Bus Systems

Physical Communication

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Physical Communication

Learning goals of this section

- Understand the concepts of physical comunication
  - Learn and understand signal types and their differences
  - Know which signals can be transmitted, and which signals can‘t
- Know different modulation schemes and their properties
- Know meaning of „signal bandwidth“ and signal spectrum
  - Understand bandwidth limitations
  - Understand fourier transformation
  - Understand sampling frequencies

Physical Communication

Physical foundations of communciation

Transmission over bus systems imply the transmission of physical information

▪ Sender	
– Modulation	Create physical signal
▪ Connection	
– Signal fading	Signal strength and quality degrades, overtalking
▪ Receiver	
– Filtering & amplification	Remove distortions from physical transmissions
– Demodulation	Reconstruct information from received physical signal

Physical Communication

Physical signals

- Modulation
  - Create physical signal from logical signal (information)
    - Unmodulated logical signals cannot be transmitted directly
    - Only physical signals can be transmitted between nodes

- Physical signal
  - Represents a logic information by mapping it to physical values
  - Transmitted logical information is represented by one or multiple parameter
    - E.g. Voltage value, carrier wave frequency, carrier wave phase, pulse duration
  - Parameter variance indicates the transmitted logical information

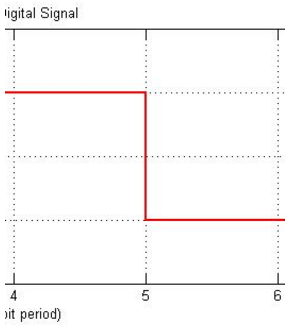
Physical Communication

Physical signals - classification

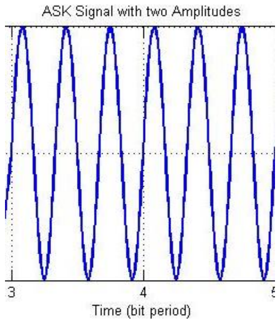
- Classification schemes for physical signals
  - Stochastic vs. deterministic signals
  - Continuous vs. discrete signals
  - Energy vs. power signals

Physical Communication

Stochastic vs. deterministic signals



- Stochastic signals are aperiodic, usually not predictable
  - Signal curve is unknown and not (fully) predictable
  - Transport information
  - Video, Audio, Messages, Sensor values



- Deterministic signals
  - Signal curve is defined by mathematical function, table, etc.
  - Carrier signals that information is modulated to
  - Sine waves

- Deterministic signals are split into periodic and aperiodic signals
  - Aperiodic: Finite duration
  - Periodic: Infinite duration

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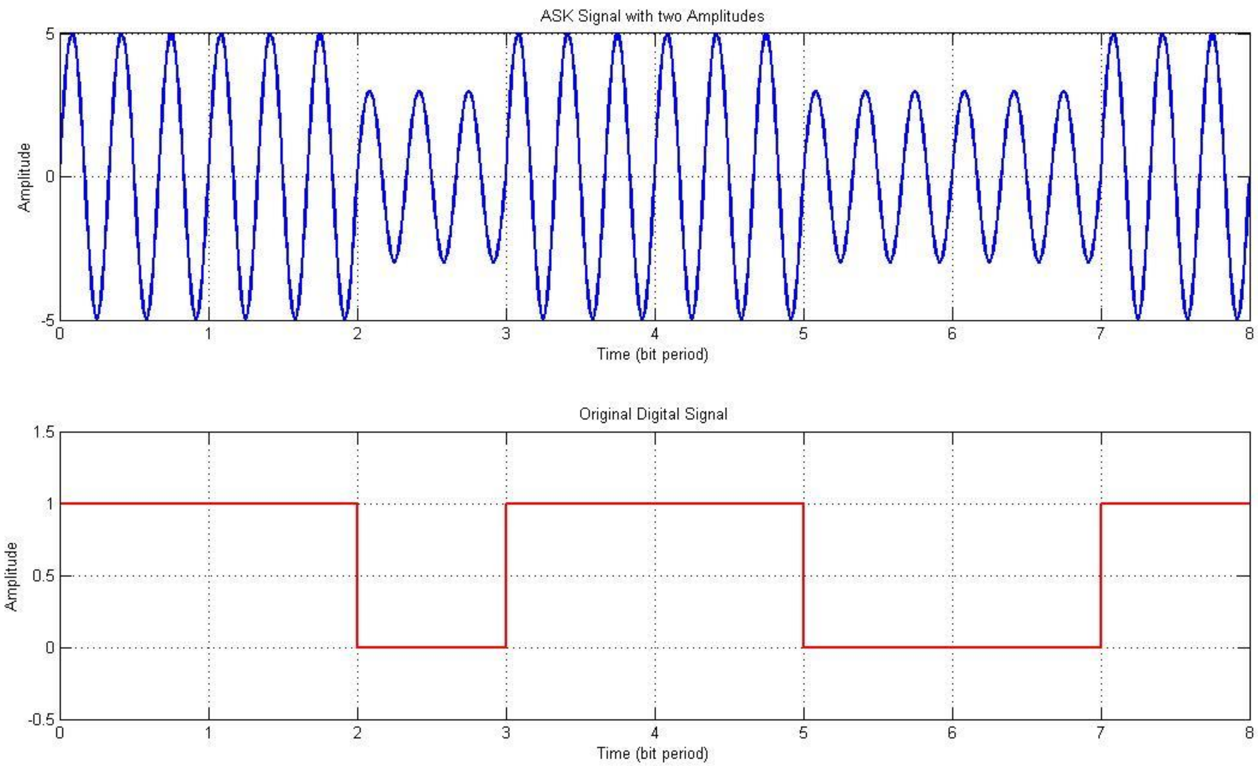
Stochastic vs. deterministic signals - modulation

- Modulation combines deterministic signals and stochastic signals
  - Creates transmittable (physical) signal



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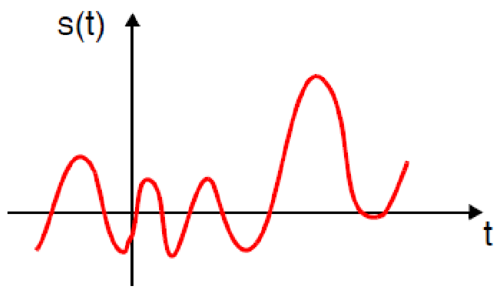
Continuous vs. discrete signals

- Continuous vs. discrete signals (time)
  - Defines time when the signal has a defined value
  - Continuous: Signal is defined at all times within an interval [t_{start}, t_{end}]
  - Discrete: Signals is defined only at specific sample times within a given interval
- Continuous vs. discrete signals (value)
  - Defines the values that are transmitted by a signal
  - Continuous: Signal may carry any value in given interval [v_{min}, v_{max}]
  - Discrete: Signals may carry defined values from an interval [v_{min}, v_{max}]

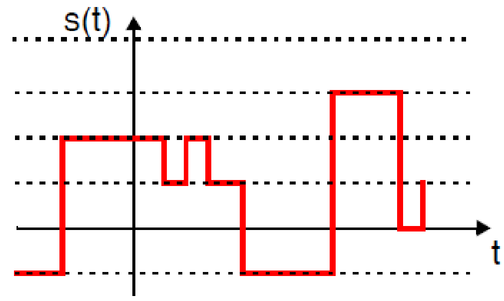
Physical Communication

Continuous vs. discrete signals - combinations

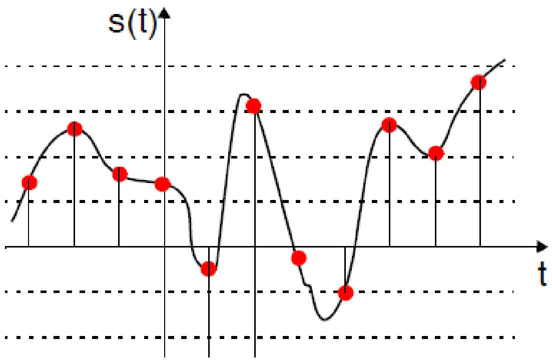
Continuous time & value
(analoguous signal)



