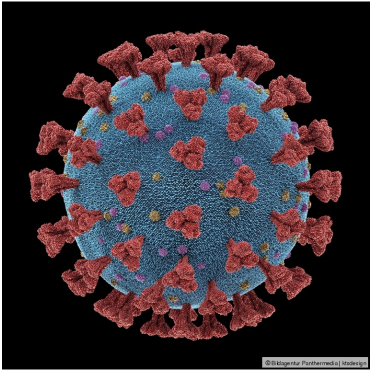
COVID-19 Measures

- Wear a mask (medical or FFP2) until you have taken a seat
- When seated you can take off the mask if you can maintain an interpersonal distance of 1,5 m
- Behave reasonable and use common sense



Computer Networks

Physical Layer - Data Signals

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Agenda

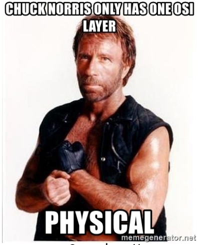
- Fundamentals of Data Signals
- Data Encoding
- Modulation

Recap: Physical Layer

- **Transmits the ones and zeros**
  - Physical connection to the network
  - Conversion of data into signals
- Protocol and transmission medium specify among others:
  - The data encoding on the transmission medium
  - The directional dependence of data transmission
  - The mechanical and electronic aspects (e.g., access point plug design, pin usage)

Hybrid Reference Model

Application Layer
Transport Layer
Network Layer
Data Link Layer
Physical Layer

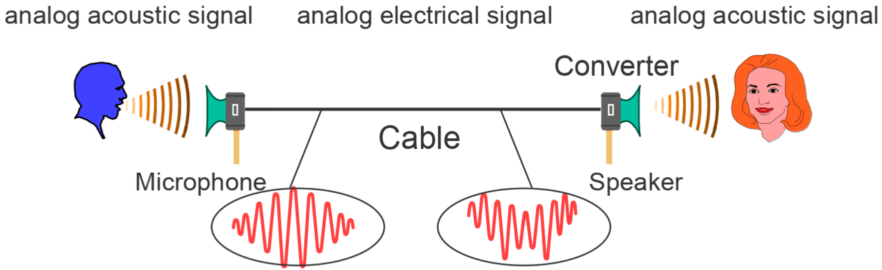


Source: https://memegenerator.net

Agenda

- Fundamentals of Data Signals
- Data Encoding
- Modulation

The Telephone Example

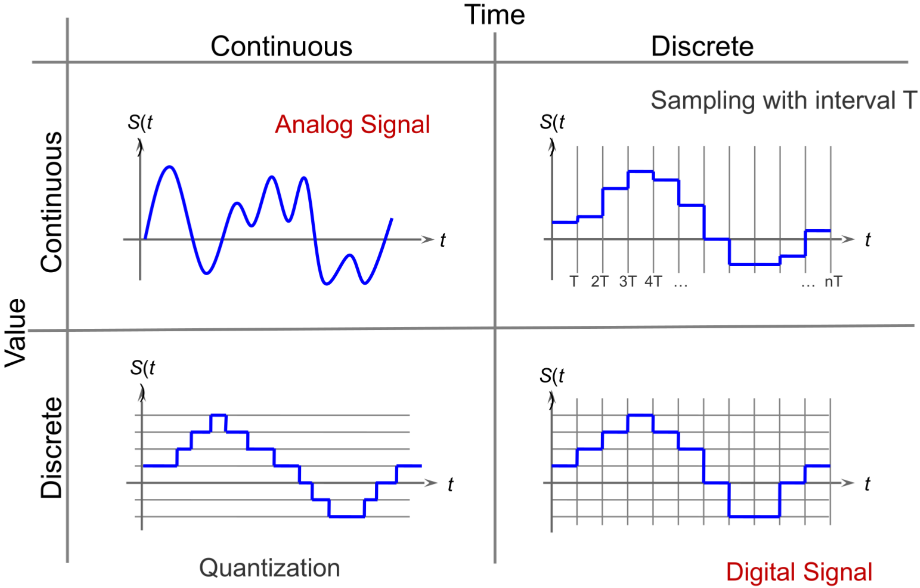


- Data is converted into a signal to be sent over a transmission channel
- A transmission channel consists of **access points** and the **physical medium** to carry the signal
- A signal is a **chronological sequence of physical values** measured on the medium

Physical Representation of Data

- A physical representation of data is called a signal
- It can be either
  - An analog signal → a sequence of continuous values
  - A digital signal → a sequence of discrete values
- The transmitter Network Interface Controller (NIC) acts as a **Co**der and **Dec**oder → **CODEC**

Continuous vs. Discrete Signals



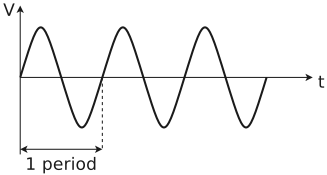
Quantization and Sampling

In order to transmit data over a transmission medium, it needs to be ...

