Computer Networks

Physical Layer - Data Signals

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Agenda

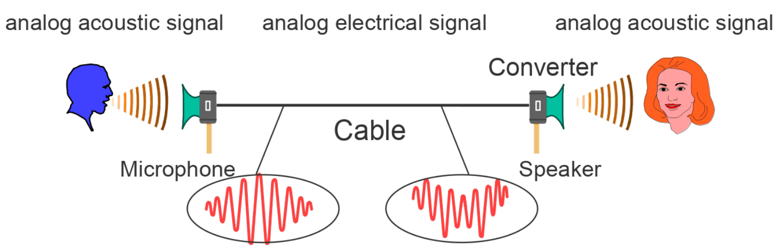
Recap: Physical Layer

- **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)

Fundamentals of Data Signals

The Telephone Example

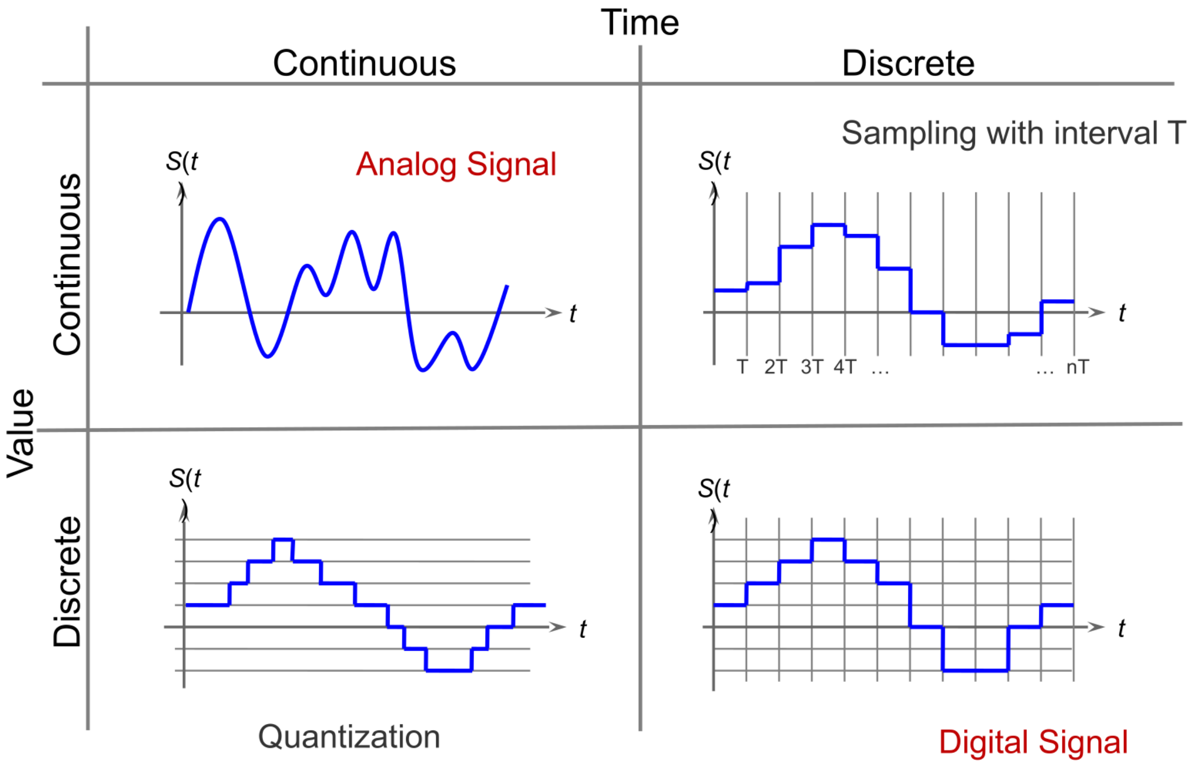
- Data is converted into a signal to be sent over a transmission channel
- A transmission channel consists of **access points** and the **physical medium** to carry the signal
- A signal is a **chronological sequence of physical values** measured on the medium



Physical Representation of Data

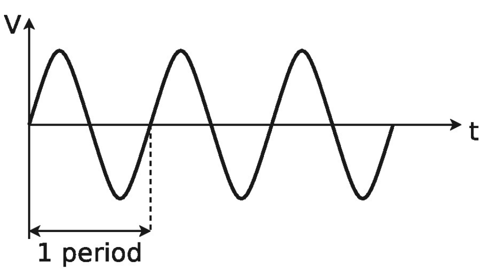
- A physical representation of data is called a signal
- It can be either
  - An analog signal → a sequence of continuous values
  - A digital signal → a sequence of discrete values
- The transmitter Network Interface Controller (NIC) acts as a **Co**der and **Dec**oder → **CODEC**