Continuous time & discrete value

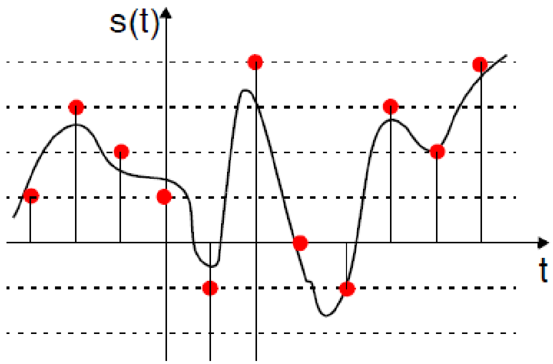


Discrete time & continuous value



Sampling period

Discrete time & value
(digital signal)



Sampling period

Physical Communication

Continuous vs. discrete signals

- Transmittable signals
  - Only analogous signals can be transmitted over physical links
- Processable signals
  - Analogous circuits process analogous signals
  - Digital circuits process digital signals
- Most processing units are nowadays digital units
  - Signals need to be transformed between transmission and processing entities

Physical Communication

Signal transformations

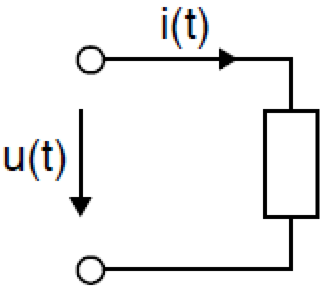
		Transformed signal			
		Cont. Time Cont. Value	Disc. Time Cont. Value	Cont. Time Disc. Value	Disc. Time Disc. Value
Original signal	Cont. Time Cont. Value		Sampling	Quantisation	A/D Conversion
	Disc. Time Cont. Value	Interpolation			Quantization
	Cont. Time Disc. Value	Smoothing			Sampling
	Disc. Time Disc. Value	D/A Conversion		Interpolation	

Physical Communication

Energy and power signals

- Physical transmission requires energy or power
  - Physically transmittable signals are either energy and power signals
  - Signals that are neither energy nor power signals cannot be transmitted over physical links

- Physical signal transmission
  - Physical signal is transmitted over physical link
  - Assume a current signal x(t) = i(t)
  - Resistor models physical line, it converts voltage current into thermal energy



$$R = \frac{u(t)}{i(t)}$$

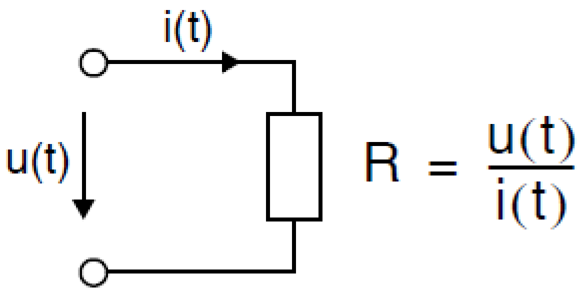
Physical Communication

Energy signals

- Real- or complex valued signal s(t) with finite energy

- Definition
  - Assume 1Ω resistor (R= 1Ω)
  - Signal s(t) is transmitted as current i(t)

$$s(t) = i(t)$$



  - Electric power that is converted at resistor into thermal energy at time t is defined as following:

$$p(t) = u(t) \cdot i(t) = i(t)^2 \cdot R$$

  - Energy that is transmitted by signal between t_1 and t_2 is defined as following:

$$E = \int_{t_1}^{t_2} p(t)\,dt = R \cdot \int_{t_1}^{t_2} i(t)^2\,dt$$

Physical Communication

Energy signals

- The following must hold for a generic energy signal:

$$0 < E = \int_{t=-\infty}^{t=+\infty} s(t)^2 \, dt < \infty$$

- Energy signals have finite (< ∞) signal energy
  - Typical energy signals consist of finite signal values s(t) and are switched on and off at defined times
  - For example individual, time bound impulse signals
- Where is factor ‘R’ from our previous equation?
  - This equation was specific for signals that are transmitted as current
  - R is a constant and finite factor, so we may disregard it here

Physical Communication

Power signals

- Remember our current signal s(t) = i(t):
  - Remember: Electrical power is: p(t) = u(t) · i(t)
  - Mean electrical power in time interval T is calculated as following

$$P = \frac{1}{T}\int_{t_0}^{t_0+T} u(t)\cdot\, i(t)\, dt = \frac{R}{T}\int_{t_0}^{t_0+T} i^2(t)\, dt$$

- Power signals must have finite (< ∞) mean signal power over infinite duration T
  - We are now considering t_0-T to t_0+T, which is twice the size of t_0+T, therefore $(\frac{1}{2T})$

$$0 < P = \lim_{T\to\infty} \frac{1}{2T}\int_{t=-T}^{t=+T} s(t)^2\, dt < \infty$$

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Power signals

- Typical power signals are periodic energy signals (sine wave) or stochastic signals (e.g. noise signals)

- Energy signals are no power signals
  - Their mean power over an infinite period of time is 0

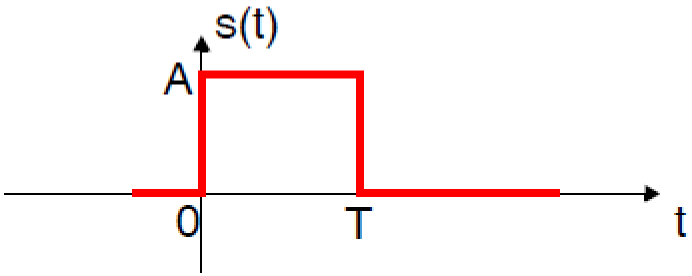
- Power signals are no energy signals
  - Their energy over an infite period of time is ∞

- Physically transmittable signals are either energy or power signals
  - Some signals are neither energy nor power signals
  - They cannot be directly transmitted, but must be modulated on a carrier signal to create an energy or power signal

Physical Communication

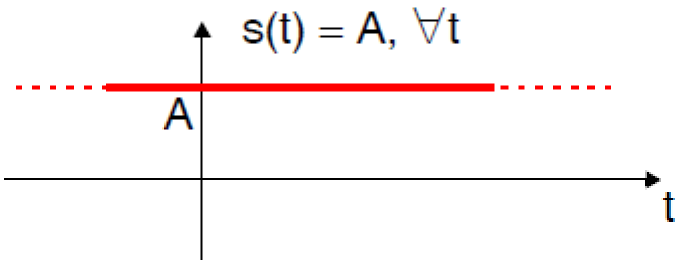
Energy or power signal - discussion

1:



One-shot rectangular pulse with duration T

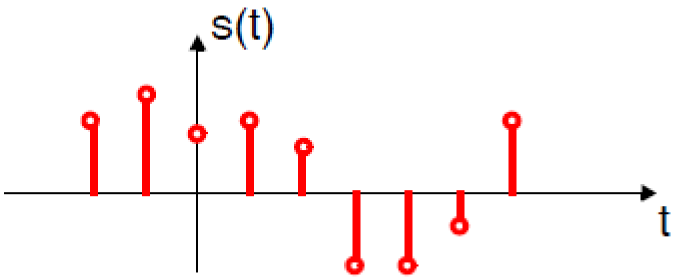
2:



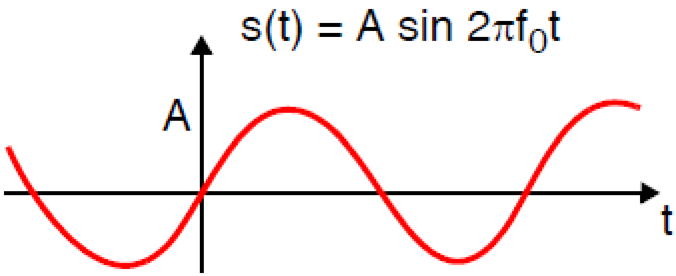
Constant, continuous signal

Physical Communication

Energy or power signal - discussion

3: 

Time discrete signal

4: 

Sinus function

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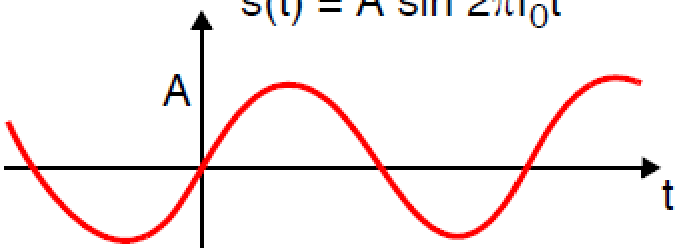
Energy or power signal – example

- Is the sine function an energy signal?