- ... converted ⟶ Quantization
  - Computer networks deal with digital data ⇒ discrete signals
  - Physical mediums are by nature analog ⇒ **continuous signals**
  - Conversion from digital to analog signals and vice versa is required
- ... measured ⟶ Sampling
  - Computer networks deal with discrete time ⇒ discrete time
  - Physical mediums have a continuously varying state ⇒ **continuous time**
  - Periodical measurement of the physical medium is required

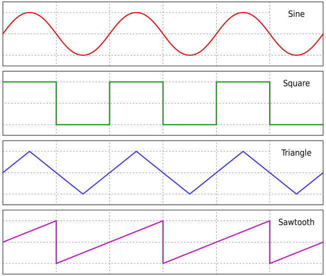
Basics of Signal Processing

- Periodic signals are the simplest signals
- Parameters for periodic signals:
  - Period T
  - Frequency $f = 1/T$
  - Amplitude $S(t)$
  - Phase ϕ



Examples

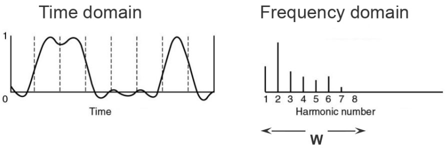
- Sinus (period $= 2 * \pi$)
- Square wave
- Triangle wave
- Sawtooth wave



Wikipedia, CC3 3.0

Fundamentals of Sampling

- In order to transform signals between time domain and frequency domain a discrete Fourier transform is required
- It specifies the bandwidth W of a signal in Hz



Whittaker-Kotel'nikov-Shannon (WSK) sampling theorem [1]

In order to allow for reconstruction of the original analog signal, the sampling frequency f_S has to be twice as large as the highest frequency:

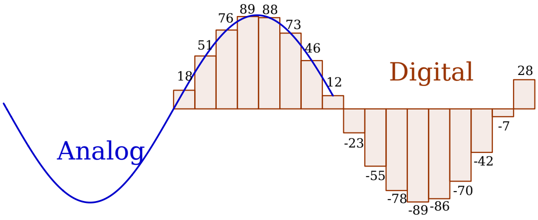
$f_S = 2 * f_{max} \rightarrow$ for baseband transmissions: $f_S = 2W$

[1] Historically also called Nyquist-Shannon sampling theorem

Fundamentals of Quantization

- Quantization approximates the full range of an analog signal into a finite number of discrete values
  $\longrightarrow$ Analog-to-Digital Conversion (ADC)
- The approximation error is called the quantization error
- The entire range is divided into equal intervals $\rightarrow$ the length of each interval is called quantization interval
- To recover an analog signal the center of the quantization interval is used for the $\longrightarrow$ Digital-to-Analog Conversion (DAC)

Sampling, Quantization, and Coding

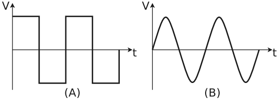


Author: Bjarne Skurdal

- Sampling and Quantization
  - The analog signal is converted to a digital representation by periodical measurements and converted by dividing the analog signal range into quantization intervals
- Coding
  - The quantization intervals are assigned to a binary code

Frequency

- Electrical engineering distinguishes between 2 types of voltage:
  1. **Direct current voltage**: Polarity of voltage and voltage level remain constant
  2. **Alternating current voltage**: Polarity of voltage and voltage level change periodically

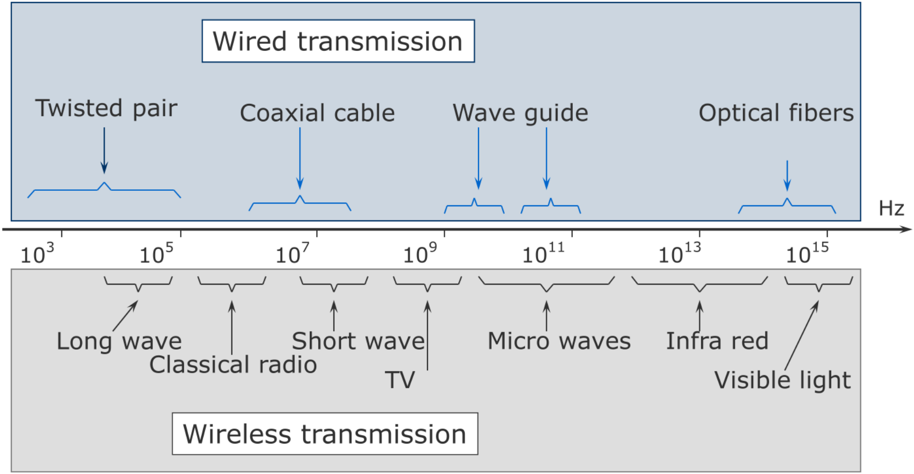


- Fig. A: *Rectangular shaped* alternating current voltage in theory
- Fig. B: *Sinus shaped* alternating current voltage in practice