Continuous vs. Discrete Signals



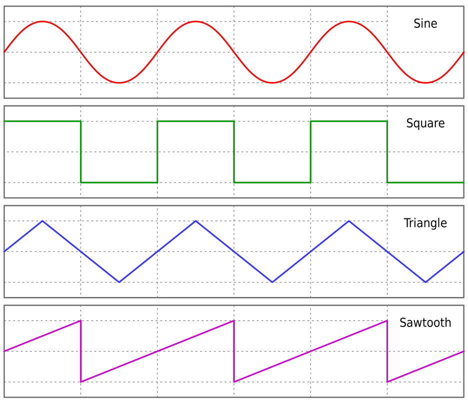
Basics of Signal Processing

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

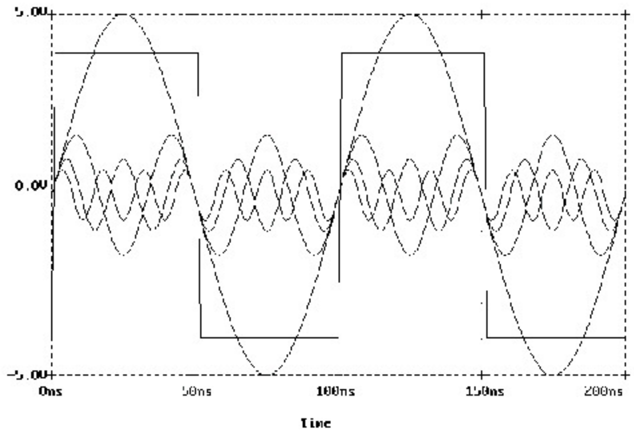


Examples

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



Fourier Series



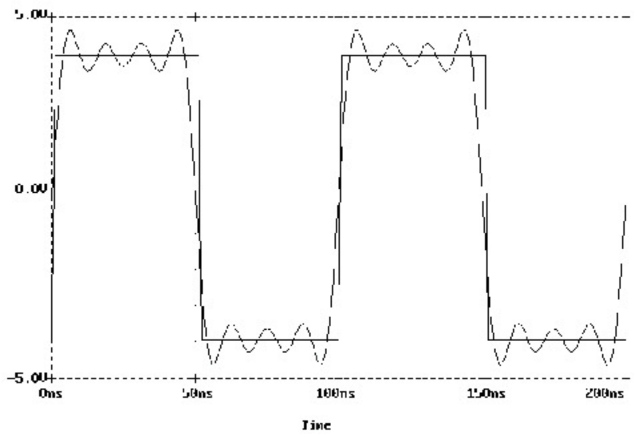


Image source: Jörg Rech. Ethernet. Heise

- According to the Fourier series 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

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

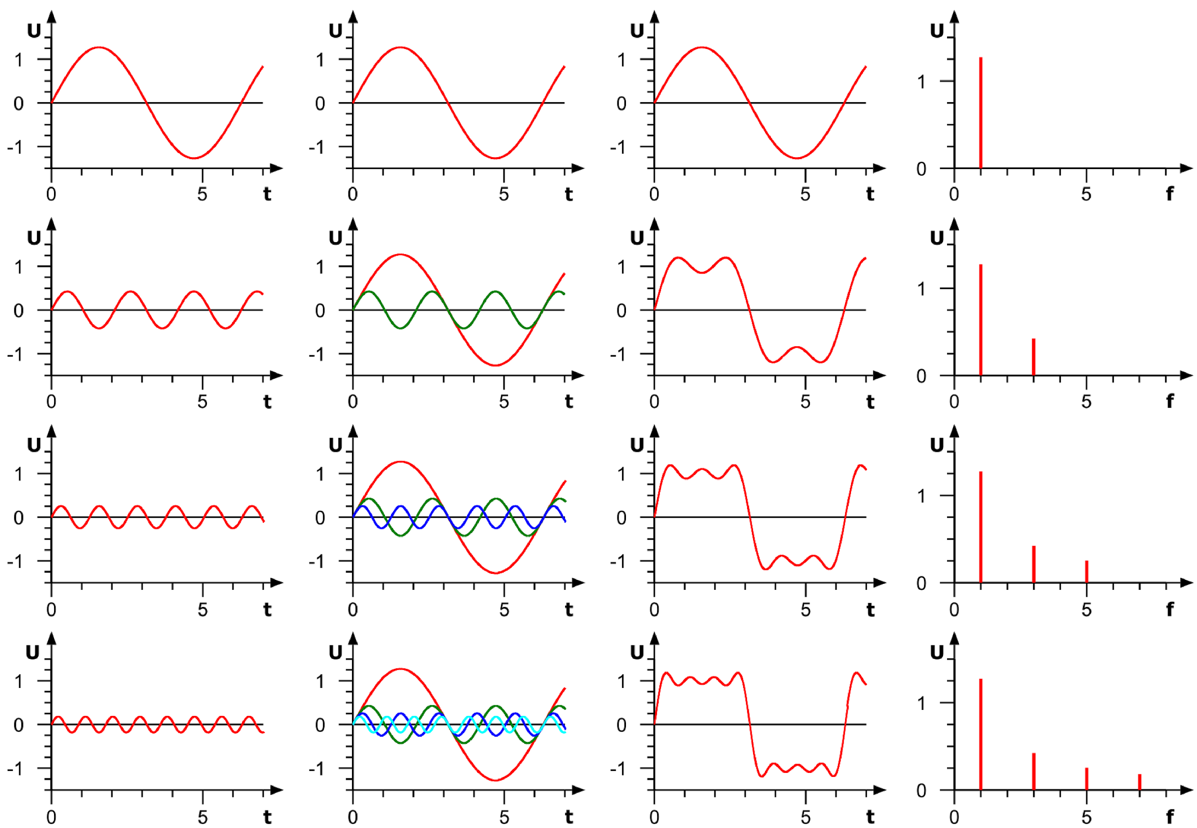


Image source: René Schwarz. Wikipedia (CC-BY-SA-1.0)

- The **1st column** show the oscillation, which is added in the respective row.
- The **2nd column** show all so far recognized oscillations
- The **3rd column** show the accumulation of all oscillations so far

- The **4th column** shows the amplitude spectrum, normalized to the fundamental frequency

Quantization and Sampling

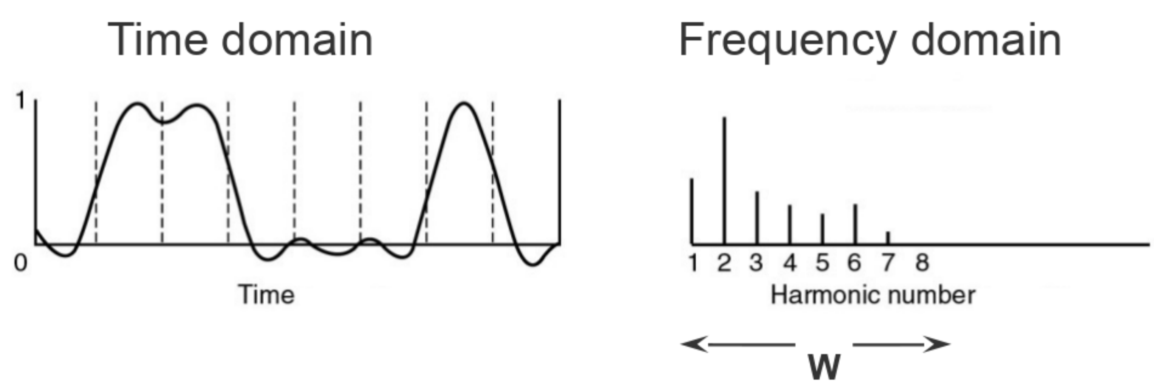
In order to transmit data over a transmission medium, it needs to be ...

