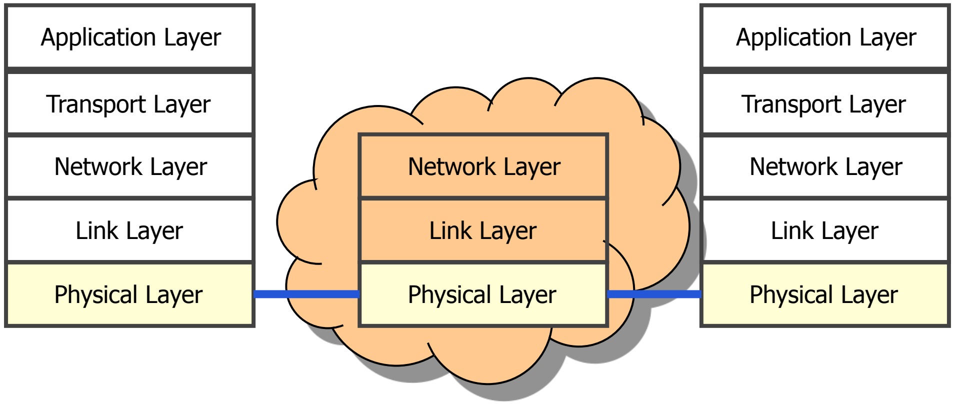
Telematics

Chapter 5

The Physical Layer



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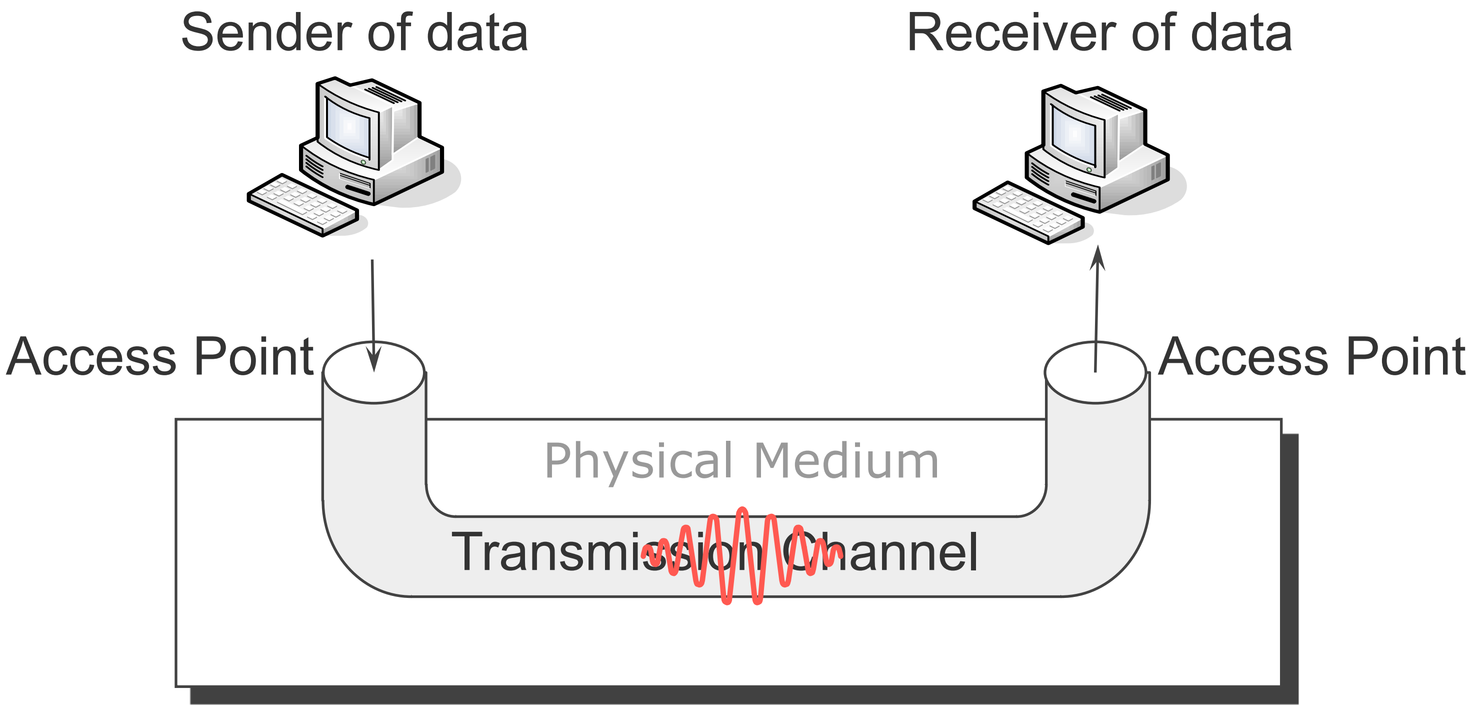
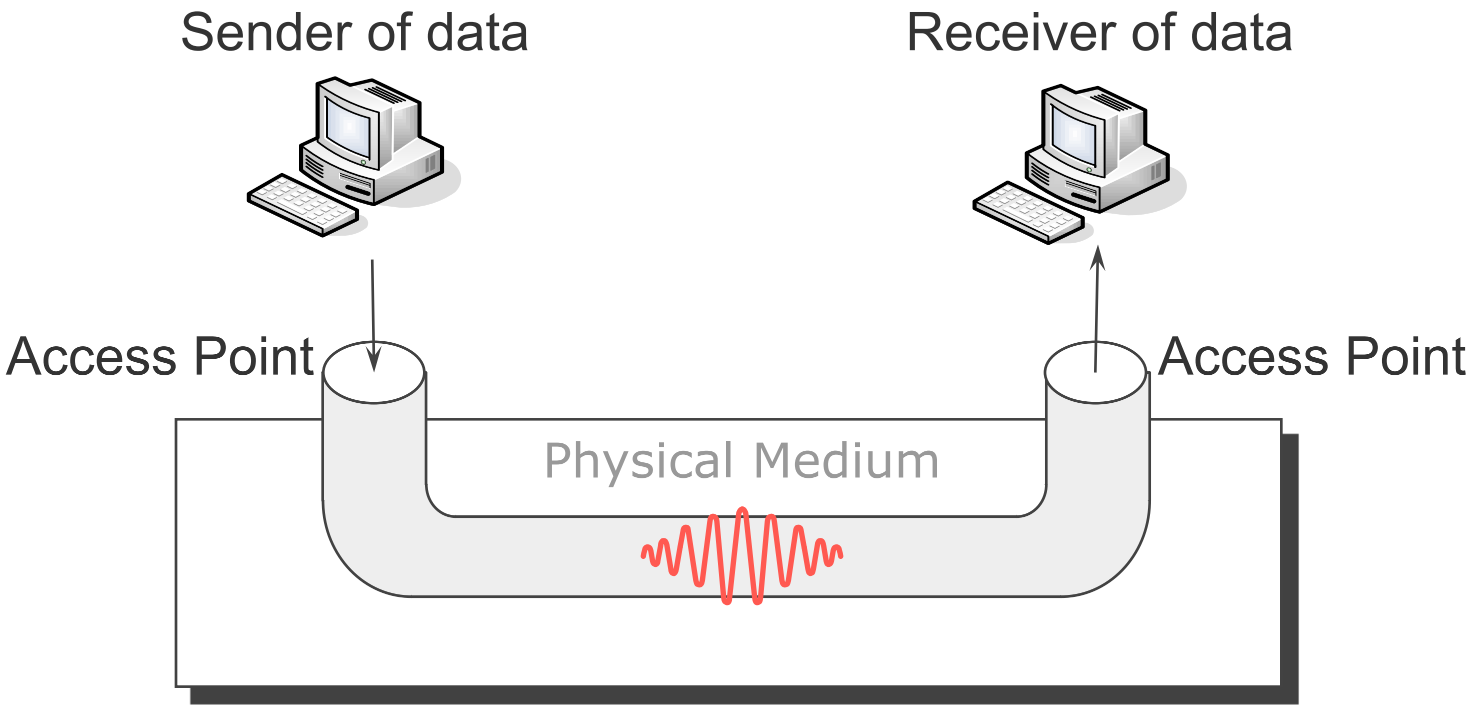
Physical Layer: Medium & Transmission Channel



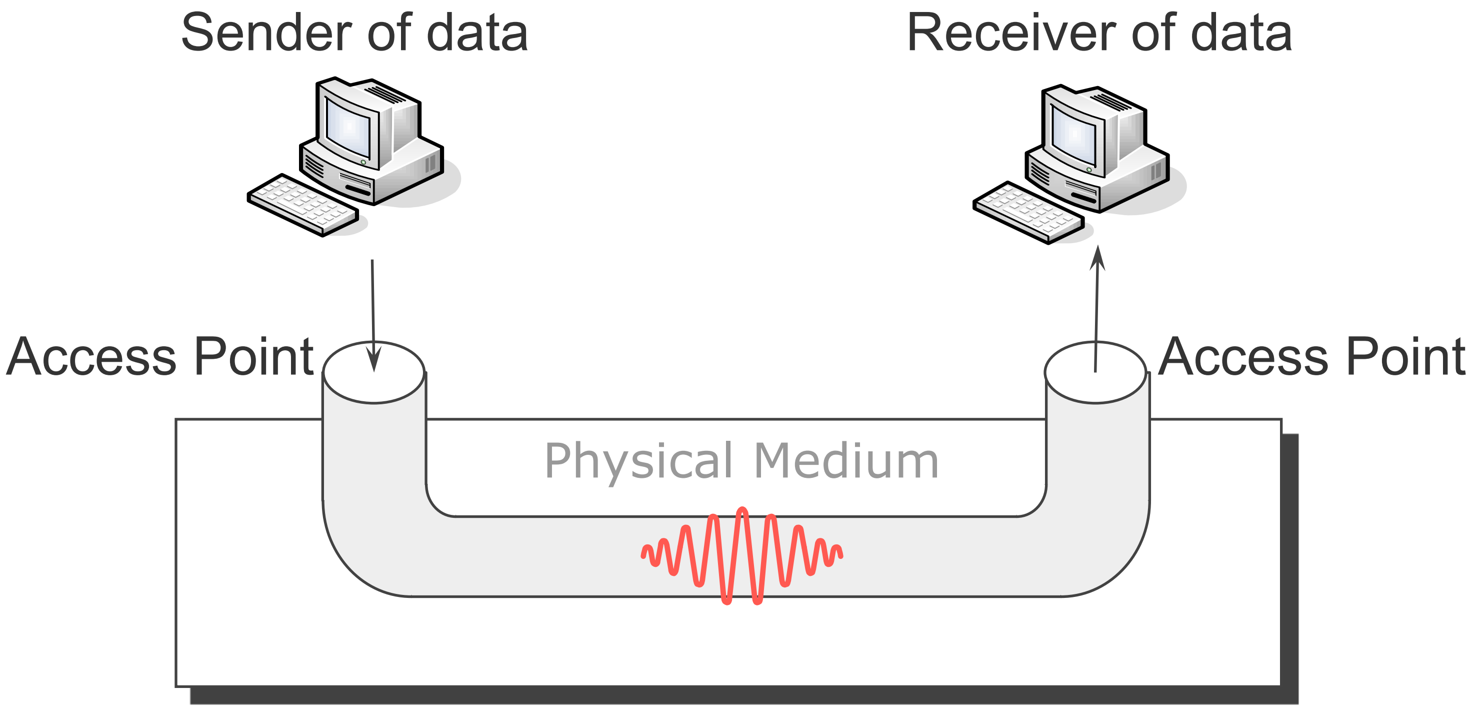
- Data is converted to signal which is sent over a transmission channel
- Transmission channel = access points + physical medium carrying signal
  - Typical examples of medium: wire, fiber, radio
- Signal = chronological sequence of physical values measured on medium

Physical Layer: Medium & Transmission Channel



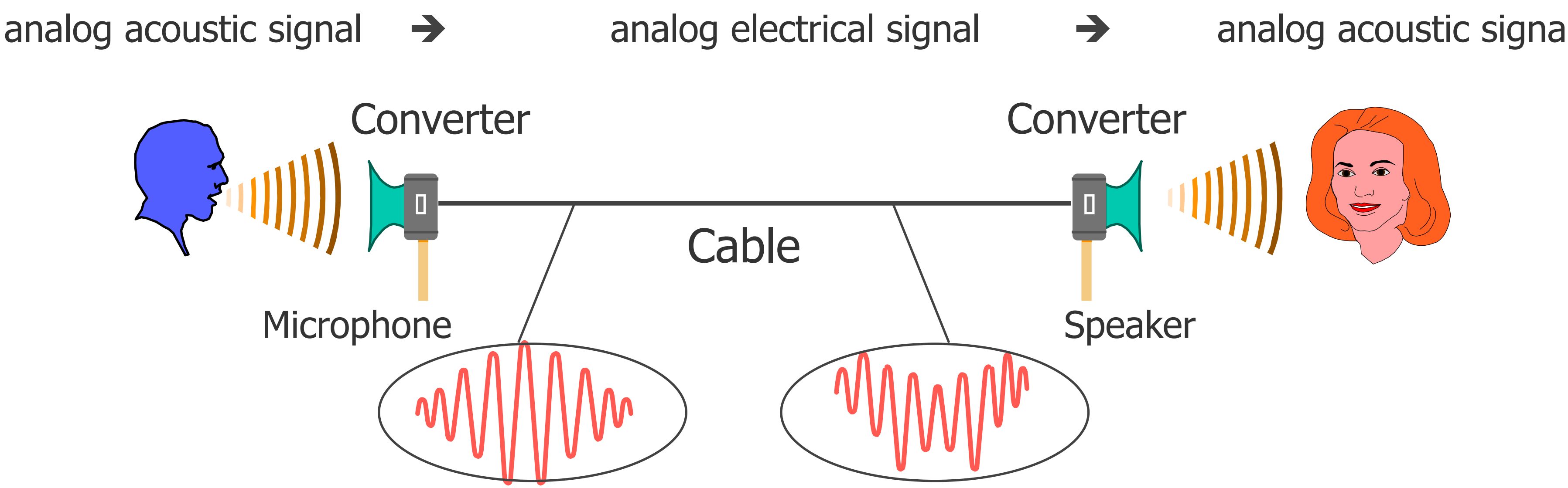
- Physical transmission medium (copper cable, optical fiber, radio…)
- Representation of raw bits (code, voltage…), data rate, control of bit flow
- Mechanical/electronic aspects (access point plug design, pin usage)
  - These aspects are not the focus of this chapter

Physical Layer: Medium & Transmission Channel



- Goal 1: give you an idea of where fundamental limits com from
  - Elements from physics: electromagnetic signal propagation properties
  - Elements from mathematics: efficient data encoding
- Goal 2: give you an idea of current techniques and deployments
  - They aim to approach these limits

Physical Layer: The Telephone Example



Physical Layer: Quantization & Sampling

- The physical layer transmits data one bit at a time, via a given medium
- The need to convert
  - Computers can only deal with digital data => discrete signal
  - Physical mediums are by nature analog => continuous signal
  - Must convert from digital signal to analog signal (and vice versa)
  - **Quantization**
- The need to measure
  - Computers can only deal with discrete time
  - Physical mediums’ state vary continuously
  - Must rely on periodical measurements of the physical medium
  - **Sampling**

CONTENT of this CHAPTER

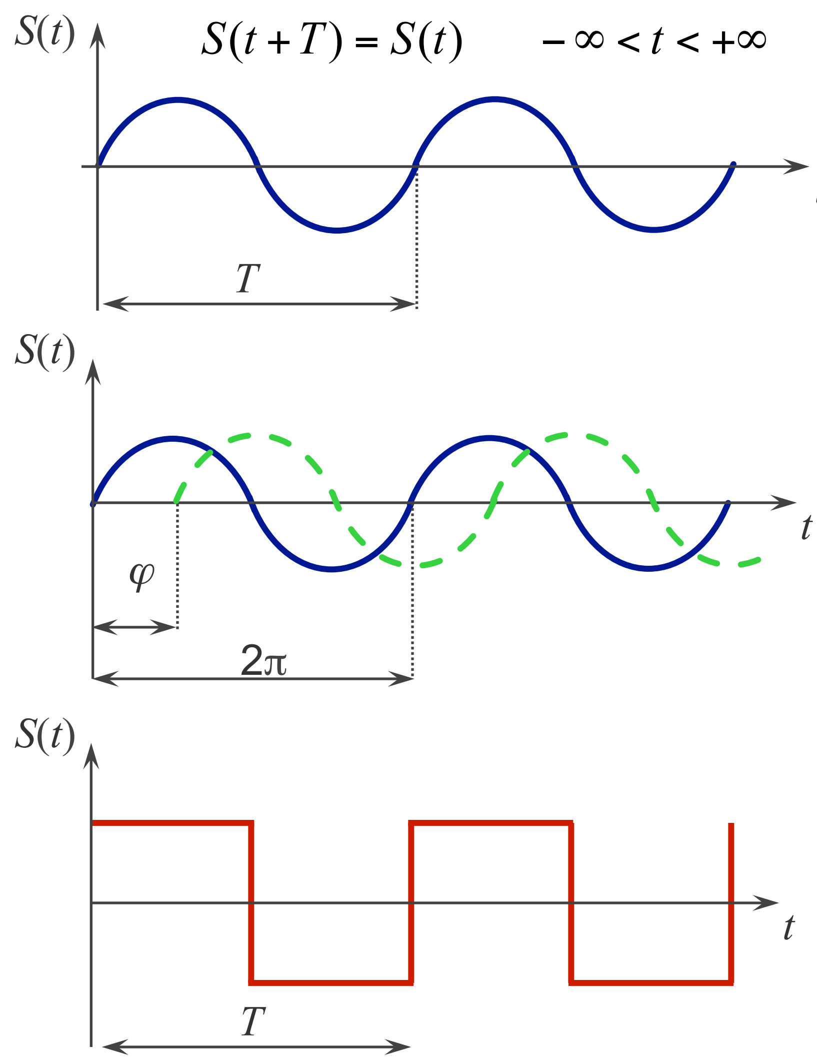
- ❖Signals, Bandwidth, Symbol Rate
- ❖Quantization, Sampling, Channel Capacity
- ❖Data Encoding
- ❖Modulation
- ❖Multiplexing
- ❖Types of physical medium

Basic Signal Processing: Periodic Signals

- Periodic signals: the simplest signals

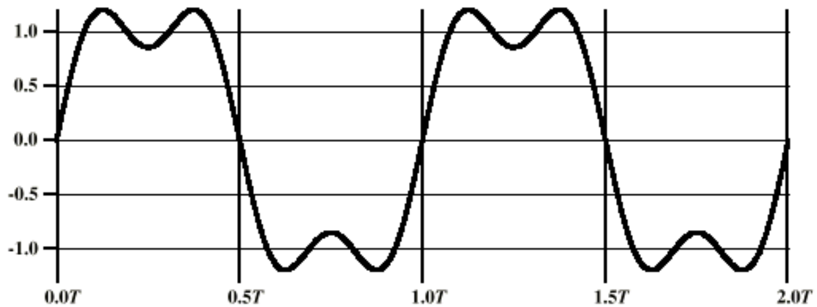
- Parameters of periodic signals:
  - Period T
  - Frequency $f=1/T$
  - Amplitude $S(t)$
  - Phase φ

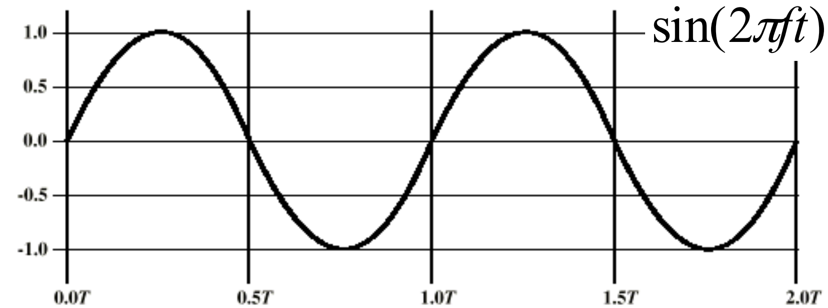
- Examples:
  - Sinus (period = 2π)
  - Phase shift φ
  - Square wave

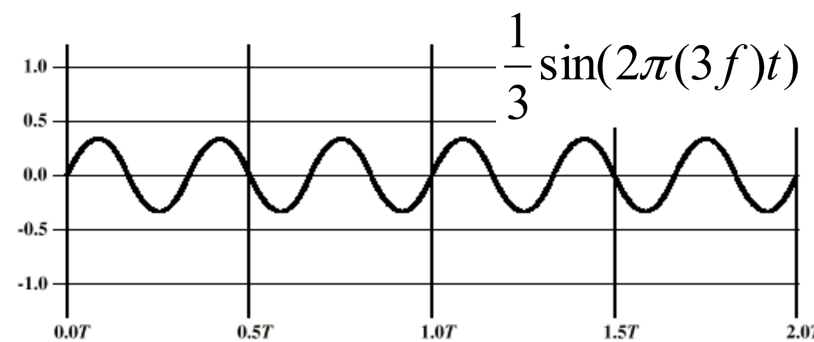


Composing Periodic Signals

- Composing multiple frequencies:
  - Example: $s(t) = \sin(2\pi ft) + \frac{1}{3}\sin(2\pi(3f)t)$



