are transmitted at a constant step rate, also known as baud rate or symbol rate. The baud rate is the rate at which the signal changes on the line (symbol change).
- 1 bit (binary signal) or several bits can be transmitted per step.
- The data transfer rate (C, bit rate) is the number of bits that are conveyed or processed per unit of time
  - 10kbit/s
  - 1 Mbit/s
  - 10GBit/s
- Transfer rate depends on the channel capacity

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Channel capacity

- Defined by Harry Nyquist in 1924
- Maximum data rate of a channel is defined as
- $2B \ \log_2 V \quad bit/s$
  - B is bandwidth of the channel
  - V is number of discrete levels of the signal (binary = 2, tertiary = 3, …)

- A channel of 3KHz transferring a binary signal has a max. data rate of 6000bits/s
- This is only valid in noiseless channels

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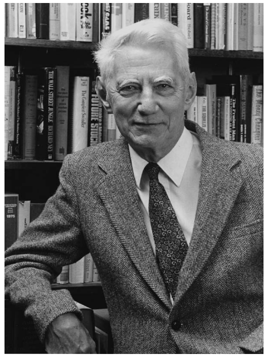
Shannon-Hartley-Theorem and SNR



- Based on work of Claude E. Shannon and Ralph Hartly
- Tells the maximum rate at which information can be transmitted over a communications channel of a specified bandwidth in the **presence** of noise.
- Applies only to band-limited signals (low-pass filters)
- Noise always disturbs a signal, so no infinitely fine quantization is possible.
- $2B\ \log_2(1+\frac{S}{N})\ \ bit/s$
  - B is bandwidth of the channel
  - S is signal power
  - N is noise power
- The signal-to-noise ratio from useful signal to noise signal is a decisive parameter for the information content of a signal.
- $SNR_{dB} = 10 * \log_{10}\frac{S}{N}$

SNR:
5 - 10 dB: Cannot establish a connection
10 - 15 dB: Can establish an unreliable connection
15 - 25 dB: Acceptable level to establish a poor connection
25 - 40 dB: Considered a good connection
41+ dB: Considered to be an excellent connection

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Modulation

- Each signal has its own frequency, varying voltage, light or sound intensity
- Each carrier has an own frequency range
  - Human ear: 20 – 20.000 kHz
  - POTS: 300 - 3.4 KHz
  - CAT6: 1 – 250 MHz
- Not every signal can be directly transferred over every carrier
  - Need for digital modulation
- **Baseband transmission:** Transmission of a digital or analog signal directly over the transmission medium without modulation. The signal is transmitted in the original frequency range.
- **Broadband transmission:** Transmission of signals using modulation methods. The signal is transmitted in the frequency range of the carrier.

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Clocking

- When bits are sent from a sender to a receiver across a network they need a **mechanism to synchronize** their **clocks** so they both know when a bit starts and when it stops. This means that clocking information needs to be sent as well as the data so that receiving station can synchronizes its own clock with the sender's clock.
- When there are lots of 1's or 0's in sequence, there is no voltage level transitions, making it difficult for the receiving station to know if it is **clocking** the signal correctly and so deducing the correct number of bits
- Synchronous connections (i.e. HDLC point to point links) use a **separate clocking line** to transmit clocking information. If a clocking signal is used along with the data signal, it is much easier to deduce where one bit starts and ends.
- However, some technologies do not have a separate line that could be used to send clocking information.
- Some encoding schemes can send clocking information within the data signal itself, without the need to send an additional clock pulses. Those are **self-clocking encoding schemes**.

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Physical Layer - Encoding

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Problems of transmissions

- In communications, sources of interference are usually present, and noise is frequently a significant problem.
- Channel capacity is limited
- Long sequences of „1“ or „0“ may disrupt the synchronisation
- Communication breaks or disruption might appear

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Encodings

- Source encoding: mapping the source data to binary data, reducing redundancy
- Channel encoding: Adding redundancy to backup, parity bit, CRC (Cyclic Redundancy Check) => No job of physical layer, is done on upper layer (typically data link layer)
- **Line coding: Assignment of digital data elements to analog or digital signal elements**

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Reasons for encoding

- Synchronization
- Clock recovery
- Minimize transmission hardware
- Convert signal to a specific medium
- Compression

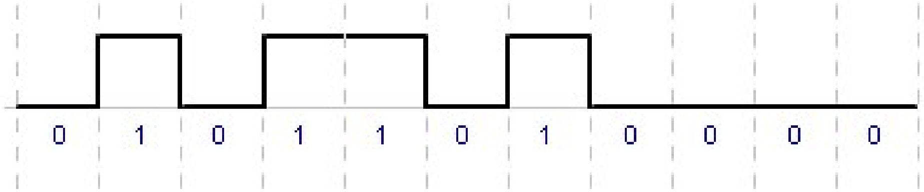
- Optimized data transmission according to the medium

Encoding techniques

Some signals are more prone to error than others as the physics of the communication channel or storage medium constrains the repertoire of signals that can be used reliably.

- Known signal codes:
  - NRZ: *Not Return to Zero*, not DC-free, not self-clocking
  - RZ: *Return to Zero*, not DC-free, not self-clocking
  - Manchester: *Ethernet*, DC-free and self-clocking
  - AMI: *Alternate Mark Inversion*, three levels, DC-free, non-self-clocking
  - HDB3: *High Density Bipolar*, DC-free and self-clocking

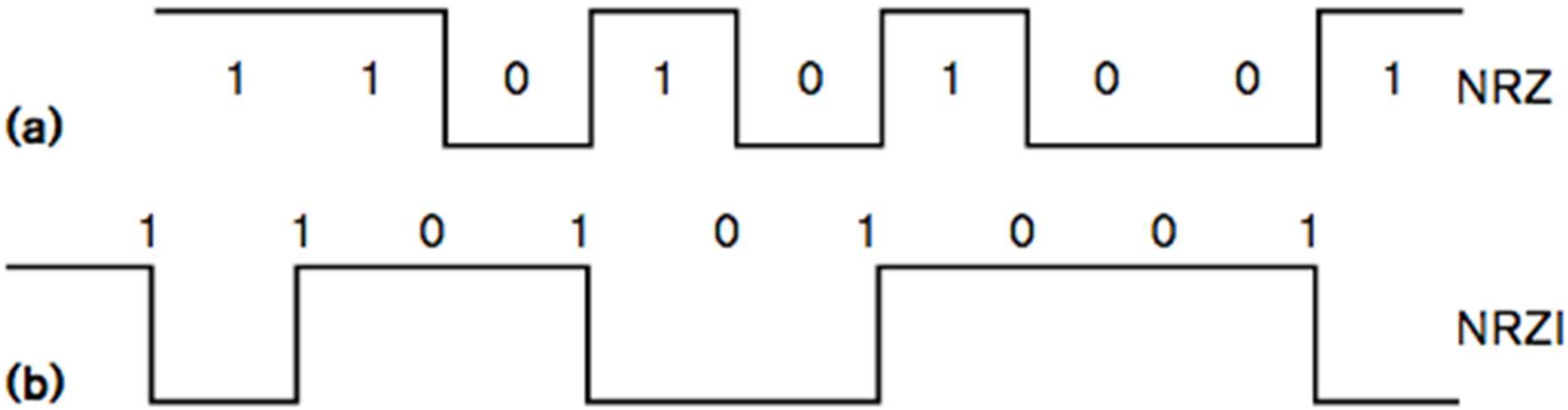
NRZ encoding



- **Non Return to Zero** encoding is one of the simplest encoding methods.
- The method uses one voltage (e.g.: 0 volts) for a logic '0' data bit and another voltage (e.g. +0.5V) for a logic '1' data bit (unipolar)
- not self-clocking
- Since it can be difficult for a receiving station to know if it is correctly detecting the boundaries of each bit with the NRZ method, other encoding methods are more often used on digital communications.

NRZI encoding

- Non-Return-to-Zero Inverted (NRZ-I)
- Used on Fast Ethernet **100BASE-FX** networks
- Different types NRZI-M (1 is transition, 0 is no transition), NRZI-S (1 is no transition, 0 is transition)



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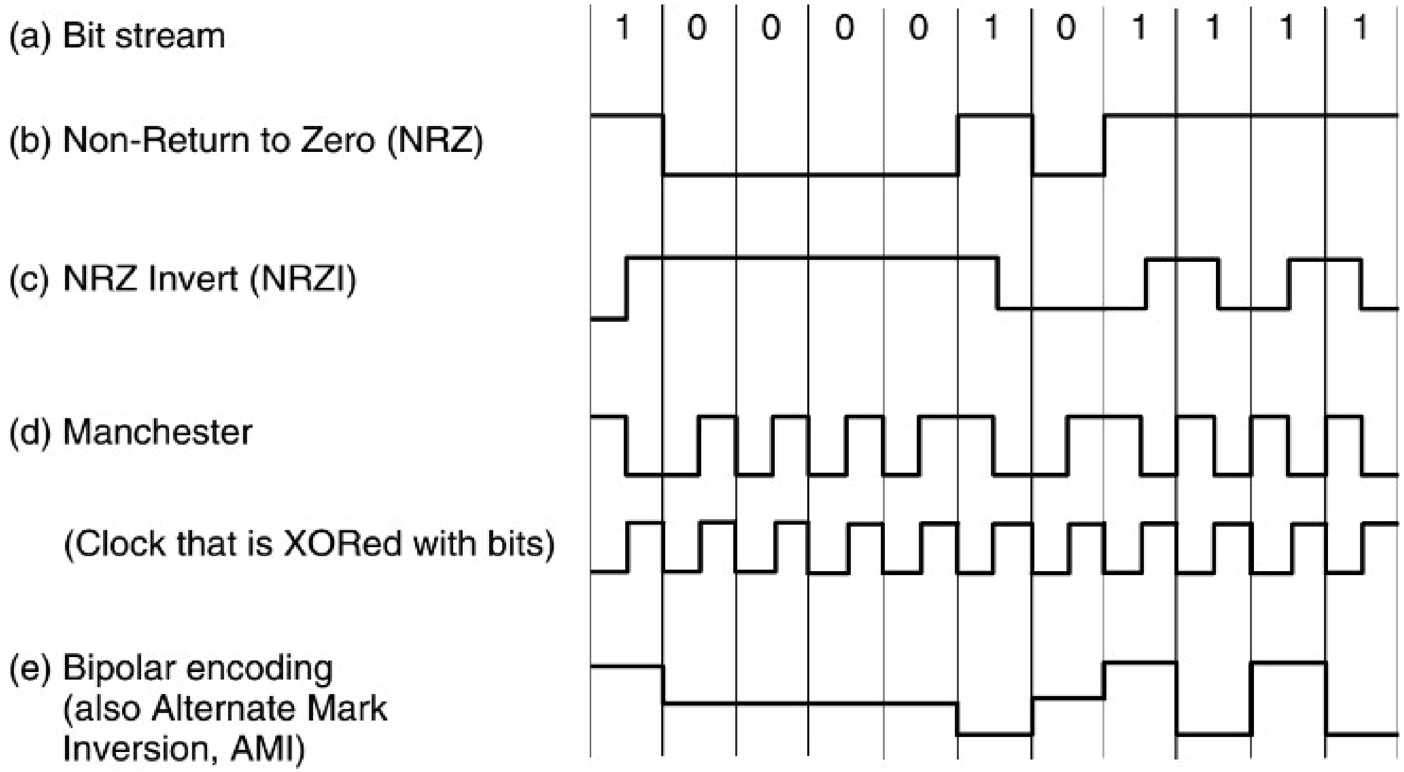
Examples of digital line codes

