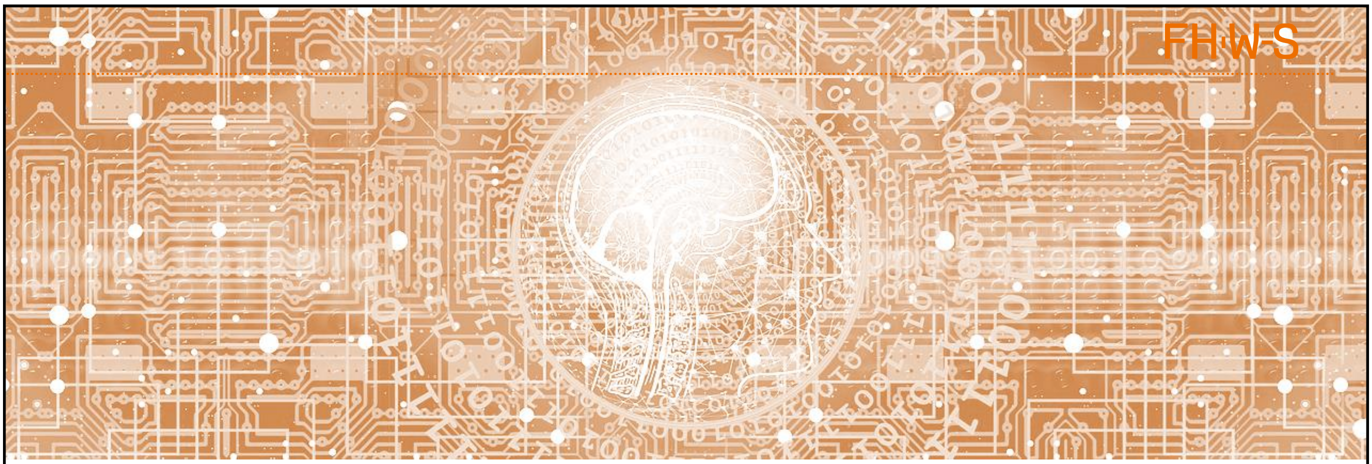

Embedded Systems and Field Buses

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Agenda

- Fundamentals
- Structure of Embedded Systems
- Behavior of Embedded Systems
- Design of Embedded Systems
- Communication
- Real-time
- Collaborative Embedded Systems

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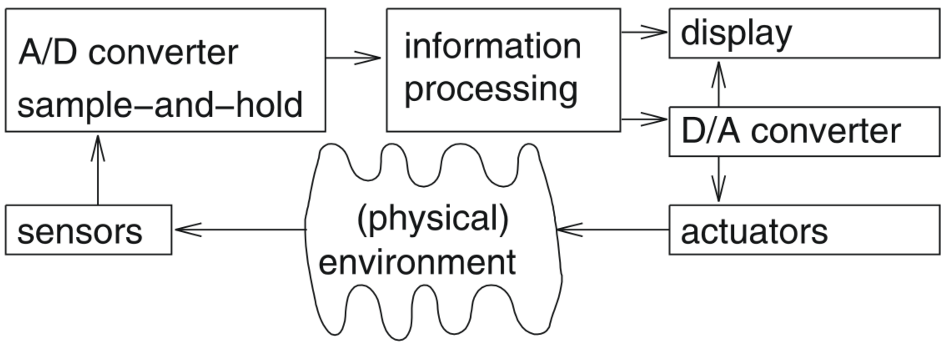
Communication

Foundations

Overview

An Embedded system consists of a variety of components



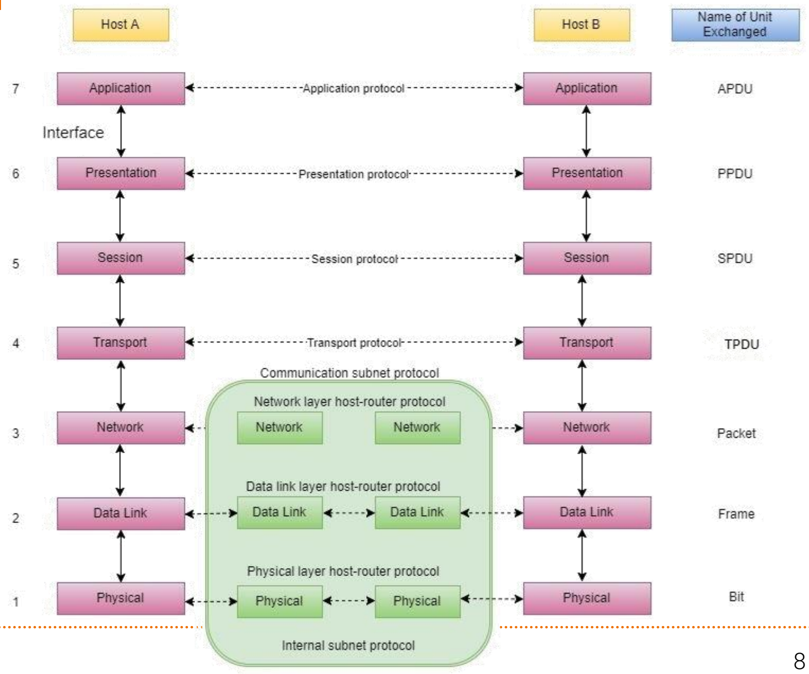
Communication in technical systems

	Phone	TV	LAN	Fieldbus
Participants	Mostly 2	many	many	Mostly less than 200
Spatial distribution	Global	global	global	From local up to a few km
Routing	Yes	No	Yes	No
Information flow direction	Bidirectional	Unidirectional	Bidirectional	Bidirectional
Transfer rate	Kbit/s	Gbit/s	Gbit/s	< 10MBit/s
Real-time	Yes	No	No	Yes
Information size	Very long	Very long	Very long	Very short
Messaging frequency	Varying	Varying	Varying	Constant
Configuration of the participants req.	No	No	No	Yes
Environment	Office	Office	Office	Industry

Group Discussion

What is important for Communication?

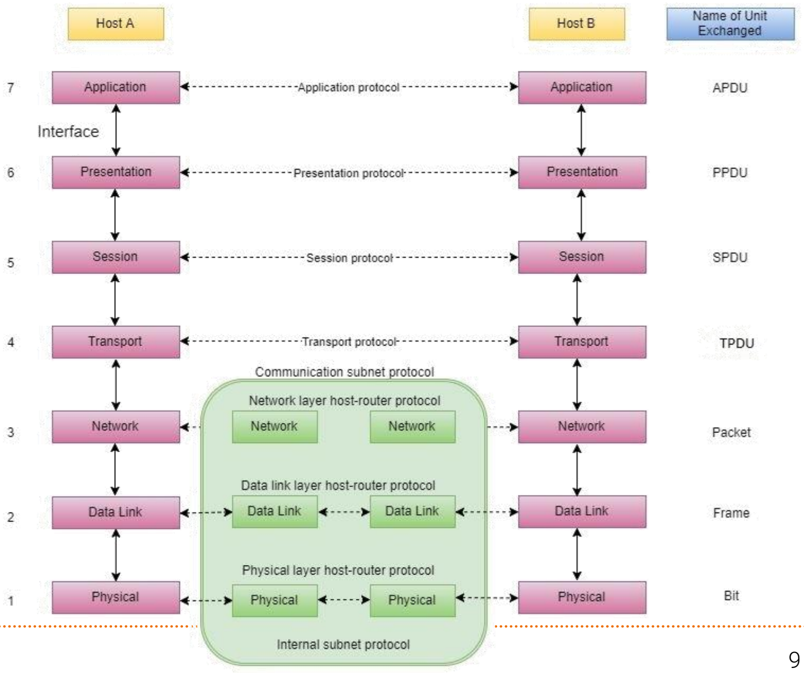
ISO/OSI Model



ISO/OSI Model

Application layer
- Specifies the shared communication protocol
- Example: HTTP
- only standardizes communication and depends upon the underlying layers to establish host-to-host data transfer channels and manage the data exchange

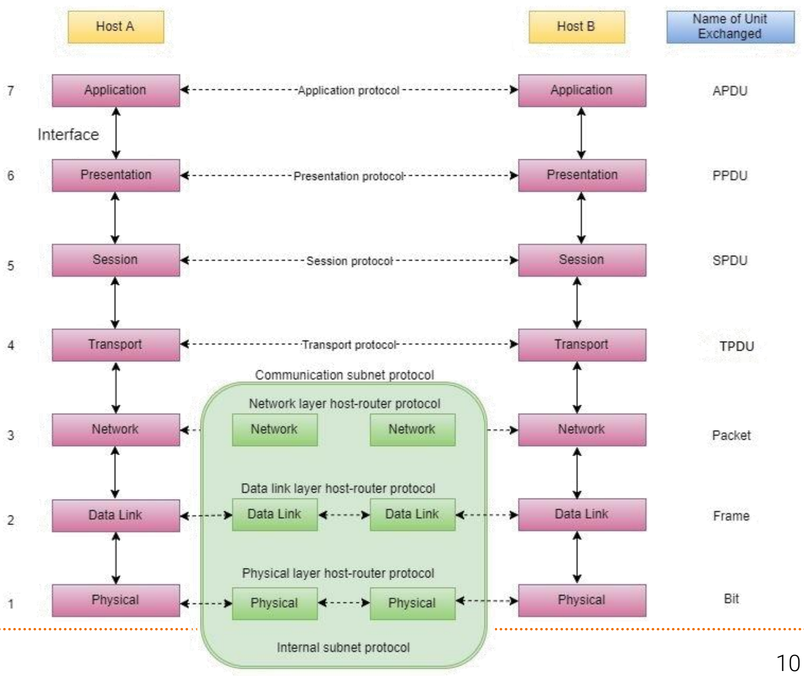
Presentation layer
- is responsible for the formatting and delivery of information to the application layer for further processing or display.
- It relieves the application layer of concern regarding syntactical differences in data representation within the end-user systems.



