4 Physical Layer

4.1 Functions

The **physical layer** (layer 1 in the ISO/OSI protocol stack, transmission layer) is responsible for the transmission of raw data (bits) via a communication channel, the transmission medium. It is built directly above the physical transmission medium.

The physical layer performs the following tasks:

- Definition and specification of mechanical and electrical equipment (cable, connector (pin definition), transceiver, repeater, ...) to handle the communication depending on the network technology (Ethernet, Token Ring, ...),
- Definition of the coding (definition and preservation of the valence of each bit when transferring data over the transmission medium, definition of the voltage levels, specification of the time duration for a bit (timing)),
- Definition of the transmission mode (simplex, duplex, etc.),
- Definition of the mechanical and electrical parameters and the logical details for the data transmission depending on the network technology (Ethernet, Token Ring, ...),
- Definition of the start and stop information during data transmission.

Various protocols for establishing communication links are located on the physical layer. Examples are Ethernet protocol, USB protocol, mobile radio protocols (e.g. Bluetooth protocol).

On the hardware side, various network components operate on the physical layer:

- **Network Interface Card (NIC):**
  Connection of a computer to a data network,

- **Modem:**
  Data transmission device, modulation/demodulation,

- **Transceiver:**
  - Junction for data station in bus system,
  - Amplifier,
  - Electronics for carrier and collision detection,

- **Repeater:**
  - Coupling between two LAN segments,
  - Matching of signals between different media
    (twisted pair cable, fiber optics, etc.),

- **Hub:**
  Network distributor with multiple ports and star cabling (star topology).

4.2 Ethernet – Example for a physical network medium

4.2.1 Basics

Ethernet-based networks are based on developments made by Robert Metcalfe, a PhD student at the Palo Alto Research Center (PARC) of the American company Xerox Corporation, in 1973. They were originally implemented both physically and logically exclusively in the form of bus systems (Ethernet version 2.0 and IEEE 802.3). All network stations were connected to a common bus medium.

Systems of different physical types are currently in use. Their identification includes the data rate, the modulation type and the maximum segment length:

<Data rate [Mbit/s]> <Modulation type> <max. Segment length [100 m]>

Two types of modulation are distinguished:

- **Baseband modulation *(Base):***
  Tansfer of data in the original form,

- **Broadband modulation *(Broad):***
  Transformation of the input data into another frequency range.

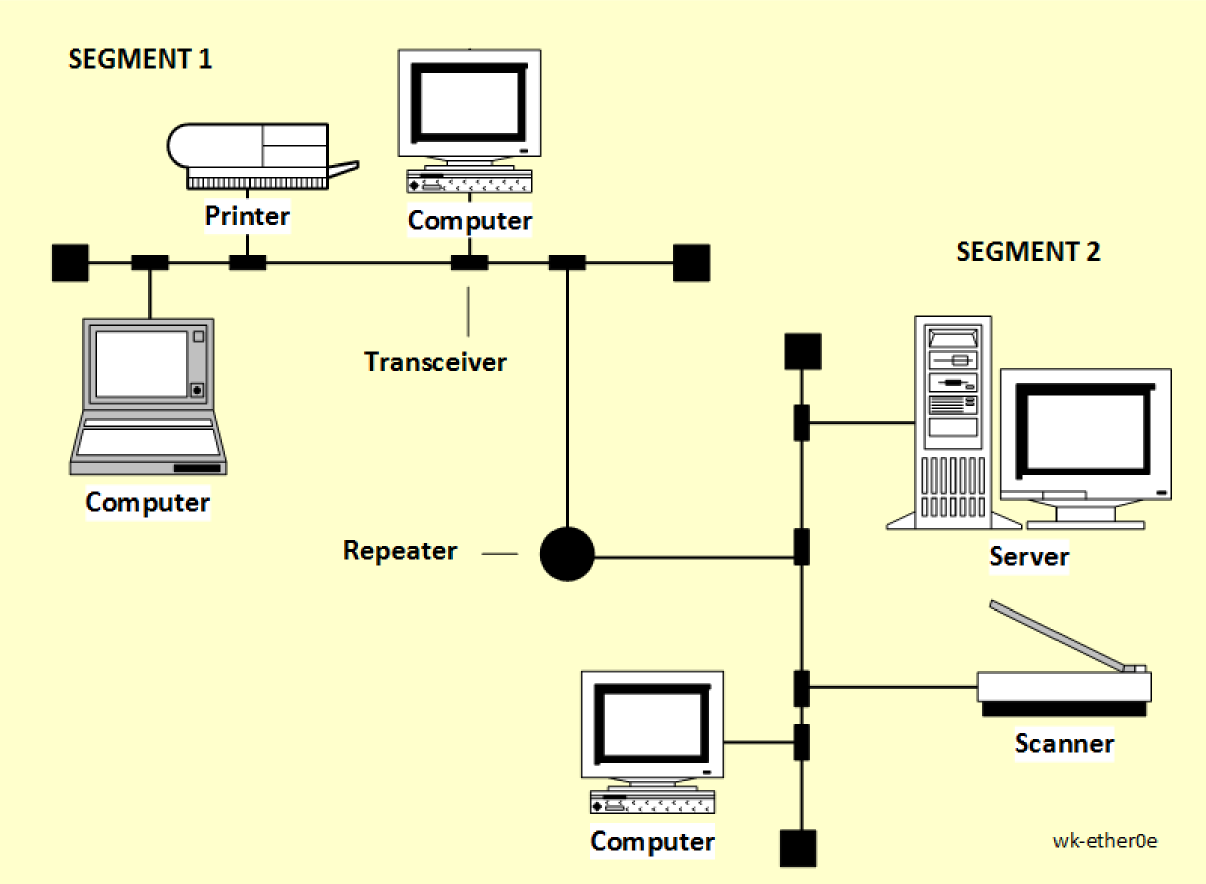


Fig. 4.2.1-1: Schematic diagram of an Ethernet network

4.2.2 Original Ethernet Network

The following table summarizes some properties of the original standard Ethernet system related to the data rate 10 Mbit/s:

Parameter	***10Base5***	***10Base2***	***10BaseT***	***10BaseF***	***10Broad36***
Name	**Standard Ethernet (Yellow Cable)**	**Thin Ethernet (Cheapernet)**	**Ethernet with Twisted Pair**	**Ethernet with fiber optics**	**Ethernet with coaxial cable**
Coding method	Manchester-II	Manchester-II	Manchester-II	Manchester-II	BPSK
Topology	Bus	Bus	Star	Star/Tree	Tree
Max. segment length [m]	500	185	100	500-2000	3600
Max. number of Transceiver/segment	100	30	1024		
Minimum distance [m] between transceiver	2.5	$\geq$ 0.5			
Max. number terminals in total network	1024	1024	500-2000		
Medium	Coax, UTP/STP $(50 \pm 2)\ \Omega$	Coax, 50 Ω	UTP/STP 85 ... 110 Ω	Fiber optics: 50/125 μm, 62.5/125 μm, Monomode	Coax 75 Ω
Connection to medium	AUI-Interface via transceiver	AUI-Interface or BNC connector	RJ-45-connector	glass fiber	practically no longer of any significance
Propagation speed	> 0.77 c	> 0.66 c (RG 58) > 0.75 c (10Base2)	> 0.585 c		
	(c: speed of light)				
Max. damping	7 dB/km				
Transceiver cable length	$\leq$ 50 m	$\leq$ 50 m			

Exercises

E.4.2.2-1 Topology of a digital LAN communication network

A LAN network consists of two subnetworks connected with a repeater according to the standard Ethernet technology 10Base5. 50 computers are integrated in each subnet.

a) What is the maximum transmission rate?

b) What is the maximum number of additional computers that could be integrated into the existing network?

4.2.3 Fast Ethernet

The following table lists characteristic properties of systems according to Fast Ethernet technology (IEEE 802.3u) with twisted pair cables and fiber optic conductors:

Parameter	**100Base-TX (100Base-T)**	**100Base-T4 (100Base-T4+)**	**100Base-FX**
Topology	Star	Star	Star
max. distance [m] between terminals	210 (Shared-/Half duplex)	practically without meaning	400 (Multimode und Shared-/Half duplex) with switches: 2000 m Monomode fiber and Full duplex: 10 km
max. distance [m] between two hubs	10		
Cascading of hubs	once		
Cable type	UTP Cat 5 (4-wire) 100 Ω oder 150 Ω	UTP Cat 3, 4, 5 (8-wire)	Multimode fiber 62.5/125 μm oder 50/125 μm (Norm: 1310 nm),
Coding type	4Bit/5Bit + NRZ/NRZI	8Bit/6Ternary	4Bit/5Bit + NRZ/NRZI
Transmission method	Full duplex, Half duplex	Half duplex	Full duplex Half duplex

4.2.4 Gigabit-Ethernet

4.2.4.1 Introduction

The Gigabit Ethernet standard was established in June 1998 as IEEE 802.3z over fiber optic and copper cables. One year later, in June 1999, the IEEE 802ab standard was added for unshielded cables. Gigabit Ethernet technology allows migration from the Fast Ethernet environment to higher bandwidths and faster networks. The technologies used are compatible with each other:

- same frame structure according to the IEEE 802.3 standard,
- Possibility of half and full duplex operation,
- CSMA/CD access method in half-duplex operation in networks with at least one repeater per collision domain,
- maintaining the minimum and maximum packet lengths.

4.2.4.2 Characteristics of the physical layer

The Gigabit Ethernet (standardization bases: IEEE 802.3z and IEEE 802.3ab) is a logical extension of the 10Base-T standard. Since it uses the original 10Base-T frame and the CSMA/CD access method, three transmission speeds can be realized in the same network: 10 Mbit/s, 100 Mbit/s, 1000 Mbit/s.

Gigabit Ethernet specifies different subtypes on the bit transmission layer:

- 1000Base-T: Unshielded twisted pair cabling,
- 1000Base-CX: Shielded twisted pair cabling,
- 1000Base-SX: Fiber optic technology in the wavelength range 770 ... 860 nm,
- 1000Base-LX: Fiber optic transmission with wavelengths 1270 ... 1355 nm.

The 1000Base-T standard (IEEE 802.3ab) regulates the transmission on conventional unshielded twisted pair (UTP) category 5 cables up to a length of 100 meters. All four wire pairs of the UTP cable are used for signal transmission. The transmission speed is therefore reduced to 250 Mbit/s. Because of the bidirectional data transmission on each wire pair, echo cancellation logic must separate transmit and receive signals. Five signal levels (-2, -1, 0, 1, 2) are used for channel coding. The frequency spectrum achieved in this way is 90 percent below 100 MHz. Because of the increased noise level with this method, the coding is not carried out according to the 8B/10B method, as in the case of the other substandards, but the eight data bits and parity bits are distributed over all five signaling stages of the four line pairs.

As with Fast Ethernet transmission, automatic definition (Auto Negotiation) of the connection parameters (speed: 10-100-1000 Mbit/s for copper media, half/full duplex mode if a repeater/switch port is present, flow control: on/off or symmetrical/asymmetrical) occurs when the cable is switched on or reconnected.

All 1000Base-X standards are based on Fibre Channel technology as a concept for connecting workstations, peripherals, storage systems and supercomputers. The 8B/10B method is used as the coding method.

There are three different variants for station connection:

- Multimode connection with maximum length of 550 m,
- Single mode connection with maximum distance of 3 km,
- Copper-based connection with maximum length of 25 m.

The 1000Base-CX variant supports 150-ohm twinax cable as the transmission medium. The maximum length is limited to 25 m.

Two different transmission types for different wavelengths are defined for fiber optic transmission

- 1000Base-SX (Short Wave): Wavelength of the laser: 770 ... 860 nm,
- 1000Base-LX (Long Wave): Wavelength of the laser: 1270 ... 1355 nm.

The following key data apply:

Data rate:	1000 Mbps at the MAC level *MAC* level,
Physical layer:	Fibre Channel technology using theFC-0 und FC-1 layers,
Characteristic data for different standards	***1000Base-T (802.3ab):*** - Medium: four-pair twisted pair cables (category 5E, 6 or 7), - Transmission rate: 4 pairs each 250 Mbit/s corresponds to 1 Gbit/s, - max. cable length: 100 m (90 m + 2*5 m für connection and patch cable), - Connector: RJ-45, ***1000Base-CX (802.3z):*** - specified for the connection of network components, - Medium: Twinax cable (150 Ω), - max. cable length: 25 m, ***1000Base-SX (IEEE 802.3z):*** - only multimode optical fiber (MM OF), - max. fiber length: < 550 m (dependent on bandwidth length product), - Wavelength: 850 nm (SX: short wavelength), - Connector: SC-Duplex, ***1000Base-LX (IEEE 802.3z):*** - Multimode and single mode optical fiber, - Wavelength: 1300 nm (multimode fiber), 1310 nm bei (single mode fiber) (LX: Long Wavelength), - max. fiber length: < 550 m (MM fiber), < 5000 m (bei SM fiber), - Connector: SC-Duplex,
Frame format:	identical with IEEE 803.2 and Ethernet V.2, smallest frame size: 512 Byte (instead of 64 Byte), possible concatenation of multiple small frames,
MAC function:	Half and full duplex modified CSMA/CD technique with max. signal delay time of 51.2 µs (collision window 200 m).

4.2.4.3 10-Gigabit-*Ethernet*

The IEEE 802.3ae standard, ratified in June 2002, extends the previous Ethernet standards to a transmission rate of 10 Gbps. The new standard includes both local area networks (LANs) and wide area networks (WANs).

Three different variants exist:

- **10GBase-SX**:
  Operation with multimode optical fiber over a maximum distance of 300 m,
  wavelength: 1310 nm.

- **10GBase-LX:**
  Operation with mono- or multimode fiber with a range of 15 km,
  wavelength: 1310 nm.