NRZI is shown different in some literature (depends on the clocking)



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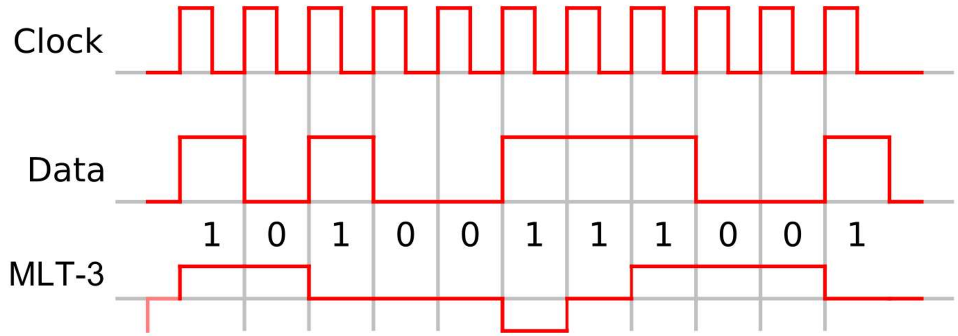
Encoding table 4B5B code

- The 4B5B code avoids long "0" or "1" sequences that could make clock recovery difficult. For this purpose, 4 data bits are encoded in 5 signal bits. There must be no more than one leading "0" and no more than 2 final "0".
- There are 5 other codons (01100, 01101, 10001, 11001 and 11111) that also follow the educational rule but are not used to encode nibbles.
  These codons can therefore be used for special purposes, for example for synchronization.
- By adding redundancy, you only achieve an efficiency of 80% (4/5).

Clear data (4-Bit Nibble)	Encoded data (5-Bit Codon)
0000	11110
0001	01001
0010	10100
0011	10101
0100	01010
0101	01011
0110	01110
0111	01111
1000	10010
1001	10011
1010	10110
1011	10111
1100	11010
1101	11011
1110	11100
1111	11101

MLT-3 (Multilevel Transmission Encoding - 3 levels)

MLT-3 (Multilevel Transmission Encoding - 3 levels) is a line code with three voltage levels (+,0,-).



MLT-3 changes the signal level for a logical one in the data stream, whereby the next level in the sequence is always 0,+,0,-,0,+,0,-,... used. At a logical zero, the signal level remains the same. MLT-3 is comparable to the binary line code NRZI. By using $n = 3$ symmetrical stages, the DC share and the bandwidth are reduced ($\log_2(3) \approx 1.59$).

Stream:		0 1 1 1	0 1 0 0	0 0 1 0	0 0 0 0	1 0 1 1
Blocks of 4:		0111	0100	0010	0000	1011
4B5B code:		01111	01010	10100	11110	10111
MLT-3 Level:	0	0+0-0	0++00	--000	+0-00	++0-0

Characteristics of digital cable codes, cycle recovery

- What the Manchester processes have in common is that they allow the clock to be recovered from the signal. However, the Manchester procedures require twice as much bandwidth for transmission as e.B. the NRZ code.
- The NRZ code does not allow clock recovery, as unfavorable bit consequences may not cause a state change for a long time. Therefore, this code is only useful if a bit conversion is done beforehand.
- This is achieved, for example, by the 4B/5B conversion (4 binary 5 binary), in which a 4-bit block (nibble) is converted into a 5-bit block in such a way that a maximum of two consecutive zeros occur in each 5-bit block.
- Example: 4B/5B block code with MLT-3 line encoding at 100 Mbps Ethernet (100 BaseTX)

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Physical Layer - Multiplexing

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Multiplexing

- All aforementioned techniques provide the transmission of bits over a carrier
- But currently, we are able to send ONE bitstream at a time
- Transferring multiple connections over one carrier requires additional techniques
- Multiplexing provides „simultaneous“ connections over one carrier
  - Time (ISDN, ATM, partly in GSM)
  - Frequency (CableTV, Broadcast radio)
    - Wavelenght Division Multiplexing (fibre optics)
  - Code (3G, GPS)

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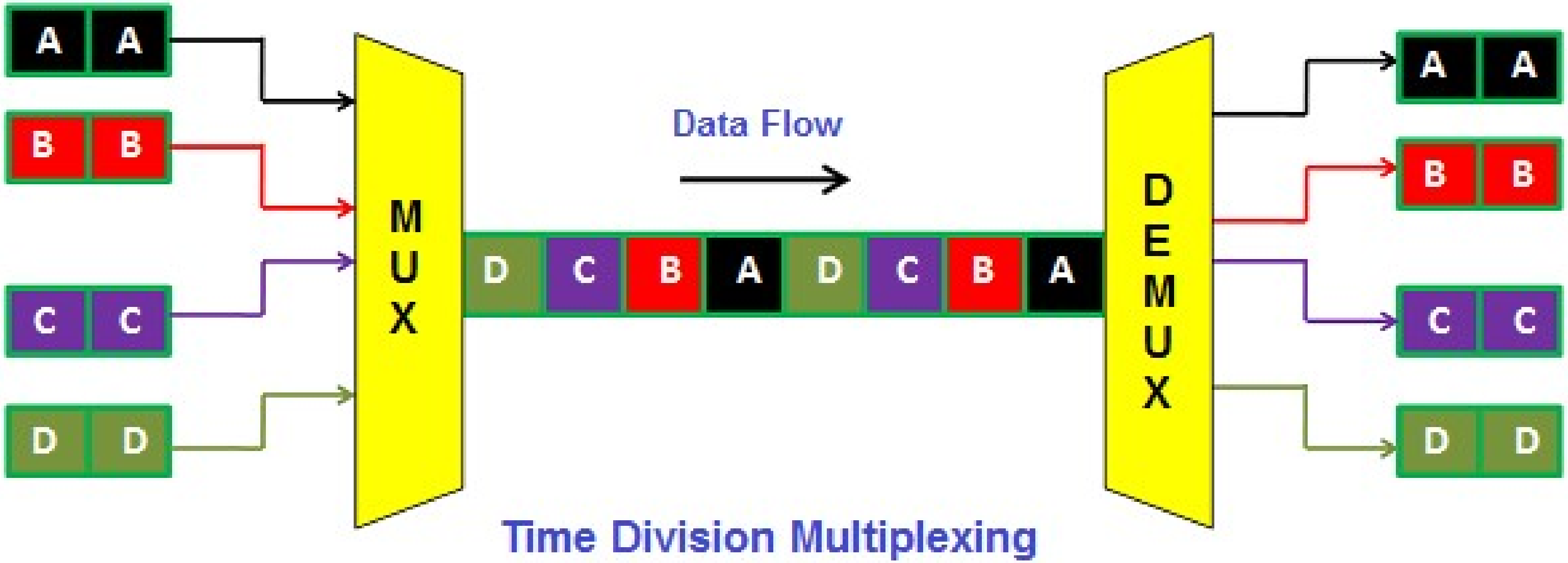
Time-Multiplexing

- Necessary in baseband transmission to transfer multiple streams „in parallel“



https://www.quora.com/What-is-time-division-multiplexing-TDM

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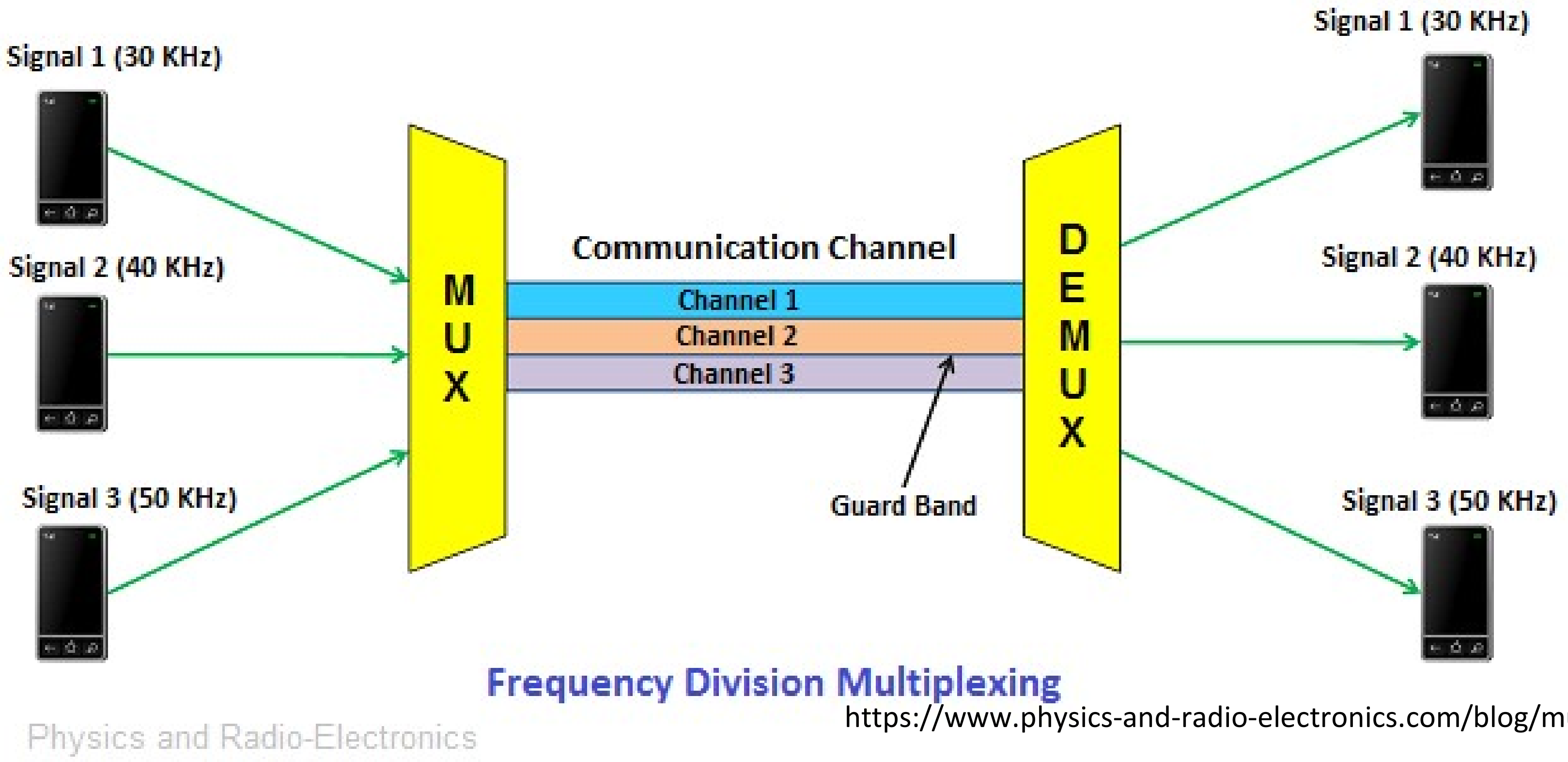
Frequency-Multiplexing

