Rechnernetze - Computer Networks

Lecture 2: Direct Link Networks
Media, Encoding, and Framing

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Direct link networks

Simplest network: two hosts are directly connected by some physical medium such as

- copper wire, optical fibre
- air or free space via radio

Besides of the connecting medium, procedures are needed for:

- encoding bits onto the transmission medium
- framing to detect message (frame) boundaries
- error detection
- error correction
- medium access control if multiple hosts share the medium

Outline

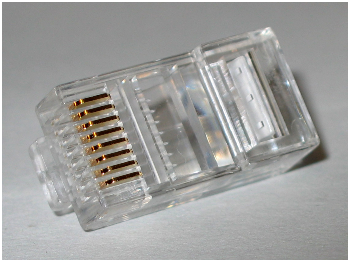
Physical transmission

Characteristics:

- mechanical, e.g., size of plugs, allocation of pins
- electrical, e.g., voltage
- procedural, e.g., timing, rules for usage

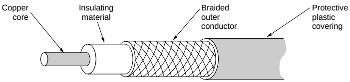
Example Connector

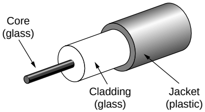
- Registered Jack (RJ) 45
- 8 Position, 8 Contact (8P8C)
- used e.g. for Ethernet



Examples

- unshielded twisted pair (UTP)
  used e.g. for Ethernet
- coaxial cable
  used e.g. for cable TV
- fiber
  used e.g. in wide-area networks

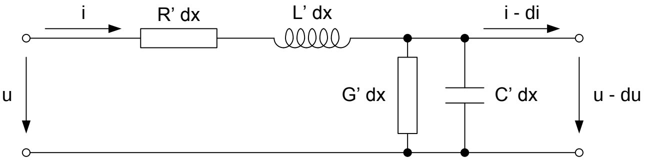




Source: Tanenbaum, Computer Networks

Cable circuit model

Model of an infinitesimally small segment dx of a cable



Intuitively,

- the two wires of the cable create an electromagnetical field resulting in an
  - inductive coupling expressed as L' per dx
  - capacitative coupling expressed as C' per dx
- the copper wires have an electrical resistance R' per dx
- the insulation has a certain conductivity G' per dx

Cable parameters

Category 5e UTP cable (Cat5e)

- 4 twisted pairs
- some electrical parameters
  - DC-loop resistance: $\leq 0.188\ \Omega/\text{m}$
  - inductance: 525 nH/m
  - capacitance: 52 pF/m

Cat5e is typically used for Ethernet, e.g. a 100 Mb/s Ethernet host

- transmits on pin 1 and 2
- receives on pin 3 and 6
- uses two differential voltage levels of $+2.5$ V and -2.5 V

Cable characteristics

Attenuation

- the quotient of input and output voltage decreases
  - with increasing length of the cable
  - with increasing frequency of the signal
- the cable behaves like a lowpass filter
  - higher frequencies are attenuated more than lower frequencies
  - high frequency signals travel less far

Distortion

- attenuation and propagation speed depend on the frequency
- signals that contain largely different frequencies are distorted

Noise and interference

- thermal noise: random motion of electrons
- crosstalk: several cables affect each other due to their electromagnetic fields inducing current on each other

Fourier series

To understand the distortion that is due to the cable's lowpass characteristic, we need to decompose the signal in frequency.

Any periodic function $g(t)$ with period T can be constructed as a Fourier series, i.e. a weighted sum of sines and cosines

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

where $f = 1/T$ and a_n, b_n, c are constant coefficients. a_n, b_n are the coefficients of the n-th harmonics.

Fourier coefficients

Given a signal $g(t)$ the Fourier coefficients can be computed as:

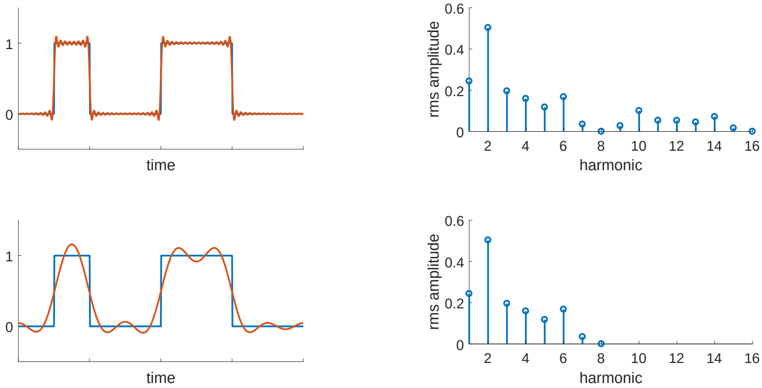
$$a_n = \frac{2}{T} \int_0^T g(t) \sin(2\pi n f t) dt$$

$$b_n = \frac{2}{T} \int_0^T g(t) \cos(2\pi n f t) dt$$

$$c = \frac{2}{T} \int_0^T g(t) dt$$

The root-mean-square (rms) amplitudes $\sqrt{a_n^2 + b_n^2}$ correspond to the energy transmitted at frequency nf.