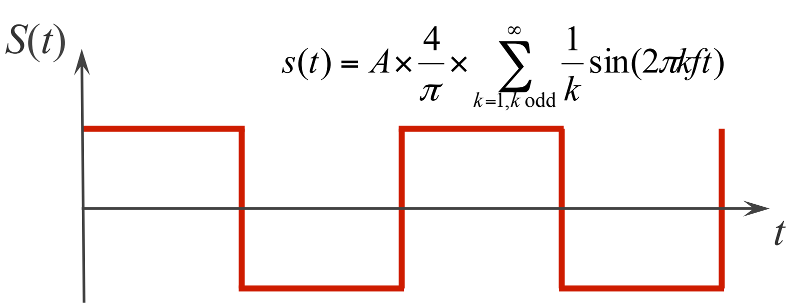




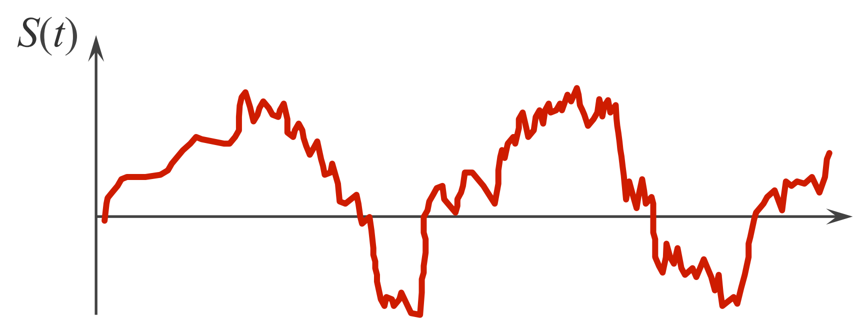
  - Components of the signal are sine waves of frequencies f and $3f$

- Composing a lot of different frequencies generates a variety of signals

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



Digital signal (mixed frequencies & amplitudes)



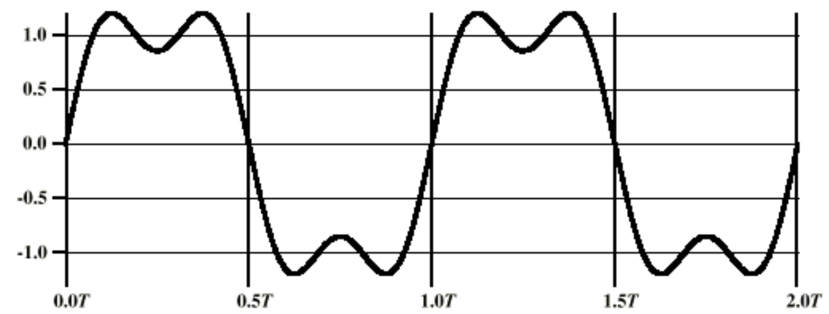
Voice signal (mixed frequencies & amplitudes)

Frequency Domain, Time Domain

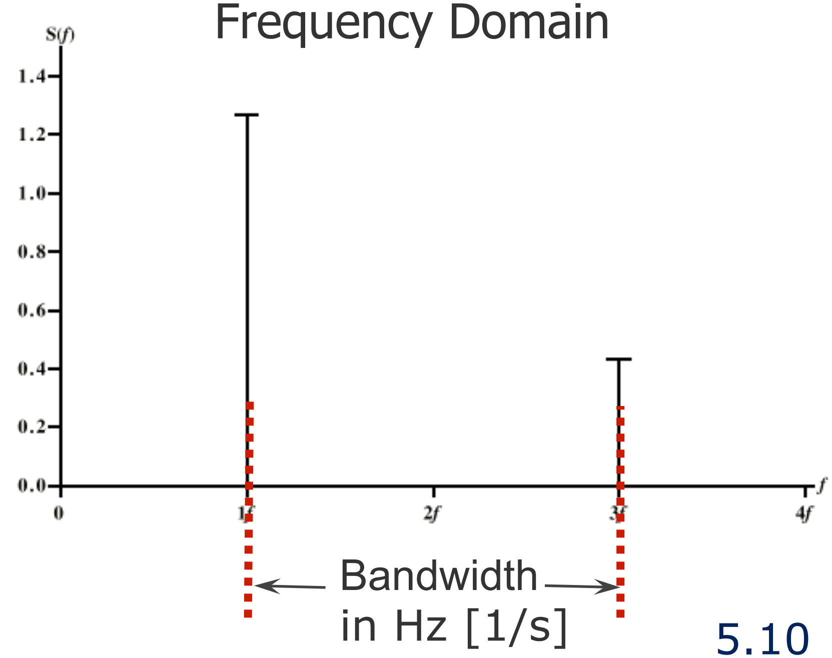
- Frequency Domain
  - The **spectrum** of a signal is the range of frequencies it consists in
    - In the example: from f to $3f$
  - The **bandwidth** of the signal is the width of the spectrum
    - In the example: $2f$
    - Effective bandwidth: narrow band of frequencies where most of the energy is contained
    - Many signals have infinite bandwidth

- **Fourier Transform**
  - mathematical transformation used to transform signals between time domain and frequency domain
  - Exists also in 2D (space-frequency transform, used for image processing)

Time Domain

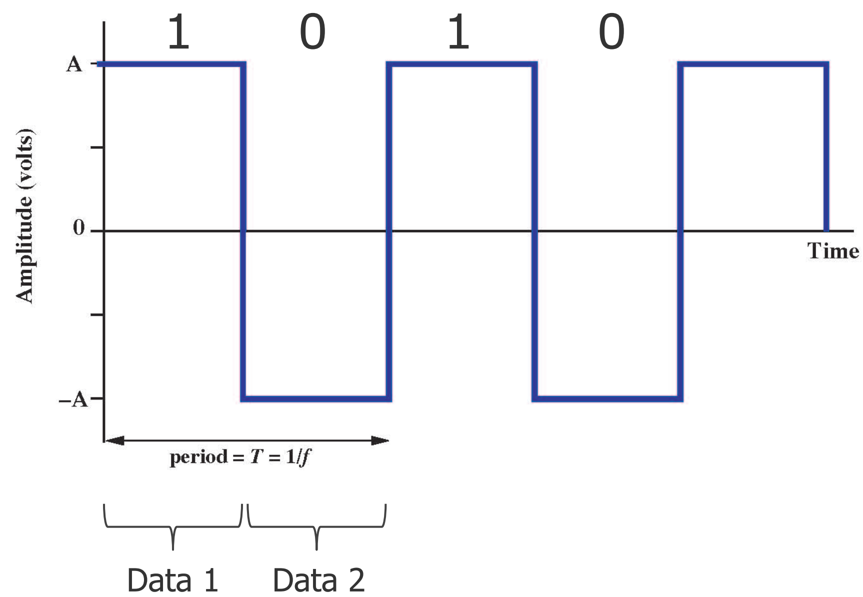


Frequency Domain



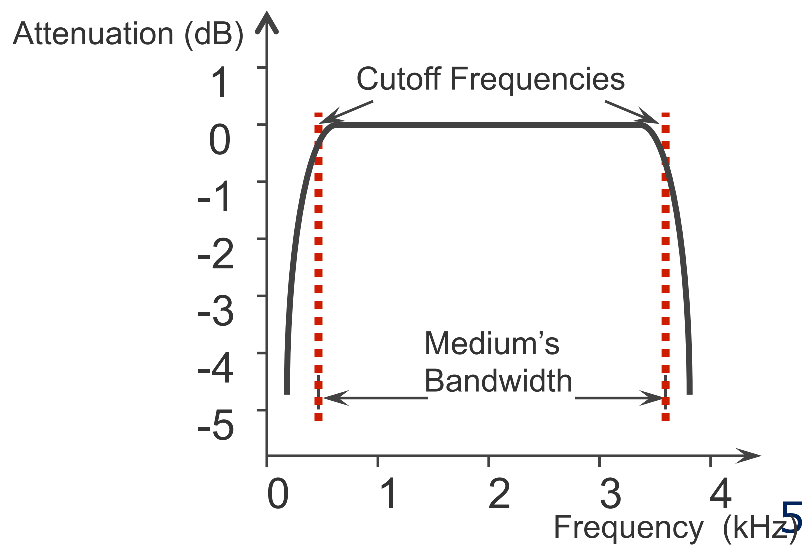
Bit Rate of a Transmission Channel

- Example with a 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 of this signal?

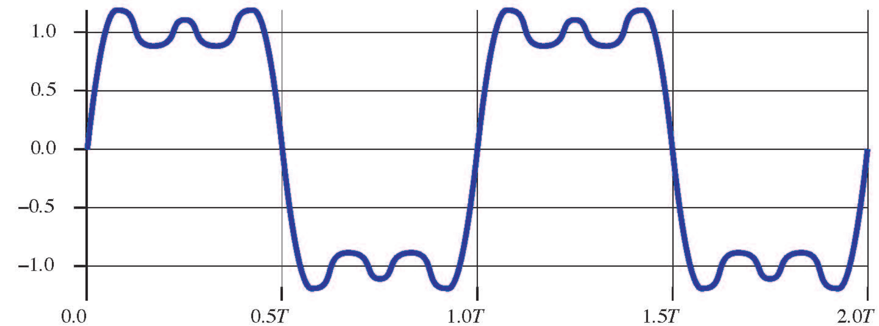
- Remark: a medium can transport only a limited frequency band.
  - **Bandwidth of the medium**: highest minus lowest frequency which can be transmitted over this medium, in Hz.
  - (The cutoff is typically not so sharp)



Bit Rate *vs* Bandwidth: Signal Frequencies

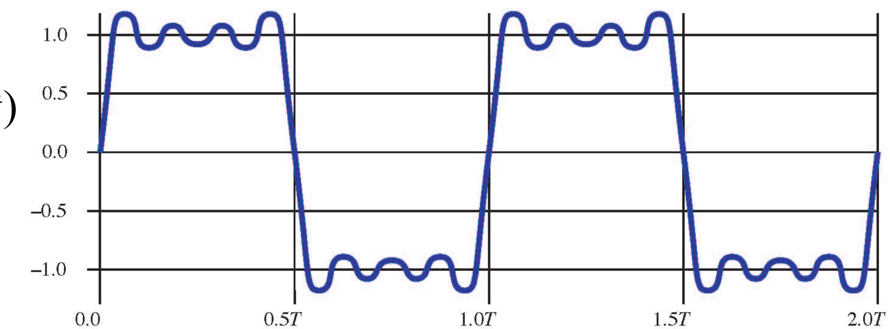
- Composition of a square wave
- Period from fundamental frequency f
  - Signal made of: f, $3f$, and $5f$

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



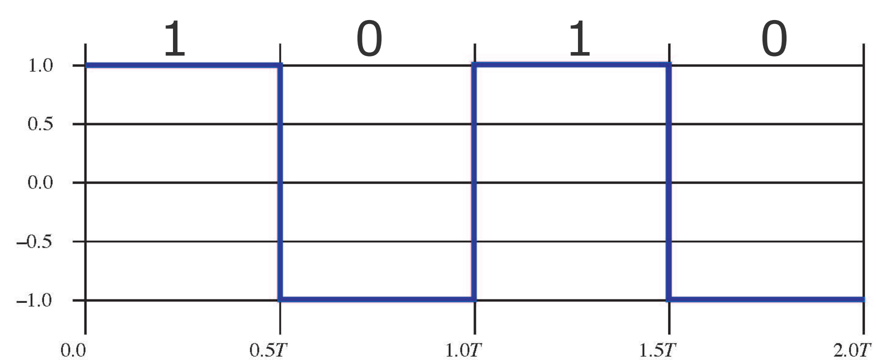
  - Signal made of: f, $3f$, $5f$, and $7f$

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



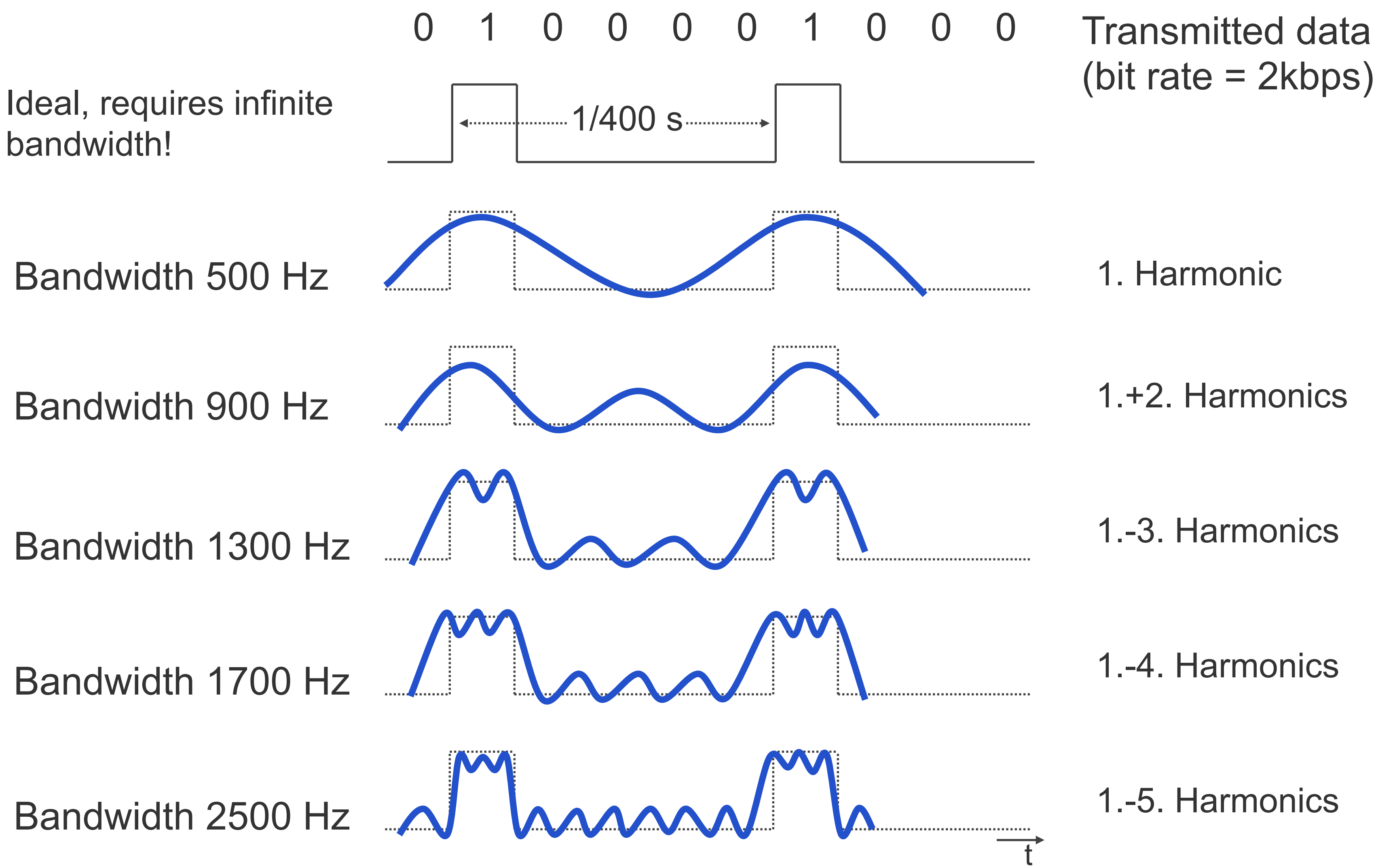
  - Square waves can be expressed as

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



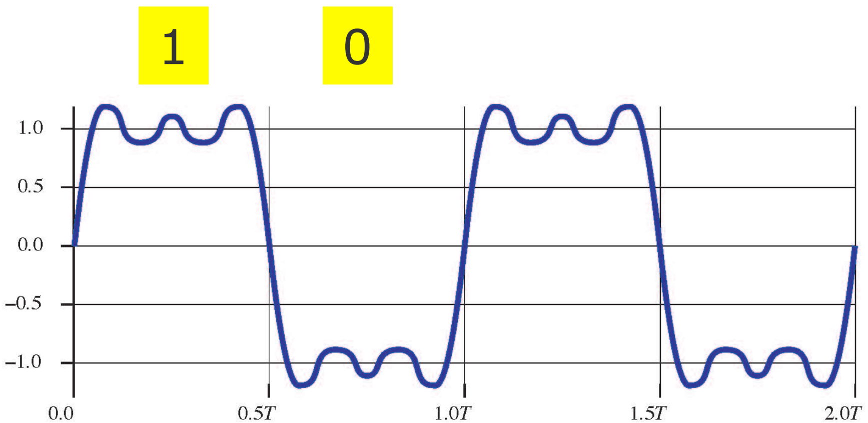
    - **Infinite number of components**
    - A component is also called a **harmonic**
    - Amplitude of the k-th harmonic is $1/k$
- So the question becomes:
  - What happens if k is limited?

Bit Rate *vs* Bandwidth: Medium Limiting Harmonics



Bit Rate *vs* Bandwidth: Numerical Examples

- Let's look at data rate *vs* bandwidth, with 5 harmonics



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

- Example with f = 1 MHz
  - Bandwidth of the signal $s(t)$
    $(5\times10^6$ Hz$)$ – $(1\times10^6$ Hz$)$ = 4 MHz
  - Period $T = 1/f = 1/10^6\text{s} = 10^{-6}s = 1\mu s$
  - 1 bit occurs every 0.5μs
  - ➡ Data rate = 2 bit × 10^6 Hz = 2 Mbps

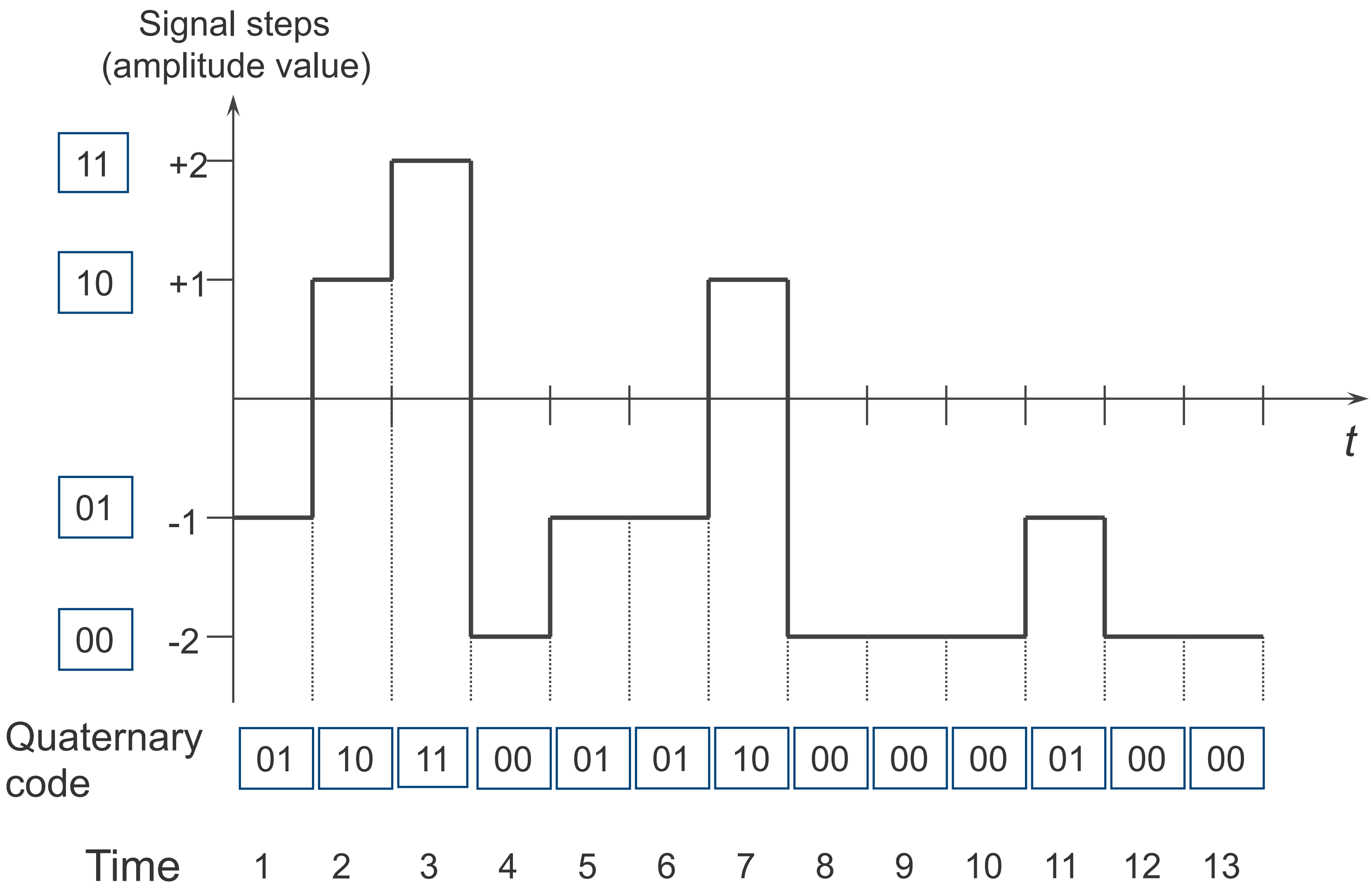
- Example with f = 2 MHz
  - Bandwidth (5×2MHz) – (1×2MHz) = 8 MHz
  - Period T = 1/f = 0.5μs
  - 1 bit occurs every 0.25μs
  - ➡ Data rate = 2 bit × 2 MHz = 4 Mbps