- Useable in broadband transmission



https://www.physics-and-radio-electronics.com/blog/multiplexing/

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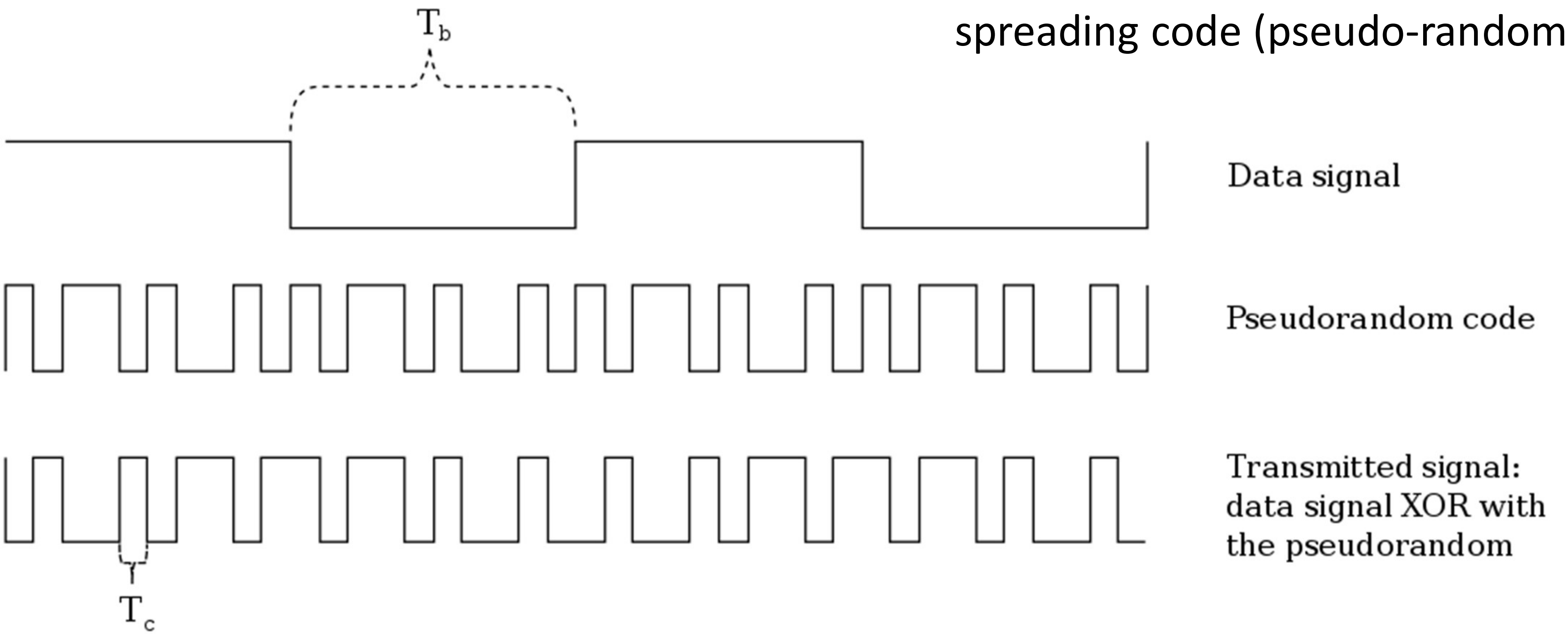
Code Division Multiple Access

Each signal is XORed with a spreading code (pseudo-random-code)



www.wikipedia.com

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Physical Layer – Hardware

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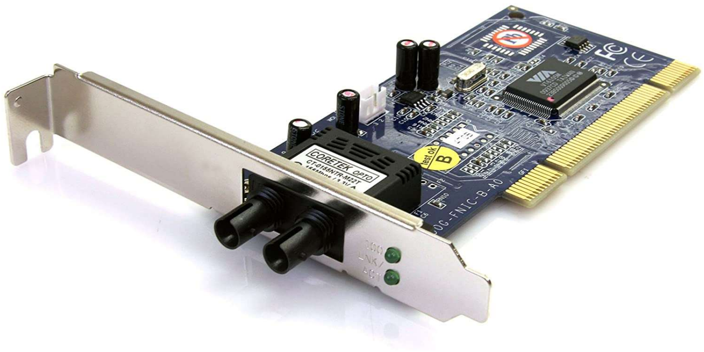
Network interface controller

- The network interface controller / card (NIC) is the connection of a hardware device to the network
- Each NIC has at least one dedicated PHY
  - an electronic circuit, usually implemented as an integrated circuit
  - Consists of Physical Coding Sublayer (PCS) and Physical Medium Depended) (PMD) layer



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Repeater

- A repeater is a device that operates on Layer 1 of the OSI model, it receives signals, amplifies them and passes them on.
- With repeaters, length restrictions can be overcome, and a topology extension of the network is made possible.
- The task of a repeater is signal conditioning, i.e., phase, amplitude and preamble generation.
- Bit transmission errors are not detected or corrected.
- Repeaters allow the physical segmentation of an Ethernet LAN, but without increasing the available bandwidth in the individual segments because it has no traffic-separating effect. Thus, all addresses in the connected segments must be unique.

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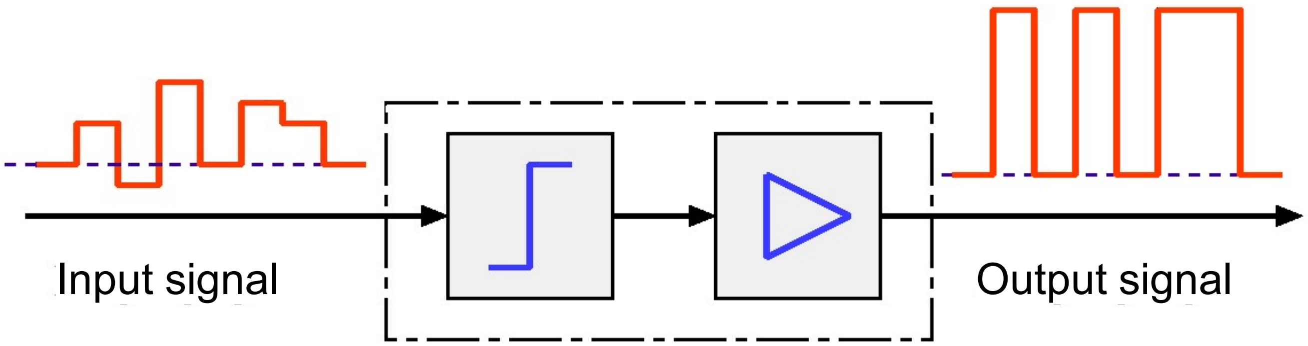
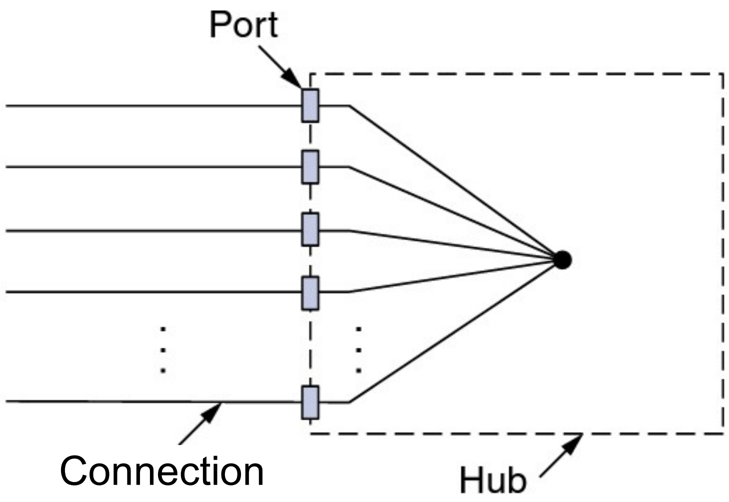
Repeater

- A repeater transmits all packets it receives it to all other segments.
- A network that is segmented via repeaters still represents one network with respect to the access procedure.
- All devices connected to this network must share a channel (shared medium) and only one device in the entire network can send a packet at a time.



Hub



- Hubs are also devices of OSI Layer 1 and thus, completely transparent to the network.
- Hubs realize a star topology, with each port of the hub forming a single segment.
- Each device connected to a hub has the bandwidth of the LAN up to the hub port.
- Due to the star topology, the entire network is much safer against failures, since only the connected device/segment is affected in the event of cable problems and not the entire Ethernet network as with repeaters.
- Multiple hubs can be connected (cascaded) to each other, which makes it easy to increase the number of possible stations.

Hub

OLD

- As with the repeater, all ports of one or more hubs form only one logical network segment, in which all stations have to share the total bandwidth of the LAN (a collision domain), only the connection from the computer to the hub is dedicated.
- With a modern hub, a backplane (i.e. the internal connection between the ports of the hub) with greater bandwidth is usually used in order not to create a bottleneck in the communication between the ports, and they can also cache packets in the event of a port currently not available.

