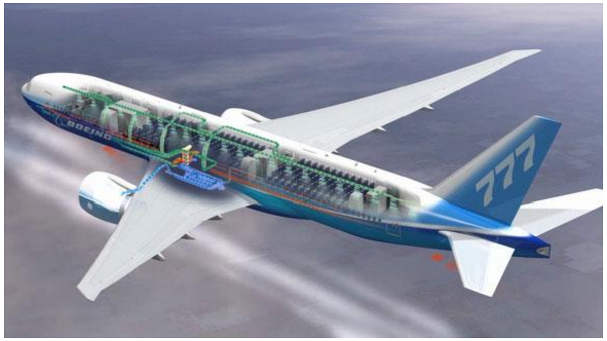
Real-Time Systems

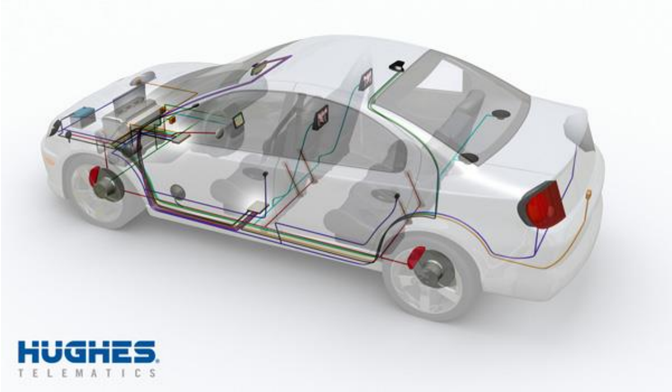
Communication

Content

Requirements

- In comparison to standard-systems, realtime systems have different requirements for the communication:
  - Deterministic latencies
  - Small jitter
  - Guaranteed bandwidth
  - Efficient protocols, short latencies
  - Fault tolerance
- Criteria for the selection of a communication protocol:
  - Maximum bandwidth
  - Maximum network size (number of nodes, length of physical connections)
  - Costs, availability of components





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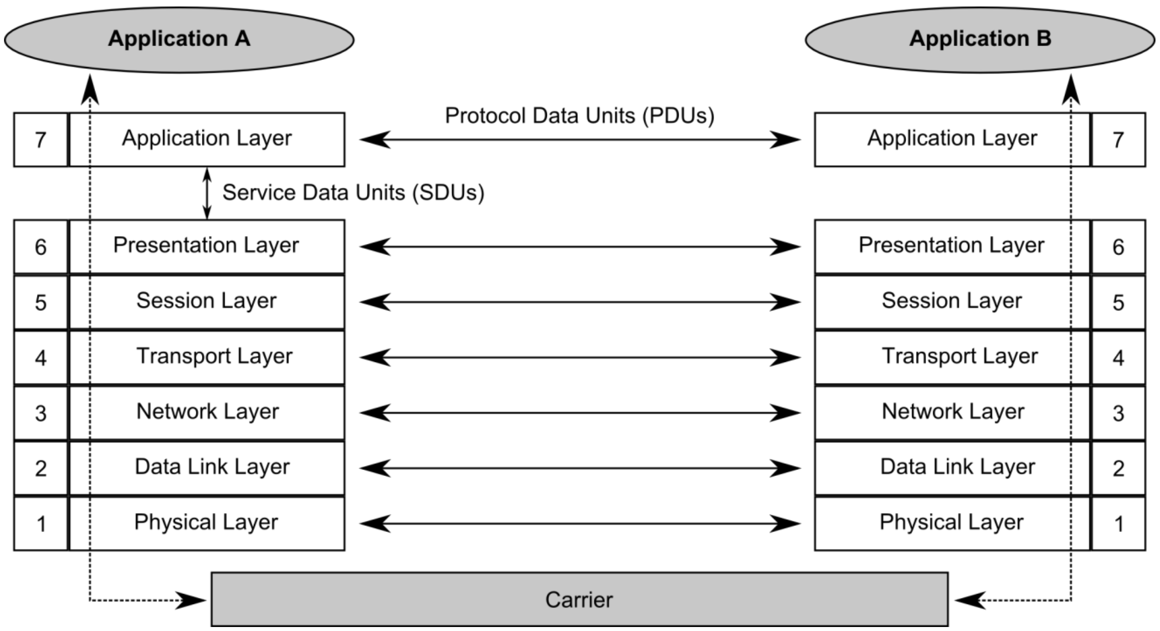
1. Requirements
2. OSI Model
3. Network Topologies
4. Media Access Control Methods
5. Communication Protocols
   a. SPI
   b. CAN
   c. Real-time Ethernet

Open Systems Interconnection (OSI) Model

- OSI is a 7-layer abstraction model for standardizing the functions of communication systems
- Standardized by the International Organization for Standardization (ISO): ISO/IEC 7498-1
- OSI Layers exchange Service Data Units (SDUs)
- Peers exchange Protocol Data Units (PDUs)