- ...converted ⟶ Quantization
  - Computer networks deal with digital data ⇒ discrete values
  - Physical mediums are by nature analog ⇒ **continuous values**
  - Conversion from digital to analog values 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

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 (WKS) [1] sampling theorem 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:
$f_S = 2W$ (⇒ for baseband transmissions: $f_S = 2 * f_{max}$)



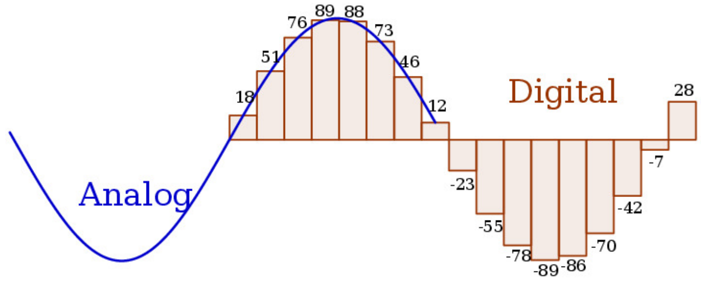
[1]Historically also called Nyquist-Shannon sampling theorem.

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)

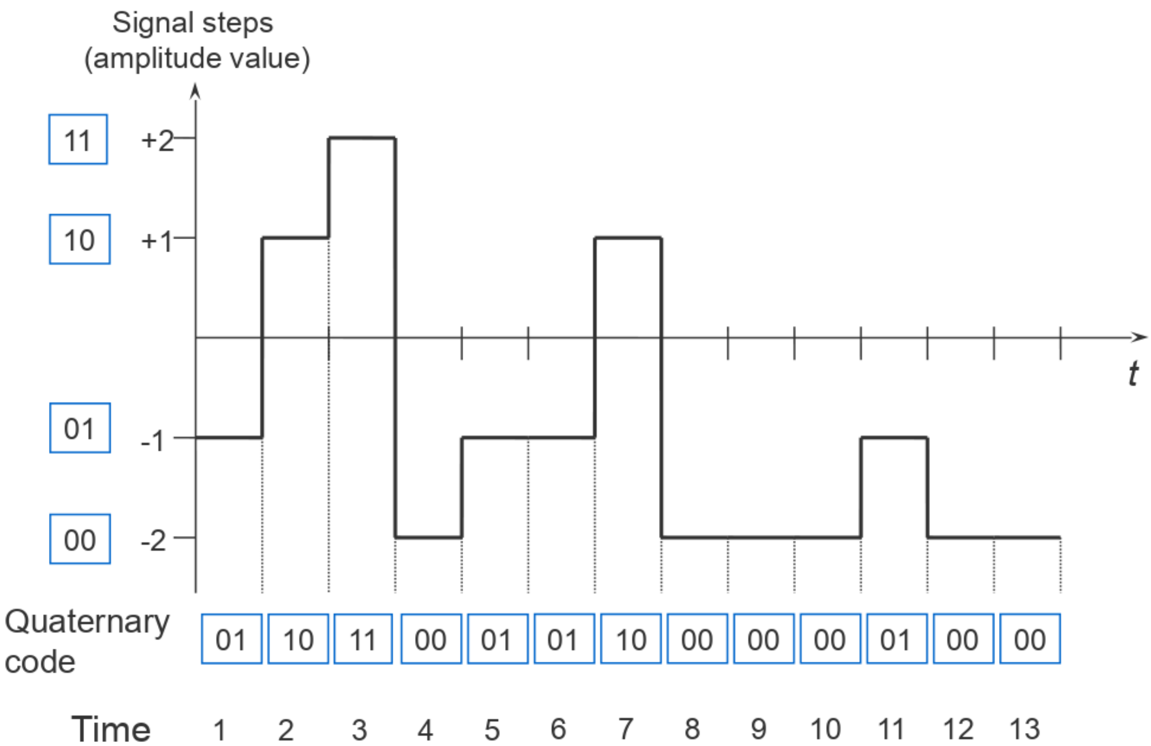
Sampling, Quantization, and Coding

- 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



Author: Bjarne Skurdal

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

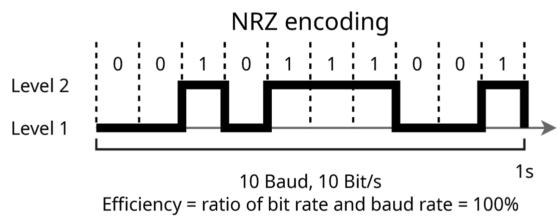
Bit Rate and Symbol Rate

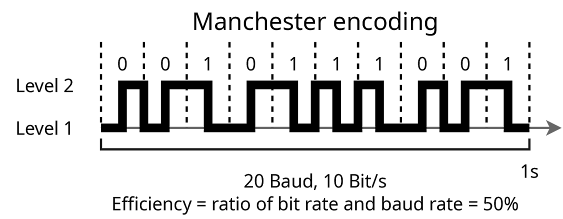
- Bit rate: Number of transferred bits per time unit specified as (**bit/s** or **bps**)
- Symbol Rate: More generically, the number of transferred symbols per time unit, specified as baud
- The ratio between bit rate and symbol rate depends on the → line encoding scheme used

- 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

Two examples...