$$E = \int_{t=-\infty}^{t=+\infty} s(t)^2 \, dt$$

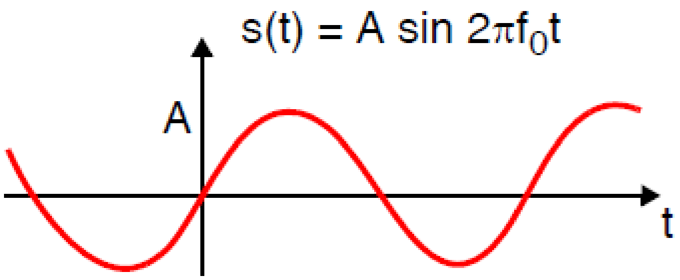
Addition theorem

$$E = \int_{-T}^{T} sin^2(t)\, dt = \int_{-T}^{T} (\frac{1}{2} - \frac{1}{2}\cos(2t))\, dt = T - \frac{1}{2}\sin(2T)$$

– Letting T → ∞ yields unlimited value → No energy signal

Physical Communication

Energy or power signal – example



- Is the sine function a power signal?

$$P = \lim_{T\to\infty} \frac{1}{2T} \int_{t=-\infty}^{t=+\infty} s(t)^2 \, dt$$

$$P = \lim_{T\to\infty} \frac{1}{2T} \left(T - \frac{1}{2} \sin(2T) \right) = \frac{1}{2}$$

  – Letting T → ∞ yields limited value between 0 and ∞ → Power signal

Physical Communication

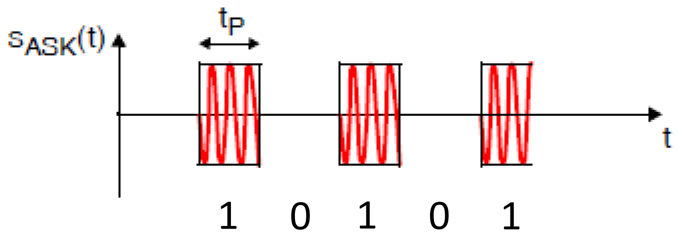
Modulation

- Conversion of time discrete information into physically transmittable signals
  - Bit sequence „10101“ is discrete
  - Needs to be converted into a physical signal before it can be transmitted
  - This conversion is called „Modulation“
- Modulation combines a carrier with information
  - This information affects the carrier in a defined manner
  - Receiver can decode the information by observing the changes to the carrier wave

Physical Communication

Modulation

- Example: Modulation via On-Off Keying
  - Special case of amplitude shift keying
  - Transmitted bit sequence is multiplied with carrier wave
    - 1 Bits are represented by visible carrier wave
    - 0 bits are represented by absence of carrier wave

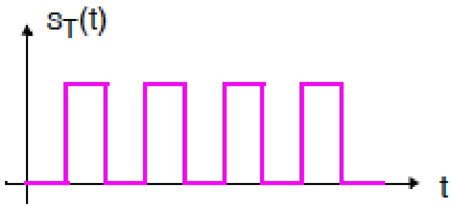


Physical Communication

Modulation

- Carrier waves are usually:
  - Sine waves (or shifted, e.g. cosine waves)
    - Modulation on analog signal
    - Modulation changes:
      - Amplitude
      - Frequency
      - Phase

  - Pulses (e.g. rectangular pulses)
    - Modulation on digital signal
    - Modulation changes
      - Amplitude
      - Frequency
      - Phase
      - Duration



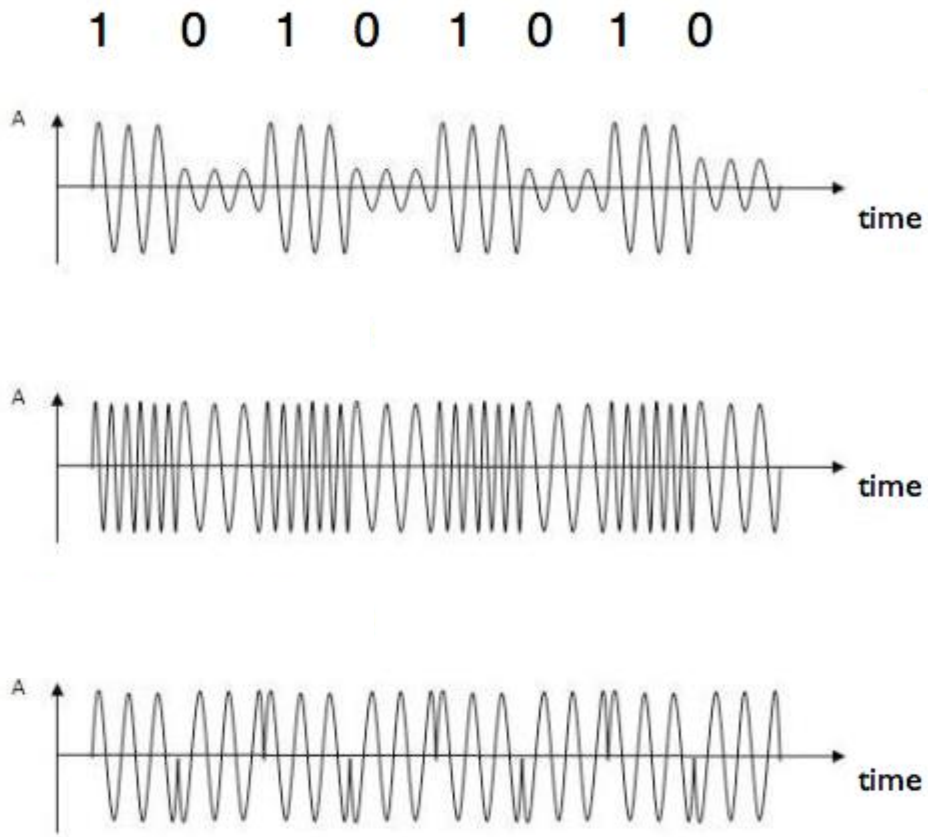
Physical Communication

Basic modulation schemes on analogue waves - Overview

Amplitude Shift Keying (ASK)

Frequency Shift Keying (FSK)

Phase Shift Keying (PSK)



Physical Communication

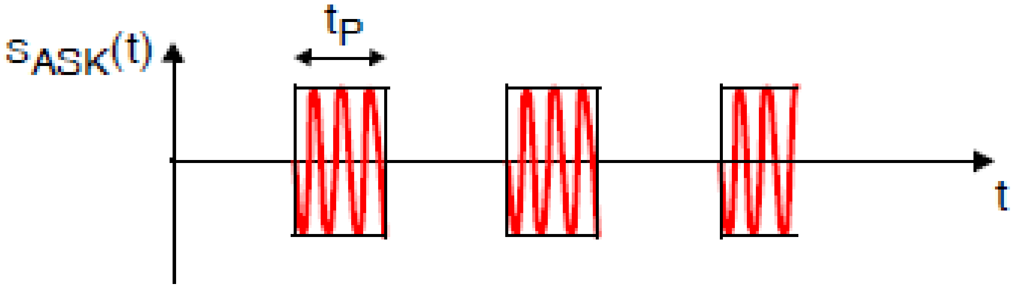
Modulation Schemes on analogue waves – Single Carrier

- **Amplitude shift keying – ASK**
  - Modulates information on the amplitude of a carrier wave
    - Two or more amplitude levels are defined to represent bits or bit sequences ‚chips‘
  - Most basic approach: On-Off Keying
    - Switches Carrier wave on or off depending on transmitted signal
    - Drawback: Receiver cannot distinguish between ‚0‘ and no active transmission

Physical Communication

Modulation Schemes on analogue waves – Single Carrier

- **Example: OOK**



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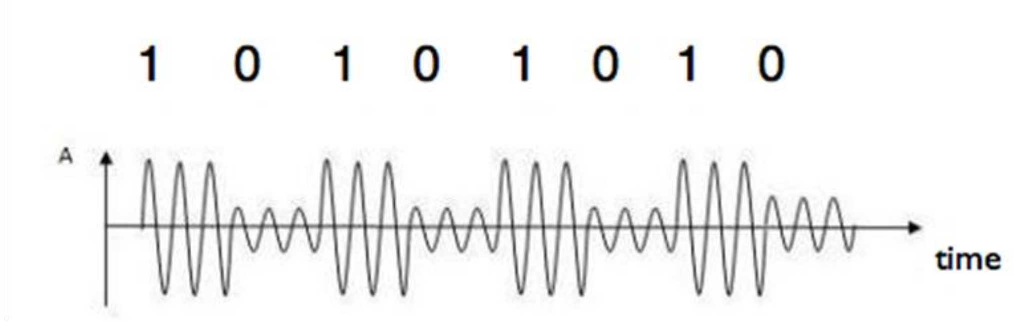
Physical Communication