ISO/OSI Model

Session layer
- provides the mechanism for opening, closing and managing a session between end-user application processes

Transport layer
- services are conveyed to an application via a programming interface to the transport layer protocols such Services comprise e.g.
- Reliability (error detection, …)
- Flow control (avoid buffer overrun)



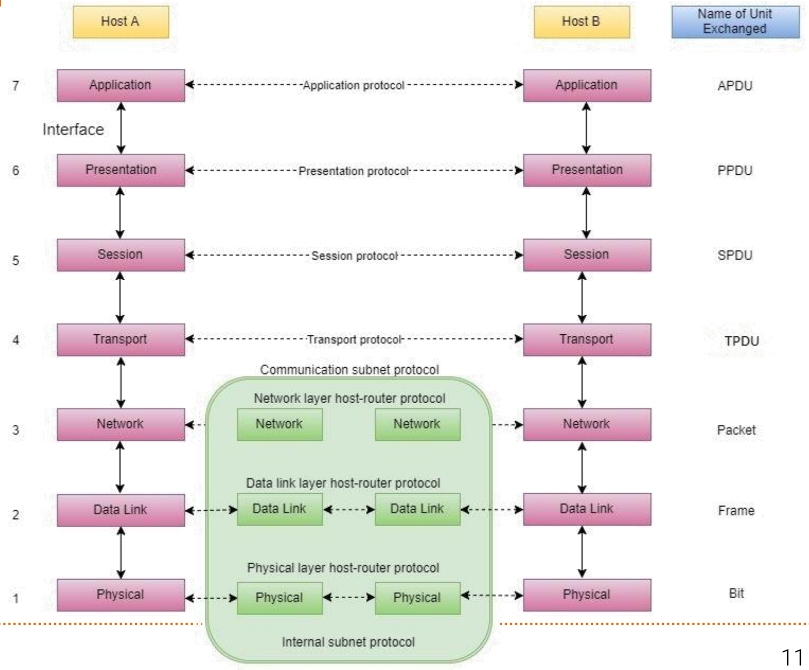
ISO/OSI Model

Network layer

- the network layer responds to service requests from the transport layer and issues service requests to the data link layer
- Functions include Host addressing (e.g. IP address)
- Message forwarding (gateways or routers to forward packets between networks)

Data link layer

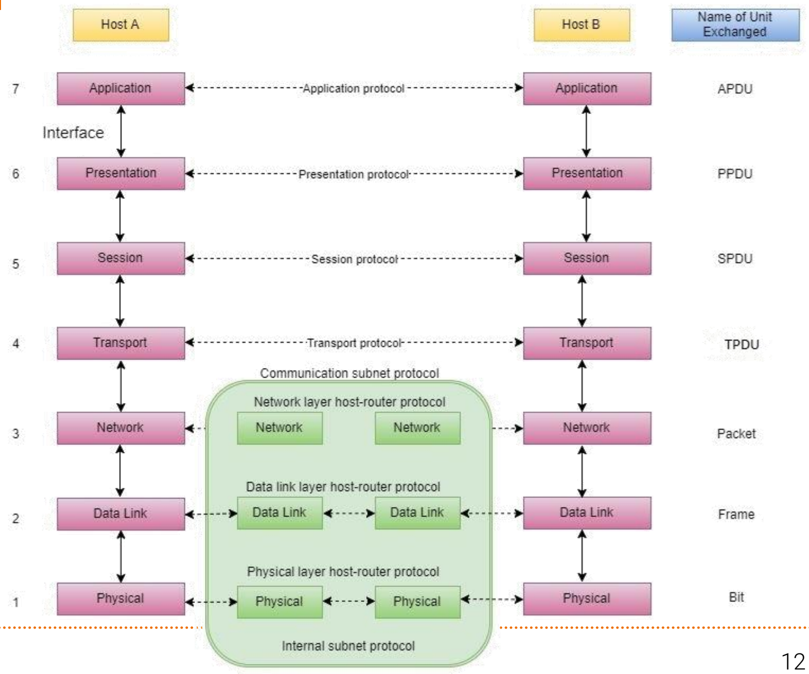
- protocol layer that transfers data between adjacent network nodes in a wide area network (WAN)
- or between nodes on the same local area network (LAN) segment.
- An examples of data link protocols is Ethernet for local area networks (multi-node)



ISO/OSI Model

Physical layer

- consists of the electronic circuit transmission technologies of a network
- is a fundamental layer underlying the higher level functions
- defines the means of transmitting raw bits



Physical Layer

Physical Layer

Sender

Channel

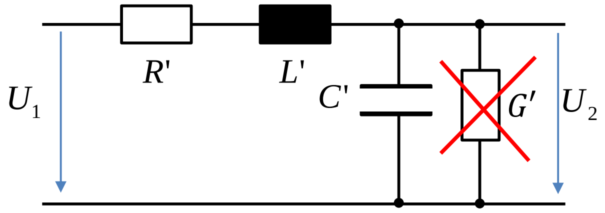
Receiver

Communication on physical layer might suffer from

- Signal attenuation due to the impedance of the cable
- Jitter due to clock that are not precise enough
- Delays due to limited signal velocity
- Noise due to non-ideal sender, receiver conditions
- Reflection

Signal attenuation

Signal attenuation due to the resistance of the cable

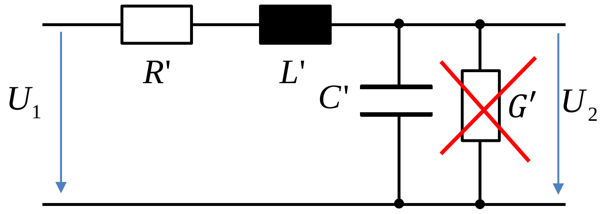


A two-wire cable can be modeled by a resistance, an inductance and a capacitance. The admittance *G´* is usually neglected.

The resistance induces an attenuation that is independent of frequency. The inductance and the capacitance entail an attenuation that is frequency dependent.

Signal attenuation

Signal attenuation due to the resistance of the cable



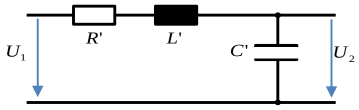
Example:

Typical values of Profibus PA

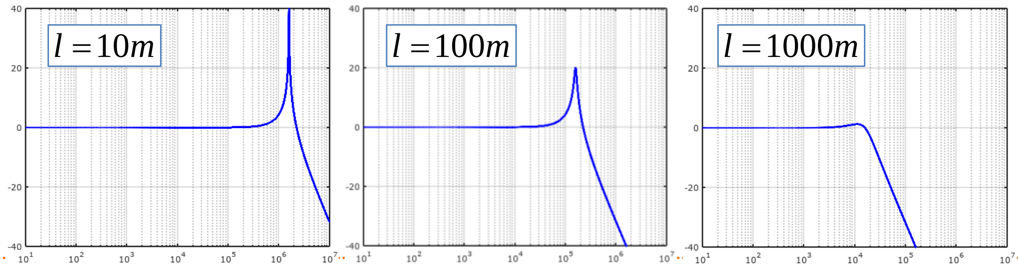
$$R' = 100\Omega / km$$
$$L' = 1mH / km$$
$$C' = 100nF / km$$

Signal attenuation

Analysis

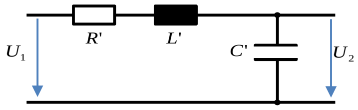


$$\frac{U_2}{U_1} = \frac{1/j\omega C}{R + j\omega L + 1/j\omega C}$$



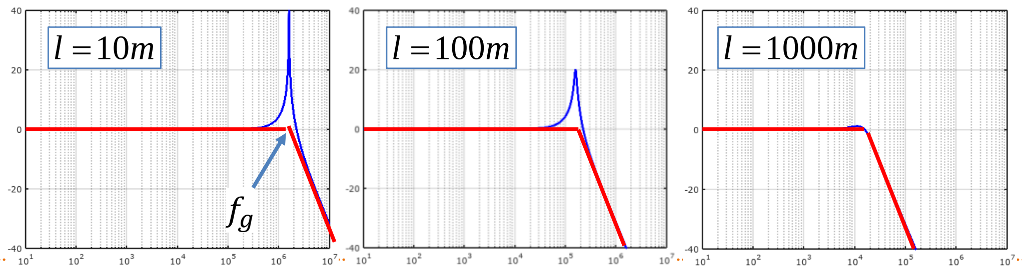
Signal attenuation

Analysis



A further common simplification is to consider the cable as a low-pass filter.

$$f_g = \frac{1}{2\pi RC} = \frac{1}{2\pi R'C'l^2}$$

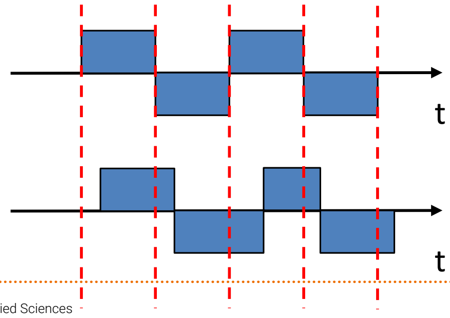


Jitter

Jitter is noise on the time axis.

Example: A sender is supposed to send a signal at a given time point. However, due to Jitter, the signal is delayed by 100 ms. Causes might be

- Limited performance of the sender
- Clock generators that aren't precise enough.



Bit sequence without Jitter

Delay

Delays due to limited signal velocity

In a cable, typical propagation velocities are 60 % to 70 % of the velocity of light. If line resistances can be neglected, the signal velocity can be calculated according to:

$$v = \frac{1}{\sqrt{L' \cdot C'}} = \frac{1}{\sqrt{50pF/m \cdot 500nH/m}} = 2 \cdot \frac{10^8 m}{s} = 0.67c$$

$$Z_L = \sqrt{\frac{L'}{C'}} \rightarrow L' = 500nH/m$$

Electrical characteristics for Cat 5e UTP

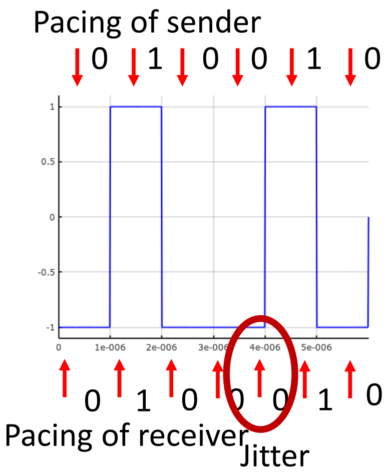
Property	Nominal	Tolerance	Unit	ref
Characteristic impedance, 1–100 MHz	100	± 15	Ω	[18]
Characteristic impedance @ 100 MHz	100	± 5	Ω	[18]
DC loop resistance	≤ 0.188		Ω/m	[18]
Propagation speed	0.64		c	[18]
Propagation delay	4.80–5.30		ns/m	[18]

Delay

When digital signals are transmitted, the start and the end of a bit must be available for each participant. Thereby, sampling issues can be mitigated.

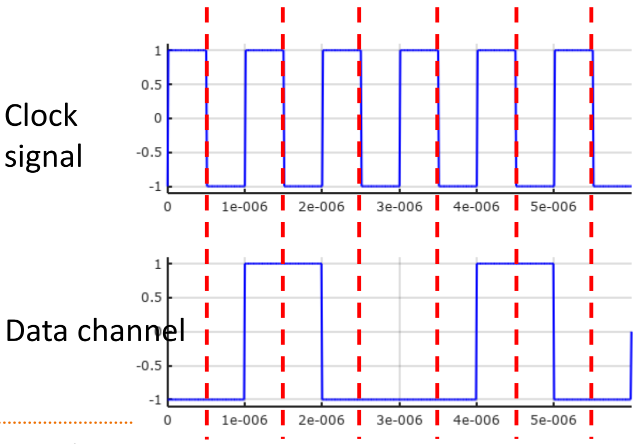
The delay of individual bits and the spatial distribution of the participants as well as different clocks can impair the synchronization.

It is distinguished between synchronous and asynchronous communication.



Synchronous transmission

A simple way to facilitate synchronous data transmission is to use a separate channel that determines the middle of a bit.

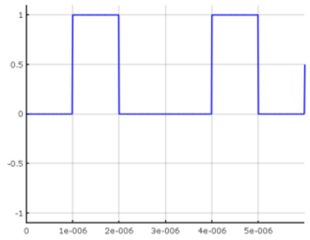


In this example, the falling edge determines the middle of a bit

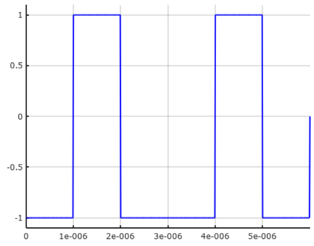
Synchronous transmission

In the non-return-zero-code (NRZ), the signal level is constant over a bit. A change in the signal level is used to indicate the start and the end of a bit.