- The unit for frequency is the hertz (Hz)
- 1 Hz = 1 event (oscillation) per second
- **Example**: Alternating current voltage in Europe with 50 Hz
- **Example**: Classical telephony supports frequencies between 300 and 3400 Hz, i.e., the bandwidth $B = 3400\ Hz - 300\ Hz = 3100\ Hz$

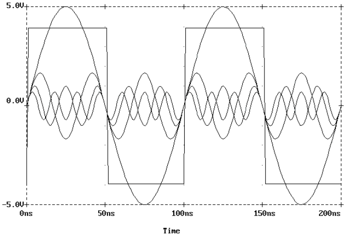
- The spectrum of a signal is the range of frequencies it consists in
- The bandwidth of a signal is the width of the spectrum

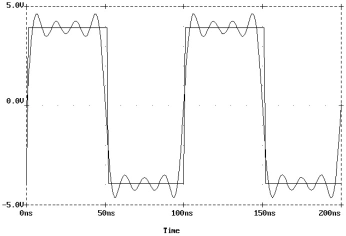
Electromagnetic Spectrum



Fourier Series

Image source: Jörg Rech. Ethernet. Heise



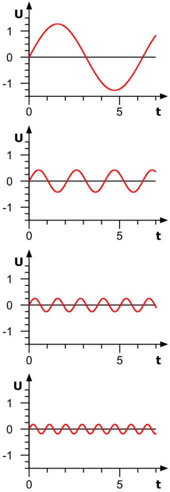


- According to the Fourier series [2] a square-wave signal consists of the sum of a set of oscillating functions
  - A square wave signal consists of a fundamental frequency and harmonics
  - Harmonics are integer multiples of the fundamental frequency
    - They are often referred to as harmonics of the 3rd, 5th, 7th, etc. order
  - The more harmonics are taken into account, the more similar becomes the result with a square wave signal

[2] Named in honour of the French mathematician and physicist Jean-Baptiste Joseph Fourier (1768-1830)

Fourier Series and Bandwidth

- To transmit a square-wave signal clearly via the transmission medium, at least the fundamental frequency and the harmonics of the 3rd and 5th order need to be transmitted
  - The harmonics of the 3rd and 5th order are necessary for keeping the square wave its rectangular shape and preventing that it looks rounded (see next slide)
  - In practice, the harmonics are more attenuated than the fundamental frequency
- The bandwidth, from the viewpoint of the transmission medium, is the range of frequencies which can be transmitted via the transmission medium without interferences



Fourier Synthesis of a square-wave Signal

Source: Wikipedia

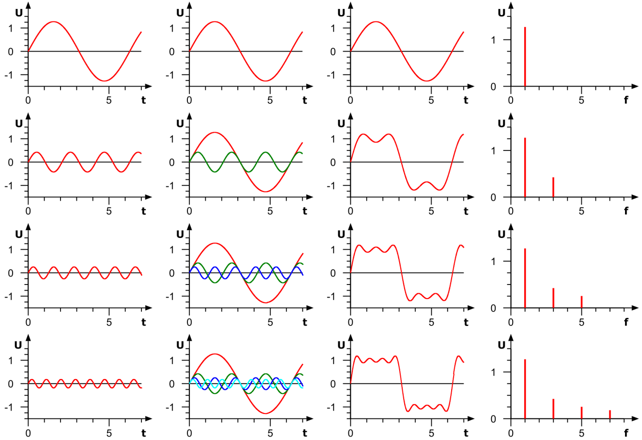


Image source:
René Schwarz.
Wikipedia

- The graphs in the **1st column** show the oscillation, which is added in the respective row. The graphs in the **2nd column** show all so far recognized oscillations, which are then added to the diagrams of the **3rd column**, to reach as close as possible the signal which shall be generated. The more harmonics (multiples of the fundamental frequency) are taken into account, the more we get an ideal square-wave signal. The **4th column** shows the amplitude spectrum, normalized to the fundamental frequency

Data Rate and Bandwidth

Two exemplary calculations of the data rate for a given bandwidth with **five harmonics**:

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

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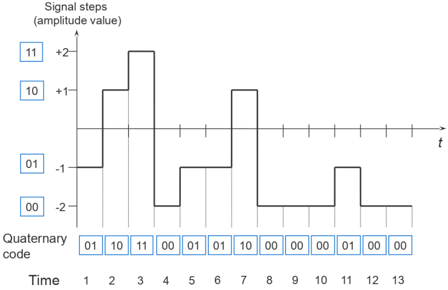
  - Data rate $= 2bit * 10^6 Hz = 2Mbps$
- Example with $f = 2\ MHz$
  - Bandwidth of the signal $s(t)$
    $(5 * 2 * 10^6 Hz) - (1 * 2 * 10^6 Hz) = 8MHz$
  - Period $T = 1/f = 1/2 * 10^6 s = 0.5\mu s \Rightarrow$ A bit occurs every 0.25 μs
  - Data rate $= 2bit * 2 * 10^6 Hz = 4Mbps$

Symbol Rate

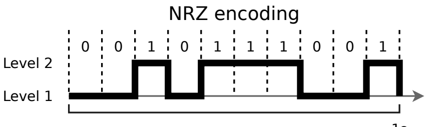


The number of discrete values of a signal are denoted as ...