Modulation Schemes on analogue waves – Single Carrier

- **Example: ASK**



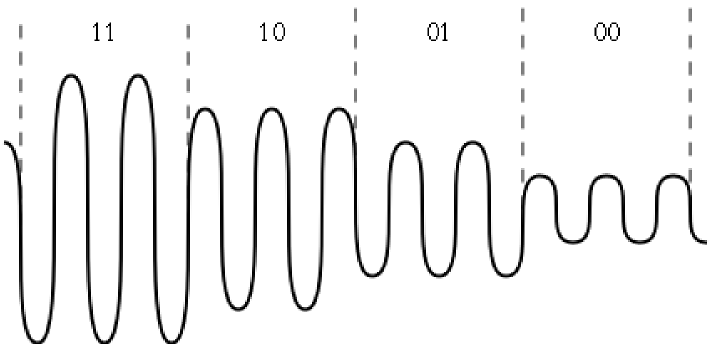
ASK

Physical Communication

Modulation Schemes on analogue waves – Single Carrier

- **Amplitude shift keying – ASK**
  - ASK is often used with more than two energy levels
  - In this case, one amplitude level represents a bit sequence

- **Example:**



Physical Communication

Modulation Schemes on analogue waves – Single Carrier

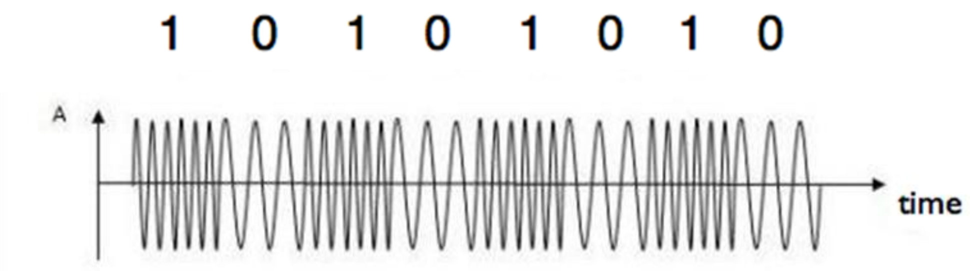
- **Amplitude shift keying – discussion**
  - Drawbacks:
    - The amplitude is affected by noise, crosstalking, reflections, signal fading…
    - With higher transmission ranges, signal fading becomes more significant
      - Energy levels get closer → Separation is getting harder
  - Advantages:
    - Continuous carrier wave (i.e. there are no jumps in the carrier wave)
      - Why is this important?

Physical Communication

Modulation Schemes on analogue waves – Single Carrier

- **Frequency shift keying – FSK**
  - Modulates information on the frequency of a carrier wave
    - Two or more frequencies are defined to represent bits or bit sequences ‚chips‘

- **Example:**



Physical Communication

Modulation Schemes on analogue waves – Single Carrier

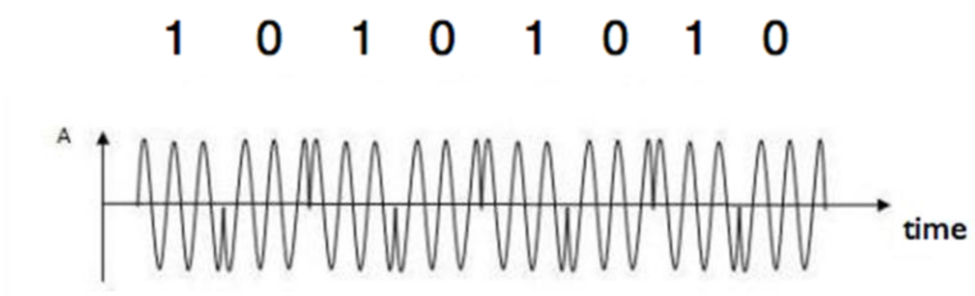
- **Frequency shift keying – discussion**
  - Drawbacks:
    - For wireless transmissions: Doppler-Effect must be considered
    - Available frequencies are usually limited
  - Advantages:
    - Frequency is much less affected by noise and signal fading than amplitude
    - Modulated signal is continuous

Physical Communication

Modulation Schemes on analogue waves – Single Carrier

- **Phase shift keying – PSK**
  - Modulates information on the phaseof a carrier wave
    - Two or more phases are defined to represent bits or bit sequences (chips)
    - Example: Phase shift by 180° to indicate bit value or bit change

- **Example:**



Physical Communication

Modulation Schemes on analogue waves – Single Carrier

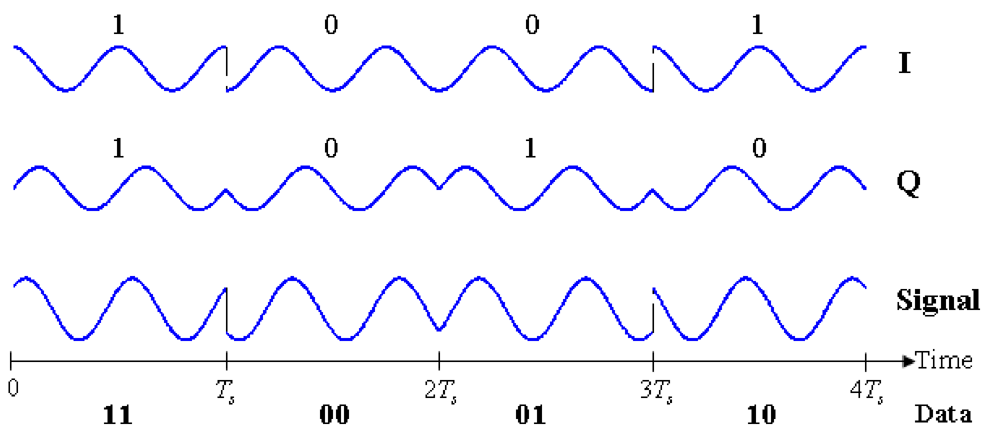
- **Phase shift keying – discussion**
  - Drawbacks:
    - Phase changes cause jumps in the modulated signal
  - Advantages:
    - Phase is much less affected by noise and signal fading than amplitude

Physical Communication

Modulation Schemes on analogue waves – Multiple carriers

- Some transmission systems use more than one carrier wave

- Example: QPSK/QAM modulation
  - Uses two carrier waves with 180° phase shift (I- and Q-Waves)
  - Information is modulated independently on both waves
  - Higher transmission rate, but requires additional effort for separating both waves
  - Receiver needs to seperate more states



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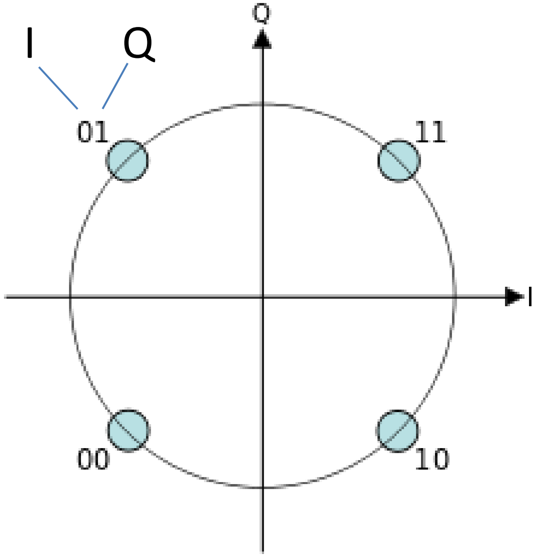
Modulation Schemes on analogue waves – Multiple carriers

- Receiver seperates carriers and distinguishes state of each phase
  - QPSK requires receiver to distinguish between four states instead of two