NRZ - Unipolar



NRZ - Bipolar

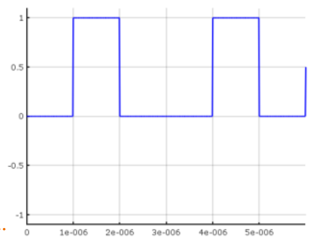


Synchronous transmission

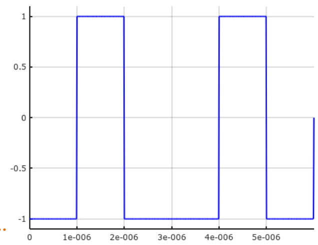
In the non-return-zero-code (NRZ), the signal level is constant over a bit. A change in the signal level is used to indicate the start and the end of a bit.

To overcome this drawback, a third state can be introduced. In half of a clock pulse, the signal returns to the rest position. Thereby, a detection of the pulse start and end is possible.

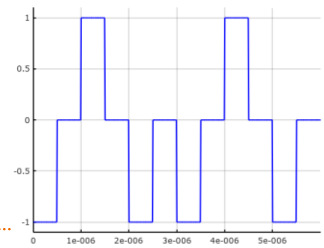
NRZ - Unipolar



NRZ - Bipolar



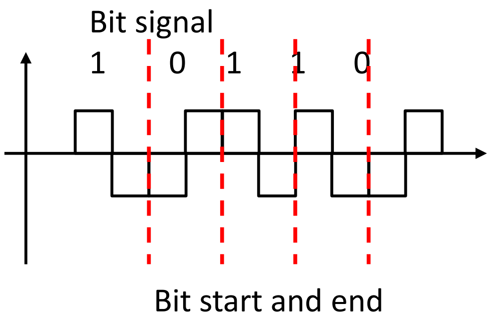
RZ



Synchronous transmission

With Manchester coding, similar to RZ coding, an edge is also guaranteed in each bit. Manchester coding is used, for example, for 10 Mbit Ethernet or Profibus PA.

One disadvantage of Manchester coding is that the sender and receiver must be able to send and receive bits at practically twice the data rate. This increases the hardware requirements and lowers the gross data rate.



Synchronous transmission

In networks with higher transfer rates, a different method is used to ensure a sufficient number of edges. A 4-bit-signal is converted to a 5-bit-signal (4B5B Coding).

Due to this mapping, there are always bit edges in any bit combination.

The bit rate increases due to coding. For example, in 100 Mbit Ethernet to a bit rate of 125 Mbit/s.

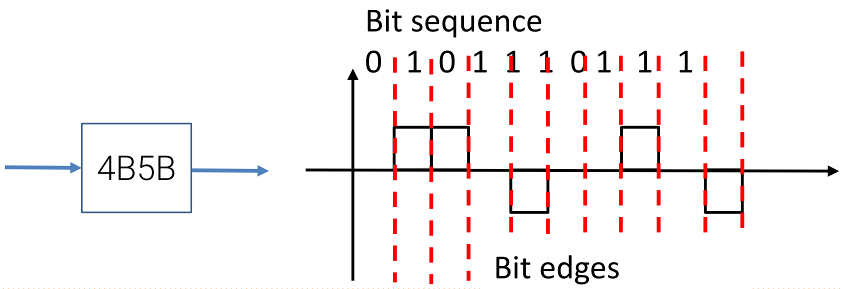
4 Bits input	5 Bits output	4 Bits input	5 Bits output
0000	11110	1000	10010
0001	01001	1001	10011
0010	10100	1010	10110
0011	10101	1011	10111
0100	01010	1100	11010
0101	01011	1101	11011
0110	01110	1110	11100
0111	01111	1111	11101

Synchronous transmission

Subsequently, the so–called multi-level transmission (MLT – Multi Level Transmission) is applied. This is based on three signal states: positive, neutral, and negative. Bits are encoded according to NRZ.

A logical "0" equals no signal change.

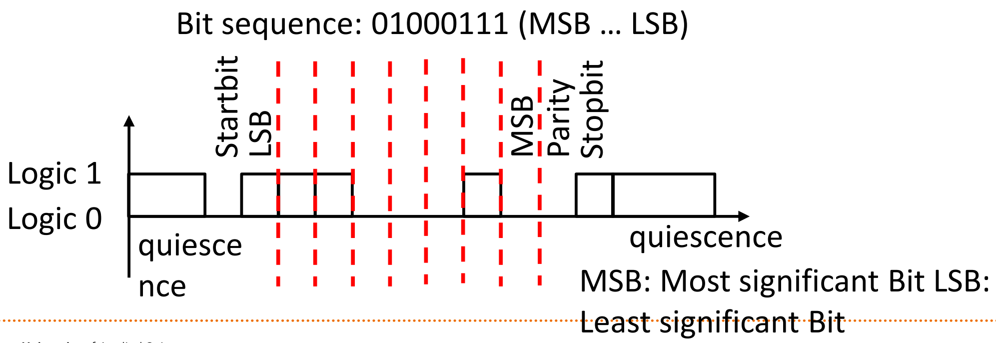
A logical "1" is represented by a periodic change: 0+0-



Asynchronous transmission

Asynchronous transmission

If signals are asynchronous, data sets must still be distinguishable. An example is the Universal Asynchronous Receiver and Transmitter (UART) method, e.g. UART used for the HART protocol. A Byte is encoded according to the following scheme:

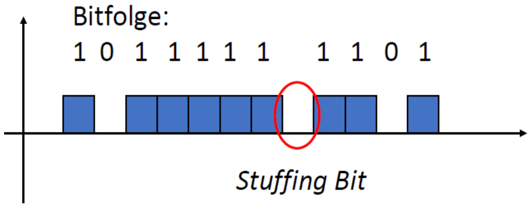


Asynchronous transmission

Bit stuffing

If you want to avoid coding with three levels you have to rely on falling or rising edges to detect bit boundaries. If several bits with identical levels appear, the synchronisation can be lost. For example, in the case of the CAN field bus, this is why after 5 identical bit levels on the line, a bit with an inverted level is inserted at the transmitter and removed again at the receiver.

A disadvantage of bit stuffing is the increase in the number of bits to be transmitted. An advantage is that a violation of the bit stuffing rule can be used for error detection.

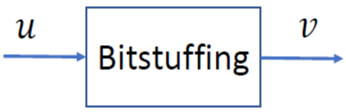


Asynchronous transmission

Bit stuffing

To ensure that there are never more than five identical levels on the line, the levels must be counted in v and not in u.

If this were not the case, error frames could not be detected unambiguously on the CAN bus.



$$u = 111110000011111$$

$$v = 11111000001011110$$

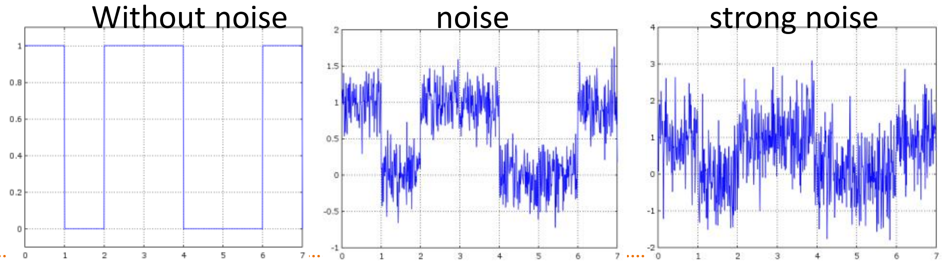
Group Discussion

What does asynchronous communication mean for the definition of an embedded system‘s behavior?

Noise

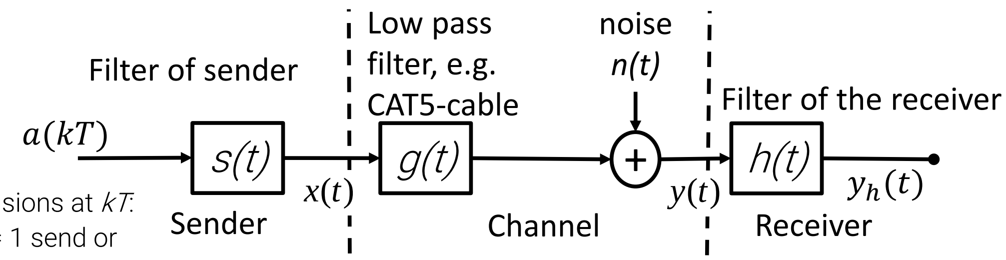
Noise due to non-ideal sender, receiver conditions

- Noise can have different origins such as electromagnetic parasitic signals, non-ideal sender or receiver, …
- Usually white noise is observed, which leads to bit errors.



Noise

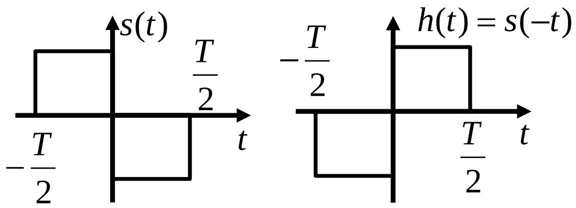
The receiver can filter the signal to reduce the noise. A very suitable filter is the MATCHED filter. Therefore, the signal is convoluted with the conjugated time-reversed of the signal.



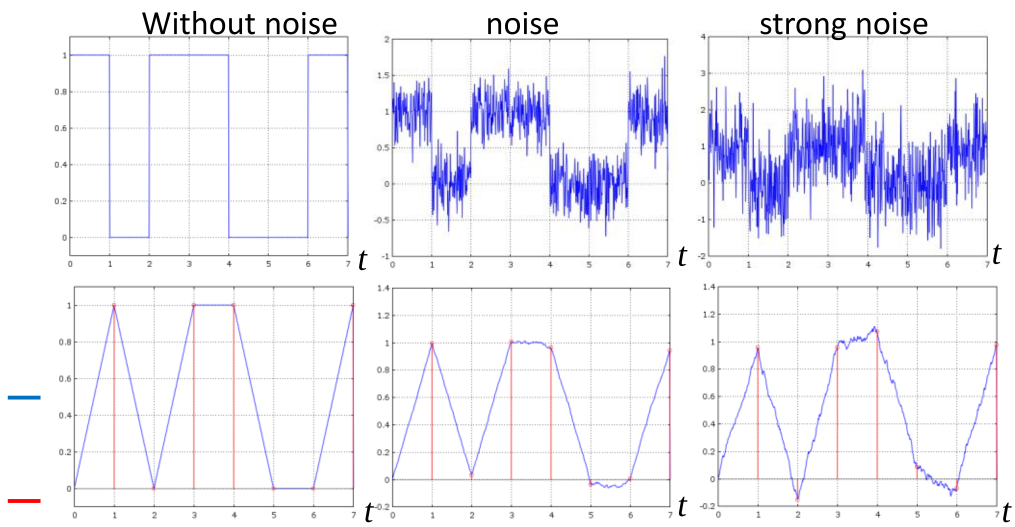
Decisions at kT:
Bit = 1 send or
Bit = 0 received

Noise

The receiver can filter the signal to reduce the noise. A very suitable filter is the matched filter. Therefore, the signal is convoluted with the conjugated time-reversed of the signal.

