Computer Networks

Chapter 3: Physical Layer

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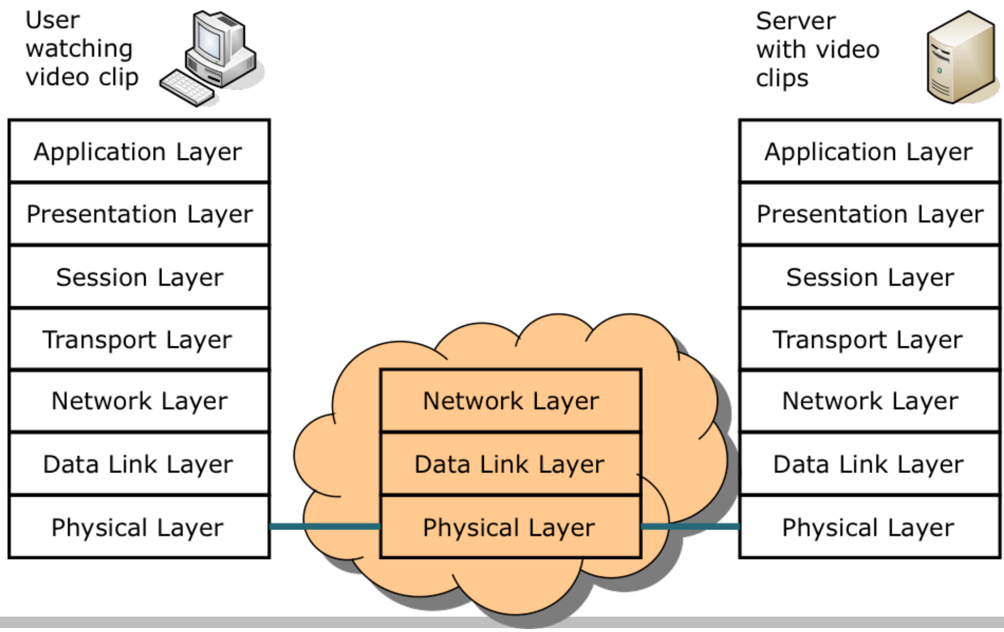


Contents

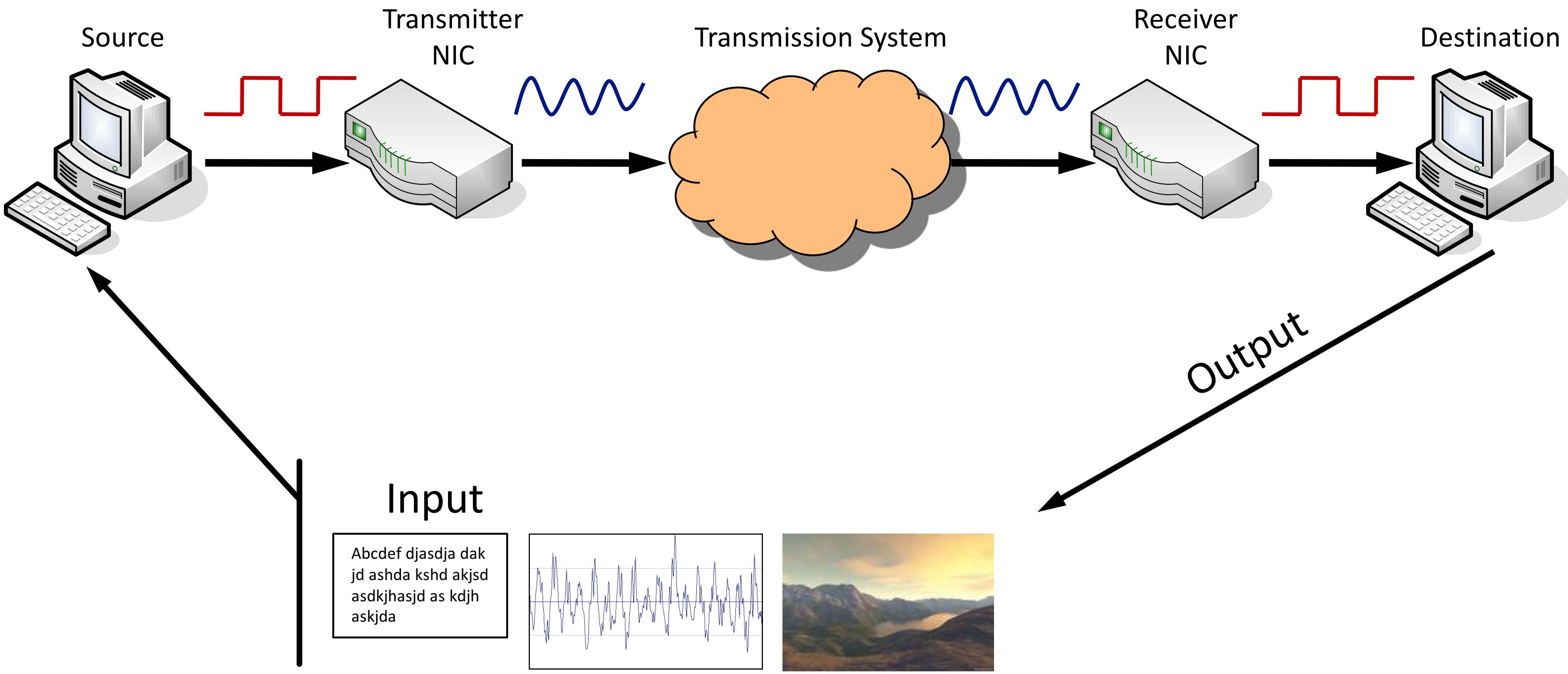
Design Issues

Design Issues

- **Connection parameters**
  - mechanical
  - electric and electronic
  - functional and procedural
- **More detailed:**
  - Physical transmission medium (Copper cable, optical fiber, radio, ...)
  - Pin usage in network connectors
  - Representation of raw bits (Code, voltage,…)
  - Data rate
  - Control of bit flow:
  - serial or parallel transmission of bits
  - synchronous or asynchronous transmission
  - simplex, half-duplex, or full-duplex transmission mode

OSI Reference Model
Application Layer
Presentation Layer
Session Layer
Transport Layer
Network Layer
Data Link Layer
Physical Layer

Design Issues



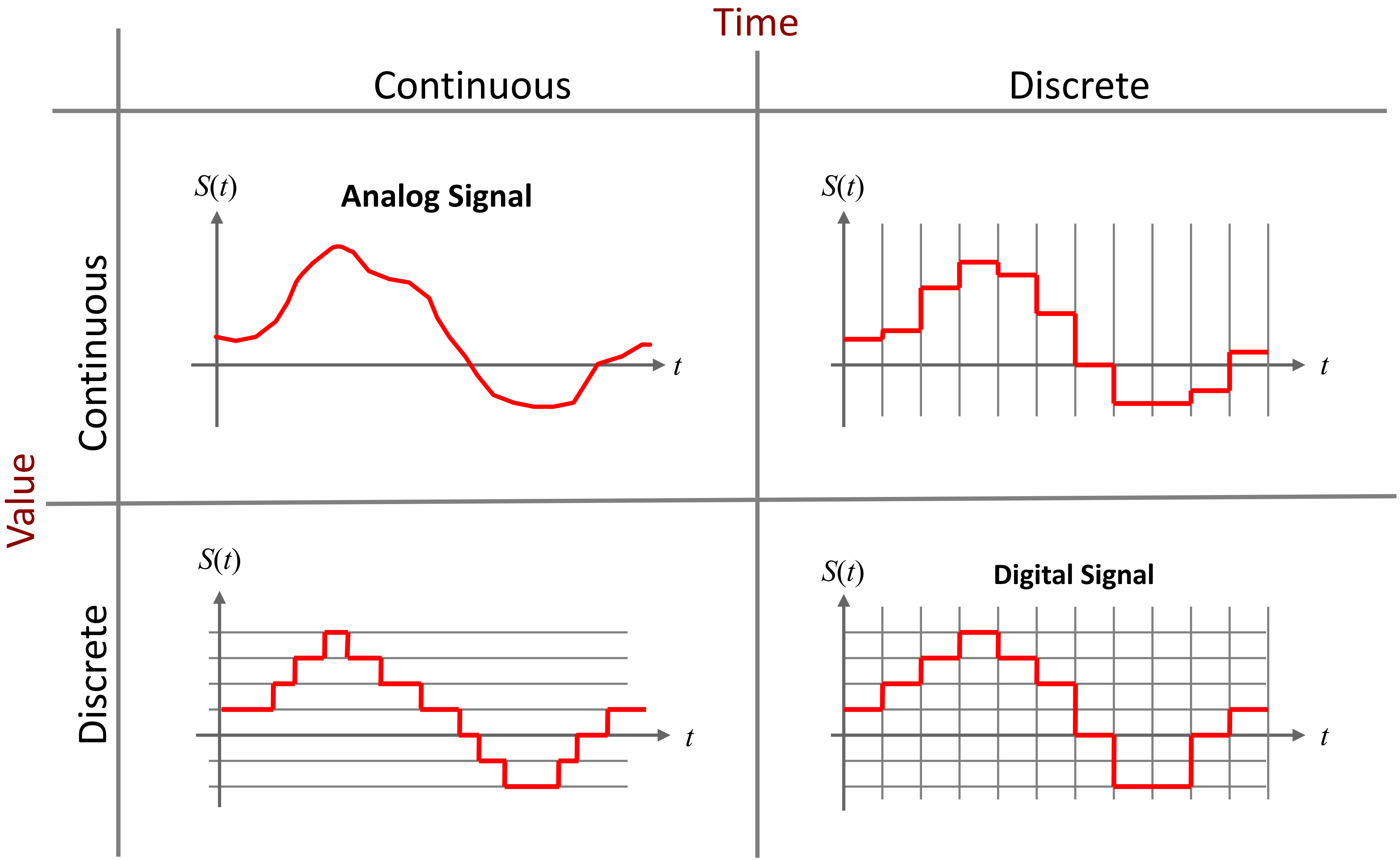
Theoretical Basis of Data Communication

Signal Parameters

- **Variable physical characteristic of a signal that represents data**
  - Spatial signals
    - The values are functions of the space, i.e., memory, space
  - Time signals
    - The values are functions of the time, i.e., $S = S(t)$

- **Classification of signals (based on time and value space)**
  - Continuous-time, continuous-valued signals
  - Discrete-time, continuous-valued signals
  - Continuous-time, discrete-valued signals
  - Discrete-time, discrete-valued signals

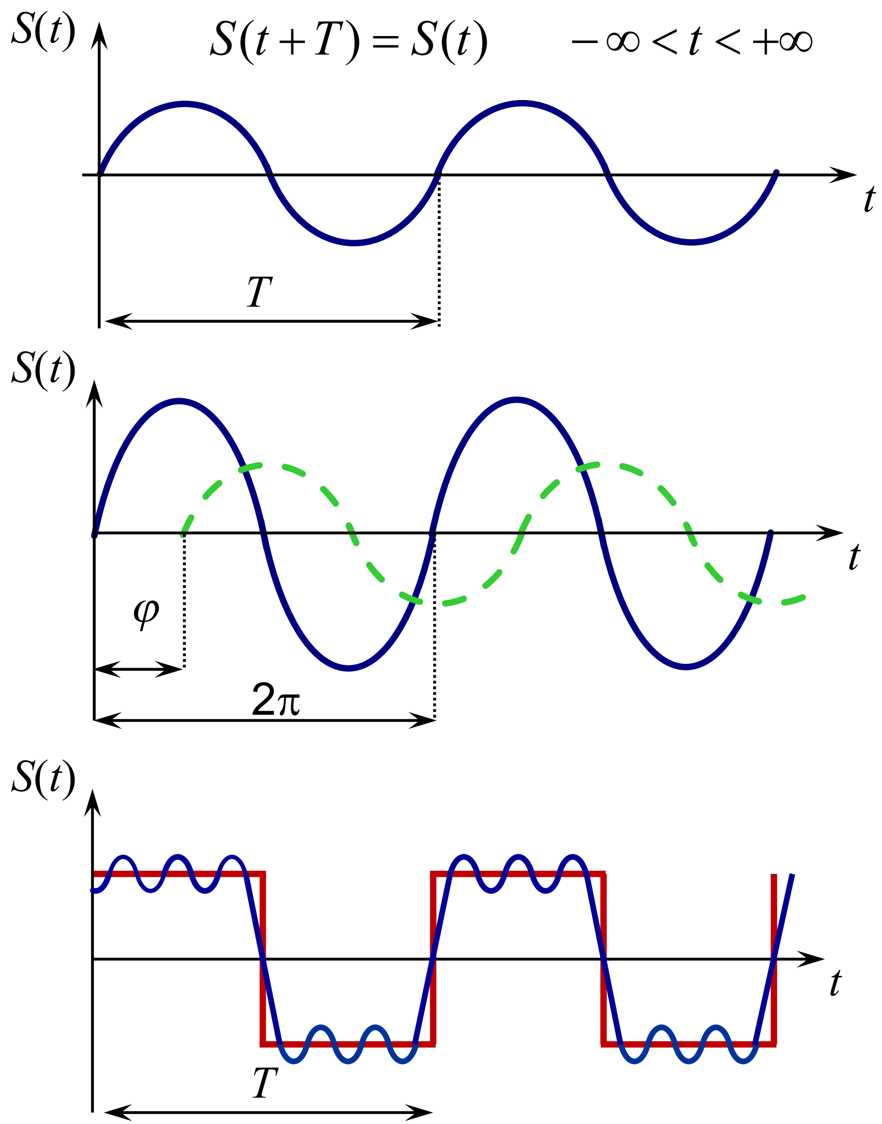
Types of Signals



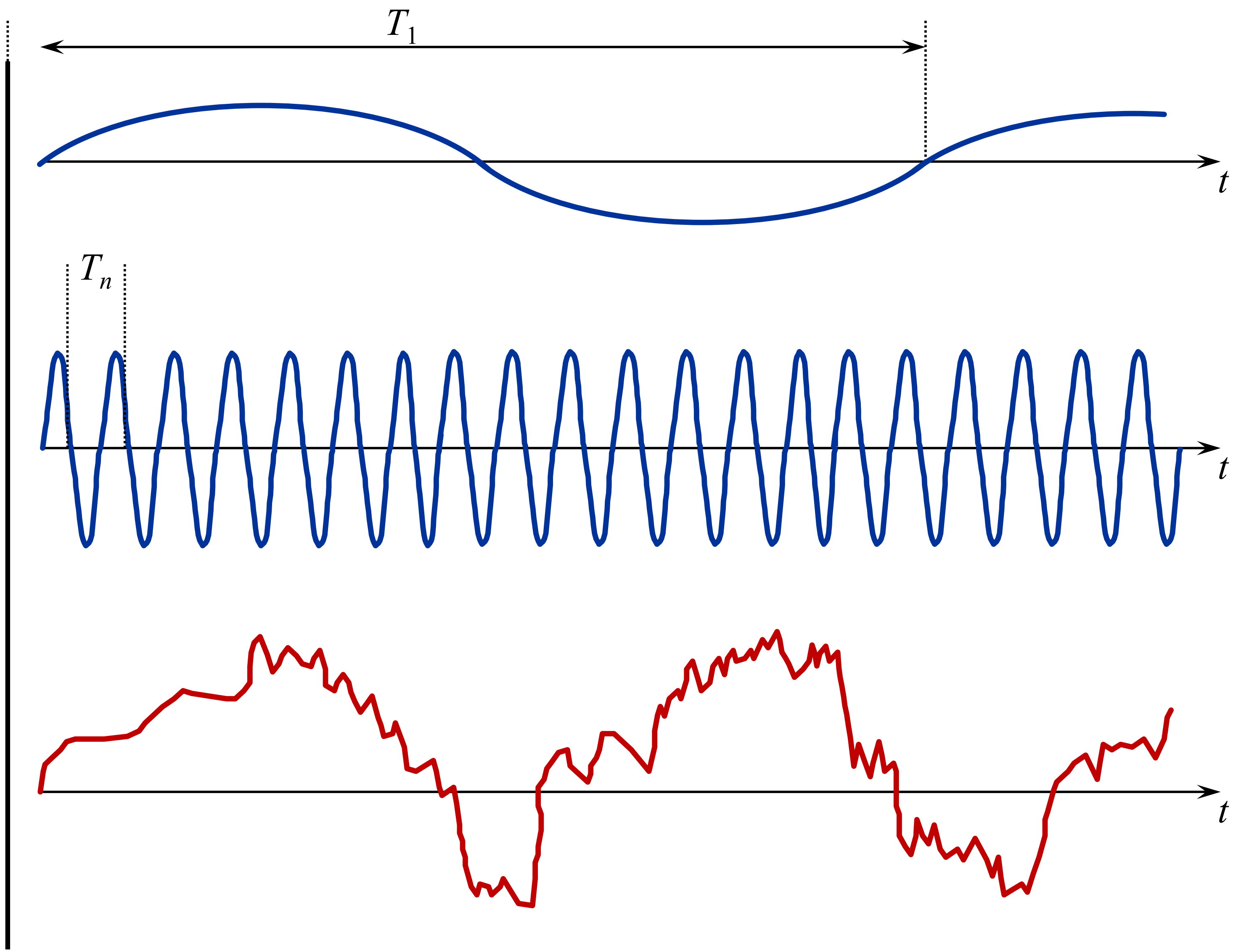
Periodic and Digital Signals

- **Periodic signals are the simplest signals**
- **Parameters of periodic signals**
  - Period T
  - Frequency $1/T$
  - Amplitude $S(t)$
  - Phase φ

- **Examples**
  - Sine wave
  - Phase difference φ
  - Square wave



Composite Signals



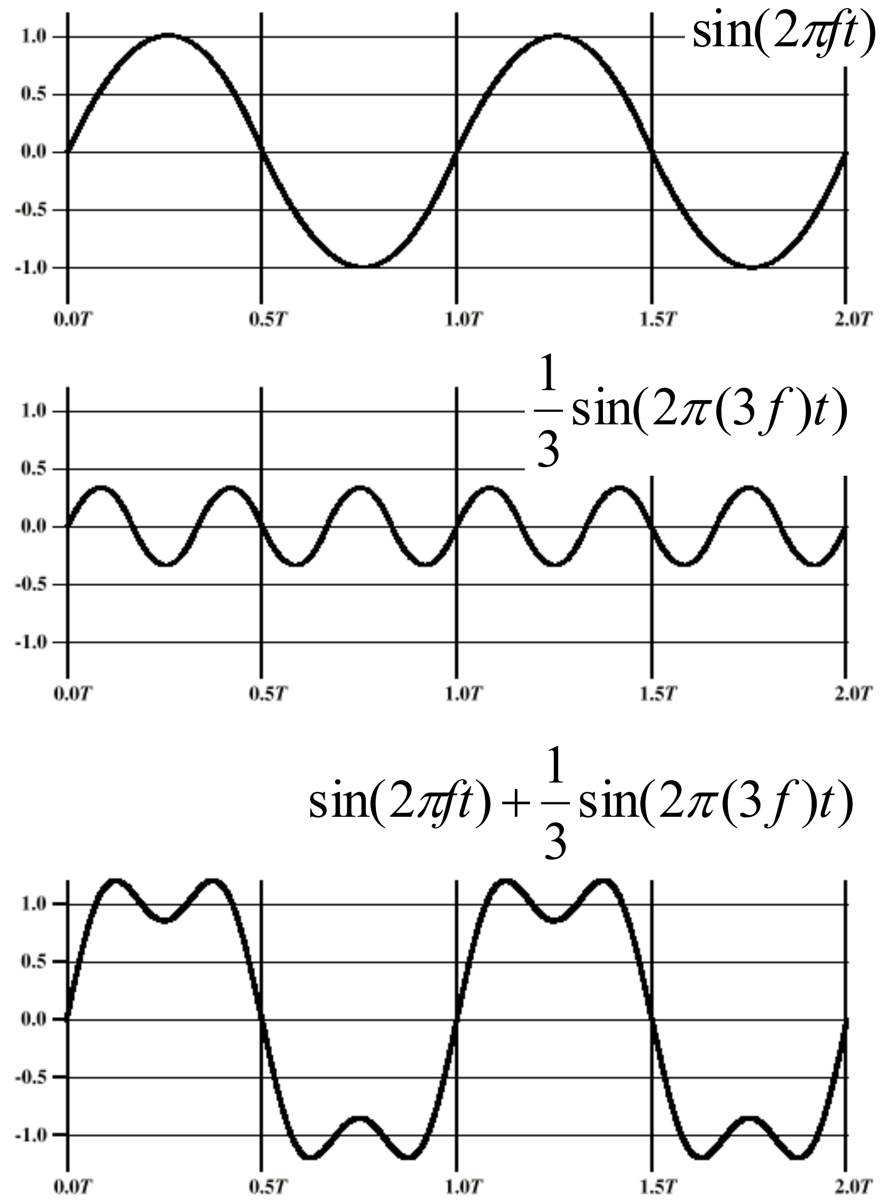
Component with low frequency (fix amplitude)

Component with high frequency (fix amplitude)

Composite voice signal with mixed frequencies and amplitudes.

Composite Signals

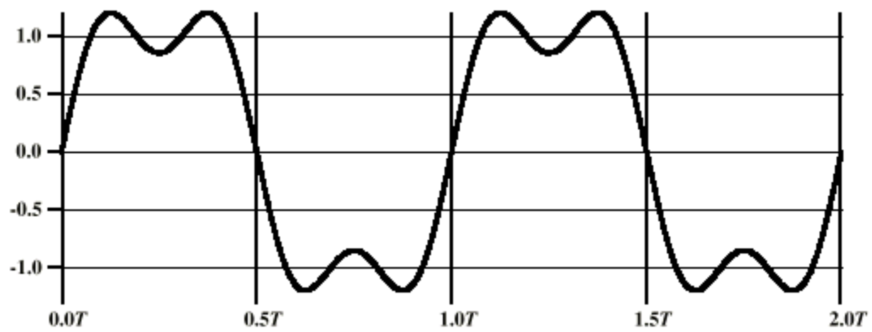
- **A signal is made up of many frequencies**
  - Example: $s(t) = \sin(2\pi ft) + \frac{1}{3}\sin(2\pi(3f)t)$
  - Components of the signal are sine waves of frequencies f and $3f$
- **Observations**
  - Second frequency is multiple of the first one, which is denoted **fundamental frequency**
  - The **period** of the composite signal is equal to the period of the fundamental frequency



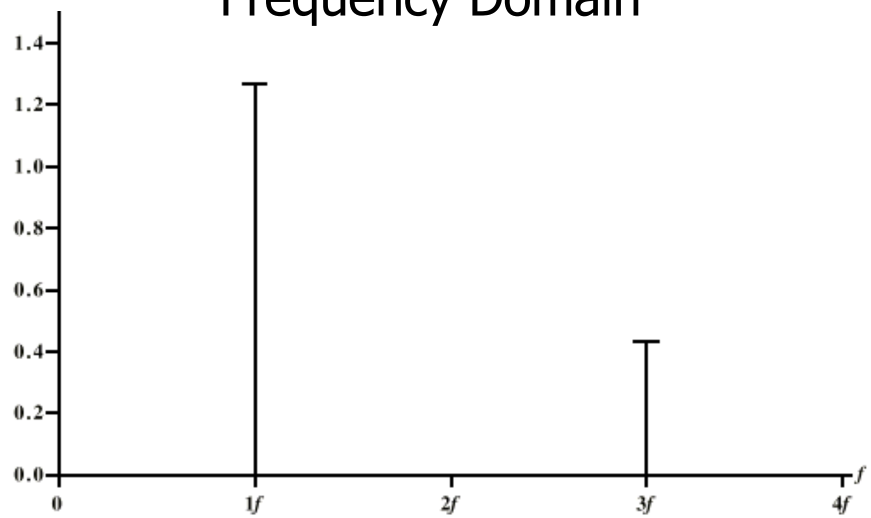
Composite Signals: Domain Concepts

- **Frequency Domain**
  - Specifies the constituent frequencies
  - **Spectrum** of a signal is the range of frequencies it contains
    - In the example from f to $3f$
  - The **absolute bandwidth** of the signal is the width of the spectrum
    - In the example $2f$
  - Many signals have infinite bandwidth
  - **Effective bandwidth**
    - Most energy is contained on a narrow band of frequencies

Time Domain



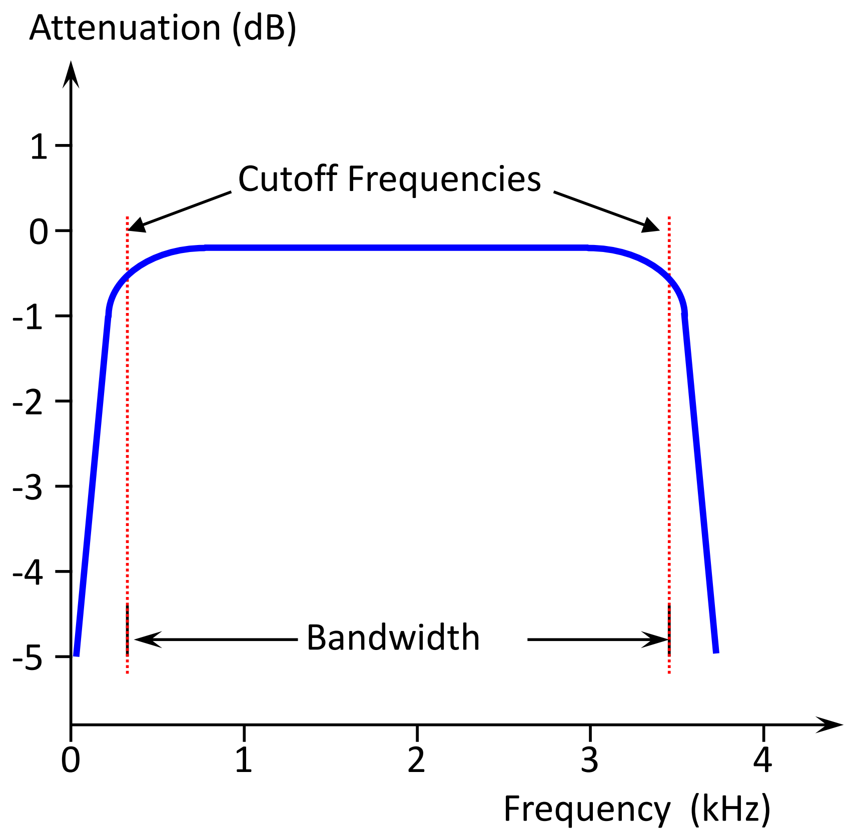
Frequency Domain



Composite Signals: Medium

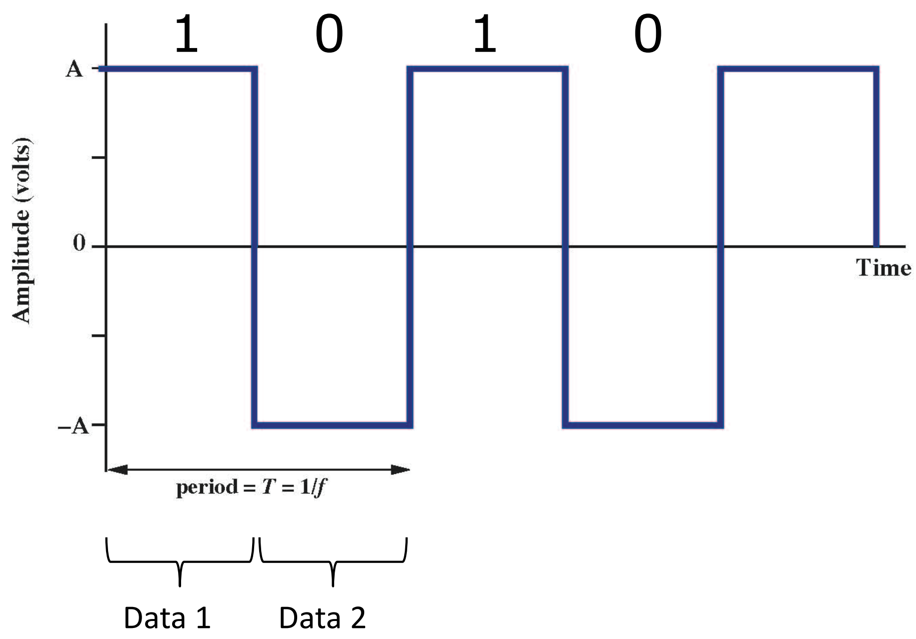
- **Bandwidth of a medium**
  - A medium transports always a limited frequency-band.

- **Bandwidth**
  - Bandwidth in Hz [1/s]
    - Frequency range which can be transmitted over a medium
  - Bandwidth is the difference of the highest and lowest frequency which can be transmitted
  - The cutoff is typically not sharp



Composite Signals

- **Relationship between data rate and bandwidth**
  - Square wave
    - positive pulse 1-bit
    - negative pulse 0-bit
  - Duration of a pulse is $\frac{1}{2}f$
  - Data rate is $2f$ bits per second

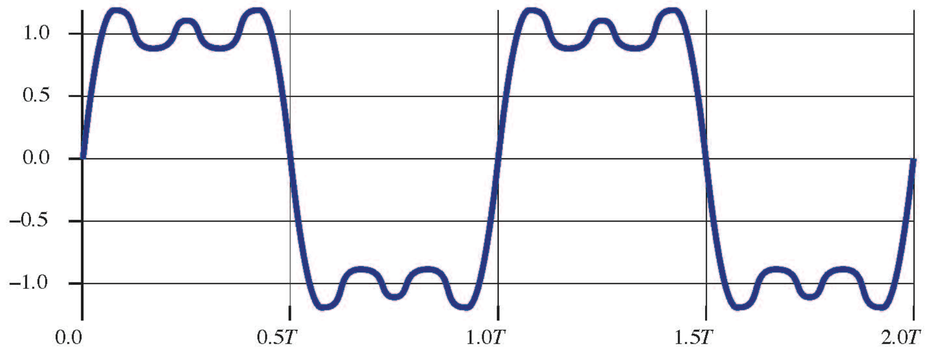


- **Question**
  - What are the frequency components?