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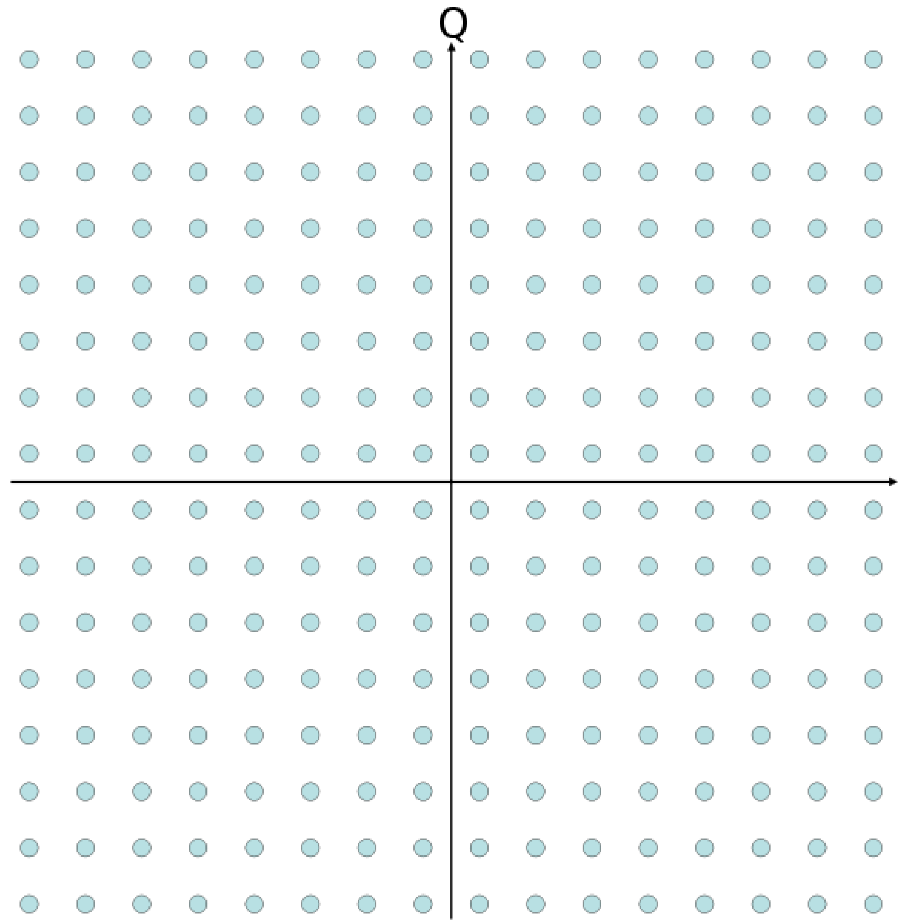
Modulation Schemes on analogue waves – Multiple carriers

- Example: QAM-256
  - Two carrier waves
  - 16 amplitudes per carrier



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Modulation on pulses

- Line Coding
  - Represents digital signal by amplitude and time discrete signal
  - Commonly used in (embedded) bus systems
- Classification
  - Is clock recovery possible?
  - Does the coding impose a DC component?
- DC component
  - Codings that are not voltage balanced over a given time interval have a DC component
  - DC components can often not be transmitted over long distances and therefore cause transmission errors

Physical Communication

Modulation on pulses

- Example: DC components in line codes

Physical Communication

Modulation on pulses

- Clock recovery
  - Clocks of senders and receivers are not perfectly synchronous
  - Clock frequencies oscillate
    - Depending on temperature, time, voltage…
    - Not predictable for both stations
  - Sender and receiver need to synchronize periodically
    - Otherwise, a signal cannot be correctly recovered
    - Example:

Physical Communication

Modulation on pulses

- Line codings with clock recovery support automatic recovery of clock data
- Discussion: Which preconditions are necessary for clock recovery?

Physical Communication

Modulation on pulses

- Popular line coding schemes
  - Unipolar Encoding
  - Non Return to Zero (NRZ)
  - Bipolar Encoding
  - Manchester Encoding

Physical Communication

Modulation on pulses

- Unipolar encoding

- A bit sequence is encoded by rectangular pulses that represent bit values
  - Positive voltage represents ‚1‘ bit
  - Zero voltage represents ‚0‘ bit

- Example bit sequence: 10011101

- Discussion:
  - Does unipolar coding has a DC component?
  - Is clock recovery possible?

Physical Communication

Modulation on pulses

- Non return to zero-level (NRZ-L)
- A bit sequence is encoded by rectangular pulses that represent bit values
  - Positive voltage represents ‚1‘ bit
  - Some other significant voltage represents ‚0‘ bit (usually negative voltage)
- Example bit sequence: 10011101
- Discussion:
  - Does NRZ-L coding has a DC component?
  - Is clock recovery possible?

Physical Communication

Modulation on pulses

- Non return to zero-inverted (NRZ-I)

- A bit sequence is encoded by rectangular pulses that represent bit values
  - Two significant voltages (usually one positive, one negative)
  - Level inversion encodes logic 1, lack of inversion encodes logic 0

- Example bit sequence: 10011101

- Discussion:
  - Does NRZ-I coding has a DC component?
  - Is clock recovery possible?

Physical Communication

Modulation on pulses

- Bipolar encoding

- A bit sequence is encoded by rectangular pulses that represent bit values
  - Two significant voltages represent logic 1 bits
    - One positive voltage value, one equivalent negative voltage value
  - Logic 0 bits are represented by a zero voltage

- Example bit sequence: 10011101

- Discussion:
  - Does bipolar coding has a DC component?
  - Is clock recovery possible?

Physical Communication

Modulation on pulses

- Manchester encoding
- Bits are represented by transitions in the middle of a transmitted symbol
  - A logical 1 is represented by high to low transition
  - A logical 0 is represented by low to high transition
- Example bit sequence: 10011101
- Discussion:
  - Does manchester coding has a DC component?
  - Is clock recovery possible?

Physical Communication

Physical signals

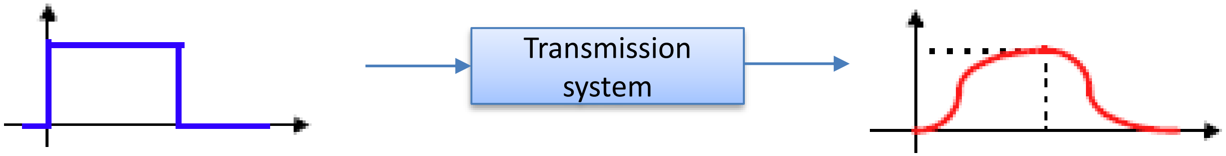
- Physical signals must be either energy or power signals
  - Modulation converts information into physical signals

- Which modulation type is best?
  - Why can jumps in the modulated signal be a drawback?
  - Why is the bitrate that can be transmitted over a physical link limited?

Physical Communication

Physical signals

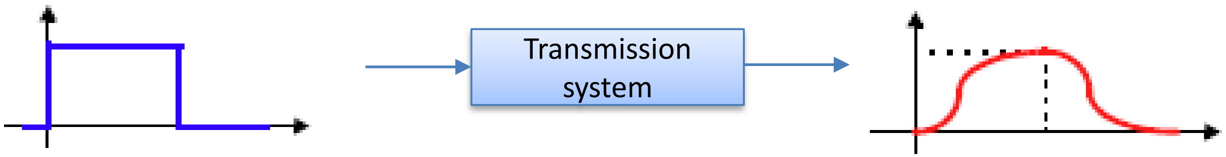
- Discrete signals cannot be transmitted
  - All physically transmittable signals are continuous
  - E.g. a modulated sine wave
- Consider a signal that is physically transmitted through a system
  - E.g. a copper wire



- What did happen?