Original signal vs. approximation using the first 64 or 8 harmonics.



Attenuation

During transmission signals generally loose power

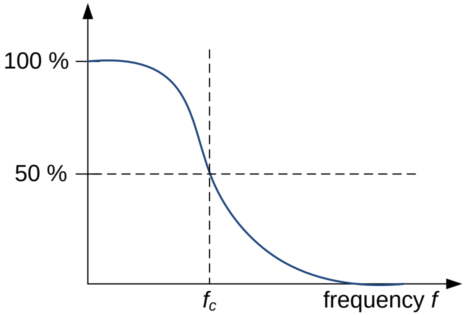
- reduces the amplitude of Fourier components
- if all coefficients are reduced by the same amount the resulting signal is a scaled copy of the original signal
- typically different coefficients are diminished by different amounts resulting in a distortion of the signal

Bandwidth-limited channel

- Fourier components up to some cut-off frequency f_c are transmitted undiminished
- Fourier components above f_c are attenuated
- in practice the cut-off is not sharp, f_c is the frequency where half the power diminishes
- the cut-off frequency of a channel is determined by its physical parameters, e.g. material, thickness, length

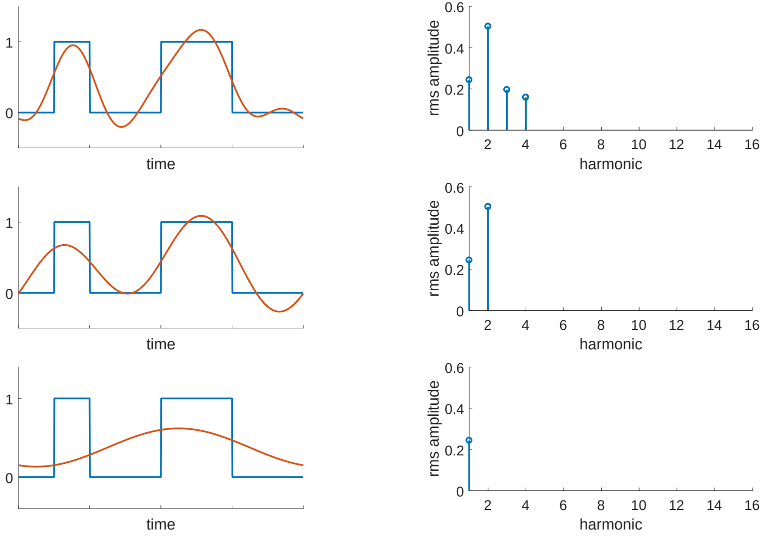
Bandwidth-limited channel

- the width of the interval $[0, f_c]$ is called the bandwidth B

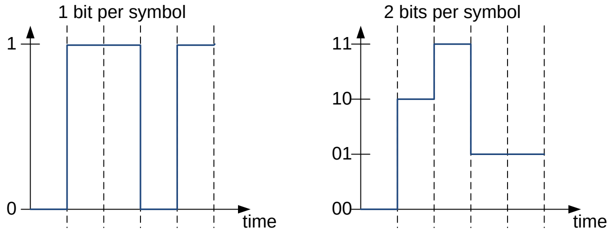


Some systems, e.g. analog telephony, add filters that limit the bandwidth of the channel, e.g. for telephony at 4 kHz that is sufficient for voice.

Signal, if only the first 4, 2, or 1 harmonics pass through a channel.



Bit rate and Baud rate



- baud rate: number of symbols transmitted per second
  - number of possible signal changes per second
  - changes in amplitude, frequency, phase
- bit rate: number of bits transmitted per second
  - bit rate $=$ baud rate times $\log_2$ (number of different symbols)

Nyquist rate

Considering a bandwidth-limited but otherwise perfect channel with bandwidth $[0, B]$, Nyquist's theorem states that

$$\text{maximum symbol rate} = 2B \text{ Baud.}$$

Using symbols with V different discrete levels it follows that

$$\text{maximum data rate} = 2B \log_2 V \text{ bit/s.}$$

Beyond these rates transmitted symbols resp. bits cannot be recovered correctly at the receiver.