Data Rate

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

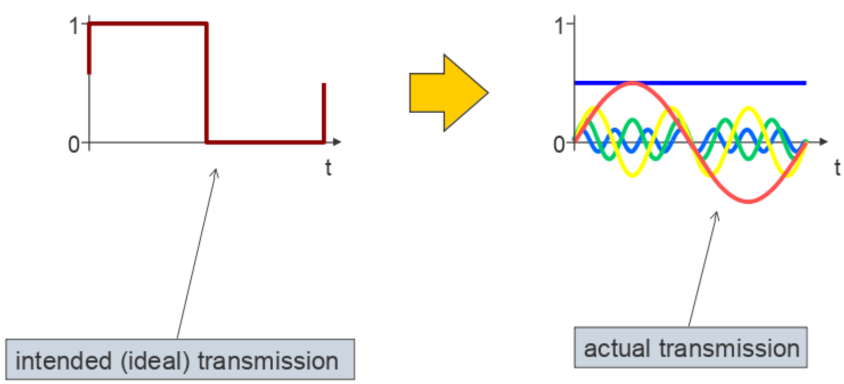
Hartley's law (1924) maximum data rate[bit/s] $= 2 * H * log_2(V)$

- 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
⇒ Given an unlimited amount of symbol levels an unlimited data rate can be achieved

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."



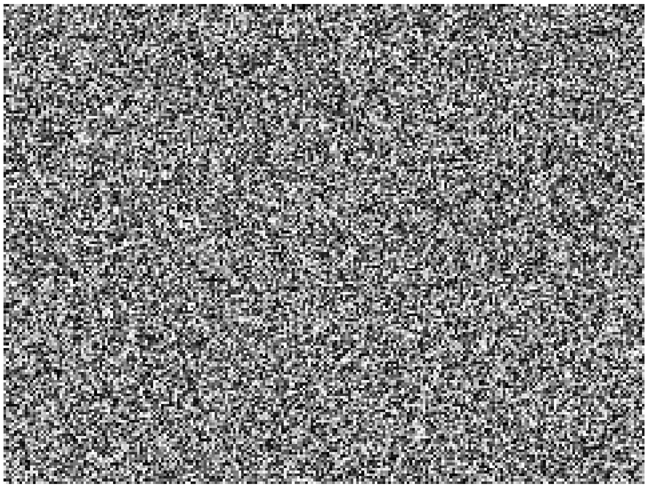
Source: A Mathematical Theory of Communication, Bell Systems, 1948

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**

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 :
  - Additive
  - White Noise
  - Gaussian



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)

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

Typical BER values for different link types:

- **POTS** (Plain Old Telephone System): $2 * 10^{-4}$
- **Radio link**: 10^{-3} – 10^{-4}
- **Ethernet**: 10^{-9} – 10^{-10}
- **Fiber**: 10^{-10} – 10^{-12}

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

$\rightarrow$ The Shannon-Hartley theorem is the basis for the information theory.

Data Encoding

Baseband and Broadband

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

- In **Baseband**
- In **Broadband**

- A $\rightarrow$ data encoding is required to specify which symbols represent a 0 resp. an 1
- The data is transmitted *as is* over the medium
- $\longrightarrow$ Typically used in LANs or inside a computer
- Requires higher frequencies in order to modulate a square wave signal

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

Encoding Requirements

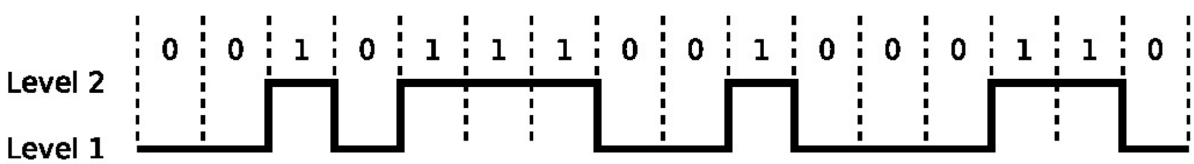
The encoding must be . . .

- 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

Well-known Line Encodings

- There are many ways to encode binary data onto a line
- Many different encodings are used in different technologies
- In the following we will review some of them but not consider all of them in detail
- It is **not important** to *memorize* the encoding schemes, but it is **important** to *understand* the principle

Non-Return-to-Zero (NRZ)



- 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:
    * **Baseline Wander**
    * **Clock Recovery**

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

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

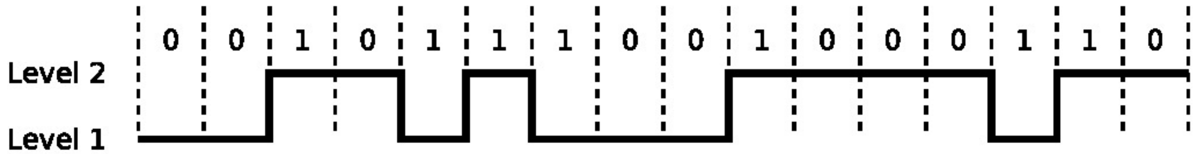
A network technology with a separate signal line just for the clock is the serial bus system I^2C (Inter-Integrated Circuit) But like comparable systems this bus system is only suited for local application and cannot be used to span large distances

- 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 can provide more physical signal levels

Non-Return-to-Zero, Inverted (NRZI)