Symbol Rate *vs* Bit Rate: Multilevel Digital Signals

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

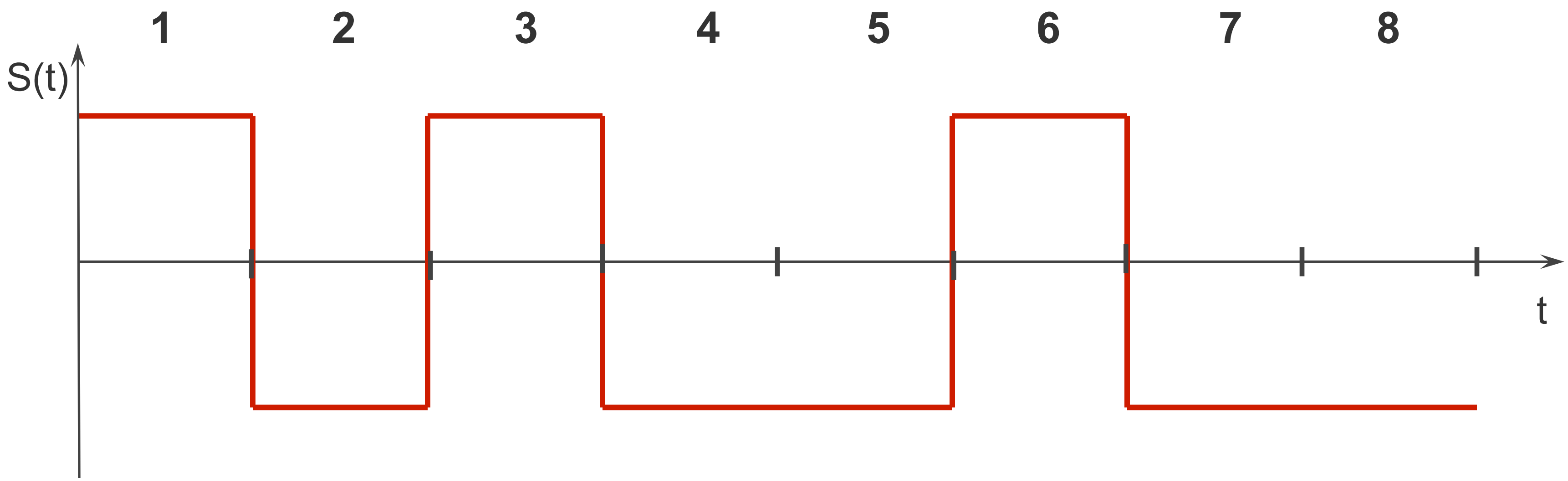
- Multilevel digital signal
  - A digital signal with more than two possible values, e.g., DIBIT = two bits per coordinate value (quaternary signal element)
  - The number of discrete values which a signal may have are denoted as follows
    - n = 2 binary
    - n = 3 ternary
    - n = 4 quaternary
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

Symbol Rate *vs* Bit Rate: Multilevel Digital Signals



Symbol Rate *vs* Bit Rate: Resulting Data Rate

- Symbol rate = number of physical **signalling events, per unit of time** on the transmission medium
  - Unit = symbol/s = **baud** (abbrv. bd)



Numerical example:

➡ Symbol rate = 5 baud

Symbol Rate *vs* Bit Rate: Resulting Data Rate

- Data rate = rate of **bits decoded from symbol rate, per unit of time**
  - Unit = **bit/s** (abbrv. bps)
  - For binary signals with frequency v
    - Each signaling event codes one bit

$$\text{Data rate} = v$$

  - For multilevel signals (n possible values)
  - Examples:
    - DIBIT ➡ 1 baud = 2 bps (quaternary signal)
    - TRIBIT ➡ 1 baud = 3 bps (octonary signal)

$$\text{Data rate} = v \times \log_2(n)$$

Units of Bit Rates

Name of bit rate	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
Exabit per second	Ebps	10^{18}	way too many zeroes

Do not get confused with binary prefixes!

- 1 byte = 8 bit (also called *octet* in telco standards)
  - term coined in 1956 by Werner Buchholz, to describe the smallest amount of data that a processor could process at once
- 1 KibiByte = 1 KiB = 1024 byte
  - In this case kilo = 2^{10} = closest 2^x to 1000

Typically 2^x in storage technology, 10^x in transmission technology

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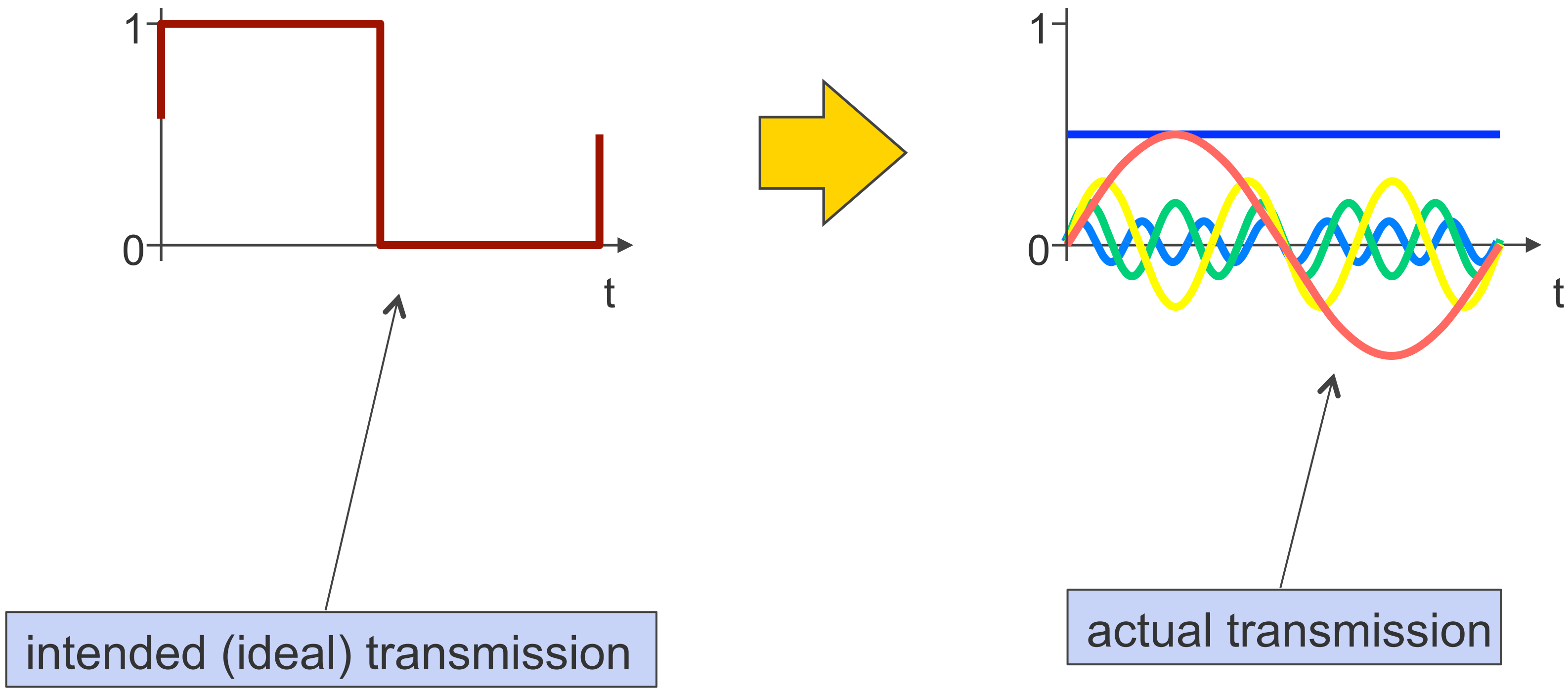
Ideal Transmission *vs* Real Transmission

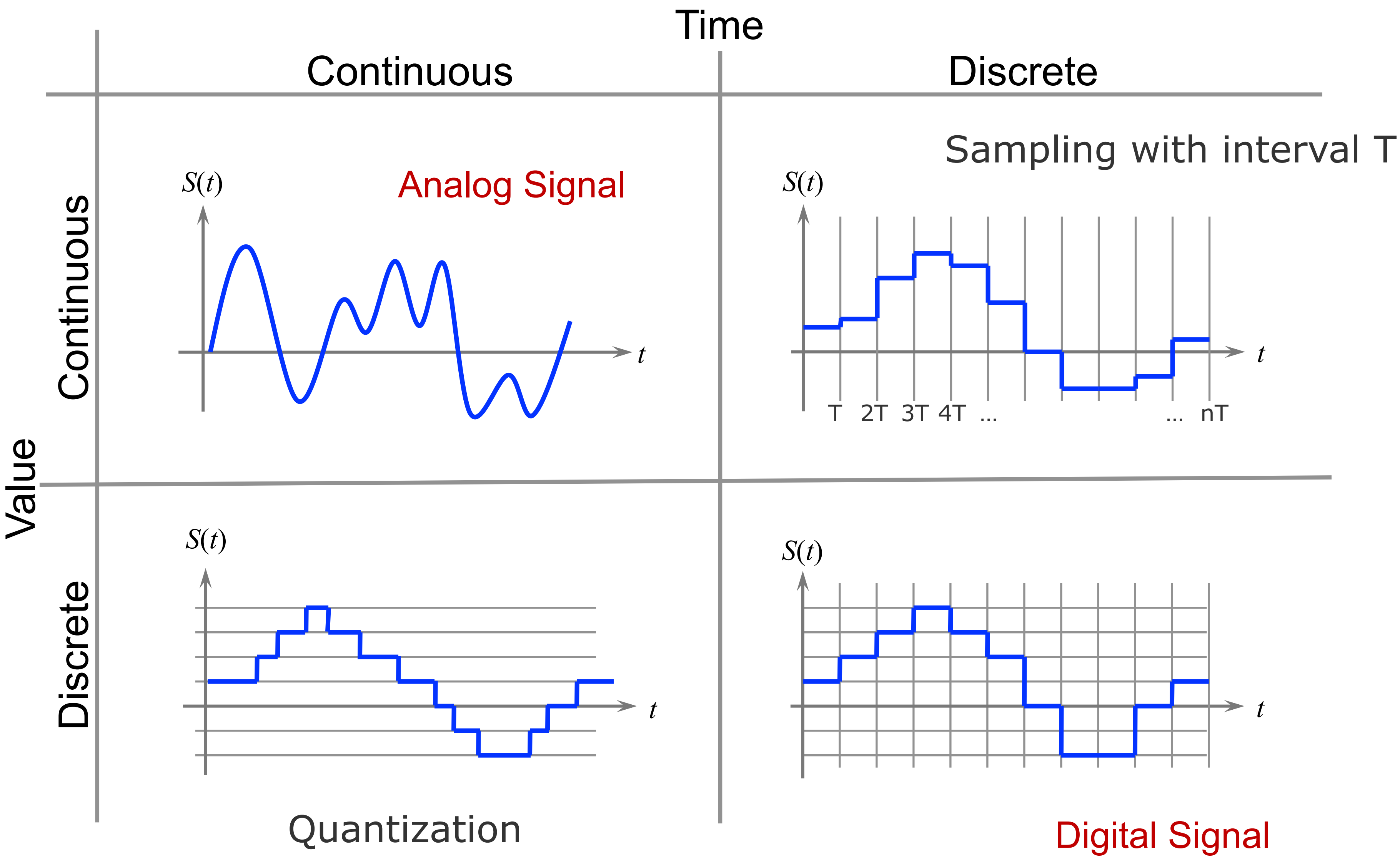


Claude Shannon

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

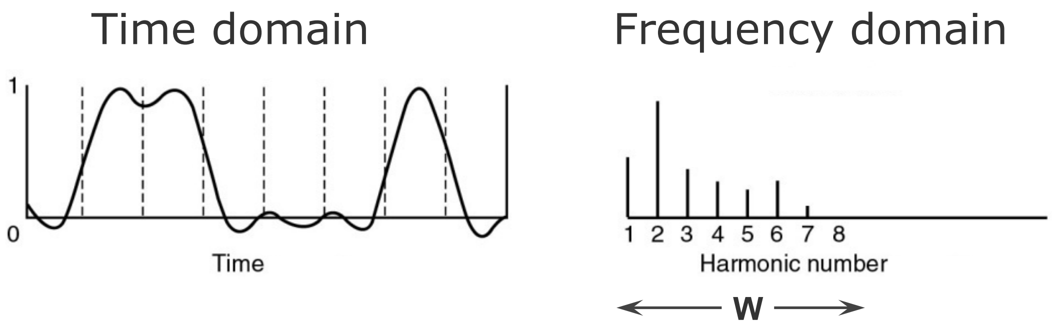
A Mathematical Theory of Communication, Bell Systems, 1948

Continuous Signals *vs* Discrete Signals



Sampling: Fundamental Result

- Fourier transform of signal
  - Bandwidth W of signal (in Hz)



- **Nyquist Sampling Theorem**: to allow reconstruction of the original analog signal, it is sufficient that the sampling frequency f_s is such that:

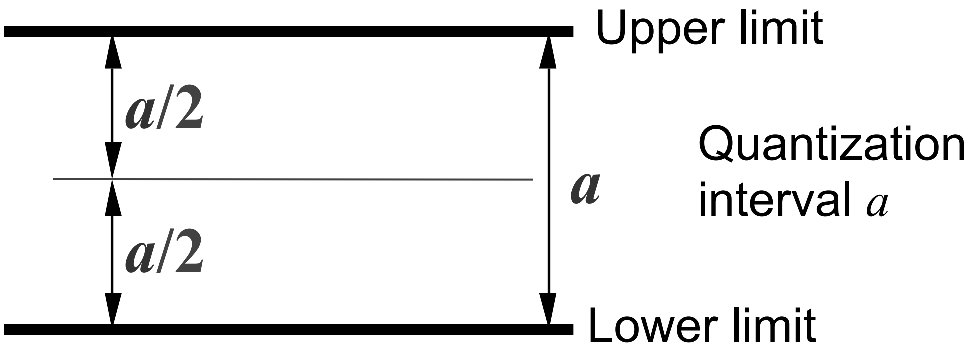
$$f_s > 2W$$

- Sampling is at the base of most digital content, including:
  - Digital photos
  - Digital videos
  - Digital sound

Quantization

- Quantization is the process of approximating the full range of an analog signal into a finite number of discrete values.
  (analog-to-digital conversion, ADC)

- There is an inherent **quantization error**: the difference between the analog signal value and the digital value, after approximation via quantization.



  - 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 conversion, DAC)

Relationship between Quantization, Coding, Sampling

- Sampling
  - The analog signal has to be converted to a digital representation.
  - Solution: periodical measurements, at given rate = sampling
  - The value of the analog signal at the sampling time is quantized (analog-to-digital conversion, ADC)

- Coding
  - The quantization intervals are assigned to a binary code
  - Basic idea: the binary code is transmitted instead of the analog signal
  - In cases where an analog signal is awaited in the end, decoding is needed (digital-to-analog conversion, DAC)

- <u>Remark</u>:
  - Sampling and quantization are to be considered independently.

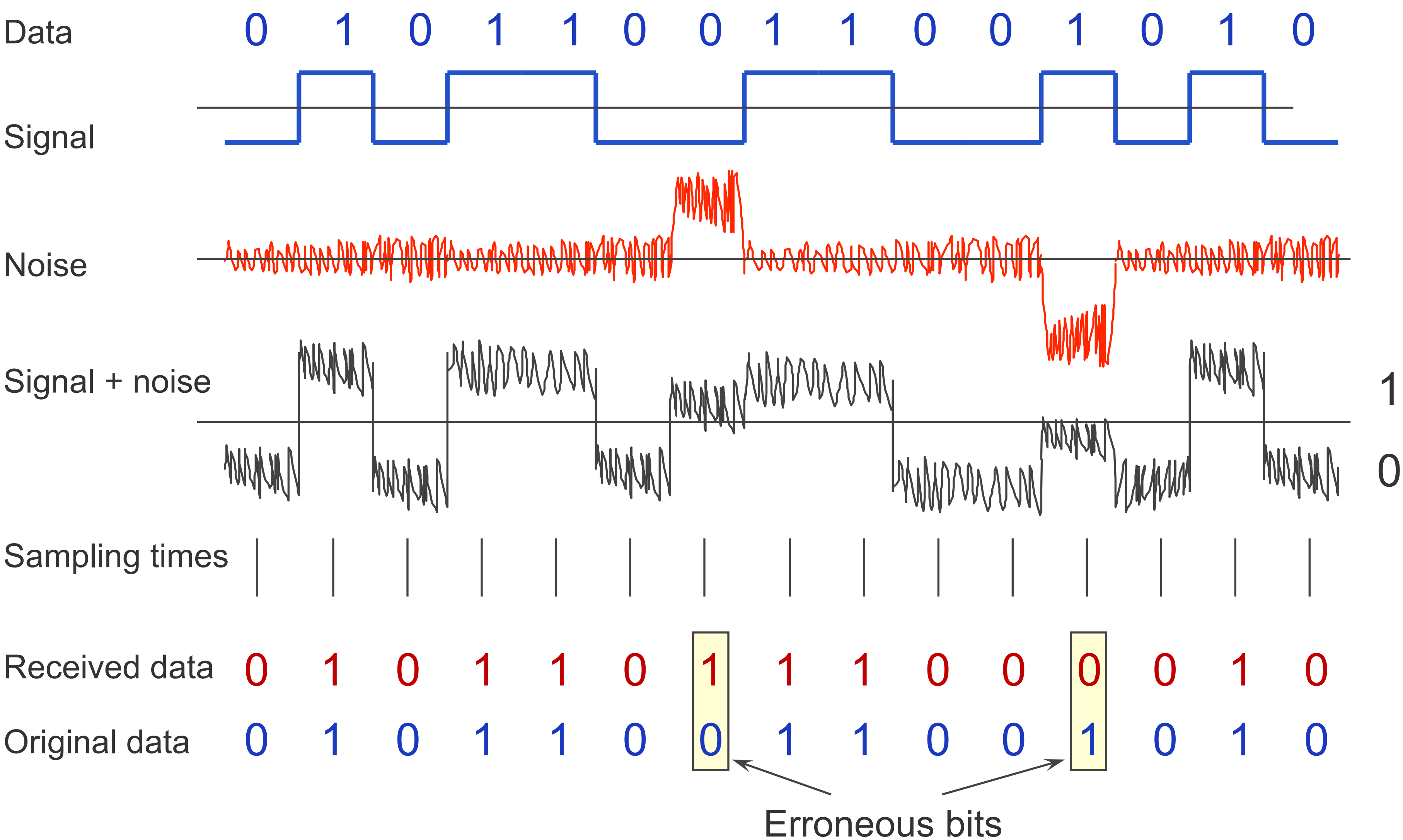
Channel Capacity: Noiseless *vs* Noisy Channel

- Digital channels are an abstract concept
- Physical channels are all analog
- So the question is: what is their **capacity** in terms of bit rate?

- If an analog channel is noiseless: infinite capacity in theory!
  - each analog signal is received exactly as sent
  - (send numbers in $\Re$ with infinite precision, coding information of arbitrary size)
  - **In reality there is always some noise**

- If the channel is noisy: finite capacity
  - Capacity depends several parameters, including noise characteristics
  - e.g. thermal noise, intermodulation noise, crosstalk, impulse noise
  - Typical noise model used for analysis: **AWGN** (also known as gaussian channel)
    - <u>Additive</u>: the noise value is added to the signal, and that's what the receiver gets
    - <u>White noise</u>: independent, random noise values with constant spectral density
    - <u>Gaussian</u>: probability distribution of the amplitude of random noise values

Channel Capacity: Effect of Noise



Channel Capacity: Effect of Noise

- On analog signals: noise degrades the signal quality
- On digital signals: noise causes bit errors

- It is possible to diminish the effect of noise by boosting signal amplitude.
  - But this also increases energy consumption, so there is a tradeoff.
  - It also causes more interference in wireless, so there is a tradeoff there too.

- Transmission impairments essentially come from:
  - Signal attenuation and attenuation distortion
  - Delay distortion
  - Noise (thermal noise, intermodulation noise, crosstalk, impulse noise)

Channel Capacity: Bit Error Rate

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

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

- depends on the environment
  - can distort the signal (noise etc.)
- depends on the communication medium and the length of the transmission line
  - high frequencies are attenuated faster than low frequencies
  - different frequencies have different speed in the medium

- Typical values for BER:

Link Type	BER
Analog telephony connection	2×10^{-4}
Radio link	10^{-3} - 10^{-4}
Ethernet (10Base2)	10^{-9} - 10^{-10}
Fiber	10^{-10} - 10^{-12}

Noisy Channel Capacity: Shannon Theorem

- Analysis of the capacity of gaussian channels (1948)
- Fundamental result from Shannon's Theorem

$$\text{maximum data rate} = W \times \log_2\left(1+\frac{P}{N}\right)$$

  - data rate in bit/s, with:
    - W = bandwidth of the channel
    - $\frac{P}{N}$ = SNR = signal to noise ratio
      where P is the average signal power and N the average noise power.

- Numerical example:
  - W = 3000 Hz
  - SNR = 1000
  - max. data rate:
    $3000 \times \log_2(1+1000) \approx 30{,}000$ bit/s

Noiseless Channel Capacity: Nyquist Theorem

- In fact, even if we do not consider noise, throughput is still finite due to:
  - Quantization at the transmitter and discrete levels of the signal
  - Sampling at the receiver

- Nyquist theorem (1924) relating maximum throughput with the number of discrete levels of signals:

$$\text{maximum data rate} = \mathbf{2}\boldsymbol{W}\mathbf{\times log_2(}\boldsymbol{n}\mathbf{)}$$

  - data rate in bit/s, with:
    - W = bandwidth of the channel
    - n = discrete levels of the signal

- Remark: this is a nice practical complement of Shannon’s upper bound
  - Shannon’s formula gives an upper bound R for the data rate
  - Let’s for example consider trying to achieve 80% of this upper bound R
  - Then Nyquist’s theorem gives the required number of discrete levels of signals.

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Baseband and Broadband

- How to actually transmit individual bits, 0s and 1s, on the medium?