Physical Communication

Physical signals



- The transmission system modified the transmitted signal
  - Physical signal transmission requires energy
  - Ideal transmission systems would reduce energy equally
  - Real transmission systems however reduce energy based on frequencies

Physical Communication

Fourier series

- How do we know the frequency spectrum that is necessary for signal transmission?
  - All physical signals have a representation in the frequency domain
  - Fourier Series represent a periodic signal s(t) as an overlapping sequence of sine and cosine waves with different frequencies

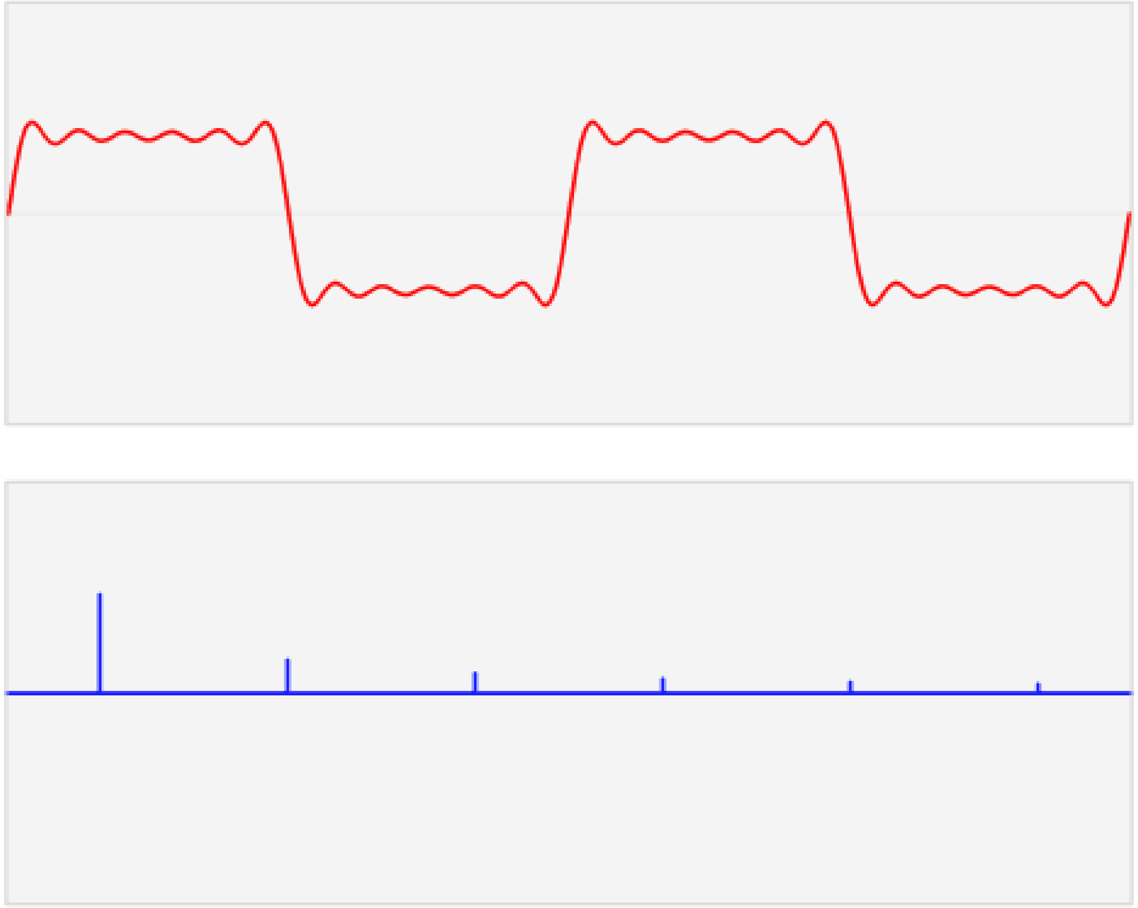
$$s(t) = a_0 + \sum_{n=1}^{\infty} a_n \cos(n\omega_0 t) + \sum_{n=1}^{\infty} b_n \sin(n\omega_0 t)$$

  - A representation as sum of cosine functions with differing frequencies and phases

$$s(t) = a_0 + \sum_{n=1}^{\infty} c_n \cos(n\omega_0 t - \varphi_n) \text{ mit } c_n = \sqrt{a_n^2 + b_n^2},\ \varphi_n = \arctan(b_n / a_n)$$

Physical Communication

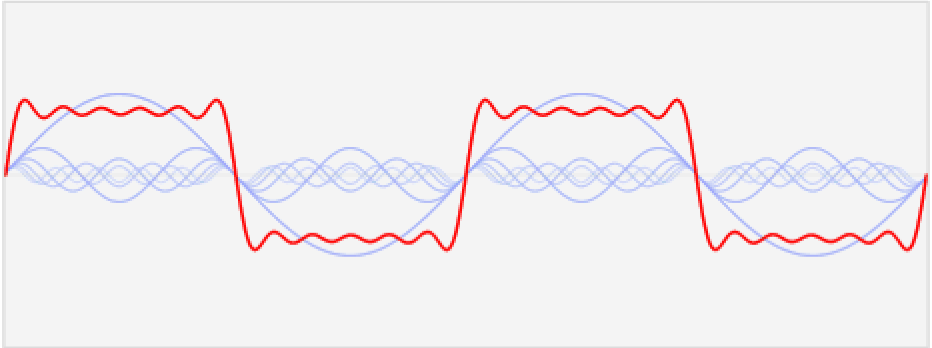
Fourier series – Example (1)



Physical Communication

Fourier series – Example (1)

$$f$$



$$a_n \cos(nx) + b_n \sin(nx)$$

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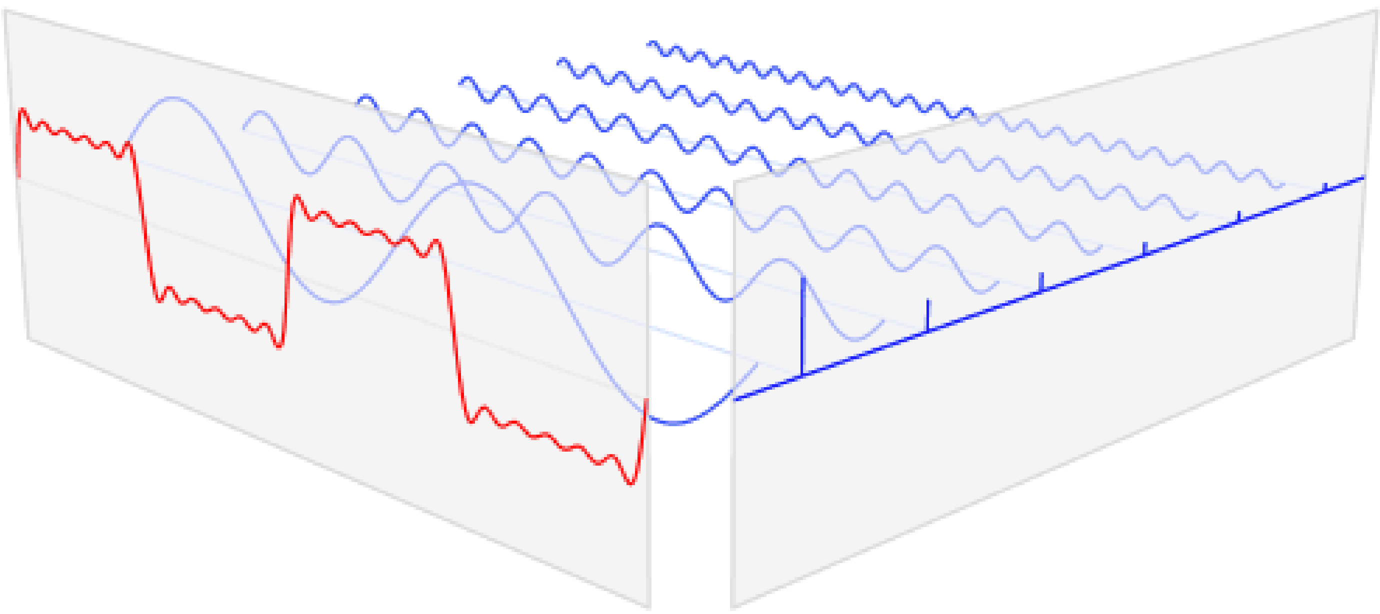
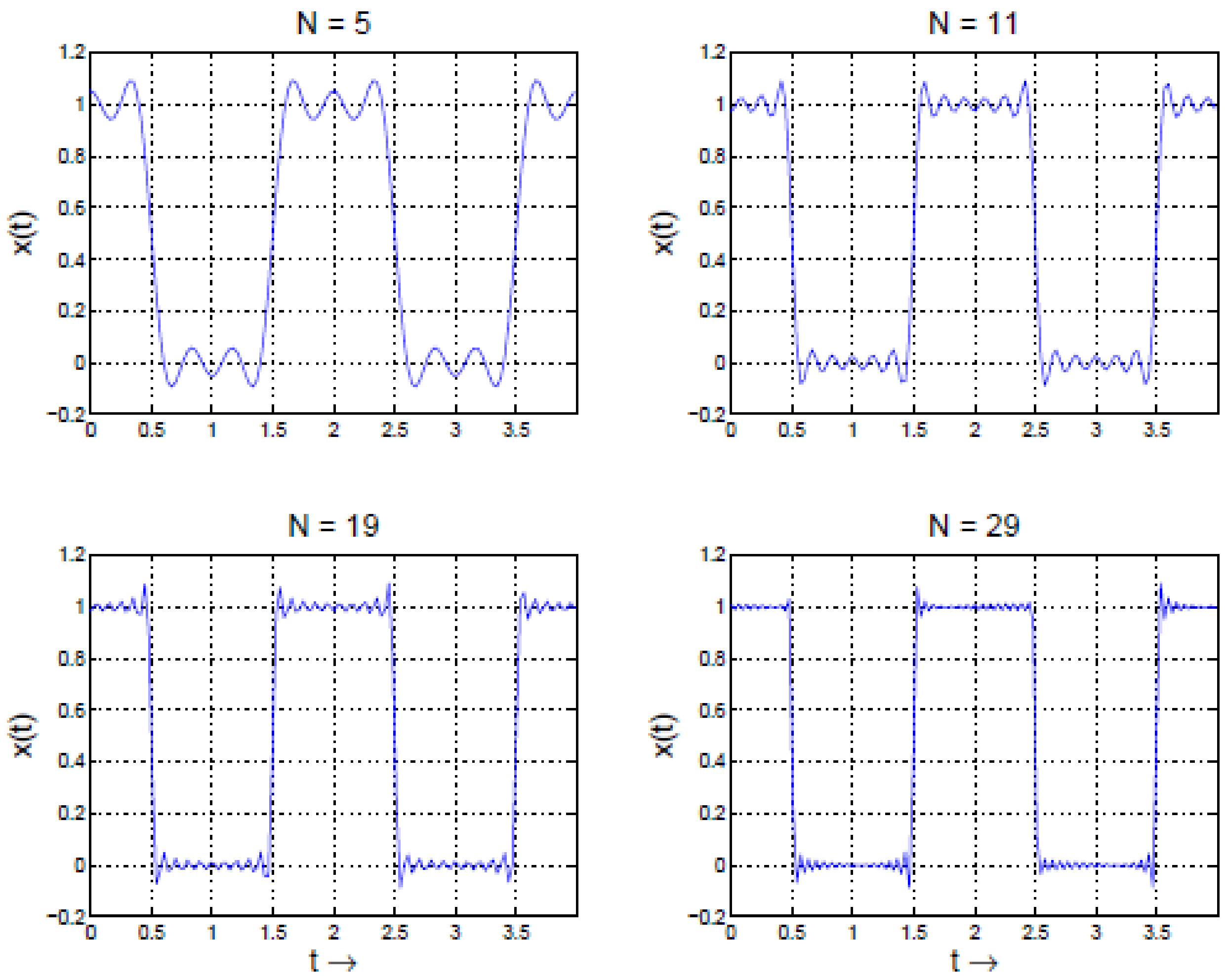
Fourier series – Example (1)