Transmission Media

- **Wired**
  - **Twisted cable pair**
  - **Broadband coaxial cable (cable TV)**
  - **Optical fibre**
- Wireless
  - Wi-Fi (will be discussed later in the corresponding session)
  - Bluetooth
  - Infrared

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Twisted Pair Cables

(a) TP Category (CAT) 3, (b) TP Category (CAT) 5

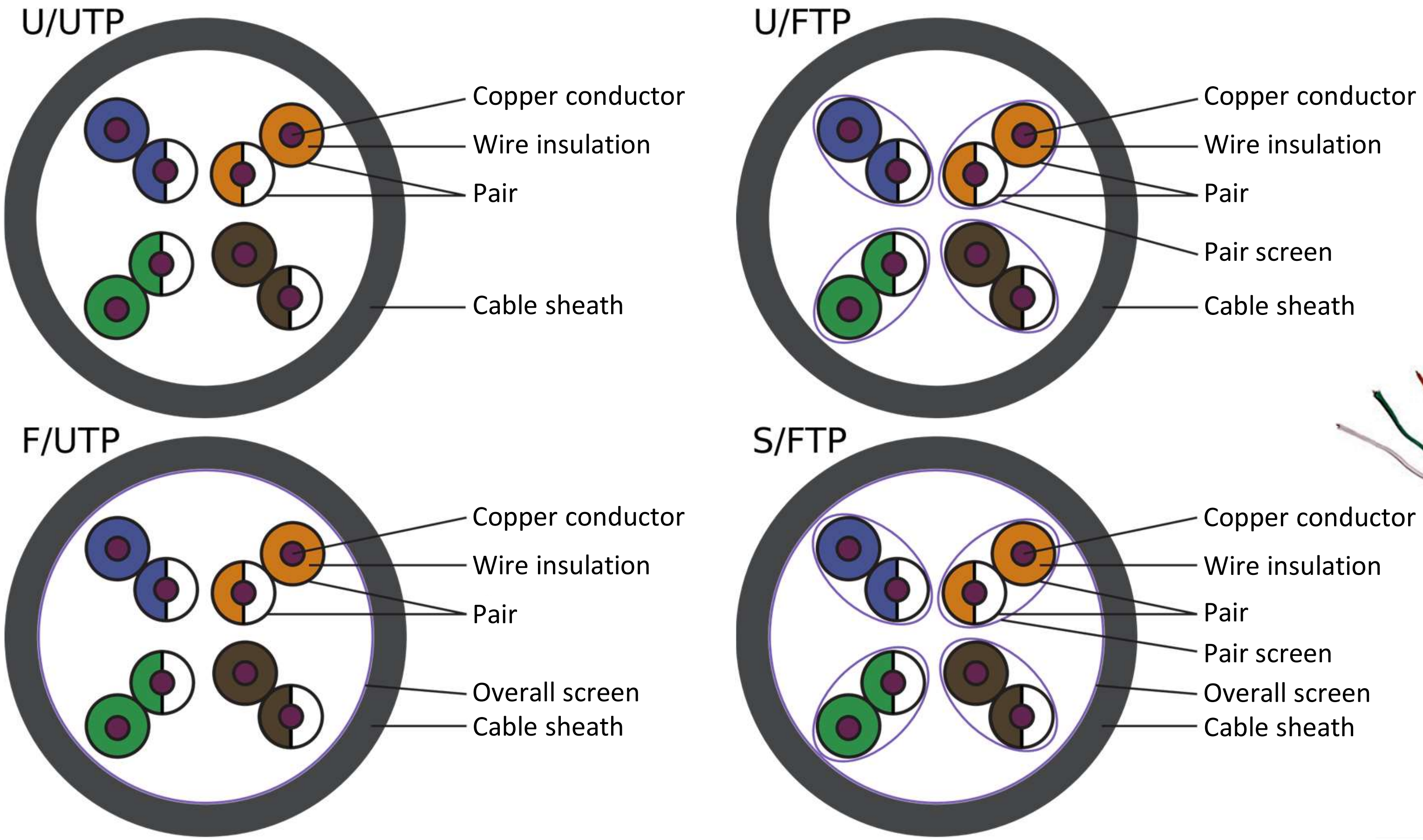
TP-Cable with RJ45

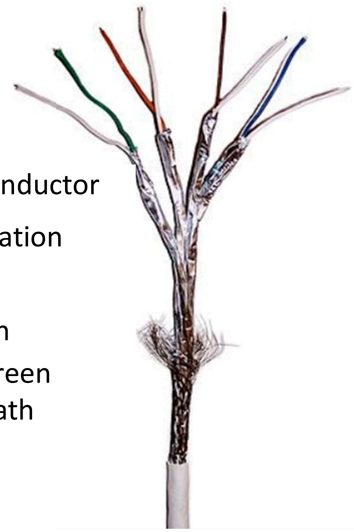
- Twisted pair cabling is a type of wiring in which two conductors of a single circuit are twisted. It was invented by Alexander Graham Bell.
- The twist rate (also called pitch of the twist, usually defined in twists per meter) makes up part of the specification for a given type of cable. When nearby pairs have equal twist rates, the same conductors of the different pairs may repeatedly lie next to each other, partially undoing the benefits of twisting.

Designations according to ISO/IEC-11801 (2002)

- Designation scheme of form XX/YZZ:
- ZZ always stands for TP = Twisted Pair
- Y stands for the wire screening:
  - U = Unshielded,
  - F = Foil shielded
- XX for the overall screening:
  - U = Unshielded,
  - F = foil shielded,
  - S = braided umbrella,
  - SF = Braided and foil shade

Different screens for TP cables





Categories of TP cables

Category	Use	Type	Bandwidth
CAT 1	Analog telephone cable	U/UTP	0,1MHz
CAT 2	ISDN	U/UTP	1MHz
CAT 3	Ethernet 10 Mbit/s	U/UTP	16MHz
CAT 4	20 Mbit/s (not common in Europe)	U/UTP	20MHz
CAT 5	100-megabit Ethernet 100 Mbps	F/UTP	100MHz
CAT 6	Gigabit Ethernet 1000 Mbps	U/FTP	250MHz
CAT 7	10 Gigabit Ethernet 10000 Mbps	S/FTP	600MHz
CAT 8	40 Gigabit Ethernet 40000 Mbps	S/FTP	1600MHz

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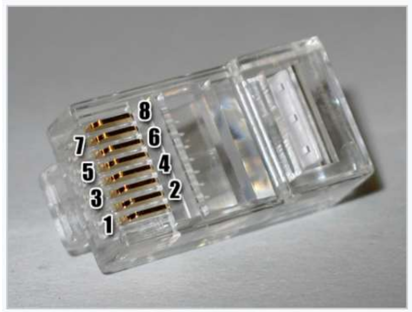
Wiring Ethernet

Pin	EIA/TIA 568A	AT&T 258A, EIA/TIA 568B	10Base-T 10Mbps Cat3	100Base-TX 100Mbps Cat5	100Base-T4 100Mbps Cat3	100Base-T2 100Mbps Cat3	1000Base-T 1Gbps Cat5+
1	white/green	white/orange	TX+	TX+	TX D1+	BI DA+	BI DA+
2	green/white	orange/white	TX-	TX-	TX D1-	BI DA-	BI DA-
3	white/orange	white/green	RX+	RX+	RX D2+	BI DB+	BI DB+
4	blue/white	blue/white	na	na	BI D3+	na	BI DC+
5	white/blue	white/blue	na	na	BI D3-	na	BI DC-
6	orange/white	green/white	RX-	RX-	RX D2-	BI DB-	BI DB-
7	white/brown	white/brown	na	na	BI D4+	na	BI DD+
8	brown/white	brown/white	na	na	BI D4-	na	BI DD-

BI=BI directional data, RX=Receive Data, TX=Transmit Data

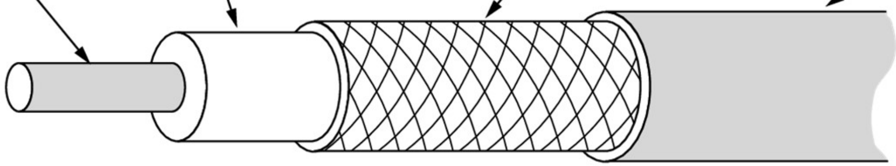
8P8C connector

Pin Assignment
8P8C connector



Coaxial Cable

- Known for use for TV
- Use for transmission of radio frequency signals
- HF-transmission with low loss
- Construction:
  - Inner conductor (core)
  - Dielectric insulater
  - concentric conducting shield
  - Protective plastic cover



Coaxial Cable

- Coaxial cables vary by gauge and impedance
- Gauge refers to the cable's thickness and is measured by the radio guide measurement or RG number.
- The higher the RG number, the thinner the central conductor core is
- RG6 is common for CCN

Type	Impe-dance (ohms)	Core (mm)	Dielectric				Outside diameter		Shields	Remarks	Max. attenuation, 750 MHz (dB/100 ft)
			Type	VF	(in)	(mm)	(in)	(mm)			
RG-6/U	75	1.024	PF	0.75	0.185	4.7	0.270	6.86	Double	Low loss at high frequency for cable television, satellite television and cable modems	5.65
RG-6/UQ	75	1.024	PF	0.75	0.185	4.7	0.298	7.57	Quad	This is "quad shield RG-6". It has four layers of shielding; regular RG-6 has only one or two	5.65[20]
RG-7	75	1.30	PF		0.225	5.72	0.320	8.13	Double	Low loss at high frequency for cable television, satellite television and cable modems	4.57
RG-8/U	50	2.17	PE		0.285	7.2	0.405	10.3		Amateur radio; Thicknet (10BASE5) is similar	5.97[21]
RG-8X	50	1.47	PF	0.82	0.155	3.9	0.242	6.1	Single	A thinner version, with some of the electrical characteristics of RG-8U in a diameter similar to RG-59.[22]	10.95[21]

Optical fibre

Fibre-Optic cables:

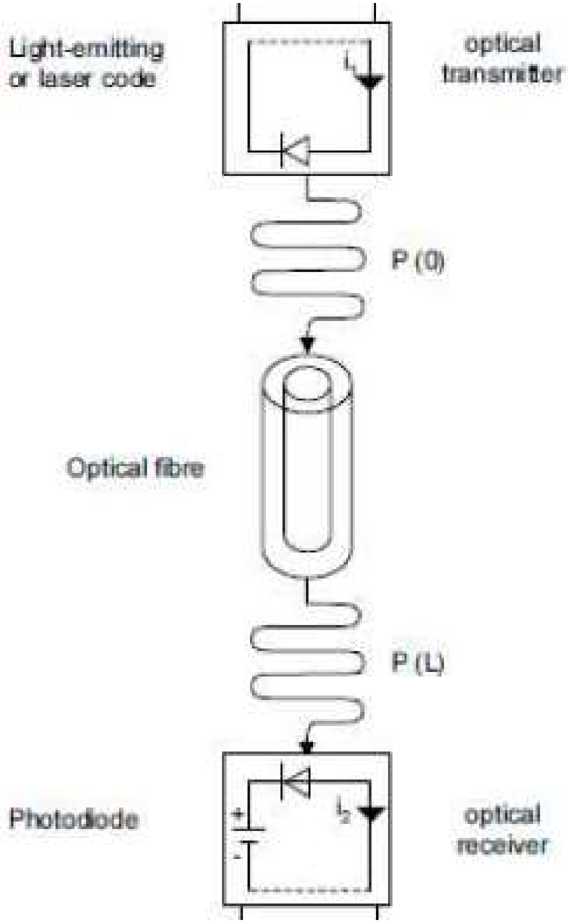
A fiber-optic cable, also known as an optical-fiber cable, is an **assembly similar to an electrical cable**, but containing one or more optical fibers that are used to carry light.