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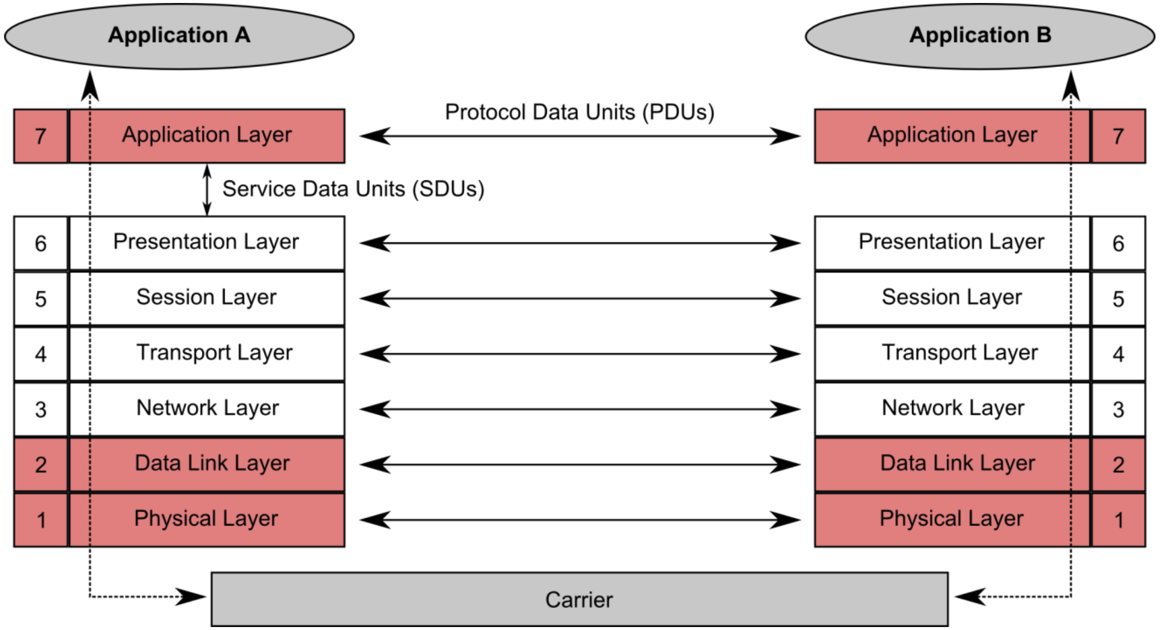
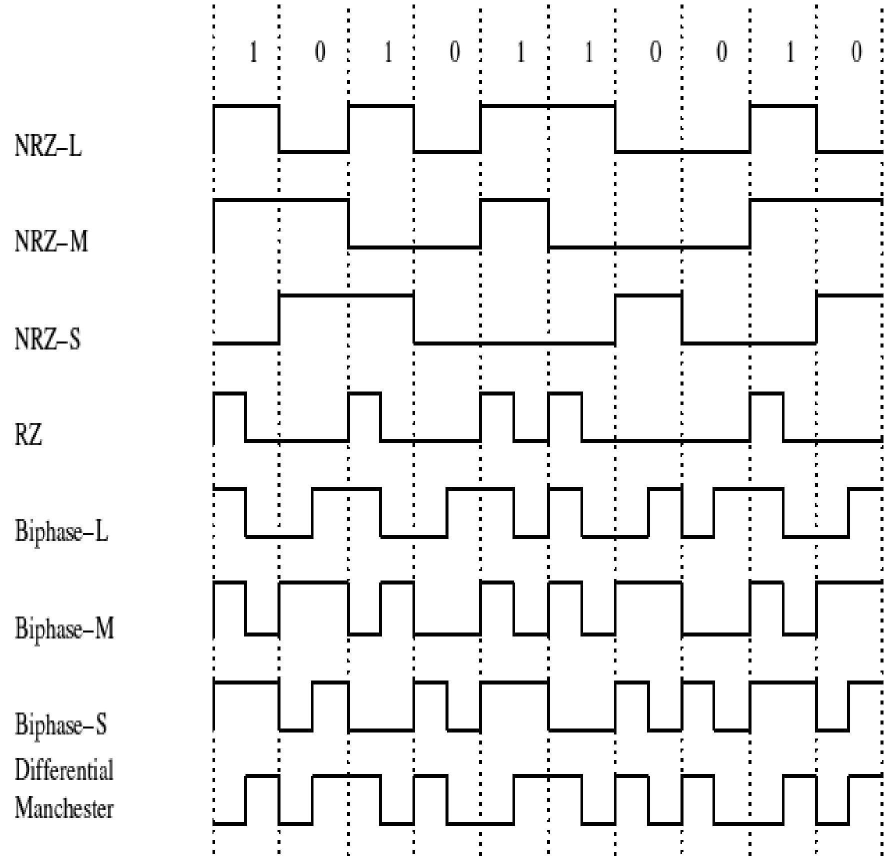
- In real-time systems typically only ***three*** layers are implemented



OSI Model: Physical Layer

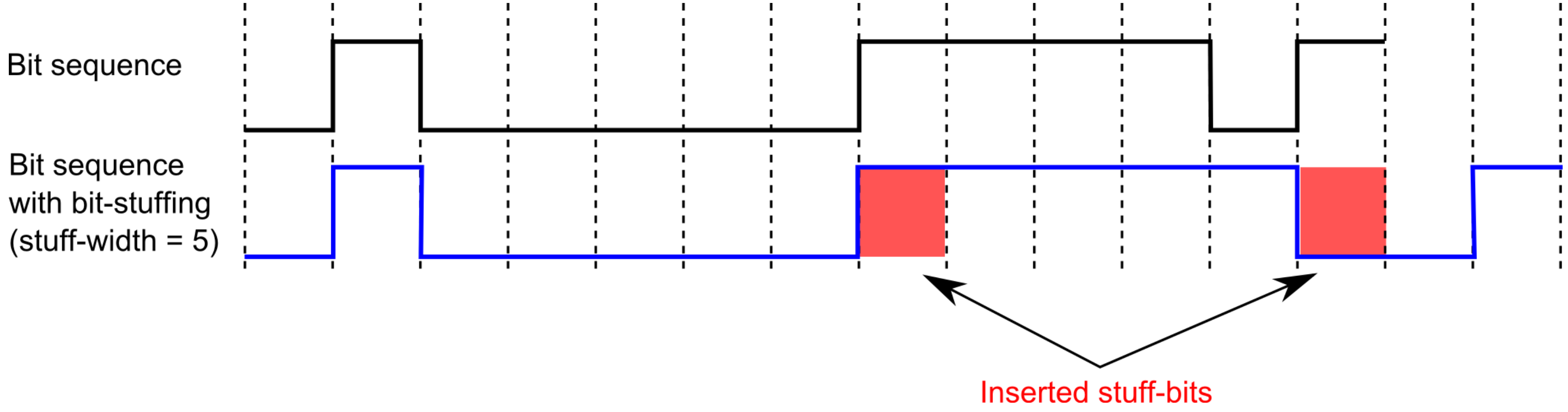
- Conveys the bit stream (e.g. electrical impulse, light or radio signal)
- Defines electrical, mechanical, functional and procedural properties of physical connection (e.g. plugs and cables)
- Defines encoding

Signal	Comments
NRZ–L	Non-return to zero level. This is the standard positive logic signal format used in digital circuits. 1 forces a high level 0 forces a low level
NRZ–M	Non return to zero mark 1 forces a transition 0 does nothing
NRZ–S	Non return to zero space 1 does nothing 0 forces a transition
RZ	Return to zero 1 goes high for half the bit period 0 does nothing
Biphase–L	Manchester. Two consecutive bits of the same type force a transition at the beginning of a bit period. 1 forces a negative transition in the middle of the bit 0 forces a positive transition in the middle of the bit
Biphase–M	There is always a transition at the beginning of a bit period. 1 forces a transition in the middle of the bit 0 does nothing
Biphase–S	There is always a transition at the beginning of a bit period. 1 does nothing 0 forces a transition in the middle of the bit
Differential Manchester	There is always a transition in the middle of a bit period. 1 does nothing 0 forces a transition at the beginning of the bit