Composite Signals

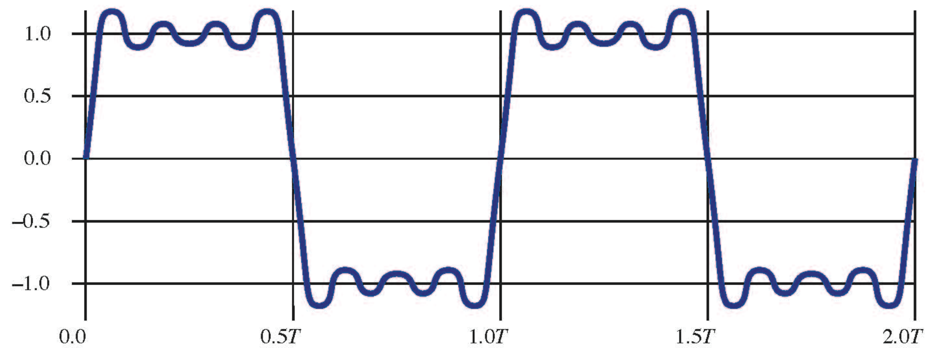
- **Relationship between data rate and bandwidth**
  - Signal made of: f, $3f$, and $5f$

$$\sin(2\pi ft)+\frac{1}{3}\sin(2\pi 3ft)+\frac{1}{5}\sin(2\pi 5ft)$$



  - Signal made of: f, $3f$, $5f$, $7f$

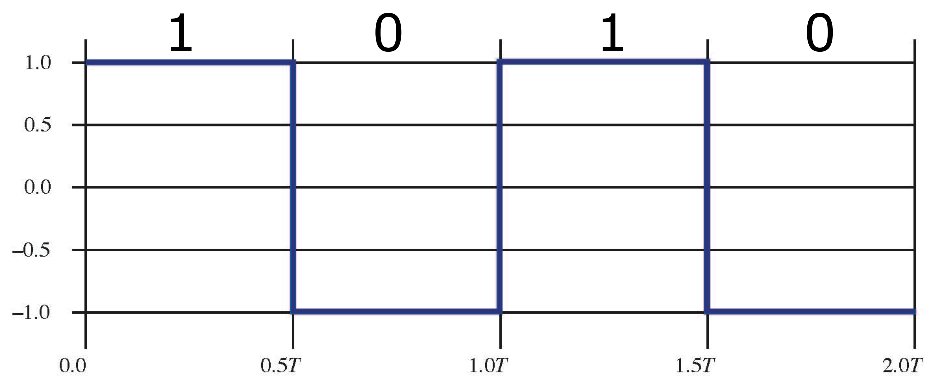
$$\sin(2\pi ft)+\frac{1}{3}\sin(2\pi 3ft)+\frac{1}{5}\sin(2\pi 5ft)+\frac{1}{7}\sin(2\pi 7ft)$$



  - Square waves can be expressed as

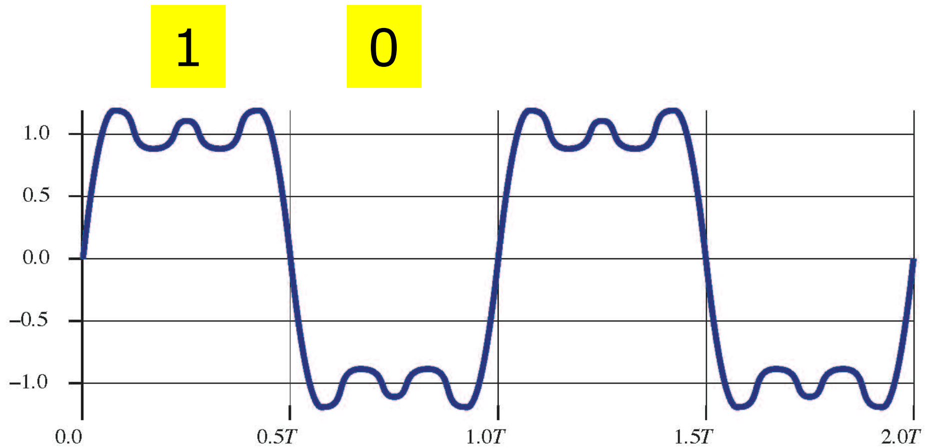
$$s(t)=A\times\frac{4}{\pi}\times\sum_{k=1,k\text{ odd}}^{\infty}\frac{1}{k}\sin(2\pi kft)$$

    - Infinite number of components
    - Amplitude of the k-th component is only $1/k$
  - What happens if k is limited?



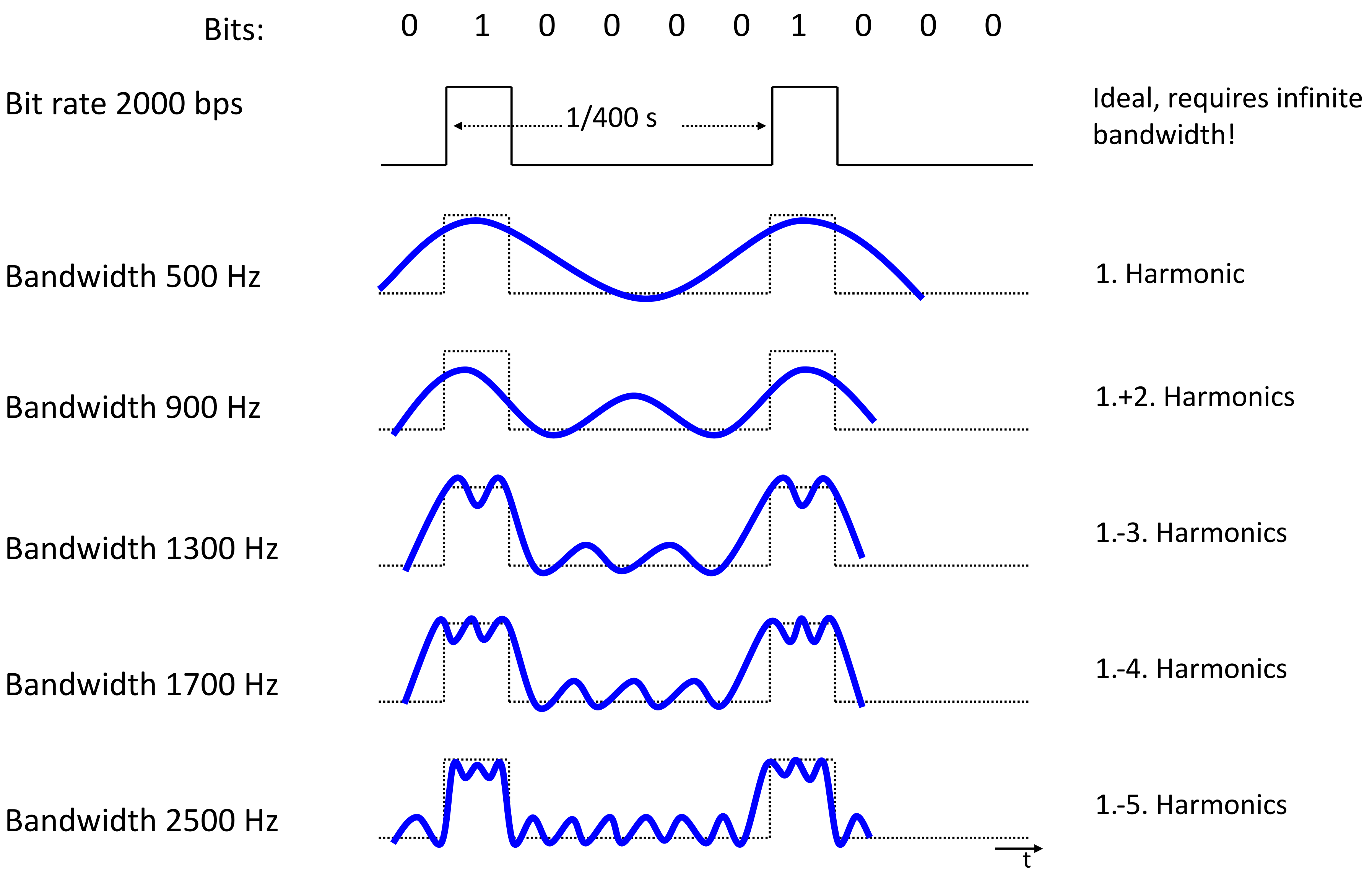
Composite Signals

- **Relationship between data rate and bandwidth**
- **Example 1**
  - $f = 10^6$ Hz = 1 MHz
    - The fundamental frequency
  - Bandwidth of the signal $s(t)$
    $(5 \cdot 10^6$ Hz$) - (1 \cdot 10^6$ Hz$) = 4$ MHz
  - $T = 1/f = 1/10^6 s = 10^{-6} s = 1 \mu s$
  - 1 bit occurs every $0.5 \mu s$
  - Data rate = 2 bit·10^6 Hz = 2 Mbps
- **Example 2**
  - f = 2 MHz
  - Bandwidth (5·2MHz) – (1·2MHz) = 8 MHz
  - $T = 1/f = 0.5\ \mu s$
  - 1 bit occurs every $0.25 \mu s$
  - Data rate = 2 bit · 2 MHz = 4 Mbps

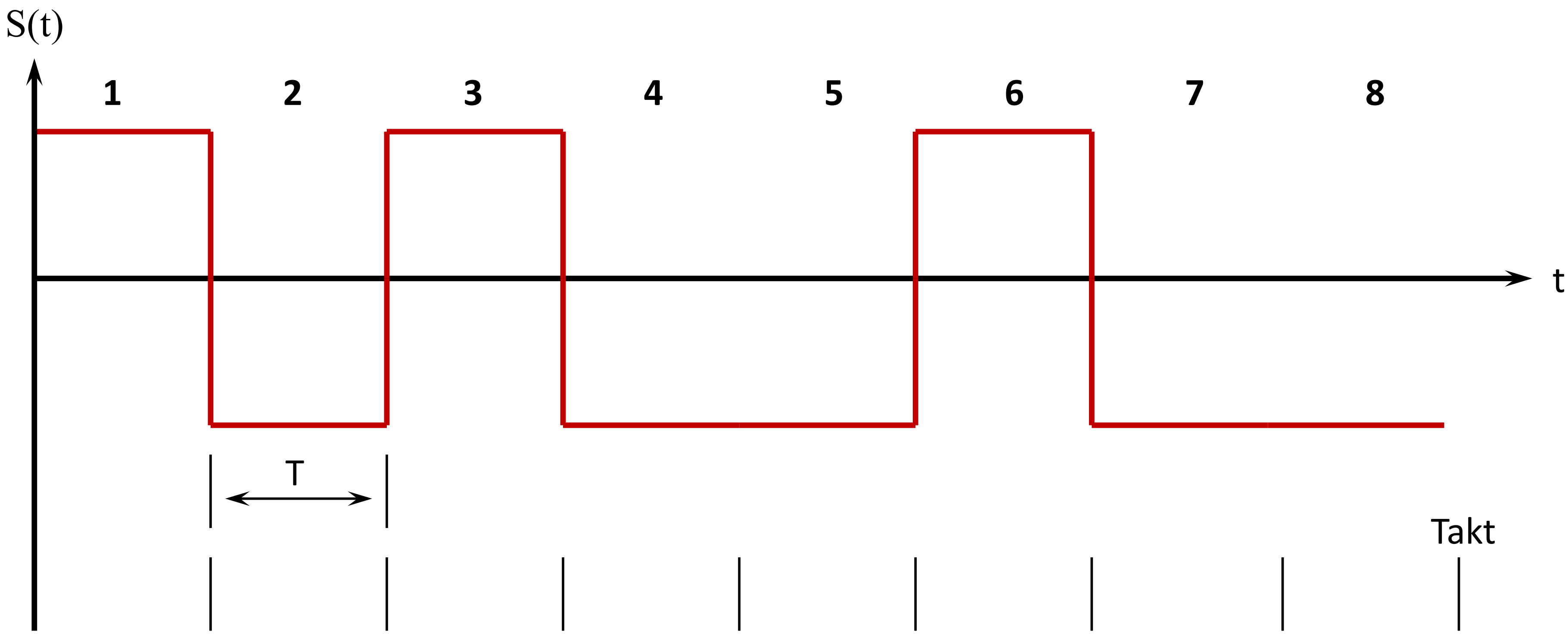


$$s(t) = \sin(2\pi f t) + \frac{1}{3}\sin(2\pi 3 f t) + \frac{1}{5}\sin(2\pi 5 f t)$$

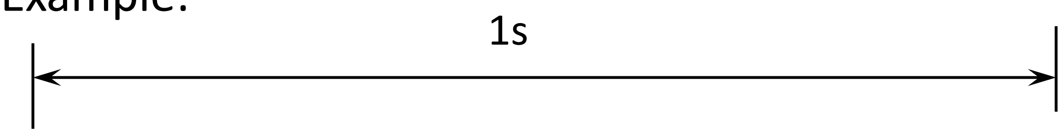
Effect of Bandwidth on a Digital Signal



Symbol Rate



Example:



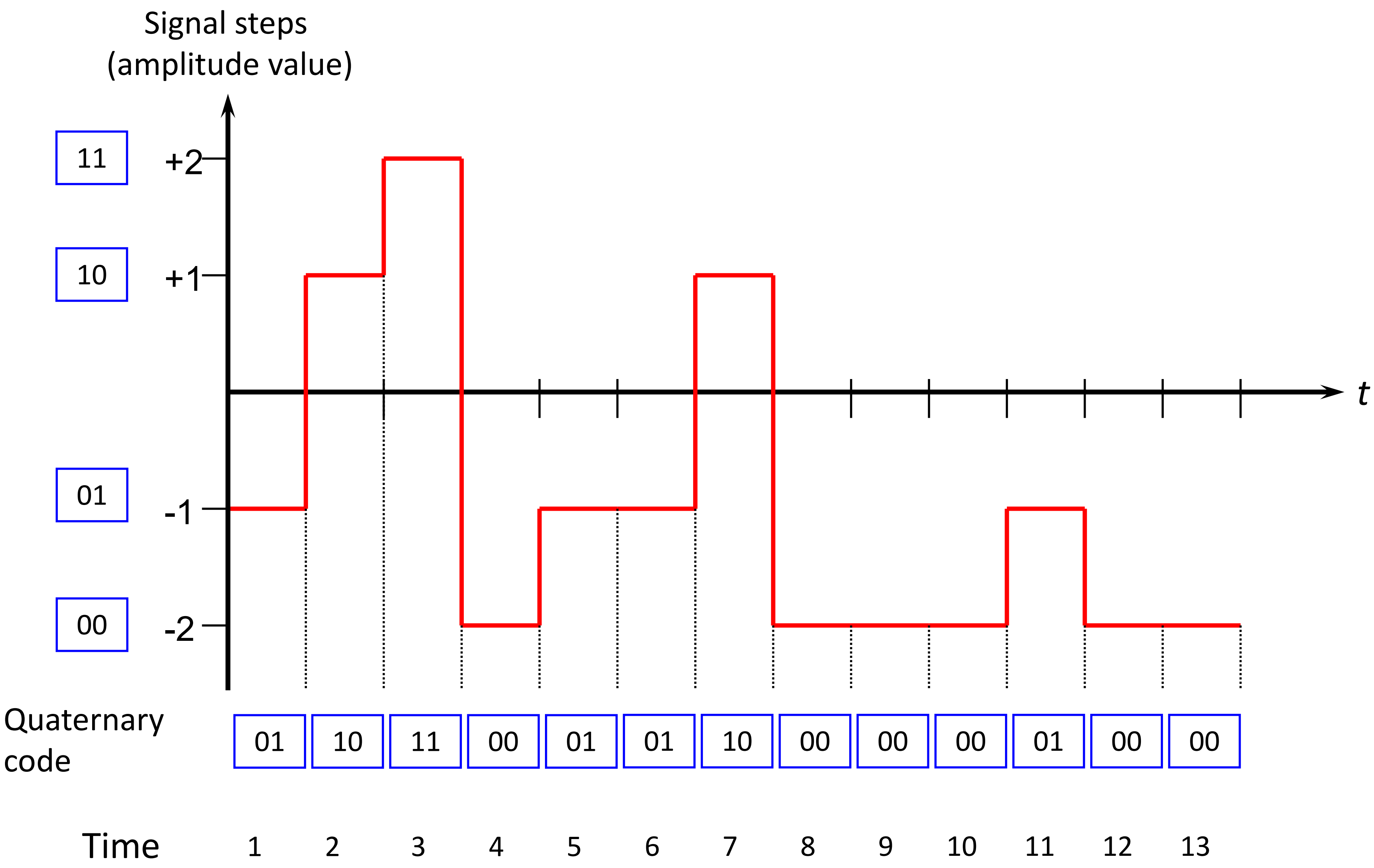
➡ Symbol rate 5 baud [1/s]

Binary and Multilevel Digital Signals

- **Binary digital signal**
  - A digital signal with two possible values, e.g., 0 and 1

- **Multilevel digital signal**
  - A digital signal with more than two possible values, e.g., DIBIT = two bits per coordinate value (quaternary signal element)
  - The number of discrete values which a signal may have are denoted as follows
    - n = 2 binary
    - n = 3 ternary
    - n = 4 quaternary
    - ...
    - n = 8 octonary
    - n = 10 denary

Multilevel Digital Signal



Symbol rate vs. Data rate

- **Symbol rate v (modulation rate, digit rate)**
  - The number of **symbol changes** (signaling events) made to the transmission medium **per second**
  - Unit 1/s = baud (abbrv. bd)

- **Data rate (Unit bps, bit/s)**
  - For binary signals
    - Each signaling event codes one bit, thus Symbol rate in baud = Data rate in bps

  - For multilevel signals (n possible values)
    - Data rate in $\mathrm{bps} = v \cdot \mathrm{ld}(n)$
    - DIBIT ➡ 1 baud = 2 bps (quaternary signal)
    - TRIBIT ➡ 1 baud = 3 bps (octonary signal)

Units of Bit Rates

Name of bit rates	Symbol	Multiple	Explicit
Bit per second	bps	10^0	1
Kilobit per second	kbps	10^3	1,000
Megabit per second	Mbps	10^6	1,000,000
Gigabit per second	Gbps	10^9	1,000,000,000
Terabit per second	Tbps	10^{12}	1,000,000,000,000
Petabit per second	Pbps	10^{15}	1,000,000,000,000,000

Do not confuse with binary prefixes

- 1 Byte = 8 bit
- 1 kByte = 2^{10} bytes = 1024 bytes

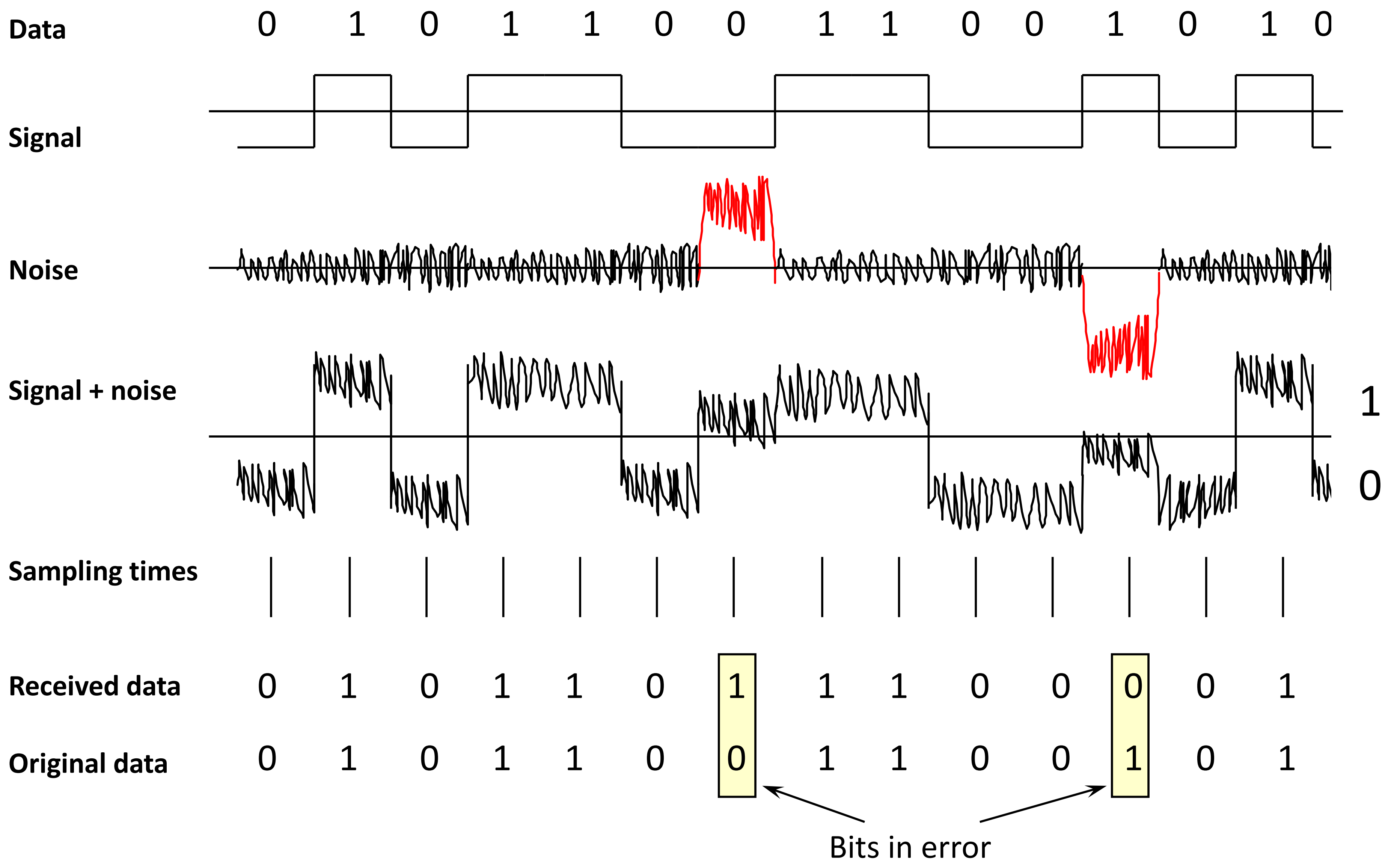
In this case kilo = 1024!

Transmission Impairments

- **Any communication system is subject to various transmission impairments.**
  - Analog signals: Impairments degrade the signal quality
  - Digital signals: Bit errors are introduced, i.e., a binary 1 is transformed into a binary 0 and vice versa.

- **Significant impairments**
  - Attenuation and attenuation distortion
  - Delay distortion
  - Noise
    - Thermal noise
    - Intermodulation noise
    - Crosstalk
    - Impulse noise

Effects of Noise on Digital Signal



Bit Error Rate

- **Metric for bit errors: Bit Error Rate (BER)**

$$\text{BER} = \frac{\text{Number of bits in error}}{\text{Number of transmitted bits}}$$

  - Depends on the communication medium
  - BER in digital networks are smaller than in analog networks
  - The BER depends also on the length of the transmission line

- **Typical values for BER:**
  - Analog telephony connection 2×10^{-4}
  - Radio link 10^{-3} - 10^{-4}
  - Ethernet (10Base2) 10^{-9} - 10^{-10}
  - Fiber 10^{-10} - 10^{-12}

Encoding of Information

Shannon:

»The fundamental problem of communication consists of reproducing on one side exactly or approximated a message selected on the other side.«

Objective: useful representation (encoding) of the information to be transmitted

Encoding categories

- Source encoding (Layer 6 and 7) → Encoding of the original message

  E.g. ASCII-Code (text), tiff (pictures), PCM (speech), MPEG (video), …

- Channel encoding (Layer 2 and 4) → Representation of the transmitted data in code words, which are adapted to the characteristics of the transmission channel (redundancy).

  → Protection against transmission errors through error-detecting and/or -correcting codes

- Cable encoding (Layer 1) → Physical representation of digital signals

Baseband and Broadband

- **Transmission of information can take place on**
  - baseband
  - broadband

- **Baseband**
  - The digital information is transmitted over the medium as it is.
  - For this, encoding procedures are necessary, which specify the representation of »0« resp. »1« (cable codes).

- **Broadband**
  - The information is transmitted analogous (thereby: larger range), by modulating it onto a carrier signal. By the use of different carrier signals (frequencies), several information can be transferred at the same time.

- **While having some advantages in data communications, broadband networks are rarely used – baseband networks are easier to realize.**
- **But optical networks and radio networks use this technology.**

Continuous vs. Discrete Transmission

- **On baseband, discrete (digital) signals are transmitted.**
- **On broadband, continuous (analogous) signals are transmitted.**

- **Signal theory: each periodical function (with period T) can be represented as a sum of**
  - weighted sine functions and weighted cosine functions:

$$g(t) = \frac{1}{2}c + \sum_{n=1}^{\infty} a_n \sin(2\pi nft) + \sum_{n=1}^{\infty} b_n \cos(2\pi nft)$$

$f = 1/T$ is base frequency

- ➢ **A series of digital signals can be interpreted as such a periodical function.**
- ➢ **Using Fourier Analysis: split up the digital representation in a set of analogous signals transported over the cable.**

Nyquist- und Shannon-Theorem

H. Nyquist (1924)

- **Maximum data rate for a noise free channel with limited bandwidth.**

max. data rate = $2 \times B \times \log_2(n)$ [bps]

- B = bandwidth of the channel
- n = discrete levels of the signal

- **Example:**
  - B = 3000 Hz, binary signal
  - max. data rate:
    $2 \times 3000 \times \mathrm{ld}(2) = 6{,}000$ bps

C. Shannon (1948)

- **Extension to channels with random noise.**

max. data rate = $B \times \log_2(1+SNR)$ [bps]

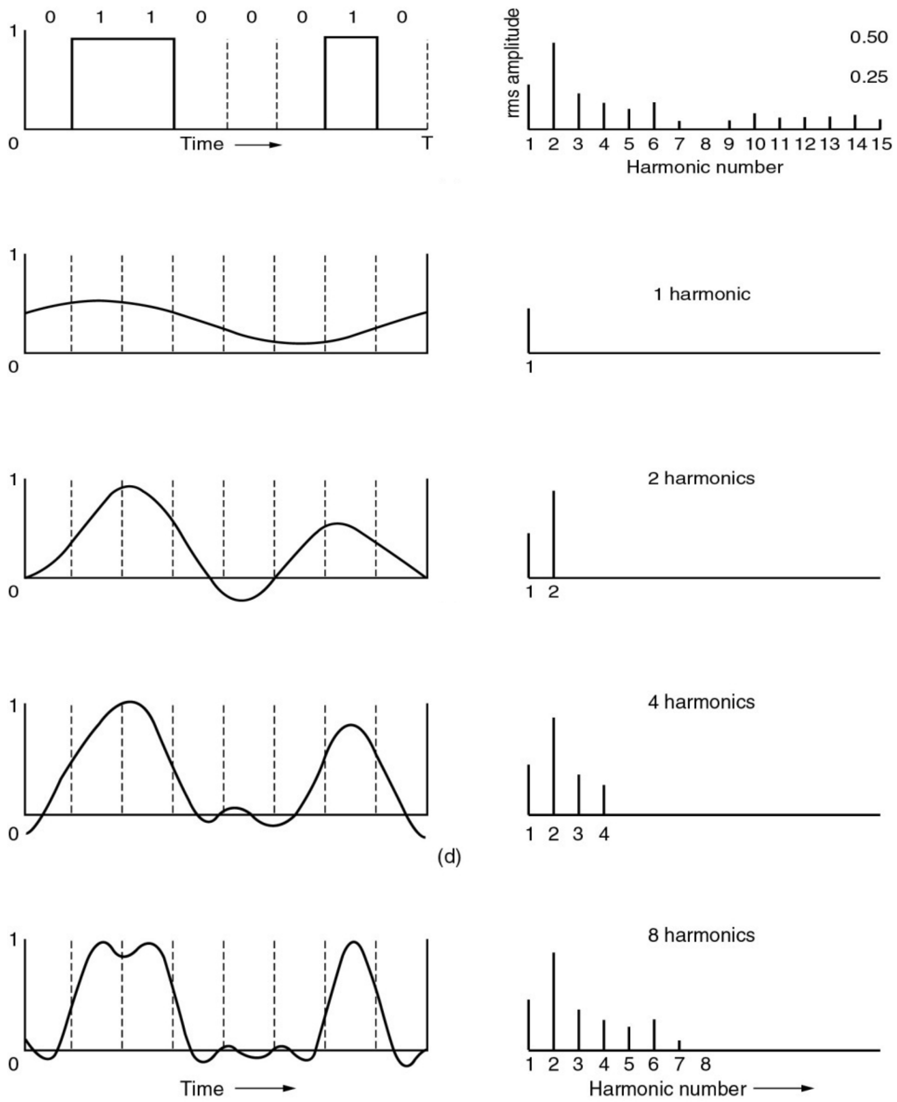
- B = bandwidth of the channel
- SNR = signal-to-noise ratio

$$SNR = \frac{\text{signal power}}{\text{noise power}}$$

$$SNR_{\mathrm{dB}} = 10\log_{10}(SNR)$$

- **Example:**
  - B = 3000 Hz
  - SNR = 1000, SNR_{dB} = 30
  - max. data rate:
    $3000 \times \mathrm{ld}(1+1000) \approx 30{,}000$ bps

Analogous Representation of Digital Signals



The original signal is approximated by continuously considering higher frequencies.