The optical fiber elements are typically individually coated with **plastic layers** and contained in a **protective tube** suitable for the environment where the cable is used.

Transmission of light

In the transmitter, the electrical signal is converted into a light signal in an **electro-optical converter** (e.g. a **light emitting diode LED** or a **laser diode LD**).

After traversing the optical fiber, the light is converted back into an electrical signal in an **opto-electric converter** (e.g. **photodiode**) at the end of the transmission route

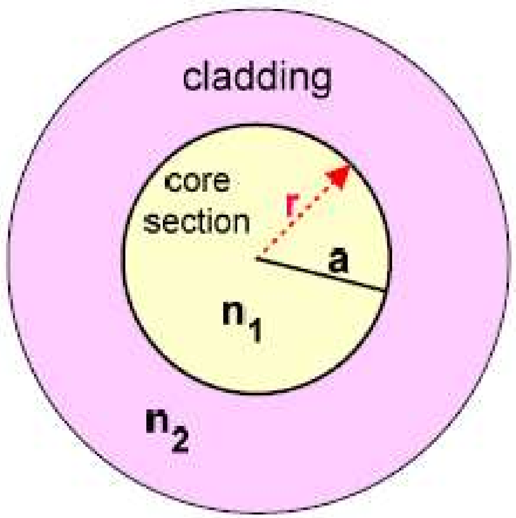


Optical fibre

- In optical transmission an effect of **total internal reflection** is desired (guided ray modes).
- This effect occurs if two transparent media are arranged one above the other. The external medium must be "better“ (in terms of reflection index) than the internal one.
- Common technique is today with two almost equally "good" types of glass.

An **optical fiber** (**OF**) consists of the following components:

- The **core**: the information-carrying **glass**
- The **cladding**: a slightly "better" **glass**
- The **coating:** A protective **plastic**



Optical fibre

Advantages:

- **High transmission capacity**
- **Low susceptibility to electromagnetic interference ,** no spacing requirements when run in parallel
- Potential separation between transmitter and receiver (no ground loop)
- Long distances between repeaters over 300 km is possible for sea cables, large production lengths, therefore greater distances between couplings, therefore fewer couplings, therefore fewer installation errors.
- Highly resistant to eavesdropping.
- Short-circuit-free (no spark formation) important in areas where there is a risk of explosions.
- Light weight, highly flexible lighter equipment, easier handling less volume forshipping, smaller cable reels, lighter trailers, smaller winches, smaller dimensions, smaller cable diameter, more effective utilization of cable ducts.
- There are no corrosion of fibers.
- Unlimited material availability

Disadvantages:

- Installation technology.
- High level of precision required.
- Sophisticated devices necessary.

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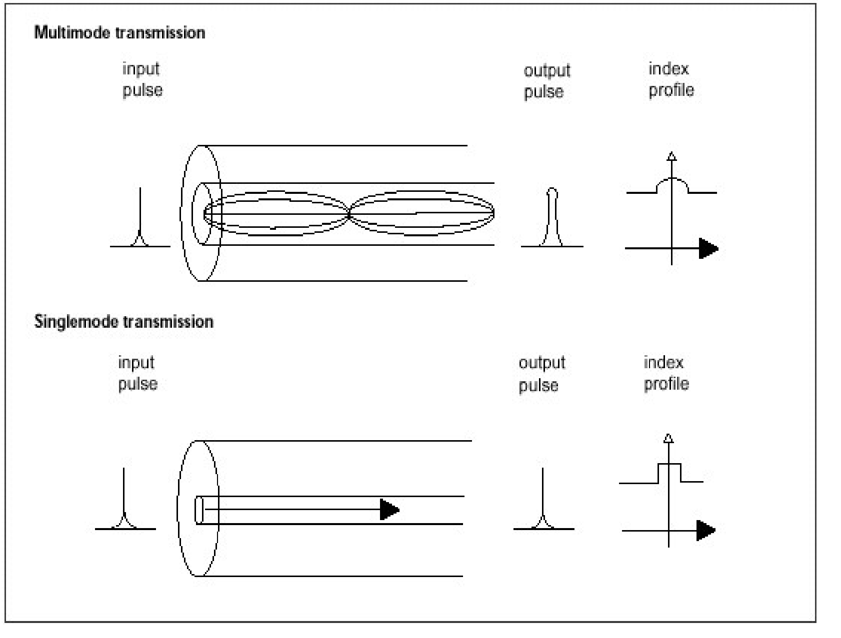
Types of optical fibre

Different types of cable are used for different applications, for example, long distance telecommunication, or providing a high-speed data connection between different parts of a building.

- **Multi-mode Fibers (MMF)**
  - **Step Index (old)**
  - **Graded Index**

- **Single-mode Fiber (SMF)**



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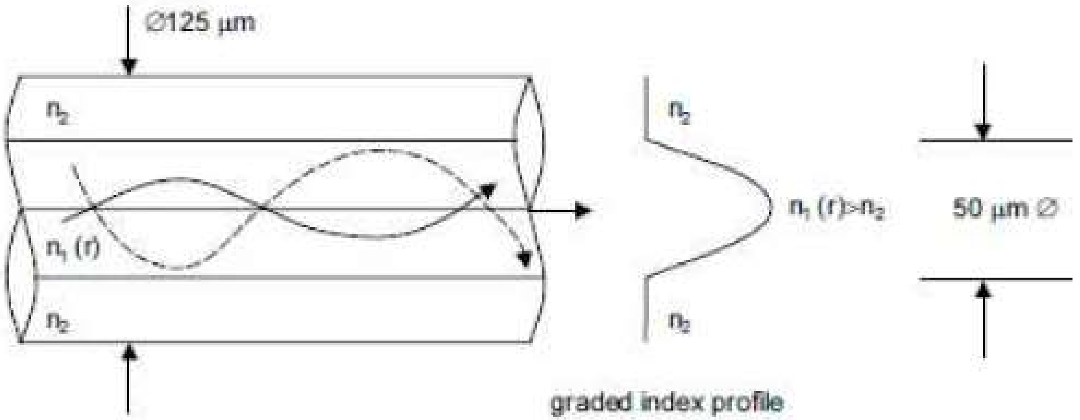
Multimode fibre

- The graded index profile of the core is achieved by **many layers of glass** (more than hundred), where each layer has its specific index of refraction.
- These **indices decrease gradually from the center toward the cladding**. Due to the continuous change of the IOR, the rays are refracted constantly when crossing the borderline between the various layers.
- The rays oscillating around the fiber axis still travel a longer path than the light rays along the fiber axis; however, due to the lower refractive indices outside of the fiber axis these rays travel correspondingly faster. The result is that **the delay time difference of the various rays disappears almost completely**.



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Multimode fibre II

Due to the difficult manufacturing process, the fiber is relatively expensive. Therefore, today it will not be employed for long distances.

The main application for these fibers are LANs with short distances (<=300m)

This fiber type is specified by ITU-T Rec. G.651

Two types are standardized:

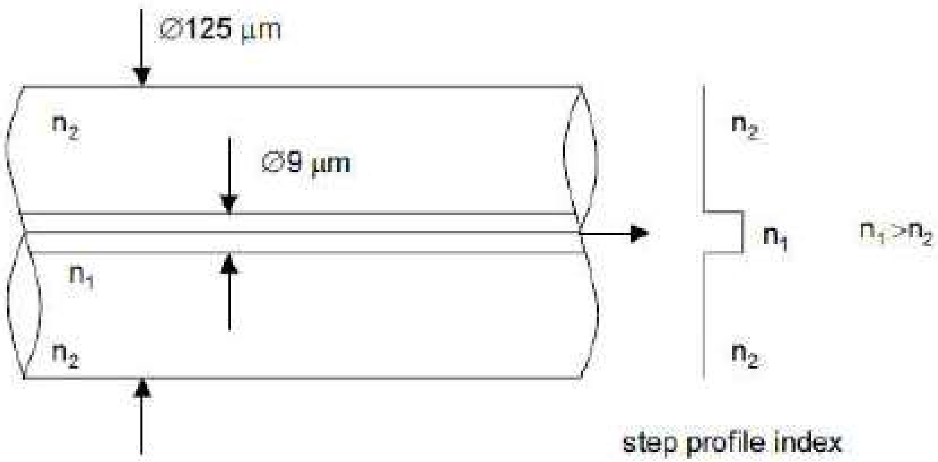
- Type A with 50 µm core diameter, and 125 µm cladding diameter.
- Type B with 62.5 µm core diameter, and 125 µm cladding diameter.

Singlemode fibre

Even in high-quality graded index fibers, a certain delay time caused by the various modes is still present.

If the **diameter** becomes **smaller**, then only a single mode, the fundamental mode, can propagate in the core => because of this it is called a single-mode fiber.

This fiber type is specified by ITU-T Rec. G.652, G.653 and G.655



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Cable Types

		Attenuation in dB/km at λ/nm				minimum modal bandwidth		
						OFL in MHz·km		EMB in MHz·km
Category	Fiber Type	850	1310	1383	1550	850	1310	
OM1	G62,5/125	3,5	1,5	n.d.	n.d.	200	500	n.d.
OM2	G50/125	3,5	1,5	n.d.	n.d.	500	500	n.d.
OM3	G50/125	3,5	1,5	n.d.	n.d.	1500	500	2000
OM4	G50/125	3,5	1,5	n.d.	n.d.	3500	500	4700
OS1	E9/125	n.d.	1,0	n.d.	1,0	n.d.		
OS2	E9/125	n.d.	0,4	0,4	0,4	n.d.		

n.d. not defined
OFL = Over-Filled Launch Bandwidth (LED) EMB = Effective Modal Bandwidth (Laser)

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Fiber optic link lengths at (1/10/40) Gigabit Ethernet

	Ethernet	λ/nm	OM1	OM2	OM3	OM4	OS1/OS2
1 Gbit/s	1000BASE-SX	850	300 m	500 m	1000 m	1000 m	
	1000BASE-LX	1310	500 m	500 m	500 m	500 m	5.000 m
10 Gbit/s	10GBASE-SR	850	30 m	80 m	300 m	500 m	
	10GBASE-LR(M)	1310	220 m	220 m	220 m	220 m	10.000 m
	10GBASE-ER	1550					40.000 m
40 Gbit/s	40GBASE-SR4	850	n.a.	n.a.	100 m	125 m	
	40GBASE-LR4	1310					10.000 m
	40GBASE-ER4	1550					40.000 m