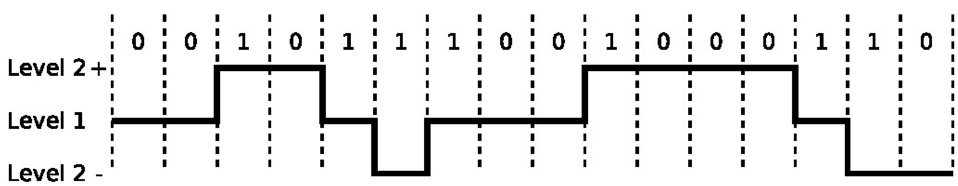
- Similar to NRZ
  - Encode 1 as voltage level change
  - Encode 0 as missing voltage level change
- **Property**:
  - Same advantages as for NRZ, but the disadvantages only occur for sequences of zeroes
    ⇒ Therefore, baseline wander can occur

Sometimes called **differential NRZ**

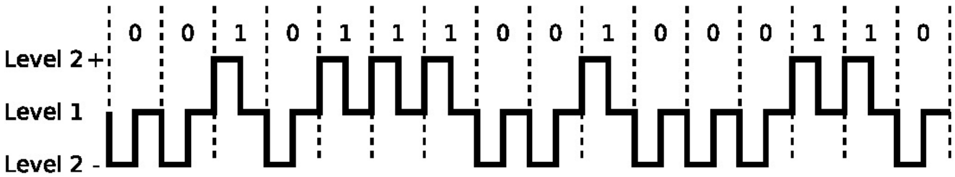
Multilevel Transmission Encoding - 3 Levels (MLT-3)

- 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

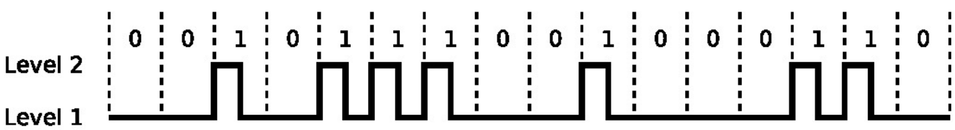


Return to Zero (RZ)



- 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

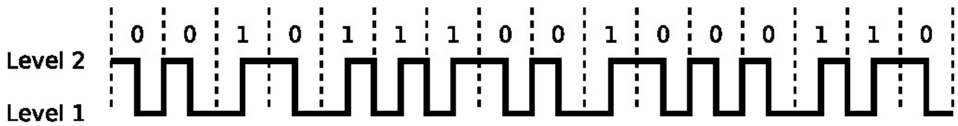
Unipolar RZ Encoding



- 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

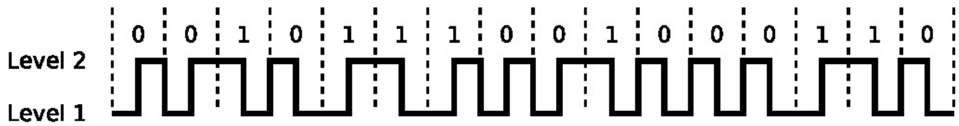
Manchester Code Properties

- **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

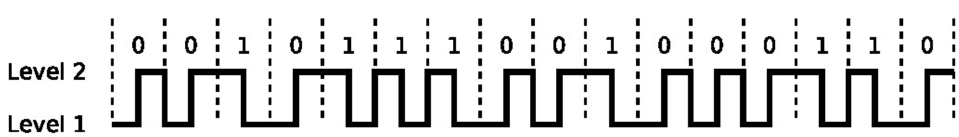


- Also called **Conditional DePhase encoding (CDP)**
  - Transmit a logical 1 $\Longrightarrow$ only in the middle of the bit cell changes the signal level
  - Transmit a logical 0 $\Longrightarrow$ a change of the signal level will take place at the beginning and in the middle of the bit cell
- In this 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

Manchester II Encoding

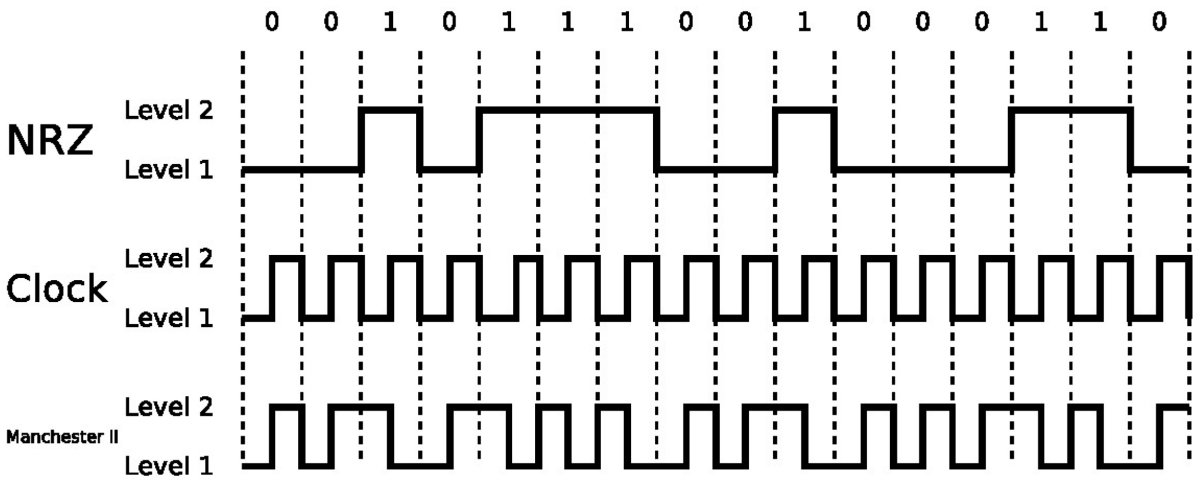
- This line code (also called Biphase-L) is the opposite of the Manchester encoding
  - Manchester encoding:
    * Transition from high to low signal corresponds to a logical 0 bit
    * Transition from low to high signal corresponds to a logical 1 bit
  - Manchester II encoding:
    * Transition from low to high signal corresponds to a logical 0 bit
    * Transition from high to low signal corresponds to a logical 1 bit
- Just as for the Manchester encoding, clock recovery is possible for the receiver and **baseline wander cannot occur** because the usage of the signal levels is distributed equally