But:

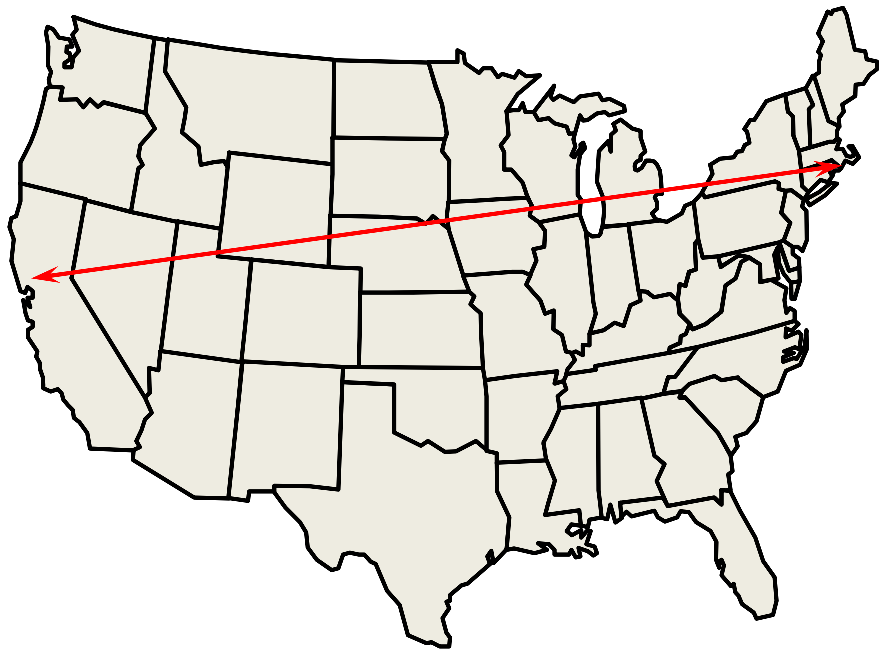
- Attenuation: weakening of the signal
- Distortion: the signal is going out of shape

Reasons:

- The higher frequencies are attenuated more than lower frequencies.
- Speed in the medium depends on frequency
- Distortion from the environment

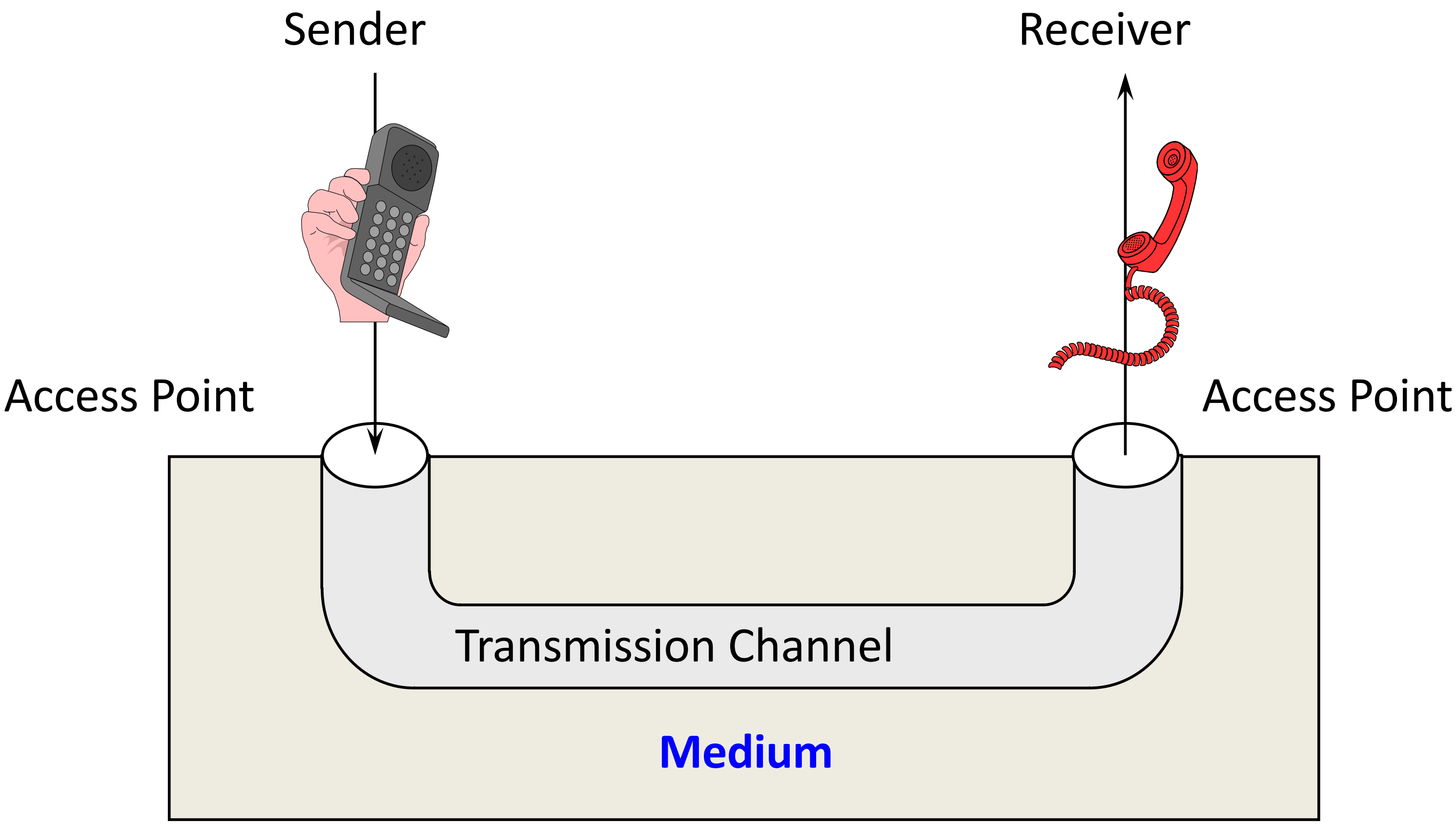
Propagation Speed of Signals

- **Optimum propagation**
  - Speed of the light ($c = 3\times10^8$ m/s) in vacuum
- **Propagation speed on lines**
  - Approx. $2/3\ c = 2\times10^8$ m/s
- **The medium has a store capacity due to the restricted propagation speed**
- **Example: data transmission from MIT to Berkeley**
  - Distance: 5000 km; propagation time: ca. 25 ms (5000 km / 2×10^8 m/s)
  - Round Trip Delay (RTT): approx. 50 ms
  - With a data rate of 100 kbps: 2500 bit memory capacity
  - With a data rate of 1 Gbps: 25,000,000 bit ≈ 3 Mbyte



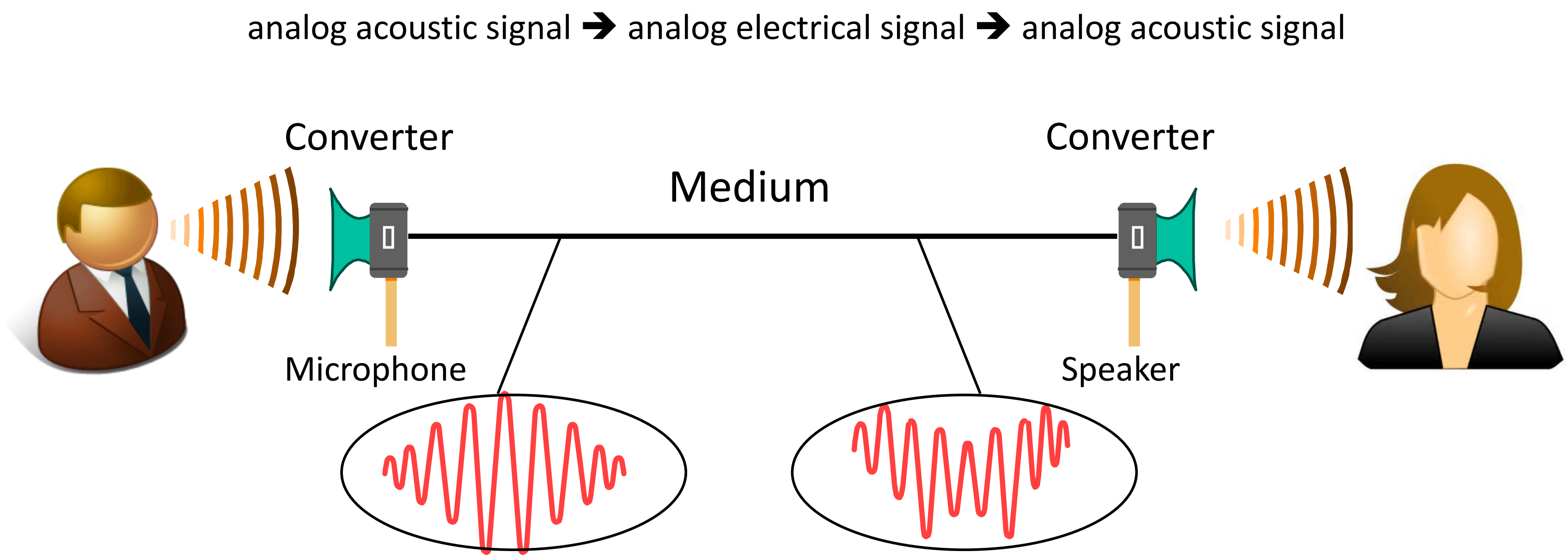
Analog Data and Digital Signals

Transmission Channel and Medium



Signal Conversion: Acoustic-to-Electrical

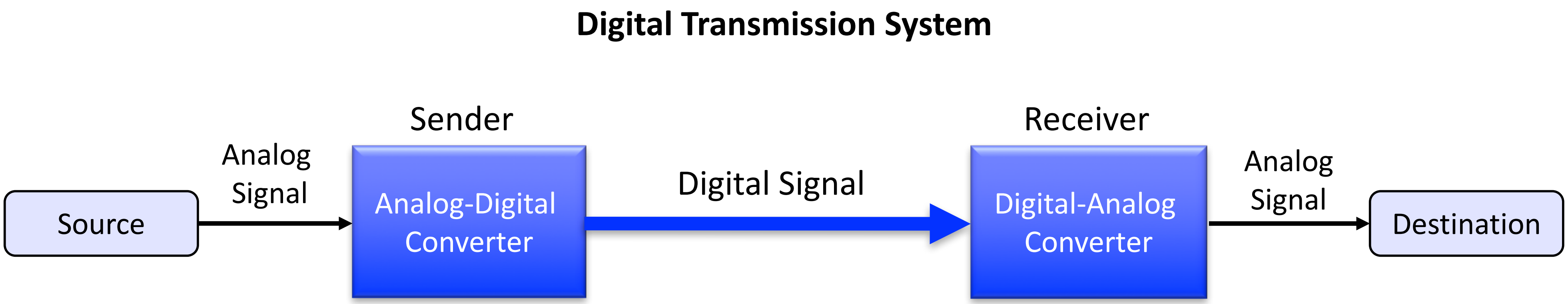
- **Signal: physical value, chronological sequence**



Classical model of the telephone system

Digital Transmission of Analog Data

- **Transmission of analog data over digital transmission systems**
  - Digitizing of the analog data is necessary!



- **A/D- and D/A-Conversion to transmit analog signals on digital transmission systems:**

Analog		**Digital**		
continuous-value	➡	discrete-value	=	Quantization
continuous-time	➡	discrete-time	=	Sampling

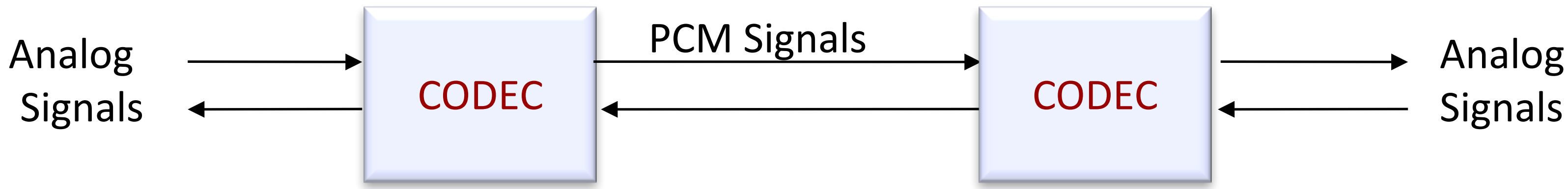
Pulse Code Modulation (PCM)

Pulse Code Modulation (PCM) is based on the sampling theorem by Shannon and Raabe

Shannon and Raabe (1939)
If a signal is sampled at regular intervals of time and at a rate higher than twice the highest significant signal frequency, then the samples contain all the information of the original signal.

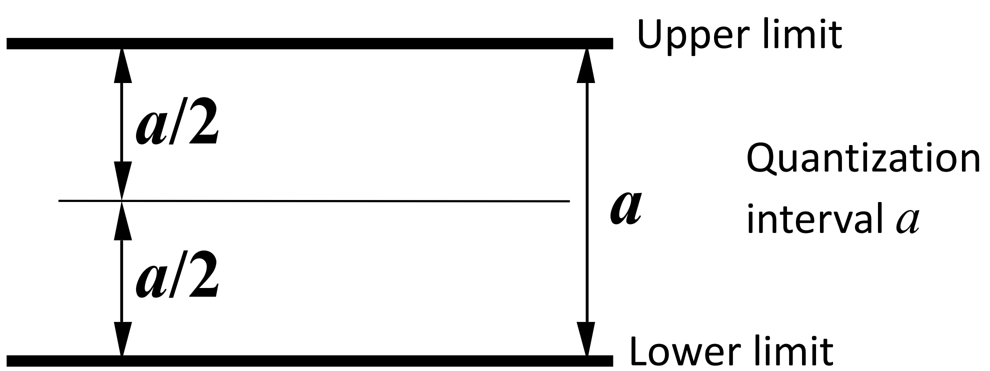
Pulse Code Modulation (PCM)

- **Method of the Pulse Code Modulation**
  - **Sampling – Quantization – Coding**
- **The analog-digital conversion and the back conversion is done by the**
  - **CODEC** (**Co**der/**Dec**oder)



PCM: Quantization

- **Quantization is the process of approximating the whole range of an analog signal into a finite number of discrete values (interval).**
- **Quantization error: The difference between the analog signal value and the digital value.**



- Quantization interval for a discrete value for all analog signals between $-a/2$ and $+a/2$
- The receiver generates an analog signal which is in the center of the quantization interval (digital-to-analog)

PCM: Coding and Sampling

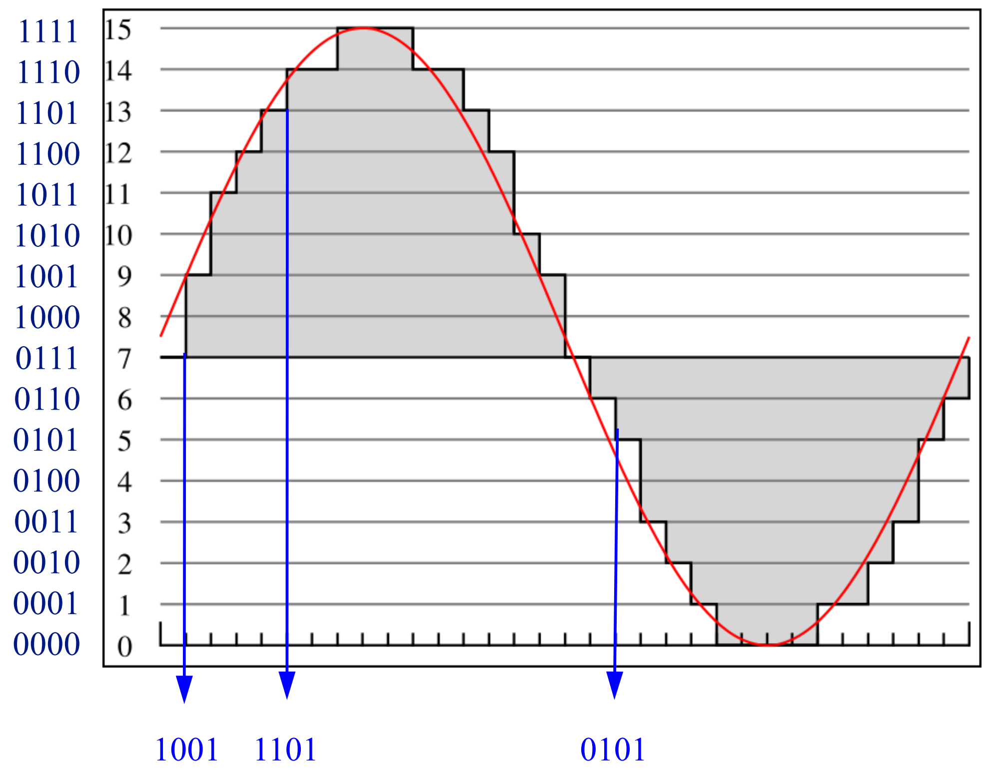
- **Coding**
  - The quantization intervals are assigned a binary code.
  - Basic idea: The digital code is transmitted instead of the analog signal.

- **Sampling**
  - The analog signal has to be sampled to get the digital representation.
    - The analog signal is periodically sampled (sampling rate)
    - The value of the analog signal at the sampling time is quantized (analog-to-digital conversion)

- **Attention:**
  - Sampling and Quantization has to be considered independently.

PCM: Example

- **Sampling and quantization of a sine wave**
  - Red curve original sine wave
  - The sine curve is sampled regularly
  - Quantization with 4 bits (0 to 15)
  - The digital representation of the sine curve is given by the binary numbers



PCM Telephone Channel: Sampling

- **Source**
  - Analog ITU-Voice channel, Frequency range 300-3400Hz, Bandwidth 3100Hz, highest Frequency 3400Hz

- **Sampling rate**
  - ITU recommends a sampling rate of

$$\mathbf{f_A = 8000\ Hz = 8\ kHz}$$

- **Sampling time**
  - $T_A = 1/f_A = 1/8000\text{Hz} = 125\ \mu s$
  - The ITU recommended sampling rate is higher than what the sampling theorem requires (3400 Hz highest frequency results in 6800 Hz sampling rate).

PCM Telephone Channel: Quantization

Quantization

- The number of quantization intervals depends by voice communication on the intelligibility at the receiver.
- Recommended are 256 quantization intervals
- With binary encoding ➡ 8 bits code length

$$\mathbf{2^8 = 256}$$

- The bit rate for a digitized voice channel is

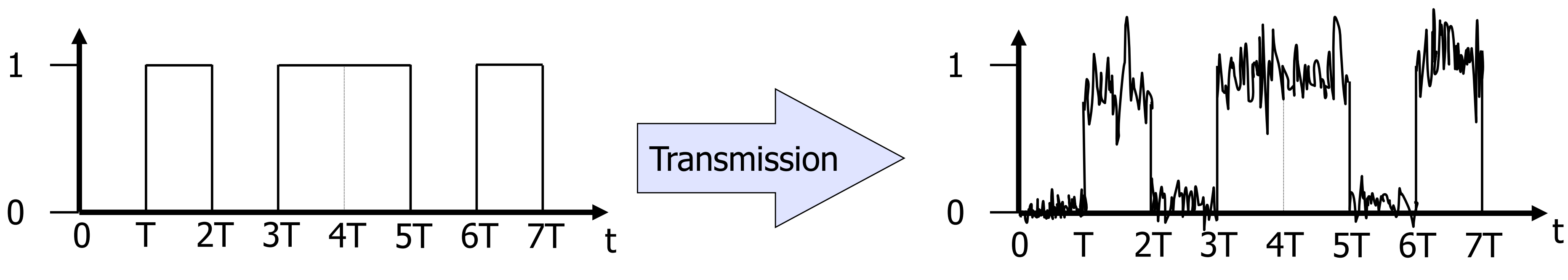
$$\begin{aligned}\text{bit rate} &= \text{sampling rate} \times \text{code length}\\ &= 8000/\text{s} \times 8\ \text{bit}\\ &= 64000\ \text{bps}\\ &= 64\ \text{kbps}\end{aligned}$$

Data Encoding

Cable Encoding on the Physical Layer

Cable Code: Requirements

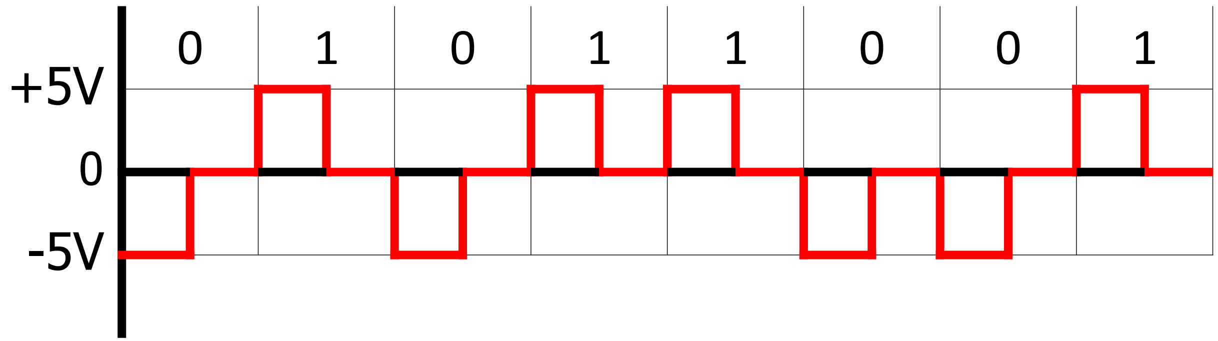
- **How to represent digital signals electrically?**
  - As high robustness against distortion as possible



- **Efficiency: as high data transmission rates as possible by using code words**
  - binary code: +5V/-5V?
  - ternary code: +5V/0V/-5V?
  - quaternary code: 4 states (coding of 2 bits at the same time)
- **Synchronization with the receiver, achieved by frequent changes of voltage level regarding to a fixed cycle**
  - Polar/Unipolar coding?
  - Avoiding direct current: positive and negative signals should alternatively arise

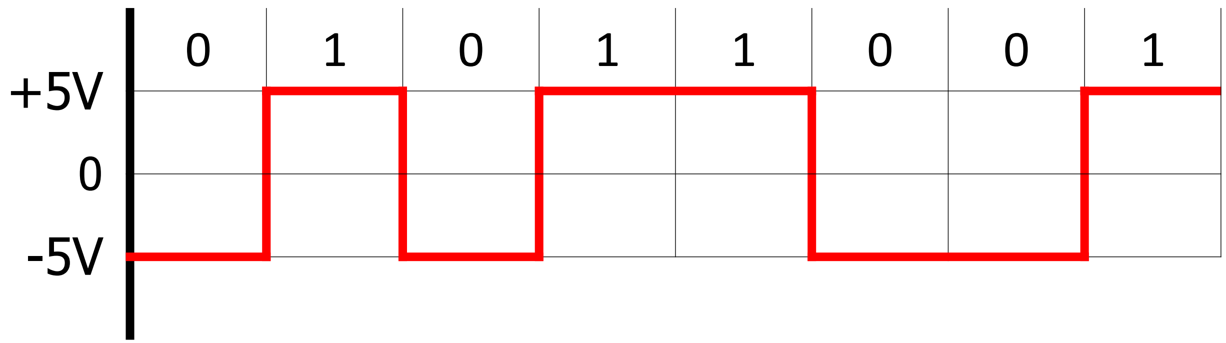
Return to Zero (RZ)

- **The signal returns to zero between each pulse.**
- **Advantage**
  - The signal is self-clocking
- **Disadvantage**
  - Needs twice the bandwidth



Non Return to Zero (NRZ)

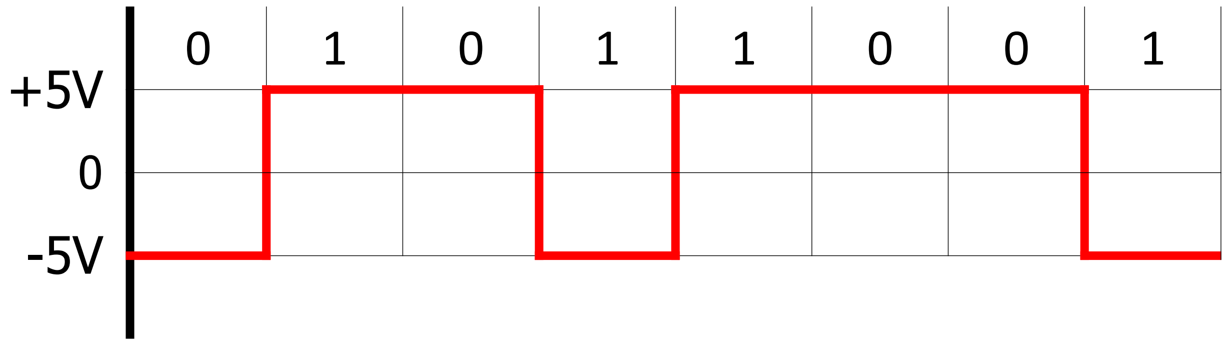
- **Simple approach:**
  - Encode “1” as positive voltage (+5V)
  - Encode “0” as negative voltage (- 5V)



- **Advantage:**
  - Very simple principle
  - The smaller the clock pulse period, the higher the data rate
- **Disadvantage:**
  - Loss of clock synchronization as well as direct current within long sequences of 0 or 1

Differential NRZ

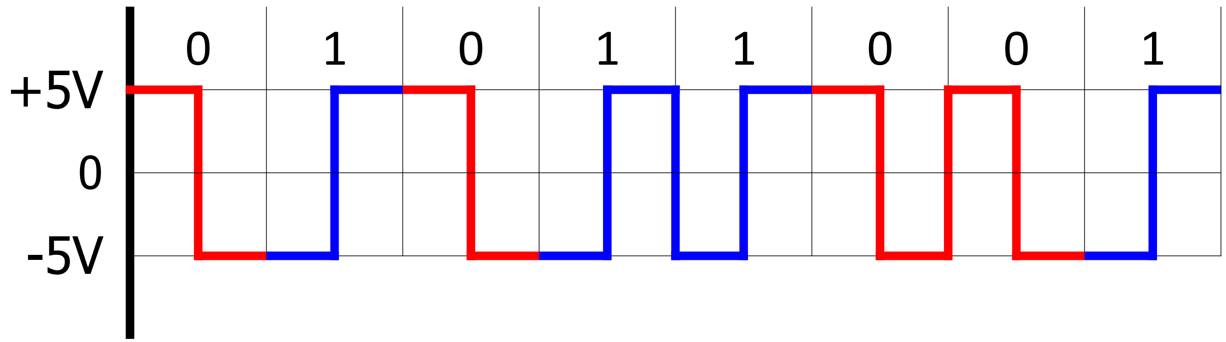
- **Differential NRZ:**
  - Similar principle to NRZ
  - Encode “1” as voltage level change
  - Encode “0” as missing voltage level change



- **Property**
  - Very similar to NRZ, but disadvantages only hold for sequences of zeros.

Manchester Code

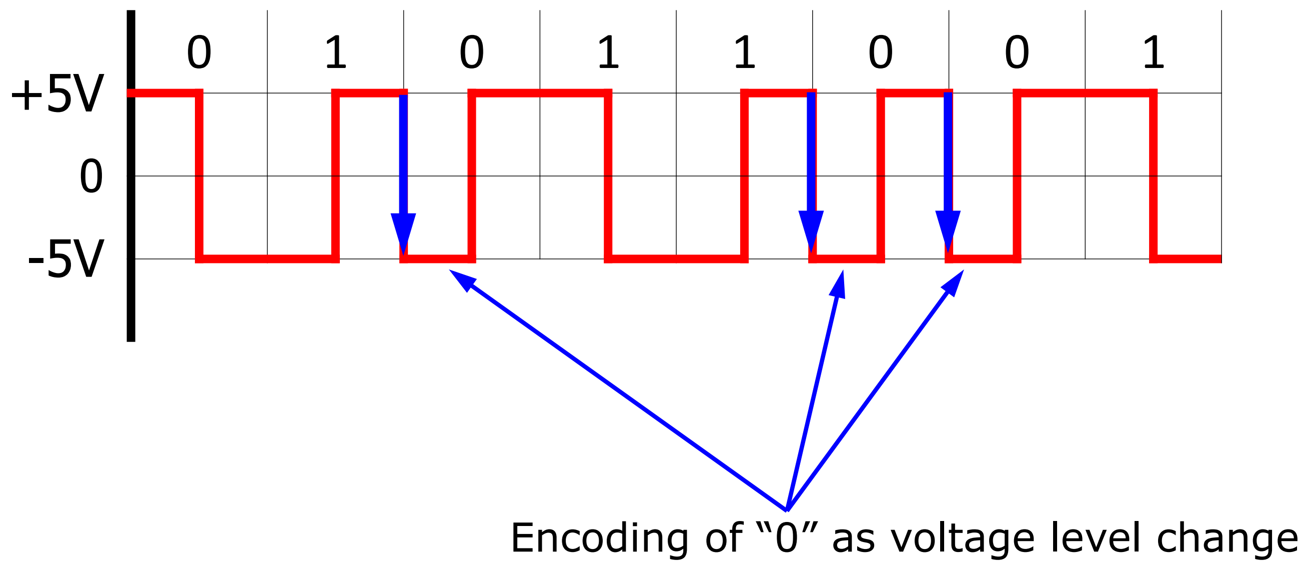
- **For automatic synchronization the clock pulse is transferred with each code element.**
  - ➢ A change of voltage level in the middle of each bit occurs:
  - Encode “0” as voltage level change from positive to negative
  - Encode “1” as voltage level change from negative to positive



- **Advantages**
  - Clock synchronization with each bit, no direct current
  - End of the transmission is easily recognizable
- **Disadvantage**
  - Capacity is used only half!

Differential Manchester Code

- **Variant of the Manchester Code. Similar as it is the case for the Manchester code, a voltage level change takes place in the bit center, additionally a second change is made:**
  - Encode “1” as missing voltage level change between two bits
  - Encode “0” as voltage level change between two bits



4B/5B Code

- **Disadvantage of the Manchester Code:**
  - 50% efficiency, i.e., 1B/2B Code (1 bit is coded with 2 bits)
- **An improvement is given with the 4B/5B Code:**
  - 4 bits are coded in 5 bits: 80% efficiency
- **Functionality:**
  - Level change with 1, no level change with 0 (differential NRZ code)
  - Coding of hexadecimal characters: 0, 1,…, 9, A, B,…, F (4 bits in 5 bits), so that long zero blocks are avoided
  - Selection of the most favorable 16 of the possible 32 code words (maximally 3 zeros in sequence)
  - Further 5 bit combinations for control information

- **Question: Expandable to 1000B/1001B Codes?**

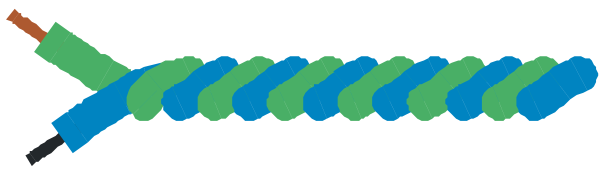
4B/5B Code Table

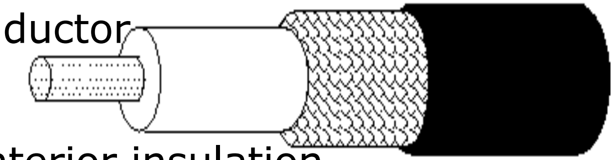
- **Groups of four bits are mapped on groups of five bits**
  - Transmission provides clocking
  - Example:
    - 0000 contains no transitions and causes clocking problems

Name	4b	5b	Description
0	0000	11110	hex data 0
1	0001	01001	hex data 1
2	0010	10100	hex data 2
3	0011	10101	hex data 3
4	0100	01010	hex data 4
5	0101	01011	hex data 5
6	0110	01110	hex data 6
7	0111	01111	hex data 7
8	1000	10010	hex data 8
9	1001	10011	hex data 9
A	1010	10110	hex data A
B	1011	10111	hex data B
C	1100	11010	hex data C
D	1101	11011	hex data D
E	1110	11100	hex data E
F	1111	11101	hex data F
I	-NONE-	11111	Idle
J	-NONE-	11000	Start of stream delimiter
K	-NONE-	10001	Start of stream delimiter
T	-NONE-	01101	End of stream delimiter
R	-NONE-	00111	End of stream delimiter
H	-NONE-	00100	Halt

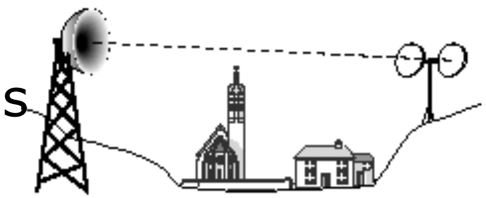
Transmission Media

Transmission Media

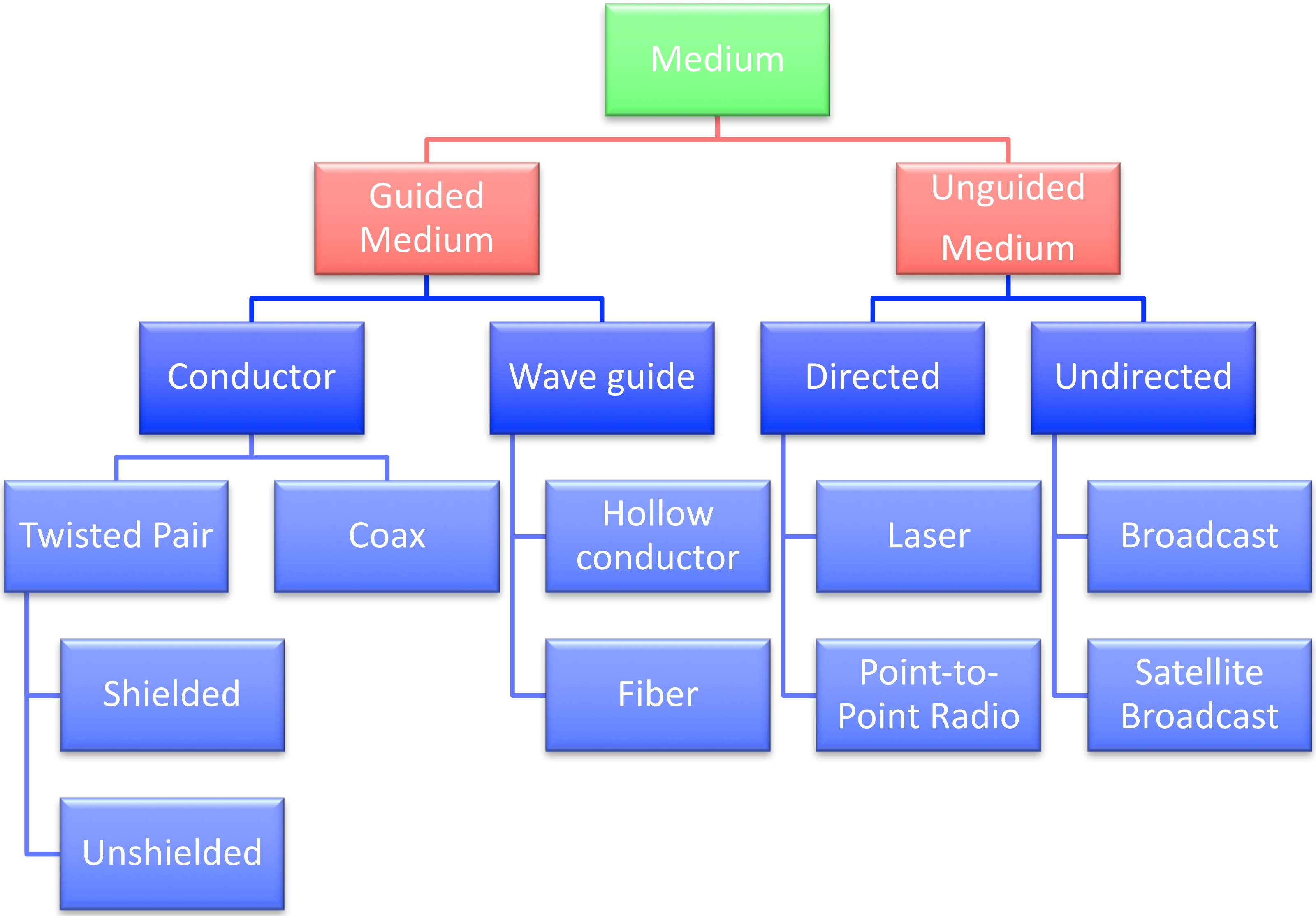




Several media, varying in transmission technology, capacity, and bit error rate (BER)