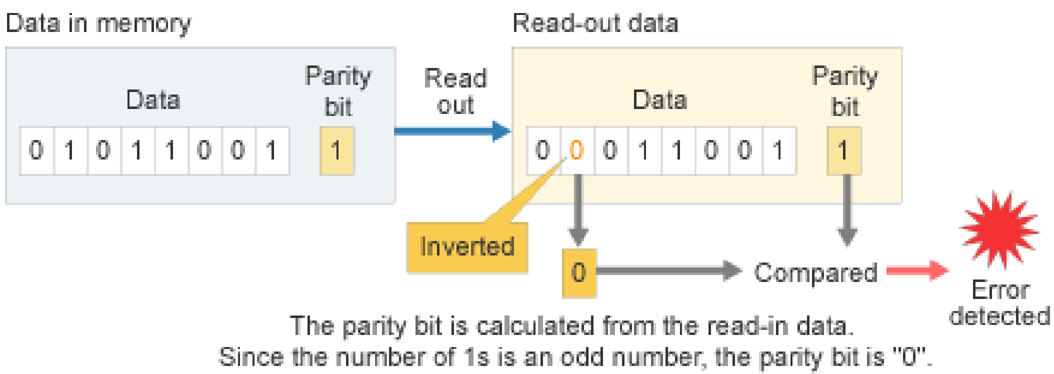
OSI Model: Physical Layer

- Problem of NRZ Code
  Long series of 0s or 1s do not induce a level change. Therefore, sender and receiver have to be in sync (either via internal clocks or via an additional clock line).
- Problem can be avoided by using ***bit-stuffing***.



OSI Model: Data Link Layer

- In some protocols (e.g. IEEE 802) separated in two sub-layers:
  - 2a: Media Access Control (MAC)
  - 2b: Logical Link Control (LLC)
- Flow control
- Media access control
- Error detection (checksums, parity bits)



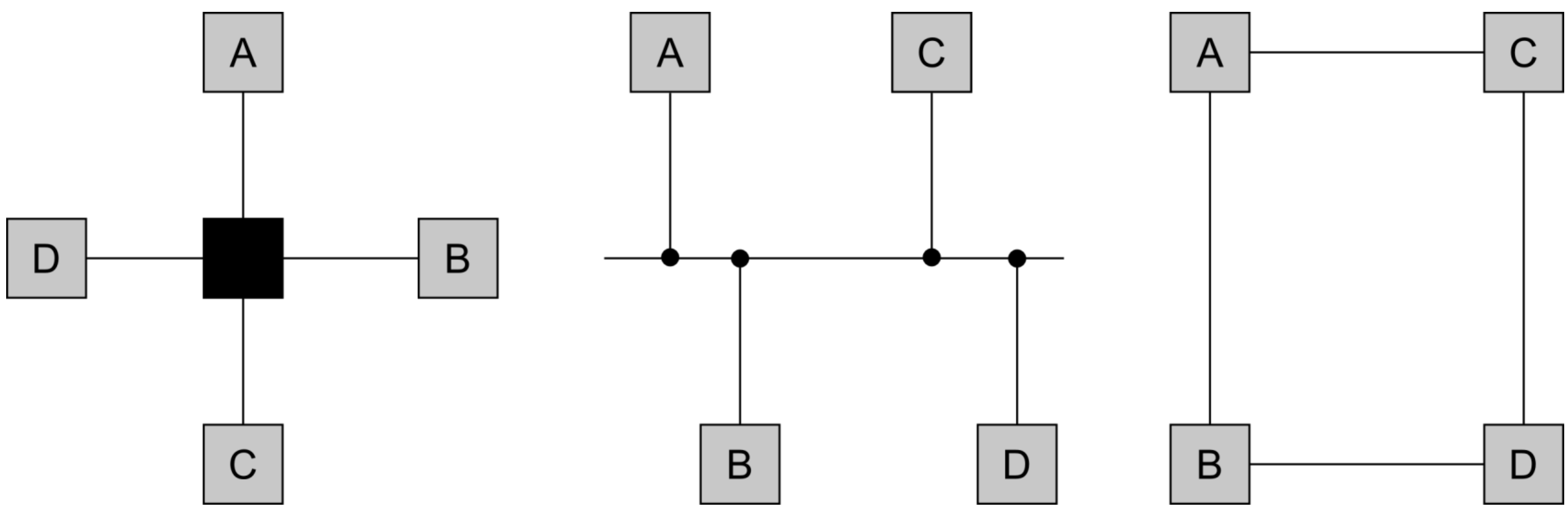
OSI Model: Application Layer

- Provides application-specific communication services (Internet)
  - File Transfer (e.g. FTP)
  - E-Mail
  - Virtual Terminal
  - Remote Login
  - Voice-over-IP (VoIP)
  - Video-On-Demand
- In Real-time applications:
  - Process data exchange for factory automation
    - Sensor data
    - Actuator data

Content

Network Topologies

- Important network topologies: (1) Star, (2) Bus and (3) Ring
- The Bus-Topology is wide-spread in real-time systems (not all domains!), as:
  - the effort for wiring is reduced
  - nodes can easily be added and/or removed



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    b. CAN
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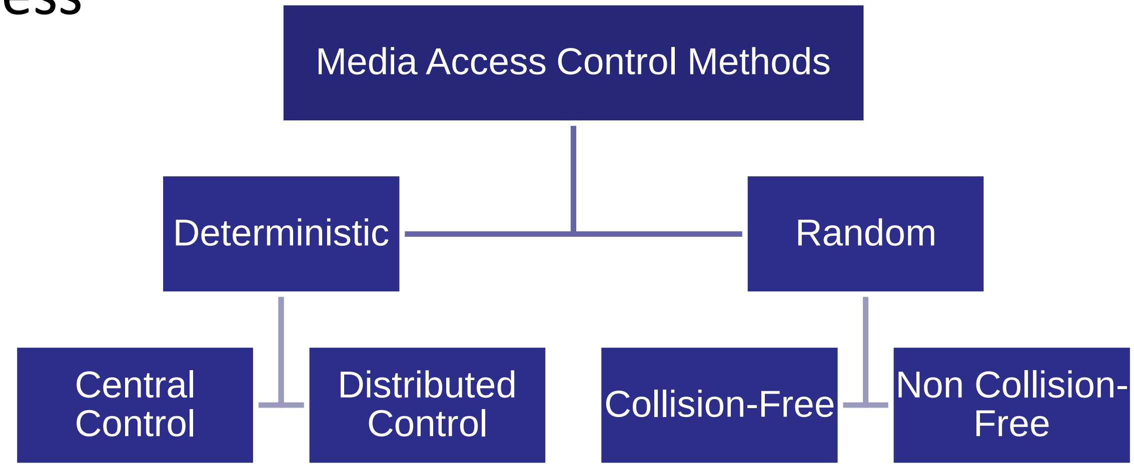
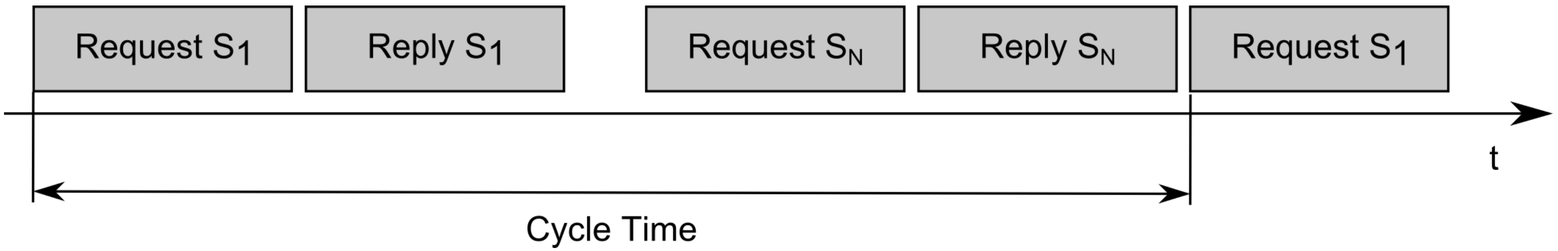
Overview