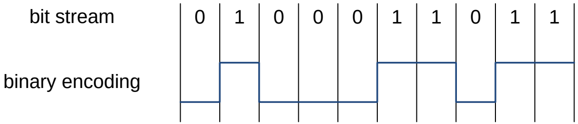
Transmission: Operation modes

- serial: signals are transmitted sequentially over one channel
- parallel: signals are transmitted simultaneously over several channels

- synchronous
  - sender and receiver have synchronized clocks
  - bits are transmitted at fixed time instances only
- asynchronous
  - transmissions use specific start and stop signals

- digital: line coding transmits bits as square impulses
- analog: bits are modulated onto a sine wave carrier

Binary encoding

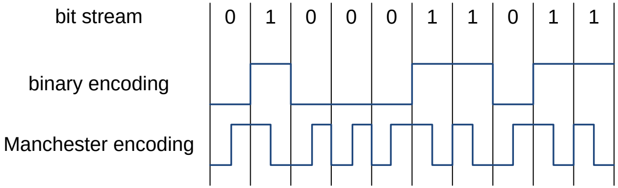


- 0: low voltage
- 1: high voltage

Characteristics

- simple, cheap, efficient, 1 bit per baud
- but no inherent self-clocking, e.g. consider a sequence of zeros

Manchester encoding

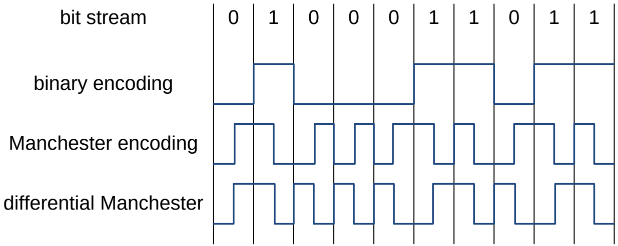


- 0: low to high transition
- 1: high to low transition

Characteristics

- 0.5 bit per baud
- inherent self-clocking
- example: IEEE 802.3 Ethernet

Differential Manchester encoding



- 0: transition at the beginning of the interval
- 1: no transition at the beginning of the interval

Characteristics

- like Manchester encoding, however,
- only transitions matter (0: two transitions, 1: one transition)
  - detecting transitions is less error prone than high/low levels
  - works also if wires are swapped

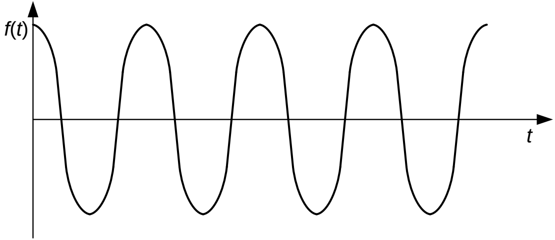
Drawbacks of line coding

Square pulses contain a wide range of frequencies (see Fourier analysis)

- attenuation is frequency dependent, high frequencies diminish more quickly
- propagation speed is frequency dependent causing additional delay distortion

To overcome these shortcomings of line coding information is modulated onto sine wave carriers.

Modulation schemes

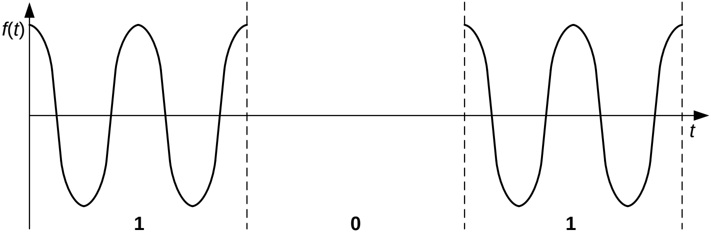


$$s(t) = a \cdot \cos(2\pi f t + \phi)$$

Using cosine (sine) functions, modulation can be used for baseband as well as passband transmission. A basic cosine (sine) function has three parameters that can be modulated to encode data:

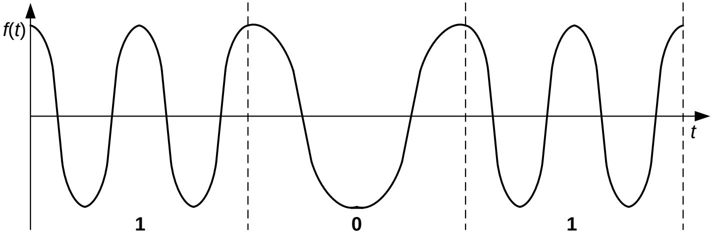
- $a =$ amplitude,
- $f =$ frequency,
- $\phi =$ phase.