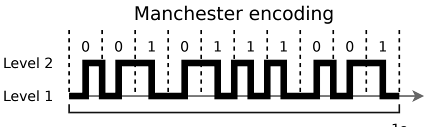
- $n = 2 \rightarrow$ binary
- $n = 3 \rightarrow$ ternary
- $n = 4 \rightarrow$ quaternary
- $n = 8 \rightarrow$ octonary
- $n = 10 \rightarrow$ denary

Bit Rate and Symbol Rate

- Bit rate: Number of transferred bits per time unit specified as (**bit/s** or **bps**)
- Symbol Rate: More generically, the number of transferred symbols per time unit, specified as baud
  - Initially, the baud rate indicated the signaling rate of a telegraph, thus the number of Morse code characters per second
- The ratio between bit rate and symbol rate depends on the → line encoding scheme used
  - Two examples. . .



10 Baud, 10 Bit/s
Efficiency = ratio of bit rate and baud rate = 100%



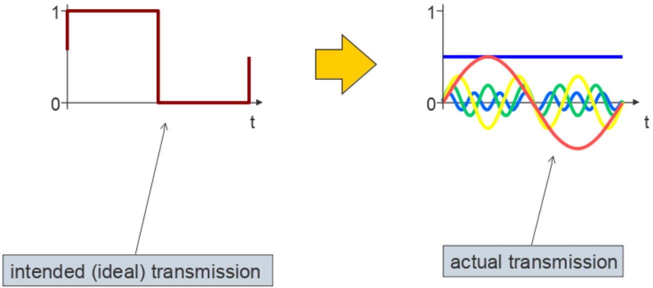
20 Baud, 10 Bit/s
Effiziency = ratio of bit rate and baud rate = 50%

- The line code specifies in computer networks the maximum number of signals that can be transmitted via the transmission media used
- The line code of a network technology is specified by the layer protocol used

Ideal 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." [3]



[3] Source: A Mathematical Theory of Communication, Bell Systems, 1948

Attenuation

- The signals are subject to physical laws
  - This includes the attenuation (signal weakening)
  - Attenuation weakens the amplitude of a signal more and more over distance on all transmission media
    - If the amplitude of a data signal has dropped below a certain value, it can no longer be clearly interpreted
  - Thus, the attenuation limits the maximum bridgeable distance for all transmission media
  - The **higher** the **frequency**, the **higher** is the **attenuation**

Data Rate

- The capacity of a channel is defined by the possible data rate
- Using symbols with multiple values increases the data rate

Hartley's law (1924) [4]

maximum data rate[bit/s] $= 2 * H * log_2(V)$

- V: number of different symbol values
- H: the channel bandwidth in *Hertz (Hz)*

This equation gives the maximum data rate for a finite-bandwidth noiseless channel

$\Rightarrow$ Given an unlimited amount of symbol levels an unlimited data rate can be achieved

[4] Also called Nyquist theorem or Nyquist Bit Rate

Data Rate on a Noisy Channel

- Any real existing channel is polluted by noise
- The achievable data rate depends on the relationship between signal strength and noise
  ⇒ The Signal-to-Noise Ratio (SNR, S/N)

Shannon-Hartley theorem

maximum data rate[bit/s] $= H * log_2(1 + S/N)$

- S: Signal strength
- N: Noise level
- H: the channel bandwidth in *Hertz (Hz)*

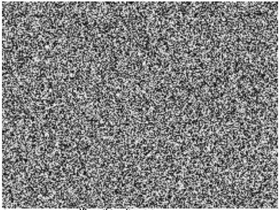
The SNR is commonly expressed in decibel (dB):

$$\text{SNR[dB]} = 10 * log_{10}(S/N)$$

→ The Shannon-Hartley theorem is the basis for the information theory.

Noise and Distortion

- Typical sources for noise are
  - Thermal noise (also *Nyquist noise*)
  - Intermodulation noise
  - Crosstalk
  - Impulse noise
- Other distortions
  - Echoes
  - Extreme low frequency (ELF), e.g., *AC*
  - Delay distorion
  - ...
- Plus attenuation, refraction, reflection ...
- Typical noise model: AWGN [5]:
  - Additive
  - White Noise
  - Gaussian



Source: Jorge Stolfi, Wikipedia, CC 3.0

[5] Also called *Gaussian Channel*

Bit Error Rate

Effects of noise

- Noise degrades the signal quality of an analog signal
- Noise causes bit errors for digital signals

It is possible to boost the signal amplitude, but there are tradeoffs:

- It increases the energy consumption
- It may cause interference in shared medium (like wireless transmissions)

Bit Error Rate (BER)

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

Typical BER values for different link types:

POTS [6]	$2 * 10^{-4}$
Radio link	$10^{-3} - 10^{-4}$
Ethernet	$10^{-9} - 10^{-10}$
Fiber	$10^{-10} - 10^{-12}$

[6] Plain Old Telephone System

Agenda

- Fundamentals of Data Signals
- Data Encoding
- Modulation

Baseband and Broadband

How can we eventually transmit the single bits on the transmission medium?