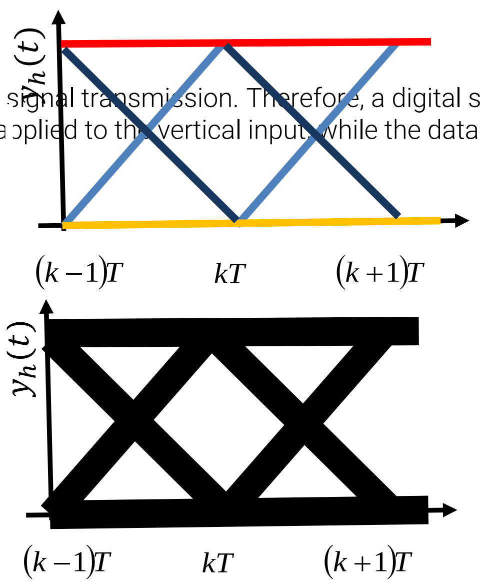


Noise



Noise

Eye pattern can be used to characterize the signal transmission. Therefore, a digital signal from a receiver is repetitively sampled and applied to the vertical input while the data rate is used to trigger the horizontal sweep.

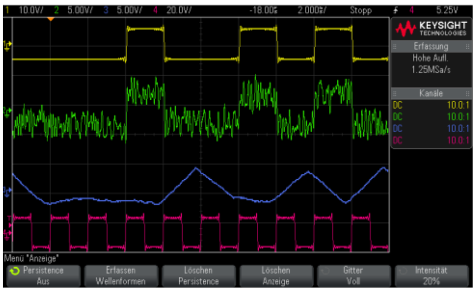


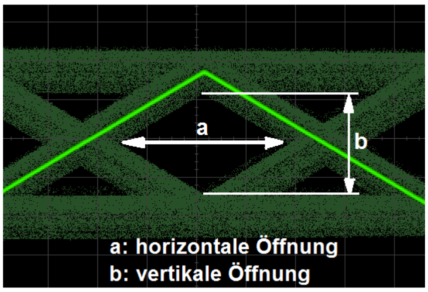
Source: Spiertz

Noise

Eye pattern reveal important characteristics:

The opening of the eye a provides information of the clock quality.
The height b asses the probability of false interpreted bits.
As long there is an opening, no bit errors can be assumed.





Reflection

The line impedance allows to characterize the cable. The line resistance depends on loop resistance, loop inductance, and isolator capacitance. For high frequencies, the impedance can be approximated by

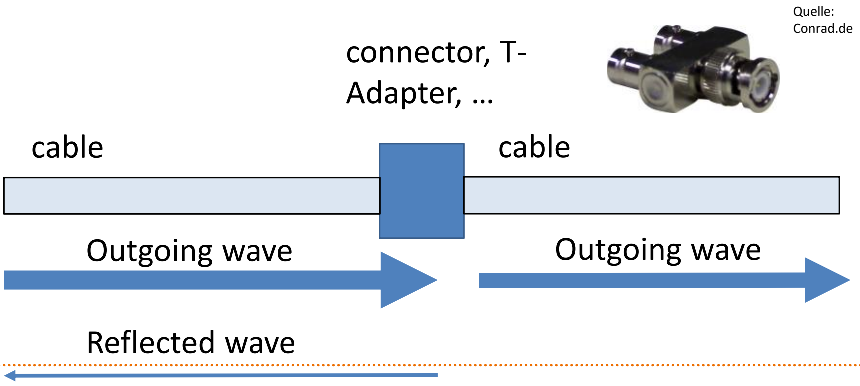
$$Z_L = \sqrt{\frac{R' + j\omega L'}{G' + j\omega C'}} \approx \sqrt{\frac{L'}{C'}}$$

Common values:

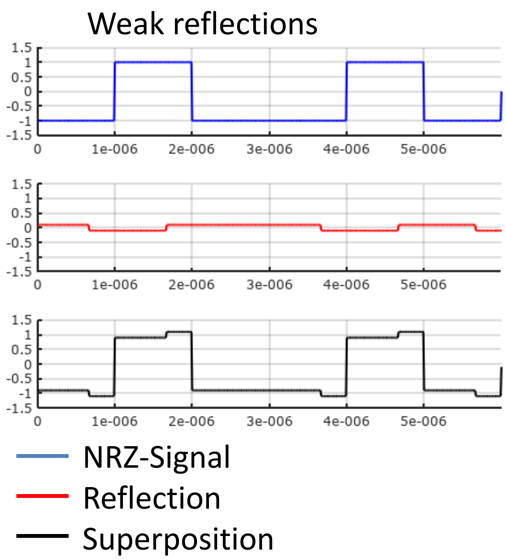
BNC-based networks	50 Ω
Coaxial cables	75 Ω
CAT5-cable	100 Ω
CAN-High	120 Ω

Reflection

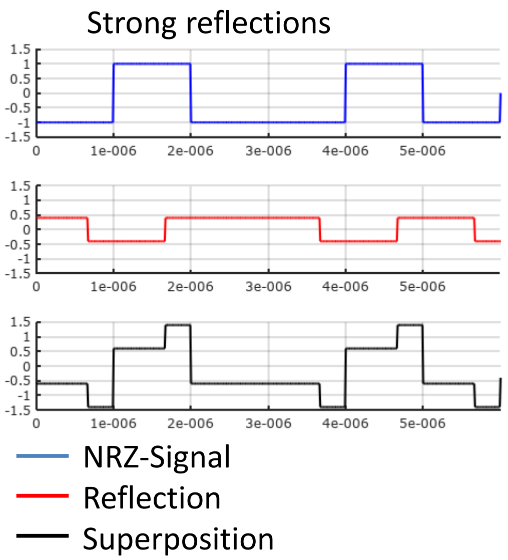
The transmission of a signal can be analyzed by outgoing and reflected waves. A change in diameter for example results in a reflection.



Reflections

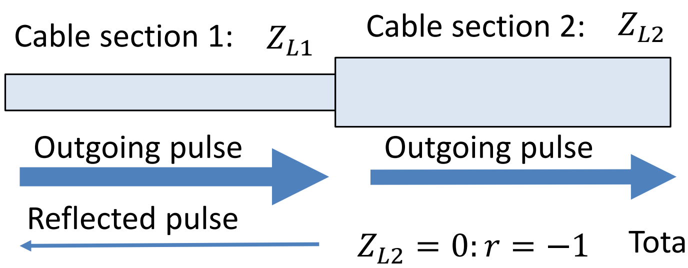


Reflections



Reflections

The reflections factor characterized the ration of outgoing and reflected signal and can be calculated from the line impedances.



$$r = \frac{Z_{L2} - Z_{L1}}{Z_{L2} + Z_{L1}}$$

$Z_{L2} = 0 : r = -1$ Total reflection at short

$Z_{L2} = Z_{L1} : r = 0$ No reflection due to compensation

$Z_{L2} \to \infty : r = 1$ Total reflection at open

Data Link Layer

Data Link Layer

Motivation

communication channels aren't ideal, bit failures are caused by noise

the second layer in the OSI model is the data link layer. This layer features functions to detect and correct errors.

If an error is detected:

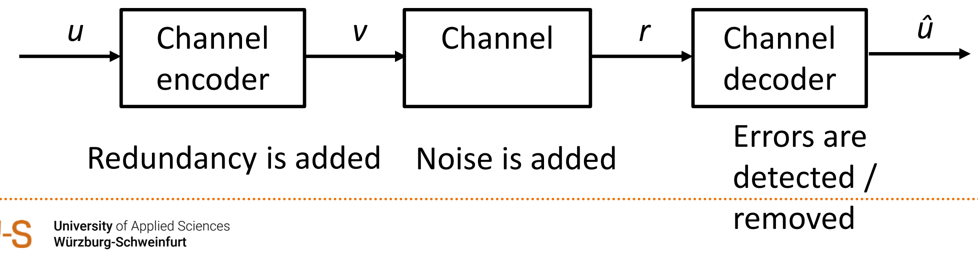
Send the data again– requires bidirectional communication

correct error – also possible for unidirectional communication

Channel coding:

Adding redundancy to message to enable error detection/correction

Encoding of the channel alters the data rate



Data Link Layer

Block codes

Instead of encoding single bits, bit packages are encoded

For a (n, k) block code, k user and n-k redundancy bits are combined

k data bits	*n-k* redundancy bits

The code rate R_C is the ratio of data bits and total bits

$$R_C = \frac{k}{n}; \quad and\ 0 \leq R_C \leq 1$$

Lower code rates facilitate improved error correction capabilities

Low code rates require increased effort for signal transmission

When the original string is part of the encoded word, the code is called systematic.

Data Link Layer

Fundamentals of coding theory

Encoding relies often on modulo 2 arithmetics

Binary addition is replaced by XOR operation, which results in a modulo 2 calculation

x_1	x_2	$y=x_1+x_2$
0	0	0
0	1	1
1	0	1
1	1	0

No calculation of carry bits required, speeds up the calculation

Data Link Layer

Fundamentals of coding theory

Binary multiplication is defined as a multiplication of polynomials

Binary addition uses modulo 2 arithmetics

$$v_1 = 1011$$
$$= x^3 + x + 1$$
$$v_2 = 101$$
$$= x^2 + 1$$

$$v_1 \cdot v_2 = (x^3 + x + 1) \cdot (x^2 + 1)$$
$$= x^5 + x^3 + x^2 + x^3 + x + 1$$
$$= x^5 + x^2 + x + 1$$
$$= 100111$$

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Data Link Layer

Hamming distance

The Hamming distance of two bit series is the number of different bits.

$$d = \sum_{i=1}^{n} (v_{1,i} + v_{2,i})$$

The minimal Hamming distance d_{min} is the smallest Hamming distance between all existing codewords.

$$x = d_{min} - 1; \quad y = \left(\frac{d_{min} - 1}{2}\right)$$

A correction algorithm can detect x bit errors and can correct y of them

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Data Link Layer

Hamming distance – Simple example
How can a shepherd count his sheep?
Counting the legs and divide by four.

Minimal distance between two data sets $d_{min} = 4$

Number of errors that can be detected $x = 3$

Number of errors that can be corrected $y = 1$

n = 16 → no error four sheep
n = 17 → one error; four sheep; error corrected
n = 18 → two errors; either four or five sheep, error not corrected

Data Link Layer

Hamming distance - Repetition code example
Hamming distance – repetition code

Each bit is repeated three times
Systematic code

data	code
0	000
1	111

The code rate is $R_c = 1/3$

The minimal distance is $d_{\min} = 3$

Number of errors that can be detected $x = d_{\min} - 1 = 2$

Number of errors that can be corrected $y = \left\lfloor \frac{d_{\min} - 1}{2} \right\rfloor = 1$

Data link layer

Hamming distance – Repetition code example

send	received	decoded		
000	000	000	No error	
000	010	000	Error detected	Error corrected
000	101	111	Error detected	Error can‘t be corrected
000	111	111	Error not detected	Error can‘t be corrected

Group Discussion

How can we detect all errors?
At what cost?