- Most of the time, the communication channel can **only** be used **exclusively** by **one** node
- Media access protocols are required to **assign** the communication channel to a node and to **resolve simultaneous** access



Deterministic Media Access Control Methods: Central Control

- Master-Slave communication
  - A master ***M*** periodically selects the slaves $S_1 \ldots S_N$
  - Easy to implement
  - Deterministic latencies
  - Example: Ethernet Powerlink (MN and CN nodes)



Deterministic Media Access Control Methods: Distributed Control

- Distributed media access control methods can be:
  - **Token-Based**
    Media access is controlled via a special message – the ***token.***
  - **Time-Based**
    Media access is controlled via ***time-slices*** (Time Division Multiple Access – TDMA).

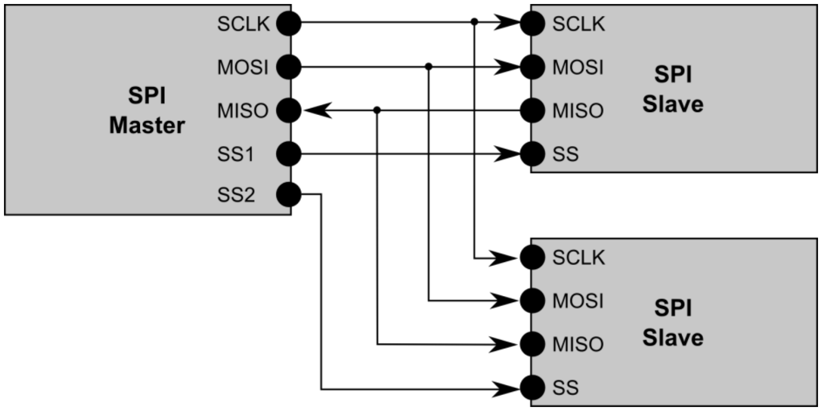
Random Media Access Control Methods

- **Carrier Sense Multiple Access / Collision Detection (CSMA/CD)**
  - Not collision free
  - Collisions are detected and signaled via a ***Jam*** signal
- **Carrier Sense Multiple Access / Collision Avoidance (CSMA/CA)**
  - Collision free
  - Use **arbitration** phase at beginning of transmission to select node with highest priority, lower priority nodes stop transmission and retry later.

Content

Serial Peripheral Interface (SPI)

- SPI is a synchronous, serial data link standard developed by Motorola
- SPI is a master/slave bus
- SPI supports full-duplex communication
- Typical transmission frequencies: 1 – 100 MHz
- SPI uses 4 wires that convey the following signals:
  - SCLK: serial clock
  - MOSI: master output slave input
  - MISO: master input slave output
  - SS: slave select



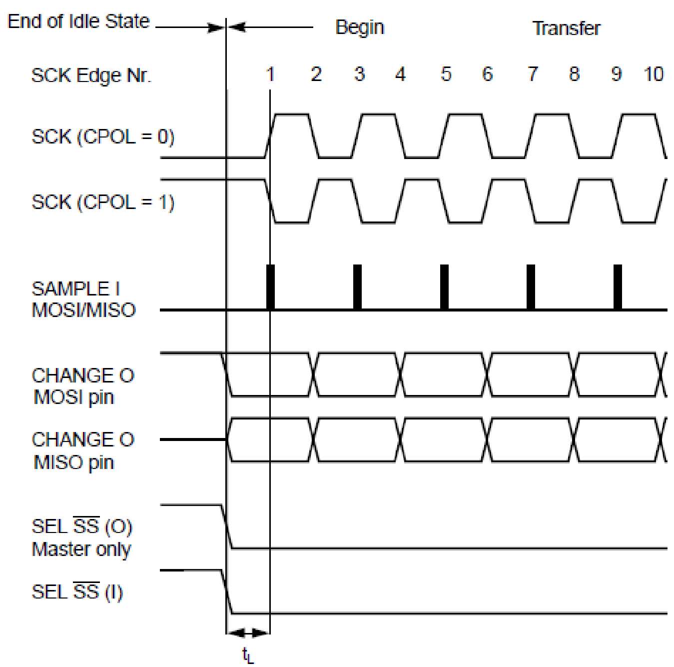
Serial Peripheral Interface (SPI)

- The serial clock (SCLK) line synchronizes the data transmission on the two data lines (MOSI and MISO)
- The master selects the slave for communication through the slave select (SS) lines
- 4 communication modes are available that can be selected through the
  - CPOL (clock polarity) and
  - CPHA (clock phase)

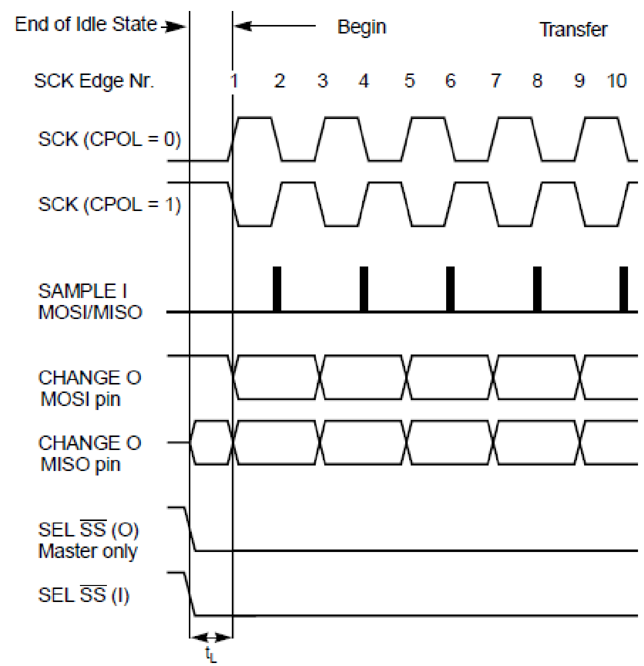
  parameters of the SPI master register.