Baseband

- A → data encoding is required to specify which symbols represent a 0 resp. an 1
- The data is transmitted *as is* over the medium
- ⟶ Typically used in LANs or inside a computer

Broadband

- A → modulation is used to transmit the data over a carrier analog signal
- By using different carrier signals (frequencies), several transmissions can happen simultaneously
- ⟶ Mainly used in optical networks, in radio communication, and cable distribution systems

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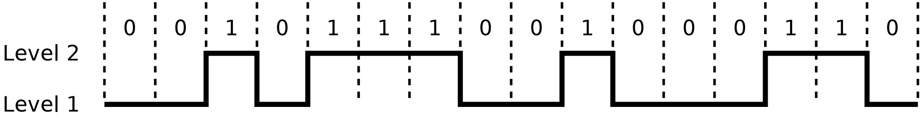
Encoding Requirements

The encoding must be . . .

- robust: tolerate as much distortion as possible
- efficient: achieve the highest possible data transmission rate
  Using code words:
  - **binary** code: 2 states
  - **ternary** code: 3 states
  - **quaternary** code: 4 states (coding of two bits at the same time)
  - . . .
- synchronized: allow the receiver to keep in synch
  Synchronization can be achieved by:
  - transmission of an explicit clock signal
  - synchronize on certain points, e.g., start of character
  - self-synchronizing signal

Non-Return-to-Zero (NRZ) [7]

- Simple approach
  - Encode a logical 0 with physical signal level 1 (low value, e.g., $-5V$)
  - Encode a logical 1 with physical signal level 2 (high value, e.g., $+5V$)



Implemented by the serial CAN (Controller Area Network) bus system, which was developed by Bosch in the 1980s for connecting control devices in cars

- **Advantage**: Very simple and efficient
- **Disadvantage**:
  - When transmitting a long series of logical 0 bits or logical 1 bits, the physical signal level does not change
  - This results in 2 problems:
    1. **Baseline Wander**
    2. **Clock Recovery**

[6] Also called Non-Return-to-Zero Level (NRZL)

Baseline Wander

- **Problem**: Shift of the average signal level
- The receiver distinguishes the physical signal levels by using the average signal level of a certain number of received signals
  - Signals **below** the average signal level, interprets the receiver as logical 0
  - Signals **above** the average signal level, interprets the receiver as logical 1
- When transmitting long sequences of logical 0 or 1 bits, the average signal level may shift so much, making it difficult to detect a change of the physical signal

Sources

- Steve Zdancewic (2004). http://www.cis.upenn.edu/~cse331/Fall04/Lectures/CSE331-3.pdf
- Charles Spurgeon, Joann Zimmerman. *Ethernet: The Definitive Guide*. O'Reilly (2014)

Detailed source, which explains baseline wander from the electrical engineering perspective

- Maxim Integrated (2008). *NRZ Bandwidth – LF Cutoff and Baseline Wander*. http://pdfserv.maximintegrated.com/en/an/AN1738.pdf

Avoid Baseline Wander

- In order to prevent Baseline Wander, when using a line code with 2 physical signal levels, the usage of both signal levels must be distributed equally
  - Therefore, the data to be transmitted must be encoded in a way, that the signal levels occur equally often
    - The data must be scrambled
- If a network technology uses 3 or 5 physical signal levels, the average signal level must match the middle signal level over the time

Clock Recovery

- **Problem**: Recover the clock signal from the transmission
- Even if the processes for encoding and decoding run on different computers, they need to be controlled by the same **clock**

> You can imagine the local clock as an internal signal, switching from low to high. A low/high pair is a clock cycle

- In each clock cycle, the sender transmits a bit and the receiver receives a bit
- If the clocks of sender and receiver drift apart, the receiver may lose count during a sequence of logic 0 or 1

Avoid the Problem of Clock Recovery

- One option: Using a separate line, which transmits just the clock

A network technology with a separate signal line just for the clock is the serial bus system I^2C (Inter-Integrated Circuit)

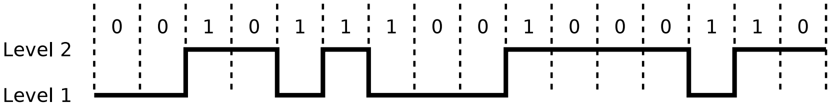
But like comparable systems this bus system is only suited for local application and cannot be used to span large distances

- In computer networks, a separate signal line just for the clock is **not practical** because of the cabling effort
  - Instead, it is recommended to **increase the number of signal level changes** to enable the clock recovery from the data stream

The next slides present several line codes, which all...