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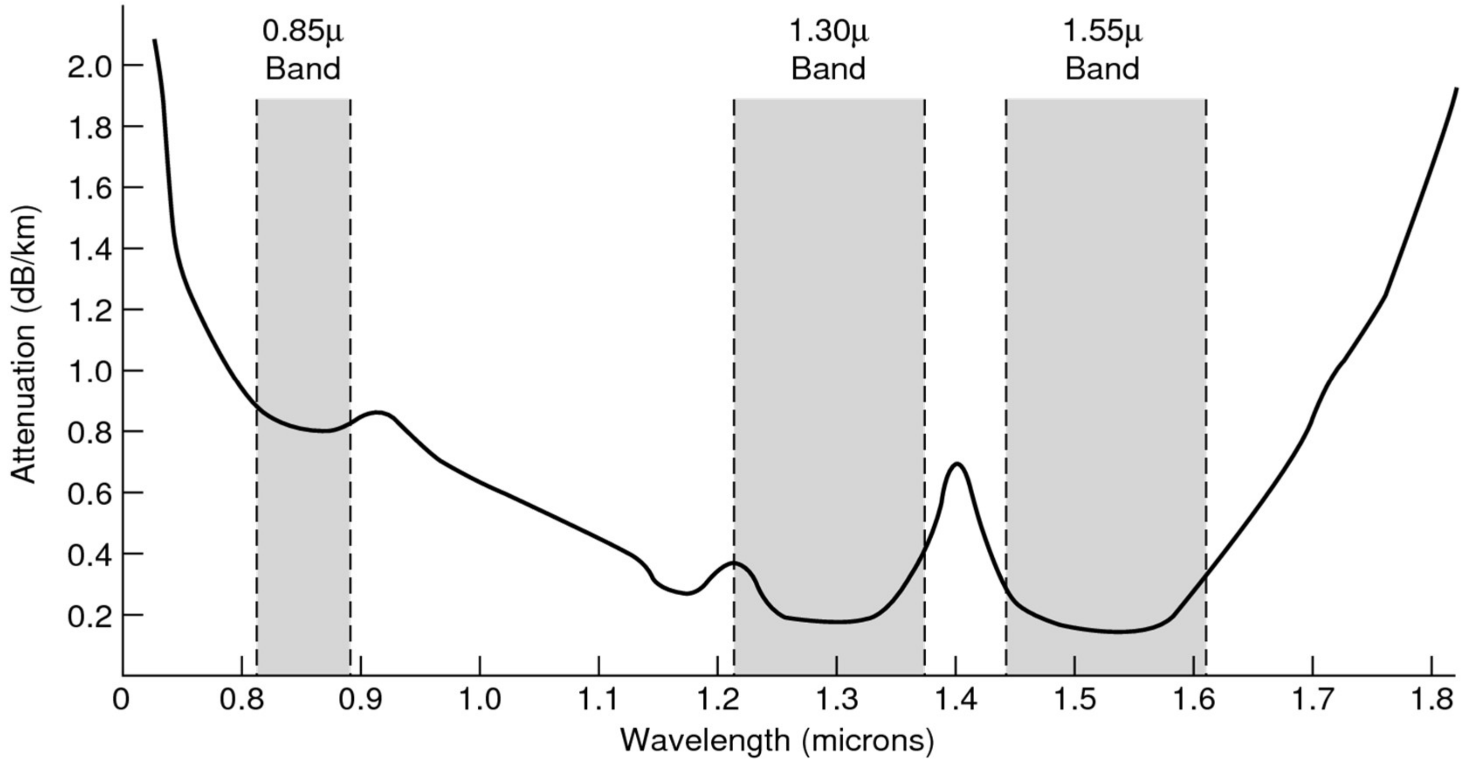
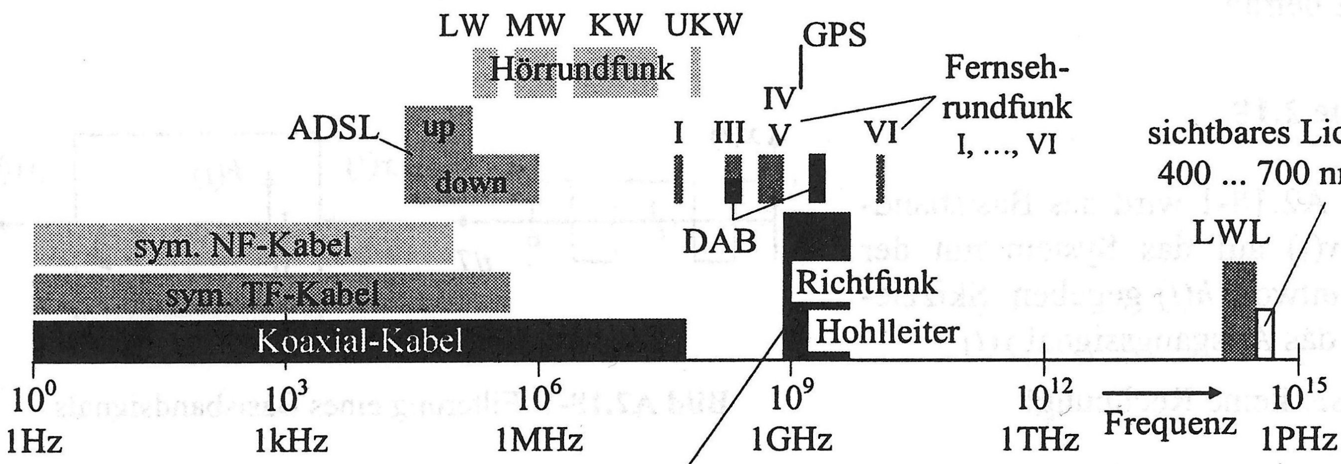
Attenuation of light by glass fiber



Frequency ranges of different transmission media



Mobilfunk, schnurlose Telephonie

GSM-900	890-915 u. 935-960 MHz
GSM-1800	1710-1785 u. 1805-1880 MHz
DECT	1880-1900 MHz
UMTS	1885-2025 u. 2110-2200 MHz

Wireless LAN, Kurzstreckenfunk (PAN)

IEEE 802.11/11b, Bluetooth ≈ 2,4 GHz (ISM-Band)

IEEE 802.11a, HIPERLAN 1/2 ≈ 5 GHz

optische Fenster der Lichtwellenleiter (LWL)

I	0,33 … 0,375 PHz	800 … 900 nm
II	0,23 … 0,3 PHz	1000 … 1300 nm
III	0,176 … 0,32 PHz	1500 … 1700 nm

Infrarot

IrDA	850 … 900 nm
Tonübertragung	950 nm

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Additional slides

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Faculty of Computer Science

Fachhochschule Dortmund
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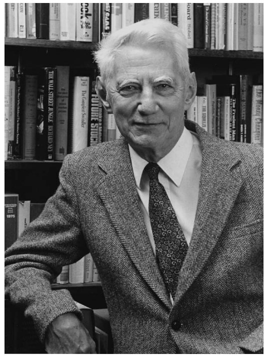
Channel capacity



- Applies only to band-limited signals (low-pass filters)
- The information content of an undisturbed, band-limited, analog signal with finite amplitude is infinitely large (it can be infinitely finely quantized).
- Noise always disturbs a signal, so no infinitely fine quantization is possible.
- The signal-to-noise ratio from useful signal to noise signal is a decisive parameter for the information content of a signal.

- 1949 by Claude E. Shannon

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Channel capacity
Calculation

According to Shannon, channel capacity C can be used as a function of bandwidth B and signal-to-noise ratio $\frac{P_s}{P_R}$ as follows:

$$\frac{C}{bit} = B \cdot \log_2\left(1 + \frac{P_s}{P_R}\right)$$

$\frac{P_s}{P_R}$ also referred to as "Signal to Noise Ratio" SNR, which is usually measured in the logarithmic measure decibels (dB):

$$SNR_{dB} = 10 \cdot \log_{10}\left(\frac{P_s}{P_R}\right)$$

Channel capacity
Calculation

This allows the channel capacity to be represented as follows:

$$\frac{C}{\text{bit/s}} = \frac{1}{3} \cdot \frac{B}{\text{Hz}} \cdot \frac{SNR}{\text{dB}}$$

the following applies:
$10 \cdot \log_{10}(2) \approx 3$

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Example task
Data Transfer Rate and Channel Capacity

What is the data transfer rate according to the Nyquist theorem at a bandwidth from 2MHz at 16 signal levels achievable?

$$\frac{C}{\text{bit}} = 2 \cdot B \cdot \log_2 n$$

Nyquist Theorem

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Example task
Data Transfer Rate and Channel Capacity

What is the data transfer rate according to the Nyquist theorem at a bandwidth from 2MHz at 16 signal levels achievable?

Nyquist Theorem

$$\frac{C}{\text{bit}} = 2 \cdot B \cdot \log_2 n$$

$$= 2 \cdot 2\,\text{MHz} \cdot \log_2 16 = 2 \cdot 2 \cdot 10^6 \cdot \frac{1}{s} \cdot 4$$

$$C = 16\,{}^{\text{Mbit}}/_{\text{s}}$$

What signal-to-noise ratio SNR in dB would be at least required according to Shannon at this bandwidth and the signal levels to carry out this data transfer rate?

$$\frac{C}{\text{bit/s}} = \frac{1}{3} \cdot \frac{B}{\text{Hz}} \cdot \frac{\text{SNR}}{\text{dB}}$$

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Nyquist Theorem

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$$\frac{C}{\text{bit}/\text{s}} = \frac{1}{3} \cdot \frac{B}{\text{Hz}} \cdot \frac{\text{SNR}}{\text{dB}}$$

$$\frac{16 \cdot 10^6 \cdot \text{bit}/\text{s}}{\text{bit}/\text{s}} = \frac{1}{3} \cdot \frac{2 \cdot 10^6\,\text{Hz}}{\text{Hz}} \cdot \frac{\text{SNR}}{\text{dB}}$$

$$\frac{3 \cdot 16 \cdot 10^6}{2 \cdot 10^6} = \frac{\text{SNR}}{\text{dB}}$$

$$\text{SNR} = 24\,\text{dB}$$

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Fourier decomposition

Fourier decomposition is the way general functions may be represented or approximated by sums of **sine waves** and **cosine waves** (the lowest frequency cosine wave is a DC signal). Fourier decomposition is important for 3 reasons.

1. A wide variety of signals are inherently created from superimposed sinusoids. Audio signals are a good example of this. Fourier decomposition provides a direct analysis of the information contained in these types of signals.
2. Second, **linear systems** respond to sinusoids in a unique way: a sinusoidal input always results in a sinusoidal output. In this approach, systems are characterized by how they **change the amplitude and phase** of sinusoids passing through them. Since an input signal can be decomposed into sinusoids, knowing how a system will react to sinusoids allows the output of the system to be found.
3. Third, the Fourier decomposition is the basis for a broad and powerful area of mathematics called Fourier analysis, and the even more advanced Laplace and z-transforms. Most cutting-edge **DSP** (Digital Signal Processing) algorithms are based on some aspect of these techniques.