Physical Communication

Physical signals

- Example (2):
  - You need infinite amount of overlapping functions to represent a periodic sequence of rectangular pulses



Physical Communication

Physical signals

- More harmonic waves lead to a better approximation of the original periodic rectangular signal

- Problem: Real signals are not periodic
  - Assume a fourier series with an infinite period T
  - Fourier transformation
    - Line spectrum of fourier series becomes continuous spectrum
    - Sum is turned into integral function

Fourier transformation

$$S(\omega) = \int_{-\infty}^{\infty} s(t) \cdot e^{-j\omega t} dt$$

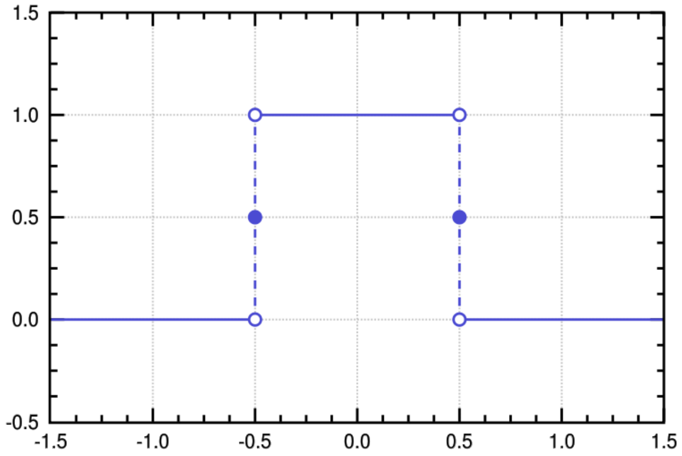
Inverse Fourier transformation

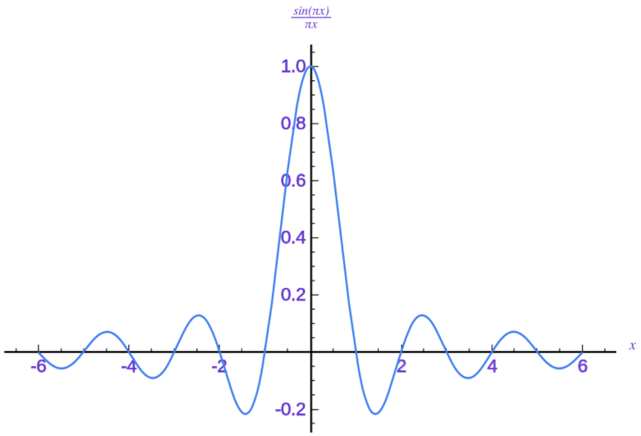
$$s(t) = \int_{-\infty}^{\infty} S(\omega) \cdot e^{j\omega t} d\omega$$

Physical Communication

Physical signals

- Example:
  - Rectangular pulse has infinite spectrum
  - It is therefore not well suited for data transmission (why?)
    - It requires high bandwidth
    - It is quickly affected by interferences that change individual frequency ranges

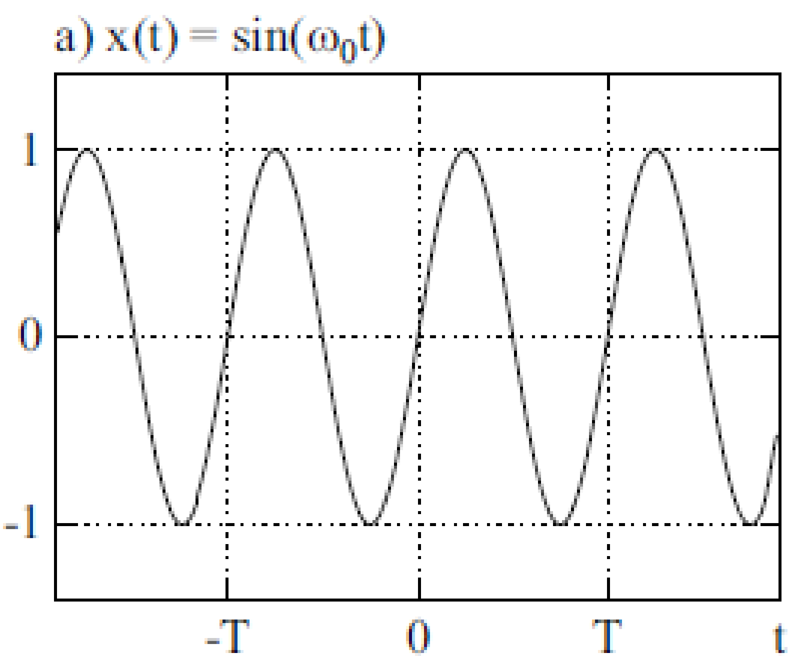


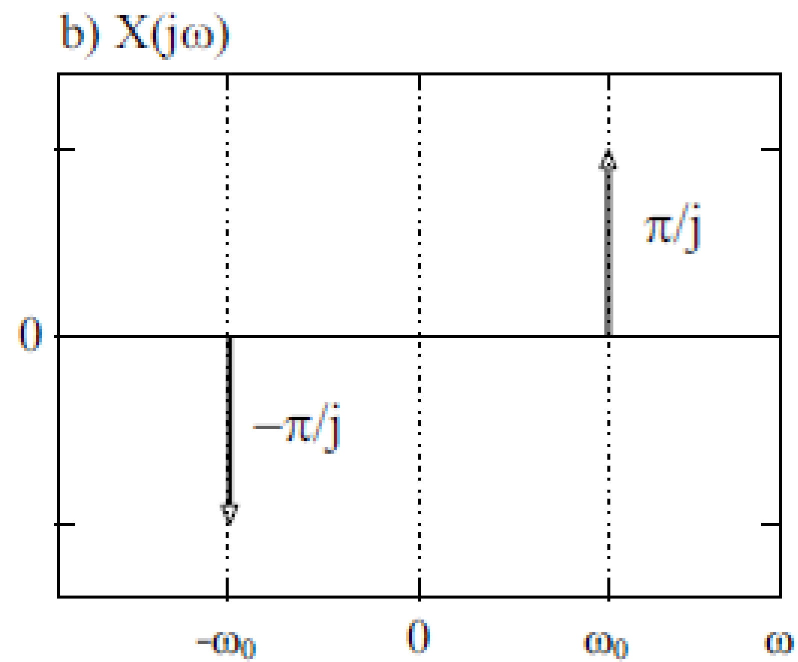


Physical Communication

Physical signals

- Examples (continued):
  - Spectrum of sine function only consists of one frequency
  - Unmodulated carrier wave