Manchester II Code

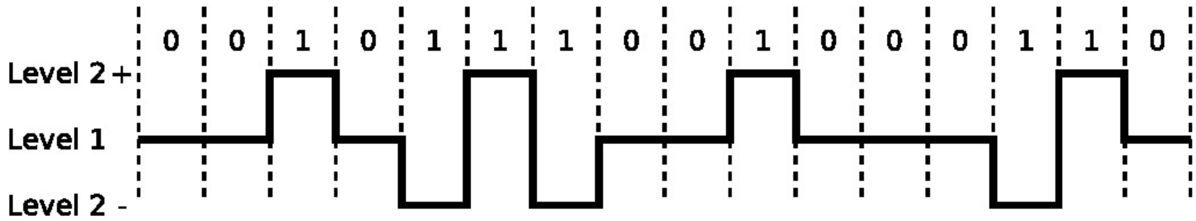
A	B	A XOR B
0	0	0
0	1	1
1	0	1
1	1	1

- The Manchester II encoding is calculated via exclusive or (XOR) of the NRZ encoded data and the clock



Alternate Mark Inversion (AMI code)

- Also called Bipolar Encoding
- Uses 3 signal levels (+, 0 und −)
  - Logical 0 bits are encoded as middle signal level (0)
  - Logical 1 bits are alternating encoded as high (+) or low signal level (−)
- **Benefit**: Baseline wander cannot occur
- **Drawback**: Clock recovery is impossible for series of logical 0 bits
- Error detection is partly possible because the signal sequences +, −−, +0+ and −0− are illegal



AMI Line Code in Practice and Scramblers

ISDN (S_0) bus uses a modified version of the *AMI* line code

With this variant, logical 1 bits are encoded as middle signal level and logical 0 bits are alternating encoded as high signal level or low signal level

- To allow for clock recovery a **scrambler** is often used, after AMI line code encoding

⇒ A scrambler is a device, which modifies a bit stream according to a simple algorithm in a way, that it is simple to reverse back to the original bit stream

- In this case, scramblers are used, to interrupt long series of logic 0 bits

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)

Label	4B	5B	Function
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

5B6B Encoding

- Maps groups of 5 payload bits onto groups of 6 code bits
  - Of the 32 possible 5-bit words, 20 are mapped to 6-bit words that contain an equal number of 1 bits and 0 bits
    $\Longrightarrow$ **neutral inequality** (*balanced*)
  - For the remaining twelve 5-bit words, a variant with two 1 bits and four 0 bits and a variant with four 1 bits and two 0 bits exist
    $\Longrightarrow$ **positive or negative inequality** (*unbalanced*)
- As soon as the first 5-bit word without neutral inequality need to be encoded, the variant with the positive inequality is used
  - For encoding the next 5-bit word without neutral inequality, the variant with the negative inequality is used
    * The variants with positive or negative inequality alternate
- After the encoding with 5B6B, another encoding with NRZ takes place
  - This is possible, because if 5B6B is used, **clock recovery is possible** for the receiver and **baseline wander cannot occur**
- Advantage compared to the Manchester encoding: higher baud rate
  - Efficiency: $5/6 = 83.\overline{3}\%$

5B6B is used by Fast Ethernet 100Base-VG

5B6B Encoding (Table)

5B	6B neutral	6B positive	6B negative	5B	6B neutral	6B positive	6B negative
00000		001100	110011	10000		000101	111010
00001	101100			10001	100101		
00010		100010	101110	10010		001001	110110
00011	001101			10011	010110		
00100		001010	110101	10100	111000		
00101	010101			10101		011000	100111
00110	001110			10110	011001		
00111	001011			10111		100001	011110
01000	000111			11000	110001		
01001	100011			11001	101010		
01010	100110			11010		010100	101011
01011		000110	111001	11011	110100		
01100		101000	010111	11100	011100		
01101	011010			11101	010011		
01110		100100	011011	11110		010010	101101
01111	101001			11111	110010		

8B10B Encoding

- Maps groups of 8 payload bits onto groups of 10 code bits
  - Thus, the efficiency is 80%
- Each 8B10B encoding is composed in a way, that in the groups of 10 code bits either...
  - Five 0 bits and five 1 bits occur $\Longrightarrow$ neutral inequality
  - Six 0 bits and four 1 bits occur $\Longrightarrow$ positive inequality
  - Four 0 bits and six 1 bits occur $\Longrightarrow$ negative inequality
- After the encoding with 8B10B, another encoding via NRZ takes place
  - **Baseline wander cannot occur**, because some of the $2^8 = 256$ possible 8-bit words can be encoded in 2 different ways
    - This way, inequalities are compensated

- Each 10-bit encoding contains at least 3 signal level changes and at the latest after 5 clock cycles, the signal level changes
  - This **enables** the receiver **to do clock recovery**

Used by Gigabit-Ethernet 1000Base-CX, -SX, -LX, FibreChannel, InfiniBand, DisplayPort, FireWire 800 (IEEE 1394b) and USB 3.0

8B6T Encoding

- 8B6T = Binary 6 Ternary
  - Useful for network technologies, that use > **2 signal levels**
- This line code encodes 8-bit blocks as groups of 6 symbols, where each one can represent the state `-`, `0` or `+`
  - The symbols of the states represent electrical signal levels
- The encoding is carried out by using a table, which contains all $2^8 = 256$ possible 8-bit combinations
  - The table shows, that the output of 8B6T makes **baseline wander impossible**, and the frequent signal level changes make **clock recovery possible** for the receiver
- In contrast to 4B5B, 5B6B and 8B10B, which only *improve* the payload and require an encoding with NRZ(I) or MLT-3 afterwards, 8B6T encoded data **can be used directly for transmission**