Sampling theorem to Nyquist

1924 by Harry Nyquist

-
- If a signal consists of n stages, the maximum data transfer rate is:

$$\frac{C}{bit} = 2 \cdot B \cdot \log_2 n$$

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Twisted Pair Cables

Advantages/benefits:

- **Electrical noise** going into or coming from the cable **can be prevented**.
- **Crosstalk** is **minimized**.
- **Cheapest** form of cable available for networking purposes.
- **Easy to handle** and install.

Disadvantages/limitations:

- **Deformation**: twisted pair's susceptibility to electromagnetic interference greatly depends on the pair twisting schemes staying intact during the installation. As a result, twisted pair cables usually have **stringent requirements** for maximum pulling tension as well as **minimum bend radius**. This fragility of twisted-pair cables makes the installation practices an important part of ensuring the cable's performance.
- **Delay skew**: due to different twist rates used to minimize crosstalk between the pairs, different pairs within the cable have different lengths and thus different delays.
- **Imbalance**: differences between the two wires in a pair can cause coupling between the common mode and the differential mode.

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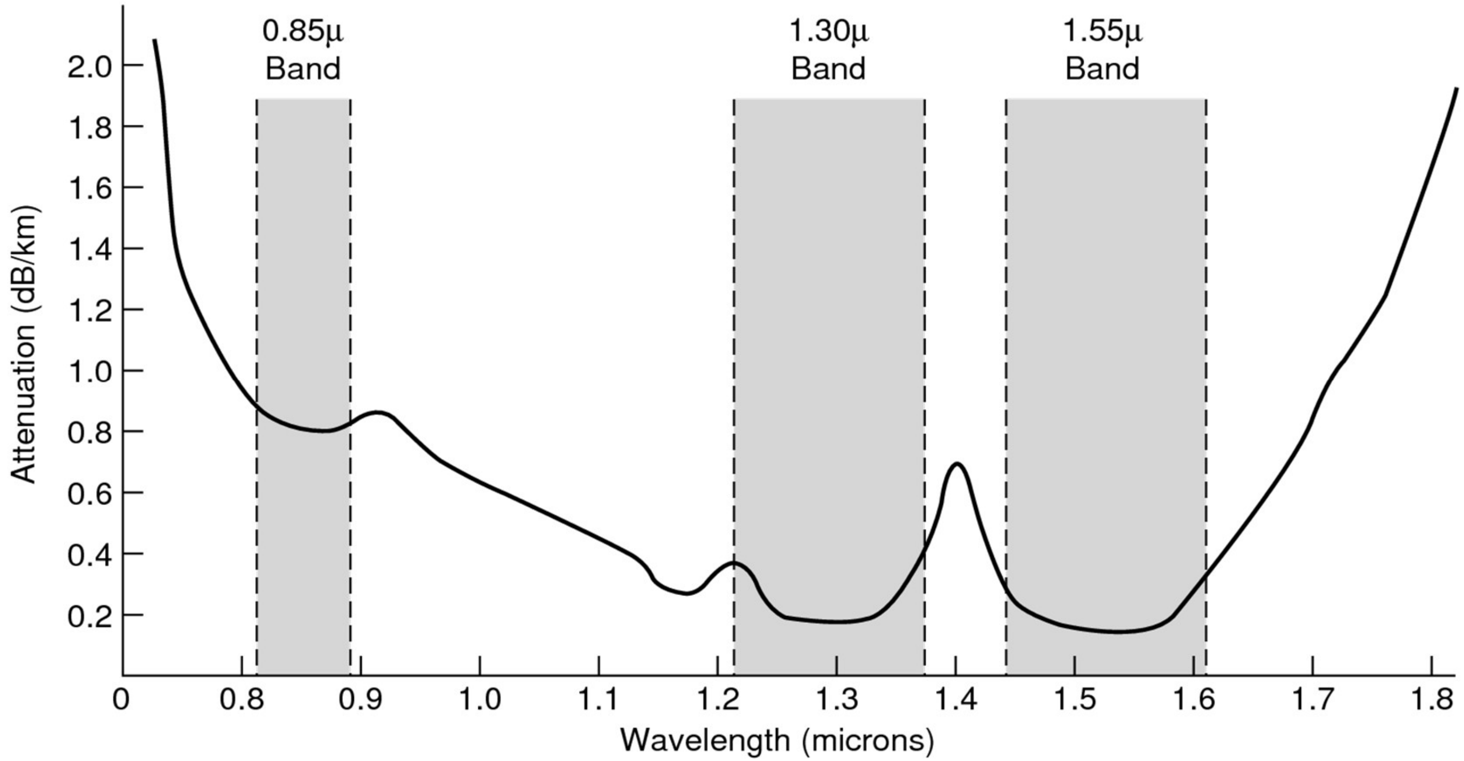
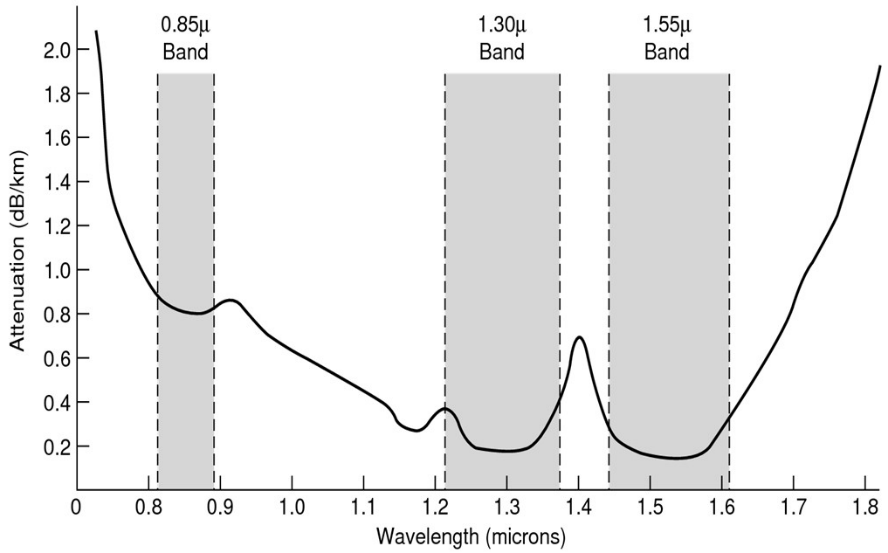
Attenuation of light by glass fiber



Optical fibre

Optical Transmission windows:

- 1st window: 850 nm band
- 2nd window: 1300 nm band
- 3rd window: 1550 nm band



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Wavelength

In the field of optical telecommunications, the **wavelength** (**λ** - lambda) is indicated instead of the frequency (f). Visible light occupies the wavelength range from 380 nm (violet) to 780 nm (red).

The frequency which meets the "red" wavelength range but is no longer visible is called the **infrared range** (IR). One differentiates between the near, medium, remote and very remote IR ranges.

Optical telecommunications uses the **near IR** range around the wavelength **1µm** (**1000 nm**). This corresponds to a frequency in the order of magnitude of 10^2 THz.

$$f = \frac{c_0}{\lambda} = \frac{300{,}000\,\frac{km}{s}}{1\,\mu m} = \frac{3 \cdot 10^8\,\frac{m}{s}}{1 \cdot 10^{-6}\,m} = 3 \cdot 10^{14}\,\frac{1}{s} = 300 \cdot 10^{12}\,Hz = 300\,THz$$

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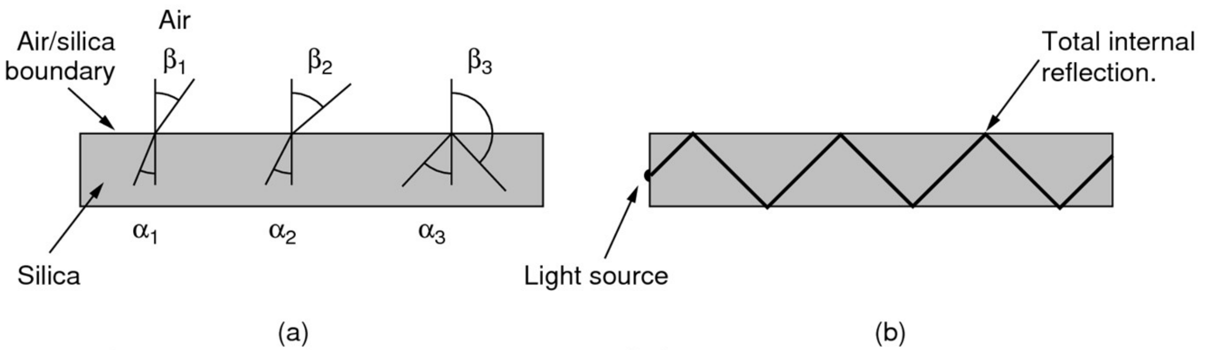
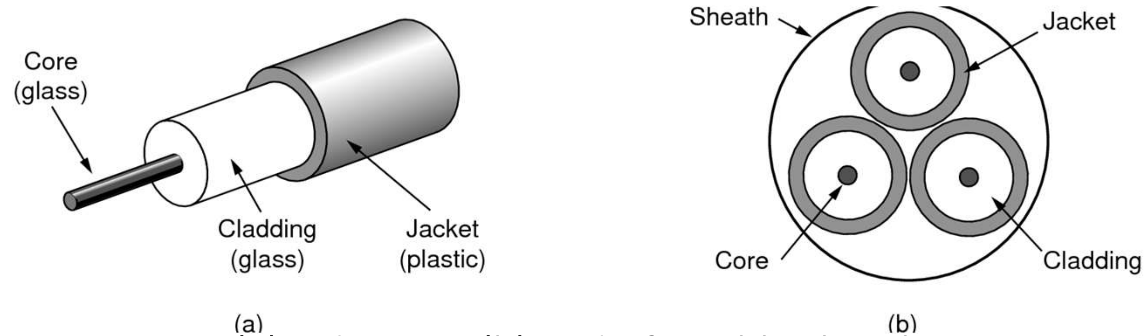
Optical fibre



(a) Three examples of a beam of light in a glass fibre that hits the air-quartz glass interface at different angles.

(b) Light beam trapped by complete internal reflection.