- **10GBase-EX:**
  Operation with single mode fiber with a maximum range of 40 km,
  wavelength: 1550 nm.

Characteristic properties of the standard are summarized in the list below:

- exclusive working mode: full duplex operation according to 802.3 x
  (half-duplex is no longer permitted),
- abandonment of the CSMA/CD access method,
- retention of the original Ethernet frame format,
- retention of minimum and maximum frame length,
- exclusive use of fiber optic links,
- star topology with point-to-point connections,
- two physical interfaces to the LAN (10 GBit/s):
  WAN: OC-192 (SONET Synchronous Optical Network) and
  SDH STM-64 (SDH: Synchronous Digital Hierarchy).

Note on work safety:

Due to the necessary short switching times of the optoelectronics, only laser diodes are used as active elements in Gigabit Ethernet. Due to possible eye injuries, never look directly into the port of an active component or into a junction box or patch panel.
The electromagnetic radiation used is in the infrared range and cannot be perceived in the visible spectrum.

4.3 Transmission media

Information transmission in data networks can be conducted via cables (symmetrical copper cables, coaxial cables, fiber optic cables) or by wireless transmission through the air, atmosphere or vacuum.

4.3.1 Symmetrical copper cables

Symmetrical copper cables (twisted-pair cables, low-frequency cables, copper twisted pairs, telephone cables) in information networks are always designed in twisted-pair form to reduce magnetic and capacitive interferences (crosstalk).
For a long time, twisted copper cables formed the backbone of the telephone infrastructure and network technology in local computer networks. In high-speed networks, they are largely being replaced by fiber optic cables.

Depending on the shielding of the cable and the pairs of cores made of copper braiding and/or aluminum foil, different types are distinguished:

Old Name	**New Name**	**Cable Shielding**	**Pair Shielding**
UTP	*U/UTP*	none	none
STP	*U/FTP*	none	foil
FTP	*F/UTP*	foil	none
S-STP	*S/FTP*	braiding	foil
S-FTP	SF/UTP	foil and braiding	none

Abbreviations:

U:	*unshielded*	(ungeschirmt)
F:	*foiled*	(mit Folie geschirmt)
S:	screened	(mit Geflecht geschirmt)
UTP:	*unshielded twisted pair*	(ungeschirmtes verdrilltes Kabel)
STP:	*shielded twisted pair*	(geschirmtes verdrilltes Kabel)
FTP:	foiled twisted pair	(mit Folie geschirmtes verdrilltes Kabel)

Fig. 4.3.1-1: *F/UTP* cable (left) and *S/FTP* cable (right)

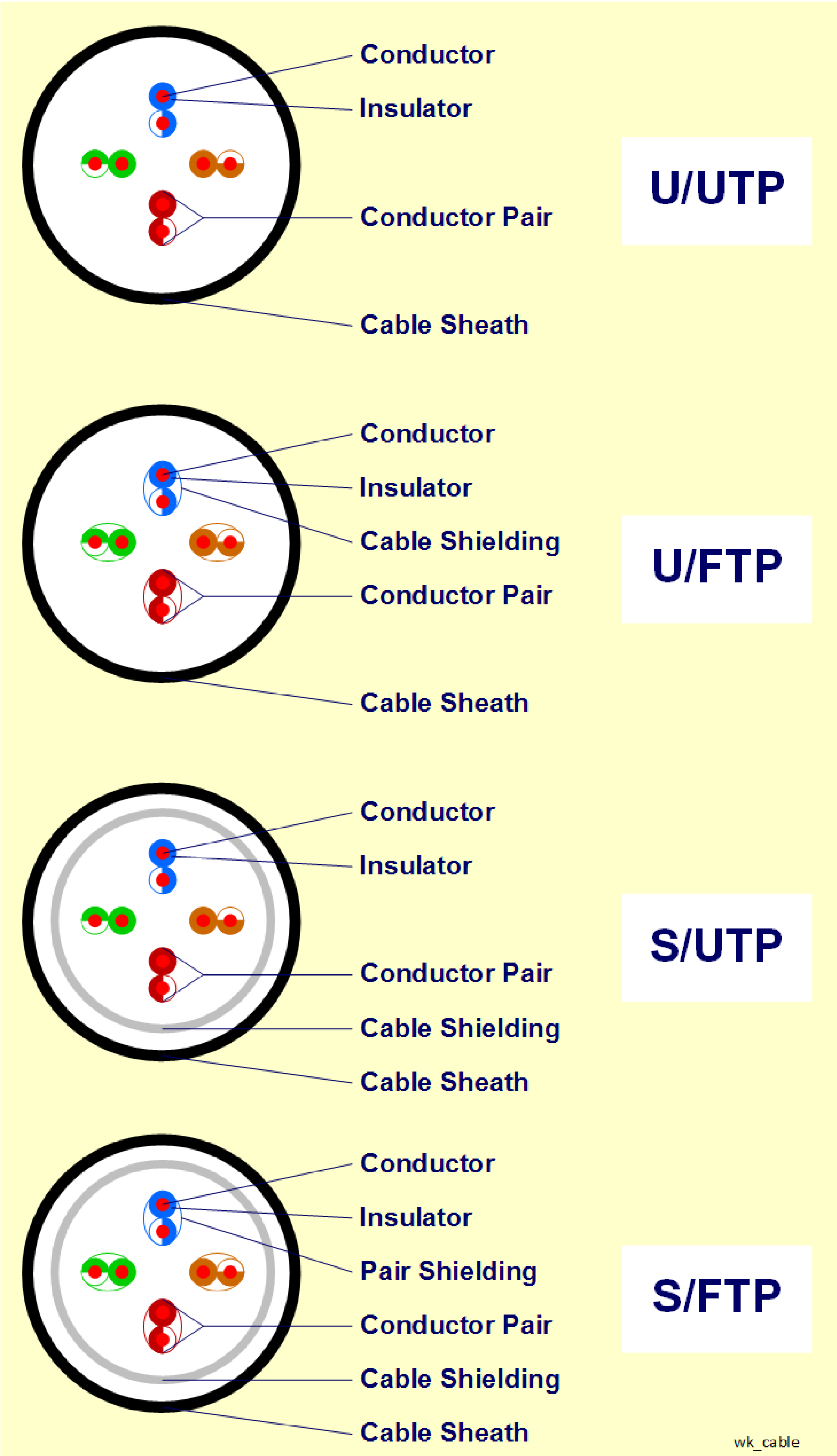


Fig. 4.3.1-2: Schematic structure of symmetrical copper cables

According to a recommendation of the International Standardization Organization ISO, different categories or link classes A ... F, I/II (transmission classes, link classes) are defined for the qualification of transmission links including transmission cables and coupling elements (plugs, distributors, junction boxes, ...) depending on the maximum transmission frequency for point-to-point connections are defined:

UTP-Category	**ISO-Link class**	**Bandwidth/ MHz**	**Transmission Rate (max.) Mbit/s (max.)**
Cat 1	A	0.1	1
Cat 2	B	1	4
Cat 3	C	16	10
Cat 4	-	20	16
Cat 5	D	100	100
Cat 5e	D	100	1 000
Cat 6	E	250	1 000
Cat 6A	E_A	500	10 000
Cat 7	F	600	10 000
Cat 7A	F_A	1000	10 000
Cat 8.1/8.2	I/II	2000	40 000

Characteristic properties of twisted copper cables:

- small dimensions (core diameter: 0.4 - 1.4 mm),
- low cost,
- easy to lay and simple connection technology,
- relatively high susceptibility to interference,
- limited performance (distance, transmission speed).

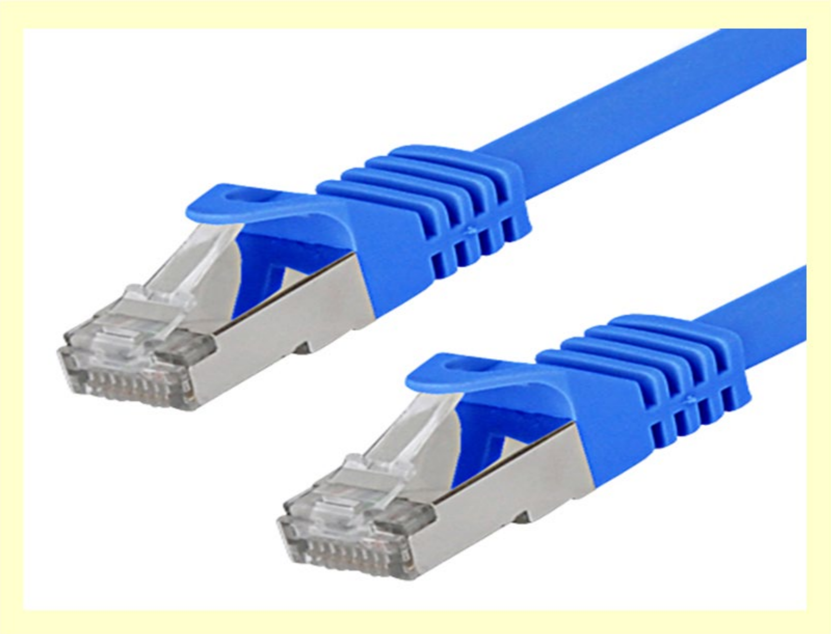


Fig. 4.3.1-3: Connector for Cat 6 cable with RJ-45 connectors

4.3.2 Coaxial cables

Coaxial cables (high-frequency cables) consist of a central inner conductor (usually copper) with concentrically arranged insulating layer (dielectric, polyurethane PU), an outer conductor (shielding of copper braiding (baseband transmission), aluminum foil (broadband transmission)) and an outer insulation (polyvinyl chloride PVC, polyethylene PE, Teflon).

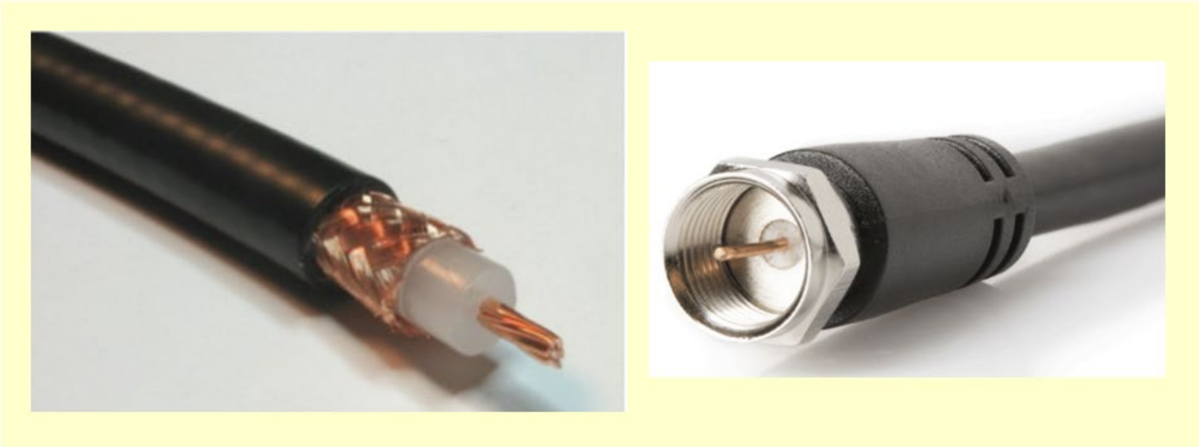


Fig. 4.3.2-1: Coaxial cable and connector

The following table summarizes characteristic values for various common coaxial cables:

Type	**Impedance**	**Application area**
RG-58/U	53.8 Ω	partly for Ethernet, because cables and connectors are chep
RG-58A/U	50 Ω	*Thinwire Ethernet, 10Base2*
RG-58C/U	50 Ω	*Thinwire Ethernet, 10Base2*
RG-59	75 Ω	Cable TV, Broadband transmission systems according to *IEEE 802.7*, Broadband LANs according to *IEEE 802.3/10 Broad 36*
RG-62	93 Ω	*SNA(3270), ARCnet*

Characteristic properties of coaxial cables:

- solid cables (diameter: 5 - 10 mm, low-damping types: 30 mm),
- relatively high weight and stiffness,
- large space requirement (less manageability when laying (larger bending radii)),

- high bandwidth (450 MHz),
- high data rates (50 Mbit/s over 1.5 km (baseband), 300 Mbit/s (broadband)),
- characteristic: characteristic impedance:
  50 Ω: instrumentation, local area networks (Ethernet),
  75 Ω: Broadband distribution networks (cable TV), broadband data networks,
  93 Ω: IBM terminals.

Due to the extremely advanced transmission performance of symmetrical cables at present and the now inexpensive fiber-optic-based solutions, coaxial cables are practically no longer used in newly established digital data networks.