Inter and Intra System Communication

Directivity of communication

Simplex: Communication in one direction
Half duplex: Communication in both directions, but only one direction at a time
Full duplex: Simultanuous communication in both directions

Connecting networks

Repeater

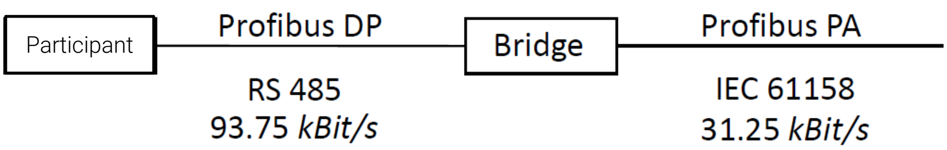
- Repeaters enable a larger number of fieldbus participants and/or a greater range of the bus.
- They receive the bits and retransmit identical bits (without attenuations, etc.).
- This introduces a certain delay which limits the number of repeaters.
- Since repeaters do not change the data, they are transparent for all other bus participants.

Wifi bridge

Connecting networks

Bridges

- Bridges connect similar fieldbuses with the same address space and telegram formats. However, the connected segments can differ in transmission medium, transmission speed and topology.
- An example from the consumer sector would be an access point (Wifi to LAN).



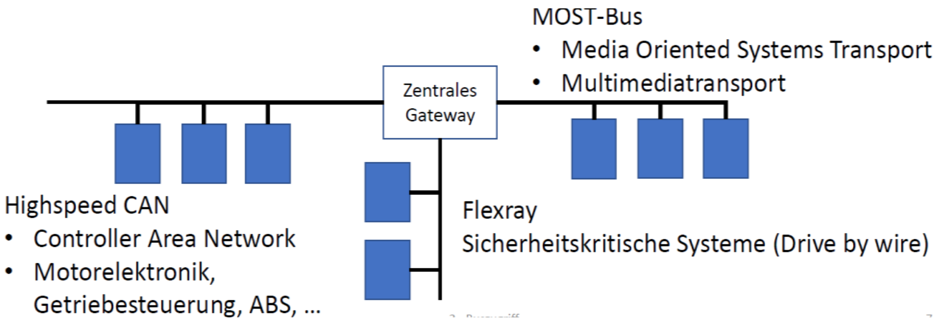
Connecting networks

Gateways

Gateways connect different fieldbuses (without the same address space).

An example of a gateway in the consumer sector is the modem, which maps LAN to WAN.

In the automotive sector, gateways are used to link field busses with clearly different areas of application in order to make information available across bus boundaries:



Bus topologies

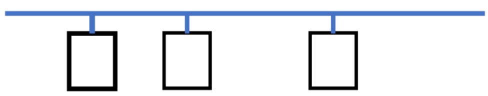
Line or bus topology

All participants are arranged in a fixed sequence. Connection of the participants via a spur line or looping through the bus line

Features:

- Multimaster capable
- Simple addition of subscribers
- Subscriber failure uncritical for bus traffic (when connected via a spur line)
- All participants listen in, this limits the number of participants for electrical reasons

Example: Highspeed CAN bus in automotive applications

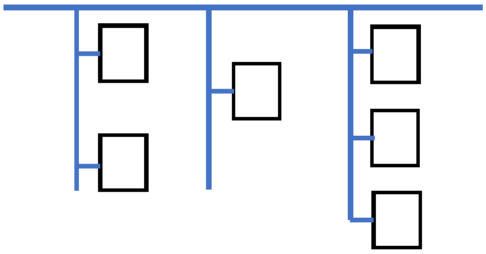


Bus topologies

Tree topology

Tree structures combine spatially connected structures into line structures. These are further combined in superordinate line structures.

The properties correspond to the line structure.



Bus topologies

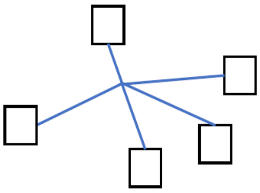
Star topology

Star structures are similar to line structures. In contrast to these, all connections are brought together in one point. This point can be a simple electrical connection or even an active component with buffers and routing, for example a switch.

Examples:

Lowspeed CAN

Fast Ethernet with a switch acting as central connection point



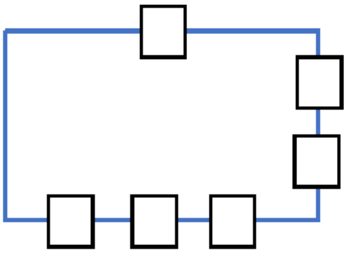
Bus topologies

Ring topology

With the ring structure, a participant failure interrupts the entire bus communication. The participants can refresh the signals and

thereby realise large distances. With the ring structure, adding participants is not trivial, as addressing is often done via the position in the ring.

Example: Ether CAT fieldb

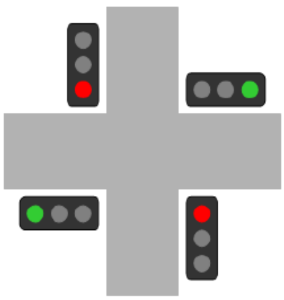


Bus access procedures

Bus access by allocation:

A participant has the right to access the bus. This usually happens cyclically.

This procedure includes master/slave, producer-consumer, token passing and TDMA. These procedures are basically deterministic (guaranteed message latency).



Bus access procedures

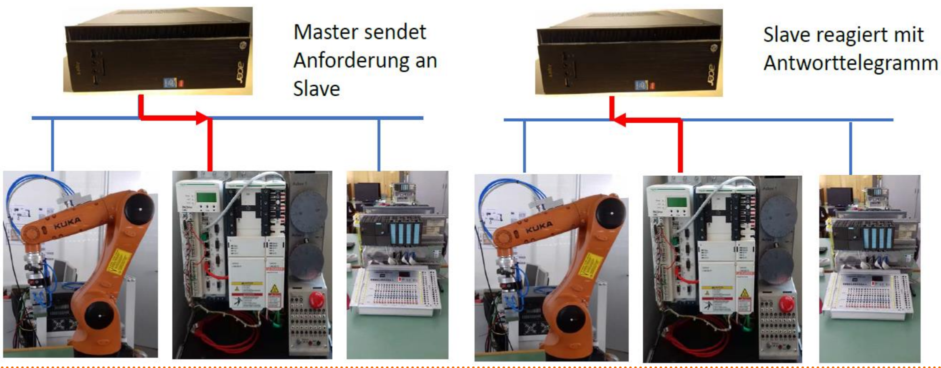
Bus access by demand

- Each participant has the right to access the bus. If several participants send at the same time, there is an access conflict that must be resolved in a suitable manner.
- The CSMA algorithms belong to this procedure. These procedures are fundamentally non-deterministic (non-guaranteed message latency).

Bus access procedures

Master / Slave:

- A central bus participant (master) requests another bus participant (slave) to send a certain data set or to perform a certain action.
- The slave only responds if it has been requested to do so by the master.



Bus access procedures

Benefits

- The coupling of the slaves is simple.
- There is participant monitoring.
- Communication is simple (question → answer).
- The time behaviour is deterministic and thus real-time capable.

Drawbacks

- If the master fails, the entire bus communication breaks down.
- There is no direct communication among the slaves. This must always be done via the master. This increases the overhead.
- In the event of an alarm, the slaves cannot independently notify other us participants but must wait for the master to call them.
- The cycle time increases with the number of slaves.

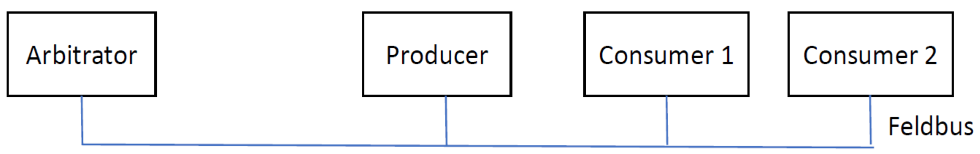
Example

- Profibus PA
- Ether CAT

Bus access procedures

Producer Consumer:

- The arbitrator stores the order of all transmissions in the scanning table. It sends a request, for example a temperature value, to the respective producer.
- The Producer recognizes the request and sends the requested value on the fieldbus.
- The consumers know which value is being sent based on the request. They decide for themselves whether this value is relevant to them.



Bus access procedures

Benefits

- Broadcast is possible, as each consumer decides for himself which values are relevant to him.
- Real-time capability is given.
- -Cyclic data transfers are reported to the arbitrator orange and the arbitrator controls the time allocation for this.

Drawbacks

- If the arbitrator fails, the entire bus fails.
- The cycle time increases with the number of producers.

Example

- Profinet IO

Bus access procedures

Token passing

The token corresponds to the send authorisation on the bus. It is passed on to another participant after the message has been sent. To prevent a total failure of the system due to the failure of a participant, the token is also passed on after a certain time has elapsed. Passing on via spatial neighbourhood, for example in a ring bus, is called token ring. Token forwarding via addresses is called a token bus.

Bus access procedures

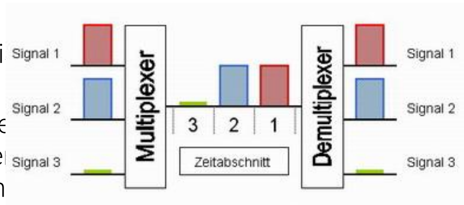
Benefits
- The participants monitor each other.
- The time behaviour is deterministic and thus real-time capable.

Drawbacks
- Time delay in the event of a token loss or an incorrect token duplication.
- Token administration and transfer is relatively time-consuming.

Example
- FoundationFieldbus
- Modbus

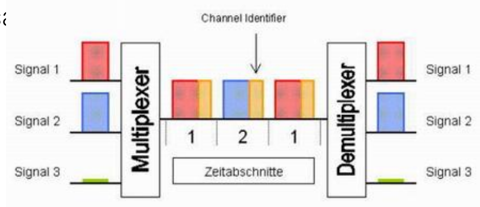
Bus access procedures

TDMA (Time Division Multiple Access): The data i he bus.



With synchronous TDMA, each participant receive no addresses are needed in the messages, as the se position. If there is no data to send, this causes in participant can send at this time.

With asynchronous TDMA, unused time slots are used by other bus participants. This makes more efficient use of the bus. However, the mess ain.



Bus access procedures

Benefits
- Each participant has a guaranteed transmission bandwidth and latency.
- Deterministic time behaviour (real-time capable).
- Simple protocol in the synchronous procedure.

Drawbacks
- All participants need a synchronous clock.
- Adding and removing participants is complicated

Example
- Interbus
- Sercos
- GSM (old mobile phone communication standard)

Bus access procedures

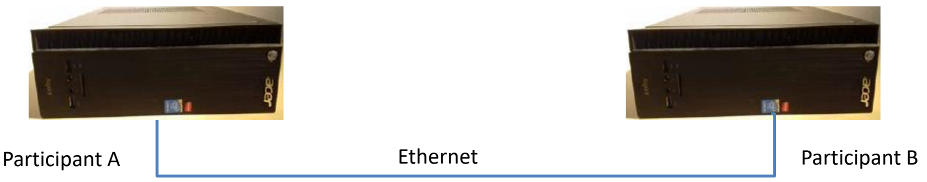
CSMA (Carrier Sense Multiple Access) describe bus access procedures, where all participants have equal rights and can transmit on the bus at any time. If two participants send simultaneously, the message is distorted by the collision on the bus.