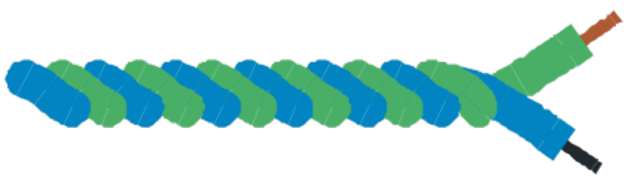
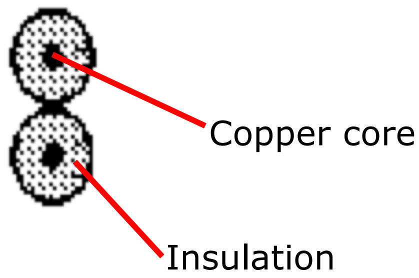
Transmission Media: Classification

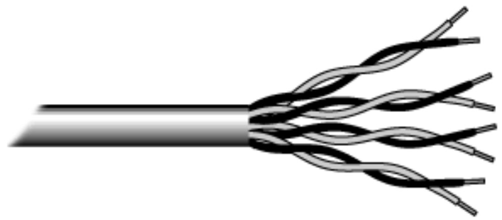
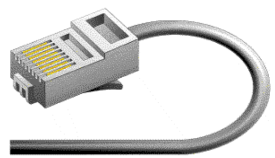


Guided Transmission Media

Twisted Pair

- **Characteristics:**
  - Data transmission through electrical signals
  - Problem: electromagnetic signals from the environment can disturb the transmission within copper cables
  - Solution: two insulated, twisted copper cables
    - Twisting reduces electromagnetic interference with environmental disturbances
  - Simple principle (costs and maintenance)
  - Well known (e.g. telephony)
  - Can be used for digital as well as analog signals
  - Bit error rate ~ 10^{-5}

Types of Twisted Pair

Category

Category 3

- Two insulated, twisted copper cables
- Shared protective plastic covering for four twisted cable pairs

Category 5

- Similar to Cat 3, but more windings/cm
- Covering is made of Teflon (better insulation, resulting in better signal quality on long distances)

Category 6,7

- Each cable pair is covered with an additional silver foil

Today mostly Cat 5/6 is used

Shielding

UTP (Unshielded Twisted Pair)

- No additional shielding

STP (Shielded Twisted Pair)

- Each cable pair is shielded separately to avoid interferences between the cable pairs

Nevertheless, mostly UTP is used

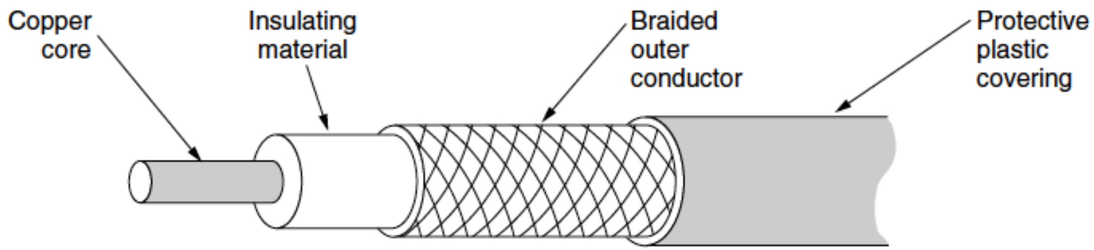
Types of Twisted Pair

Category	Spectral Bandwidth	Length	LAN Applications
Cat3	16 MHz	100 m	10Base-T, 4 Mbps
Cat4	20 MHz	100 m	16 Mbps
Cat5	100 MHz	100 m	100Base-Tx,ATM
Cat5e	100 MHz	100 m	1000Base-T
Cat6	250 MHz	100 m	1000Base-T
Cat6a	625 MHz	100 m	10GBase-T
Cat6e	500 MHz	100 m	10GBase-T
Cat7	600 MHz 1000 MHz	100 m	10GBase-T

Coaxial Cable

Structure

- Insulated copper cable as core conductor
- Braided outer conductor reduces environmental disturbances
- Interior insulation separates center and outer conductor



Characteristics:

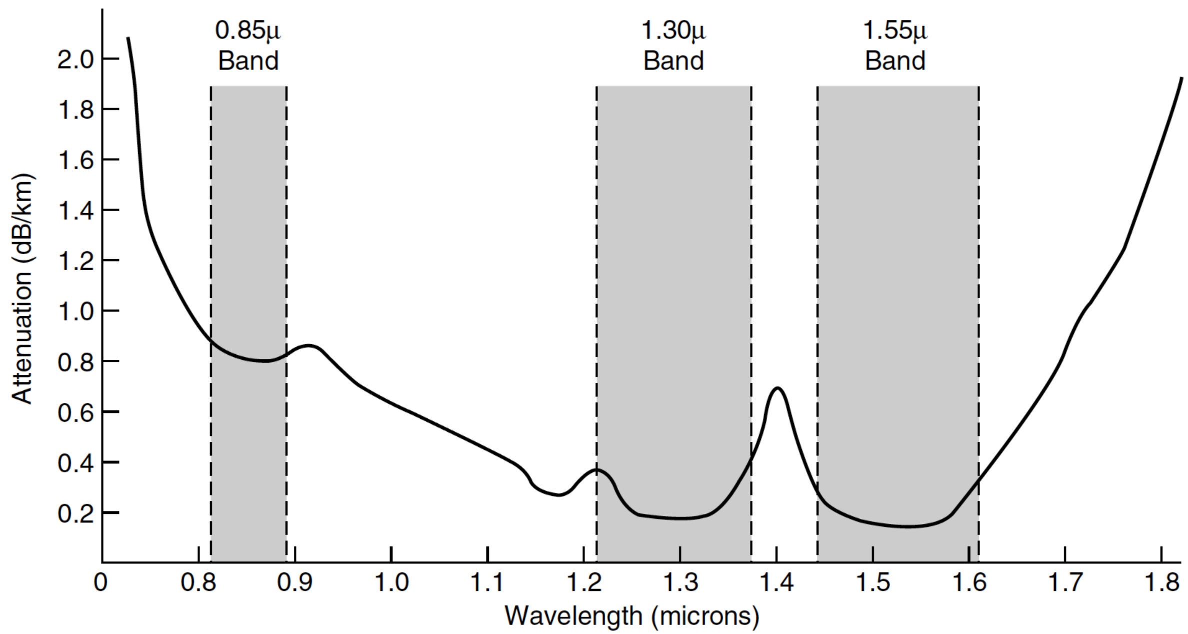
- Higher data rates over larger distances than twisted pair: 1-2 Gbps up to 1 km
- Better shielding than twisted pair, resulting in better signal quality
- Bit error rate ~ 10^{-9}

Early networks were build with coaxial cable, however it was more and more replaced by twisted pair.

Optical Fiber

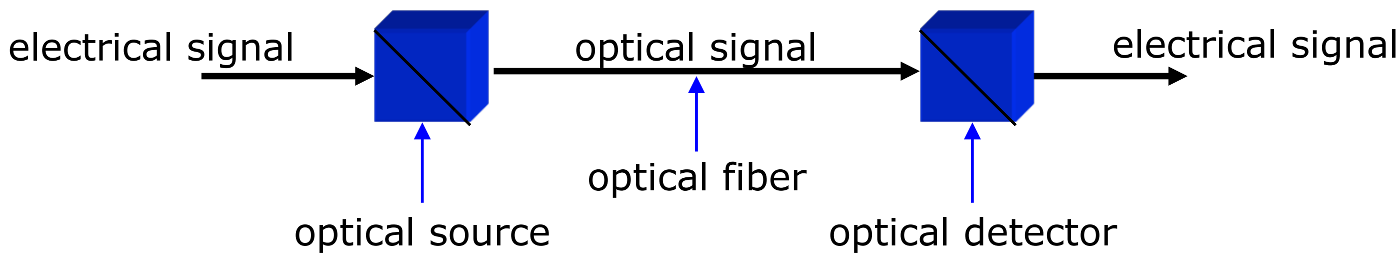
- **Characteristics:**
  - Nearly unlimited data rate (theoretically up to 50,000 Gbps) over very large distances
  - Wavelength in the range of microns (determined by availability of light emitters and attenuation of electromagnetic waves: range of the wavelength around 0.85µm, 1.3µm and 1.55µm are used)
  - Insensitive to electromagnetic disturbances
  - Good signal-to-noise-ratio
  - Bit error rate ~ 10^{-12}

$$Att_{dB} = 10 \log_{10}\left(\frac{input\ power}{output\ power}\right)$$

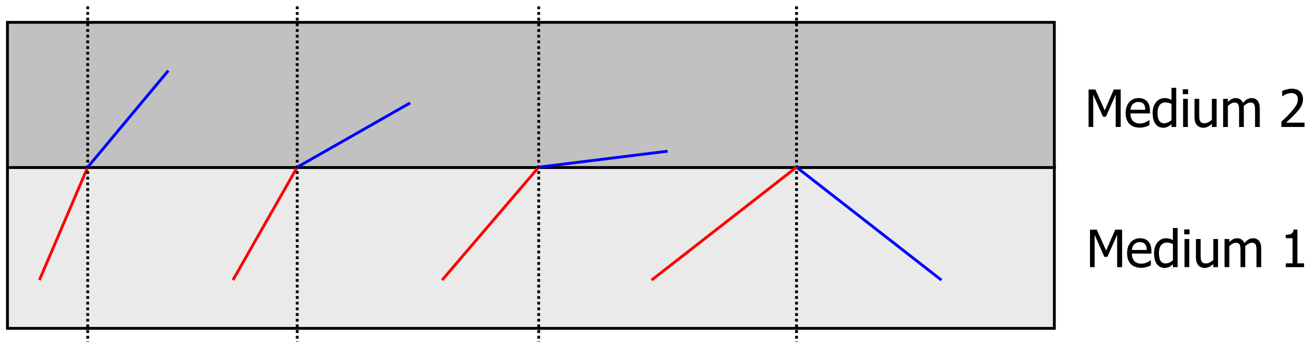


Optical Transmission

- **Structure of an optical transmission system**
  - Light source: Converts electrical into optical signals, i.e., “1 – light pulse” and “0 – no light pulse”
  - Transmission medium (optical fiber)
  - Detector: Converts optical into electrical signals



Physical principle: Total reflection of light at another medium



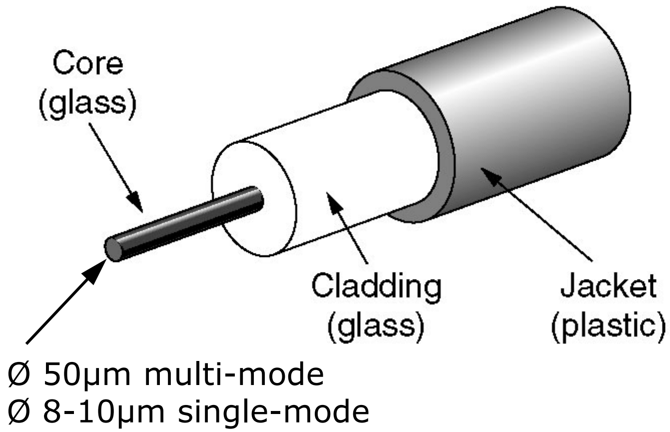
Refractive index:

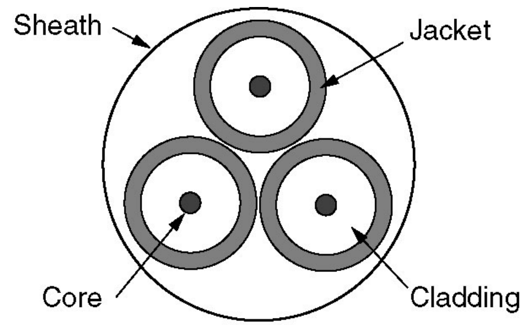
Indicates refraction effect relatively to air

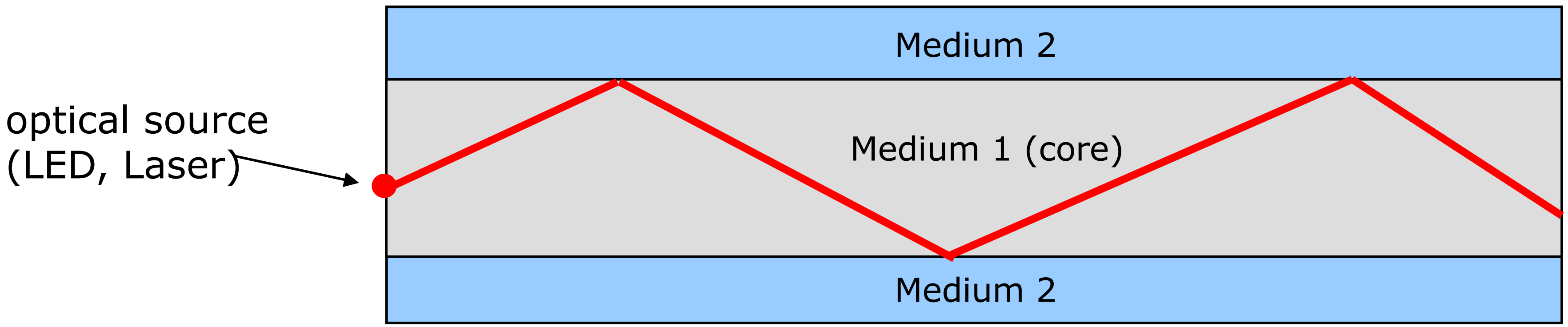
Optical Fiber

Structure of a fiber

- Core: optical glass (extremely thin)
- Internal glass cladding
- Protective plastic covering
- The transmission takes place in the **core** of the cable
  - Core has higher refractive index, therefore the light remains in the core
  - Ray of light is reflected instead of transiting from medium 1 to medium 2
- Refractive index is material dependent
- A cable consists of many fibers

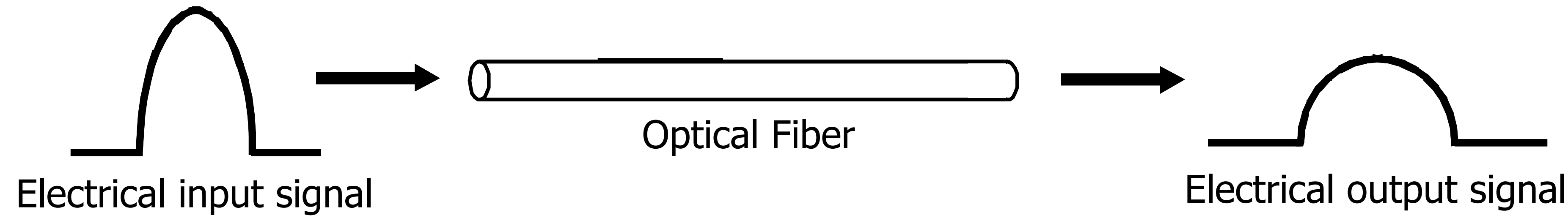






Problems with Optical Fiber

- **The ray of light is increasingly weakened by the medium!**
  - Absorption can weaken a ray of light gradually
  - Impurities in the medium can deflect individual rays
- **Dispersion (less bad, but transmission range is limited)**
  - Rays of light are spreading in the medium with different speed:
    - Ways (modes) of the rays of light have different length (depending on the angle of incidence)
    - Rays have slightly different wavelengths (and propagation speed)
  - Refractive index in the medium is not constant (effect on speed)
  - Here only a better quality of radiation source and/or optical fiber helps!



Types of Fiber

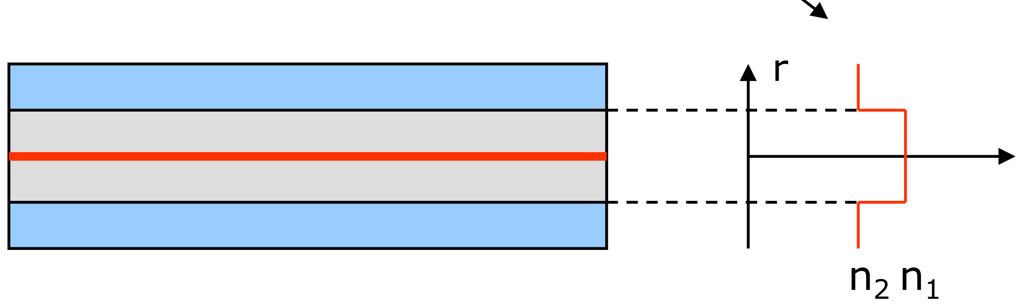
The profile characterizes the fiber type:

- *X* axis: Size of refractive index
- *Y* axis: Thickness of core and cladding

Note: Single-mode does not mean that only one wave is simultaneous on the way. It means that all waves take "the same way". Thus dispersion is prevented.

Single-mode fiber

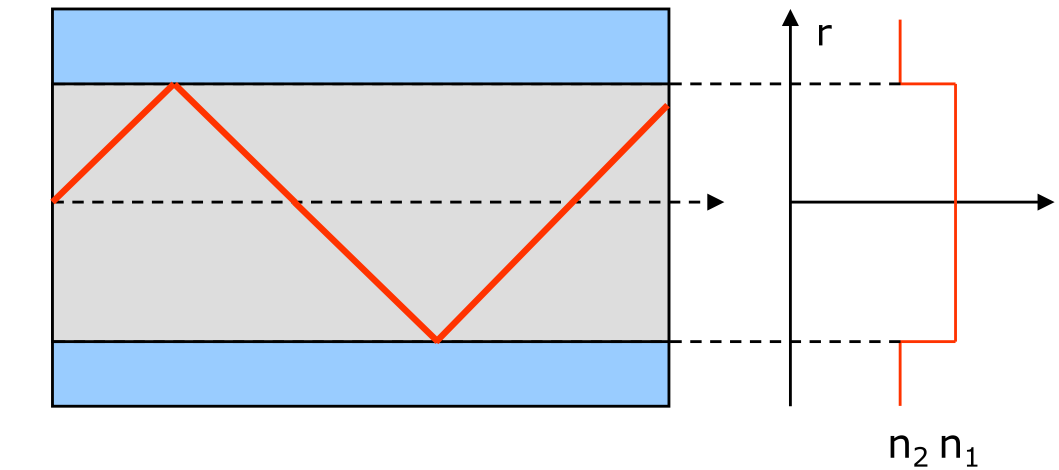
- Core diameter: 8 - 10 µm
- All rays can only take one way
- No dispersion (homogeneous signal delay)
- Expensive due to the small core diameter



Optical Fiber Types

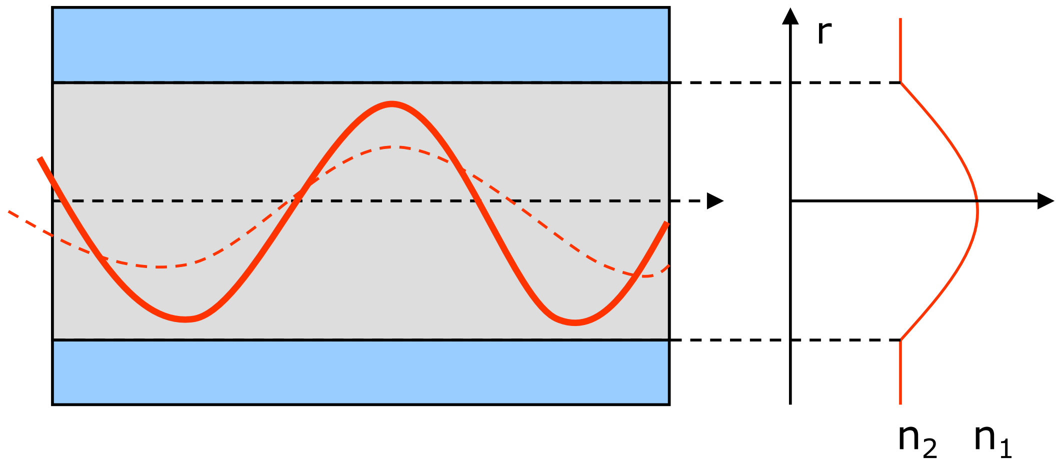
Simple multimode fiber

- Core diameter: 50 µm
- Different used wavelengths
- Different signal delays
- High dispersion



Multimode fiber with gradient index

- Core diameter: 50 µm
- Different used wavelengths
- Refractive index changes continuously
- Low dispersion



Radiation Sources and Detectors

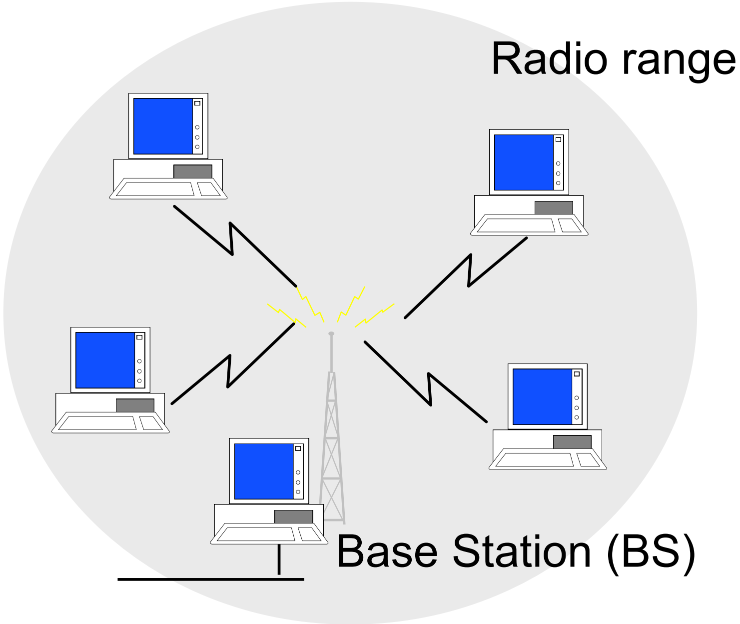
- **Radiation sources**
  - Light emitting diodes (LED)
    - cheap and reliable (e.g. regarding variations in temperature)
    - broad wavelength spectrum, i.e., high dispersion and thus small range
    - capacity is not very high
  - Laser
    - expensive and sensitive
    - high capacity
    - small wavelength spectrum and thus high range

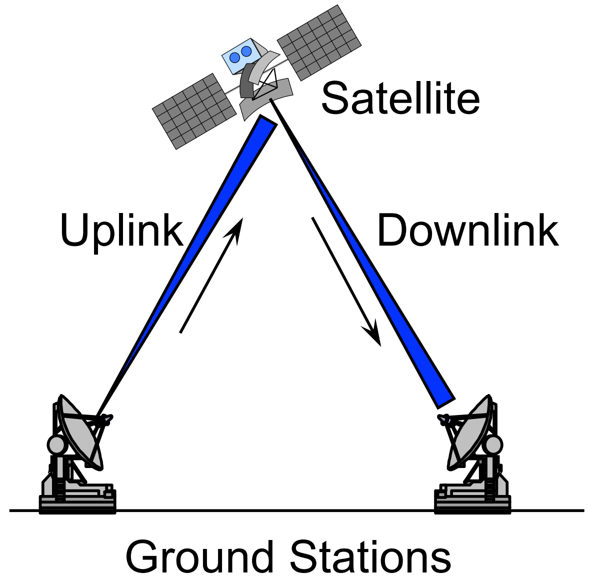
	LED	**Laser**
Data rate	Low	High
Fiber type	Multimode	Single-/Multimode
Distance	Short	Long
Lifetime	Long life	Short life
Temperature sensitivity	Minor	Substantial
Cost	Low	High

- **Photon detector**
  - Photodiodes differ in particular within signal-to-noise ratio
- **Through the usage of improved material properties of the fibers, more precise sources of light and thus reduction of the distances between the utilizable frequency bands, the amount of available channels constantly increases.**

Wireless Transmission and Communication Satellites

Wireless Communication

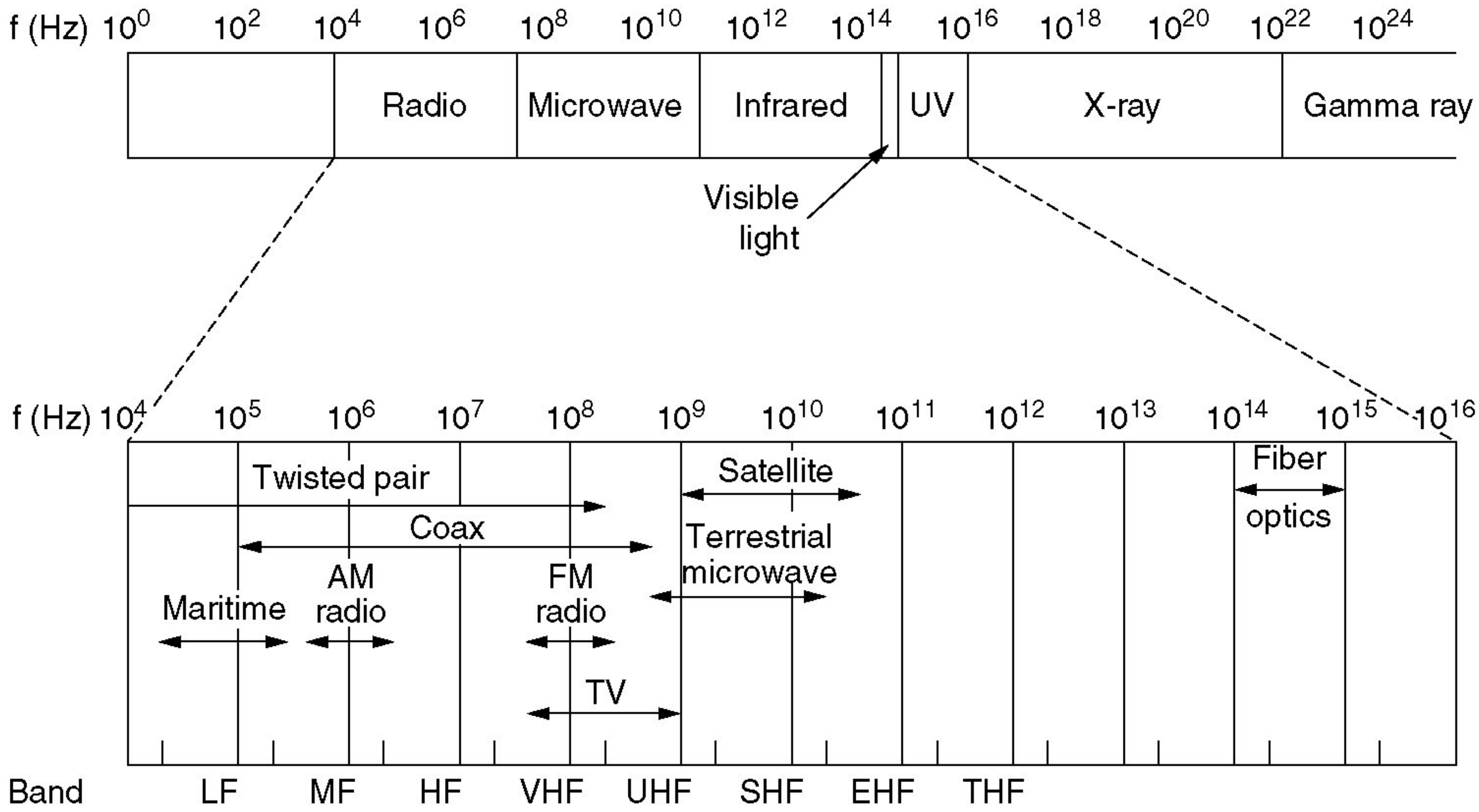




- **Medium: Electromagnetic Wave (10^4 - 10^9 Hz)**
- **Data is modulated**
- **Communication range depends on**
  - signal power
  - environment
- **Data rates: 10kbps - 1Gbps**

- **Medium: Electromagnetic wave (10^9 - 10^{11} Hz)**
- **Transponder on the satellite receives on one channel and sends on another channel**
- **Several transponders per satellite**
- **High bandwidth (500MHz) per channel**

Electromagnetic Spectrum and its use for Communication



LF = Low Frequency
MF = Medium Frequency
HF = High Frequency

VHF = Very High Frequency
UHF = Ultra High Frequency
SHF = Super High Frequency

EHF = Extremely High Frequency
THF = Tremendously High Frequency

Wireless Communication: IEEE 802.1 Overview

Protocol	Release	Frequency [GHz]	Bandwidth [MHz]	Data Rate [Mbps]	Modulation	Range Indoor [m]	Range Outdoor [m]
802.11	06/1997	2.4	22	2	DSSS,FHSS	20	100
a	09/1999	5	20	54	OFDM	35	120
b	09/1999	2.4	22	11	DSSS	35	140
g	06/2003	2.4	20	54	OFDM,DSSS	35	140
n	10/2009	2.4 5	20 40	72.2 150	OFDM	70	250
ac	12/2013	5	20 40 80 160	96.3 200 433.3 866.7	OFDM	35	
ad	12/2012	60	2/160	6912	OFDM	60	100
ah	m/2016						
ay	2017	60		30-40Gbps			300-500

Electromagnetic Waves

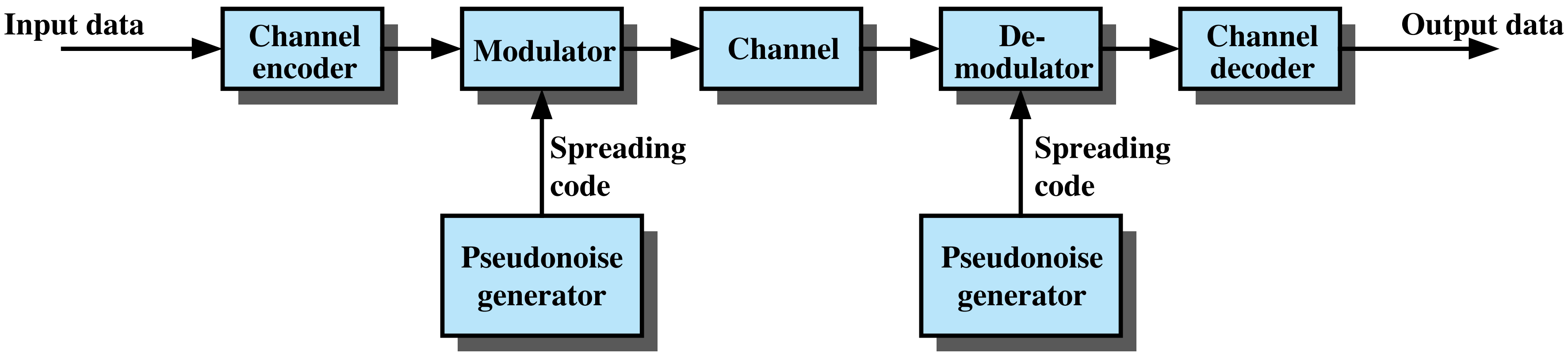
- **In vacuum all electromagnetic waves travel at the speed of light**
  - $c = 3 \times 10^8$ m/s
  - In copper or fiber the speed slows to 2/3 of c
  - Fundamental relationship between
    - wave length λ,
    - frequency f, and
    - Speed of light c (in vacuum)

$$\lambda \cdot f = c$$

- **Examples**
  - 100MHz waves are approx. 3 m long
  - 1,000MHz (1GHz) waves are approx. 0.3 m long
  - 2,4GHz WiFi waves approx. 0.125 m = 12,5 cm long
  - 5GHz WiFi waves approx. 0.06 m = 6 cm long
  - 60GHz waves approx. 0.005 m = 0.5 cm long