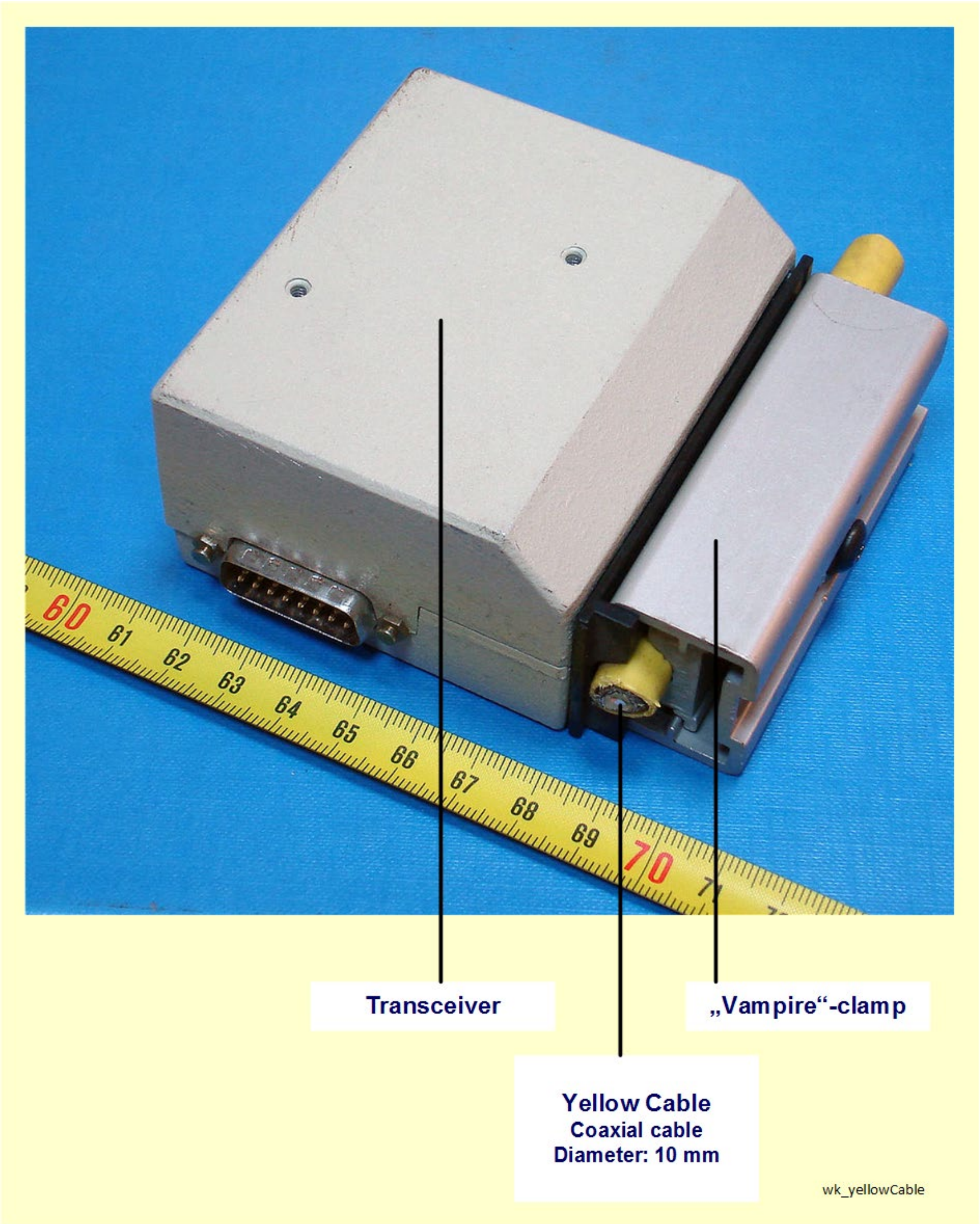


Fig. 4.3.2-2: Historical “Yellow cable” with Vampire-clamp and transceiver (10Base5)

4.3.3 USB Standard

In 1996, the US company Intel introduced the USB standard (USB: Universal Serial Bus) as a wired connection technology in the PC environment. The aim was to replace the then prevailing interfaces (serial interface, parallel interface) for data exchange between computers and peripheral devices (printers, measuring devices, external data storage devices, headsets, etc.).

Special advantages of the USB technology are

- Switching on and off during operation,
- power supply of peripheral devices besides data transport,
- extensive avoidance of new driver installations when connecting small devices (keyboard, mouse),
- independence from the operating system (Windows, Linux, Ubuntu, Max OS x, Android, etc.).

The table below shows the development of the releases:

Old Term Bezeichnung	**New Term Bezeichnung**	**max. Transmission Speed (theoretical)**	**max. Electrical Current**
USB 1.0		12 Mbit/s	500 mA
USB 2.0		480 Mbit/s	500 mA
USB 3.0		5 GBit/s	900 mA
USB 3.1 Gen 1	*USB 3.2 Gen 1*	5 GBit/s	900 mA
USB 3.1		10 GBit/s	5 A
USB 3.1 Gen 2	*USB 3.2 Gen 2*	10 GBit/s	5 A
USB 3.2	*USB 3.2 Gen 2x2*	20 GBit/s	?

The transfer rates actually achieved are lower.

With the USB 3.x specifications, power supply, data transfer and the transmission of video signals are possible simultaneously via a single cable.

The USB-C connector is intended to combine the various existing USB connector types (USB-A, USB-B, mini and micro connectors, DVI, DisplayPort, HDMI, audio jack for headphones, charging jacks for mobile devices) into one connector type.

The USB-C cable is designed for higher voltages than 5 V and higher currents than 5 A. Special cables (USB Power Delivery (USB-PD)) allow a total power of 100 W.

The USB-C connector includes 24 pins. The middle 8 pins form the so-called control channel, which performs a logical check of how it is plugged in.

Current carrying lines are A4/B4 and A9/B9. Ground lines are A12/B12.

Multiple contacts can be used to increase the conductor cross-section and thus enable the use of higher currents.

Buchse

A1	A2	A3	A4	A5	A6	A7	A8	A9	A10	A11	A12
GND	TX1+	TX1-	V BUS	CC1	D+	D-	SBU1	V BUS	RX2-	RX2+	GND
GND	RX1+	RX1-	V BUS	SBU2	D-	D+	CC2	V BUS	TX2-	TX2+	GND
B12	B11	B10	B9	B8	B7	B6	B5	B4	B3	B2	B1

Stecker

A12	A11	A10	A9	A8	A7	A6	A5	A4	A3	A2	A1
GND	RX2+	RX2-	V BUS	SBU1	D-	D+	CC	V BUS	TX1-	TX1+	GND
GND	TX2+	TX2-	V BUS	V CONN			SBU2	V BUS	RX1-	RX1+	GND
B1	B2	B3	B4	B5	B6	B7	B8	B9	B10	B11	B12

elektronik-kompendium

Fig. 4.3.3-1: USB-C connector and jack

When operating USB 3.x systems, the base operating frequency is 2.5 GHz. It is radiated by cables, connectors and devices and can thus interfere with other radio-based communication systems, such as WLAN or Bluetooth.

4.3.4 Fiber optic cables

Fiber optic cables are made of high-purity silicate glass (fused silica SiO_2). They have a cylindrical structure with a core and an optically thinner cladding (relative refractive index change about 1%). Additional coating is used passively for mechanical protection.

Fiber optic cables transport data by continuous total reflection of electromagnetic waves in the infrared spectral range.

Depending on the structure, two types of optical waveguides are distinguished:

- **Multimode fiber:** Many (several hundred!) waves (modes) contribute to signal transmission,

  - **Step-Index fiber:** abrupt change of refractive index between core and cladding,

  - **Graded-Index fiber:** steady decrease of optical density between core and cladding,

- **Monomode fiber:** Only one single mode is capable of propagation. Monomode fibers always have an extremely thin core and a step index profile.

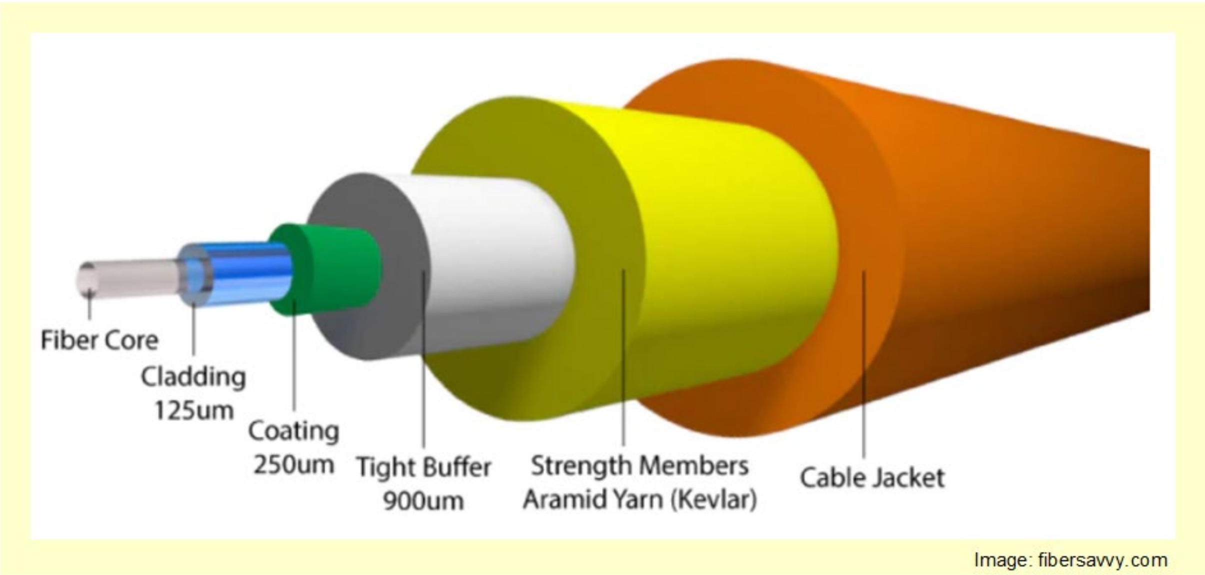
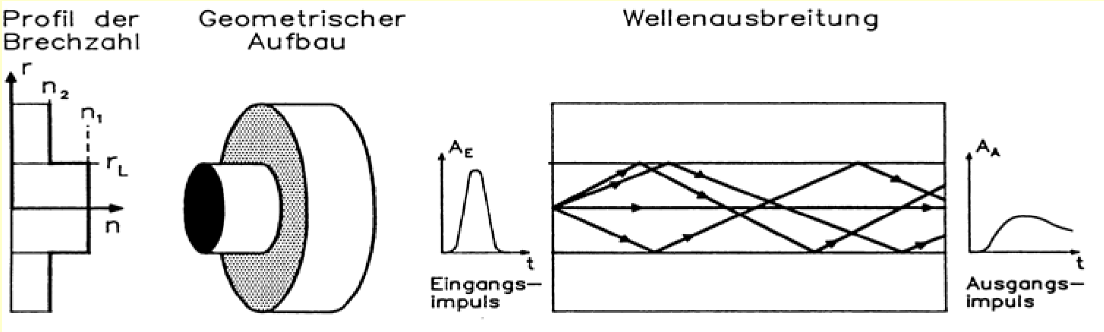
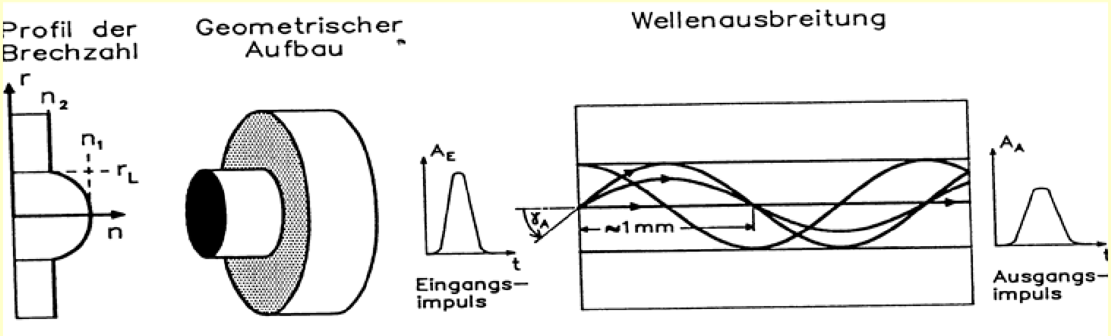


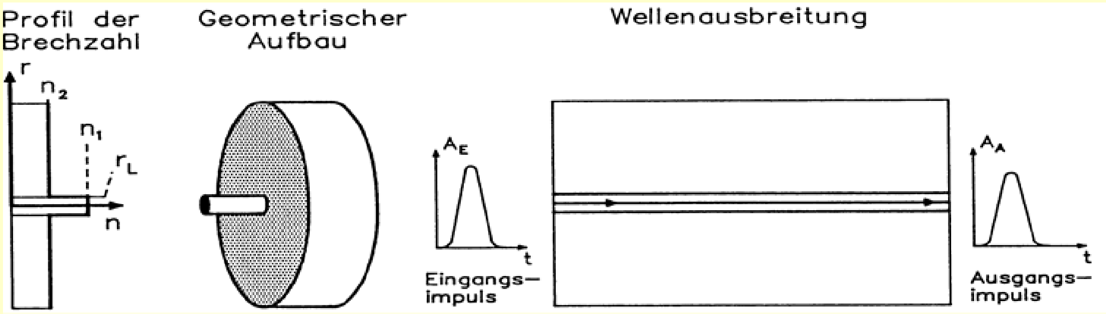
Fig. 4.3.4-1: Schematic diagram of the structure of a fiber optic cable



Prinzip der Wellenausbreitung in Stufenindexfasern



Prinzip der Wellenausbreitung in Gradientenfasern



Prinzip der Wellenausbreitung in Monomodefasern /CONR96/

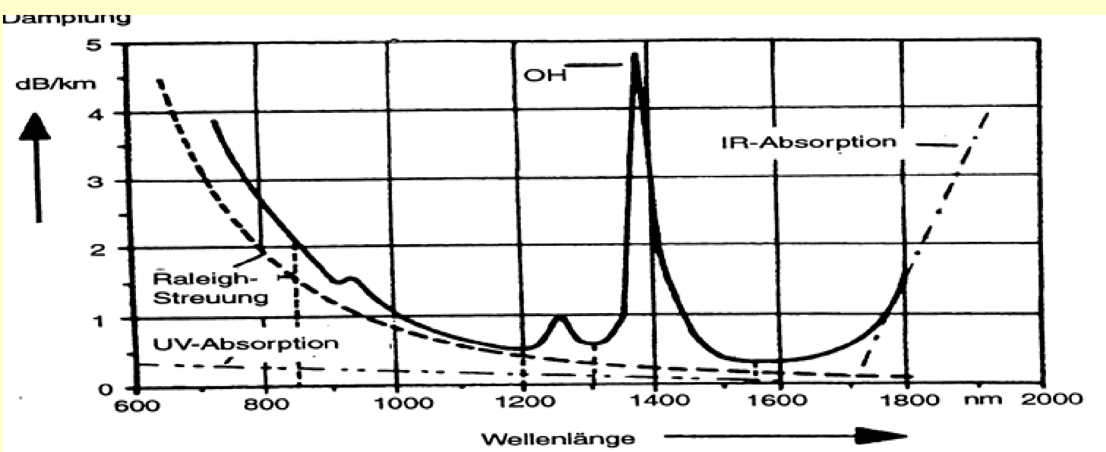


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Fig. 4.3.4-2: Fiber types and fiber attenuation