Serial Peripheral Interface (SPI)

CPHA = 0



CPHA = 1

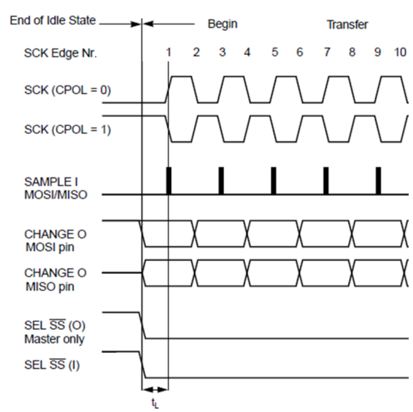


Source: Motorola SPI Block Guide, V03.06

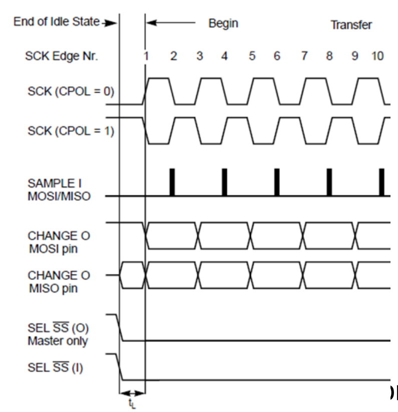
Serial Peripheral Interface (SPI)

- At CPOL=0 the base value of the clock is zero,i.e. the active state is 1 and idle state is 0.
  - For CPHA=0, data are captured on the clock's rising edge (low→high transition) and data is output on a falling edge (high→low clock transition).
  - For CPHA=1, data are captured on the clock's falling edge and data is output on a rising edge.
- At CPOL=1 the base value of the clock is one (inversion of CPOL=0), i.e. the active state is 0 and idle state is 1.
  - For CPHA=0, data are captured on clock's falling edge and data is output on a rising edge.
  - For CPHA=1, data are captured on clock's rising edge and data is output on a falling edge.

CPHA = 0



CPHA = 1

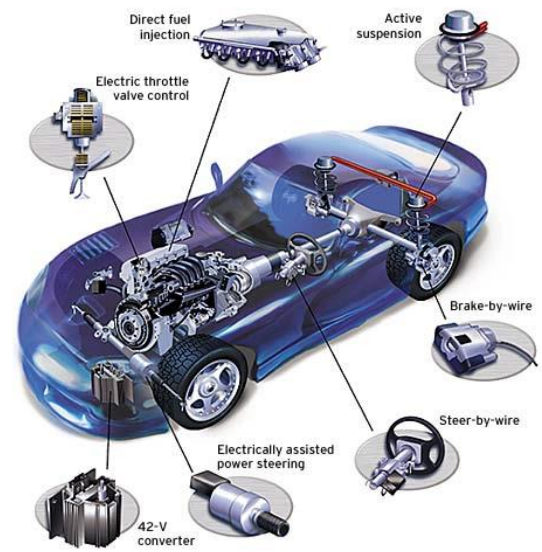


ɿrola SPI Block Guide, V03.06

Content

Controller Area Network (CAN)

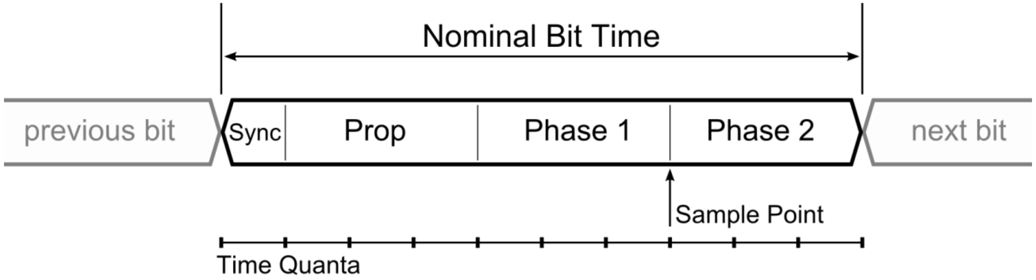
- CAN (Controller Area Network) was developed in 1983 by Bosch
- CAN is a multi-master broadcast serial bus standard
- Topology: Bus
- CAN is message-based (each message is uniquely identified by an ID)
- Typically used in automotive and automation tasks/scenarios
- Max. bitrates depend on bus length
- CAN uses CSMA/CA for media access control



Max. Length	Max Bitrate
40 m	1 Mbit/s
100 m	500 kbit/s
500 m	125 kbit/s

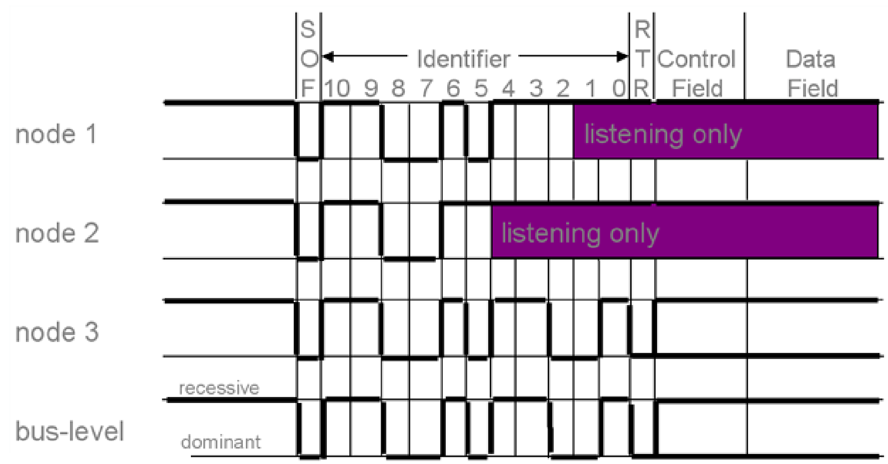
Controller Area Network (CAN)

- There are several physical layer standards (e.g. ISO 11898-2 or SAE-J1939-11)
- ISO 11898-2 is the most wide-spread physical layer standard used in automotive and automation tasks
- Coding: NRZ-L (Non-Return-to-Zero-Level) with bit-stuffing (stuff-width = 5)
- Synchronization is done by dividing each bit of the message frame into four segments: Synchronization, Propagation, Phase 1 and Phase 2
- The „value“ of the bit is sampled between phase 1 and 2



Controller Area Network (CAN)

- CAN implements an **arbitration** scheme based on message identifiers to achieve collision avoidance (CA)
- Transmitted bits are either ***dominant*** (typically 0) or ***recessive*** (1).
- Arbitration takes place during transmission of identifier
- **Nodes** that **lost** arbitration **stop** transmission
- **Starvation** possible:
  Messages with higher priority suppress messages with lower priorities



Node 3 wins arbitration and transmits his data.