Solution 1: Baseband

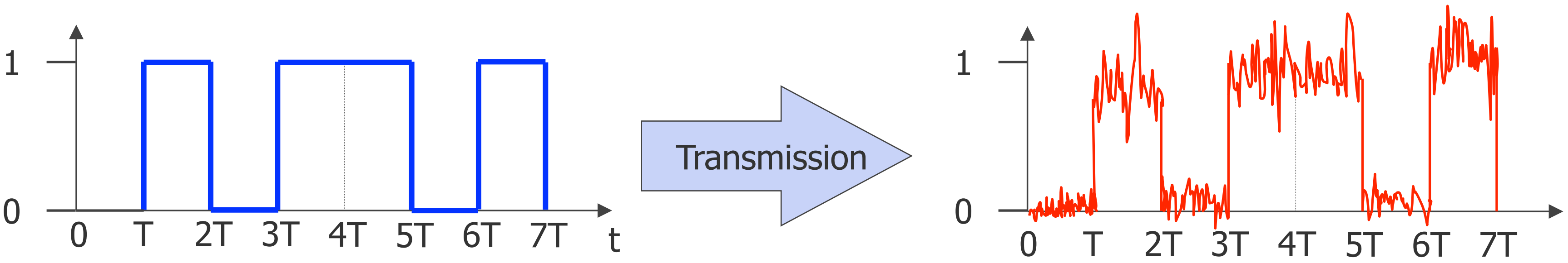
- The digital data is transmitted "as is" over the medium.
- For this, **data encoding** necessary, which specifies the symbols representing "0" resp. "1" (cable codes).

Solution 2: Broadband

- The digital data is transmitted by **modulating** it onto a **carrier** analog signal. By using different carrier signals (frequencies), several transmissions can happen simultaneously.

- Baseband is used mainly in LANs
- Broadband is used mainly in optical, radio networks & cable distribution systems

Cable Codes: Requirements



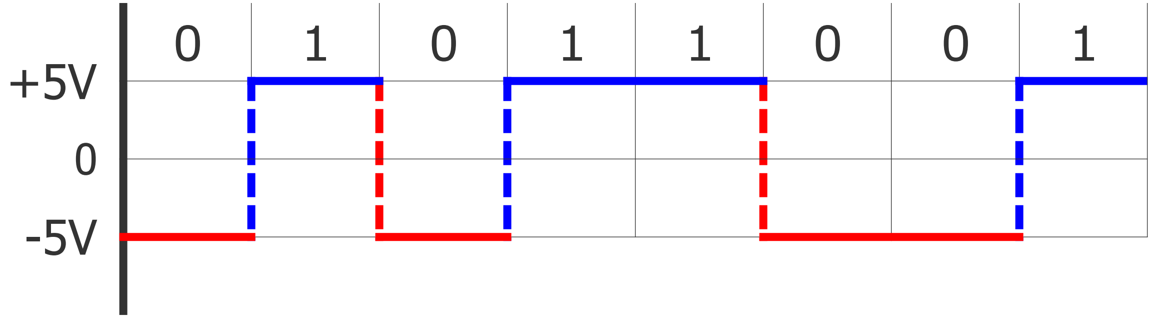
- Robustness: as much tolerance to distortion as possible

- Efficiency: the highest possible data transmission rate
  - Achieved using code words
    - binary code: 2 states +5V/-5V?
    - ternary code: 3 states +5V/0V/-5V?
    - quaternary code: 4 states (coding of 2 bits at the same time)

- Synchronization with receiver: less opportunities for out-of-synch
  - achieved by frequent changes of voltage level regarding to a fixed cycle
    - Avoiding direct current: positive and negative signals should alternatively arise
    - Bipolar/Unipolar encoding

Non Return to Zero (NRZ)

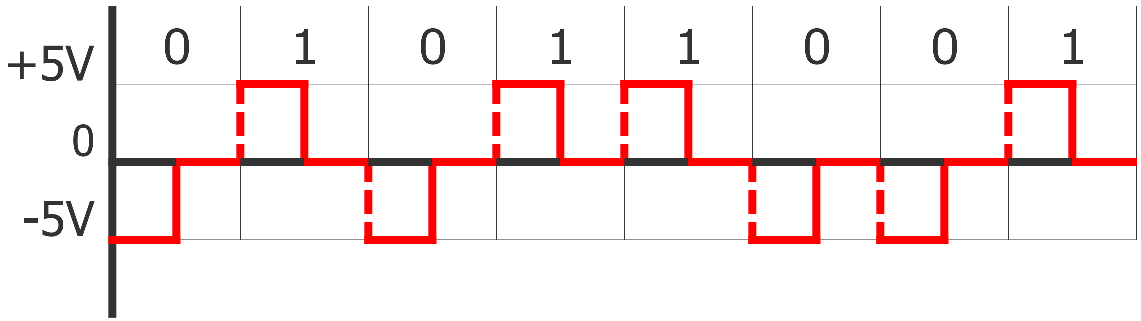
- Simple approach:
  - Encode “1” as positive voltage (+5V)
  - Encode “0” as negative voltage (- 5V)



- Advantage:
  - Very simple principle
  - The smaller the clock pulse period, the higher the data rate
- Disadvantage:
  - Prone to loss of clock synchronization
  - Direct current during long sequences of 0 or 1

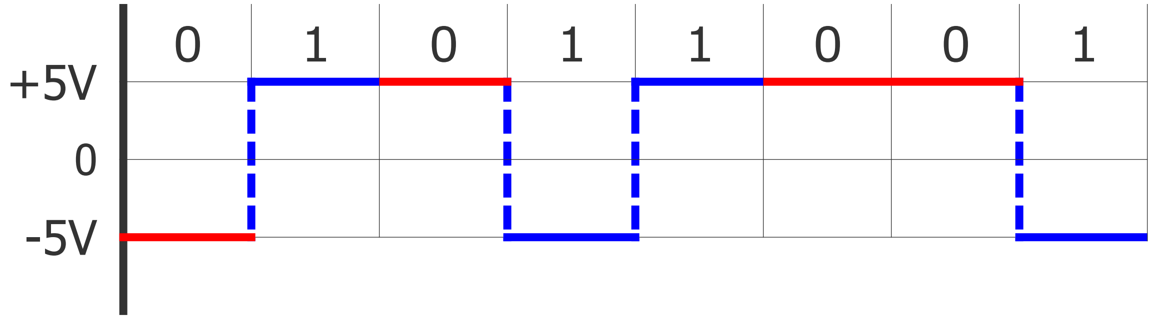
Return to Zero (RZ)

- The signal returns to zero between each pulse.
- Advantage
  - The signal is self-clocking
  - No build up of DC
- Disadvantage
  - Needs twice the bandwidth



Differential NRZ

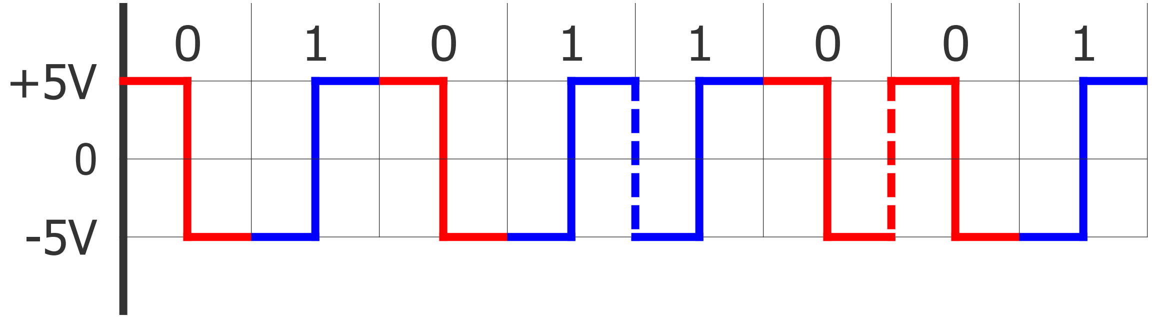
- Differential NRZ:
  - Similar principle to NRZ
  - Encode "1" as voltage level change
  - Encode "0" as missing voltage level change



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

Manchester Code

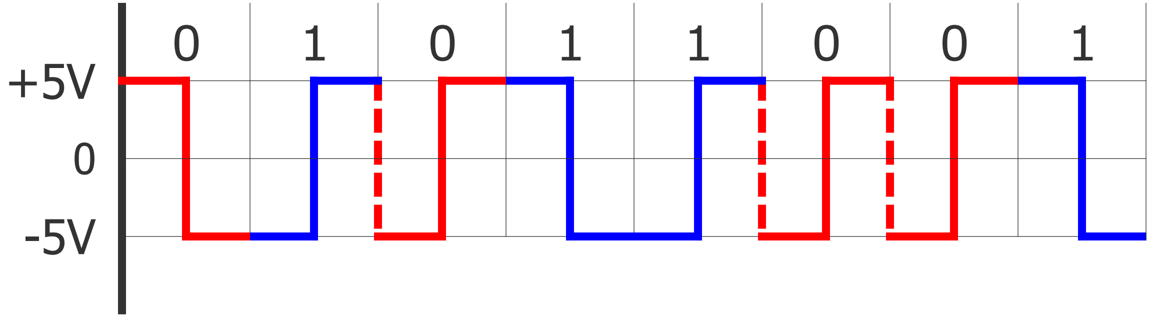
- With each code element the clock pulse is transferred: voltage level change occurs in the middle of each bit:
  - Encode “0” as voltage level change from positive (+5V) to negative (-5V)
  - Encode “1” as voltage level change from negative (-5V) to positive (+5V)



- Advantages
  - Clock synchronization of sender and receiver with each bit, no direct current
  - End of the transmission 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
  - It is a 1B/2B code : one bit is coded into two binary symbols

- An improvement is given with the 4B/5B Code:
  - four bits are coded in five 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

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 #1
K	-NONE-	10001	Start #2
T	-NONE-	01101	End
R	-NONE-	00111	Reset
H	-NONE-	00100	Halt

Summary: Bandwidth *vs* Baud rate *vs* Bit rate

- 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 data send over the channel
    - Equals to: $\frac{Symbols}{sec} \times \frac{Bits}{Symbol} = \frac{Bits}{sec}$

CONTENT of this CHAPTER

- ❖Signals, Bandwidth, Symbol Rate
- ❖Quantization, Sampling, Channel Capacity
- ❖Data Encoding
- ❖Modulation
- ❖Multiplexing
- ❖Types of physical medium

Baseband and Broadband

To be transmitted, digital signals are transformed into **electromagnetic signals.**

Solution 1: Transmit signal "as-is" over the medium

- Baseband
- For this, data encoding necessary, which specifies the symbols representing "0" resp. "1" (cable codes).

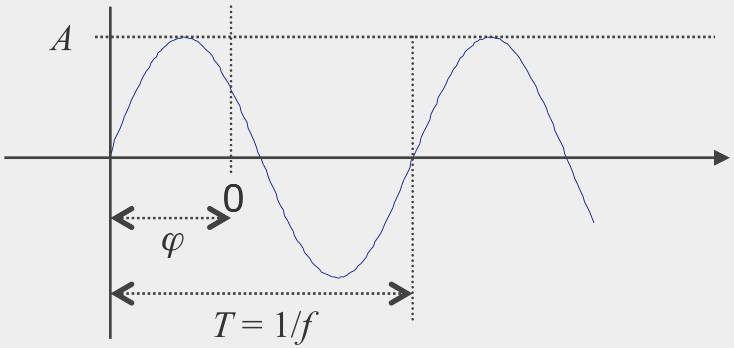
Solution 2: Modify a carrier analog signal

- Broadband
- Method called **modulation**. By using different carrier signals (frequencies), several transmissions can happen simultaneously.

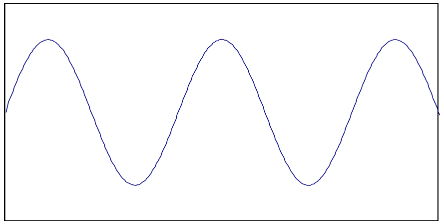
Modulation of Digital Signals: Principle

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

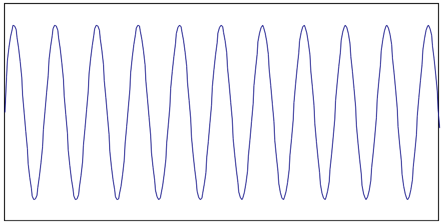


Modulation means to choose a **carrier frequency** and "inject" somehow your data:

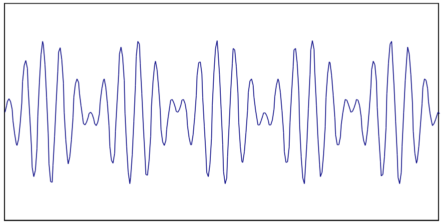


Not modulated signal

x



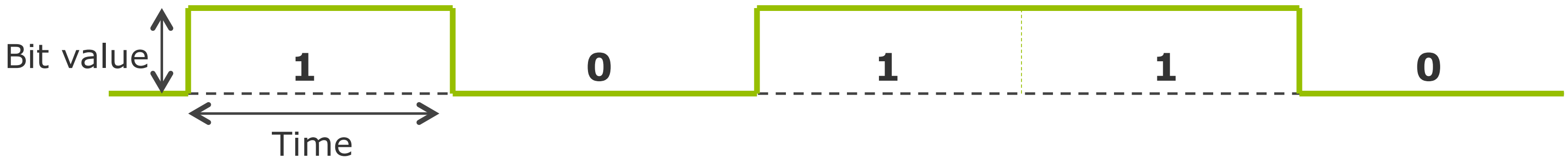
Carrier frequency (sin)



modulated signal

Modem = abbreviation for the **Mo**dulation-**Dem**odulation process

Modulation of Digital Signals: ASK

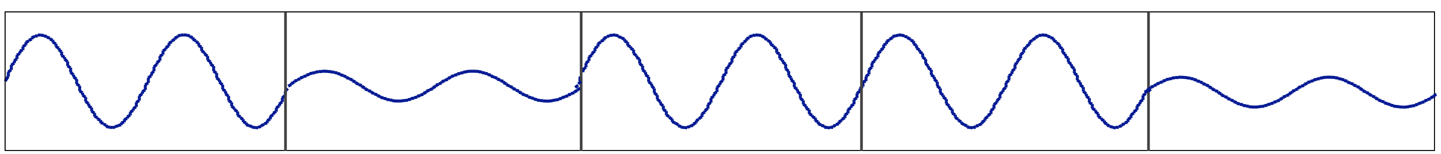


The conversion of digital signals can take place in various ways, based on the parameters of an analog wave:

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

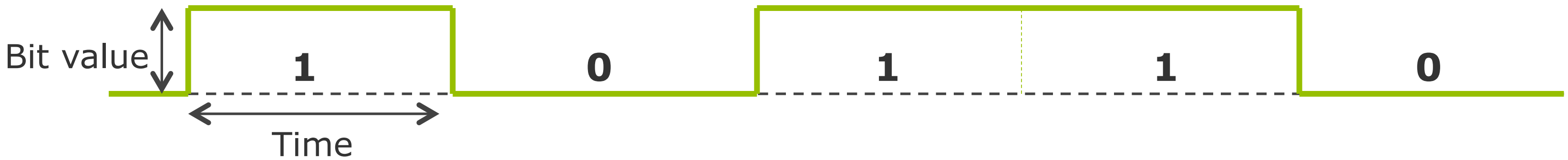
Amplitude Frequency Phase

Amplitude Modulation (Amplitude Shift Keying, ASK)



- Technically easy to realize
- Does not need much bandwidth
- Not very robust against distortion
- Often used in optical transmission (where noise is low)

Modulation of Digital Signals: FSK

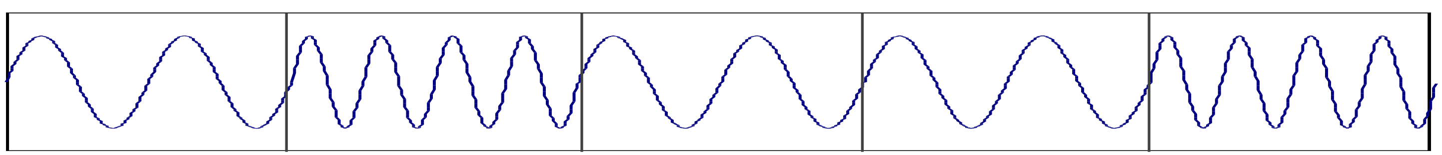


The conversion of digital signals can take place in various ways, based on the parameters of an analog wave:

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

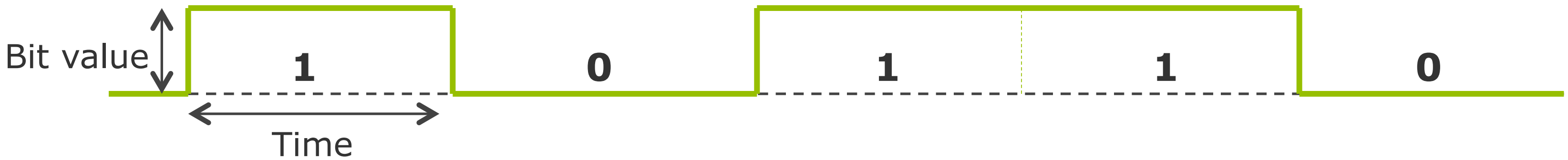
Amplitude **Frequency** Phase

Frequency Modulation (Frequency Shift Keying, FSK)



- "Waste" of frequencies
- Needs a lot of bandwidth
- Initial principle used in data transmission using phone lines

Modulation of Digital Signals: PSK

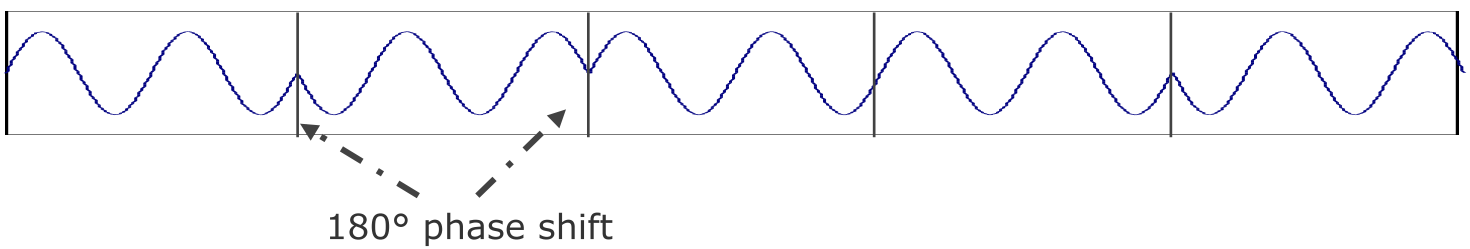


The conversion of digital signals can take place in various ways, based on the parameters of an analog wave:

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

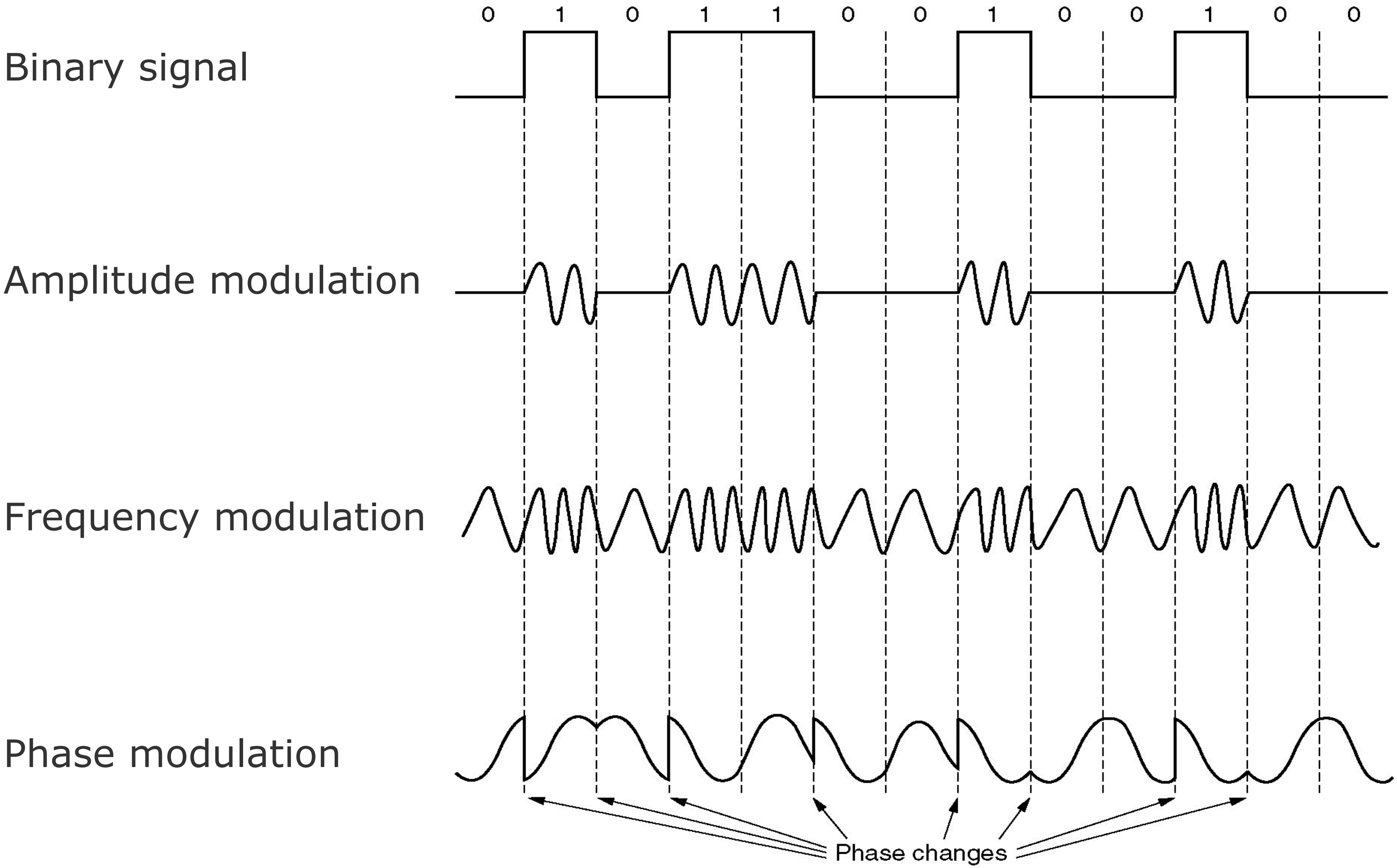
Amplitude   Frequency   **Phase**

Phase Modulation (Phase Shift Keying, PSK)