The following table provides an overview of commonly used optical fibers:

Cable type	**Diameter (core/cladding)**	**Bandwidth (length 1 km)**	**Application area**
Multimode with Step-Index profile	100 ... 400 μm/ 200 ... 500 μm	100 MHz	Distances $\leq$ 1 km, Production industry
Multimode with Graded-Index	50 μm/125 μm	1 GHz	*LAN, Backbone, ATM* (mainly Europe)
Multimode with Graded-Index	62.5 μm/125 μm	1 GHz	*LAN, Backbone, ATM* (mainly USA)
Monomode with Step-Index profile	8 μm/125μm	100 GHz	Networks with $\geq$ 1 Gbit/s Telefone companies, High speed networks

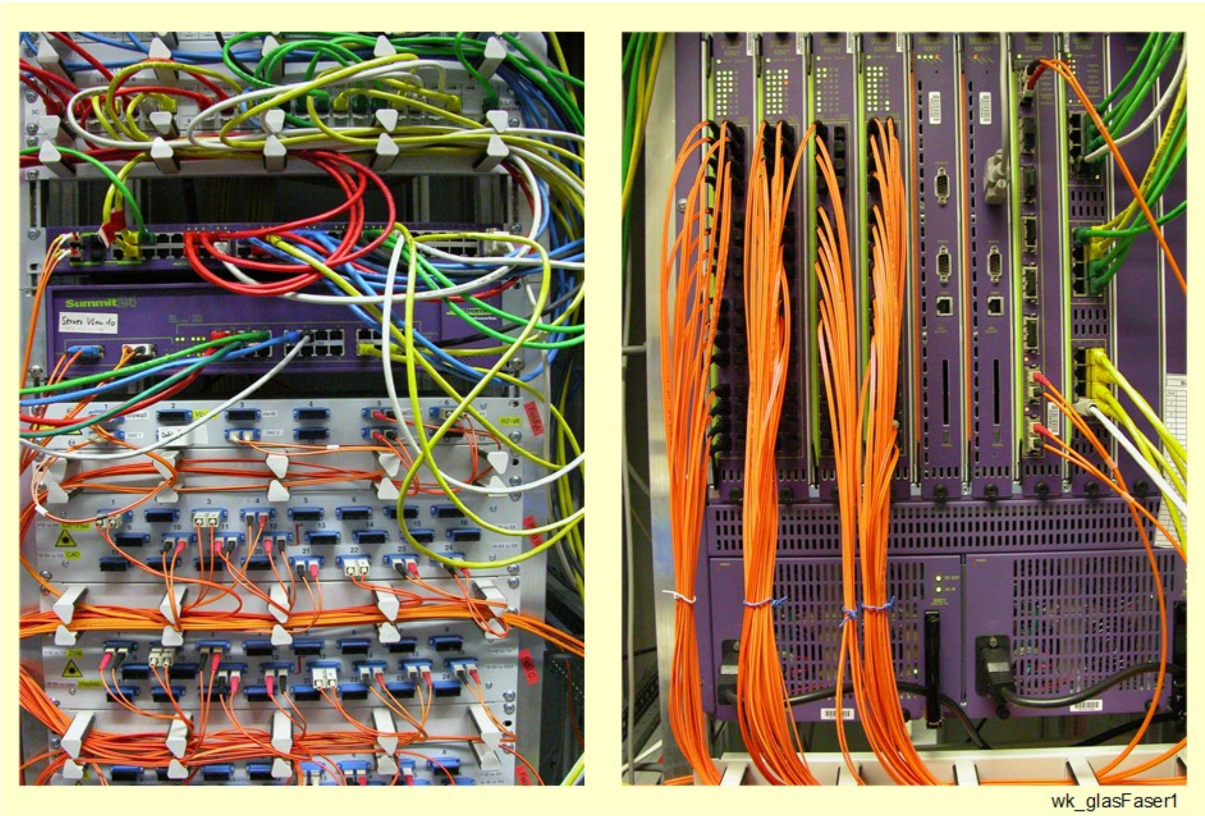

Fig. 4.3.4-3: Fiber optic patch panels in a server room

Wavelength-dependent losses in optical waveguides arise from system-inherent Rayleigh scattering at short wavelengths (scattering intensity ~ ω^{-4}), resonance absorption due to molecular excitations (metal ions, OH^--ions), and infrared absorption at longer wavelengths.

For operation wavelength windows with local minima of attenuation at 850 nm (use of LEDs), 1300 nm (LEDs) and 1550 nm (laser diodes) are used. For silicate glass, the theoretical minimum of attenuation is 0.12 dB/km (1550 nm). Technically, about 0.2 dB/km is achieved.

Fluorine-based glass materials, which are in the research stage, shift the attenuation minimum to longer wavelengths and smaller values for the attenuation.

Further losses occur due to various dispersion effects, i.e., the variation of signal propagation times for different optical modes:

- **Mode dispersion:** Pulse broadening due to propagation time differences of the different modes in multimode fibers
- **Material dispersion:** Different signal delays due to a frequency-dependent propagation speed (transmitters do not emit monochromatic radiation: LED: $\Delta\lambda \approx 30 \ldots 40$ nm, Laserdiode: $\Delta\lambda \approx 1 \ldots 3$ nm),
- **Waveguide dispersion:** Due to non-monochromatic radiation sources, the ratio of core diameter and wavelength becomes wavelength-dependent.

A measure of the dispersion of an optical waveguide and of the achievable bit rate is its bandwidth B. It depends on the length L of the optical waveguide, and it is described by the g factor (length-dependent material parameter) to be determined experimentally. The phenomenological exponential relationship applies

$$\frac{B}{B_1} = \left(\frac{L}{L_1}\right)^{-g}$$

with L_1: length of the fiberoptic cable at bandwidth B_1.

The g factor varies in the range g = 0.5 for the case of long lengths up to g = 1.0 for short fiber lengths and must be determined experimentally.

With the approximation g = 1 for the LAN range, the following relation follows for the bandwidth length product (bit rate length product)

$$BL = B_1 L_1 = \text{const.}$$

The bandwidth-length product is considered a characteristic parameter in the planning of data networks with optical fibers.

Characteristic values for the bandwidth-length product are

100 MHz·km	für Stufenindex-Multimode-Fasern,
1 GHz·km	für Gradientenindex-Multimode-Fasern,
10 GHz·km	für Stufenindex-Monomode-Fasern.

The properties summarized below are characteristic of optical fibers:

- insensitive to electrical and magnetic interference,
- no production of own interference radiation,
- low attenuation (amplifier-free distances of over 100 km),
- no crosstalk,
- suitability for explosive environments,
- complete galvanic decoupling of transmitter and receiver,
- high eavesdropping security,
- small cable cross-section and low cable weight,
- trouble-free coupling of power and signal cables for simultaneous supply and control tasks,
- no lightning protection required,
- safely protected against nuclear electromagnetic pulse (EMP),
- relatively expensive due to complex connection technology.

4.3.5 Wired networks in the industrial environment

In the past, industrial networking of machines was dominated by fieldbus systems such as CANBUS or PROFIBUS.

Meanwhile, the Ethernet standard is also increasingly finding its way into production and manufacturing. In particular, its higher data transmission rates, simple integration options and the variety of service offerings and interfaces are convincing. It enables the digital networking and communication of sensors, machines, employees, all the way to administration and management.

For IIOT applications (IIOT: Industrial Internet of Things), the so-called "Single Pair Ethernet (SPE)" is the particular focus of developments. It is designed for gigabit communication, based on twisted copper pair cables with cable lengths of up to 1000 meters.

4.3.6 Wireless communication networks

4.3.6.1 Introduction

Wireless communication networks are divided into three groups depending on their possible spatial extent:

- WPAN: Wireless Personal Area Network
- (examples: Bluetooth, IrDA, ...),

- WLAN: Wireless Local Area Network
- (examples: Bluetooth Mesh, IEEE 802.11, ...),

- WWAN: Wireless Wide Area Network
- (examples: UMTS, LTE, ...).

4.3.6.2 Electromagnetic wave propagation

Non-wired, radio-based networks are currently rapidly evolving into ubiquitous communication systems for technical and scientific applications.

The frequency ranges of electromagnetic radiation used extend from the kHz range to millimeter waves.

To describe the propagation characteristics of the electromagnetic wave, various technical system components must be considered:

- Output power of the signal source
- Properties of the transmitting antenna,
- Geometry-related signal decay in space,
- Attenuation of the radiated matter,
- Parameters of the receiving antenna and receiving electronics.

The output power P_S of the transmitter is fixed. In free space, a point transmitter radiates isotropically three-dimensionally into space.

Transmitting antennas exhibit geometrical antenna characteristics. They can radiate the transmitting power differently in different spatial directions and angular segments. The ratio of the radiated power with respect to a three-dimensional isotropic radiation is called antenna gain G_S of the sender. Antenna gain describes the power that would have to be added to an isotropic omnidirectional radiator to make it emit the same radiated power in the preferred direction. The antenna gain is expressed in dBi (Decibel isotropic). The "i" added to the unit dB indicates the isotropic reference radiator.

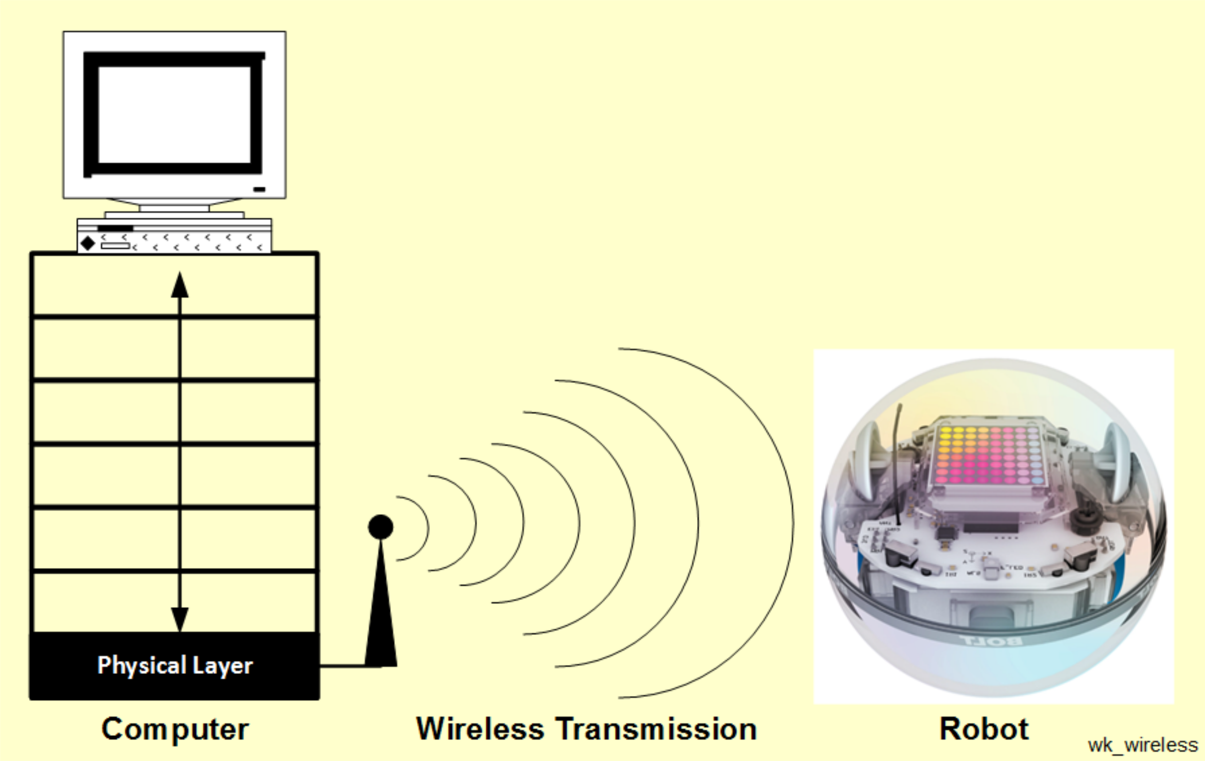

Fig. 4.3.6.1-1: Robot control via *Bluetooth*

Fig. 4.3.6.1-2: Prosthesis calibration using *Bluetooth*

Fig. 4.3.6.1.3: ***Personal Area Network (Bluetooth)*** **in the clinical sleep laboratory**
/SOMN2021/

This network technology could also be used for humanoid robot diagnostics.

The product of the transmitted power P_S and the antenna gain G_S is called "Equivalent Isotropically Radiated Power (EIRP)":

$$\mathrm{EIRP} = P_S G_S \,.$$

EIRP corresponds to the power that a fictitious spherical radiator (G_S = 1) would have to radiate to ensure the same power flux density at the receiver.