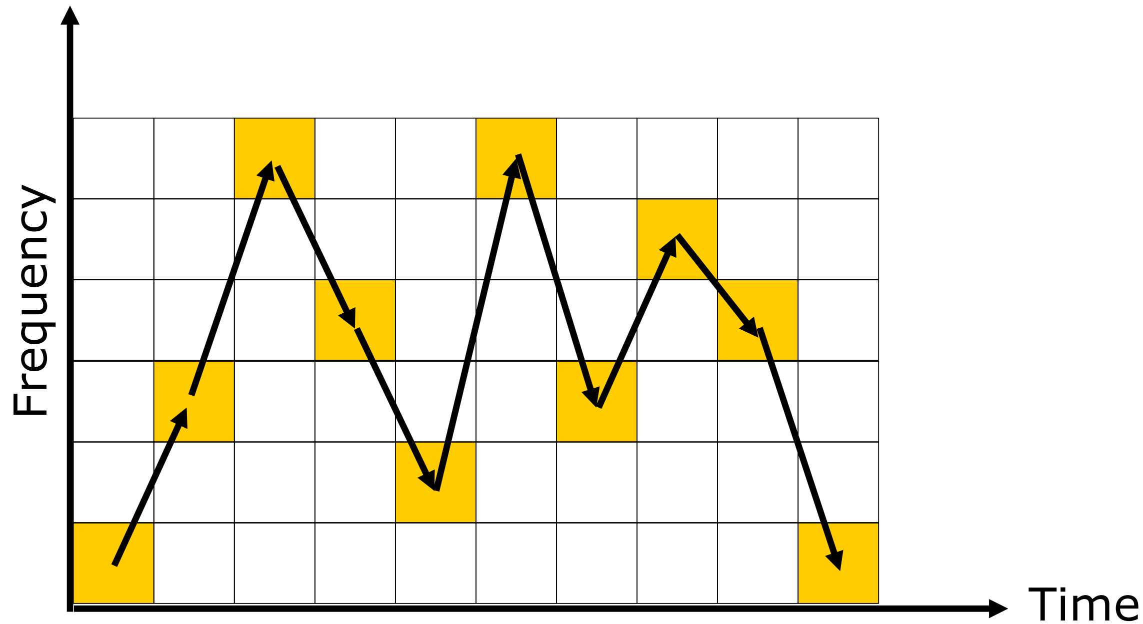
Spread Spectrum

- **Encoding method for wireless communications**
- **Analog and digital data with analog signal**
- **Spreads data over wide bandwidth**
- **Makes jamming and interception harder**
- **Two approaches:**
  - Frequency Hopping
  - Direct Sequence



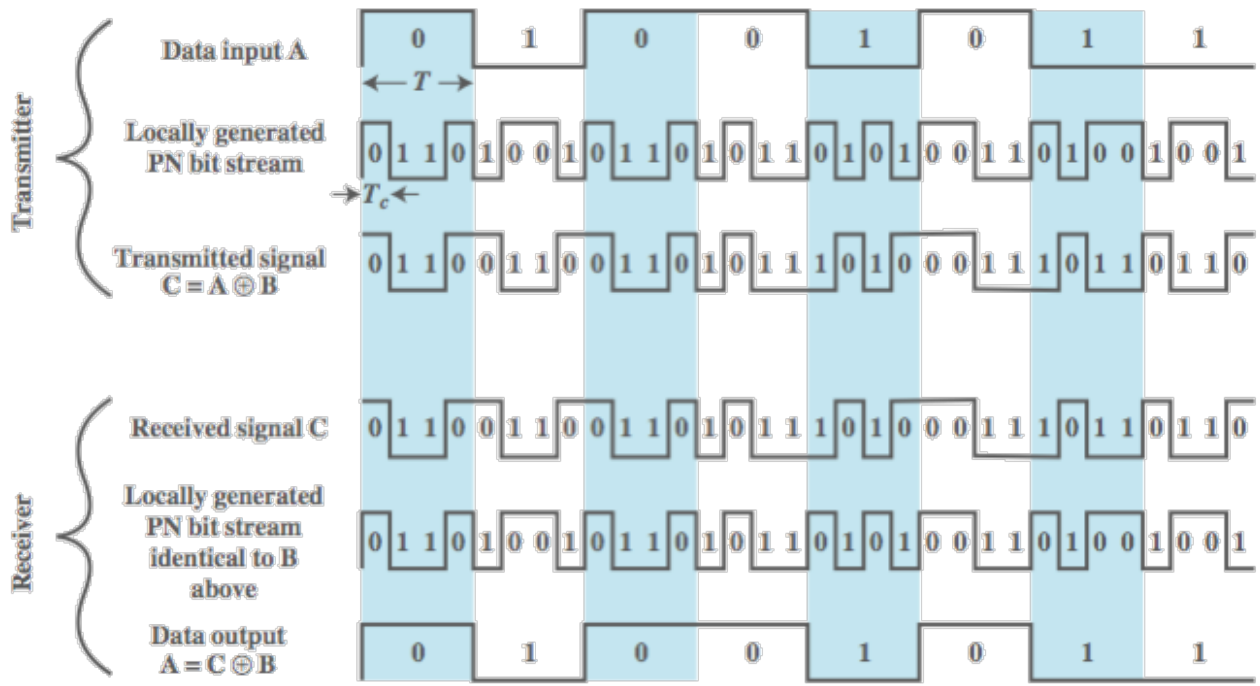
Frequency hopping spread spectrum

- **Transmitter hops from frequency to frequency**
- **Pseudorandom sequence known to sender/receiver**
- **Hopping frequency: Hundreds of times per seconds**
- **Popular for military applications**
    - Hard to detect
- **Applied in IEEE 802.11 and Bluetooth**



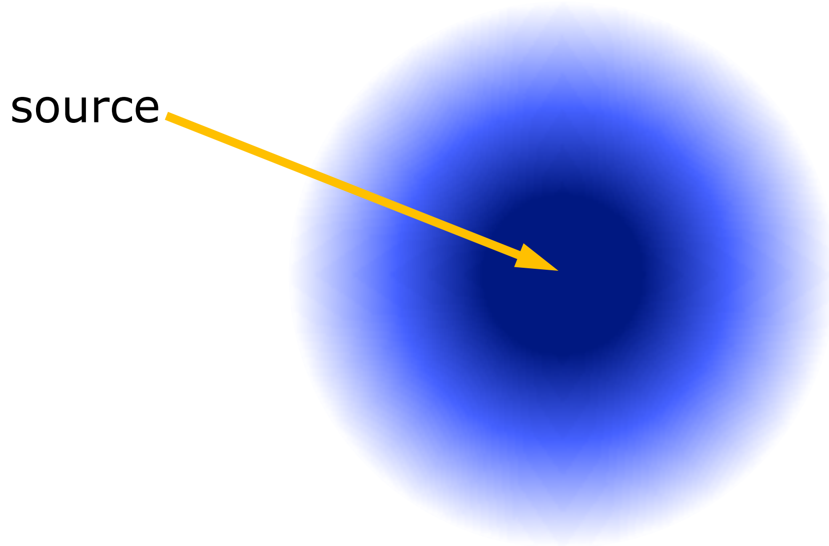
Direct sequence spread spectrum

- **Spreading of the signal over a wide frequency band**
  - Example: 1 bit data is spread on 10 bit
- **Multiply the data by a noise signal**
  - Pseudo random number sequence
- **Applied in GPS, WLAN, UMTS, UWB**



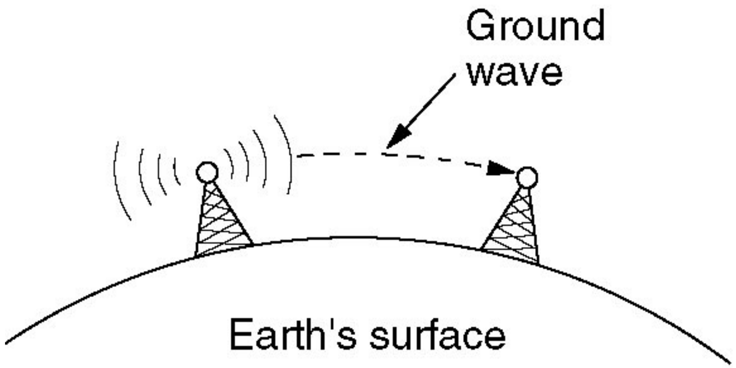
Radio Transmission

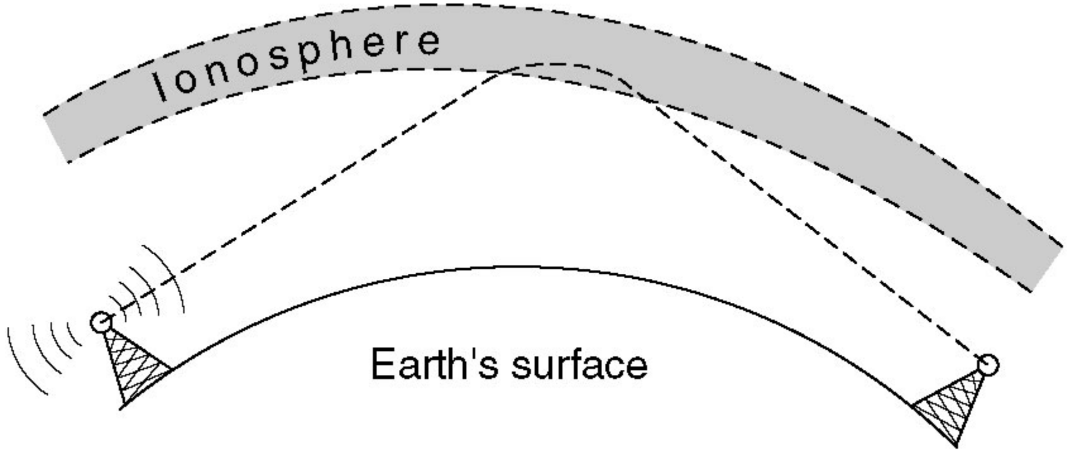
- **Radio waves are …**
  - easy to generate
  - can travel long distances
  - can penetrate buildings
  - omnidirectional,
    i.e., they travel in all directions



- **Properties of radio waves are frequency dependent**
  - At low frequencies, they pass through obstacles well
  - The power fall off with distance from the source, roughly $\frac{1}{r^2}$
  - At high frequencies they travel on straight lines and bounce off obstacles, and are absorbed by water
- **Problem**
  - Interference between users

Radio Transmission



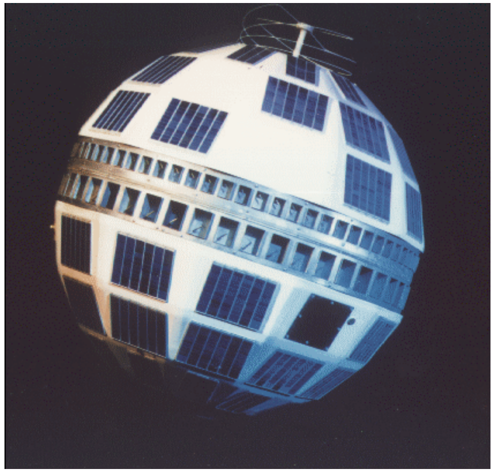


In the LF and MF bands, radio waves follow the curvature of the earth.

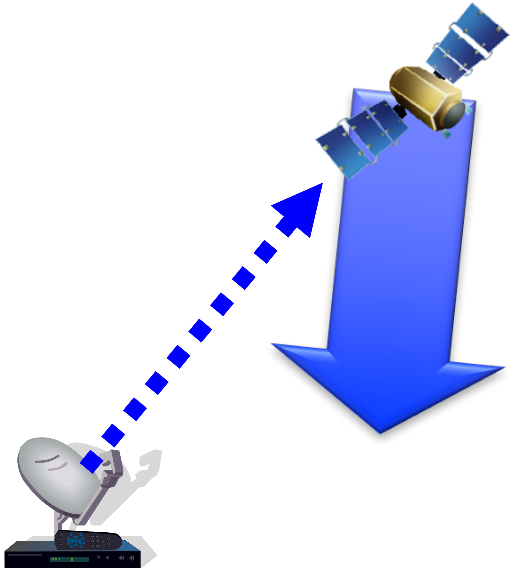
In the HF and VHF bands, they bounce off the ionosphere.

Communication Satellites

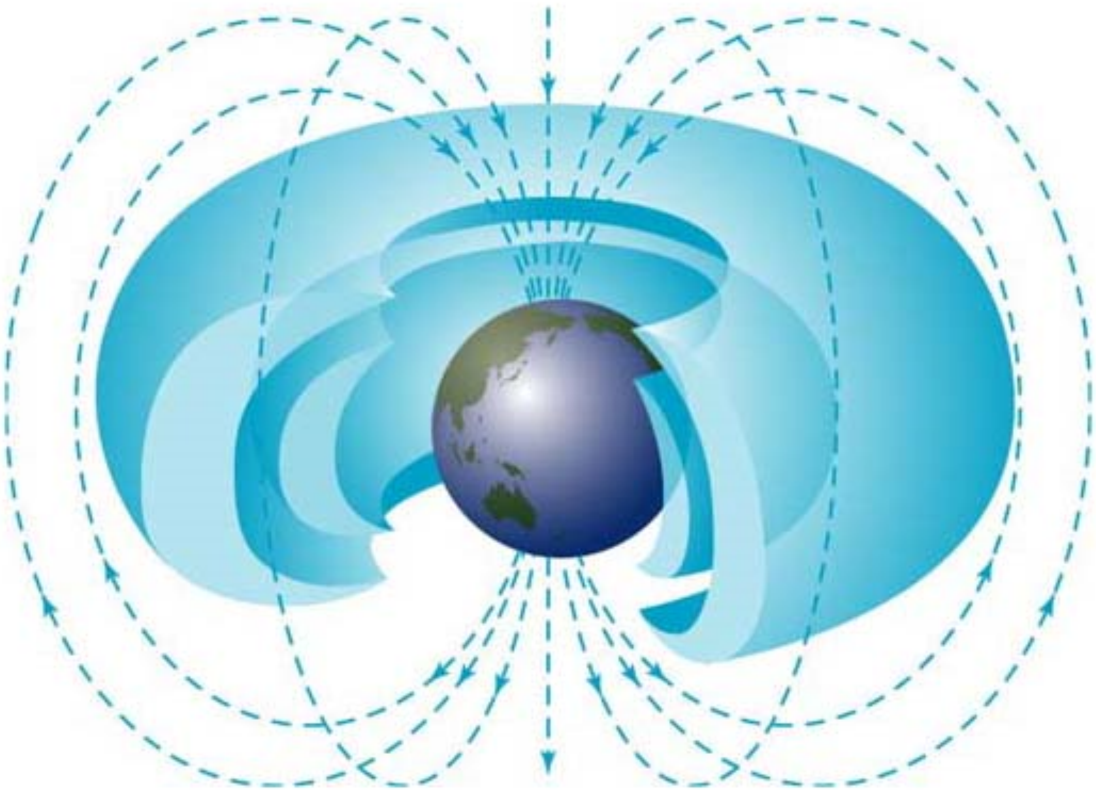
- **Satellites**
  - First experiments in 1950s and 1960s with weather balloons
  - Later bouncing off of signals by the moon (US Navy)
  - First communications satellite, Telstar, 1962
- **Method**
  - A satellite contains several transponders
  - A transponder receives, amplifies, and relays signals
- **Position of satellites**
  - Orbital period varies with the radius of the orbit
  - The higher the satellite, the longer the period
  - Problem: Van Allen belts
    - Layers of highly charged particles



Telstar

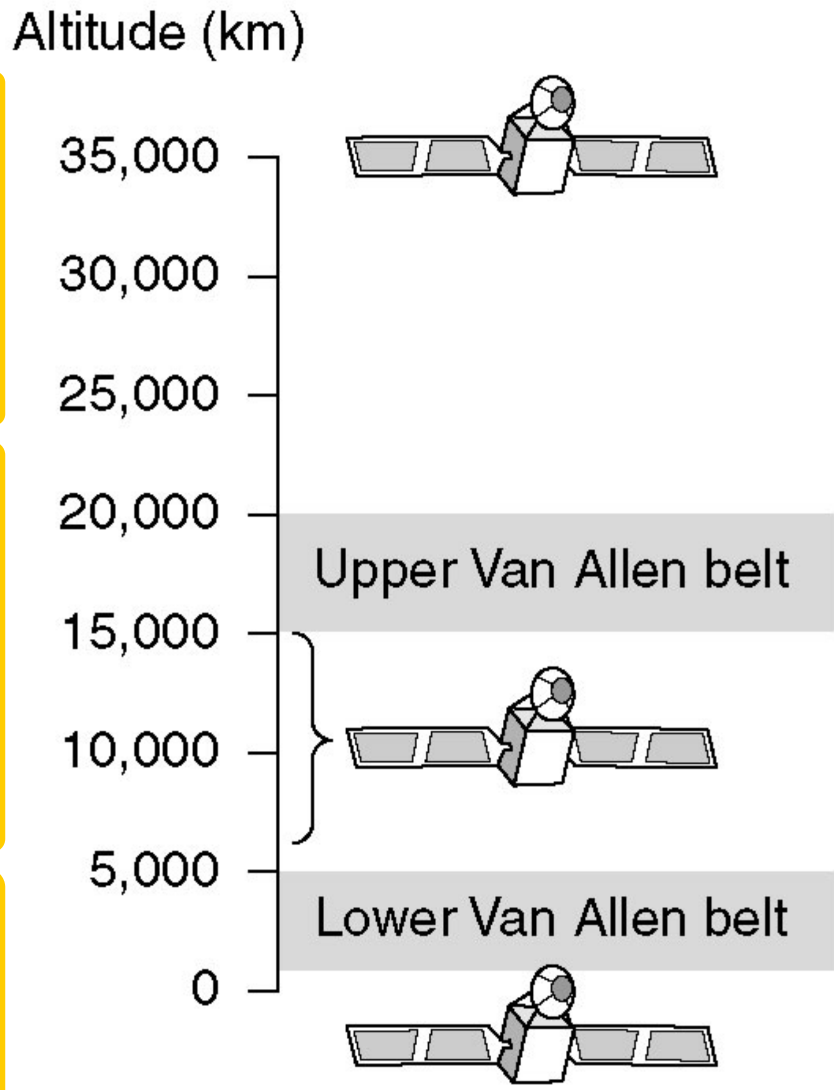


Communication Satellites: Van Allen Belts

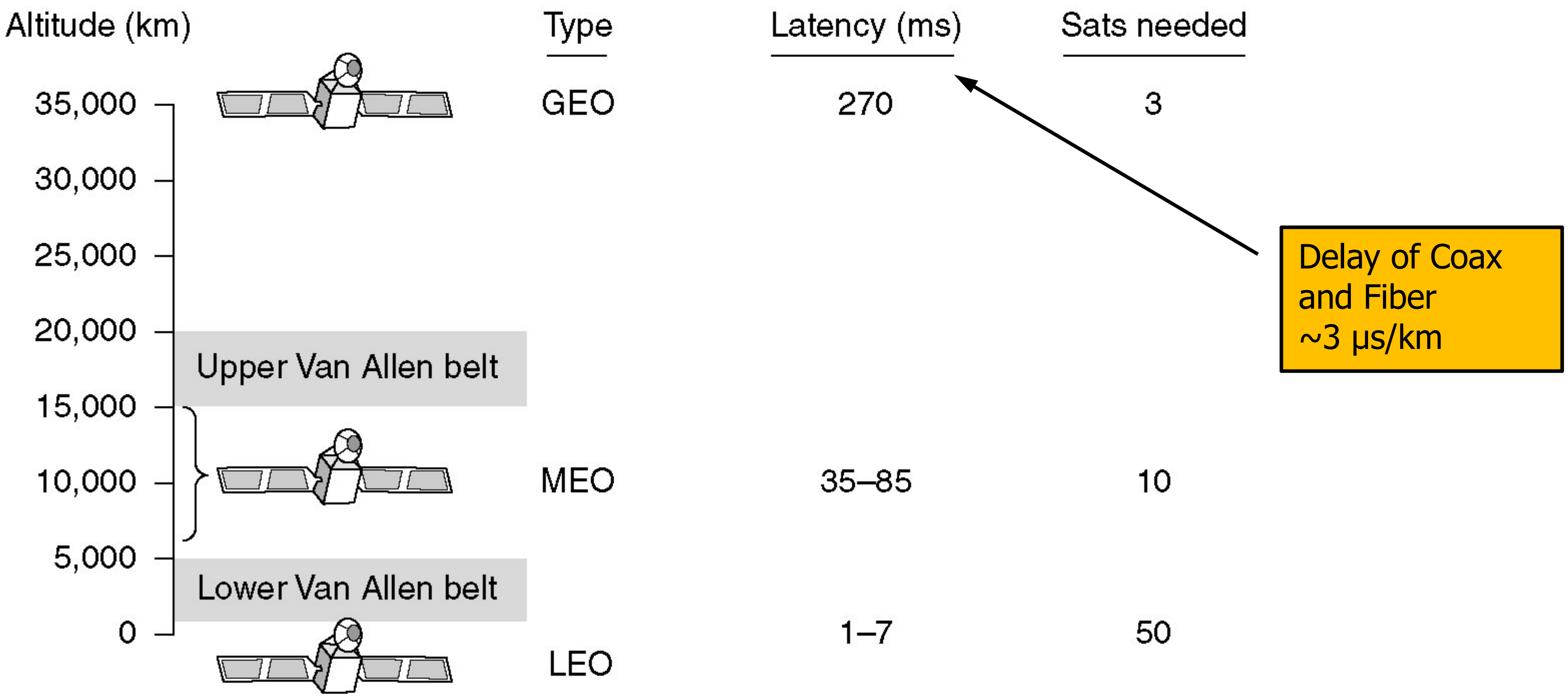


Communication Satellites: Types of Satellites

- **Geostationary Earth Orbit (GEO)**
  - Position over the two Van Allen belts
  - Quasi stationary on their positions
    - Planetary gravity moves GEOs
  - Large footprint, approx. 1/3 of earth's surface
- **Medium-Earth Orbit (MEO)**
  - Position between the two Van Allen belts
  - Orbital period approx. 6h
  - Smaller footprints than GEOs
  - Must be tracked
  - The 24 GPS satellites belong to this class
- **Low-Earth Orbit (LEO)**
  - Position below the two Van Allen belts
  - Rapid motion
    - Needs to be tracked



Communication Satellites



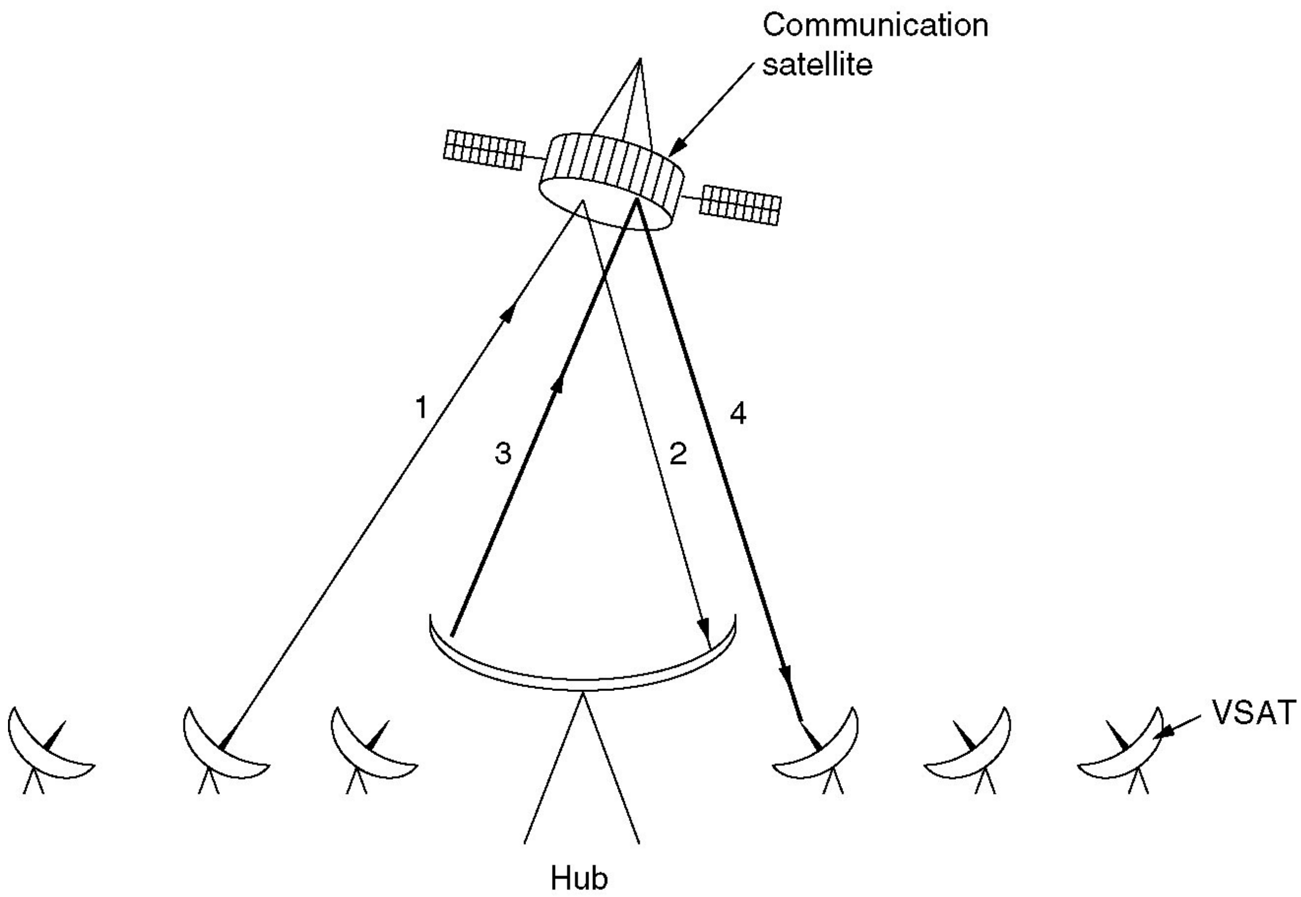
Communication satellites and some of their properties, including altitude above the earth, round-trip delay time, and number of satellites needed for global coverage.

Communication Satellites

- **Very Small Aperture Terminals (VSAT)**
  - Low-cost microstations
  - Small terminals ~1m (GEO ~10m)
  - Uplink 19.2kbps
  - Downlink 512kbps
  - Many stations do not have enough power to communicate directly via the satellite
  - A relay station is required → the **hub**
    - Either the sender or the receiver has a large antenna
    - Disadvantage: Longer delay

Communication Satellites

VSATs using a hub



Communication Satellites

- **Advantages**
  - Cost of messages independent from distance
  - Broadcast media
    - Message sent to one person or thousands does not cost more
    - Proxies for web access

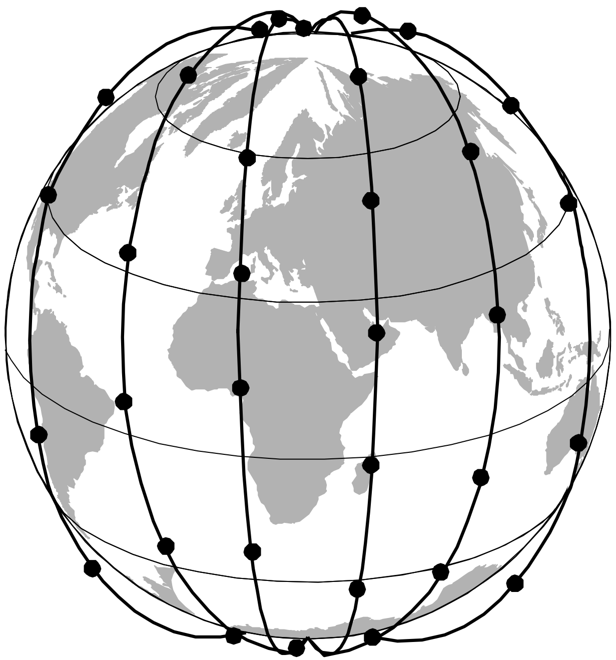
- **Disadvantages**
  - Long round-trip-time ~270 msec (540 msec for VSAT)
  - Broadcast media
    - Security issues

Communication Satellites

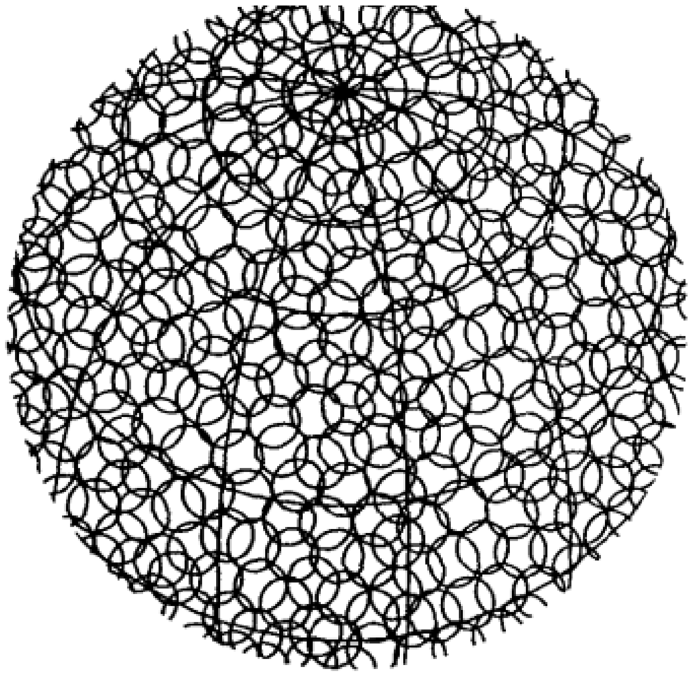
- **Iridium (LEO)**
  - www.iridium.com
  - Launch of the satellites 1997
  - Start of service 1998
  - Goal: Providing worldwide telecommunication service using hand-held devices that communicate directly with the satellites
    - Voice, data, paging, fax, navigation service
  - Position: 750 km
  - Total of 66 satellites
  - Relaying of distant calls is done in space

- **Globalstar (LEO)**
  - www.globalstar.com
  - Total of 48 satellites
  - Relaying of distant calls is done on the ground

Communication Satellites: Iridium

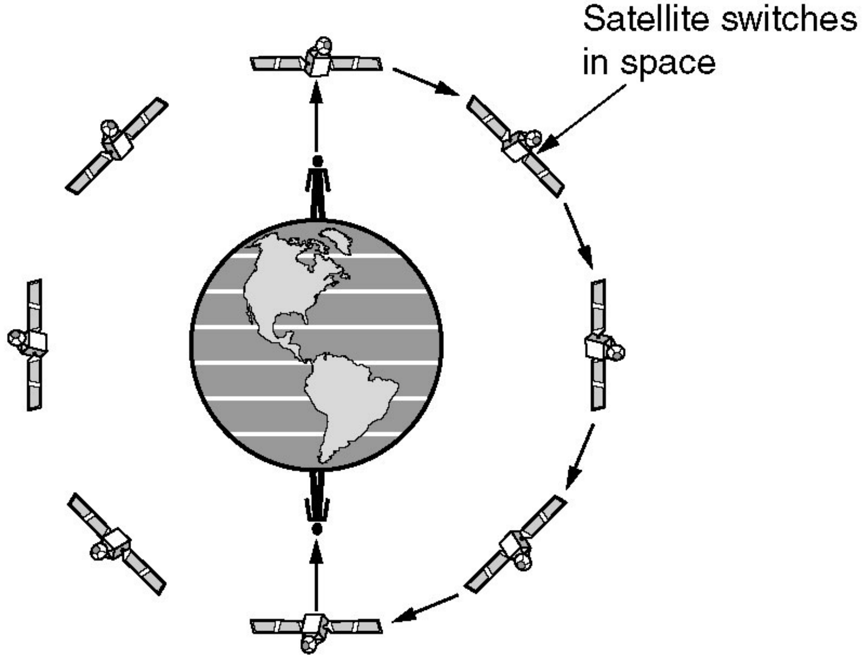


The Iridium satellites
form six necklaces
around the earth
[Iridium Constellation Applet]