With CSMA/CD (Carrier Sense Multiple Access / Collision Detection), the transmitter reads the bus signal.
- If it detects a collision, it immediately stops sending the message. After a transmitter-specific waiting time, the message is sent again, since the previously sent message was disturbed by the collision. CSMA/CD is not deterministic, as collision-free transmission can never be guaranteed.
- Example: 10 Mbit Ethernet in half duplex

Bus access procedures

Worst case scenario:

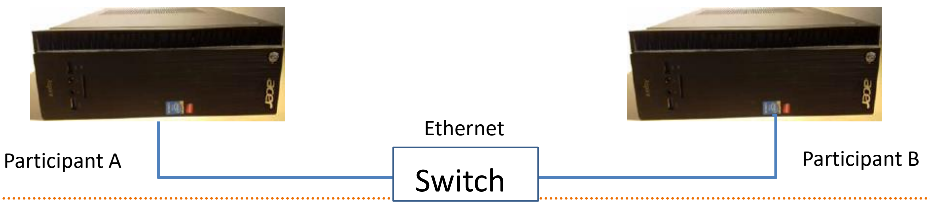
- Participant A sends an Ethernet telegram of minimum length.
- In the worst case, participant B begins to send its own telegram exactly when the telegram from A arrives at B.
- In order for participant A to notice this collision, the beginning of B's telegram, responsible for the collision must reach participant A before A has finished sending the message.
- This is why minimal telegrams are critical.
- The signal must therefore pass through the length l twice within one telegram period
- The time required for this is called round trip delay.



Bus access procedures

Fast Ethernet (100 Mbit) is the basis for all current fieldbus technologies that are based on Ethernet.

- Here, one pair of the four wire pairs is used for the transmitting direction and one pair for the receiving direction. This means that each cable between the switch and participant A/B is used in full duplex mode and collision detection can be avoided.



Bus access procedures

CSMA/CR (Carrier Sense Multiple Access / Collision Resolution):

- Each message has a specific priority. If several participants send simultaneously, the message with the highest priority prevails.
- For this purpose, it must be detected for each bit whether it is sent by another transmitter.
- With CSMA/CD, the interference only has to be detected for each telegram.

Benefits:

- Messages with the highest priority have the shortest waiting times.
- The data transmission is event-driven.
- In case of collisions, a message always gets through anyway.

Drawback

- Non-deterministic bus access for messages with low priority.

Example: CAN

Delays

Delays can cause problems in fieldbus systems: A system reacts with delay to an alarm, for example an increased temperature in a chemical process.

Delays are caused by

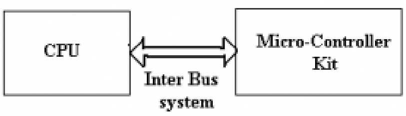
- the data link layer, as bits may only be used after the CRC has been received.

The bus access procedures:

- In the case of master/slave access, the query by the master alone causes a delay.
- With cyclic messages, the cycle time causes a delay.

Inter system protocols

The inter-system protocol using to communicate the two different devices. Like communication between computer to microcontroller kit



Main categories

- UART (Universal Asynchronous Receiver and Transmitter)
- USART (Universal Synchronous and Asynchronous Receiver and Transmitter)
- USB (Universal Serial Bus)

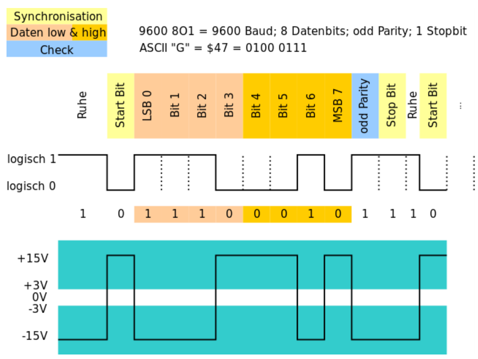
Inter system protocols

Universal Asynchronous Receiver Transmitter (UART)

- ART describes the arrangement of the bits during transmission
- Often referred to as serial interface

Working principle

- Data is transmitted in frames of 8 bits
- Parity bit enables verification of correct transmission



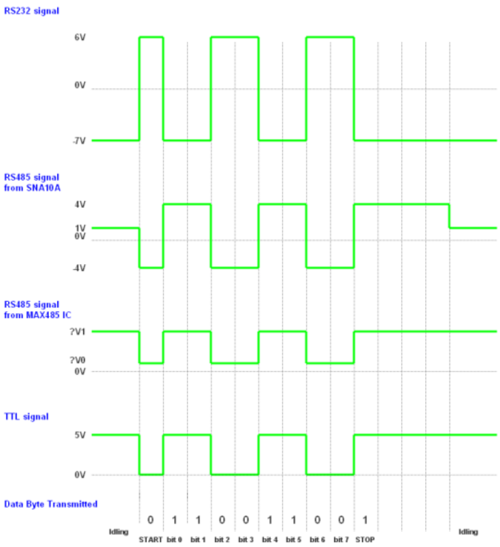
Inter system protocols

In microcontrollers the UART method is implemented with two lines for the transmission of data (level from 0V to 5V)

- RX for receiving data
- TX for sending data

The RS232 interface is well known. Here, however, the UART communication protocol is implemented with a level of -15V to 15V.

Inter system protocols



Inter system protocols

Universal Serial Bus (USB)

Serial communication of two-wire protocol. The data cable signal lines are labeled D+ and D-. Additionally, two cables for power supply.

This protocol is nowadays mainly used to communicate with the system peripherals.

Name	möglich ab	Brutto-Datenrate	Symbolrate Modulation[18][19]
Low Speed	USB 1.0	1,5 Mbit/s (187,5 kByte/s)	1,5 MBd NRZI-Code mit Bit-Stuffing
Full Speed	USB 1.0	12 Mbit/s (1,5 MByte/s)	12 MBd NRZI-Code mit Bit-Stuffing
Hi-Speed	USB 2.0	480 Mbit/s (60 MByte/s)	480 MBd NRZI-Code mit Bit-Stuffing
SuperSpeed	USB 3.0	4000 Mbit/s (500 MByte/s)	5000 MBd 8b10b-Code
SuperSpeed +	USB 3.1	9697 Mbit/s (1212 MByte/s)	10000 MBd 128b132b-Code

Inter system protocols

Universal Serial Bus (USB)

- The USB standard has some advantages:
  - High data rate can be achieved with comparatively little effort.
  - Automatic detection of peripherals during operation.

The USB standard is comparatively complex:

- A host controller (in the form of a chip) is required for communication.
- Dynamic addressing of connected devices.
- Tree structures with up to 127 devices on one host controller possible.

Inter system protocols

UART	USART	USB
The term UART stands for Universal Asynchronous Transmitter and Receiver	The term USART stands for Universal Synchronous and Asynchronous Data Transmitter and Receiver	The term USB stands for Universal Serial Bus
UART mainly includes two wire-based protocols like transmitter and receiver	USART is a two-wire protocol like Transmitter and Receiver	USB is a two-wire protocol like D+ & D-
It transmits as well as receives pockets of data by byte without classes pulse	It transmits and receives a block of data through classes pulses	It transmits and receives the data through clock pulses
UART is a half-duplex communication	USART is a full-duplex communication	USB is also full-duplex communication
UART is slow as compared to USART	USART is slow as compared to USB	It is fast as compared to USART and UART

Fieldbuses

Definition

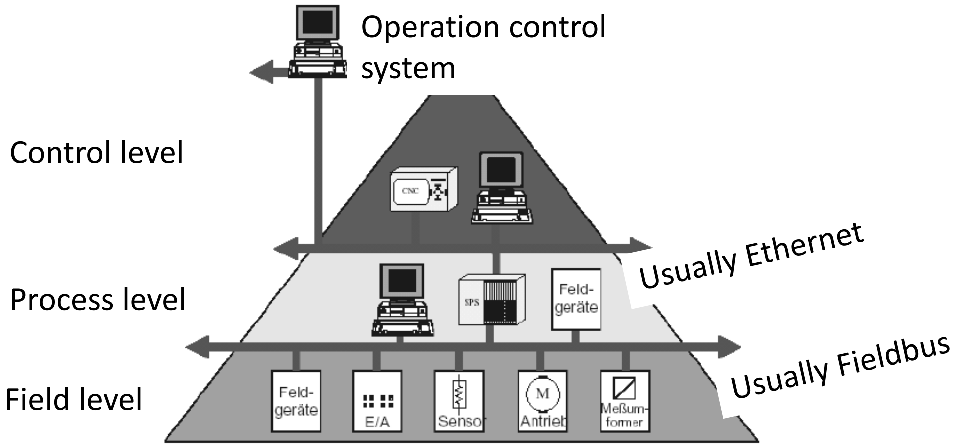
Different definitions of fieldbuses are used:
- Fieldbus describes a group of industrial computer protocols (for communication). It is used for real-time control.
- Fieldbuses are industrial networks which define the communication protocols and hardware interface.
- A fieldbus is a communication network usually based on the OSI seven-layer model, connecting field devices such as sensors, actuators, and field controllers such as PLC, drive controllers

Fieldbuses

Fieldbuses allow
- Reduction of weight
- Simple connection of components
- Maintenance via remote access

Fieldbuses are described in IEC 61156 “Digital Data Communication for Measurement and Control“
It contains ca. 20 different fieldbus systems with different parameters such as
- Data rate
- Latency
- Robustness

Fieldbuses

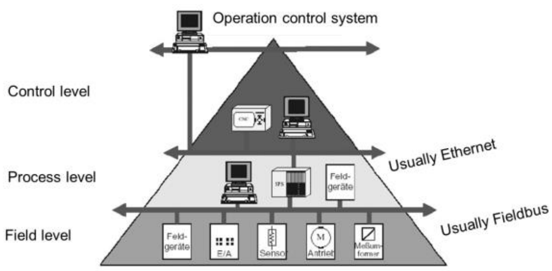


(Grafik: Prof. Dr. Form, TU Braunschweig)

Fieldbuses

Process level:
- Processing of data
  - Control of sub processes
  - Calculation of derived parameters
- Visualization
- Interface for operator

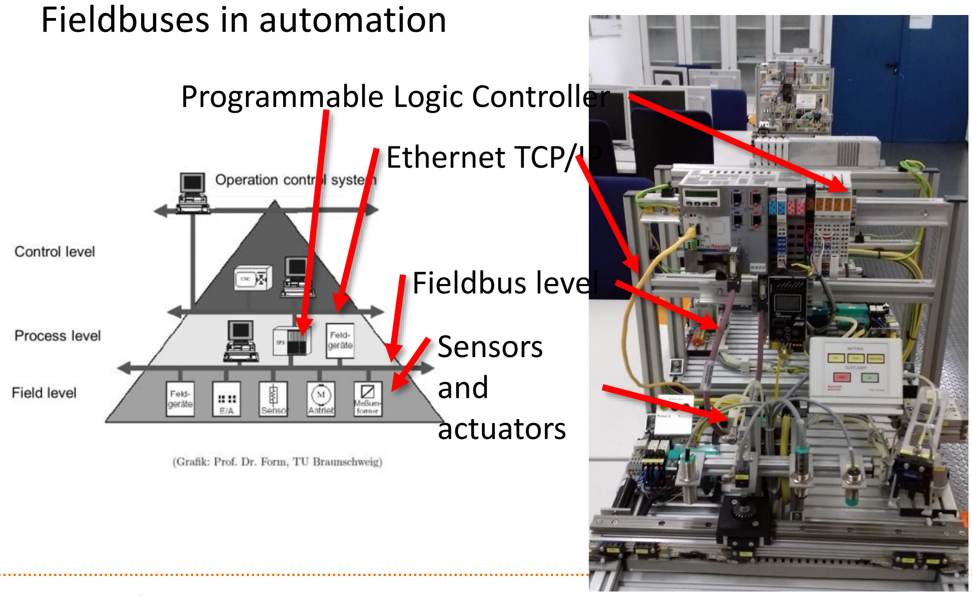
Field level
- Recording of sensor values
- Control of actuators
- Data exchange with Fieldbus
- Control of sub processes



(Grafik: Prof. Dr. Form, TU Braunschweig)

Fieldbuses

Fieldbuses in automation



(Grafik: Prof. Dr. Form, TU Braunschweig)

Fieldbuses

Some of the numerous fieldbus systems will be presented here.
The individual systems differ significantly in the following parameters:
- How many participants can be supplied with data?
- How much latency does the fieldbus system cause?
- What data volumes can be transmitted?
- Is the latency and the data rate predictable, is the fieldbus deterministic or not?