If the wave propagates three-dimensionally in space, the transmitted energy is distributed over a spherical wave front whose surface grows in proportion to the distance square from the point-shaped imaginary transmitting device. Thus, for the power flux density S in vacuum at distance r the following applies:

$$S(r) = P_S G_S \frac{1}{4\pi r^2} \quad .$$

If the radiation penetrates absorbing materials on its way, it is exponentially weakened by the absorption. The influence of absorption is described by the frequency-dependent attenuation coefficient μ:

$$S(r,\mu) = P_S G_S \frac{1}{4\pi r^2} e^{-\mu r} \,.$$

For wave transmissions through the air without absorbing materials, the range is essentially limited by the free space loss, which takes into account the energy loss of the radiated energy due to absorption and multipath propagation.

The free space loss FSL is calculated as follows

$$\mathrm{FSL}/\mathrm{dB} = 20 \cdot \log_{10} \frac{4\pi r}{\lambda} \,.$$

If there are optical obstacles on the path of beam propagation, absorption, reflection, refraction and diffraction effects must also be taken into account.

At the receiver side, suitable antenna systems can receive and amplify the signals (antenna gain G_R).

The received radiated power P_R is calculated for radio transmissions in free space according to the relationship

$$P_R = A_E G_S$$

with A_E : Effective area of the antenna

$$A_E = \lambda^2 \frac{P_S}{4\pi r^2} e^{-\mu r} G_R \,.$$

With optimal matching of power and polarization follows for the received power P_R at the receiver:

$$P_R = \lambda^2 \frac{P_S}{4\pi r^2} e^{-\mu r} G_S G_R .$$

4.3.6.3 Short range networks

Short-range wireless communication systems for voice and data transmission (Short Range Devices SRDs) are characterized by their particularly low output power. They have high electromagnetic compatibility and are therefore very resistant to interference. They operate with low bandwidths and transmit only small amounts of data.

Frequencies of digital near-field radio systems lie in the wide range from 6 kHz to 2.45 GHz.

Applications can be found, for example, in the areas of alarm systems, home automation (smart home) or Internet of Things (IOT).

4.3.6.4 Bluetooth Technology

4.3.6.4.1 General

Bluetooth is a short-range wireless networking technology (WPAN: Wireless Personal Area Network). The technology is developed and standardized by an association of companies, the Bluetooth SIG (Bluetooth Special Interest Group). Bluetooth enables the digital transmission of data and voice. The technology was introduced in 1999 with the aim of connecting portable devices, such as cell phones, PDAs or notebooks, by low-power radio links.
Technical details are specified in the industry standard IEEE 802.15

4.3.6.4.2 Wireless technology

Bluetooth devices operate in the license-free ISM band (ISM: Industrial, Scientific, Medical) in the frequency range between 2.402 GHz and 2.480 GHz.
Bluetooth provides two different radio technologies:

- Bluetooth Classic (Bluetooth Basic Rate/Enhanced Data Rate (BR/EDR)),
- Bluetooth Low Energy (LE).

Bluetooth Classic (standards: Bluetooth 1.0 - 3.0) transmits data with relatively low power consumption over 79 frequency steps with respective bandwidths of 1 MHz in the ISM band. To optimize freedom from interference and frequency band spreading during data transmission, the Bluetooth standard requires a frequency hopping method (Frequency-Hopping Spread Spectrum (FHSS)). The individual frequency steps are automatically changed up to 1600 times per second during operation. Data transport can be asynchronous connection-oriented or synchronous connection-oriented.

The maximum data rates are 735 kbit/s - 24 Mbit/s, depending on the standard version and the modulation technique.

Bluetooth Classic is mostly used for wireless audio streaming (wireless speakers, headphones, entertainment systems in cars), but also for data transfer tasks.

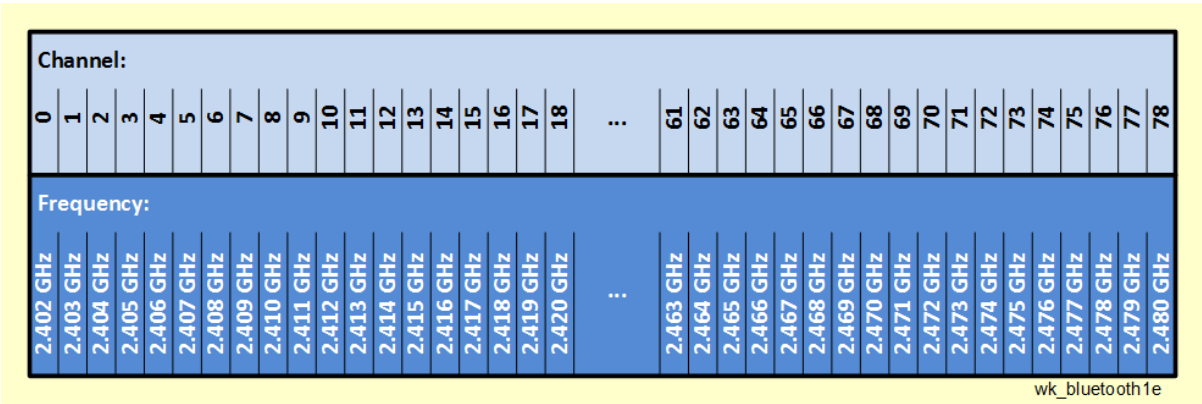

Fig. 4.3.6.4.2-1: Channel partitioning for *Bluetooth Classic (Basic Rate/Enhanced Data Rate (BR/EDR)*

In addition to Bluetooth Classic, the Bluetooth 4.0 standard defines the new Bluetooth Low Energy (LE) technology for low-energy operation. The aim is to transmit small amounts of data at longer intervals. Devices with this Bluetooth technology transmit data in very energy-saving operation over 40 frequency steps with respective bandwidths of 2 MHz in the ISM band (3 channels for establishing connections and for broadcast applications, 37 data channels).

Like Bluetooth Classic, the standard uses the frequency hopping method Frequency-Hopping Spread Spectrum (FHSS) to optimize interference-free data transmission.

The data rates are 125 kbit/s, 500 kbit/s, 1 Mbit/s or 2 Mbit/s, depending on the modulation technique.

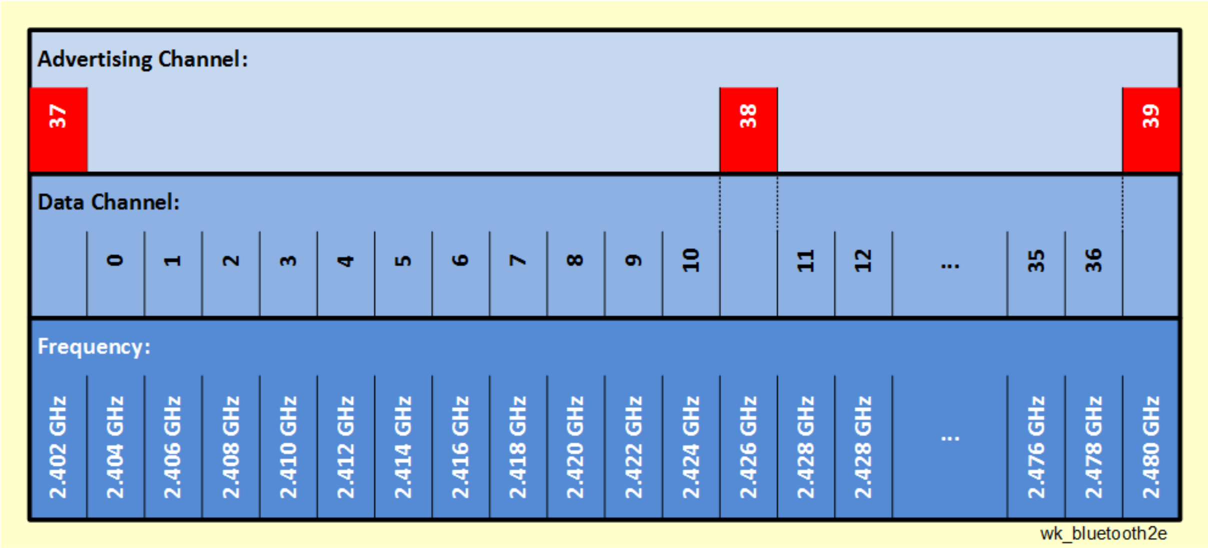

Fig. 4.3.6.4.2-2: Channel partitioning for *Bluetooth Low Energy (LE)*

Data transport can be connection-oriented (asynchronous, isochronous) or connectionless (asynchronous, synchronous, isochronous).

Bluetooth Low Energy (LE) allows various communication topologies and in particular enables the development of complex radio networks. The determination of presence, distance and direction of other devices is possible.

In addition, profiles for secure data transmission (authentication, encryption) are added.

Depending on the transmission power, the devices are divided into different classes with different operation ranges (with good line-of-sight):

Class	Power	Level Difference	Max. Range (in free field of view)
1	100 mW	20 dBm	200 m
2	2.5 mW	4 dBm	50 m
3	1 mW	0 dBm	10 m

The level difference L is defined as a logarithmic ratio of powers P or signal amplitudes U. The unit is decibels (dB):

$$L/_{dB} = 10 \cdot \log_{10} \frac{P_{signal}}{P_{reference}} = 20 \cdot \log_{10} \frac{U_{signal}}{U_{reference}}$$

with P_{signal}: Signal power
$P_{reference}$: Power of reference signal,
U_{signal}: Signal amplitude,
$U_{reference}$: Amplitude of reference signal.

Exercises

E.4.3.6.4.2-1: *ISM*-Band

a) Calculate the average wavelength of the radiation in the ISM band.

b) What is the free-space attenuation at a distance of 100 meters?

c) What is the power ratio between transmitting power and receiving power in the case of transmitting and receiving antennas with isotropic radiation pattern at a distance of 100 m?

d) An ISM band transmitter transmits with a power of 14 dBm in the free field.
The antenna gain of a connected antenna is 4 dBm.
The receiver sensitivity is -79 dBm.
For safety reasons, a power reserve for the transmission of 10 dBm should be planned.
What is the maximum achievable distance between transmitter and receiver?

e) Can a diving robot in water be controlled via the ISM band?
The attenuation coefficient is 0.71 cm^{-1} in water.
Estimate the distance at which the radiation intensity drops to half of the original value due to absorption alone has dropped to half of the original value.

4.3.6.4.3 Network topologies

4.3.6.4.3.1 Piconet topology

The basic network of the Bluetooth topology is the piconet. It is the only topology in the Bluetooth Classic technology. The Bluethooth standard distinguishes between two types of nodes:

- *Master,*
- *Slave.*

The node that initiates a Bluetooth connection appoints itself as the master. Only the master can establish and operate a Bluetooth connection between master and slave. If there is only one active slave in the transmission range besides the master, a point-to-point connection (1-slave piconet) is established. In case of several active slaves, a point-to-multipoint connection (multislave piconet) is established. If several piconets overlap, this is referred to as a scatternet. In a connected active network, only one master may be active at a time.

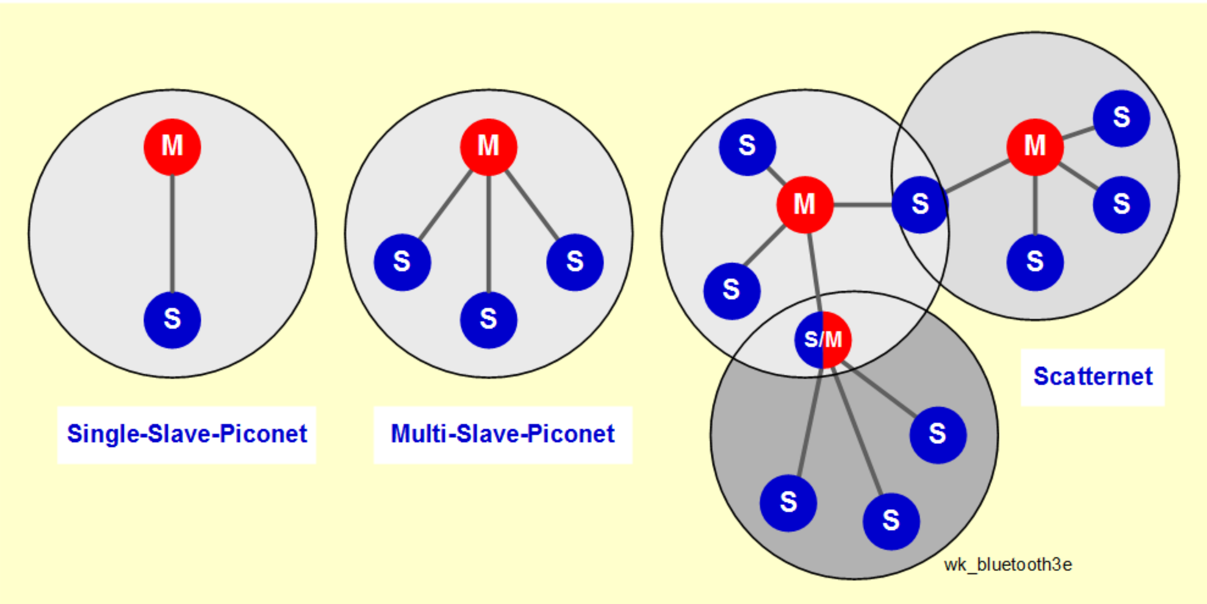

Fig. 4.3.6.4.3-1: Piconet variants

A piconet can accommodate up to 255 participants. However, only eight of these may be active at the same time. All active nodes transmit on the same frequency at any one time.

All non-active nodes are in the so-called "park mode" and are still synchronized with the master. The network access of active and parked slaves is controlled by the master. The master may send data to and request data from all slaves within its piconet. Slaves may only receive data from and send data to their master.

Communication between the slaves is not possible.

4.3.6.4.3.2 Mesh Topology

In 2019, Bluetooth SIG standardized the mesh topology in addition to the piconet topology within the Bluetooth Low Energy (LE) technology. In this topology, each node can communicate with any other node in the network. A total of up to 32,000 nodes can be integrated in a network.