(a) Side view, (b) End of a cable sheath

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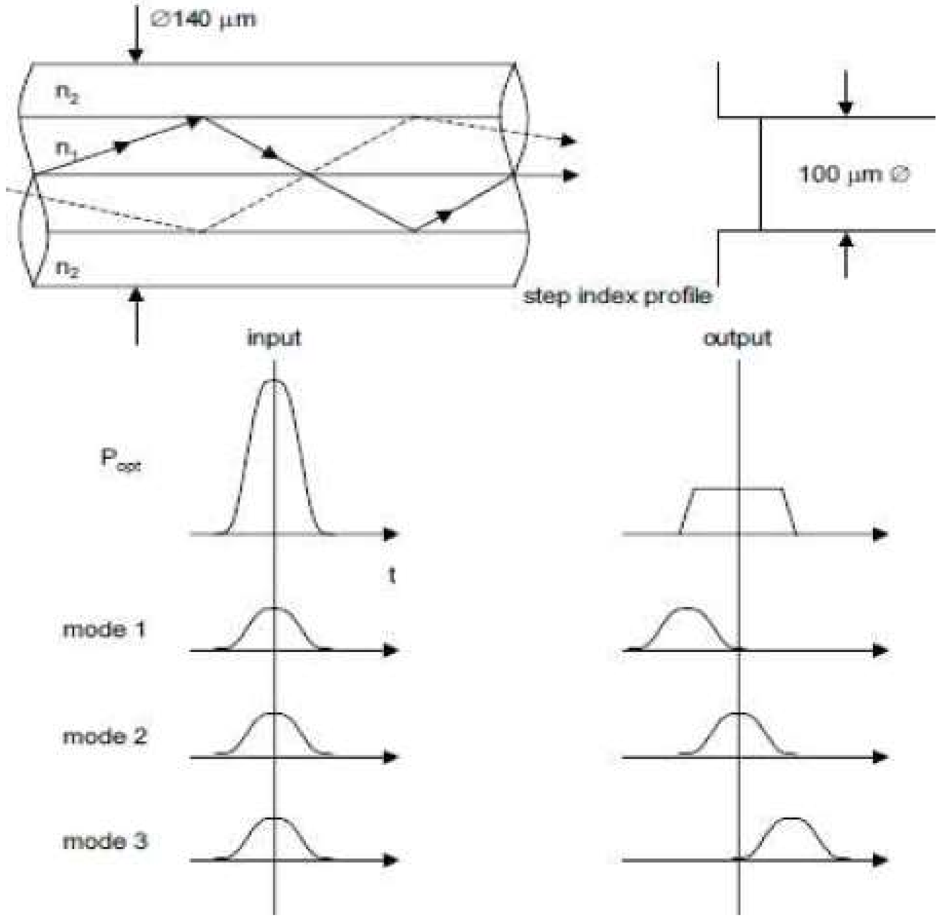
Optical fibre

- **Multi-mode Fibers w/Step Index Profile**

The optical power of a light pulse is distributed over multi (many) modes (rays). In **multimode** fibers, the modes propagate by **different paths**. The rays travel by different paths but all with the same velocity, and thus they have **different transit times**. Therefore the length of the pulses increases with increasing fiber length.

This type of fiber is employed **only for short distances** (approx. 50 - 100 m), at **low data rates**. Moreover, today this fiber type is not employed anymore.



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Optical fibre

Propagation velocity - Refraction index

In **air** or a **vacuum**, light has a propagation velocity of **c=300.000 km/s**

If light enters a different **transparent medium**, its velocity changes. The change in velocity corresponds to the ratio by which the medium is denser than air. The factor by which a material is denser than air is called the **refraction index** and designated with "**n**". It indicates how many times denser than air a medium is.

n0 = 1 = lowest density = highest light velocity

All other **transparent media** are denser **n>1**.

The propagation velocity of light (determines transit time of the pulses) decreases in direct relation to the increase in density.

Glass has an index of refraction n of approximately **1.5**.

However, the refraction factor of a material is dependant on the particular wavelength (it is **wavelength-dependent**).

Optical fibre

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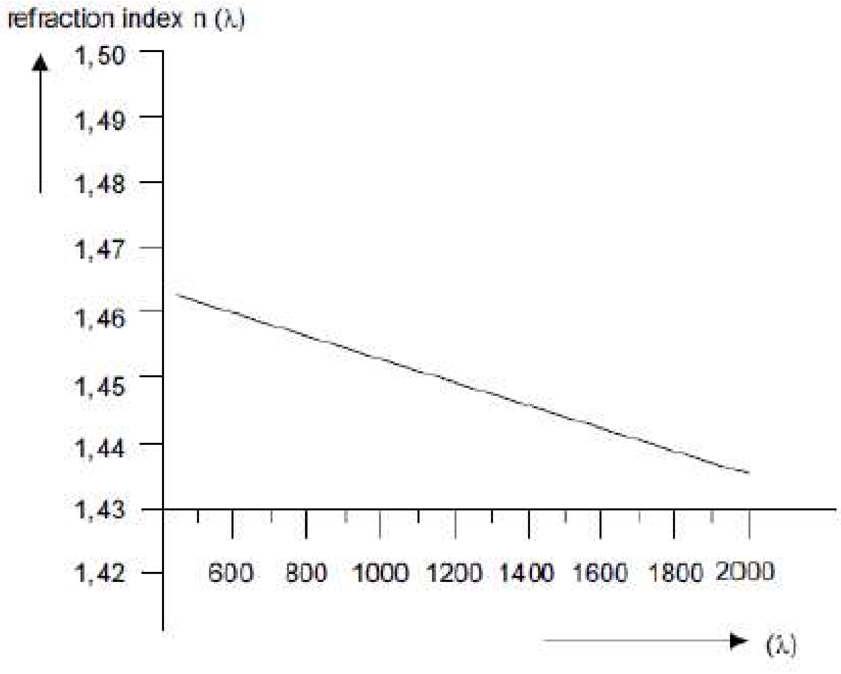
Silica Glass

The material for fibers used in today's cables is exclusively silica glass.

The earth's crust consists of 26 % silicon. Quartz appears in its pure crystalline form, as rock crystal for example. Silica glass, on the other hand, is an amorphous, solidified, molten mass. It has no melting point, but becomes increasingly soft at high temperatures and vaporizes without entering the liquid state.

Quartz appears in its natural form as the chemical compound **SiO2**. As a product of erosion (e.g. of granite), it appears mainly as sand; and in practically **unlimited quantities**.



Refraction index n (λ) for 100% SiO_2

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Optical fibre

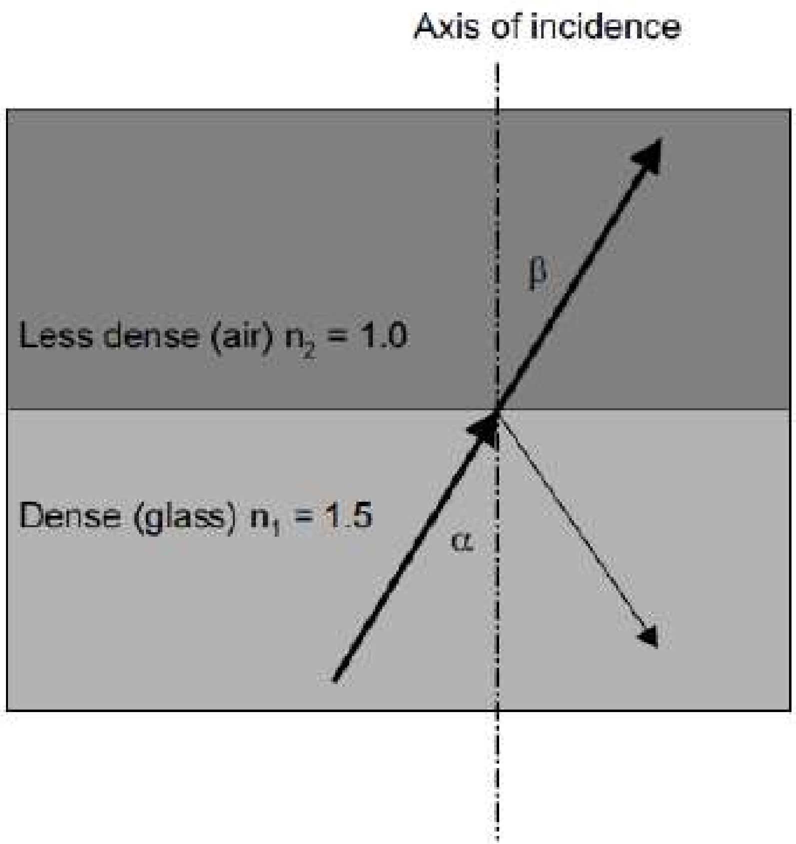
Refraction & Snell's law

A beam of light meets a **different transparent medium** at an **incidence angle α**.

One part of the beam is **reflected** (angle of reflection = angle of incidence). The other part of the beam enters the other medium. The angle of propagation of the beam changes at this point. It is **refracted**. This effect is called refraction of light.

According to the **Snellian law**, the sines of the angles α and β are inversely related to the refraction factors n1 and n2

$$n1 \sin \alpha = n2 \sin \beta$$



Optical fibre

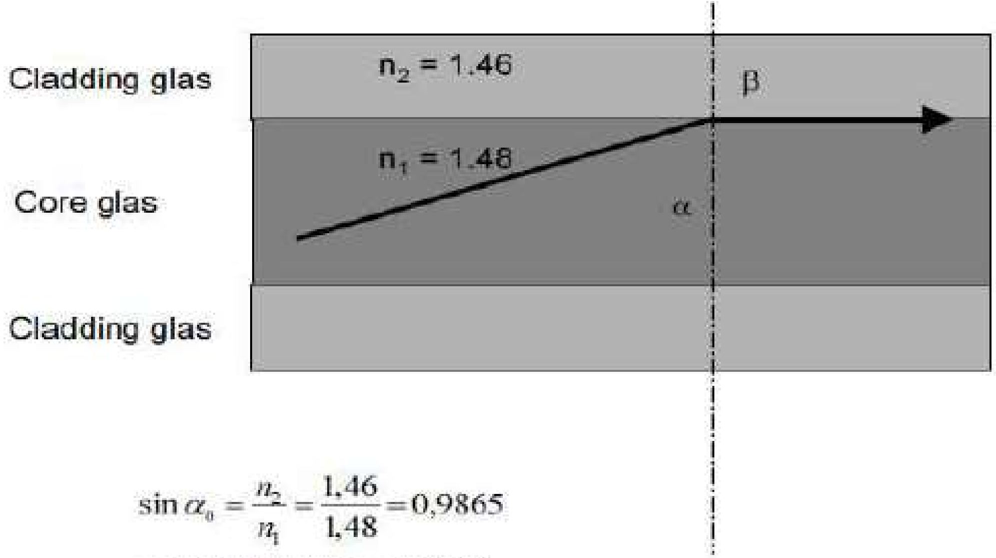
Critical Angle & total reflection

If the angle of incidence α becomes steeper and steeper, one arrives at a situation where the beam of light is no longer refracted into the other medium. It then runs in the boundary layer between the two media. An angle β0 = 90°, with sine "1" results. This special angle is called the **critical angle**.

All angles which are steeper than the critical angle cause the beam to be reflected into the denser medium. This means that **total reflection** takes place.

The critical angle is determined by the ratio of the refraction factors of the media.

sin α = n2 / n1



$$\sin \alpha_0 = \frac{n_2}{n_1} = \frac{1{,}46}{1{,}48} = 0{,}9865$$

$$critical\ angle\ \alpha_0 = 80{,}53^\circ$$

$$\beta = 90^\circ$$