The bus systems presented and their areas of application are:
- CAN bus in the automobile
- Profibus DP and Profibus PA for process automation
- Profinet and EtherCAT as an Ethernet-based fieldbus for various areas of application

CAN Bus

The CAN bus was developed in the 1980s by Bosch and Intel for automotive industries. The aim was to reduce the weight of the cabling and to reduce maintenance costs of the electrical system.

- ISO 11898-1: Data Link Layer (data link layer)
- ISO 11898-2: Bit transmission layer for Highspeed (up to 1 MBit/s)
- ISO 11898-3: Data link layer for low speed (up tospeed (up to 125 kBit/s)
- ISO = International Organisation for Standardisation

CAN Bus

Characteristics

- Distribution: over one billion installed devices (as of 2008)
- Topology: Line
- Medium: twisted pair cable
- Transmission rate: 50 kBit/s at 1000 m line length, 1 MBit/s at 40 m length
- Transmission: Asynchronous with bit stuffing (bipolar, NRZ)
- Bus access: CSMA / CA

Number of participants:

- The maximum number of possible participants is limited by the driver components used. Common limits are 32, 64 or 110 participants. The limitation of the number of participants is due to the fact that the dominant bit must be realised as a voltage difference and the respective other participants count as consumers for this dominant bit.

CAN Bus

CAN high speed:

1 Mbit/s with a maximum cable length of 40 m. Used for large amounts of cyclic data, e.g. engine control unit.

CAN low speed:

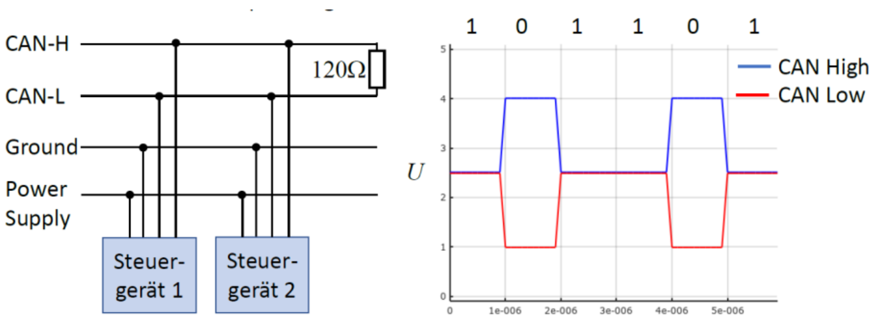
125 kbit/s with a maximum cable length of 500 m. Typically transports user inputs such as windscreen wipers, window regulators, and so on.

Gateways:

CAN buses and the other fieldbus systems (such as MOST, Flexray) are usually connected via gateways.

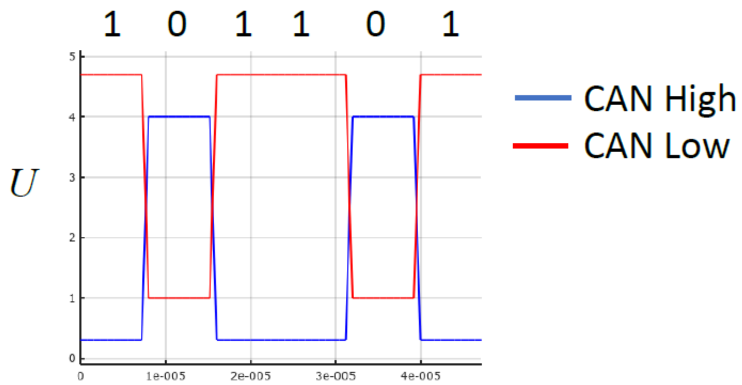
CAN Bus

The high speed version is a linear bus with 120 Ohm terminating resistor. The minimum voltage difference at the dominant level is 0.9 volts, the ideal voltage difference is 2.0 volts. The recessive bit has no voltage difference.



CAN Bus

The lowspeed version has a linear or star topology. Due to a possible star topology, the terminating resistors must be installed in the control units. The minimum voltage difference at the dominant level is 2.3 volts. The dominant bit has the smaller voltage difference.



CAN Bus

Bus access and identifier

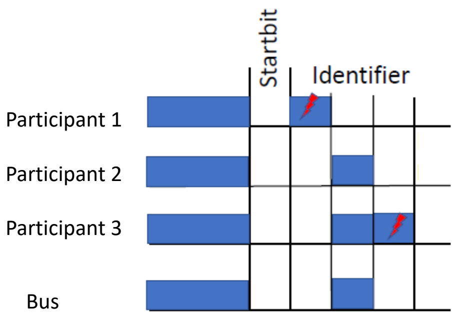
Identifiers determine the priority of a message. If a sender detects that it has sent a recessive bit, but that a dominant level is present on the bus, it stops sending because of the observed collision.

Example:

Logic 0 is the dominant level.

Assumption: three participants start transmitting at the same time.

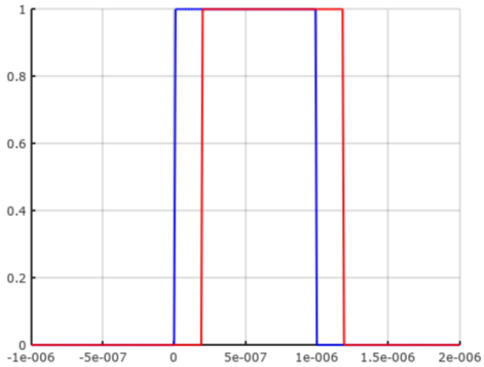
Participant 2 prevails with the highest priority (dominant identifier). All other participants wait for the bus to rest and then try to send again.



CAN Bus

Maximum cable length

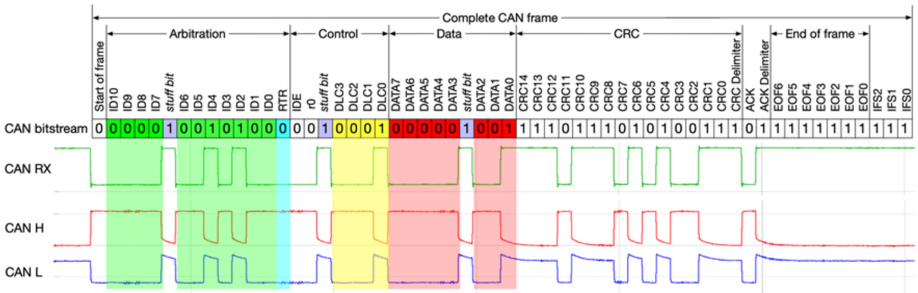
A two-wire line (twisted pair line) is usually used for CAN. Assuming a bit rate of 1 MBit/s, a line length of 40 m and a propagation speed of approx. 70% of the speed of light, there is already a visible delay of the individual bits. The bus access control via the identifier and the necessary processing time in the nodes processing time in the participants results in the limitation of the line lengths.



CAN Bus

CAN has four different telegrams

- Data Frame: Standard format for data transport
- Remote Frame: Request to send a specific data frame.
- Error Frame: Telegram can be sent by every bus participant that detects an error.
- Overload Frame: This telegram forces a pause on the bus.



Base frame format

Field name	Length (bits)	Purpose
Start-of-frame	1	Denotes the start of frame transmission
Identifier (green)	11	A (unique) identifier which also represents the message priority
Stuff bit	1	A bit of the opposite polarity to maintain synchronisation;
Remote transmission request (RTR) (blue)	1	Must be dominant (0) for data frames and recessive (1) for remote request frames (see Remote Frame, below)
Identifier extension bit (IDE)	1	Must be dominant (0) for base frame format with 11-bit identifiers
Reserved bit (r0)	1	Reserved bit. Must be dominant (0), but accepted as either dominant or recessive.
Data length code (DLC) (yellow)	4	Number of bytes of data (0–8 bytes)
Data field (red)	0–64 (0-8 bytes)	Data to be transmitted (length in bytes dictated by DLC field)
CRC	15	Cyclic redundancy check
CRC delimiter	1	Must be recessive (1)
ACK slot	1	Transmitter sends recessive (1) and any receiver can assert a dominant (0)
ACK delimiter	1	Must be recessive (1)
End-of-frame (EOF)	7	Must be recessive (1)
Inter-frame spacing (IFS)	3	Must be recessive (1)

Extended frame format

Field name	Length (bits)	Purpose
Start-of-frame	1	Denotes the start of frame transmission
Identifier A (green)	11	First part of the (unique) identifier which also represents the message priority
Substitute remote request (SRR)	1	Must be recessive (1)
Identifier extension bit (IDE)	1	Must be recessive (1) for extended frame format with 29-bit identifiers
Identifier B (green)	18	Second part of the (unique) identifier which also represents the message priority
Remote transmission request (RTR) (blue)	1	Must be dominant (0) for data frames and recessive (1) for remote request frames (see Remote Frame, below)
Reserved bits (r1, r0)	2	Reserved bits which must be set dominant (0), but accepted as either dominant or recessive
Data length code (DLC) (yellow)	4	Number of bytes of data (0–8 bytes)
Data field (red)	0–64 (0-8 bytes)	Data to be transmitted (length dictated by DLC field)
CRC	15	Cyclic redundancy check
CRC delimiter	1	Must be recessive (1)
ACK slot	1	Transmitter sends recessive (1) and any receiver can assert a dominant (0)
ACK delimiter	1	Must be recessive (1)
End-of-frame (EOF)	7	Must be recessive (1)

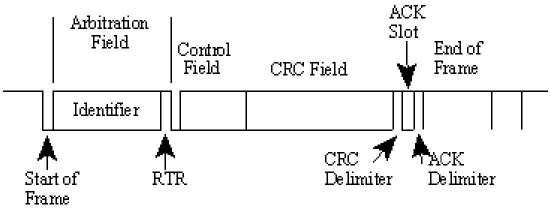
Remote frame

A message (data frame) can be queried by sending a remote frame.

The identifier is identical to the identifier of the queried data frame.

If the data frame and the corresponding remote frame are sent at the same time, the data frame wins because of the dominant RTR bit.

The remote frame has no data field, the data length code is identical to the corresponding data frame.



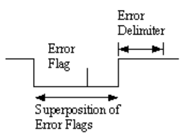
Error / Overload frame

If a participant detects an error, it sends an error frame.

This consists of 6 dominant bits in a row and thus violates the bit stuffing rule.

The 6 dominant bits in succession destroy the faulty message just sent.

All participants that detect an error frame discard the current message.



Participants send overload frames when their receive buffer is full and they can cannot receive any more messages.

Overload frames are identical to error frames (six dominant bits).

Error frames are sent directly when an error is detected, i.e. in the middle of another active frame.