Two types of Mesh topologies are distinguished:

- Partial Mesh,
- Full Mesh.

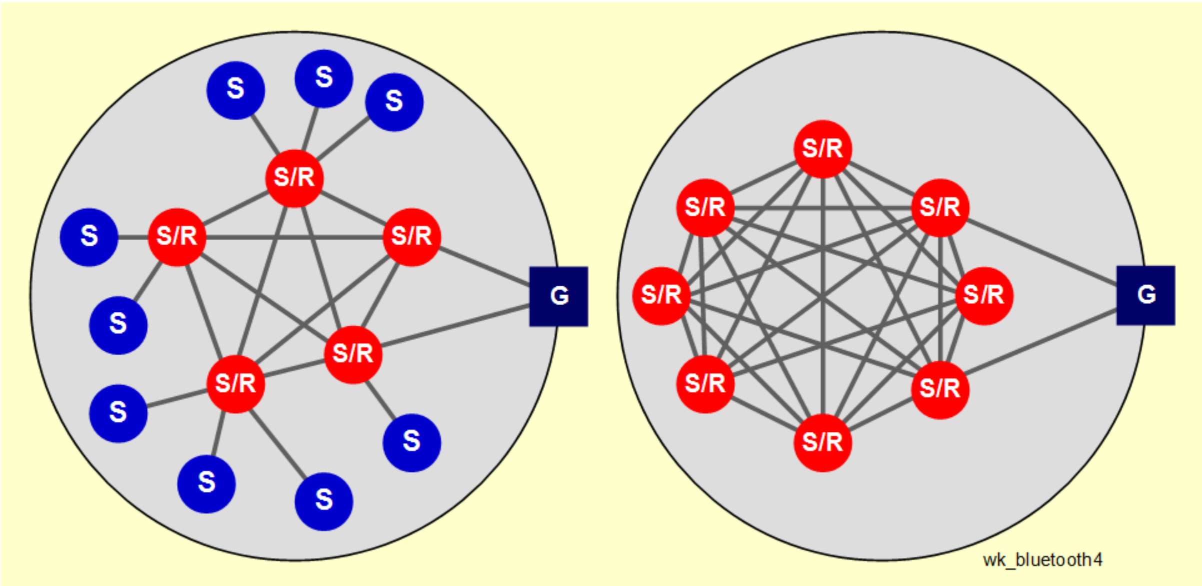

Fig. 4.3.6.4.3-2: Partial Mesh (left) and Full Mesh (right)
(S: Sensor node, S/R: Sensor node with *Relay* function, G: Gateway)

Sensor nodes pick up data values and forward them to sensor nodes with relay function. Sensor nodes with relay function can both record data values themselves and forward the data received from other sensor nodes in the network, enabling larger network dimensions (Repeater function). Gateways transfer data from the local network to another network, e.g. from the Bluetooth network to the WiFi or the Internet.

4.3.6.4.3.3 Broadcast Topology

Finally, Bluetooth LE audio technology enables the creation of a broadcast network topology. One transmitter sends data to multiple receivers simultaneously.

For broadcast operation, Bluetooth uses the advertising channels.

4.3.6.5 Wireless USB networks

Wireless USB networks serve as a cable substitute for connecting keyboards, computer mice or printers to computers.

The networks use the ISM band. Like Bluetooth Classic, the ISM band is divided into 79 channels, each with 1 MHz bandwidth, for use. The connected devices operate in a frequency-agile manner, i.e. they do not use a fixed transmission channel. If the transmission quality is poor, the devices change channels dynamically.
DSSS (Direct Sequence Spread Spectrum) technology is used for signal spreading.

4.3.6.6 IEEE 802.11 networks

IEEE 802.11 networks (WiFi: Wireless Fidelity) enable computers, communication devices (smartphones, ...), and peripherals (printers, ...) to be connected wirelessly to the Internet.
WiFi technologies on the IEEE 802.11 standard are originally based on the wired Ethernet standard (IEEE 802.3). This means that Ethernet and WiFi networks are compatible with each other.

IEEE 802.11 networks operate in the ISM frequency band on three different channels.

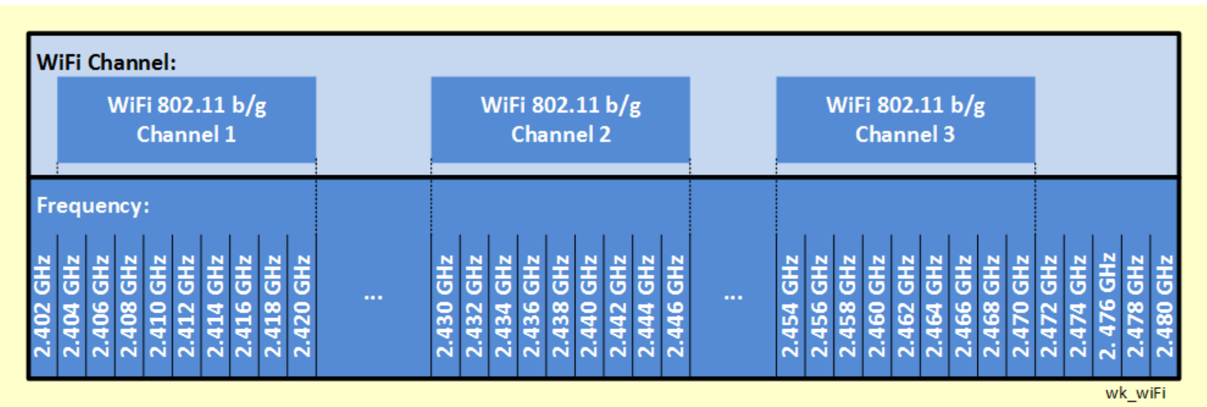

Fig. 4.3.6.5-1: WiFi channels in the ISM band in relation to Bluetooth LE center frequencies

In addition, three frequency bands are available in the 5 GHz band with channels of 20 MHz bandwidth each (lower and upper channel: 30 MHz):

Frequency Band	Bandwidth	Max. Transmitting Power
5.15 - 5.25 GHz	20 MHz (30 MHz)	23 dBm
5.25 - 5.35 GHz	20 MHz (30 MHz)	23 dBm
5.47 - 5.725 GHz	20 MHz (30 MHz)	30 dBm

Exercises

E.4.3.6.6-1: 5-GHz-Band

a) Compare the free space attenuation at a distance of 1000 m in the case of the ISM band and the 5 GHz band. How great is the difference?

b) How significant is the difference in the necessary transmitting powers in the two frequency bands under the same conditions?

4.3.6.7 ZigBee Standard

The ZigBee standard (IEEE 802.15.4) represents a WPAN wireless technology for solving control and monitoring tasks and for networking intelligent sensors (industry and automation technology, home and building automation, shipping and logistics, medical technology, computer peripherals).

Zigbee operates in the ISM band and in the 868 MHz band. In the ISM band, 16 channels and a data rate of 250 kbps are provided. In the 868 MHz band, one channel provides the data rate of 20 kBit/s. ZigBee is capable of detecting and avoiding channels already occupied by other systems.

The transmission power is 1-10 milliwatts. The maximum range is specified as 100 m.

The mesh topology and tree topology are available as network topologies.

4.3.6.8 IrDA Network

In the infrared spectral range, IRDA technology (IRDA: Infrared Data Association) is available for setting up a WPAN network. The (further) development and standardization is carried out by an industry consortium (Infrared Data Association).

The radio wavelengths used are in the infrared spectral range between 700 nm and 1050 nm. Data rates of 2.4 kBit/s to 1 GBit/s are provided in various specifications.

The maximum distance between data stations is one meter. A line-of-sight connection between transmitter and receiver is necessary.

4.3.6.9 *LiFi* Communication Network

LiFi (Light Fidelity) is a novel wireless communication technology using radiation in the visible spectral range (Visible Light Communication (VLC)).

Pulsed high-power LEDs serve as light sources. The fast pulse sequences cannot be resolved by the human eye.
Bidirectional data rates of up to 3 GBit/s are currently possible. Latency times are low at less than two milliseconds.
LiFi networks can be integrated directly into Ethernet networks via universal RJ45 Ethernet interfaces.

The technology promises fast, reliable and secure communication.