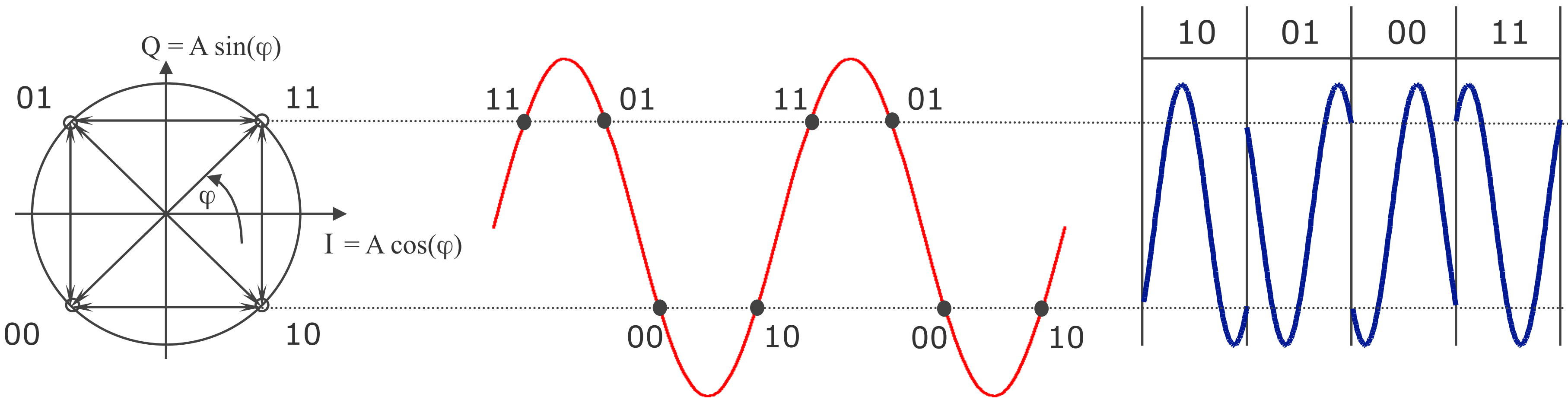
- Complex demodulation process
- Robust against disturbances
- Best generic solution

Modulation of Digital Signals: Overview



Advanced PSK Techniques: QPSK

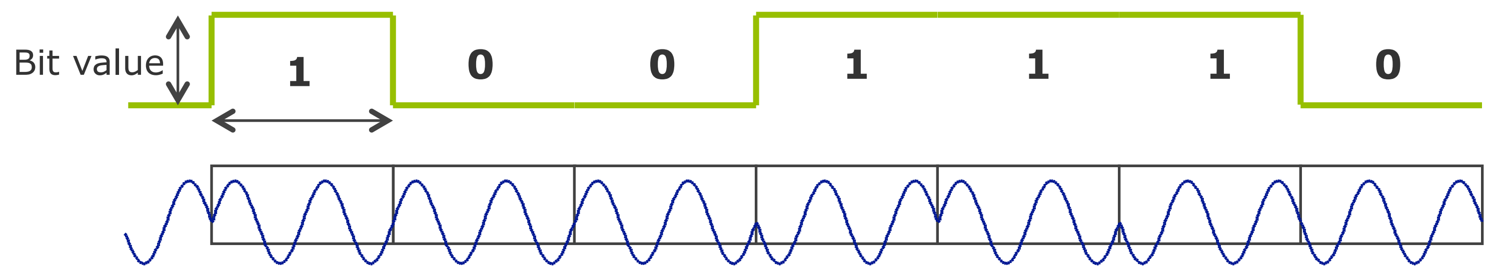
- The phase shift can also cover more than two phases: shift between M different phases, whereby M must be a power of two.
  - Thus, more information can be sent at the same time.
- Example: **Quadrature Phase Shift Keying (QPSK)**
  - Shifting between 4 phases
  - 4 phases permit 4 states: code 2 bits 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)

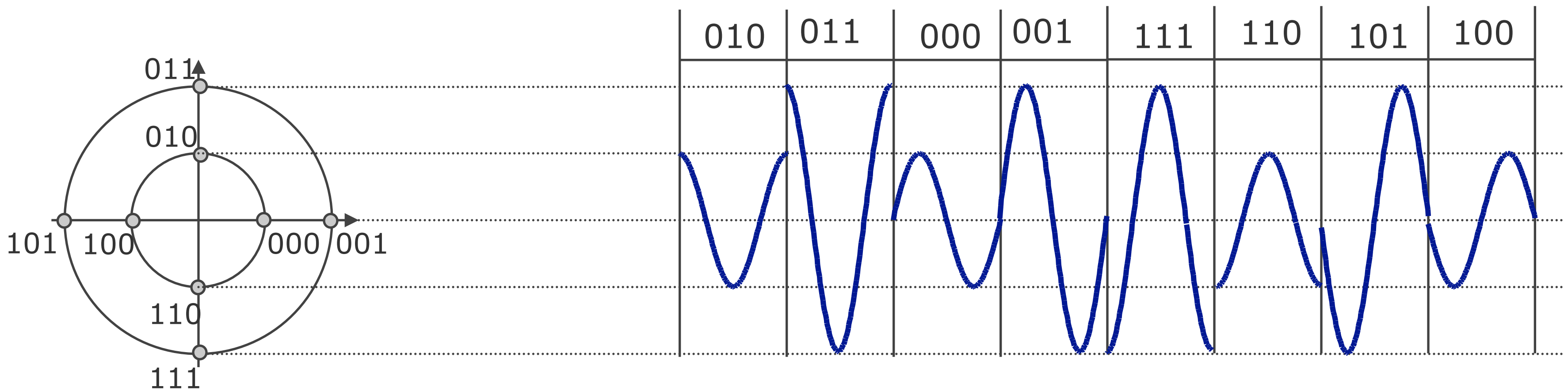
Advanced PSK Techniques: Other PSK Variants

- Other modems in use:
  - BPSK = Binary PSK = PSK
  - 2B1Q = 2 Binary on 1 Quaternary = QPSK
  - CAP = Carrier-less 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:



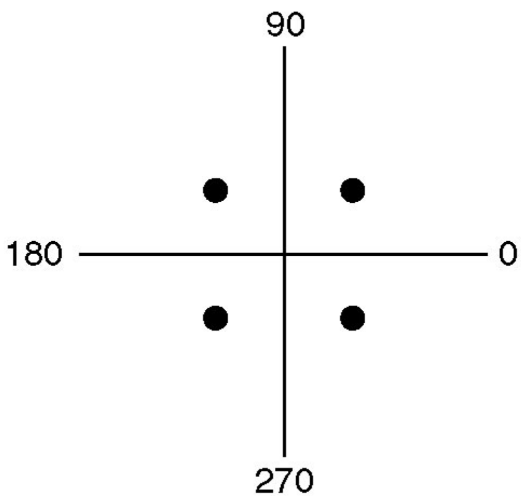
Advanced PSK Techniques: QAM

- Quadrature Amplitude Modulation (QAM)
  - **Combination of ASK and QPSK**
  - n > 2 bits can be transferred at the same time (n =2 is QPSK)
  - Bit error rate rises with increasing n, but less than with similar PSK technique
  - Example: QAM-8 which transfers 3 bits per symbol

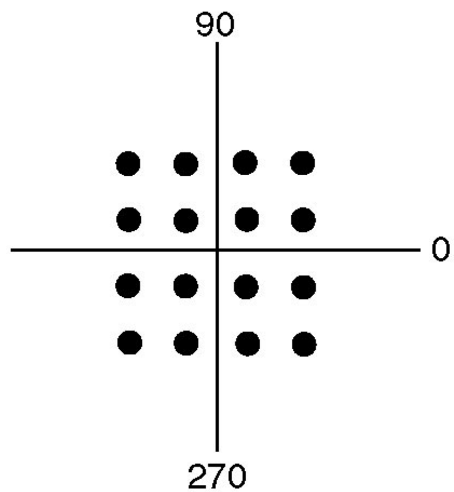


Advanced PSK Techniques: QAM-64

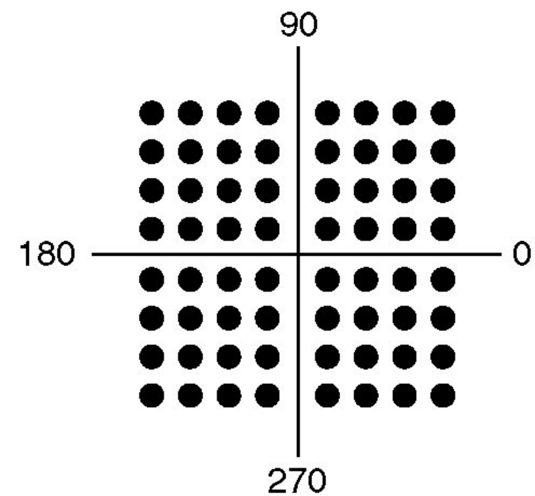
Constellation Diagrams



QPSK
2 bit/symbol



QAM-16
4 bit/symbol
Four amplitudes and four phases

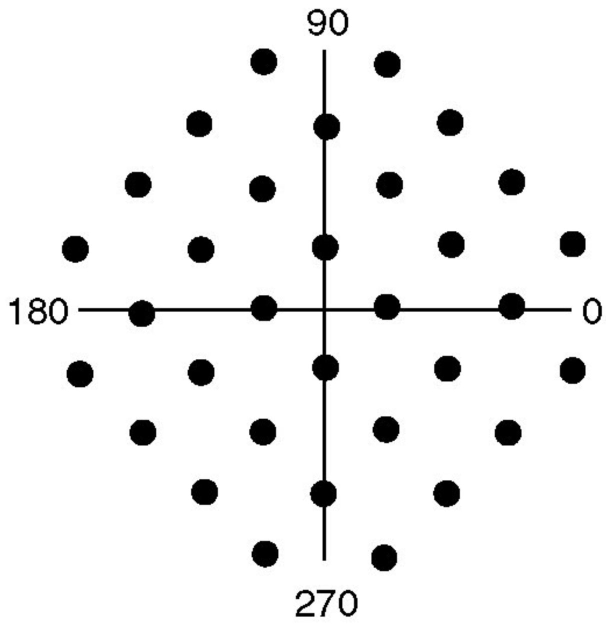


QAM-64
6 bit/symbol

Advanced PSK Techniques: V.32

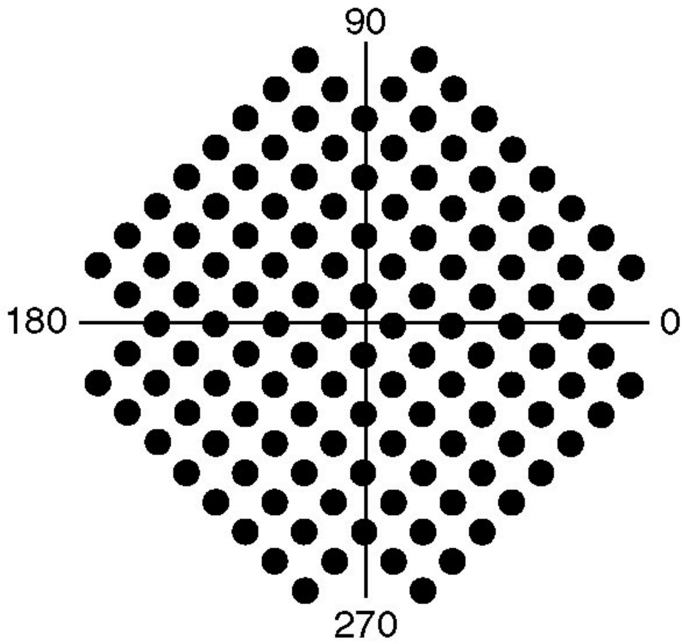
V.32 for 9600 bit/s

32 constellation points
4 data bit and 1 parity bit



V.32bis for 14400 bit/s

128 constellation points
6 data bits and 1 parity 1
Used by Fax



- Standardized by the ITU.
- Newer standard: V.90 for 56kbps

CONTENT of this CHAPTER

- Signals, Bandwidth, Symbol Rate
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- Modulation
- Multiplexing
- Types of physical medium

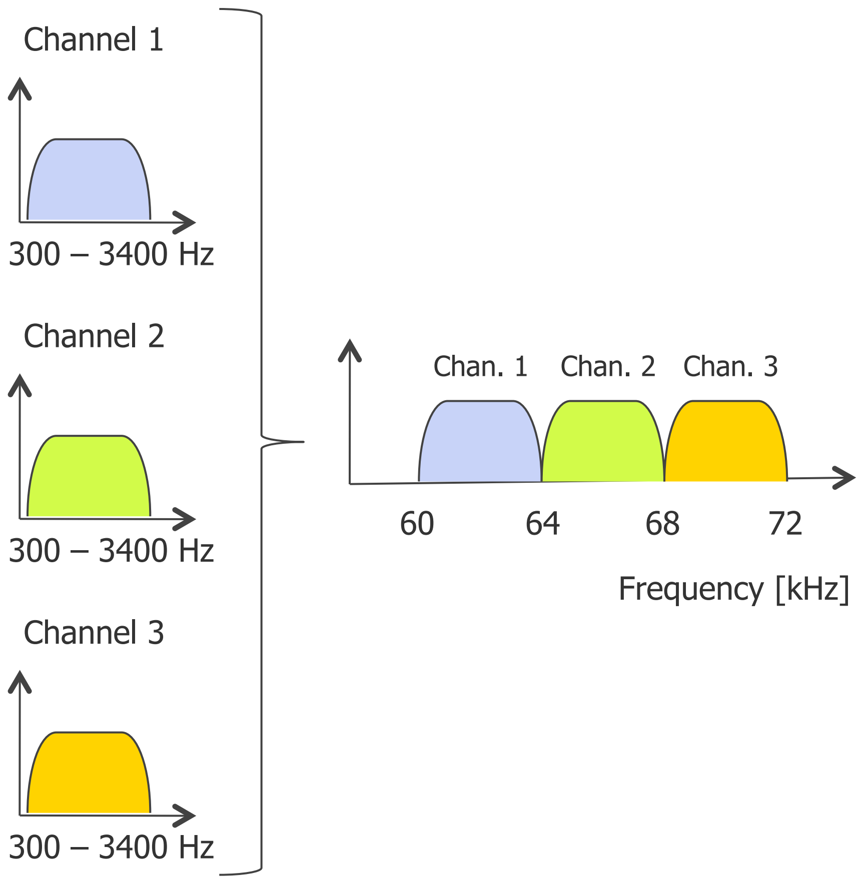
Multiplexing

- Lines are expensive and should be used as efficiently as possible
  - Resource sharing

- Multiplexing
  - Technique providing simultaneous connections over a single physical line

- Two main 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

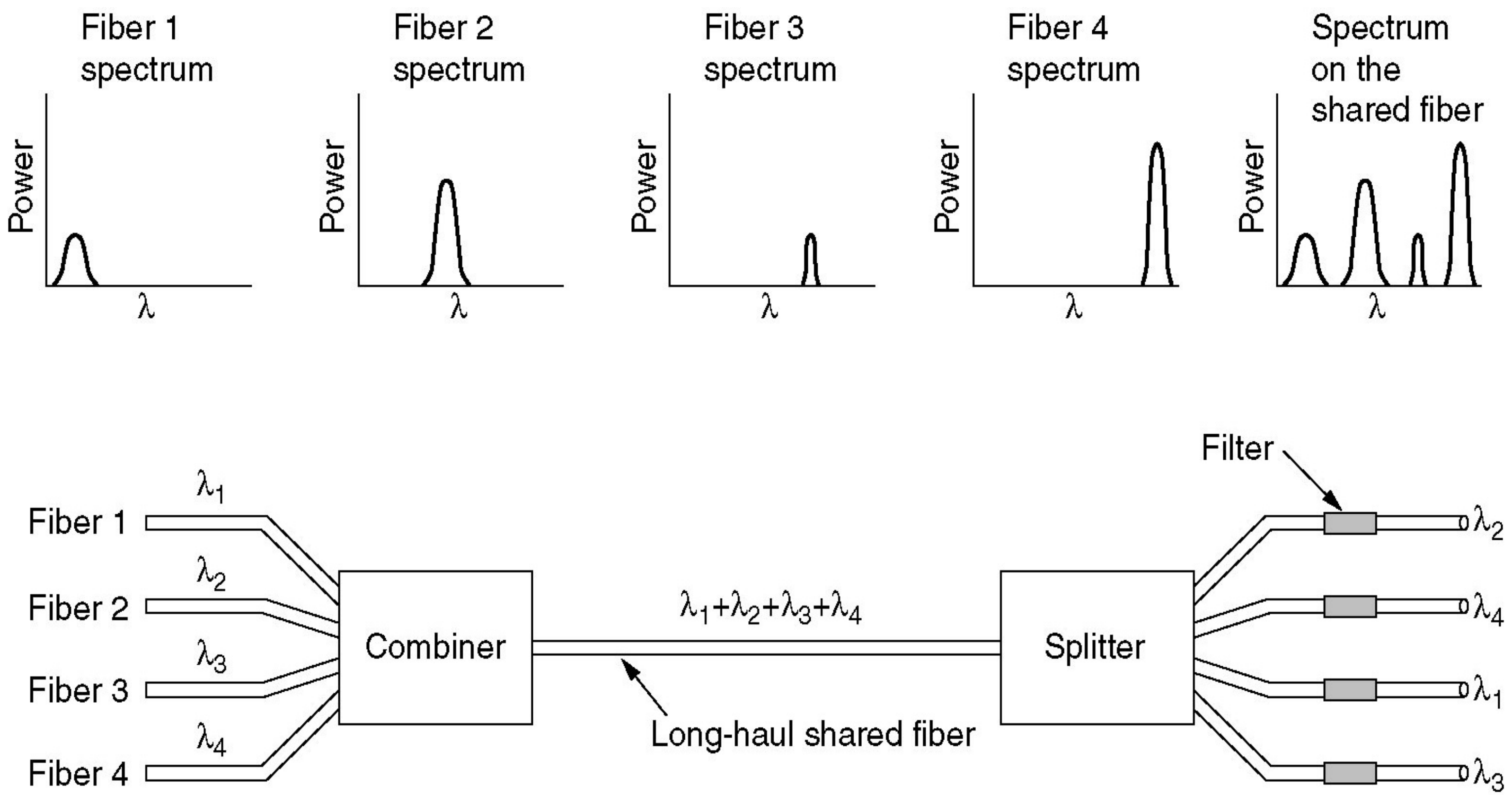
Frequency Division Multiple Access (FDMA)



- Simultaneous transmissions on separate frequency bands
  - Similar to people's voices with sufficiently different *pitch* that they can be distinguished when they talk at the same time.
- Example: CCIT standard (now ITU-T)
  - Multiplexing of 12 voice channels of 4kHz into 60-108kHz band
    - This unit is called a **group**
    - Five groups built a **supergroup**
    - Five supergroups built a **mastergroup**

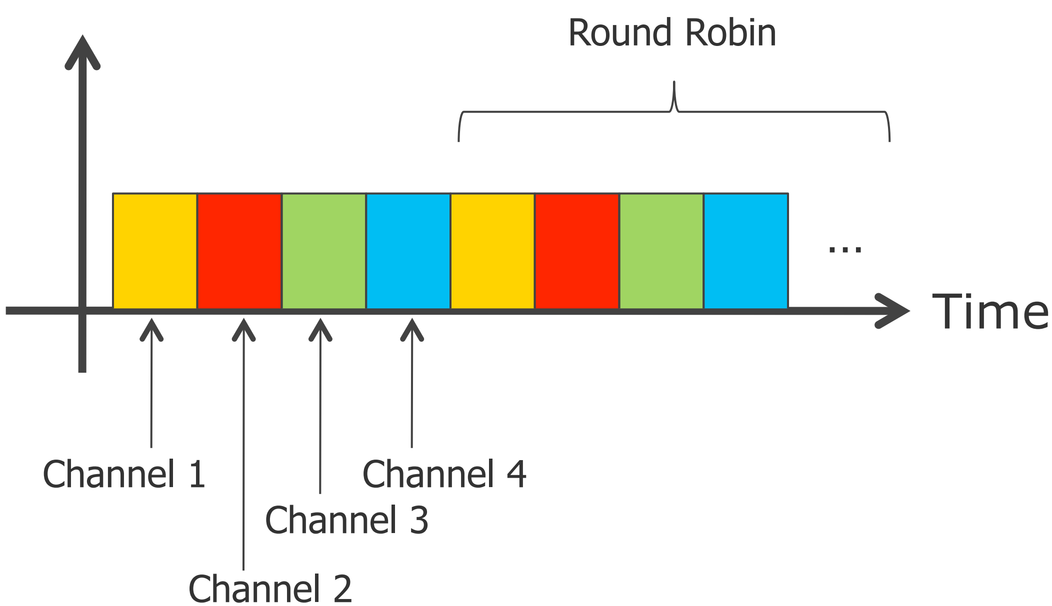
Wavelength Division Multiple Access (WDMA)