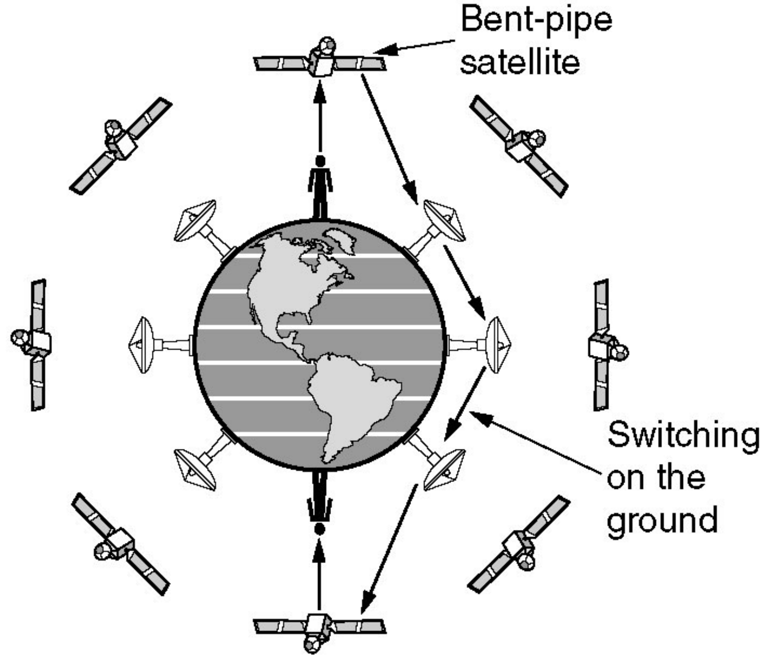


1628 moving cells
cover the earth

Communication Satellites



Relaying in space
Used in Iridium

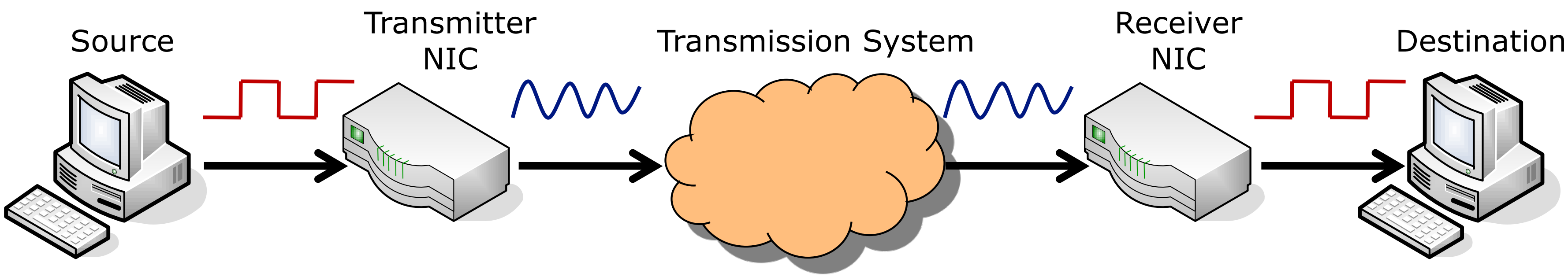


Relaying on the ground
Used in Globalstar

The Last Mile Problem

The Last Mile Problem

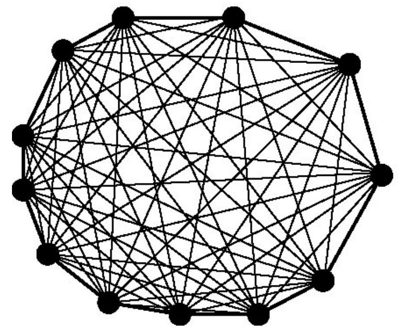
- **LAN, MAN, WAN – how to connect private users at home to such networks?**
  - Problem of the last mile: connect private homes to the Internet without installing many new cables
  - Use existing telephone lines: re-use them for data traffic
- **Examples:**
  - Classical Modem
  - Integrated Services Digital Network (ISDN)
  - Digital Subscriber Line (DSL)



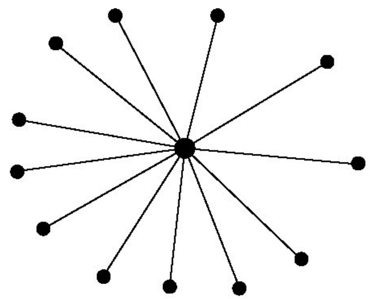
Structure of the Telephone System

Evolution of the telephone system

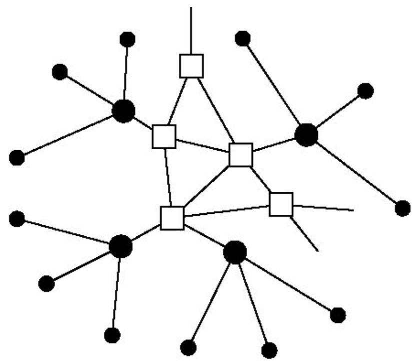
- **First, pairs of telephones were sold**
  - If a telephone owner wanted to talk to n different people, n separate wires were needed
  - Fully-interconnected network



- **Centralized switches (Switching offices)**
  - Telephones are connected to a central switch
  - Manually connecting of »talks« by jumpers

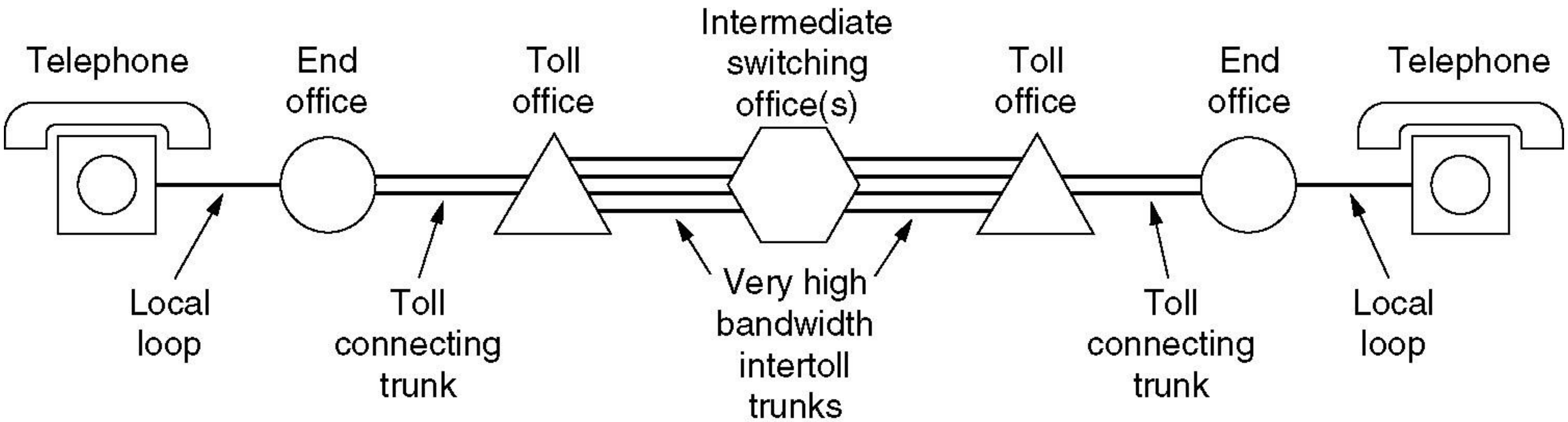


- **Second-level switches**
  - Connection of switching offices



Structure of the Telephone System

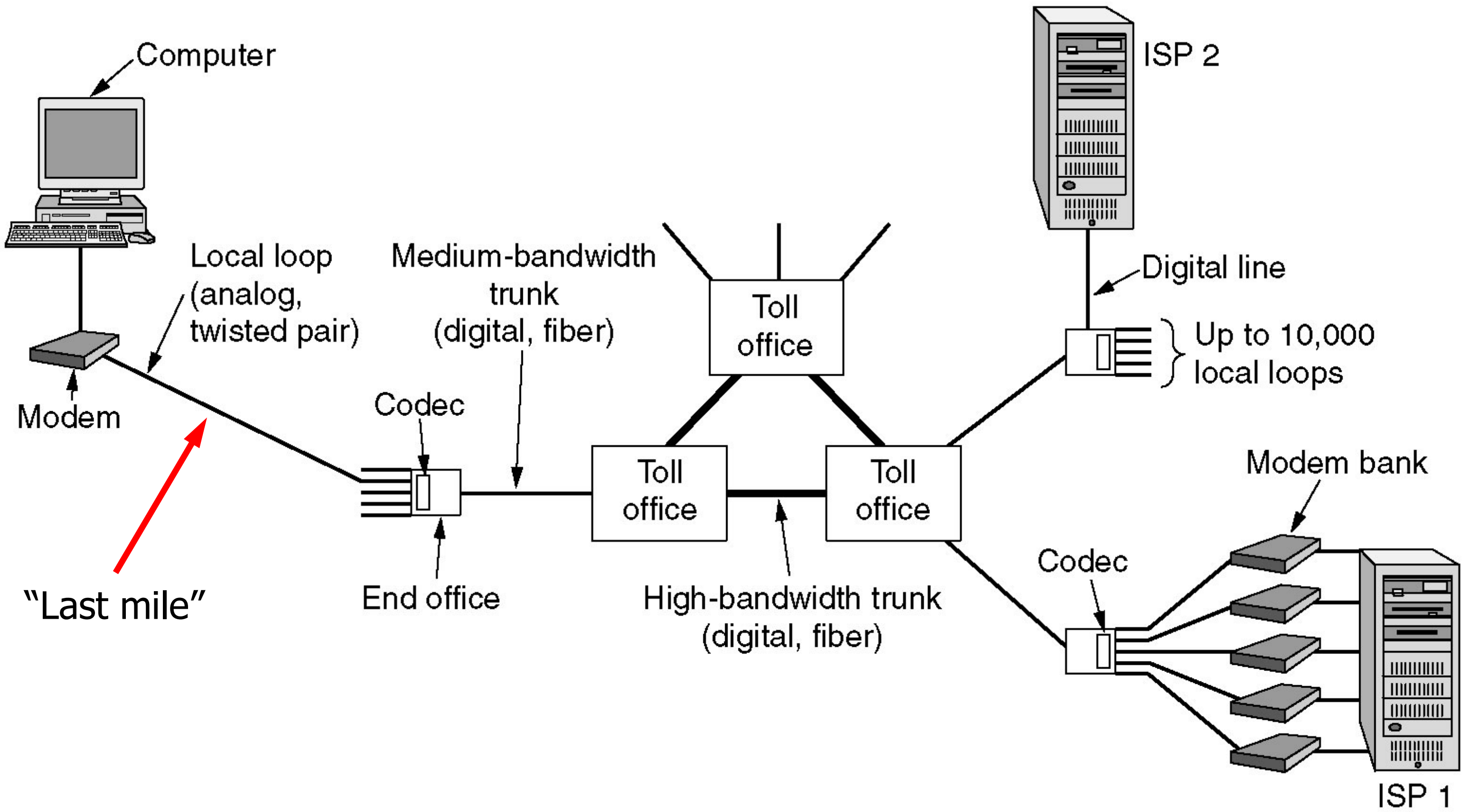
A typical circuit route for a medium-distance call.



- **Local loops**
  - Analog twisted pairs going to houses and businesses
- **Trunks**
  - Digital fiber optics connecting the switching offices
- **Switching offices**
  - Where calls are moved from one trunk to another

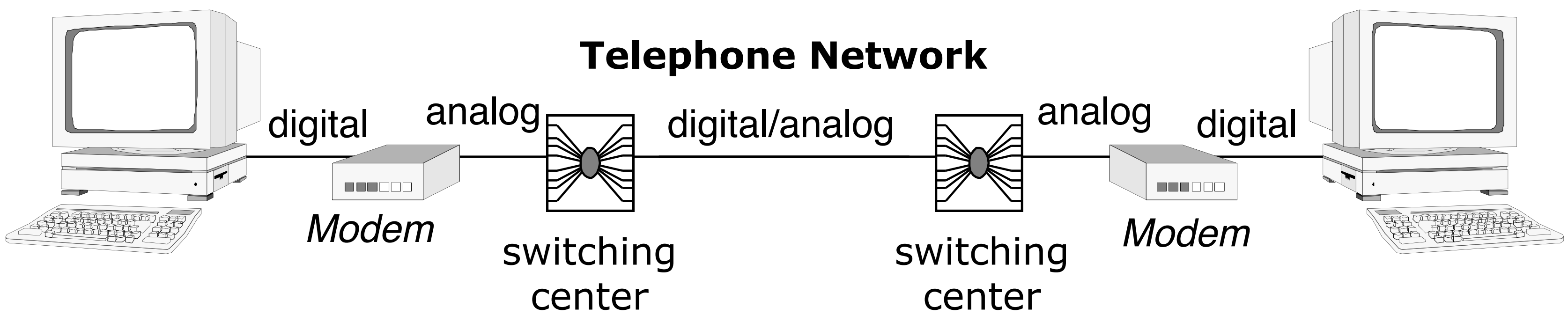
The Local Loop: Modems, ADSL, and Wireless

- **The use of both analog and digital transmissions for a computer to computer call. Conversion is done by modems and codecs.**



Data Transmission via Modem

- **Early approach: use existing telephone network for data transmission**
  - Problem of transmitting digital data over an »analog« medium
  - Necessary: usage of a Modem (**Mo**dulator - **Dem**odulator)
  - Digital data are transformed in analog signals with different frequencies (300Hz to 3400Hz, range of voice transmitted over the telephone network). The analog signals are transmitted to the receiver over the telephone network. The receiver also needs a modem to transform the analog signals into digital data.
  - For the telephone network the modem seems to be a normal phone, the modem even takes over the exchange of signaling information
  - Data rate up to 56 kbps
  - High susceptibility against transmission errors due to telephone cables



Modems

- **Problems**
  - Attenuation
  - Delay distortion
  - Noise
- **Square waves used in digital communication have a wide frequency spectrum**
  - Subject to attenuation and delay distortion
- **Solution**
  - AC (Alternating Current) signaling is used
  - Sine wave carrier is used
    - Continuous tone in range of 1000Hz to 2000Hz
  - Amplitude, frequency, or phase is modulated to transmit data

Acoustic Coupler

Modem Standards (CCITT)

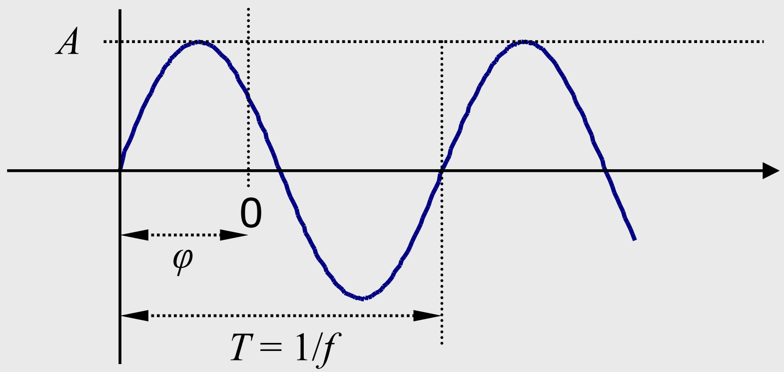
ITU-T standard	Mode	Downlink	Uplink
V.21 (FSK, 4 frequencies)	duplex	300 bps each	
V.22 (QPSK, 2 frequencies)	duplex	1.200 bps each	
V.22bis (16-QAM 4 phases, 2 amplitudes)	duplex	2.400 bps each	
V.23 (FSK, more frequencies)	halfduplex	1.200 bps	
	duplex	1.200 bps	75 bps
	duplex	75 bps	1.200 bps
V.32 (32-QAM)	duplex	9.600 bps each	
V.32bis (128-QAM)	duplex	14.400 bps each	
V.34 (960-QAM)	duplex	28.800 bps each	
V.34bis	duplex	33.600 bps each	
V.90 (128-PAM)	duplex	56.000 bps	33.600 bps

Modulation of Digital Signals

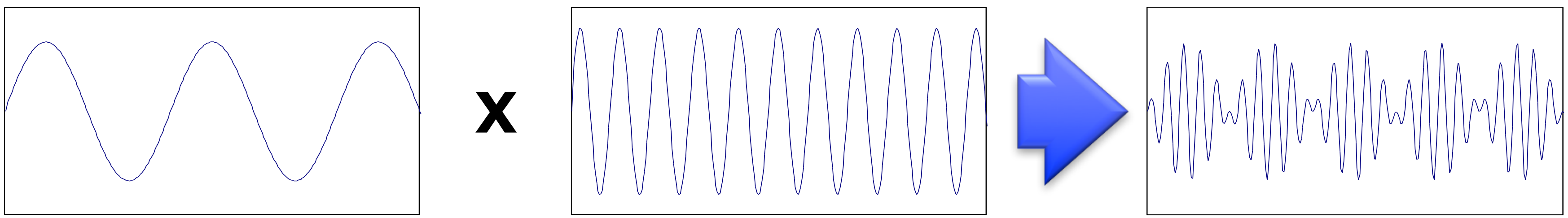
The digital signals (0 resp. 1) have to be transformed into **electromagnetic signals.** The process is called **modulation.**

Electromagnetic signal: $s(t) = A \cdot \sin(2 \cdot \pi \cdot f \cdot t + \varphi)$

- A: Amplitude
- f: Frequency
- T: Duration of one oscillation, period
- φ : Phase



Modulation ≈ choose a **carrier frequency** and »press« on your data.

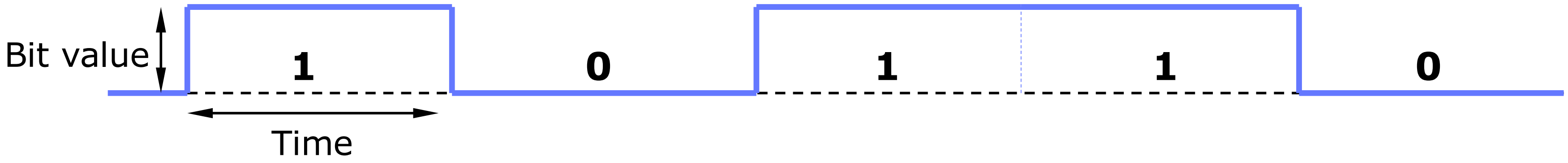


Not modulated signal

Carrier frequency (sin)

modulated signal

Modulation of Digital Signals

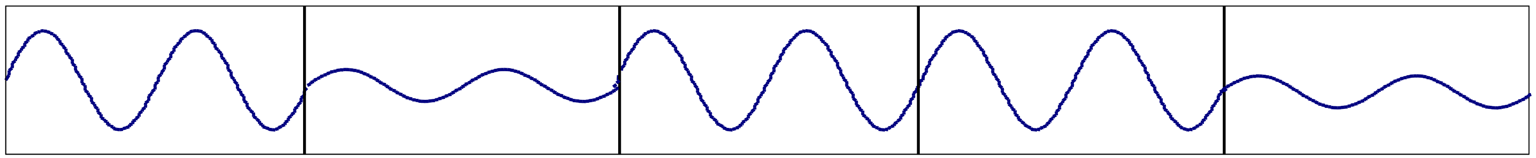


The conversion of digital signals can take place in various ways, based on the parameters of an analog wave:

$$s(t) = A \cdot \sin(2 \cdot \pi \cdot f \cdot t + \varphi)$$

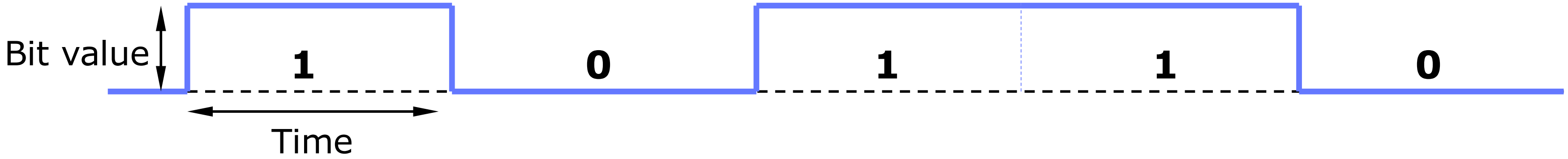
Amplitude Frequency Phase

Amplitude Modulation (Amplitude Shift Keying, ASK)



- Technically easy to realize
- Needs not much bandwidth
- Susceptible against disturbance
- Often used in optical transmission

Modulation of Digital Signals

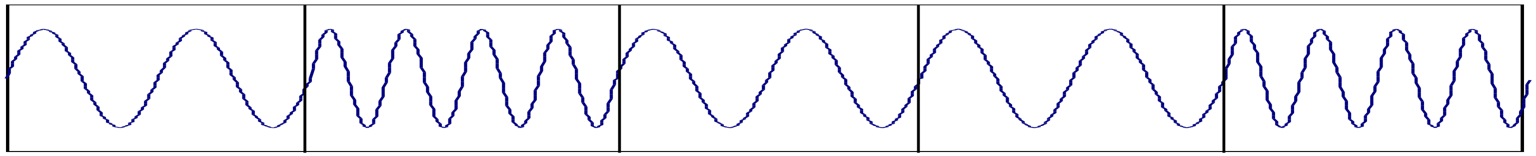


The conversion of digital signals can take place in various ways, based on the parameters of an analog wave:

$$s(t) = A \cdot \sin(2 \cdot \pi \cdot f \cdot t + \varphi)$$

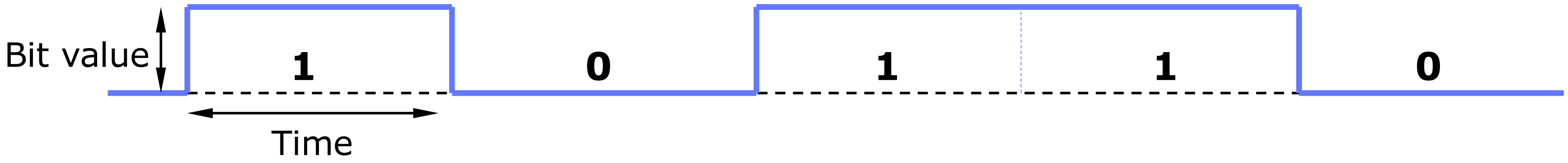
Amplitude **Frequency** Phase

Frequency Modulation (Frequency Shift Keying, FSK)



- »Waste« of frequencies
- Needs high bandwidth
- First principle used in data transmission using phone lines

Modulation of Digital Signals

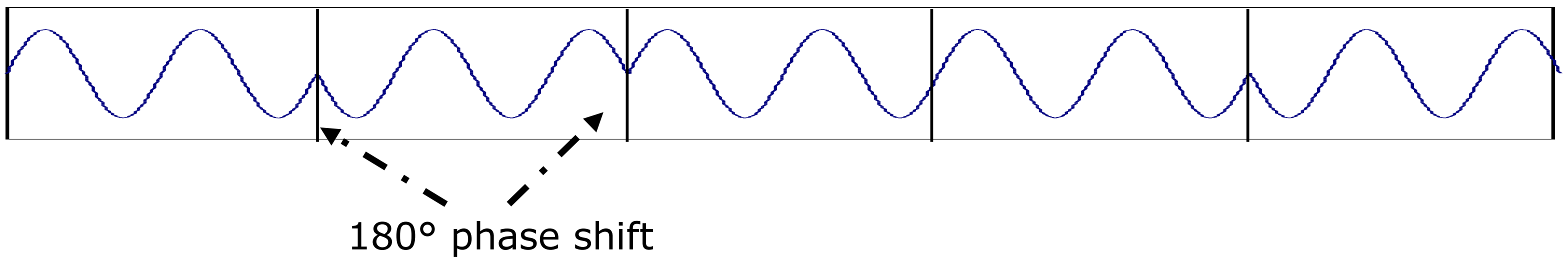


The conversion of digital signals can take place in various ways, based on the parameters of an analog wave:

$$s(t) = A \cdot \sin(2 \cdot \pi \cdot f \cdot t + \varphi)$$

Amplitude Frequency **Phase**

Phase Modulation (Phase Shift Keying, PSK)



- Complex demodulation process
- Robust against disturbances
- Best principle for most purposes

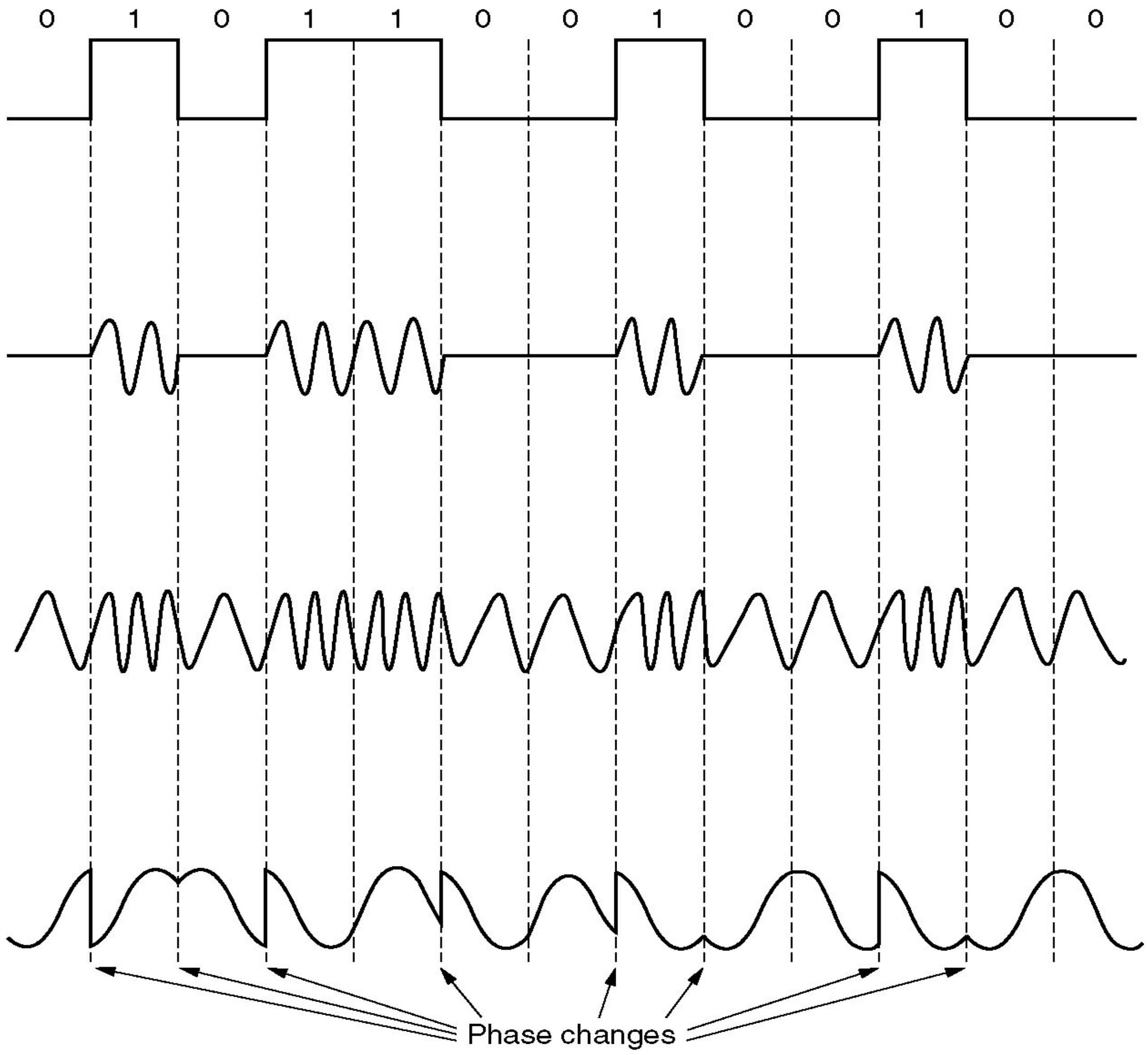
Modulation of Digital Signals: Overview

Binary signal

Amplitude modulation

Frequency modulation

Phase modulation

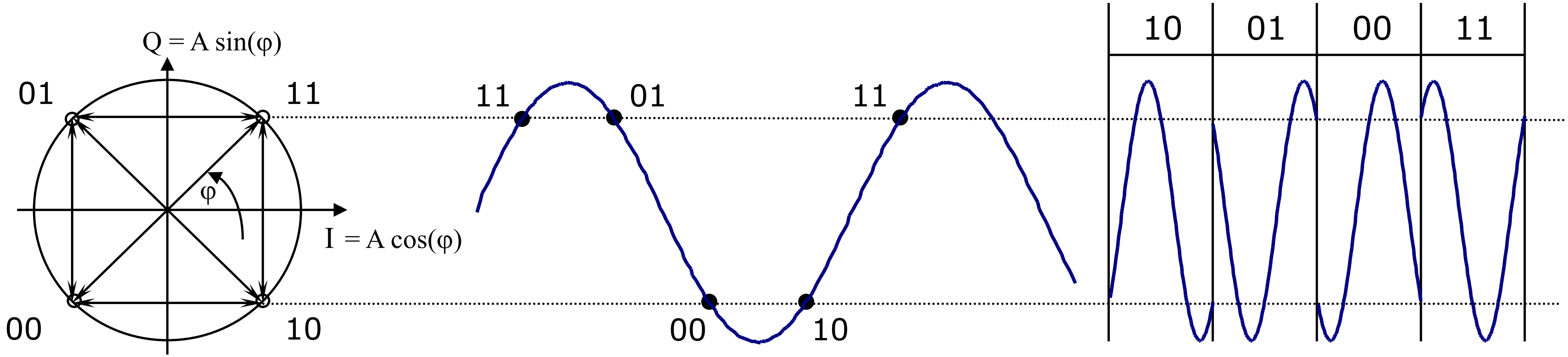


Advanced PSK Procedures

The phase shift can also cover more than two phases: shift between *M* different phases, whereby *M* must be a power of two. Thus at the same time more information can be sent.