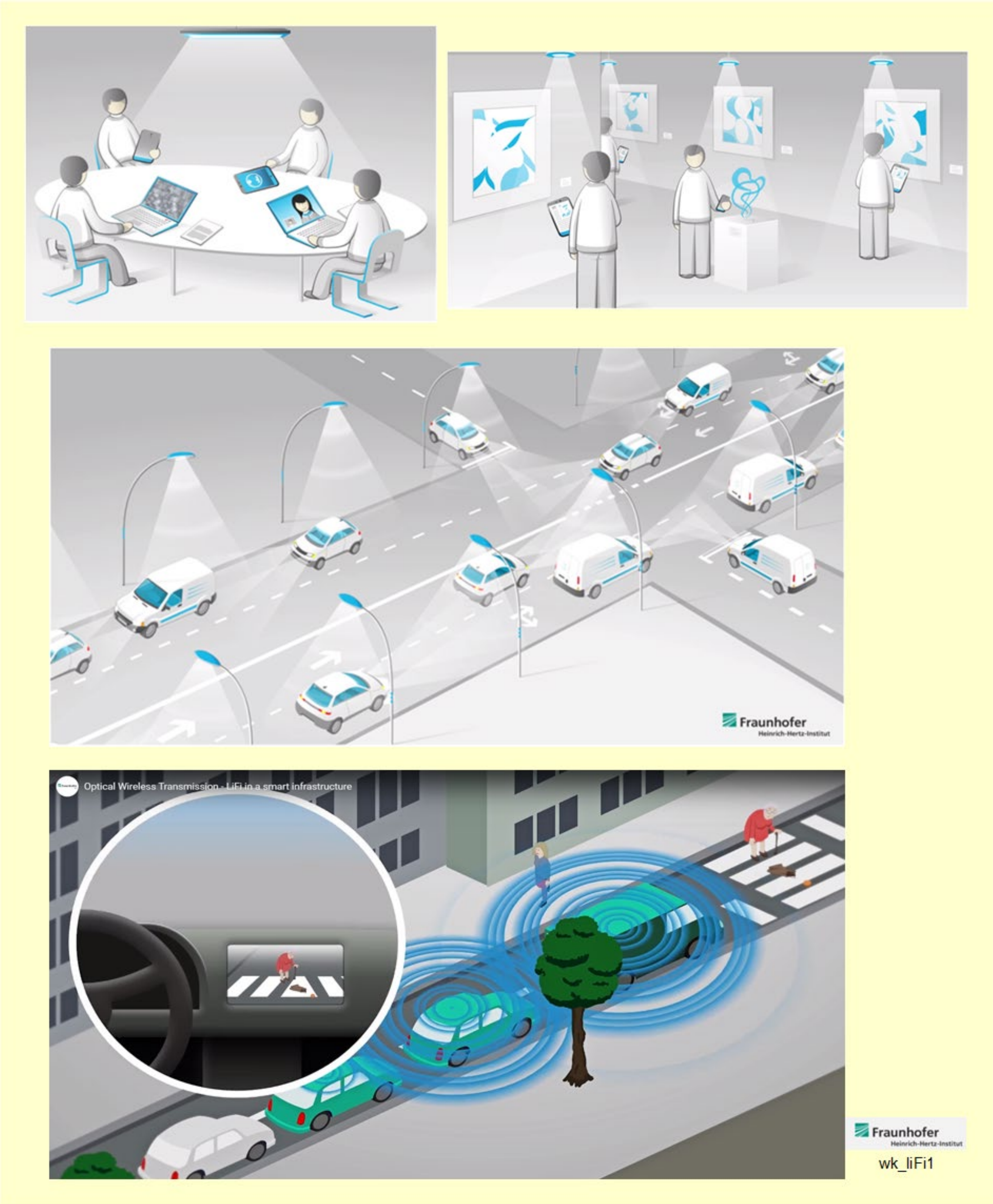

Fig. 4.3.6.9-1: LiFi applications in industrial pre-production

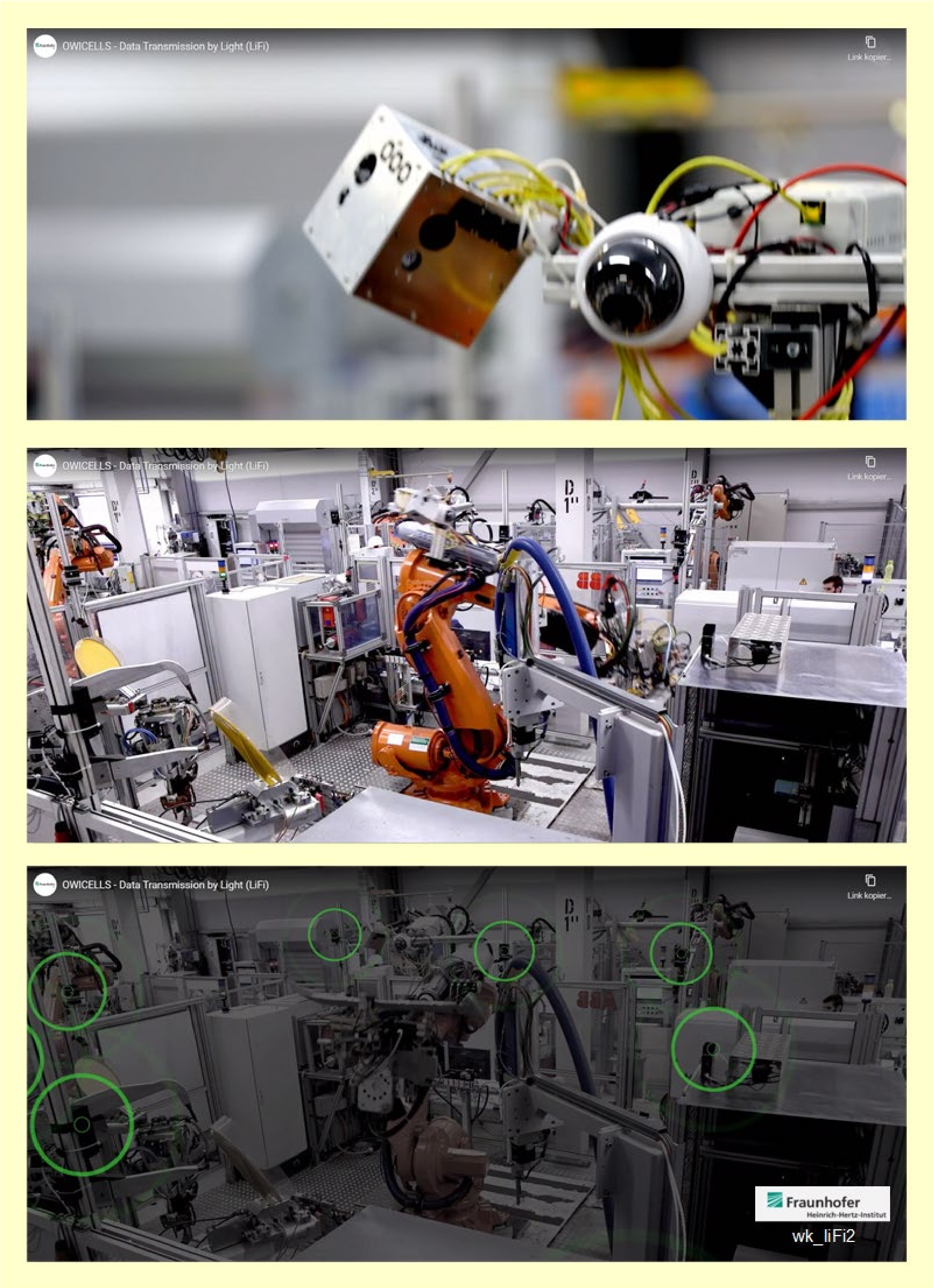

Fig. 4.3.6.9-2: LiFi test setup with robots in industrial automotive production

4.3.6.10 Wireless relay for remote data transmission

In the field of long-distance data transmission directional antennas (f < 1 GHz: Dipole arrays; f $\geq$ 1 GHz: beamforming parabolic antennas with lobe widths 1° ... 2.5° and antenna gains of 35 ... 43 dB) allow the establishment of point-to-point links (earth-earth, earth-satellite in earth orbit).
At frequencies above 1 GHz, industrial and atmospheric interference as well as cosmic noise are negligible.
For wave propagation, refraction effects due to varying refractive indices of the atmosphere and scattering effects due to temporally fluctuating turbulence in the troposphere must be taken into account.
In the f $\leq$ 10 GHz frequency range, wireless field lengths of about 50 km are common. Above the frequency f $\approx$ 10 GHz, resonance absorption in oxygen, water vapor, rain, snow and fog become dominant, shortening the possible radio field lengths and necessitating the use of additional relay stations (13 GHz: 25 km; 20 GHz: 10 km; 30 GHz: 5 km).

Fig. 4.3.6.10-1: Satellite ground station Fuchsstadt near Hammelburg

4.3.6.11 Interplanetary communication networks

Increasingly, robotic missions are taking place on planets in the solar system, especially Mars. Interplanetary wireless communications are usually carried out in the X-band (λ: 2.4 - 4.5 cm).

The U.S. space agency NASA uses the Deep Space Network (DSN) for communications, with 34 m and 70 m diameter parabolic antennas in California, Spain, and Australia.

In direct Earth connection, the data rate to the robot on Mars varies between 500 bit/s and 32 kbit/s. The Mars Reconnaissance Orbiter enables data rates of up to 2 Mbit/s.

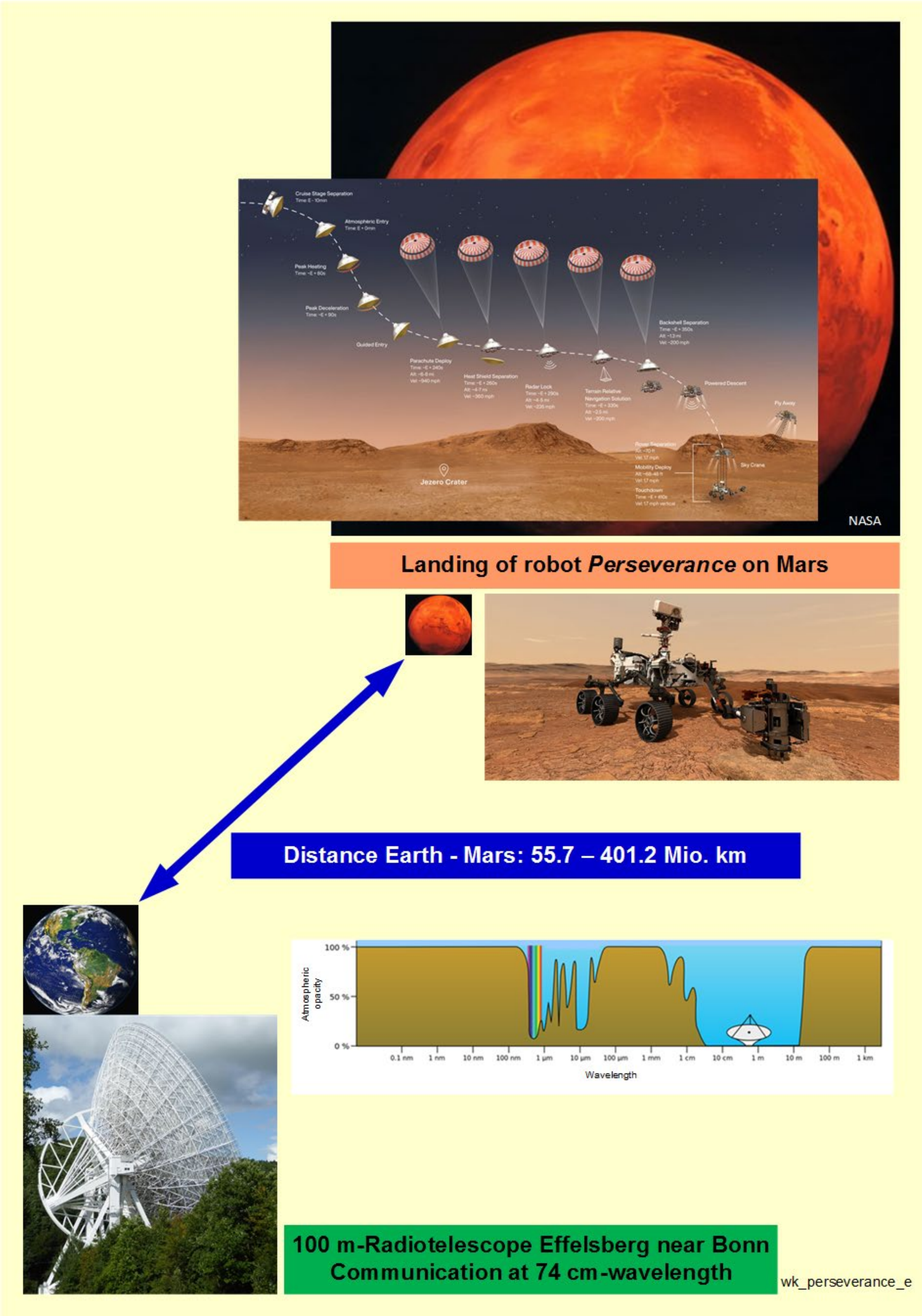

Fig. 4.3.6.11-1: Communication between the Earth (100 m-radio telescope of the Max-Planck Institute for Astrophysics, Effelsberg) and the robot Perseverance on Mars during its landing on February 18, 2021

4.4 Basics of digital information transmission

In 1924, the Swedish-American electrical engineer Harry Nyquist formulated the fundamental theorem named after him for the limit of the **maximum transmittable data rate in a noise-free transmission channel**:

- If an arbitrary signal is limited during transmission by a low-pass filter of bandwidth B, the filtered signal can be reconstructed in the noise-free case by sampling at least 2B values per second.

- The twofold sampling interval $2t_s$ must be less than or equal to the time corresponding to the maximum frequency occurring in the signal or the cutoff frequency f_G of the lowpass filter for unambiguous reconstruction:

  $$2t_S \le \frac{1}{f_G}$$

  Special case: $f_G = \frac{1}{2t_S}$: **Nyquist frequency**

- Sampling at a higher frequency is not necessary due to the bandwidth limitation. In this case, however, noise suppression can be applied.

- The maximum data rate is

  $$\text{maximumDataRate} = 2B \cdot \log_2 n \ \frac{\text{bit}}{\text{s}}$$ **Nyquist theorem**

  with B: bandwidth, n: number of quantization levels.

In 1948, the American mathematician and electrical engineer Claude E. Shannon extended the theory for transmission under the condition of thermal white noise. Accordingly, the following applies to the **maximum data rate in a noisy channel**

$$\text{maximumDataRate} = B \cdot \log_2\left(1 + \frac{S}{N}\right) \frac{\text{bit}}{\text{s}}$$

with B: bandwidth, S: signal power, N: noise power.

The signal-to-noise ratio L, a quality factor for evaluating the transmission medium, is often defined in practice according to the following logarithmic relationship:

$$L/\text{dB} = 10 \cdot \log_{10} \frac{S}{N} \ .$$

In order to transmit a given amount of messages per time unit t, the mutual exchange of signal-to-noise ratio S/N and bandwidth B is possible. Error-free transmission becomes feasible even with a low signal-to-noise ratio if the bandwidth is selected to be sufficiently large:

$$B \cdot \frac{S}{N} \cdot t = \text{const.}$$

This fact can be graphically visualized by the example of the "information box with constant volume" (according to C.E. Shannon):

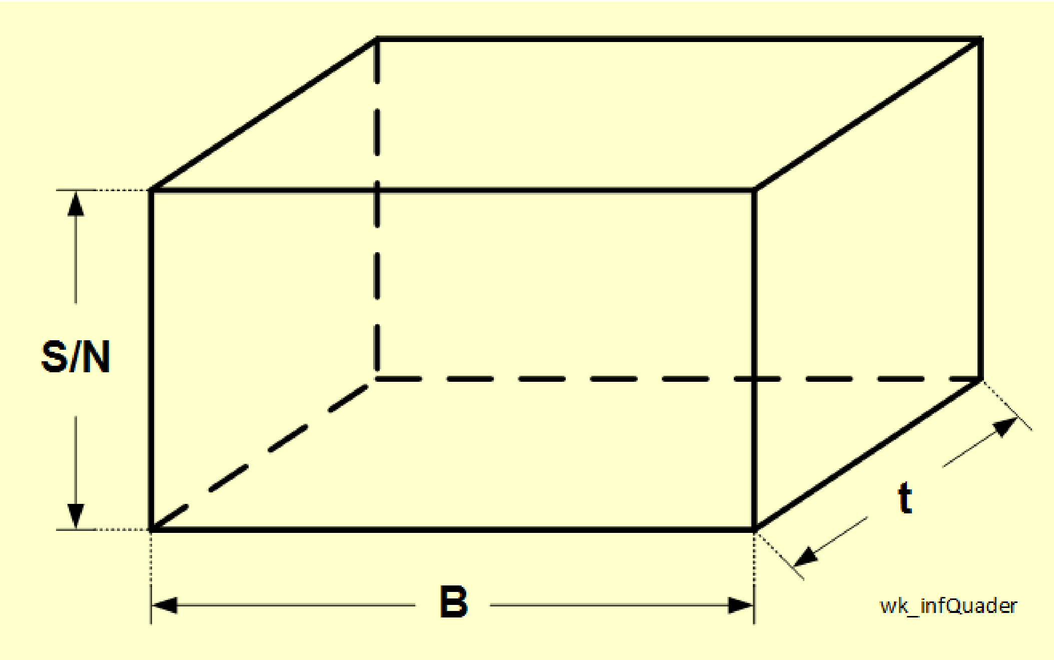

Fig. 4.4-1: Information box according to C.E. Shannon

Exercises

E.4.4-1: Maximum data rate

a) The analog telephone network operated with the frequency band 300 Hz … 3400 Hz.
Estimate the maximum data rate for binary coding in an ideal, noise-free environment.

b) What would be the maximum data rate in a Bluetooth Classic network, if noise-free data transmission could be realized?

c) In a 1-Gbit Ethernet network, a maximum data rate of 117 MByte/s is measured. What is the theoretical signal-to-noise ratio?

4.5 Pulse code modulation

In digital data transmission, pulse code modulation (PCM) dominates as part of the transmission technology. Several processing steps are run through:

- Bandwidth limiting of the original signal by low-pass filtering,
- Temporal sampling in equidistant time intervals,
- Quantization of the sampled values with the aid of a linear or non-linear characteristic,
- Coding: representation of the quantized values by a bit sequence.