Amplitude shift keying



Amplitude shift keying (ASK)

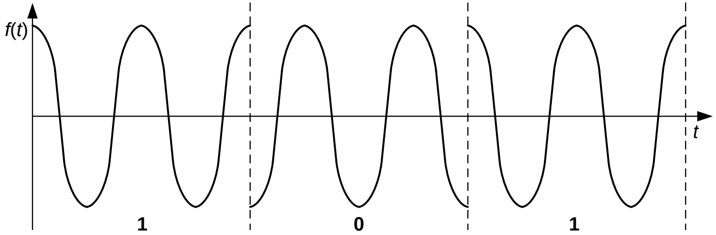
- different amplitudes represent different symbols
- simple scheme with low bandwidth requirement
- susceptible to interference that influences the amplitude
- used for optical transmission, i.e. light pulses



Frequency shift keying (FSK)

- different frequencies represent different symbols
- usually sudden changes in the phase are avoided, so-called continuous phase modulation
- demodulation can simply be performed using different bandpass filters and a comparator

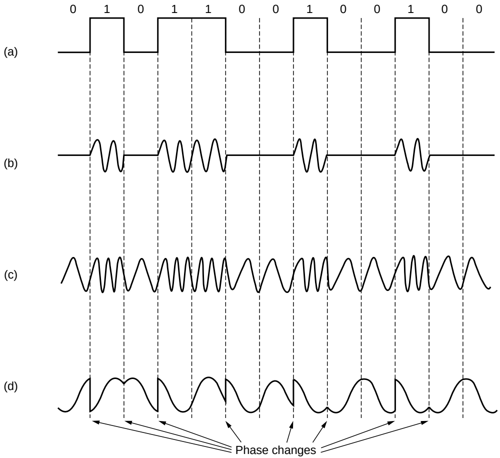
Phase shift keying



Phase shift keying (PSK)

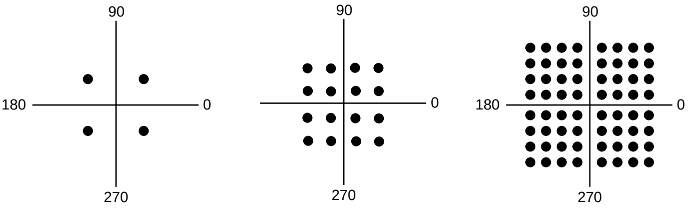
- shifts in the phase of the signal represent different symbols
- to decode the signal the receiver has to synchronize in frequency and phase using a so-called phase locked loop
- more resistent to interference than FSK but also more complex transmitter and receiver

Comparison of basic modulation schemes



Source: Tanenbaum, Computer Networks

Higher order modulation



(a) (b) (c)

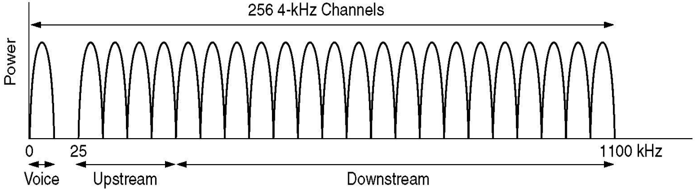
Source: Tanenbaum, Computer Networks

- quadrature phase shift keying (QPSK):
  - distinguishes 4 different phases $\Rightarrow$ 2 bit per baud
- quadrature amplitude modulation (QAM):
  - In-phase (cos) plus Quadrature (sin) signals each with
  - 4 different amplitudes $\Rightarrow$ 16 different symbols (16-QAM)
  - 8 different amplitudes $\Rightarrow$ 64 different symbols (64-QAM)

Asymmetric digital subscriber line (ADSL)

ADSL typically uses discrete multitone (DMT) modulation

- divides 1.1 MHz spectrum into 256 independent channels
- each channel has a width of 4312.5 Hz
- channel 0 is used for the plain old telephony service (POTS)
- channels 1-5 are not used to avoid interference
- two channels are used for upstream resp. downstream control
- the remaining 248 channels are allocated for upstream or downstream data



Source: Tanenbaum, Computer Networks

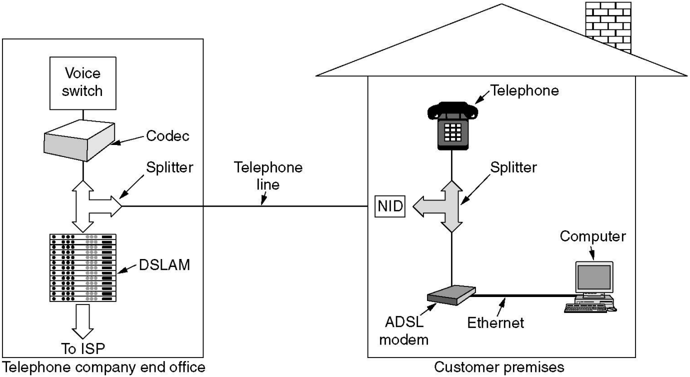
Asymmetric digital subscriber line (ADSL)