Fast-Ethernet 100BASE-T4 uses this line code

8B6T Encoding (Table)

8-bit sequence	8B6T code	8-bit sequence	8B6T code	8-bit sequence	8B6T code
00	+-00+-	10	+0+--0	20	00-++-
01	0+-+-0	11	++0-0-	21	--+00+
02	+-0+-0	12	+0+-0-	22	++-0+-
03	-0++-0	13	0++-0-	23	++-0-+
04	-0+0+-	14	0++--0	24	00+0-+
05	0+--0+	15	++00--	25	00+0+-
06	+-0-0+	16	+0+0--	26	00-00+
07	-0+-0+	17	0++0--	27	--+++-
08	-+00+-	18	0+-0+-	28	-0-++0

8-bit sequence	8B6T code	8-bit sequence	8B6T code	8-bit sequence	8B6T code
09	0-++-0	19	0+-0-+	29	--0+0+
0A	-+0+-0	1A	0+-++-	2A	-0-+0+
0B	+0-+-0	1B	0+-00+	2B	0--+0+
0C	+0-0+-	1C	0-+00+	2C	0--++0
0D	0-+-0+	1D	0-+++-	2D	--00++
0E	-+0-0+	1E	0-+0-+	2E	-0-0++
0F	+0--0+	1F	0-+0+-	2F	0--0++

etc.

Summary

Line code	Signal levels	Baseline wander possible	Signal level change	Self-synchronizing[1]
NRZ	2	yes	at changes	no
NRZI	2	yes	for 1-bits	no
MLT-3	3	yes	for 1-bits	no
RZ	3	yes	always	yes
Unip. RZ	2	yes	for 1-bits	no
Manchester	2	no	always	yes
Diff. Manch.	2	yes	always	yes
4B5B	2	yes	—	yes
5B6B	2	no	—	yes
8B10B	2	no	—	yes
8B6T	3	no	—	yes

[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).

Modulation

Baseband and Broadband

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

- In **Baseband**
- In **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
- Preferable over longer distances

Principle of Modulation

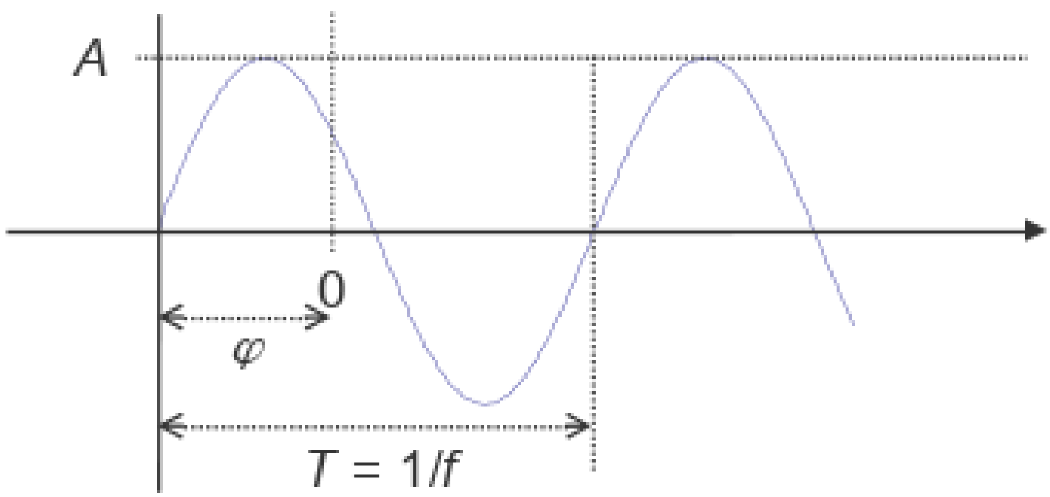
Electromagnetic signal: $s(t) = A * sin(2 * \pi * f * t + \phi)$

A: Amplitude

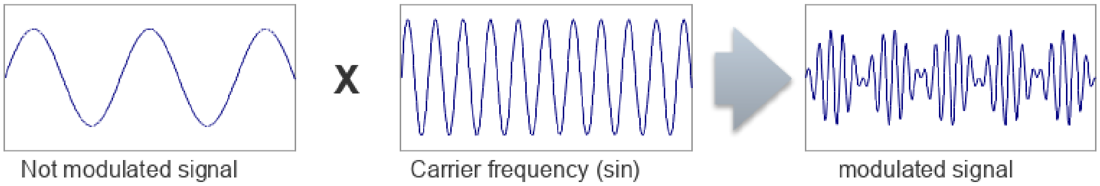
f: Frequency

T: Duration of one oscillation, period

ϕ: Phase

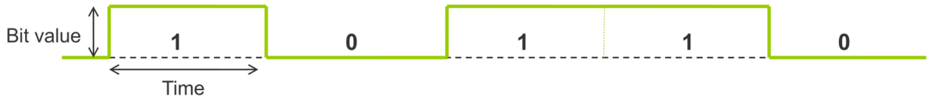


The data is modulated into a carrier frequency

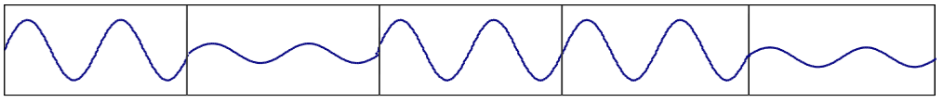


→ **Modem** = **Mo**dulation-**Dem**odulation process

Amplitude Shift Keying (ASK)

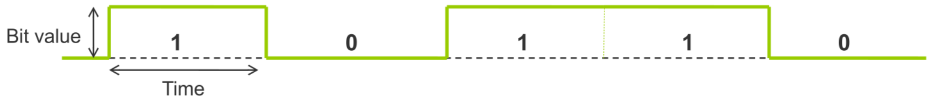


$s(t) = A * sin(2 * \pi * f * t + \phi)$
Amplitude Modulation (discrete, Amplitude Shift Keying, ASK)