Example: **QPSK** (Quadrature Phase Shift Keying)

- Shifting between 4 phases
- 4 phases permit 4 states: code 2 bits at one time
- Thus double data rate



A = amplitude of the signal

I = in phase, signal component (in phase with carrier signal)

Q = quadrature phase, quadrature component (perpendicular to the carrier phase)

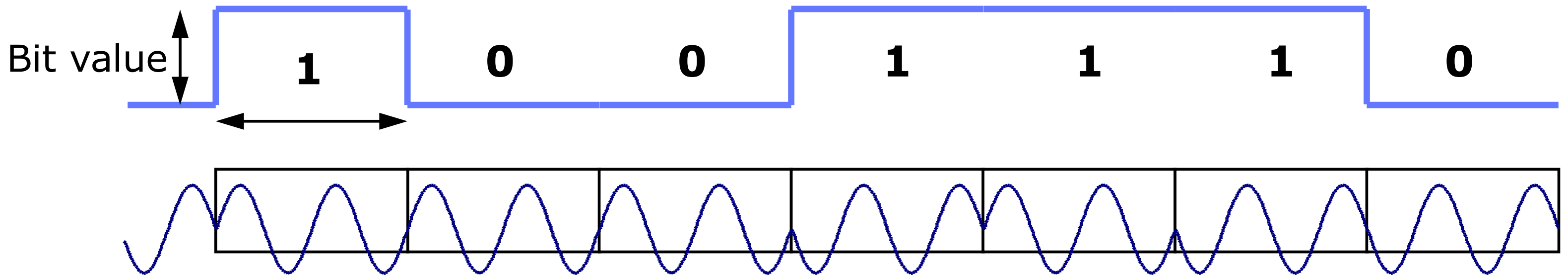
PSK Variants

Terms also in use:

- BPSK = Binary PSK = PSK
- 2B1Q = 2 Binary on 1 Quaternary = QPSK
- CAP = Carrierless Amplitude Phase Modulation (~QAM)

Differential techniques are also in use, e.g., DBPSK = Differential PSK

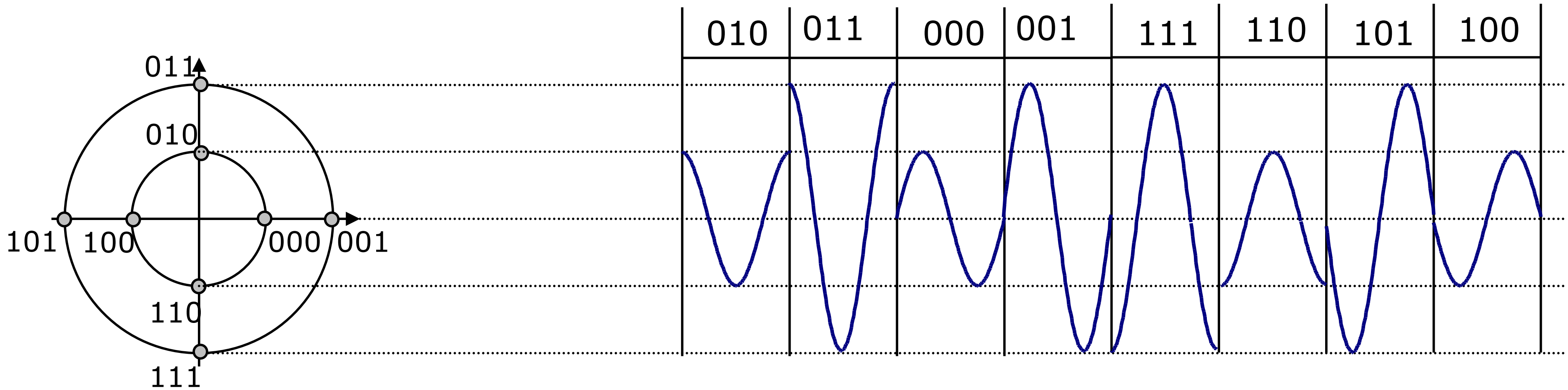
- Two different phases like in PSK
- Shift phase only if a 1 is the next bit – for a 0, no change is done.
- Example:

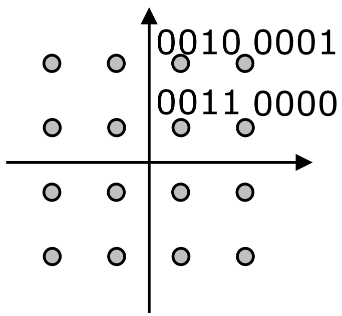


Advanced PSK Procedures

Quadrature Amplitude Modulation (QAM)

- Combination of ASK and QPSK
- *n* bit can be transferred at the same time (*n* =2 is QPSK)
- Bit error rate rises with increasing *n*, but less than with comparable PSK procedures



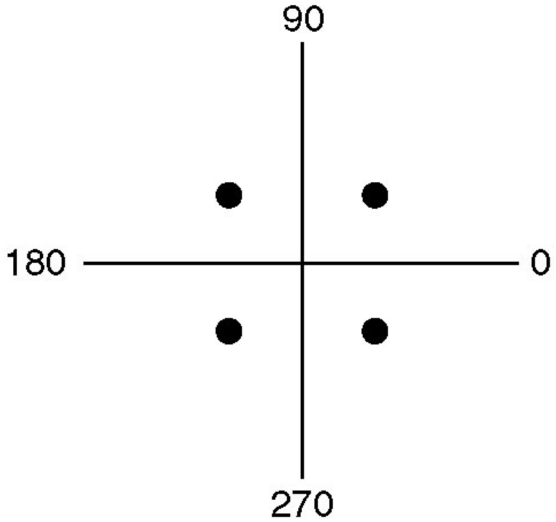


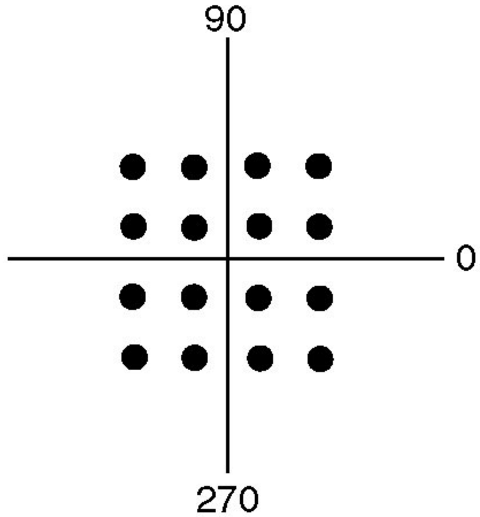
16-QAM: 4 bits per signal:

- 0011 and 0001 have same phase, but different amplitude
- 0000 and 0010 have same amplitude, but different phase

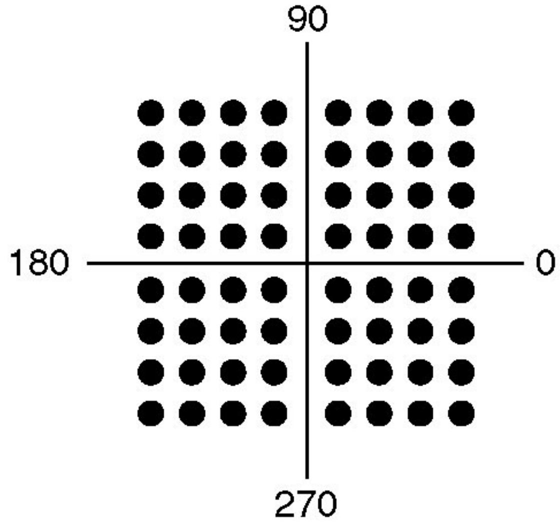
Modems: Constellation Diagrams

QPSK
2 bits/symbol





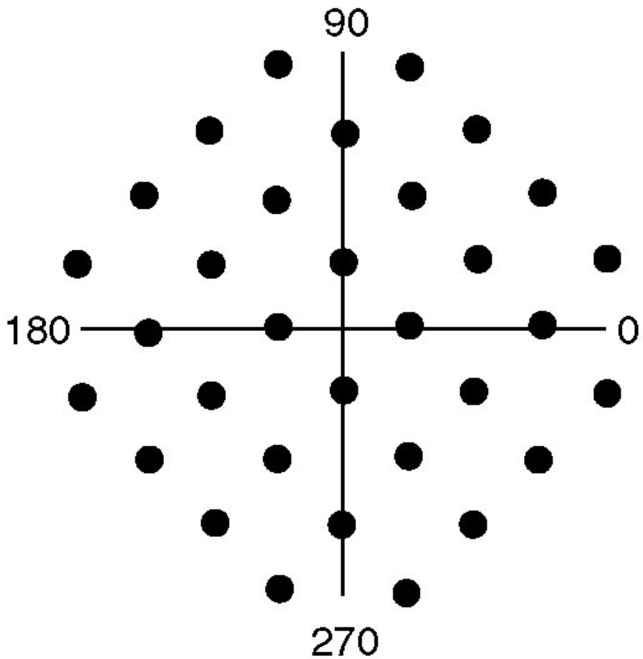
QAM-64
6 bits/symbol



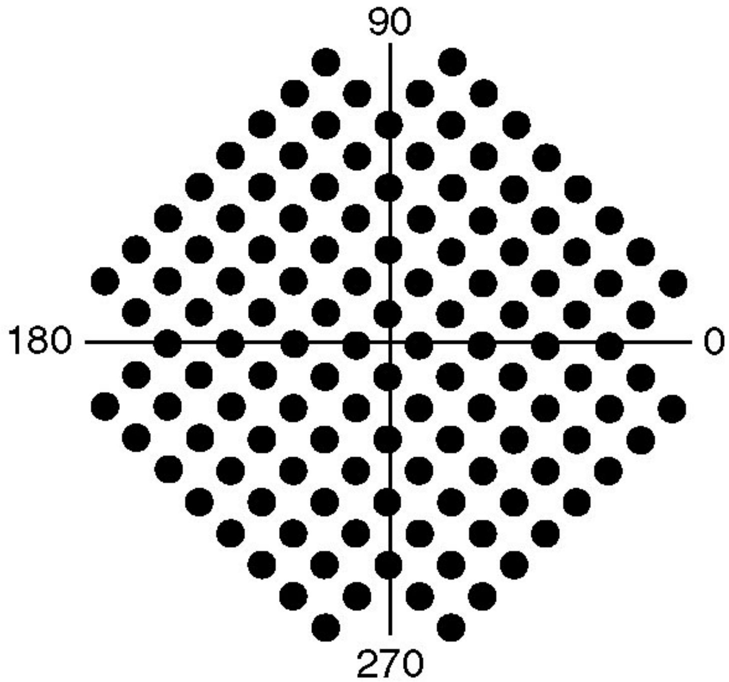
QAM-16
Four amplitudes and four phase
4 bits/symbol

Modems: Constellation Diagrams

V.32 for 9600 bps
32 constellation points
4 data bit and 1 parity bit



V.32bis for 14,400 bps
128 constellation points
6 data bits and 1 parity 1
Used by Fax



Pulse Amplitude Modulation (PAM)

- **Problem of QAM:**
  - 960-QAM for 28 kbps ➙ hard to increase the number of phases.

- **Thus forget all about FSK, PSK, ASK, …; for 56 kbps modems: 128-PAM.**
- **Simple principle:**
  - Define 128 different amplitudes
    - ➢ in this case: voltage levels
  - Transfer one signal (that means, voltage level) all 125 µs
  - By this, similar like in PCM, 56 kbps can be transferred
  - Thus: coming in principle back to cable codes…

Relationship of the Concepts

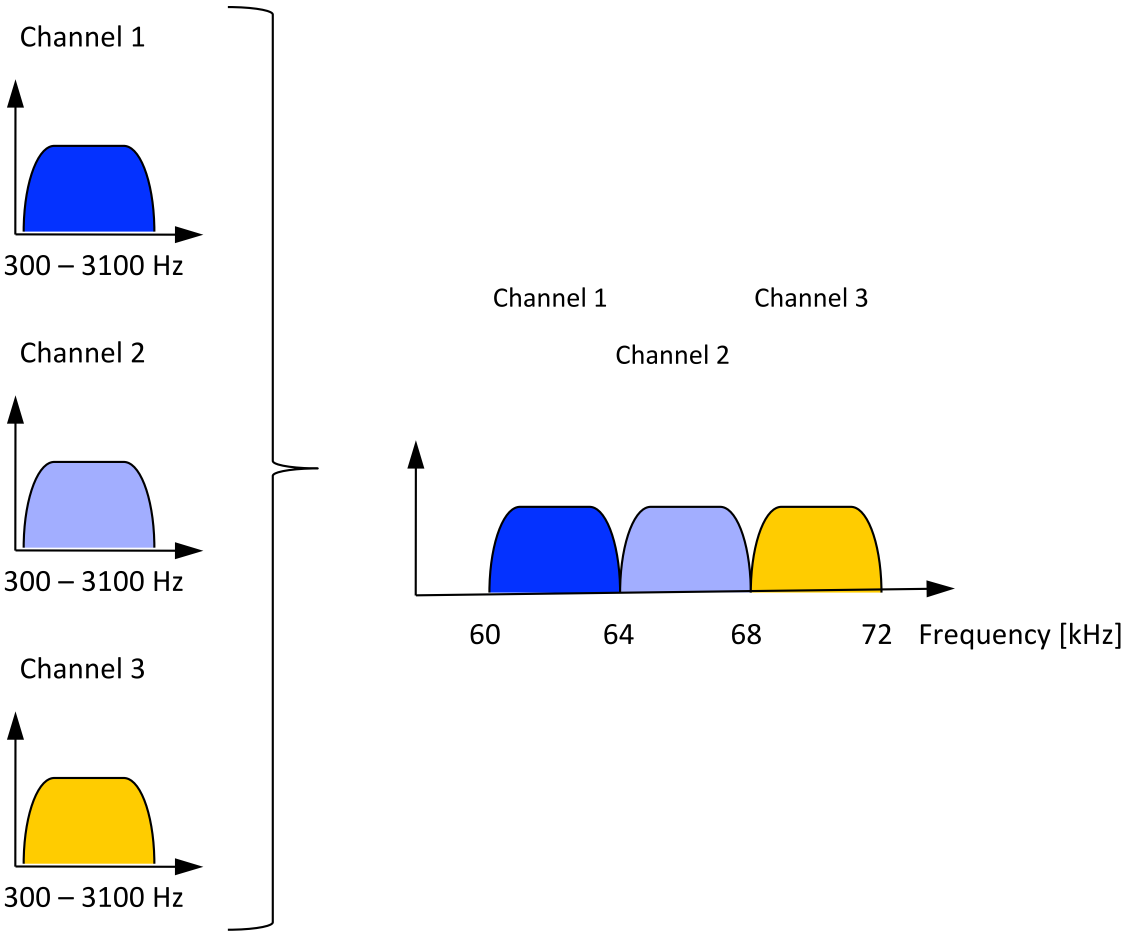
- **Relationship between bandwidth, baud, symbol, and bit rate**
  - Bandwidth [Hz]
    - Property of the medium
    - Range of frequencies that pass through with minimum attenuation
  - Baud rate = Symbol rate [bd]
    - Number of samples per second
    - Each sample = one piece of information
    - Modulation technique determines the number of bits per symbol
  - Bit rate [bps, bit/s]
    - Amount of information send over the channel
    - Equals to: Number of symbols/sec × Number of bits/symbol

Multiplexing

Multiplexing

- **Lines are expensive and should be used very effective**
- **Multiplexing**
  - Sharing of an expensive resource, e.g., transmit multiple connections over the same line
- **Two basic categories of multiplexing**
  - Frequency Division Multiplexing (FDM)
    - Frequency spectrum is divided into frequency bands, which are used exclusively
  - Time Division Multiplexing (TDM)
    - The full frequency spectrum is used in a round-robin fashion by the users

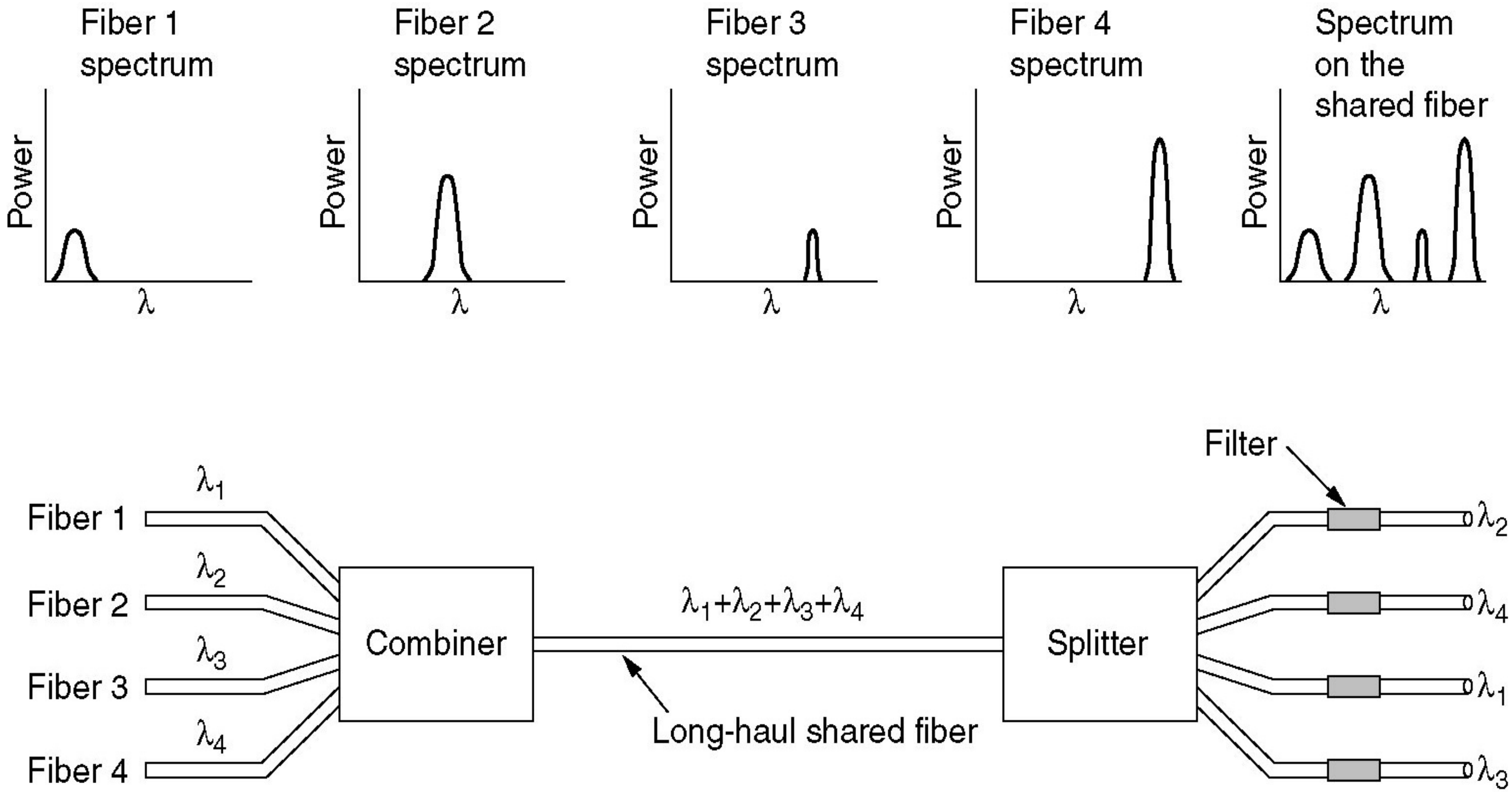
Frequency Division Multiplexing



- **To some degree standardized**
  - Multiplexing of 12 4000-Hz voice channels into 60-108kHz band
  - This unit is a **group**
  - Five groups built a **supergroup**
  - Five supergroups built a **mastergroup**

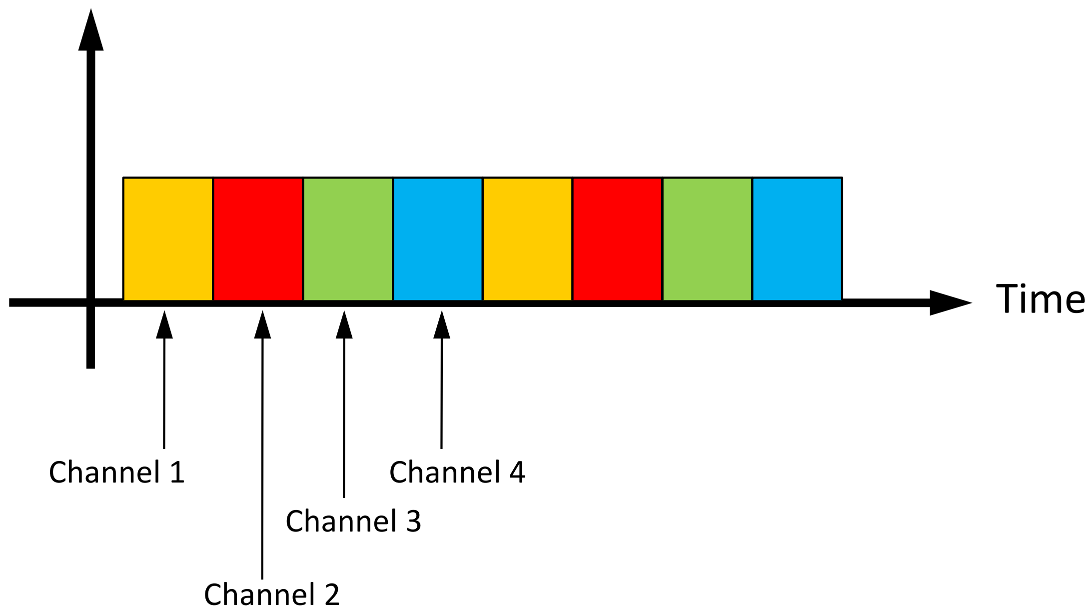
Wavelength Division Multiplexing

- **FDM for optical transmission ➡ Wavelength Division Multiplexing (WDM)**

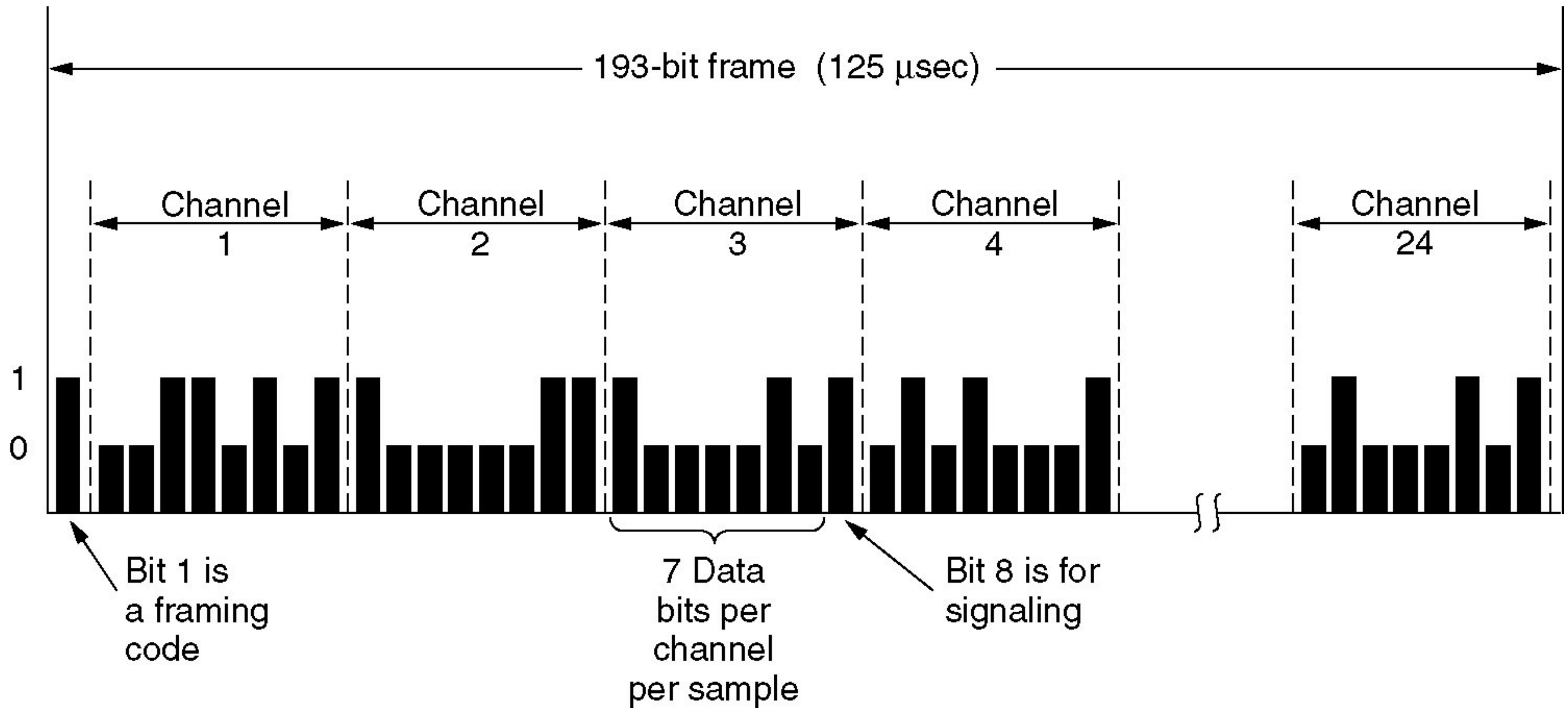


Time Division Multiplexing

- **Time domain is divided into timeslots of fixed length**
  - Each timeslot represents one subchannel



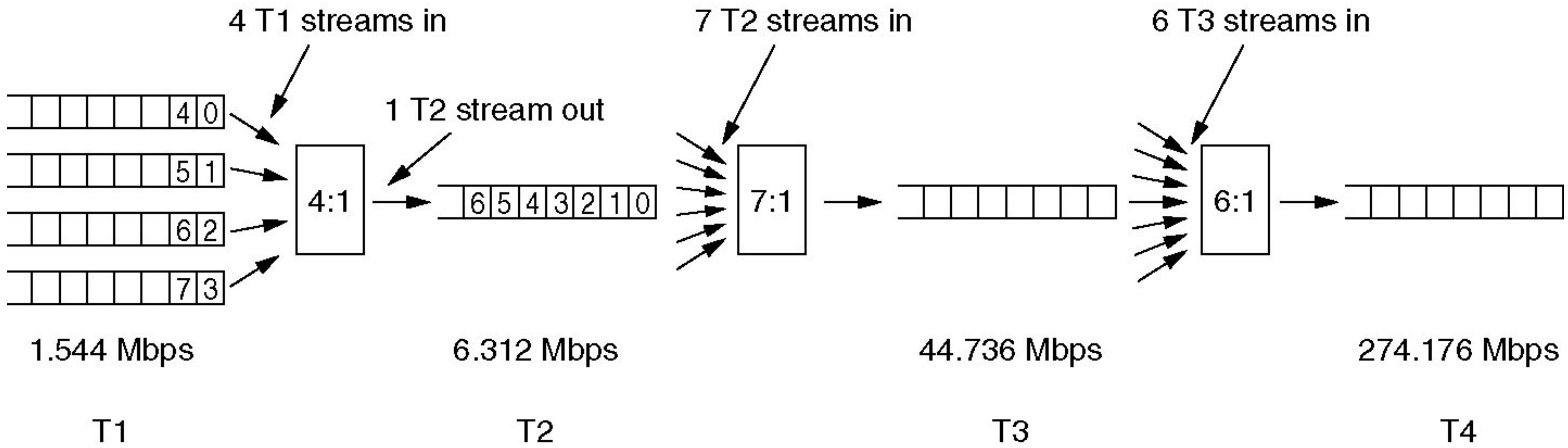
Time Division Multiplexing



The T1 carrier (1.544 Mbps)

Time Division Multiplexing

Multiplexing T1 streams into higher carriers



Time Division Multiplexing

- **Synchronous Optical Network (SONET)**
  - Optical TDM system
  - Long distance telephone lines
- **Synchronous Digital Hierarchy (SDH)**
  - Standard developed by the ITU
- **Goals**
  - Different carriers should interwork
  - Unification of US, European, and Japanese digital systems
    - All based on 64kbps PCM, but different combinations
  - Multiplexing of multiple digital channels
  - Support for operations, administration, and maintenance (OAM)
- **Method**
  - Synchronous, i.e., there is a master clock with an accuracy of 10^{-9}

▪ Used in US and Canada
▪ Rest of the world

Integrated Services Digital Network (ISDN)

Networks and Services

- **It is possible to combine telephony and data networks more efficient than modems do**
  - ATM: digitization of speech/modem: analogization of data
  - Telephone core networks today are digital, why not digitize voice already at the end user?
- **Thus: service integration – integrate several kinds of data transfer already on user site, with lower costs than ATM technology would cause**

- **Integrated Services Digital Network (ISDN)**
  - Integration of different communication services (voice, fax, data, ...)
  - Digital communication
  - Higher capacity than modem-based data transfer
  - Uses existing infrastructure: ISDN is no new network, but something added to an existing network
  - Different standards (Euro-ISDN resp. national ISDN)

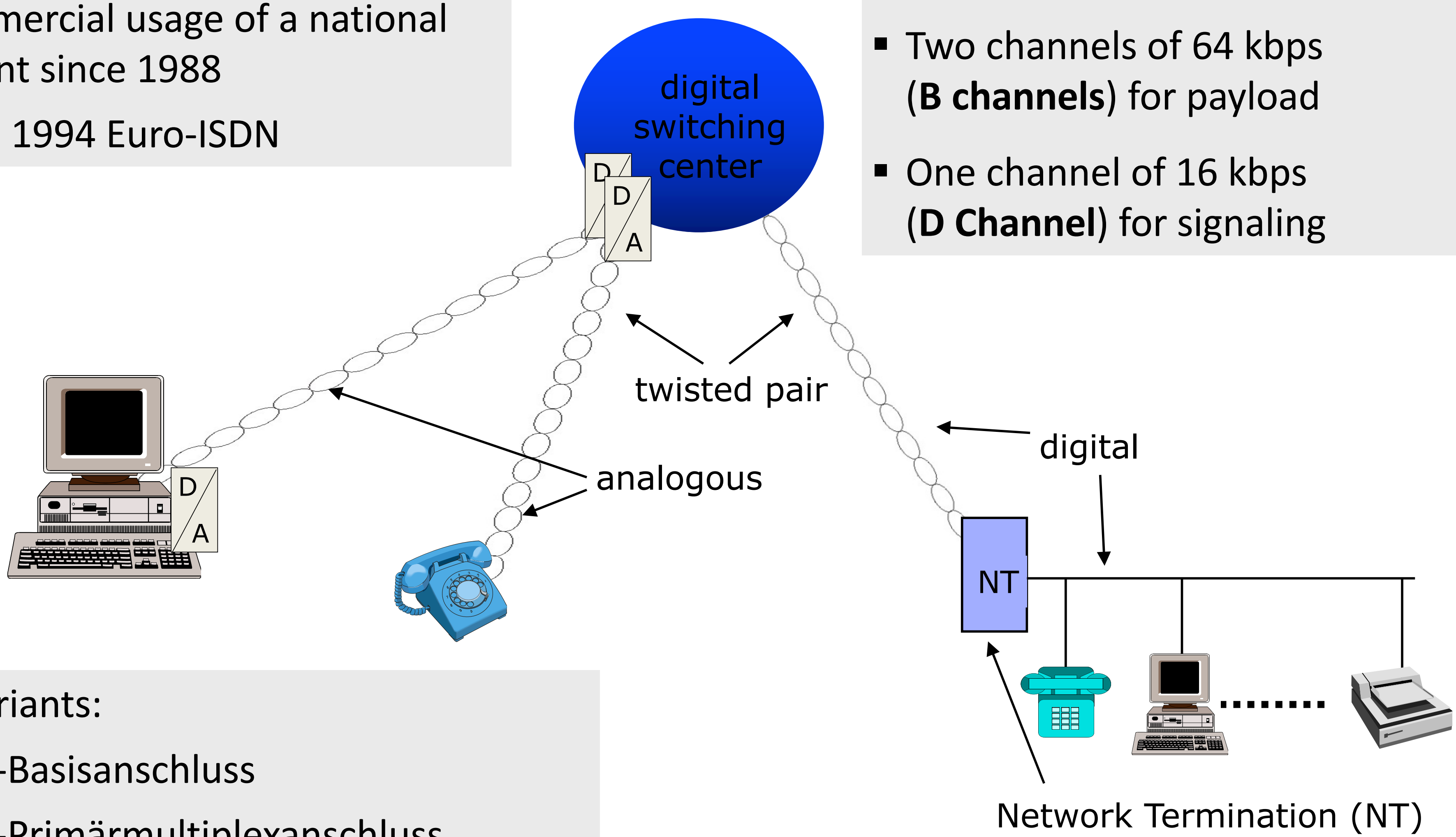
Services in ISDN

- **Telephony**
  - Most important service: voice transmission
- **But with new features, e.g.**
  - Several numbers for single telephones
  - Transmission of own phone number to the receiving party
  - Forwarding of incoming calls to other phones
  - Creation of closed user groups
  - Conferencing with three parties
  - Handling of several calls in parallel
  - Presentation of tariff information
  - Physical relocation of phones
- **Computer**
  - Network access with a data rate up to 144 kbps