- FDMA for optical transmission ➡ Wavelength Division Multiplexing (WDM)

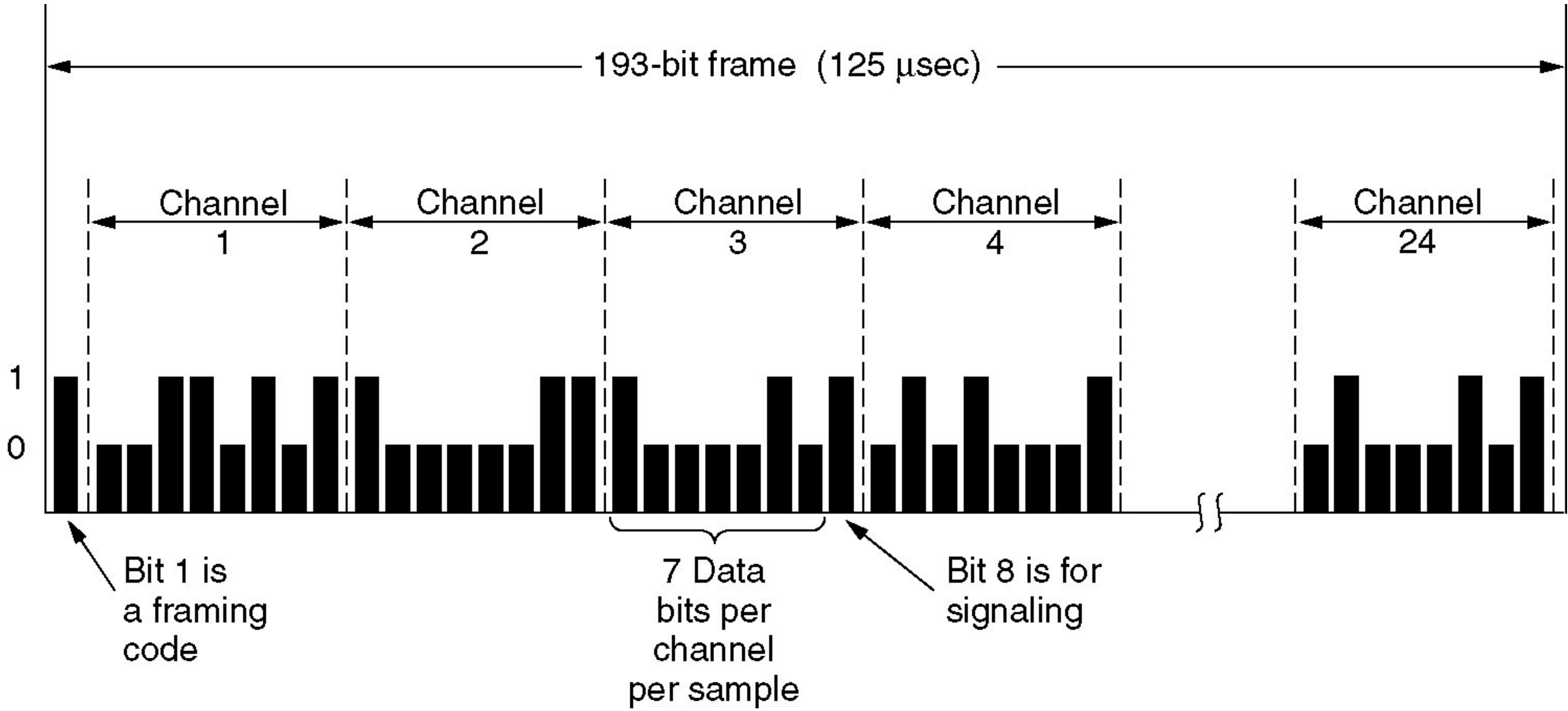


Time Division Multiple Access (TDMA)

- Time domain is divided into timeslots of fixed length
  - Each timeslot represents one sub-channel
  - Similar to a discussion where people talk one after the other, in a specific order



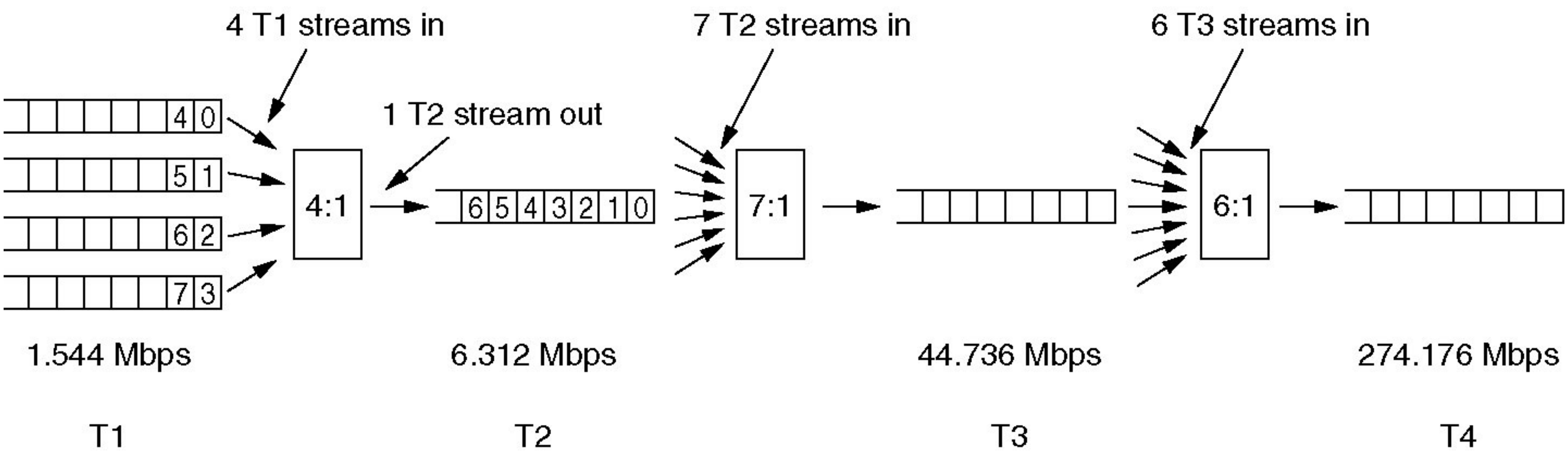
Time Division Multiplexing: The T1 Example



- 24 channels in parallel, 8 bits per channel (1 bit for control)
- 193 bit frame, lasting 125 micro sec
- 1.544 Mbit/s

Time Division Multiplexing: T2, T3, T4

Multiplexing T1 streams into higher carriers



Similar standards family from ITU, using TDMA:

- E1 (2.048 Mbit/s)
- E2, E3,… E5 (565 Mbit/s and 8182 channels)

Time Division Multiplexing: SONET and SDH

- Standards for even higher data rates:
  - Synchronous Optical Network (SONET)
    - Optical TDM system
    - Long distance telephone lines
    - Standard developed by Telcordia
  - Synchronous Digital Hierarchy (SDH)
    - Equivalent standard developed by the ITU

- Used in US and Canada
- Rest of the world

- Example data rates (SONET / SDH):
    - OC-48 / STM-16 (at 2 Gb/s)
    - OC-192 / STM-64 (at 9 Gb/s)
    - OC 768 / STM-256 (at 38 Gb/s)

- SONET and SDH are similar & interoperable
  - Synchronous: master clock with an accuracy of 10^{-9}
  - Multiplexing of multiple digital channels
  - Support for operations, administration, and maintenance (OAM)

Code Division Multiple Access (CDMA)

- **FDMA**: different user => different frequency
  - Drawback: wasted frequency if a user has nothing to send
- **TDMA**: different user => different timeslot of one frequency
  - Drawback: wasted time slot if a user has nothing to send
- **CDMA**: different user => same channel/time but different spread spectrum code

- Transmiters use pre-assigned signature sequences called spread code
  - use of noise-like carrier waves, and bandwidths much wider than that required for simple point-to-point communication at the same data rate
  - Similar to each transmiter speaking a different language
- Receivers perform a correlation operation to distinguish transmissions associated with a given spread code

- Advantages of CDMA include :
  - Frequency/timeslot reuse! Efficient utilization of the available bandwidth/timeslots
  - Flexible allocation of available resource in terms of bandwidth
  - Harder to detect (low spectral power density) and to wiretap, or jam

Code Division Multiple Access: Example

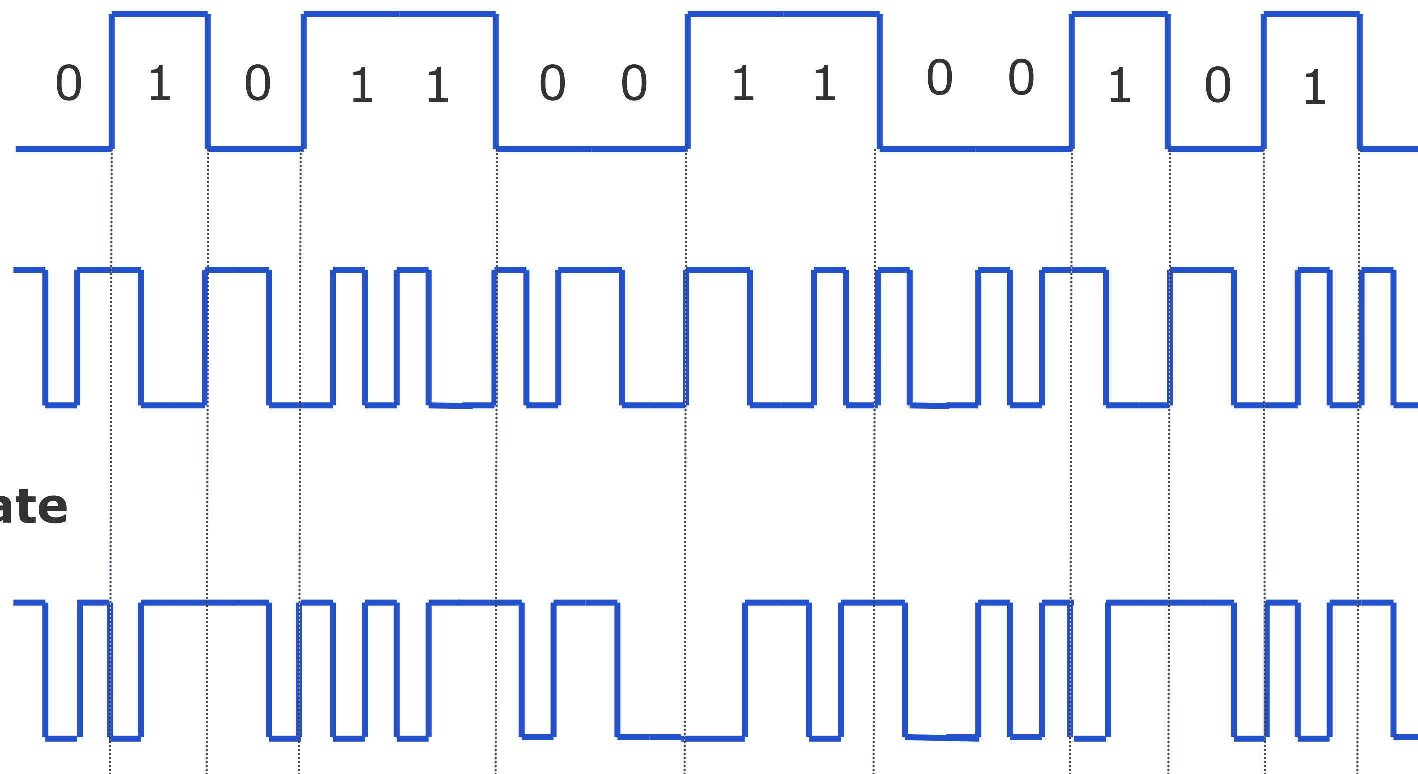
- Spread codes must be chosen carefuly so that it is possible for the receiver to distinguish the sender’s transmission. Two techniques are used:
  - Synchronous technique using orthogonal codes (Walsh codes)
  - Asynchronous technique using pseudorandom codes, as shown below:

Data Signal
(bit rate)

Pseudo-random
spread code
(chip rate)

chip rate >> bit rate

Transmitted signal
(Data **XOR** Code)



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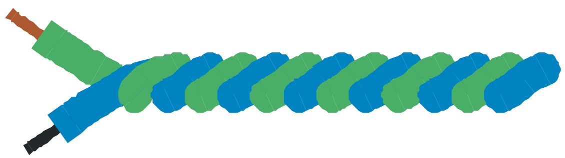
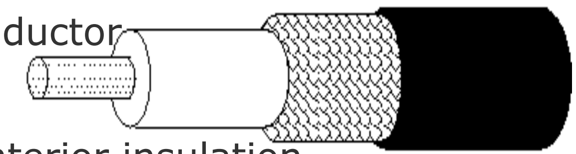
Transmission Media



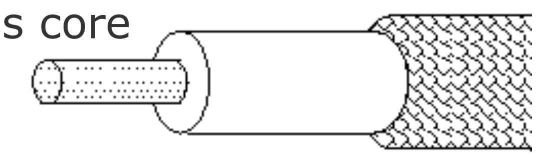
Twisted Pair

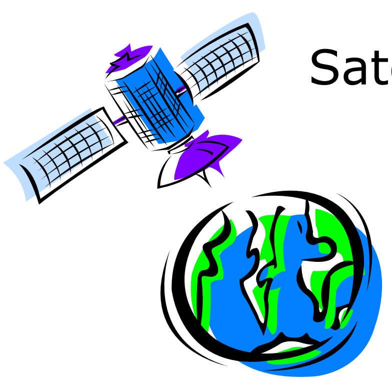


Coaxial cable

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

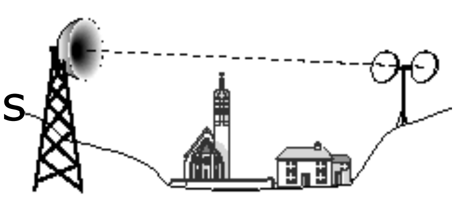
Optical fiber



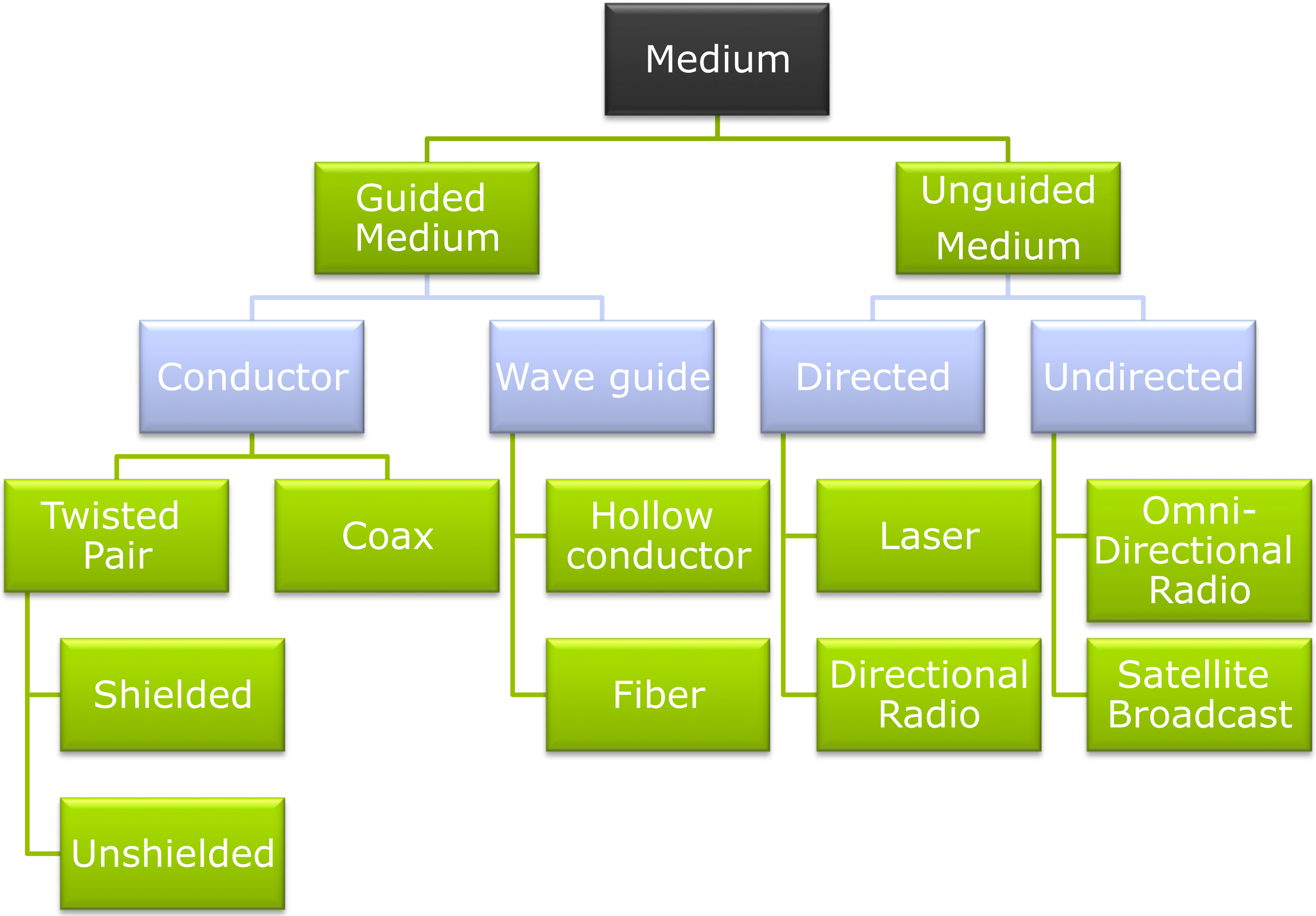


Satellites

Radio connections



Transmission Media: Classification



Signaling through Electromagnetic Waves

- Electromagnetic waves are used to transmit the signal
  - over wireless of course, but also on cables!

- In vacuum all electromagnetic waves travel at the speed of light
  - 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 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

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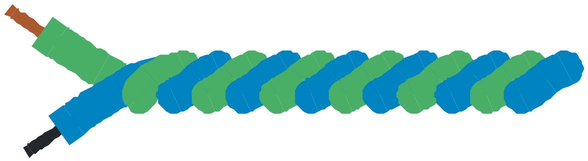
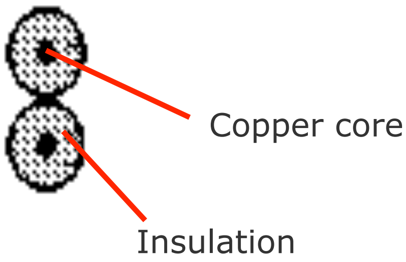
  - Guided Medium
  - Unguided Medium
  - The Last Mile

Twisted Pair: Basic Characteristics





- 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
    - Additionally: individual twist length per copper pair to reduce crosstalk
  - 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}

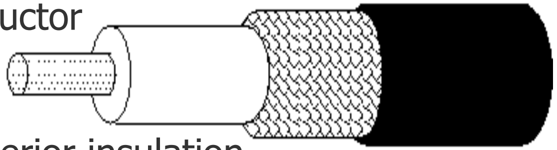
Twisted Pair: Categories (Cat3, Cat5…)

Category	**Category 3** ▪ Two insulated, twisted copper cables ▪ Shared protective plastic covering for four twisted cable pairs **Category 5 (< 100MHz)** ▪ Similar to Cat 3, but more turns/cm ▪ Covering is made of Teflon (better insulation, resulting in better signal quality on long distances) **Category 6 (<250MHz) , 7 (<600MHz)** ▪ Each cable pair is covered with an additional silver foil **Today Cat 5e is used most of the time**
Shielding	**UTP** (Unshielded Twisted Pair) ▪ No additional shielding, typical for patch cables **STP** (Shielded Twisted Pair) ▪ Each cable pair is shielded separately to avoid interferences between the cable pairs ▪ Typical for structured cabling in buildings

Coaxial Cable

Structure

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



Characteristics:

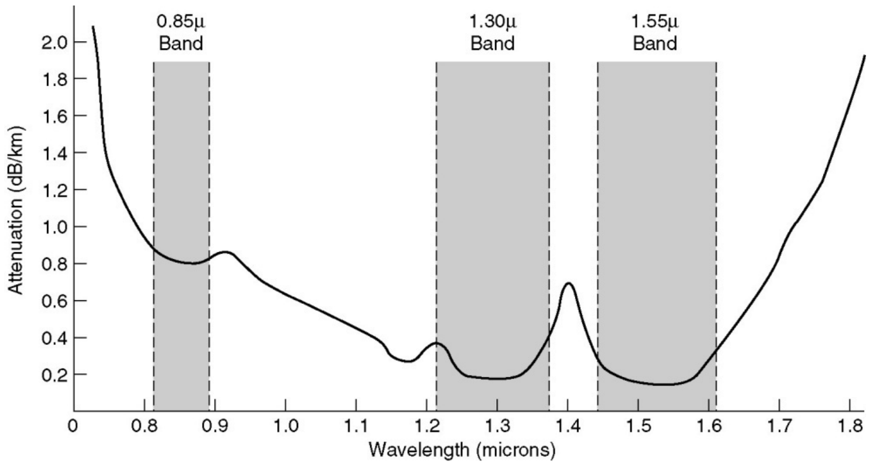
- Bit error rate ~ 10^{-9}
- Higher data rates over larger distances than twisted pair: 1-2 Gbit/s up to 1 km
- Better shielding than twisted pair, resulting in better signal quality

Early networks were build with coaxial cable, however it was more and more replaced by twisted pair. **Today coaxial cables are typically used in cable networks**.