Each of the DMT channels

- is modulated independently
- is monitored and the data rate is adjusted accordingly
- the signalling rate is 4000 baud
- quadrature amplitude modulation is used with 2 up to 15 bit per baud
- a theoretical gross data rate of 14.88 Mb/s is split between upstream and downstream
- protocol overhead and non-perfect channel conditions reduce the achievable data rate

ADSL2+ uses 2.2 MHz and VDSL2 up to 35 MHz to increase the sum of up- and downlink data rate up to 400 Mb/s.

Asymmetric digital subscriber line (ADSL)



Source: Tanenbaum, Computer Networks

- splitter: analog filter, separates the 0-4000 Hz telephony band
- digital subscriber line access multiplexer (DSLAM)

Outline

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Framing

So far: transport of a raw bitstreams, possibly with errors

- bits may take different values at the receiver
- the number of bits received may even be less or more

Protocols use data packets, respectively, frames

- need to identify frame boundaries in the bit stream

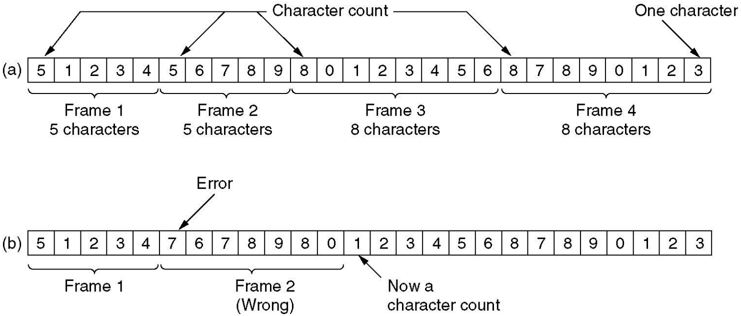
Source: Tanenbaum: Computer Networks

Framing

Considering the possibility of bit errors, framing is non-trivial. A number of different methods exist to mark frame boundaries:

- character count (frequently combined with the use of flags)
- flag bytes with specific patterns
  - byte stuffing
  - bit stuffing
- specific code violations
  - can be used in case the physical encoding on the medium contains redundancy
  - e.g. Manchester encoding only uses two out of four possible symbols (low-high and high-low transitions)
  - the remaining symbols (low-low, high-high) can be used for specific purposes such as framing
  - violates the programming concept of information hiding

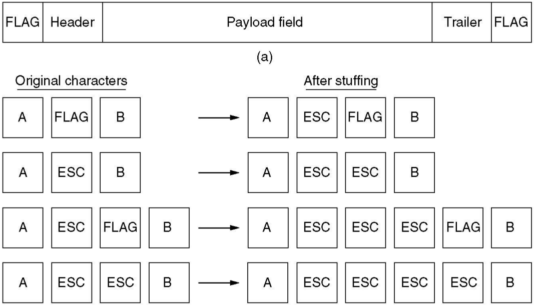
Character count



Source: Tanenbaum: Computer Networks

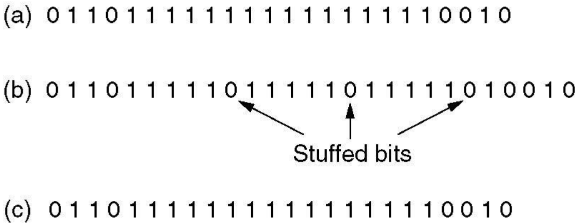
- the header contains a field that specifies the number of characters in the frame
- the method is error-prone, even if the checksum indicates a bad frame the receiver has no chance of recovering

Flag bytes with byte stuffing



Source: Tanenbaum: Computer Networks

- frames start and end with specific bytes, so called flag bytes
- avoids the re-synchronization problem, receiver just uses flags
- if FLAG (or ESC) occurs in the data the sender marks it with an extra ESC character that is removed at the receiver



(a) original data, (b) data sent, (c) data at the receiver after de-stuffing,
Source: Tanenbaum: Computer Networks

- bit stuffing uses
  - flag bytes 01111110
  - if five consecutive ones appear in the data a zero bit is stuffed
  - if the receiver encounters 111110 it de-stuffs the zero bit
  - the receiver can detect frame boundaries by scanning for flags