Overload frames may only be sent during the "inter frame" time.

Each participant may only send two overload frames in succession in order not to occupy the bus for too long. bus for too long.

CAN Bus

Bit monitoring:
Each node monitors the level on the bus. If this deviates from the transmitted level after the identifier, a "bit error" has occurred.
Bit stuffing:
If the bit stuffing rule is violated, a “Stuff error" has occurred.
Frame check:
The CAN telegrams have certain fixed bits, for example CRC delimiters. If these fixed bits are violated, this is a "form error".
Acknowledgement:
Each participant that receives a message correctly sets the bit in the ACK slot to the dominant level. If the sender does not receive a dominant bit in the ACK slot, this is an "acknowledgement error".
CRC:
Any participant that performs an incorrect CRC sends a "CRC error".

CAN Bus

Bit stuffing
With CAN, an additional inverted bit is inserted after five identical bits at the transmitter. is inserted. The receiver removes these additional bits again independently. The following contents of a telegram are not subject to the stuffing rule.
- CRC Delimiter
- ACK Slot
- ACK Delimiter
- End of frame

Corresponding to the last 10 bits of the telegram

CAN Bus

A CRC check with 15 bits is used. The generator polynomial is

$$g = x^{15} + x^{14} + x^{10} + x^{8} + x^{7} + x^{4} + x^{3} + x^{0}$$

The minimum Hamming distance is 6. 5 random bit errors can be detected.

Max. telegram length (Base frame)	108 Bits	$R_c = \frac{108-15}{108} = 0{,}86$
Max. telegram length (Extended frame)	128 Bits	$R_c = \frac{128-15}{128} = 0{,}88$
Min. telegram length (Base frame)	44 Bits	$R_c = \frac{44-15}{44} = 0{,}66$
Min. telegram length (Extended frame)	64 Bits	$R_c = \frac{64-15}{64} = 0{,}77$

CAN Bus

If messages are sent at the same time, the message with the highest priority goes through. This results in a greater average delay of the messages in case of a high bus load. The unsent messages must be stored temporarily. The finite memory size can lead to data loss. A good rule of thumb says: The bus load should not exceed 80 % for CAN. This corresponds to at least 20 % bus quiescence.

Profibus

Profibus was developed in the 1980s by Siemens, Bosch and others. There are several versions for different areas of application

- Profibus - DP: (Decentralised periphery) Is used for fast data exchange at the field level. Its main area of application is in manufacturing technology and building automation.
- Profibus - PA: (Process Automation) is originally designed for use in explosion/hazardous areas, but nowadays often used.
- Profisafe: Main application in safety-critical areas because of additional measures for data protection.

The recommended plug connection for Profibus is a 9-pin D-Sub plug.

Profibus

Profibus DP characteristics:

- Distribution: approx. 25 million installed devices (as of 2008).
- Topology: Line
- Medium: twisted pair, optical fibre
- Transmission rate: 9.6 kBit/s at 1200 m, 12 Mbit/s at 100 m
- Transmission: asynchronous UART, even parity, bus silence logic 1 (bipolar, NRZ)
- Bus access: token passing between the masters, master-slave between the active master and the associated slaves
- Number of participants: < 127
- In the address byte, the addresses are coded from 1 to 126. 1 stands for the master class 1, 126 is the default setting.

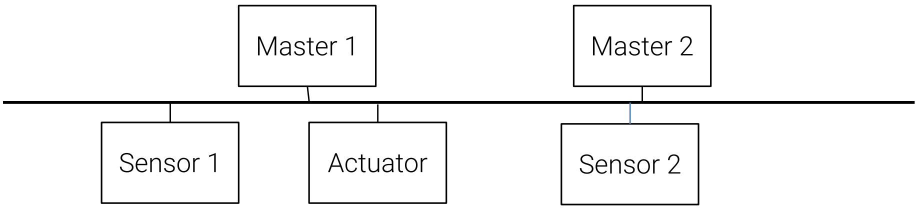
Profibus

Profibus DP – device classes:

The class 1 master is usually a PC or a PLC. It carries out the cyclic data traffic with its slaves via request and response telegrams.

The master class 2 is usually a PC. It carries out the acyclic data traffic with the slaves, for example to configure devices.

The slaves are all other participants in the bus traffic, including sensors, actuators, operating devices, etc.



Profibus

Profibus DP – message cycle

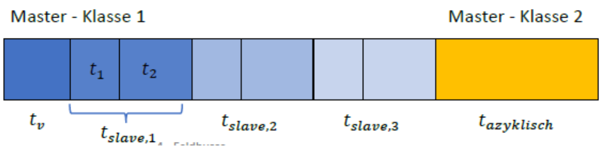
The duration of a complete message cycle is:

$$t_{cycle} = t_v + t_{acyclic} + \sum_{n=1}^{N} t_{slave,n}$$

t_v is the administration time of the class 1 master for token administration and searching for new participants.

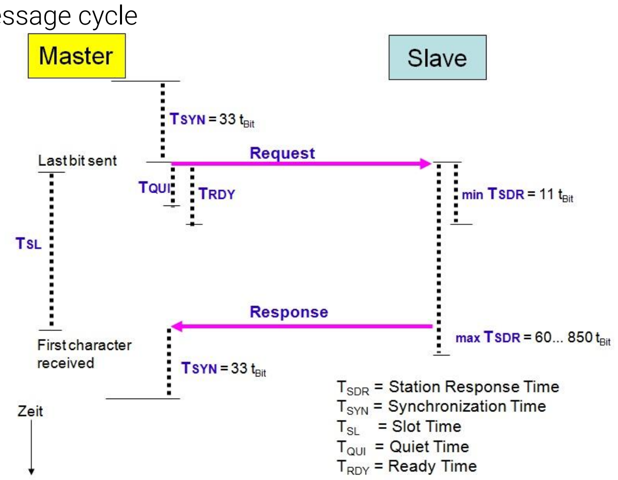
$t_{acyclic}$ is the administration time of the class 2 master for device configuration.

$t_{slave,n}$ is the time required for request telegram t_1 and response telegram t_2 between the class 1 master and the corresponding slave.



Profibus

Profibus DP – message cycle



Profibus

Profibus DP – message cycle

The time that must be spent by the master for communication with a slave can be estimated as follows:

$$T_{slave,n} \approx T_{syn} + T_{SDR} + 11 \cdot (request\ telegram\ in\ Bytes) + 11 \cdot (response\ telegram\ in\ Bytes)$$

$$t_{slave,n} = \frac{T_{slave,n}}{r}$$

T_{syn} designates the 33 bit synchronization pause

T_{SDR} is the time the slave has to wait until he responds, at least 11 bits (SDR = Station Delay of Responder)

r is the bit rate of the bus, e.g. 9600 Bits/s for a maximum cable length of 1200 m

Profibus

Available telegram formats

- Telegrams without data field
- Telegram with variable length of 4 to 249 bytes and therefore a payload in the range 1 to 246 bytes
- Telegram with fixed data length of 8 bytes data
- Token telegram
- Short Confirmation for positive responses.

Telegram without data field:

SD1	DA	SA	FC	FCS	ED

Telegram with variable length:

SD2	LE	LEr	SD2	DA	SA	FC	PDU	FCS	ED

The PDU has a variable length between 1 and 246 bytes.

Telegram with fixed data length:

SD3	DA	SA	FC	PDU	FCS	ED

The PDU has a fixed length of 8 bytes.

Token telegram:

SD4	DA	SA

Short confirmation:

SC

Profibus

Example: Token Telegram

- SD4 (Start Delimiter) to identify telegram format
- DA is the destination address (1 Byte)
- SA is the source address (1 Byte)

Example: Telegram with fixed data length (e.g. for sensor response)

- FC Function Code, determining telegram type
- PDU Protocol Data Unit
- FCS Frame Checking Sequence
- ED End Delimiter

Token telegram:

SD4	DA	SA

SD1	SD2	SD3	SD4	ED	SC
0x10	0x68	0xA2	0xDC	0x16	0xE5

Telegram with fixed data length:

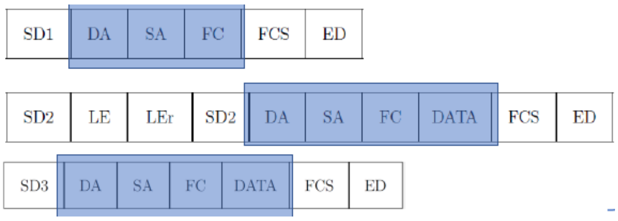
SD3	DA	SA	FC	PDU	FCS	ED

The PDU has a fixed length of 8 bytes.

Profibus

Frame Checking Sequence

- Profibus DP is using a FCS instead of a CRC.
- All bytes of the telegram are added up in the frame check sequence, carry bits are ignored. The addition starts at the destination address. The Hamming distance is given as 4 in the literature.



Profibus

Profibus DP - General Station Description (GSD)

- Every class 1 master and all field devices with slave functionality that conform to the standard must be described by the manufactu
- The GSD file is a master file containing device
- Text file using ASCII encoding

```
;======================================
; file name: EH_1510.gsd
; project: Prowirl 77 Profibus PA
; author(s): xxxxxxxxx
;======================================
#Profibus_DP
GSD_Revision        = 2
Vendor_Name         "Endress+Hauser Flowtec AG"
Model_Name          = "Prowirl 77"
Revision            = "1.00.0x"
Ident_Number        = 0x1510 ;Number in Hex!
Protocol_Ident    = 0      0 = Profibus DP
Station_Type      = 0      0 = DP-Slave
;
93.75_supp        = 1      unterstütze Übertragungsrate
MaxTsdr_93.75     = 1000   Wartezeit, die Slave maximal benötigt, um auf ein An-
                           forderungstelegramm zu antworten (in Bitzeit)
```

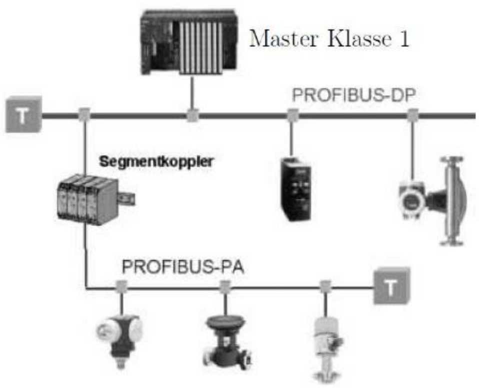
Profibus

Profibus PA
- The Profibus PA was specified in 1995.
- Intrinsic safety (can also be used in explosive atmospheres)
- Power supply of the field devices via the bus cable,
- Interoperability (standardisation of the device functions).

Since the field devices do not need any power supply other than the bus cable, the Profibus PA is used in many different applications
- Topology: line, star
- Medium: twisted pair
- Transmission rate: 31.25 kBit/s only
- Transmission: synchronous (Manchester-coded, logical 0 = falling edge in the middle of the bit)
- Bus access: master / slave
- Error protection: CRC with 16 bits
- Number of participants: maximum 32

Profibus

The Profibus - PA cannot be operated standalone, but requires a connection to the Profibus DP via a segment coupler (bridge). This fulfils the fo
- Power supply of the PA participants,
- Galvanic isolation
- Rate adaptation
- Telegram conversion



Thanks

This Lecture Material is based on Lecture Material provided by
Prof. Dr. Martin Spiertz and Prof. Dr. Marco Schmidt