Optical Fiber: Characteristics

Characteristics

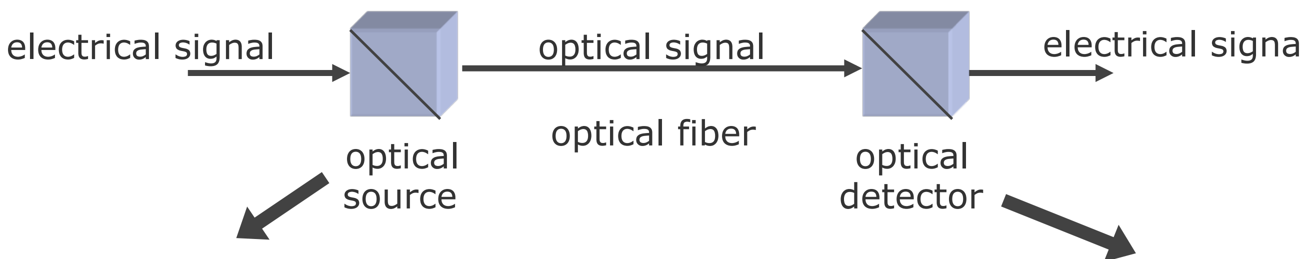
- Ever higher capacity, nearly unlimited data rate over long distances
- Insensitive to electromagnetic disturbances
- Good signal-to-noise-ratio
- Greater repeater spacing
- Smaller in size and lighter in weight
- Bit error rate ~ 10^{-12}



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)

Optical Fiber: Transmission

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

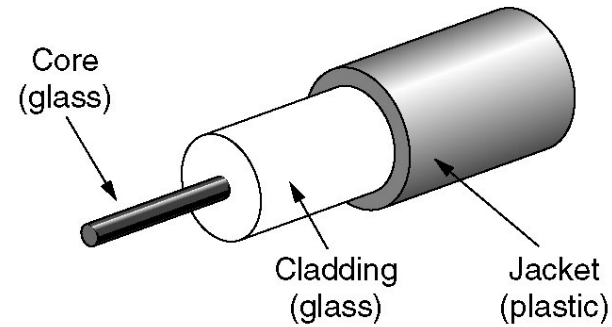


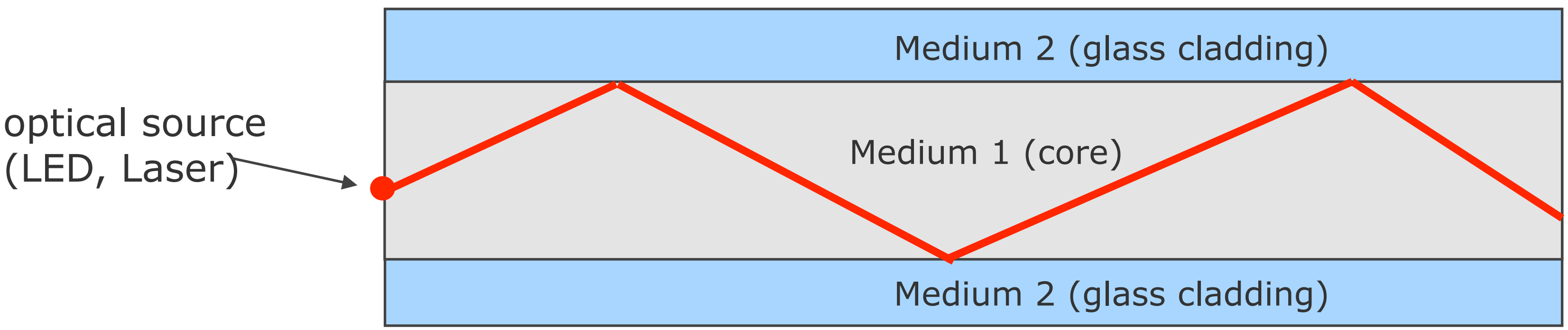
	LED	Laser
Data rate	Low	High
Fiber type	Multimode	Single-/ Multimode
Distance	Short	Long
Lifetime	Long life	Short life
Temperature sensitivity	Minor	Substantial
Cost	Low	High

Photodiodes
models differ in particular wrt. signal-to-noise ratio)

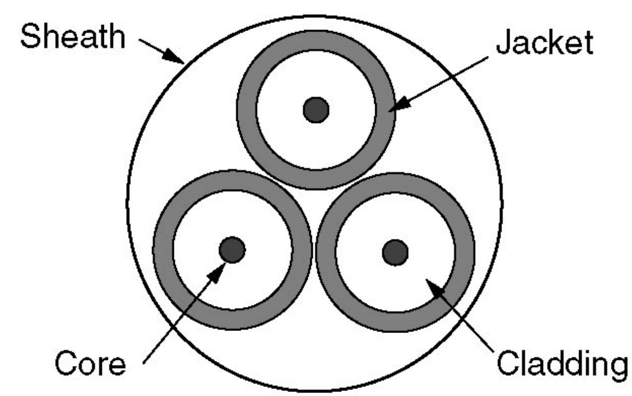
Optical Fiber: Structure

- Structure of a fiber
  - Core: optical glass (extremely thin and pure)
  - Internal glass cladding
  - External protective plastic covering



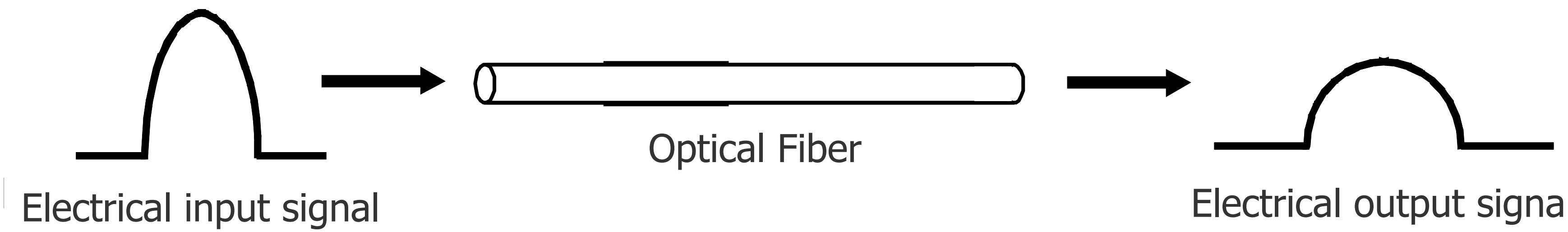


- The transmission takes place in the **core** of the cable
  - Core has higher refractive index, therefore the light remains in the core
  - Ray of light is reflected instead of transiting from medium 1 to medium 2
- Remark 1: refractive index is material dependent
- Remark 2: a cable consists of many fibers



Optical Fiber: Challenges

- **Attenuation**: the ray of light is increasingly weakened along the medium!
  - Absorption can weaken a ray of light gradually
  - Impurities in the medium can deflect individual rays

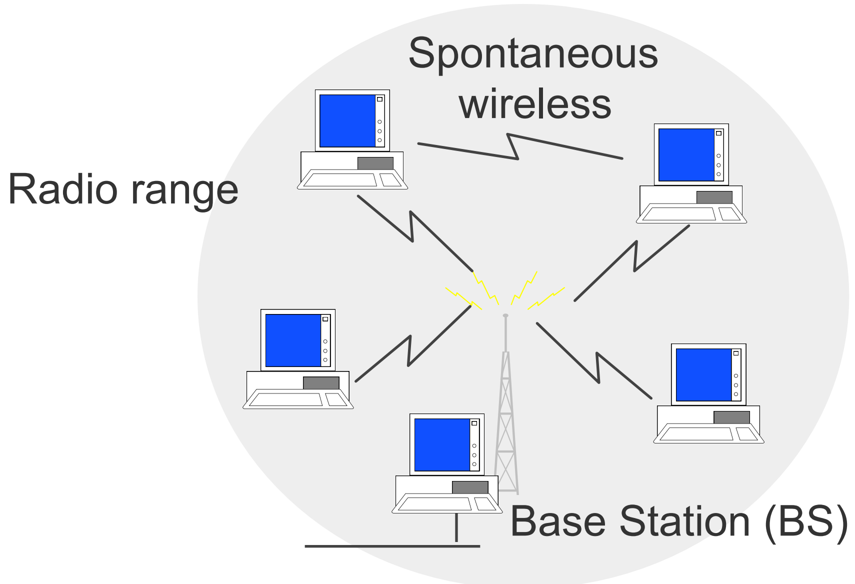


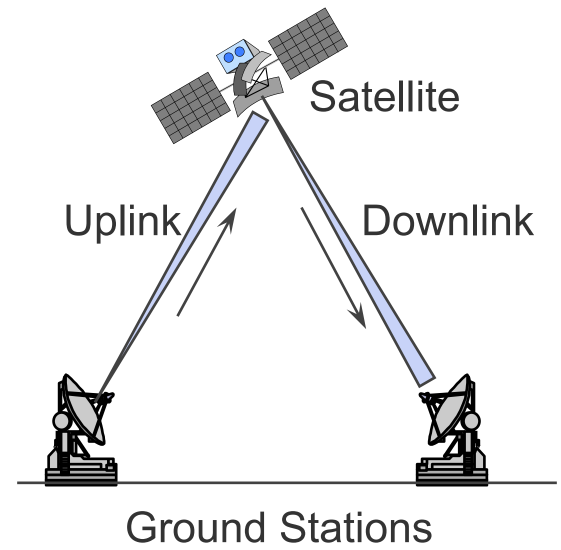
- **Dispersion**: not as bad, but transmission range is nevertheless limited
  - Rays of light spread in the medium with different speed:
    - Ways (modes) of the rays of light have different length (depending on the angle of incidence)
    - Rays have slightly different wavelengths (and propagation 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!

CONTENT of this CHAPTER

- Signals, Bandwidth, Symbol Rate
- Quantization, Sampling, Channel Capacity
- Data Encoding
- Modulation
- Multiplexing
- Types of physical medium
  - Guided Medium
  - Unguided Medium
  - The Last Mile

Wireless Communication

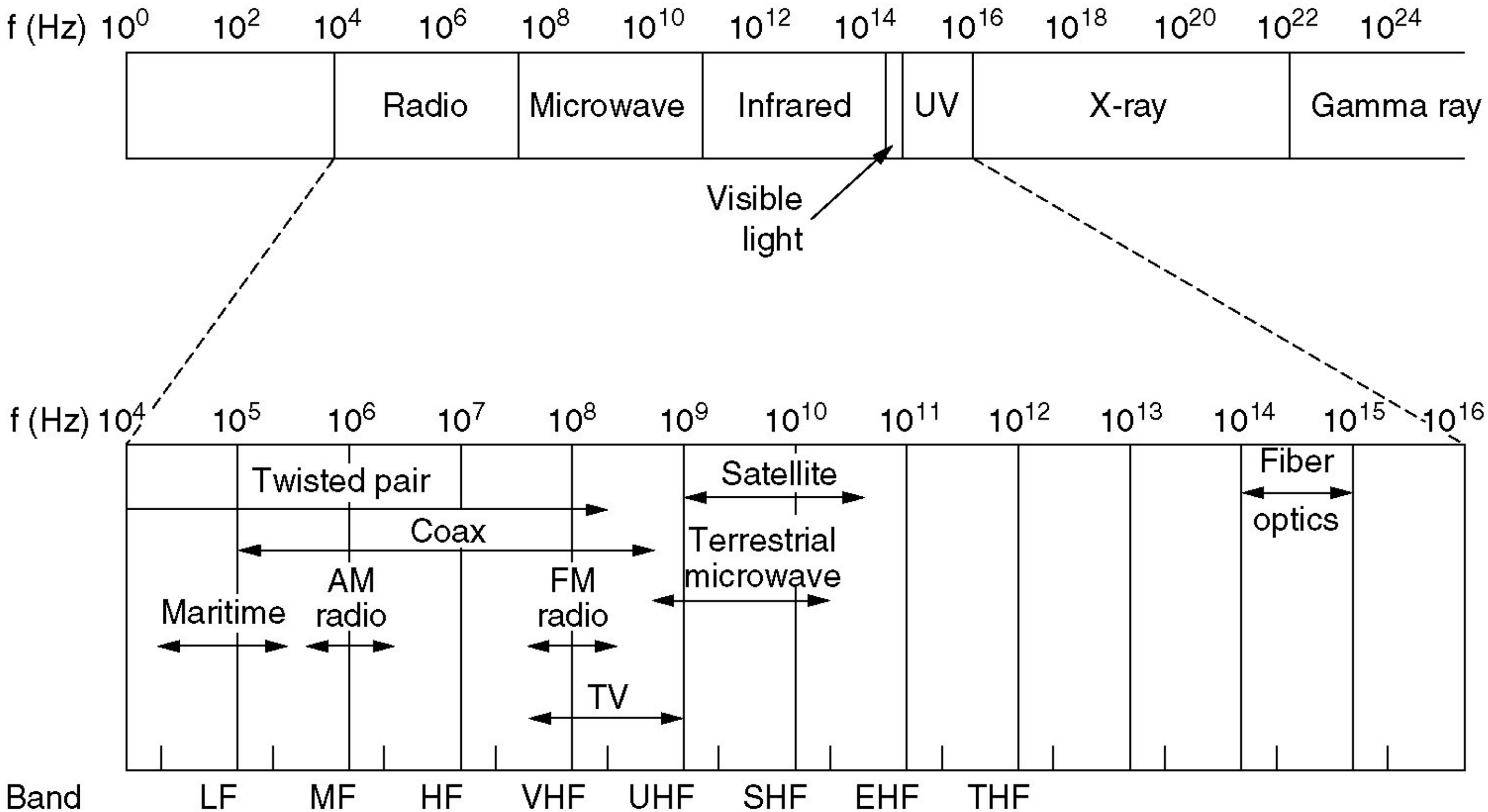




- Medium: electromagnetic wave **(10^4 - 10^9 Hz)**
- Data is modulated
- Restricted range
  - depends on signal power
  - environment
- Data rates vary from10kbps to 100Mbps

- 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



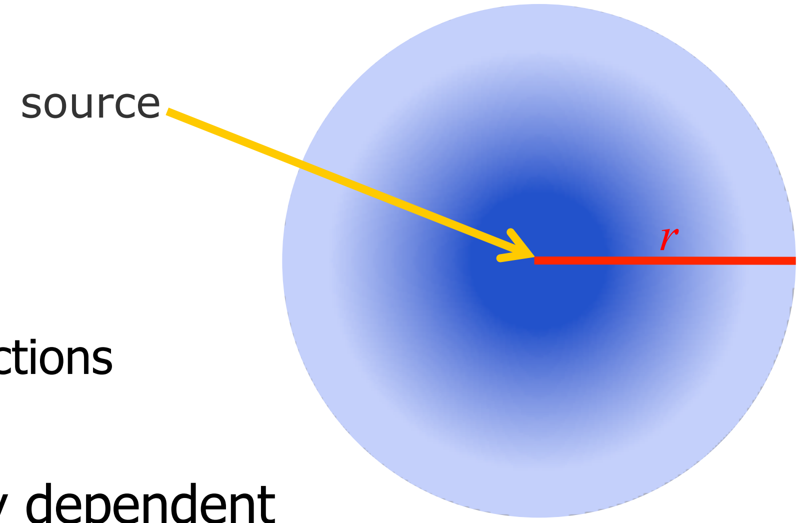
LF = Low Frequency
MF = Medium Frequency
HF = High Frequency

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

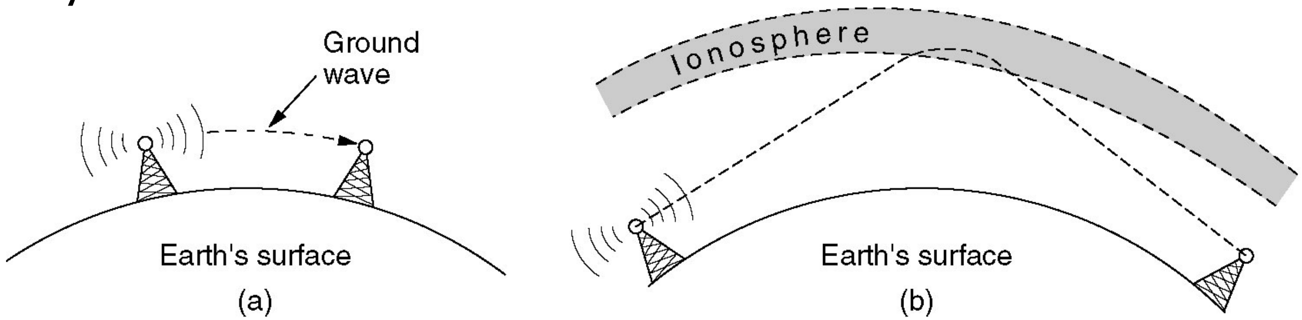
EHF = Extremely High Frequency
THF = Tremendously High Frequency

Radio Transmission

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



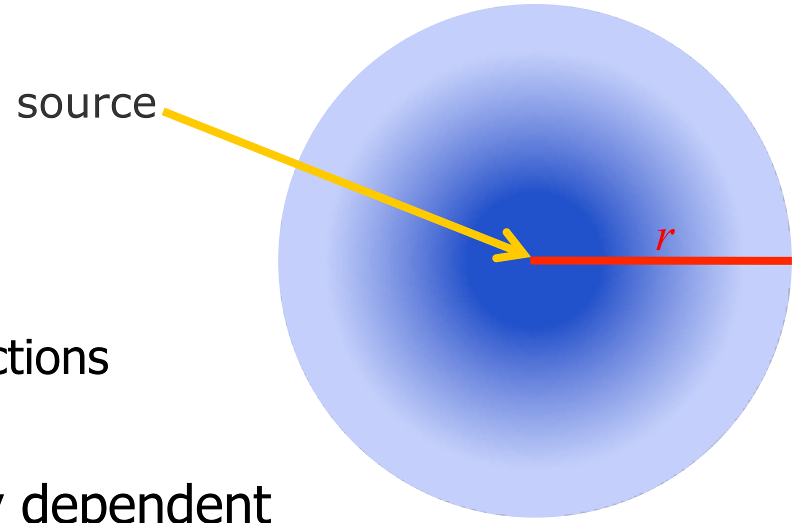
- Properties of radio waves are frequency dependent
  - At low frequencies, they pass through obstacles well
  - The power falls off with distance from the source, roughly $\frac{1}{r^2}$
  - At high frequencies they travel on straight lines and bounce off obstacles, and are absorbed by water



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.