- (more or less successful) try to solve the challenges of baseline wander and/or clock recovery
- must consider the limitations of the transmission medium used
  - Fiber-optic cables and wireless transmissions via infrared and laser provide just 2 physical signal levels
  - Copper cables and wireless transmissions via radio waves provide ≥ 2 physical signal levels

Non-Return-to-Zero, Inverted (NRZI) [8]

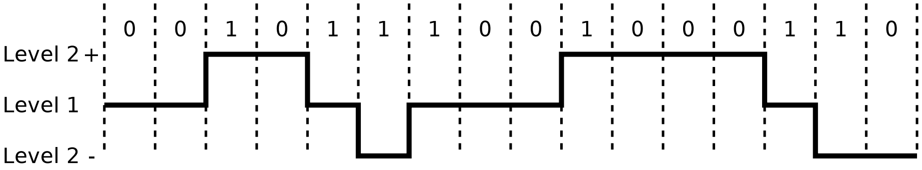


- Similar to NRZ
  - Encode 1 as voltage level change
  - Encode 0 as missing voltage level change
- **Property**:
  - Same advantages as for NRZ, but the disadvantages only occur for sequences of zeroes
    $\Rightarrow$ Therefore, baseline wander can occur

[7] Sometimes called differential NRZ

Multilevel Transmission Encoding - 3 Levels (MLT-3)

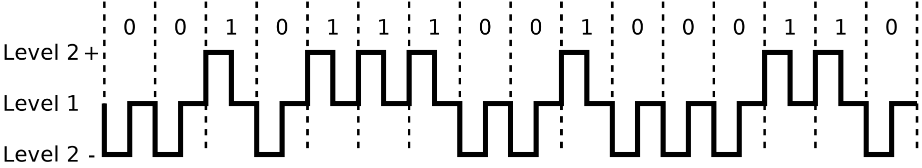
- This line code uses 3 signal levels +, 0 and –
  - If a logical 0 is transmitted, no signal level change takes place
  - A logical 1 is alternating encoded, according to the sequence [+, 0, –, 0]
- Just as for NRZI, the clock recovery problem exists with series of logical 0 and baseline wander can occur



Implemented by Ethernet 100BASE-TX

Return to Zero (RZ)

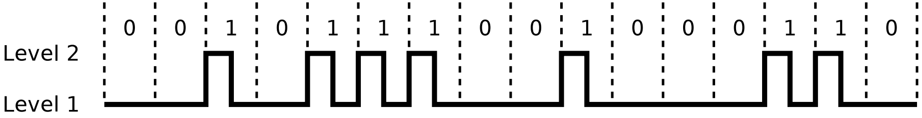
- RZ uses 3 signal levels
  - Transmit a logical 1 $\Longrightarrow$ high signal level is transmitted for **a half clock** and then the signal level returns to the middle signal level
  - Transmit a logical 0 $\Longrightarrow$ low signal level is transmitted for **a half clock** and then the signal level returns to the middle signal level



- **Advantage**: Each transmitted bit causes a signal level change
  - Enables the receiver to do the clock recovery (synchronization)
- **Drawbacks**:
  - Requires double as much bandwidth compared with NRZ
  - Baseline wander can occur for series of logical 0 or 1

Unipolar RZ Encoding

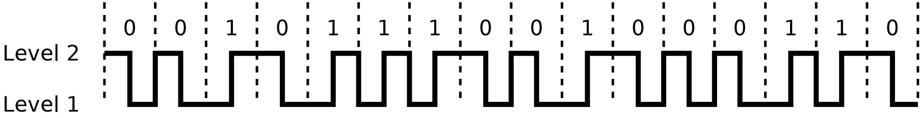
- Special form of return-to-zero (RZ)
  - Uses only 2 signal levels
    - Logical 0 bits are encoded as low signal level
    - Transmit a logical 1 bit $\Longrightarrow$ high signal level is transmitted for a half clock and then the signal level returns to the low signal level
- Clock recovery is impossible for series of logical 0 bits
- The usage of the different signal level is not equally distributed
  - Therefore baseline wander can occur



This line code is used for optical wireless data transmission via IrDA in the transmission mode SIR

Manchester Code

- Uses 2 signal levels
  - A logical 1 is encoded with a **rising edge**
    - Change from signal level 1 (low value) to signal level 2 (high value)
  - A logical 0 is encoded with a **falling edge**
    - Change from signal level 2 (high value) to signal level 1 (low value)
- If 2 identical bits follow each other, at the end of the bit cell, the signal level changes to the initial level
  - Bit cell = time period, that is reserved for the transmission of a single bit



10 Mbps Ethernet (e.g. 10BASE2 and 10BASE-T) uses this line code

Manchester Code Properties

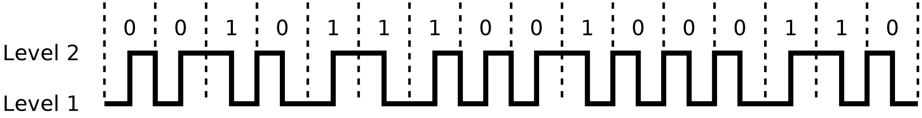
- **Advantages**:
  - Signal level changes happen all the time to allow clock recovery
    $\Longrightarrow$ Clock recovery is no problem for the receiver
  - The usage of the signal levels is equally distributed
    $\Longrightarrow$ baseline wander cannot occur
- **Disadvantage**: The transmission of a single bit requires on average 1.5 signal level changes