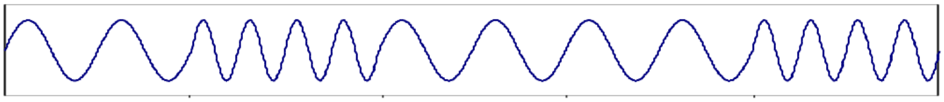


- Technically easy to realize
- Does not need much bandwidth
- Not very robust against distortion
- Often used in optical transmission (→ low noise)

Frequency Shift Keying (FSK)

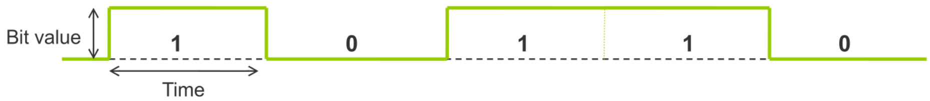


$s(t) = A * sin(2 * \pi * f * t + \phi)$
Frequency Modulation (discrete, Frequency Shift Keying, FSK)

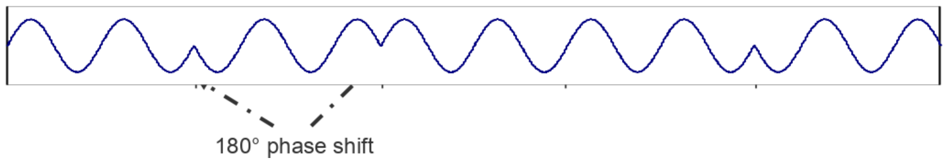


- *Waste* of frequencies
- Needs a lot of bandwidth
- Initial principle used in data transmission on phone lines

Phase Shift Keying (PSK)



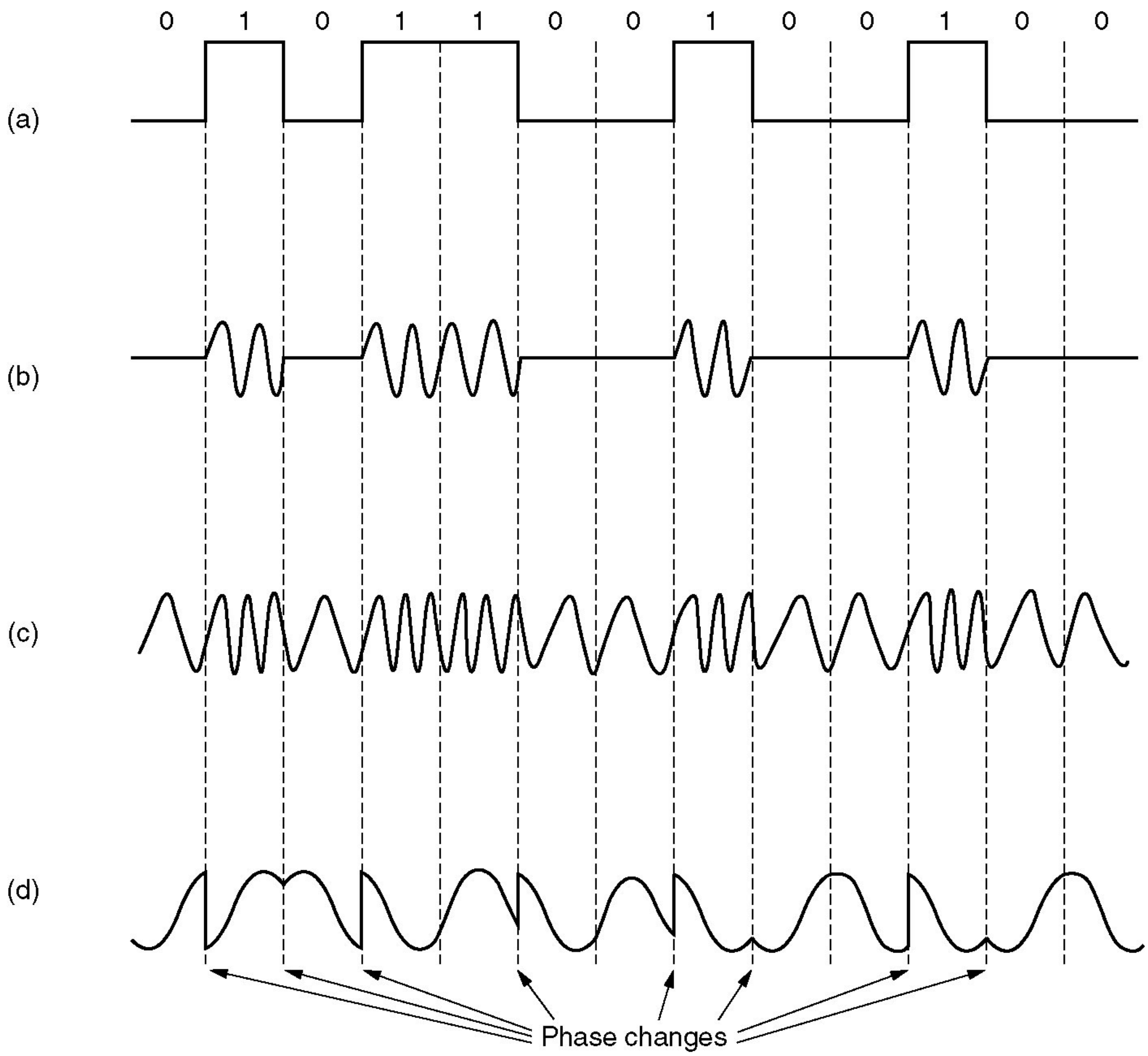
$s(t) = A * sin(2 * \pi * f * t{+}\phi)$
Phase Modulation (discrete, Phase Shift Keying, PSK)



- 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)

Summary

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?