ISDN

- First tests since 1983
- Commercial usage of a national variant since 1988
- Since 1994 Euro-ISDN

- Connection of up to 8 devices to the NT
- Two channels of 64 kbps (**B channels**) for payload
- One channel of 16 kbps (**D Channel**) for signaling



Two variants:

- ISDN-Basisanschluss
- ISDN-Primärmultiplexanschluss

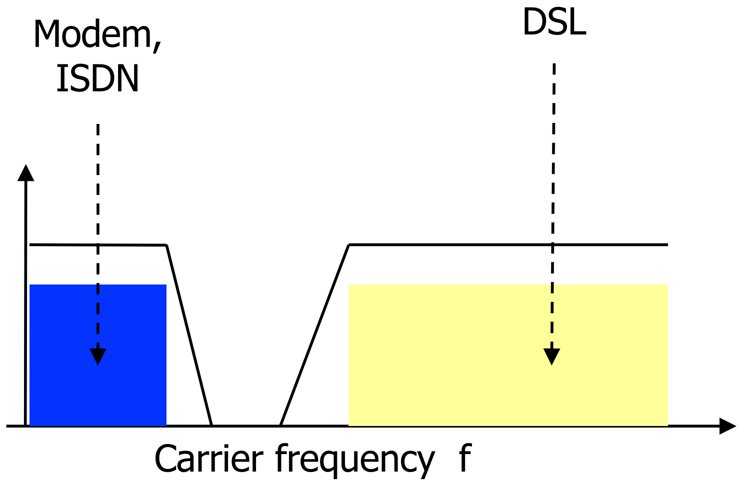
ISDN Connections

- **ISDN-Basisanschluss**
  - Two independent channels of 64 kbps each for voice or data transmission
  - Signaling information on the D channel (e.g. path establishment, transfer of phone number to the other party, …)
  - Overall capacity of 144 kbps for data bursts by combining all channels
  - Time multiplexing of the channels on the cable
- **ISDN-Primärmultiplexanschluss**
  - Simply a combination of several basic connections
    - one D channel of 64 kbps, 30 B channels
  - Overall 2 Mbps capacity
- **Broadband-ISDN (B-ISDN)**
  - Was planned as a ISDN variant with a higher bandwidth using the same mechanisms
  - Two much problems: thus, ATM was used as a basis here

Digital Subscriber Line (DSL)

Today: Digital Subscriber Line (DSL)

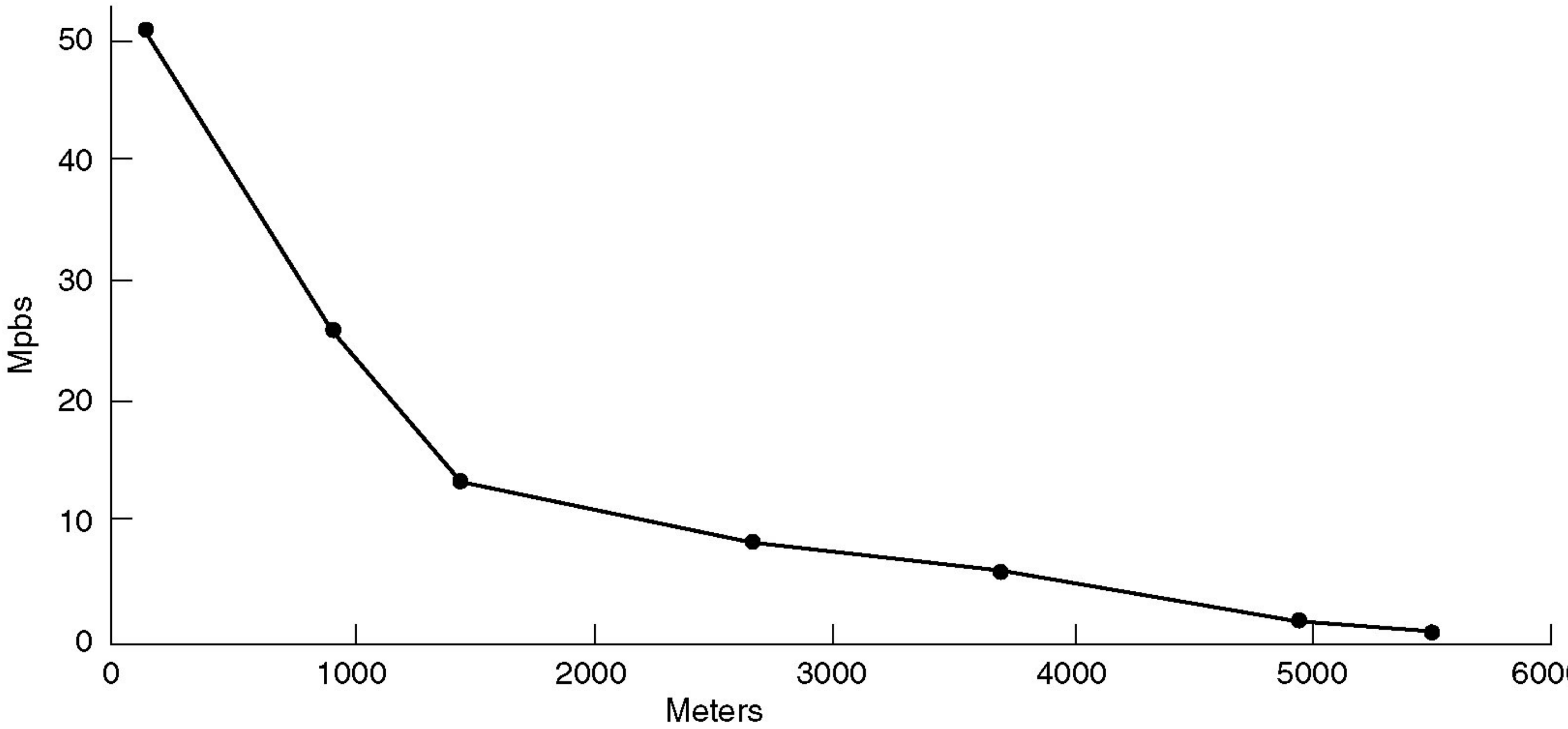
- **Characteristics of DSL**
  - High capacity (up to 50 Mbps)
  - Usage of the existing infrastructure
  - Combination of usual phone service (analog/ISDN) and data service
    - simply use the whole spectrum a copper cable can transfer, not only the range up to 3.4 kHz!
  - Data rate depends on distance to the switching center and the cable quality (signal weakening)
  - Automatic adaptation of data rate in case of distortions
  - Modulation by means of Discrete Multi-tone Modulation (**DMT**) or Carrierless Amplitude Phase Modulation (CAP)
  - Several variants, general term: xDSL



Distance	Downstream	Upstream
1.4 km	12.96 Mbps	1.5 Mbps
0.9 km	25.86 Mbps	2.3 Mbps
0.3 km	51.85 Mbps	13 Mbps

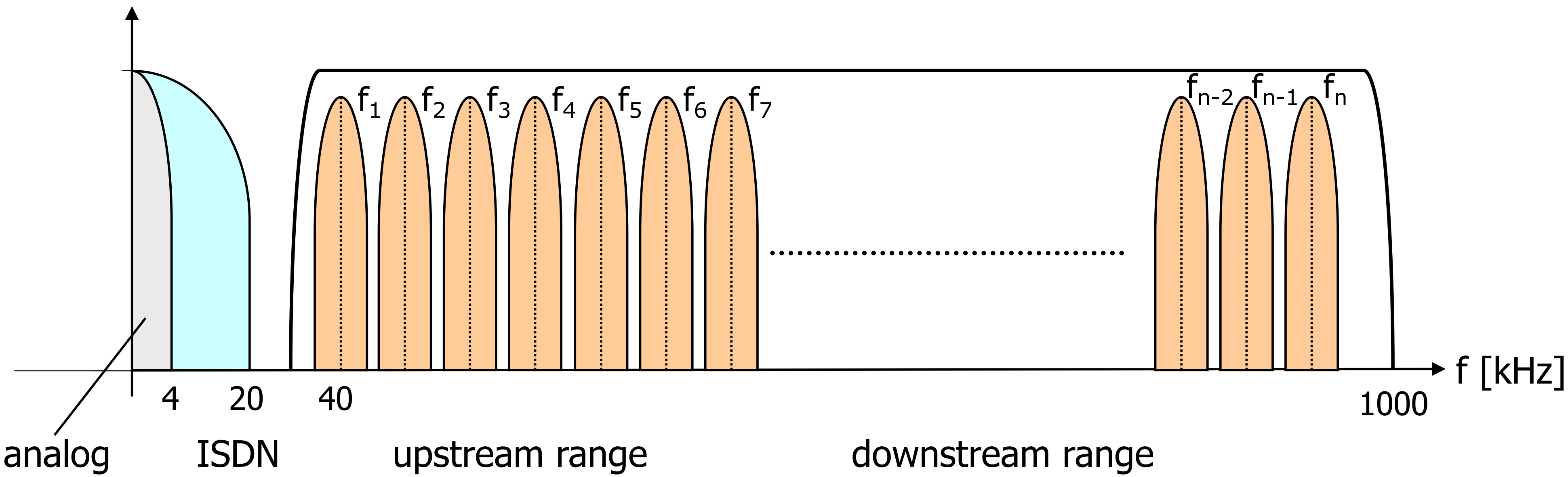
Digital Subscriber Lines

Bandwidth versus distance over category 3 UTP for DSL.

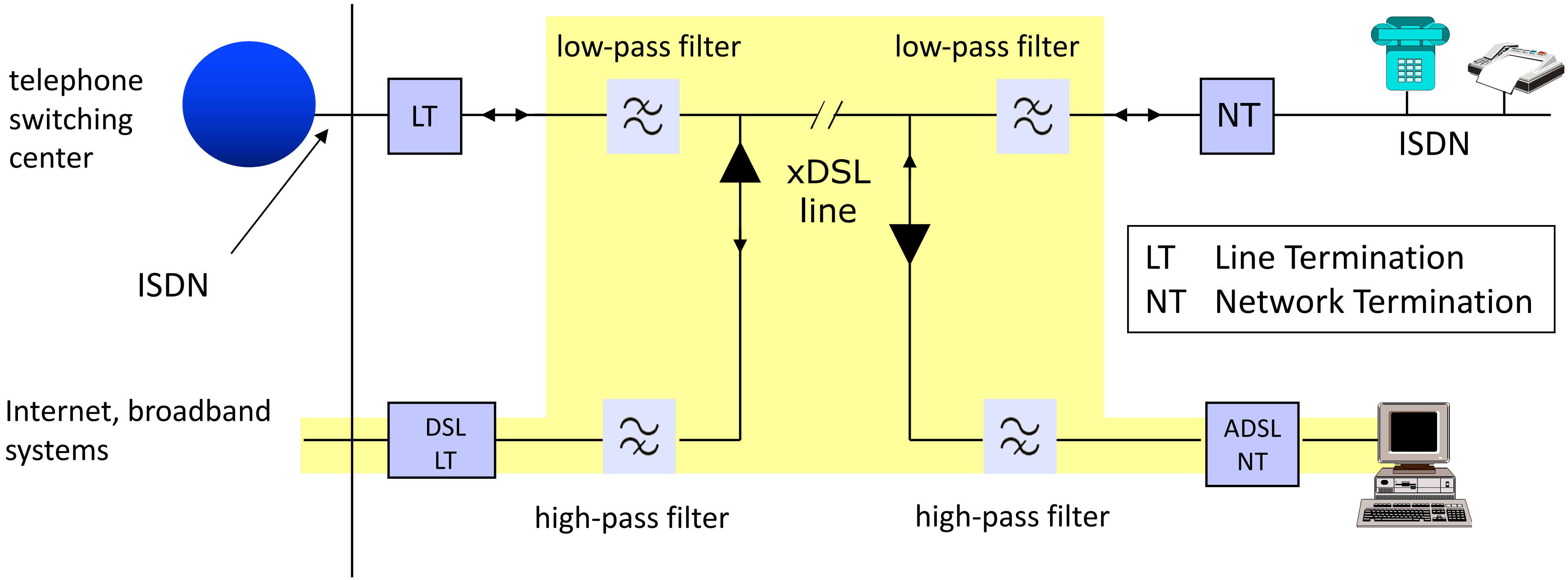


Discrete Multitone Modulation (DMT)

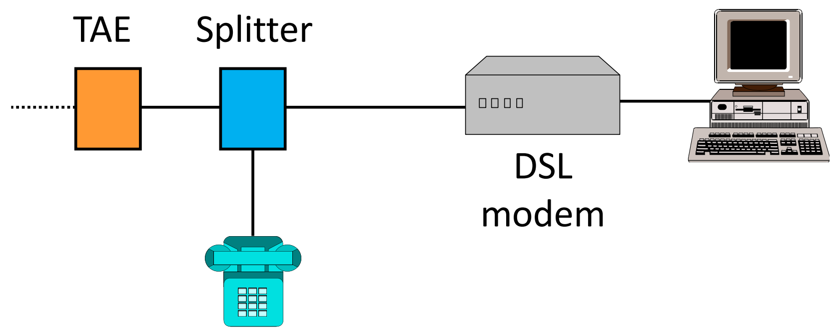
- **Use multiple carriers (e.g. 32 channels of 4 kHz bandwidth each for upstream and 256 channels for downstream)**
- **Each channel uses a suitable (optimal) modulation method: QPSK up to 64-QAM**
- **Easiest case: use same method on each carrier**
- **Channels in high frequency range are usually of lower quality (faster signal weakening in dependence of the distance)**
- **Modulation method depends on the signal quality, i.e., robustness is given**
- **Only up about 1 MHz, higher frequencies are to susceptible to distortions**



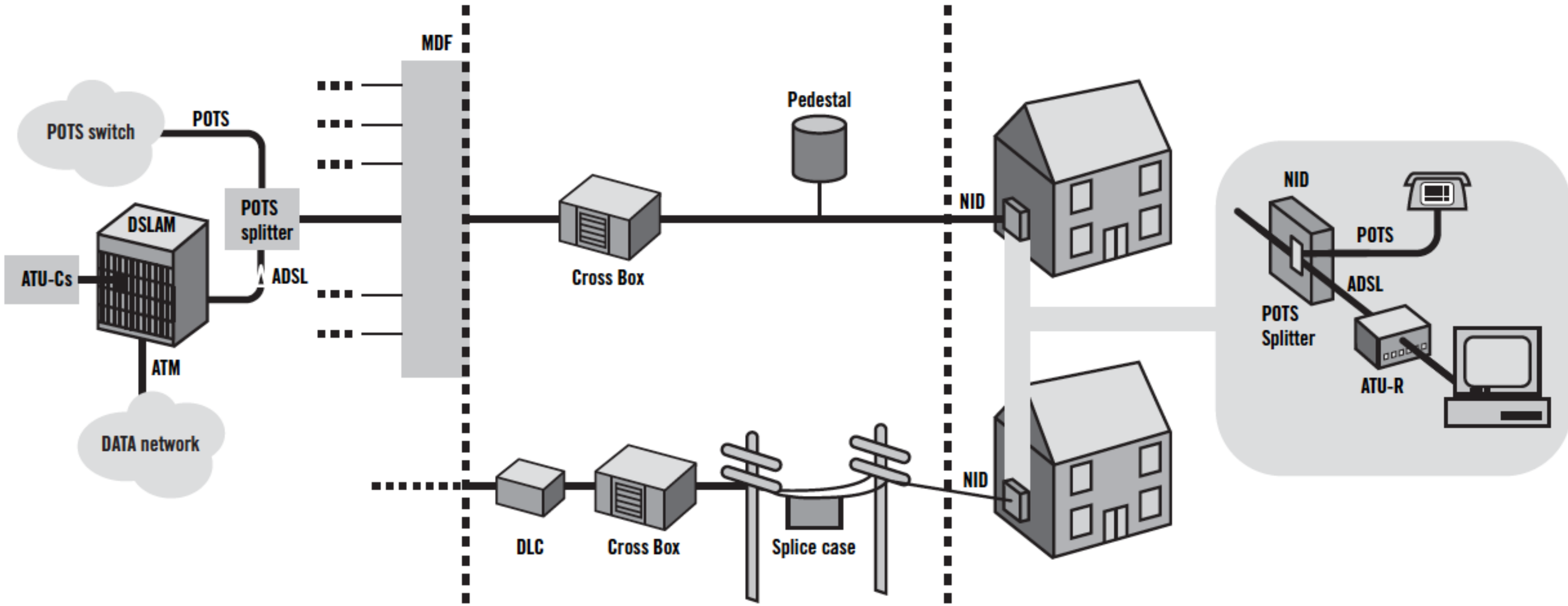
Necessary Equipment



- **Splitter**: combines low- and high-pass filter to separate data and voice information
- **DSL modem**: does modulation
- **TAE**: normal phone connector



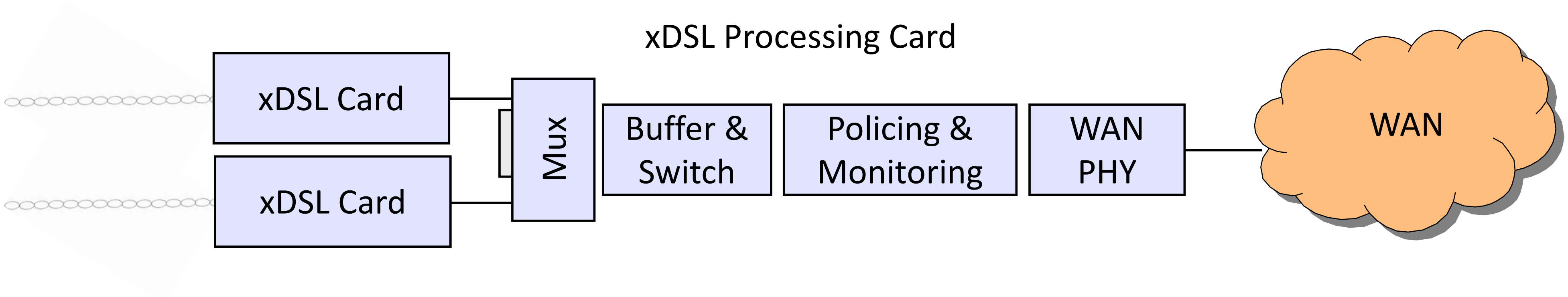
DSL



MDF
Pedestal
POTS switch
POTS
POTS
splitter
DSLAM
ATU-Cs
ADSL
ATM
DATA network
Cross Box
NID
NID
POTS
ADSL
POTS
Splitter
ATU-R
DLC
Cross Box
Splice case
NID

DSL Access Multiplexer (DSLAM)

- **In the switching center of the provider a splitter separates phone data from computer data**
  - Phone data are forwarded into the telephone network
- **Computer data are received by a DSLAM (DSL Access Multiplexer)**
  - In the DSLAM, all DSL lines are coming together
  - The DSLAM multiplexes DSL lines into one high speed line
  - The multiplexed traffic is passed into an WAN, usually SDH



xDSL: Variants

HDSL (High Data Rate Digital Subscriber Line)

- High, symmetrical data rate using only two carriers, not DMT
- Based on 2B1Q or CAP modulation
- No simultaneous telephone possible

- Distance: 3 - 4 km
- Bandwidth: 240 KHz
- Sending rate: 1,544-2,048 Mbps
- Receiving rate: 1,544-2,048 Mbps

SDSL (Symmetric Digital Subscriber Line)

- Variation of HDSL using only one carrier
- Symmetrical data rates
- 2B1Q, CAP or DMT modulation

- Distance : 2 - 3 km
- Bandwidth : 240 KHz
- Sending rate: 1,544-2,048 Mbps
- Receiving rate: 1,544-2,048 Mbps

ADSL (Asymmetric Digital Subscriber Line)

- Duplex connection with asynchronous rates
- Data rate depends on length and quality of the cables, adaptation to best possible coding
- CAP or DMT modulation

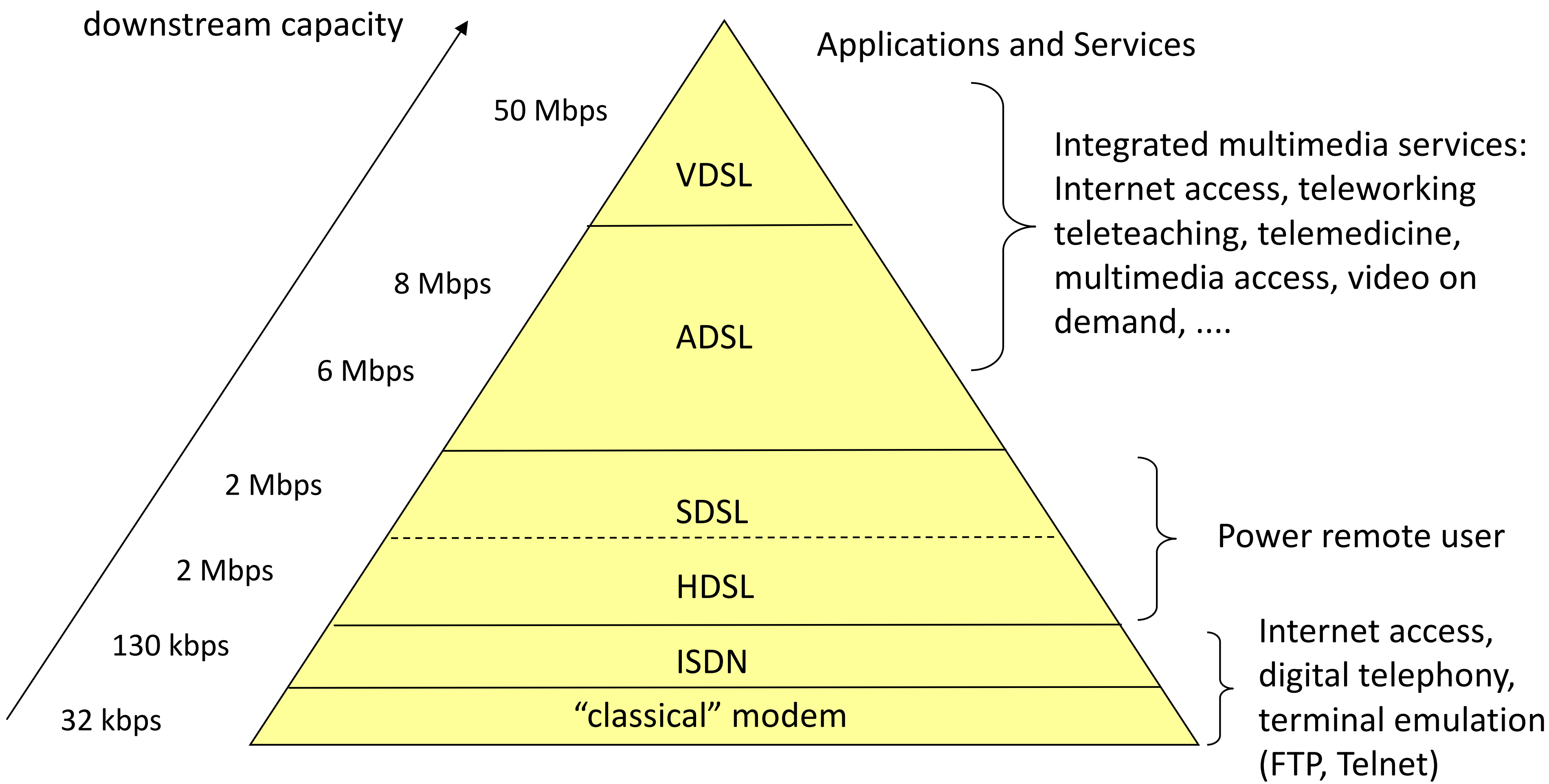
- Distance: 2,7 - 5,5 km
- bandwidth: up to 1 MHz
- Sending rate: 16-640 kbps
- Receiving rate: 1,5-9 Mbps

VDSL (Very High Data Rate Digital Subscriber Line)

- Duplex connection with asynchronous rates
- Higher data rate as ADSL, but shorter distances
- Variants: symmetrical or asymmetrical

- Distance: 0,3 - 1,5 km
- Bandwidth: up to 30 MHz
- Sending rate: 1,5-2,3 Mbps
- Receiving rate: 13-52 Mbps

xDSL: Variants



Mobile Telephone System

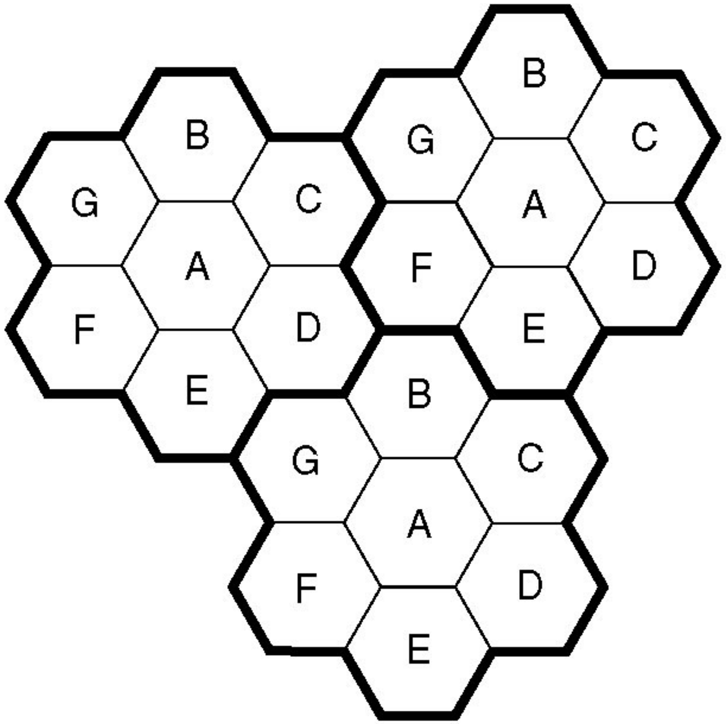
The Mobile Telephone System

- **Generations of Mobile Telephone Systems**
  - First-Generation
    - Analog Voice
  - Second-Generation
    - Digital Voice
  - Third-Generation
    - Digital Voice and Data
  - Fourth-Generation
    - All digital
    - IP based

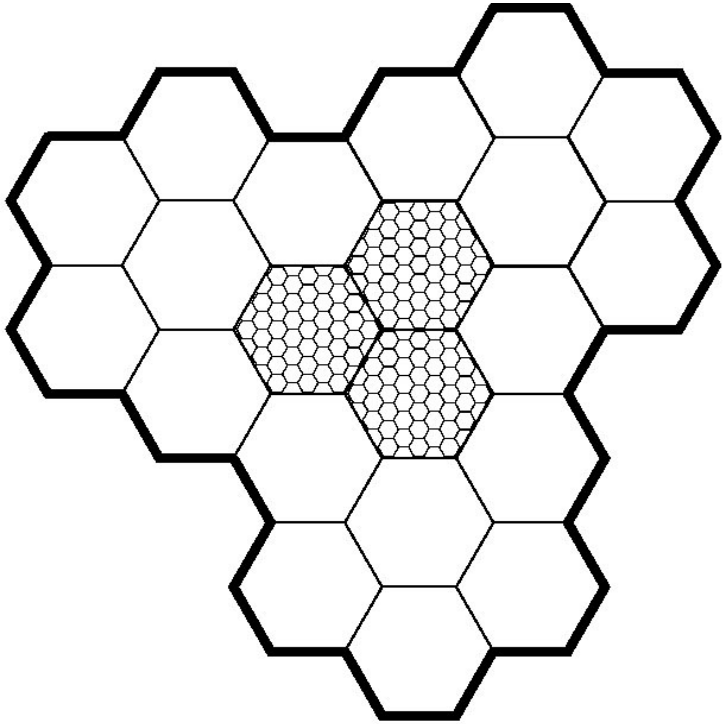
The Mobile Telephone System

- **Geographic area is divided up into cells**
  - Size of cells varies
  - Grouped in units of 7 cells
  - **Microcells** are used to support more user
  - **Nanocells** are used to cover special areas
- **Reuse of frequency**
- **At the center of a cell is a base station**
  - Base station manages and transmits data
  - When a mobile leaves the cell a **handoff** is performed

The Mobile Telephone System



Frequencies are not reused in adjacent cells



To add more users, smaller cells are used

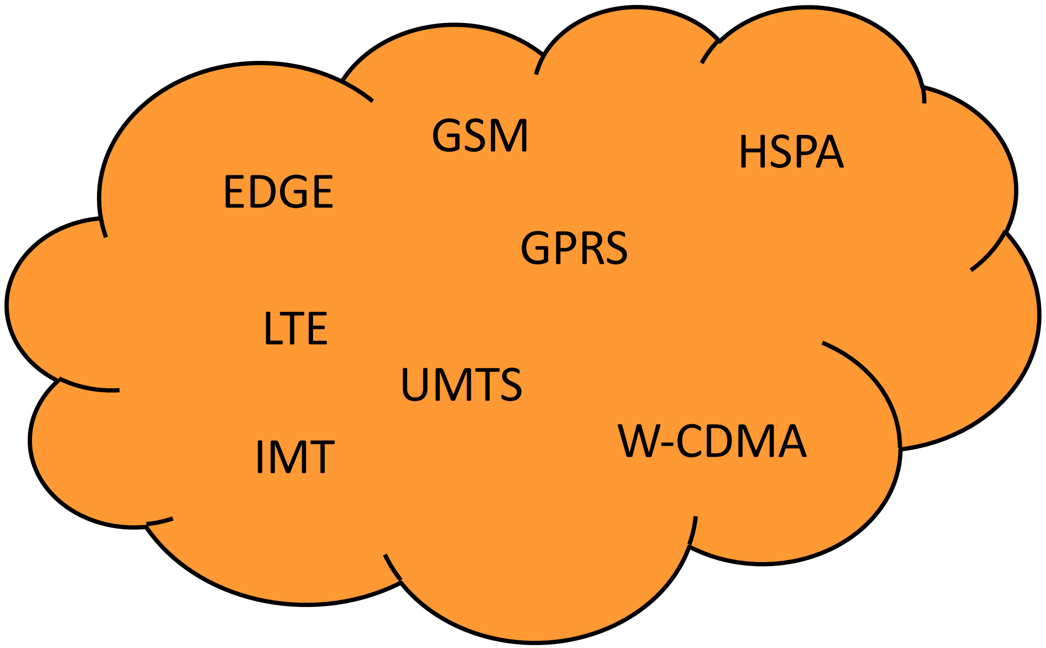
The Mobile Telephone System

- **Global System for Mobile Communications (GSM)**
  - Frequency division multiplexing
  - A single frequency is split by time division multiplexing into time slots
  - Each frequency is 200kHz wide
    - Each supporting 8 separate connections
  - Transmission principle is half-duplex, since GSM radios cannot send and receive at the same time

The Mobile Telephone System

http://www.3gpp.org

- **Long Term Evolution (LTE)**
  - Next generation of mobile communication systems
  - Up to several 100 Mbps



Summary

- **Types of networks**
  - LAN, MAN, WAN
- **The physical layer is the basis of all networks**
  - Relationship between bandwidth, symbol rate, and data rate
- **There are two fundamental limit on all communication channels**
  - Nyquist limit for noiseless channels and the Shannon limit for noisy channels
- **Kinds of transmission media**
  - Guided transmission media and unguided transmission media
- **The last mile problem**
  - ISDN
  - DSL
- **Mobile communication systems**
  - Satellites
  - Cellular networks