> Because the number of level changes is a limiting factor of the transmission medium, modern network technologies do not use the Manchester encoding as line code

- For this line code, the bit rate is half the baud rate
  - Therefore, the efficiency of the line code is only 50 % compared to NRZ

Differential Manchester Code

- Also called **Conditional DePhase encoding (CDP)**
  - Transmit a logical 1 $\Longrightarrow$ only in the middle of the bit cell changes the signal level
  - Transmit a logical 0 $\Longrightarrow$ a change of the signal level will take place at the beginning and in the middle of the bit cell
- In this variant of the Manchester encoding, too,...
  - clock recovery is possible for the receiver and
  - baseline wander cannot occur
- Depending on the initial signal level, **2 signal sequences, inverse to each other, are possible**



Token Ring (IEEE 802.5) uses this line code

Interim Conclusion

- All line codes presented so far have drawbacks

1. Baseline wander
   - Problem with series of logical 0 and 1 when NRZ is used
   - Problem with series of logical 0 when NRZI, MLT-3 or Unipolar RZ are used
2. Clock recovery
   - Not guaranteed when NRZ, NRZI, MLT-3, or Unipolar RZ are used
3. Lack of efficiency
   - With the variants of the Manchester encoding

→ **Possible Solution**: encode groups of bits

The objective is to achieve the positive characteristics of the Manchester encoding and a high efficiency at the same time

4B/5B Code

- Groups of 4 payload bits onto groups of 5 code bits
  - With 5 bits, 32 different encodings are possible
    - Only 16 encodings are used for data (0–9 and A–F)
    - Some of the remaining 16 encodings are used for connection control
  - Because of the additional bit, added to each group of 4 bits payload, the output is increased by factor 5/4
    - Efficiency of the 4B5B encoding: 80%
  - Each 5-bit encoding has a maximum of a single leading 0 bit and in the output data stream, a maximum of three 0 bits in a row
    - Therefore, clock recovery for the receiver is possible
- After the encoding with 4B5B, another encoding e.g. with NRZI or MLT-3 takes place
  - If 4B5B is combined with NRZI (for 2 signal levels) or with MLT-3 (for 3 signal levels), baseline Wander cannot occur

- Ethernet 100BASE-TX: After 4B5B, a further encoding with MLT-3 takes place
- FDDI and Ethernet 100BASE-FX: After 4B5B, a further encoding with NRZI takes place

4B5B Encoding (Table)

Label	4B	5B	Function
0	0000	11110	0 hexadecimal (Payload)
1	0001	01001	1 hexadecimal (Payload)
2	0010	10100	2 hexadecimal (Payload)
3	0011	10101	3 hexadecimal (Payload)
4	0100	01010	4 hexadecimal (Payload)
5	0101	01011	5 hexadecimal (Payload)
6	0110	01110	6 hexadecimal (Payload)
7	0111	01111	7 hexadecimal (Payload)
8	1000	10010	8 hexadecimal (Payload)
9	1001	10011	9 hexadecimal (Payload)
A	1010	10110	A hexadecimal (Payload)
B	1011	10111	B hexadecimal (Payload)
C	1100	11010	C hexadecimal (Payload)
D	1101	11011	D hexadecimal (Payload)
E	1110	11100	E hexadecimal (Payload)
F	1111	11101	F hexadecimal (Payload)
Q	—	00000	Quiet (the line is gone dead) $\Longrightarrow$ Signal loss
I	—	11111	Idle (the line is idle) $\Longrightarrow$ Pause
J	—	11000	Start (Part 1)
K	—	10001	Start (Part 2)
T	—	01101	Stop (Part 1)
R	—	00111	Stop (Part 2) $\Longrightarrow$ Reset
S	—	11001	Set
H	—	00100	Halt (transmission failure)

- The missing 5-bit combinations are invalid because they contain more than a single leading 0 bits or more than two 0 bits in a row

If Fast Ethernet 100BASE-TX is used, frames begin with JK and end with TR

Summary

Line code	Signal levels	Baseline wander possible	Signal level change	Self-synchronizing[1]	Efficiency[2]	Directly transferable	Additional encoding
NRZ	2	yes	at changes	no	100%	no	—
NRZI	2	yes	for 1-bits	no	75%	no	—
MLT-3	3	yes	for 1-bits	no	100%	no	—
RZ	3	yes	always	yes	50%	no	—
Unip. RZ	2	yes	for 1-bits	no	75%	no	—
Manchester	2	no	always	yes	50%	yes	—
Diff. Manch.	2	yes	always	yes	50%	yes	—
4B5B	2	yes	—	yes	80%	no	NRZI or MLT-3

[1] Specifies if the clock recovery is possible with this line code.
[2] Ratio of bit rate (payload in bits per time) and baud rate (signal changes per second).