Radio Transmission



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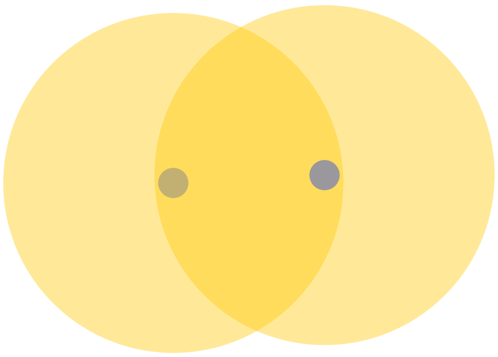
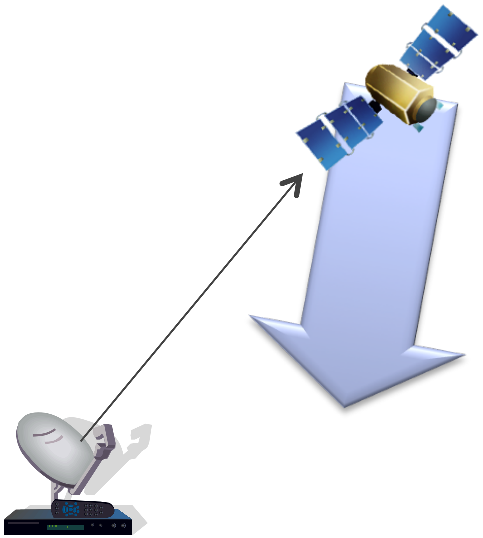
  - At high frequencies they travel on straight lines and bounce off obstacles, and are absorbed by water
- And another BIG problem:
  - Interference between users



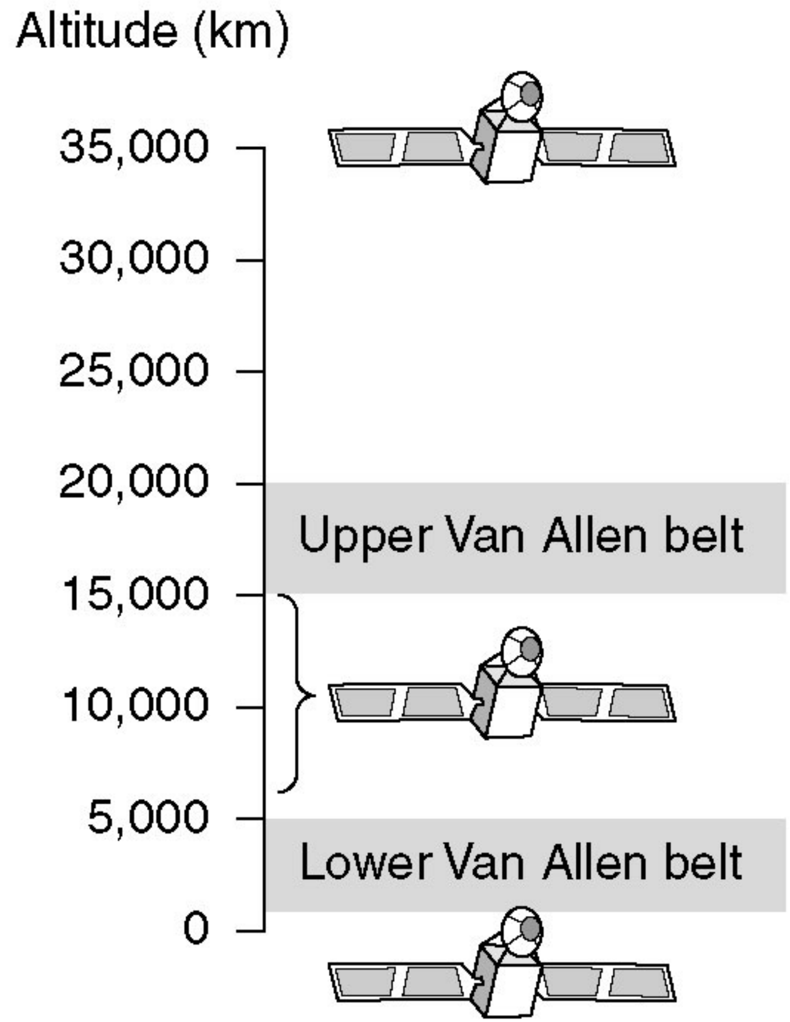
Communication Satellites: Principle

- Principle:
  - A satellite contains several transponders
  - A transponder receives, amplifies, and relays signals

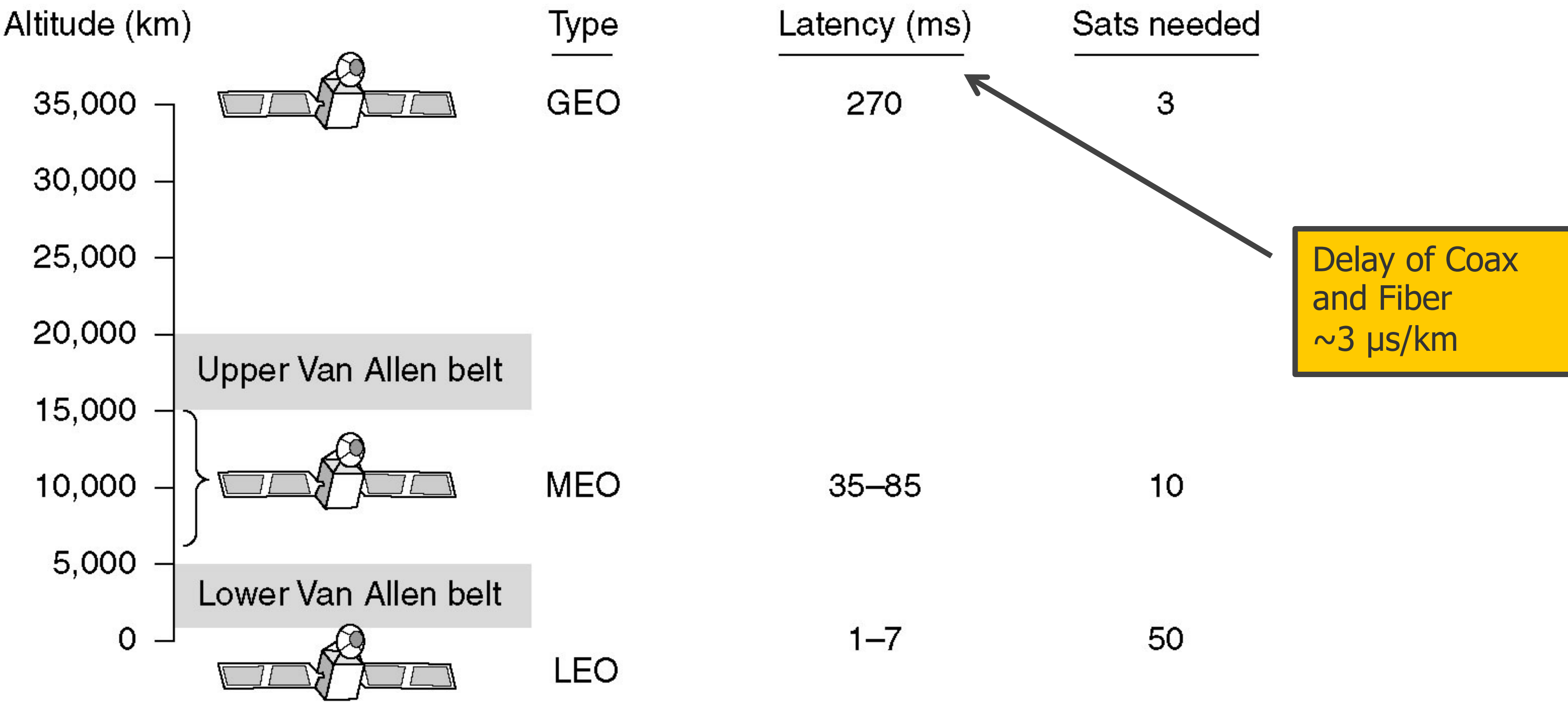


Communication Satellites: Orbits

- 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: RTT



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: Pros & Cons

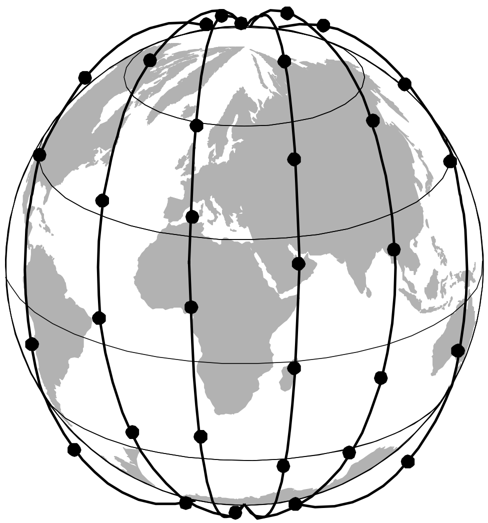
- Advantages
  - Cost of messages independent from distance
  - Broadcast media
    - Message sent to one person or thousands does not cost more
    - Proxies for web access

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

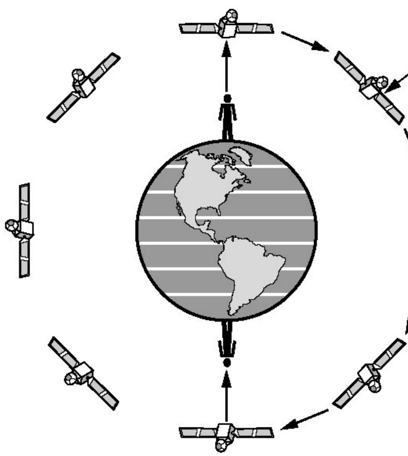
Communication Satellites: Example Deployments

- Iridium
  - LEO
  - Altitude: 750 km
  - Total of 66 satellites
  - Launch of the satellites 1997
  - Start of service 1998
  - Service: Worldwide voice & data using hand-held devices that communicate directly with the satellites
  - www.iridium.com
- Globalstar
  - LEO
  - Altitude: 1440 km
  - Total of 48 satellites
  - Launch of satellites in 1998
  - Start of service in 2000
  - Voice & data in almost all regions of the globe
  - www.globalstar.com

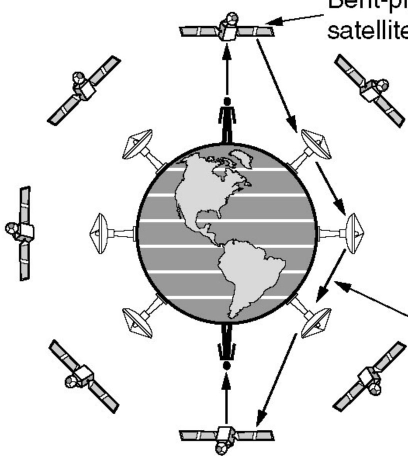
Communication Satellites: Example Topology



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



Relaying in space
Used in Iridium



Relaying on the ground
Used in Globalstar

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The Last Mile

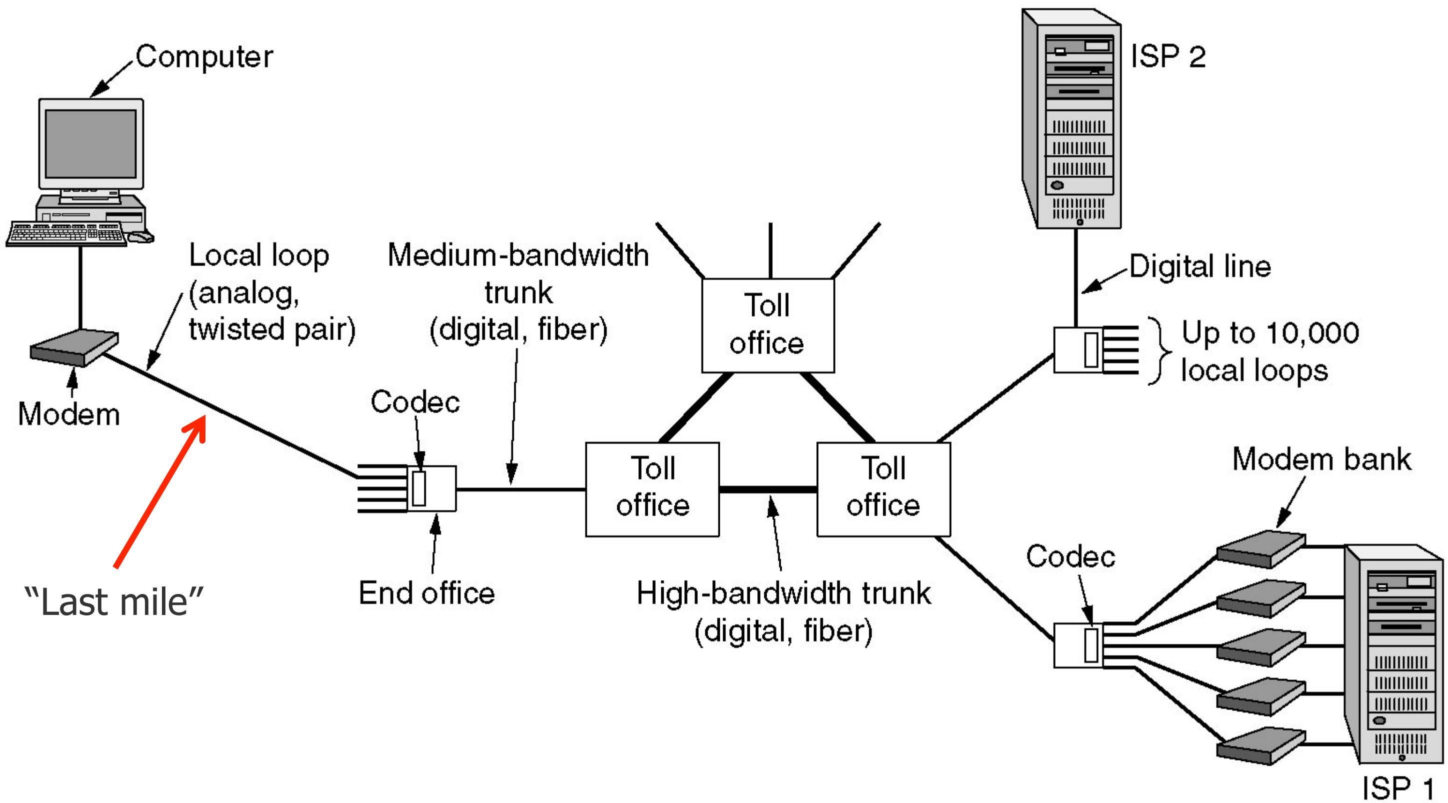
- Problem: how to connect homes to the Internet, without it being to costly?
  - i.e. if possible not too many new cables!

- Popular solutions:
  - Access through existing phone lines local loop (**DSL**)
  - Access through existing **cable TV** network connections
  - Access through deployed **cellular networks** (3G / 4G)

- Other solutions:
  - Access through existing **powerline** connections
  - Access through **satellite** communication
  - Access through WiMAX
  - Access through new optical **fiber-to-the-home**

Access via DSL (Digital Substriber Line)

- Medium: **twisted pair**
- Modulation with DSL modem
- Upstream multiplexing with DSL Access Multiplexer (**DSLAM**)
- 288 channels spread from 40kHz to 1MHz. Each channel is 4kHz.
- 32 channels for upstream, 256 for downstream.



Access via DSL: Standards

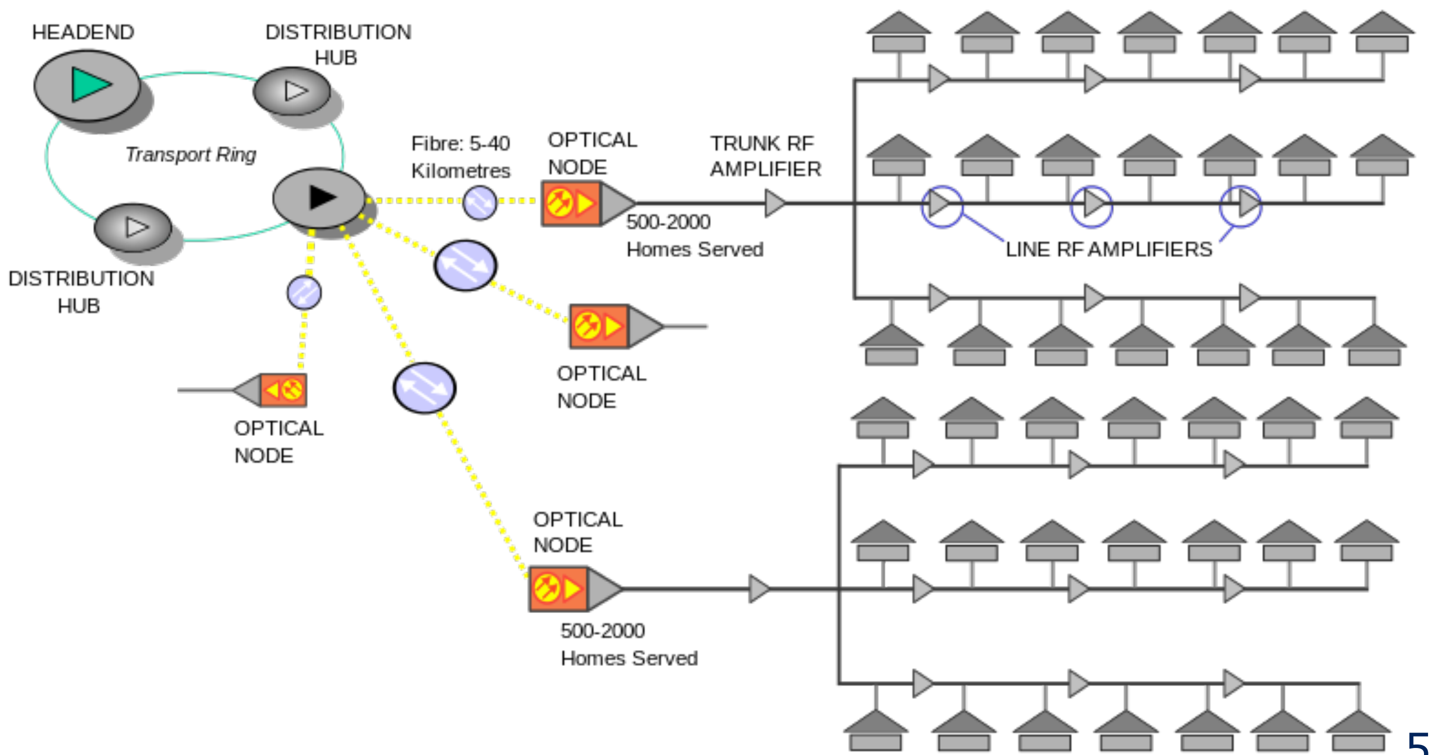
- VDSL (Very-high-bit-rate digital subscriber line):
  - ITU recommendation G.993.1 published 2004
  - up to 52 Mbit/s downstream and 16 Mbit/s upstream
  - Using frequency band from 25 kHz to 12 MHz

- VDSL2 (Very-high-bit-rate digital subscriber line 2):
  - ITU recommendation G.993.2 published 2006
  - up to 200 Mbit/s down- and upstream using frequencies up to 30 MHz
  - 100 Mbit/s at 500m, 50 Mbit/s at 1 km
  - Still up to some Mbit/s up to 5 km

- Noticeable trade-off: **bandwidth *vs* distance**
  - the longer the twisted pair, the less bandwidth available

Access via Cable Television

- Medium: **coaxial cable**
- Modulation with cable modem
- Upstream multiplexing with **CMTS** (Cable Modem Termination System)
- Use of multiple channels from low-end radio spectrum (6MHz to 8MHz)

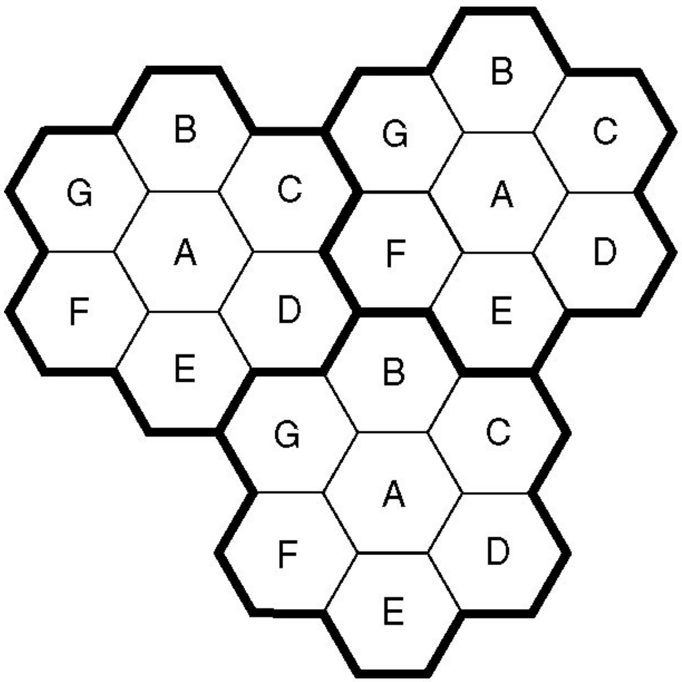


Access via Cable Television: Standards

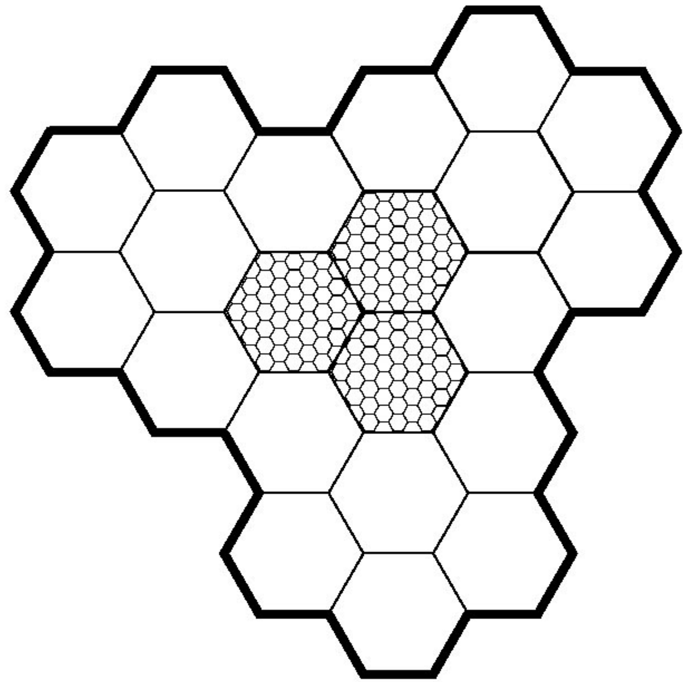
- Data Over Cable Service Interface Specification (**DOCSIS**)
  - Standard developed and maintained by CableLabs
  - Ratified as ITU-T Recommendation
- DOCSIS1.0 published in 1997 (ITU-T J.112)
- DOCSIS2.0 published in 2001 (ITU-T J.122)
- DOCSIS3.0 published in 2006 (ITU-T J.222)
  - Downstream up to 160 Mbit/s, and upstream up to 20Mbit/s
- Modern architecture: hybrid fiber/coaxial architecture (HFC)
  - Higher throughputs achievable

Access via Cellular Networks

- Medium: **wireless omnidirectional**
- Modulation with modem integrated in cell phone
- Upstream multiplexing with **base station** (which manages its **cell**)
- Use of multiple channels in 806–960 MHz, 1,710–2,025 MHz, 2,110–2,200 MHz and 2,500–2,690 MHz



Coverage area split into cells. Frequencies not reused in adjacent cells



To add more users, smaller cells can be used

Access via Cellular Networks: 3GPP Standards

- Standardization body: 3GPP (3rd Generation Partnership Project)

- Well-known 3GPP standards:

  - 3G : UMTS (Universal Mobile Telecommunications System)
    - 42 Mbit/s downlink

  - 3G+ : HSPA (High Speed Packet Access)
    - 168 Mbit/s in the downlink, and 22 Mbit/s in the uplink

  - 4G: LTE (Long Term Evolution)
    - 300 Mbit/s in the downlink, and 75 Mbit/s in the uplink

- Debate over « what is really 4G? »

Summary: The Physiscal Layer

- The physical layer is the basis of all networks
  - Relationship between bandwidth, symbol rate, and data rate
- There are fundamental limits on all communication channels
  - Nyquist sampling theorem, Shannon capacity theorem
- There are several ways to represent data sent through the channel
  - Various data encodings (NRZ, 4B/5B…)
  - Various modulation techniques (ASK, QAM…)
- There are several multiplexing techniques to share a channel
  - TDMA, FDMA, CDMA…
- There are several types of physical medium, with different characteristics
  - Guided transmission media (fiber, twisted pair…)
  - Unguided transmission media (wireles LAN, satellite…)