SOF	11-bit Identifier	RTR	IDE	r0	DLC	0…8 Bytes Data	CRC	ACK	EOF	IFS

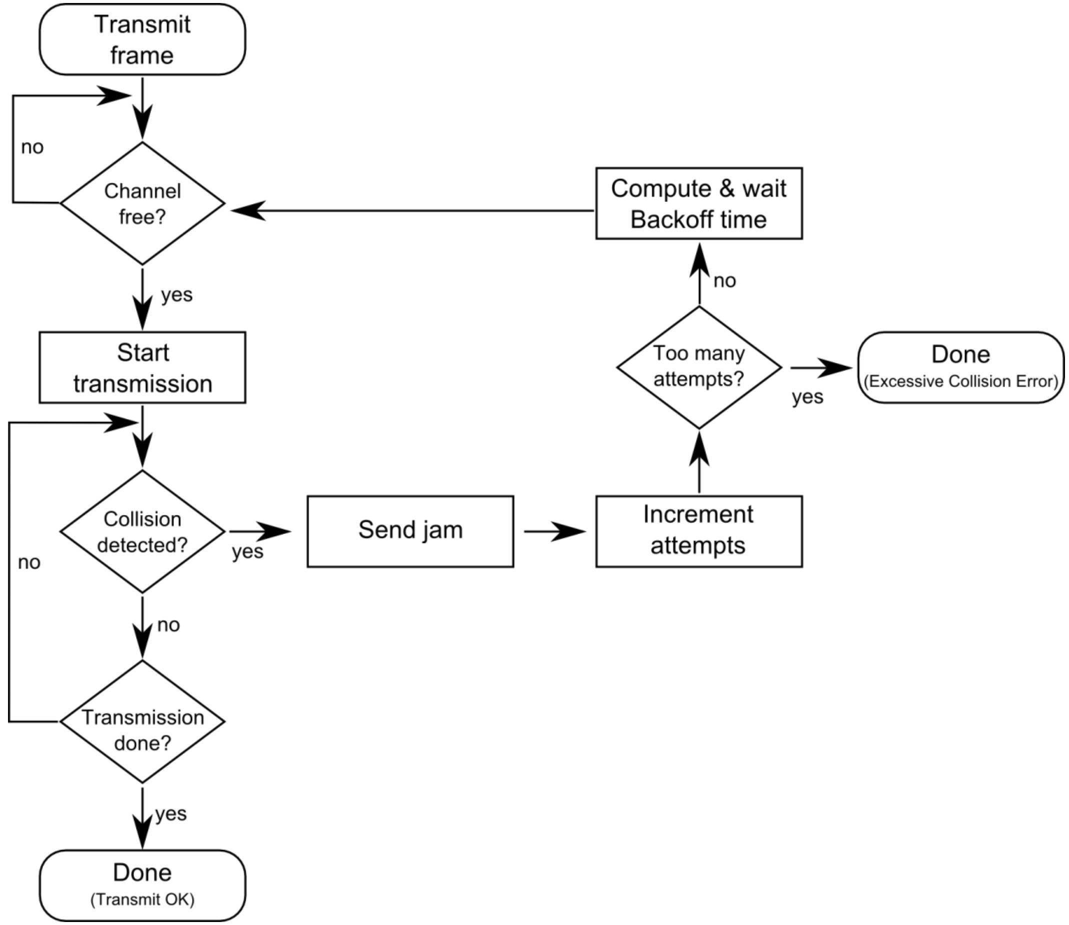
Content

Real-time Ethernet

- Goal
  To use standard ethernet hardware and infrastructure for real-time applications (e.g. automation).
- Reasons
  - Cheap hardware
  - High availability of hardware
  - No additional infrastructure costs (existing wires, switches, etc. can be used)
- Problem
  Standard Ethernet (IEEE 802.3) does not support realtime applications.

Real-time Ethernet: IEEE 802.3 Overview

- IEEE 802.3 uses CSMA/CD
- Collision:
  - Nodes stop transmission
  - Nodes send Jam signal
  - Nodes wait backoff time then try to retransmit



Real-time Ethernet

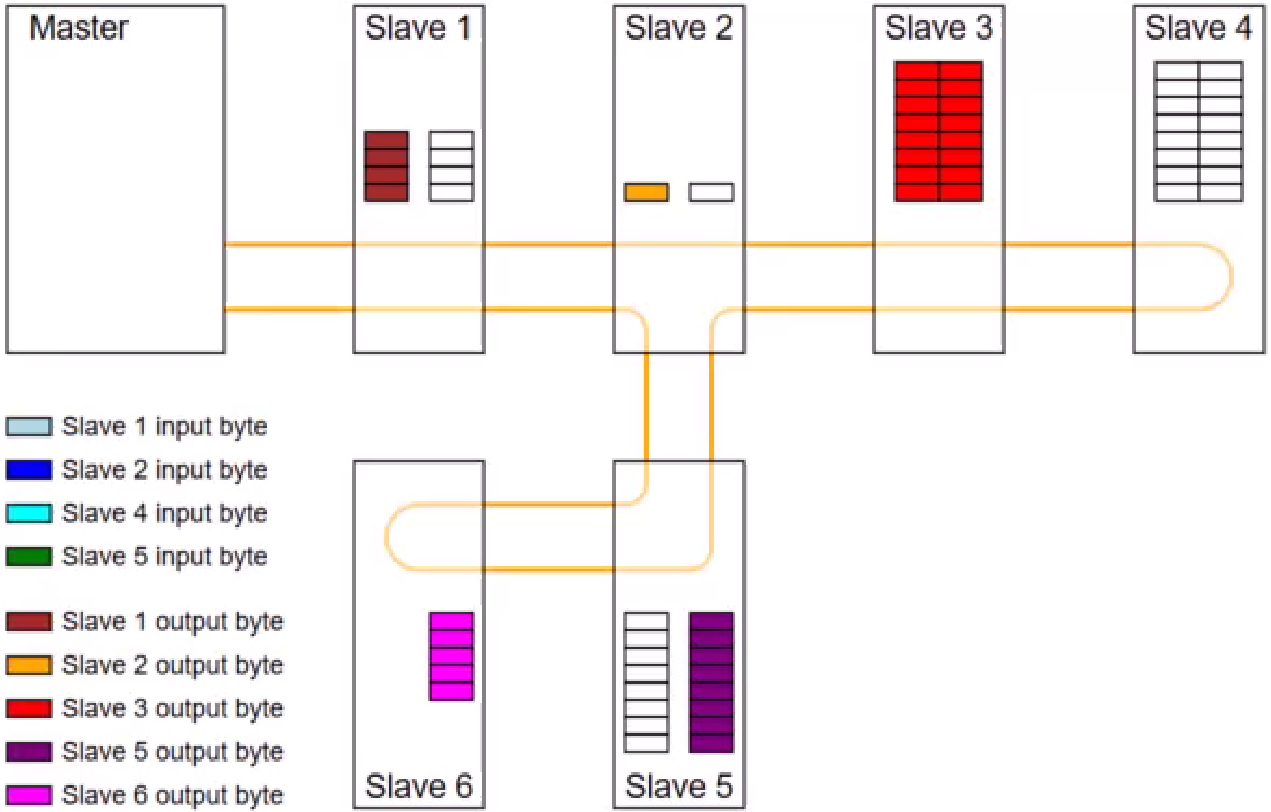
- Various approaches exist to overcome the limitations of IEEE 802.3 for realtime applications.