Agenda

- Fundamentals of Data Signals
- Data Encoding
- Modulation

Baseband and Broadband

How can we eventually transmit the single bits on the transmission medium?

Baseband

- A → data encoding is required to specify which symbols represent a 0 resp. an 1
- The data is transmitted *as is* over the medium
- ⟶ Typically used in LANs or inside a computer

Broadband

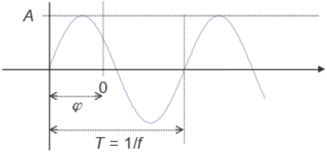
- A → modulation is used to transmit the data over a carrier analog signal
- By using different carrier signals (frequencies), several transmissions can happen simultaneously
- ⟶ Mainly used in optical networks, in radio communication, and cable distribution systems

Principle of Modulation

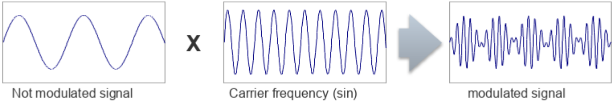
Electromagnetic signal

$$s(t) = A * sin(2 * \pi * f * t + \phi)$$

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

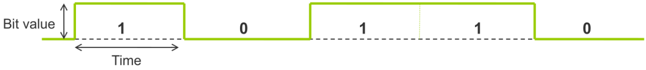


The data is modulated into a carrier frequency



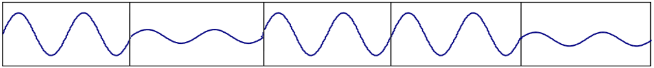
→ **Modem** = **Mo**dulation-**Dem**odulation process

Amplitude Shift Keying (ASK)



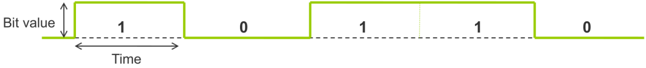
$$s(t) = A * sin(2 * \pi * f * t + \phi)$$

Amplitude Modulation (discrete, Amplitude Shift Keying, ASK)



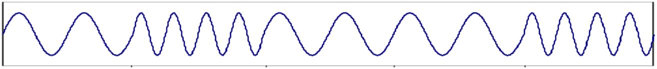
- Technically easy to realize
- Does not need much bandwidth
- Not very robust against distortion
- Often used in optical transmission ($\rightarrow$ low noise)

Frequency Shift Keying (FSK)



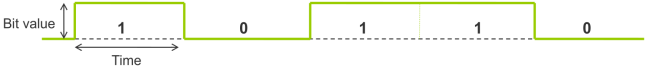
$$s(t) = A * sin(2 * \pi * f * t + \phi)$$

Frequency Modulation (discrete, Frequency Shift Keying, FSK)



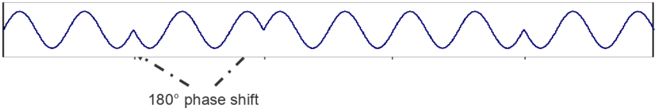
- *Waste* of frequencies
- Needs a lot of bandwidth
- Initial principle used in data transmission on phone lines

Phase Shift Keying (PSK)



$$s(t) = A * sin(2 * \pi * f * t + \phi)$$

Phase Modulation (discrete, Phase Shift Keying, PSK)



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

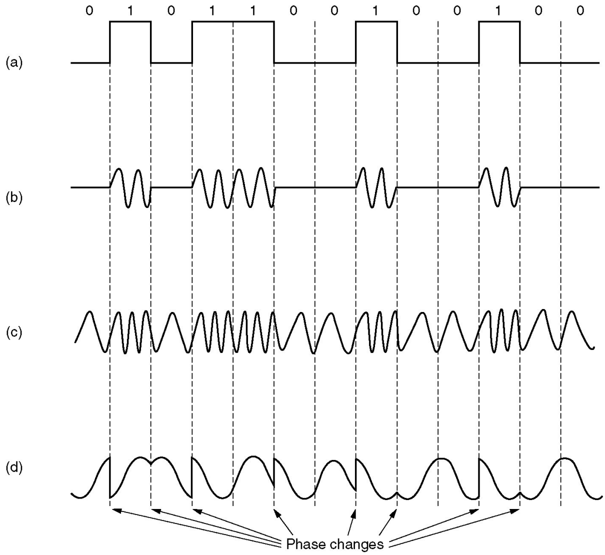
Overview

Binary signal

Amplitude modulation

Frequency modulation

Phase modulation



Advanced PSK Techniques

- Quadrature Phase Shift Keying (QPSK)
- Binary Phase Shift Keying (BPSK)
- Carrier-less Amplitude Phase Modulation (CAP/QAM)
- Differential Phase Shift Keying (DPSK)

You should now be able to answer the following questions:

- How can data be transmitted over different transmission media?
- What does quantization, sampling, encoding, and modulation mean?
- Why do we need line codes, which properties are important, and which typical line codes exist?
- How can data signals be modulated onto a carrier frequency?