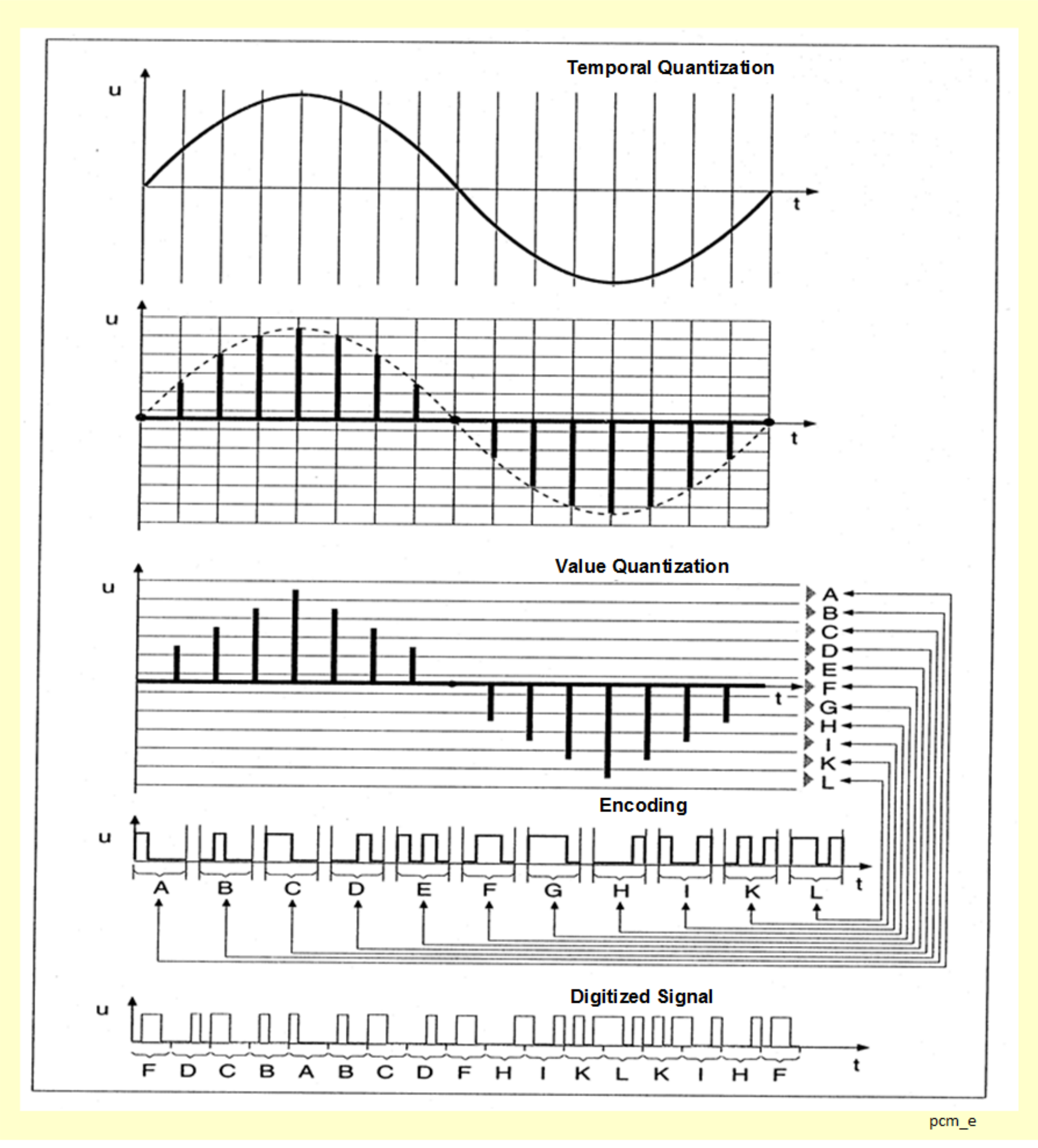

Fig. 4.5-1: Step sequence for pulse code modulation / FREY1997 modified/

4.6 Transmission channel encoding

4.6.1 Code elements, velocities und channel codes

Digital transmission systems usually work with two logical states:

- logical zero („0“), *Low* level (L),
- logical one („1“), *High* level (H).

The smallest unit of a digital signal is called a **code element**:

- two-level code element: binary code element (bit),
- three-level code element: ternary code element,
- four-level code element: quaternary code element (corresponds to two-bit group).

The speed of data transmission in data networks is characterized by two characteristic "speeds":

- **Step rate v_s, Baud rate:**

  $v_s = \frac{1}{T}$ with T: duration of one code element, step duration
  $[v_s]$ = 1 Baud,

- **Transfer speed v_{bit}, equivalent bitrate, channel capacity:**

  $v_{bit} = v_s \mathrm{ld}(n)$ with n: number of discrete code states of a code element
  $[v_{bit}]$ = 1 bit/s.

In the case of binary code elements, the step rate (baud rate) and bit rate match.

Various requirements are placed on the channel codes:

- Use of code elements with as many identification states as possible to increase information throughput for a given bandwidth,

  problems:
  - increasing requirements on signal/noise ratio,
  - necessary increased transmitting power increases interference radiation and EMC problems,

- Absence of direct current due to galvanically decoupled stations in baseband transmission,

- Clock recovery for signal analysis on the receiver side.

The following overview shows a compilation of different line codes:

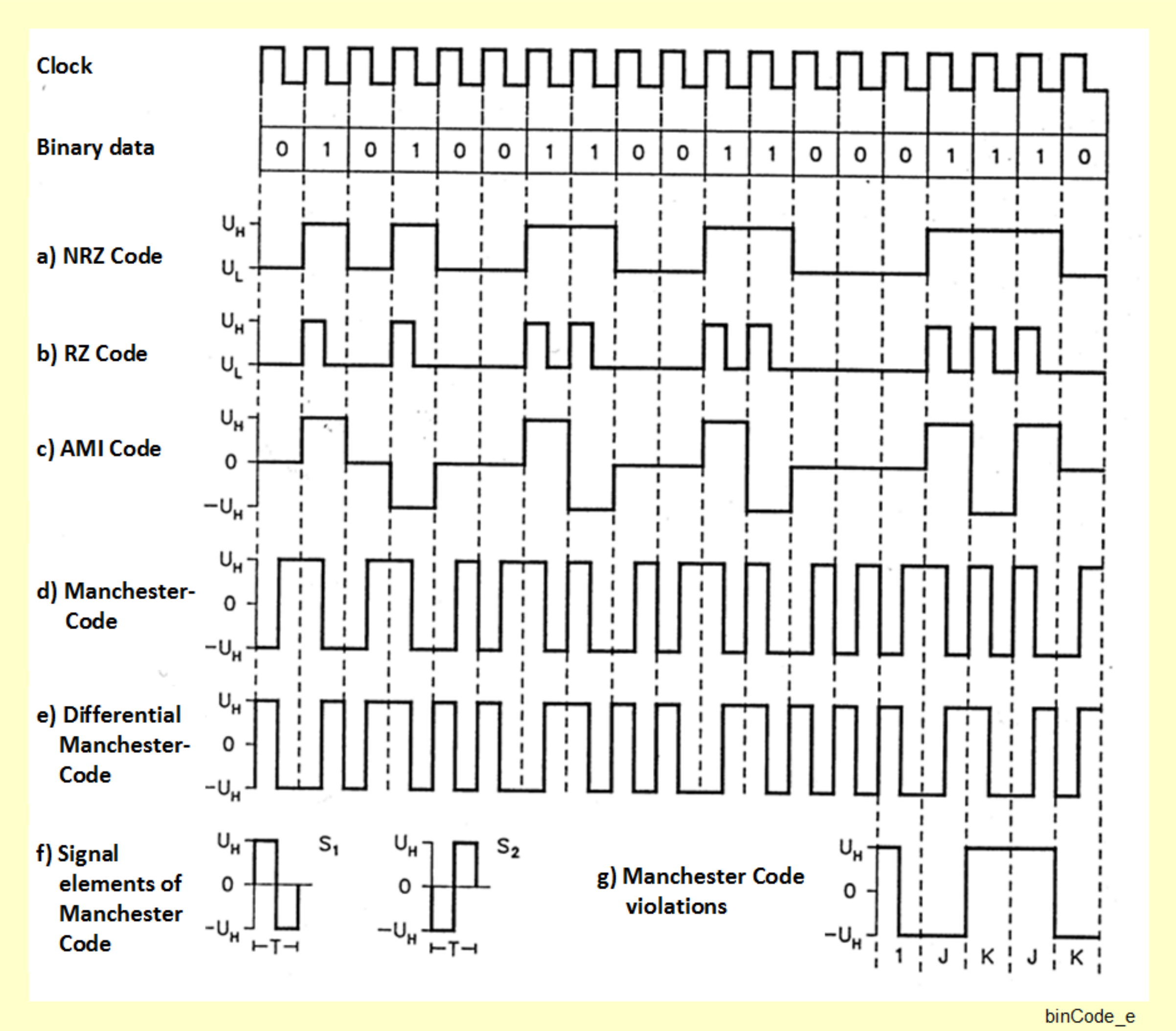

Fig. 4.6.3.1-1: Coding methods for digital signal transmission /CONR1996 modified/

Characteristic properties of channel codes:

- **NRZ Code (Non Return To Zero):**
  - Encoding rule : ‚0' = U_L
    ‚1' = U_H,
  - Pulse duration of the square pulses corresponds to the step duration,
  - not DC free,
  - no clock recovery possible,

- **NRZI Code (Non Return To Zero Inverted):**
  - Encoding rule: ‚0' = U_H
    ‚1' = U_L,
  - Pulse duration of the square pulses corresponds to the step duration,
  - not DC free,
  - no clock recovery possible,

- **RZ Code (Return to Zero):**
  - Encoding rule: ‚0' = U_L
    ‚1' = U_H,
  - Pulse duration of the square pulses corresponds to half the step duration,
  - not DC free,
  - 1' sequences transmit clock, '0' sequences do not,
  - no clock recovery possible,

- **AMI Code (Alternate Mark Inversion), Bipolar Code:**
  - pseudoternary code:
  - three different signal states for the representation of two discrete values,
  - direct current free,
  - ‚1' sequences transmi clock, ‚0' sequences do not,
  - no clock recovery possible,
  - application in modified form: S_0 interface of ISDN,

- **Manchester Code (Manchester II):**
  - Composition of two signal elements shifted by 180°:
    Element S1: ‚1' = $+U_H$ -> $-U_H$ after T/2,
    Element S2: ‚0' = $-U_H$ -> $+U_H$ after T/2,
  - direct current free,
  - clock recovery possible,
  - higher bandwidth required for transmission, since clock frequency corresponds to twice the stepping speed,
  - use in local area networks (LANs),

- **Differential Manchester Code:**
  - same signal elements as for the Manchester code,
  - Encoding rules: ‚0' = polarity change at the beginning of the step,
    ‚1' = no polarity change at the beginning of the step .

4.6.2 Comparison of human and machine channel capacity

The channel capacity is a measure of the transmission rate of information via an information channel. It corresponds to the maximum bit rate at which information can just be sent error-free over a transmission channel.

The channel capacity in humans when perceiving or delivering information depends on the activity and is very limited:

Activity	Human channel capacity [bit/s]
Reading	18 – 45
Writing with keyboard	16
Playing piano	23
Calculating	12
Counting	12

The table below shows the maximum transmission speeds (channel capacity, bit rate, data rate) of some technical information systems.

Technical system	Channel capacity, Bit rate [bit/s]
Telefon (V.21 Standard)	300 bit/s
RS-232	20 kbit/s
RS-485	10 Mbit/s
I^2C	0.1 / 0.4 / 1.0 /3.4 MBit/s
Datex-P	2.4 - 64 kbit/s
ISDN	2 Mbit/s bei Primärmultiplexanschluss
CD-ROM	7.2 Mbit/s
Audio-CD	1.411 Mbit/s (44.1 kHz Abtastrate, 16 Bit, 2 Kanäle)
Ethernet	10 Mbit/s
Fast-Ethernet	100 Mbit/s
Gigabit-Ethernet	100 Gbit/s
Terabit-Ethernet	400 Gbit/s
SCSI	40 Mbit/s – 2.5 GBit/s
USB 2.0	480 MBit/s
USB 3.0	5 Gbit/s (Bruttorate mit 8b10b-Kodierung)
LTE	
Downlink	3 Gbit/s
Uplink	1.5 Gbit/s
GSM	9.6 kbit/s
IrDA 1.0 (Infrarot-Schnittstelle)	9.6 kbit/s – 115 kbit/s
IrDA 1.1	4 Mbit/s
IrDA 1.3	16 Mbit/s
GPRS	53.6 kbit/s (theoret. bis 171.2 Mbit/s)
DECT	ca. 800 kbit/s
UMTS	384 kbit/s
Bluetooth 2.0+EDR	2.1 Mbit/s
Bluetooth 3.0 + HS	24 Mbit/s
WLAN	1 – 1300 Mbit/s
ZigBee	250 kbit/s
HD-Video (720 p, 60 Hz, 24 b/px, unkomprimiert)	ca. 1.3 Gbit/s
Full-HD-Video (1080 p, 60 Hz, 24 b(px, unkomprimiert)	ca. 3 Gbit/s
Fibre Channel	2, 4, 8, 16, 20 Gbit/s
5G-Netzwerke	10 – 50 Gbit/s (wird erwartet).

Exercise

E.4.6-1: Optimization of an information transmission system

An information transmission system has c parallel transmission channels.
Each channel can transmit b states (code elements).
Let the cost of transmission be proportional to the number of transmission channels and proportional to the number of states per channel.

Assuming fixed, constant costs, how should the number of states be chosen to maximize the number of numbers (values) that can be represented?

4.7 Operating modes

Three basic operating modes are distinguished in the operation of data networks:

- **Simplex operation (directional operation):**
  - unidirectional signal transmission,
  - no possibility for the receiver to send signals back to the transmitter,
  - examples: Broadcast communication: radio, television,

- **Half-duplex operation (alternating operation):**
  - alternating bidirectional message transmission,
  - communication partners can act alternately as sender and as receiver,
  - possibility of dialog,
  - both sides have transmitting and receiving equipment,
  - bidirectional transmission link is required,

- **Full duplex operation (two-way operation):**
  - possibility of simultaneous bidirectional data transmission,
  - communication partners can transmit and receive simultaneously,
  - both sides have independent transmitting and receiving facilities,
  - simultaneously bidirectionally usable transmission path is required.