  Examples:
  - Powerlink (B&R) -- next week
  - EtherCAT (Beckhoff)
  - Profinet (Siemens)
  - Time-Triggered Ethernet

Real-time Ethernet: EtherCAT

- Suitable for hard and soft realtime requirements
- EtherCAT messages are conform with the Ethernet standard
- Messages are send by a master and are forwarded by the slaves
- Each slave extracts relevant user data or inserts them
- The EtherCAT slaves process incoming messages “on-the-fly” which reduces the latency

Real-time Ethernet: EtherCAT



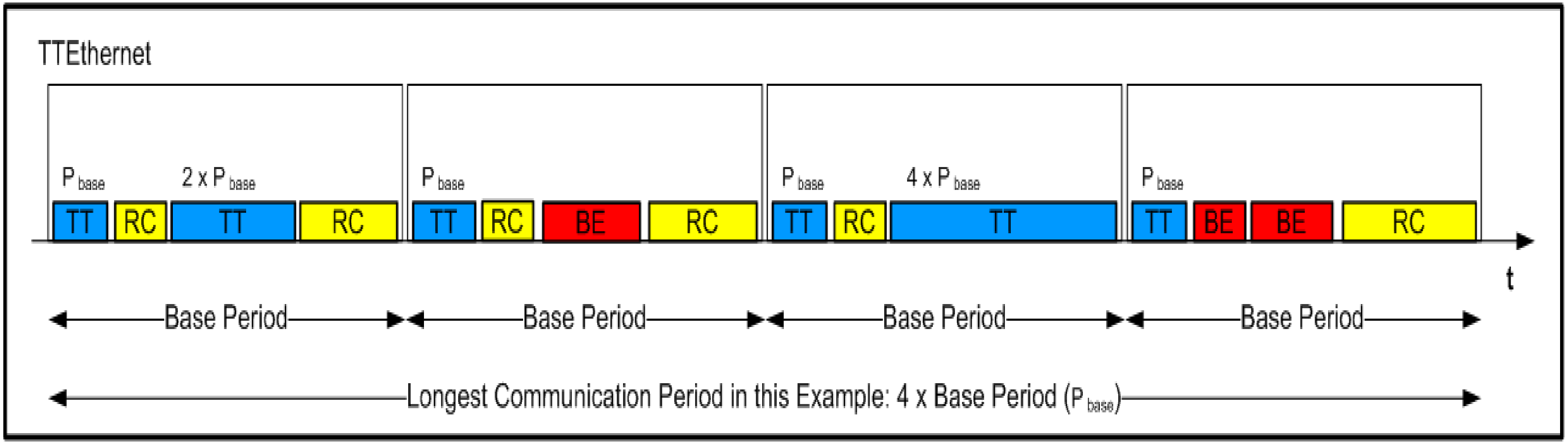
Real-time Ethernet: Profinet

- Standardized in IEC61158 and IEC61784
- Three protocol levels with different reaction times
  - TCP/IP: ~ 100 ms
  - Real-Time Protocol: < 10ms
  - Isochronous Real-Time (IRT): < 1ms
    uses PTP for time synchronization
- Profinet IRT uses pre-defined and reserved time slots to transmit realtime data
- IRT requires special and modified switches (Drawback?)
- In the rest of the time, standard Ethernet is used

Real-time Ethernet: Time-Triggered Ethernet

- Uses a global time base to provide time-triggered communication over Ethernet
- Three different traffic types are supported:
  - Time-Triggered (TT)
    TT messages are send at predefined times.
  - Rate-Constrained (RC)
    RC messages guarantee that bandwith is predefined for each application and that delays have defined limits. RC messages do not depend on global time base (simultaneous sending possible).
  - Best-Effort (BE)
    BE messages use remaining bandwidth. No guaranteed delays.
- Uses special switches (Drawback?) to ensure low delays (e.g. TT messages are forwarded with a constant delay, while RC are buffered)