Physical Communication

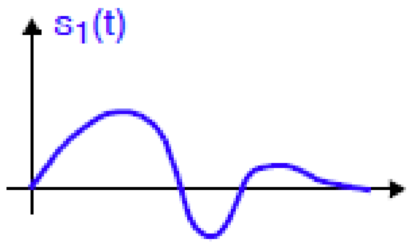
Physical signals

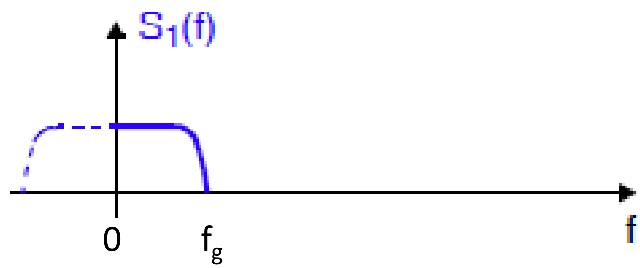
- As soon as data is modulated on carrier wave, multiple overlapping sinus waves are required to represent the resulting aperiodic function
- The range of frequencies that is required to correctly transmit the modulated signal is the required bandwidth
- Modulation changes required bandwidth as well
  - Jumps require infinite bandwidth
  - Physics of real communication systems therefore smooth jumps
- When the same modulation scheme is used to create signal s(t), the required bandwidth increases with the number of bits that are transmitted per interval
  - When multiple independent signals are transmitted on the same medium, their frequency bands need to be seperated to prevent interferences

Physical Communication

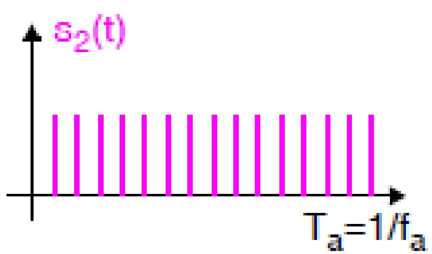
Receiving physical signals (correctly)

- A continuous signal that is physically transmitted has a defined spectrum
  - Between 0 and f_g





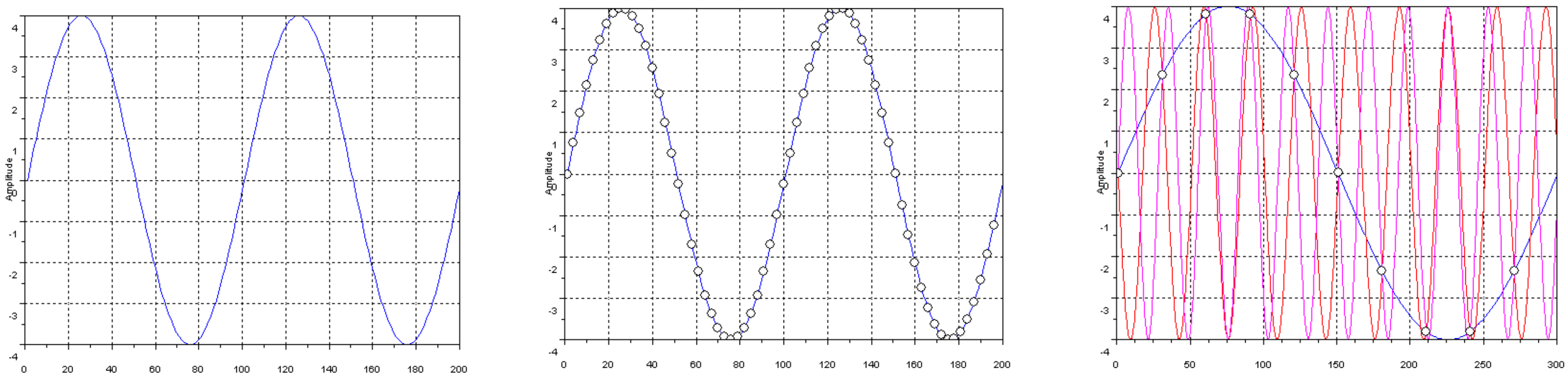
- Sampling with frequency f_a yields a periodic spectrum



Physical Communication

Receiving physical signals (correctly)

- Why does sampling yield a periodic spectrum?

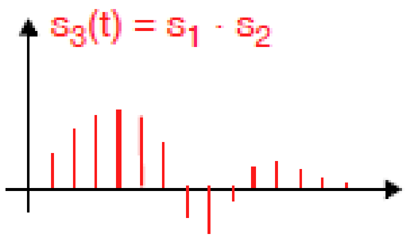


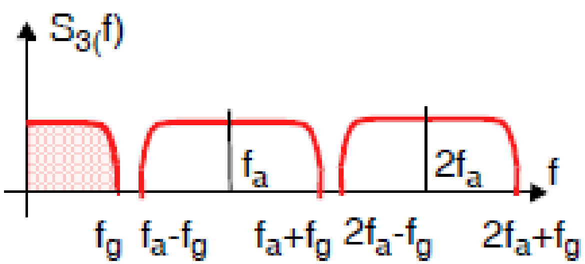
- Sampling points could also fit to higher frequency carriers
  - They could therefore have a different meaning as well

Physical Communication

Receiving physical signals (correctly)

- Sampled signal therefore yields a periodic spectrum





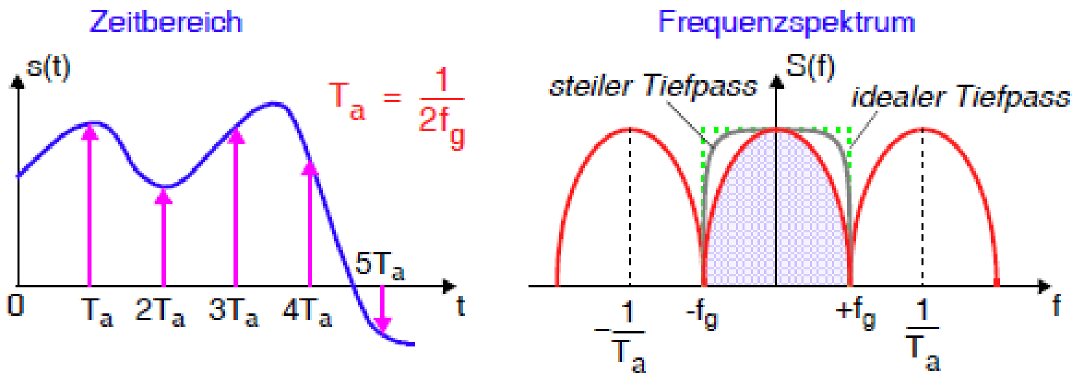
- Which sampling frequency is necessary to reconstruct the original signal s(t)?
  - Sampling frequency f_a must be bigger than two times the highest frequency in the spectrum of s(t)

$$f_a > 2 \cdot f_g$$

Physical Communication

Receiving physical signals (correctly)

- Reason for $f_a > 2 \cdot f_g$
  - Ideal low-pass filter would be able to seperate periodic spectrums if $f_a = 2 \cdot f_g$ holds
  - Higher f_a seperate these spectrums with higher distance
  - Therefore we need $f_a > 2 \cdot f_g$ or sampling period $T_a < \frac{1}{2f_g}$



Physical Communication

Physical Communication

- Signal types
  - Only analogous signals may be transmitted over a physical medium
  - Classification of signals
    - Continuous and discrete signals
    - Deterministic vs. stochastic signals
    - Energy- or power signals
  - Digital signals must be transformed, e.g. through modulation
- Modulation schemes
  - Modulation on carrier waves & modulation on pulses
- Physical signals
  - Bandwidth limitations
  - Fourier transformation
  - Sampling theorem