Real-time Ethernet: Time-Triggered Ethernet



Use case: Networked Medical Systems

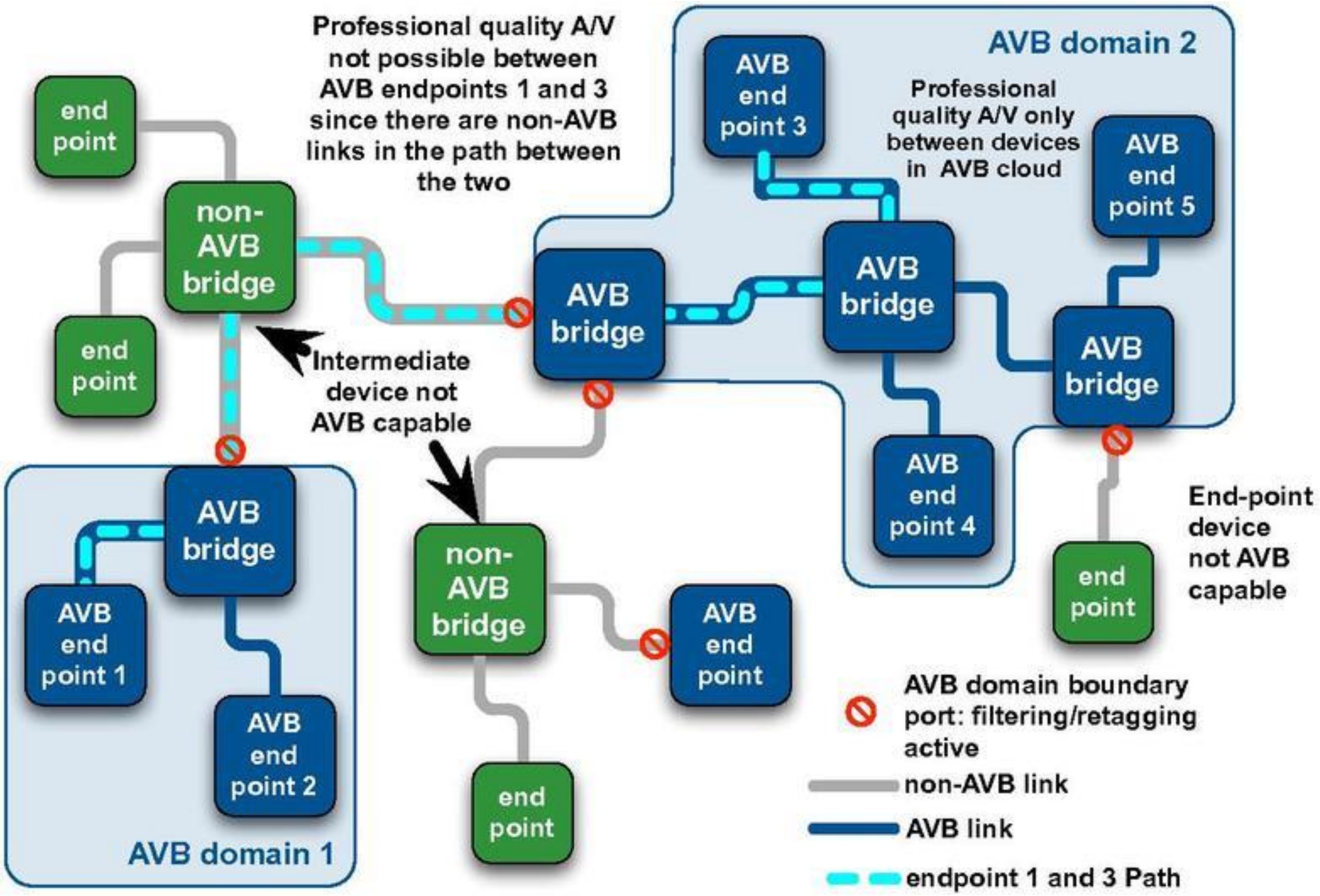
Real-time Ethernet: Switched Ethernet

- Is there any collisions with switched Ethernet technologies? why?
- Why is switched Ethernet not suitable for hard real-time communication?

Real-time Ethernet: Audio Video Bridging (AVB)

- The available real-time Ethernet solutions are proprietary and isolated solutions using different approaches
- Licensing problems (e.g. EtherCAT)
- Why not standard real-time Ethernet?
- (IEEE) Audio Video Bridging Task Group of the IEEE 802.1 standards committee
- Initial idea: low latencies for audio and video applications using switched Ethernet
- Latency guarantee for messages (for max 7 bridges):
  - Class A: 2ms
  - Class B: 50ms

Audio Video Bridging (AVB)



IEEE 802.1BA (overall architecture)

- Defines general architecture of the AVB networks
- Describes the co-existence of AVB and standard Ethernet
- Defines the requirements on AVB devices

IEEE 802.1AS (time synchronization)

- Time Synchronization for AVB
- Based on IEEE 1588-2008
- Uses layer 2 and not layer 3 like IEEE 1588

IEEE 802.1Qat (stream reservation)

- Stream reservation protocol
- There are talkers and listeners
- Talker T announce its stream and the listeners can register for the stream. Based on that the routes are calculated.
- AVB switch checks the ports for available bandwidth
- A communication can take place only if the bandwidth is available
- If requirements of a stream exceed the capacities of the AVB switch, the communication will not take place
- AVB switch gives the max latency for a stream
- Two classes A) 2ms and B) 50 ms

IEEE 802.1Qav (shaper)

- Transport of high priority data must not stop transmission of less critical data
- Forwarding and Scheduling Enhancements
- The idea of credit-based shaper is presented
- Frames with higher priority are preferred but can take max 75% of the bandwidth so that other frames can be transmitted

Real-time Ethernet: Time-sensitive Networking

- Further development and improvements of AVB required
- Lower latencies in microseconds range required
  - Time aware shaper
  - Frame preemption
  - …

IEEE 802.1ASbt (time synchronization)

- Improvements for 802.1AS
- High-available time synchronization
- Specification of redundancy mechanisms
- Support for multiple timing domains transmitting different times

IEEE 802.1Qbv (time aware shaper)

- Similar concept such as TT-Ethernet
- AVB shaper is able to calculate the max latency for a given stream in range of milliseconds
- Qbv brings a time aware shaper
- A new type of traffic possible (scheduled traffic)
- Latencies in microsecond range

IEEE 802.1Qca (routing in layer 2)

- Extensions for shortest path bridging
- More efficient than RSTP (rapid spanning tree protocol)
- Shorter reconfiguration time
- Find redundant paths and using it

IEEE 802.1Qbu (frame preemption)

- Support for frame-preemption
- Low priority frames are preempted if a high priority frames arrives
- Modifications in lower layers required (802.3)!
- Both sender and receiver have to be aware of frame preemption
- IEEE 802.3 DMLT Study Group is also working on the same modifications for reduction of latencies

IEEE 802.1CB

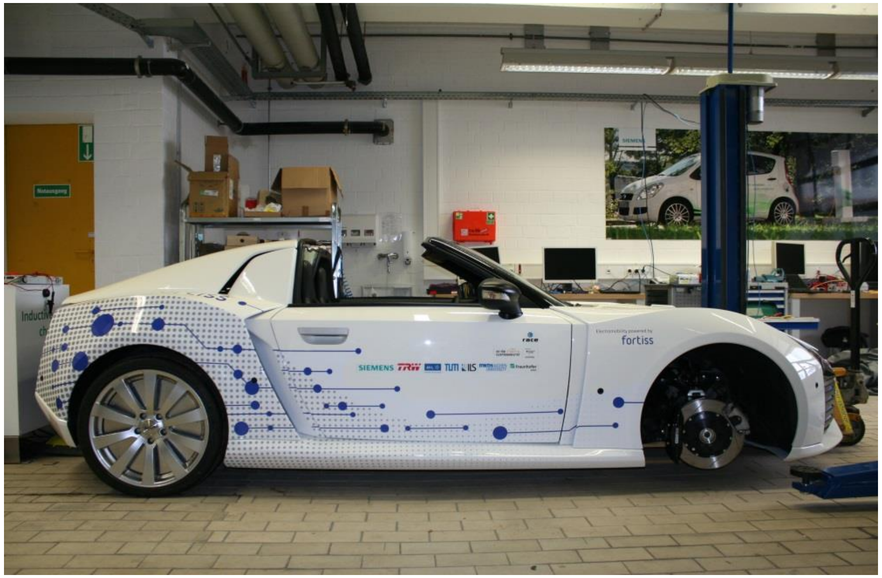
- Frame replication
- Redundant packet transmission
- Elimination of redundant packets

IEEE 802.1Qcc

- Support for more streams
- Configurable SR (stream reservation) classes and streams
- Better description of stream characteristics
- Support for Layer 3 streaming
- UNI (User Network Interface) for routing and reservations

Use case: Automotive

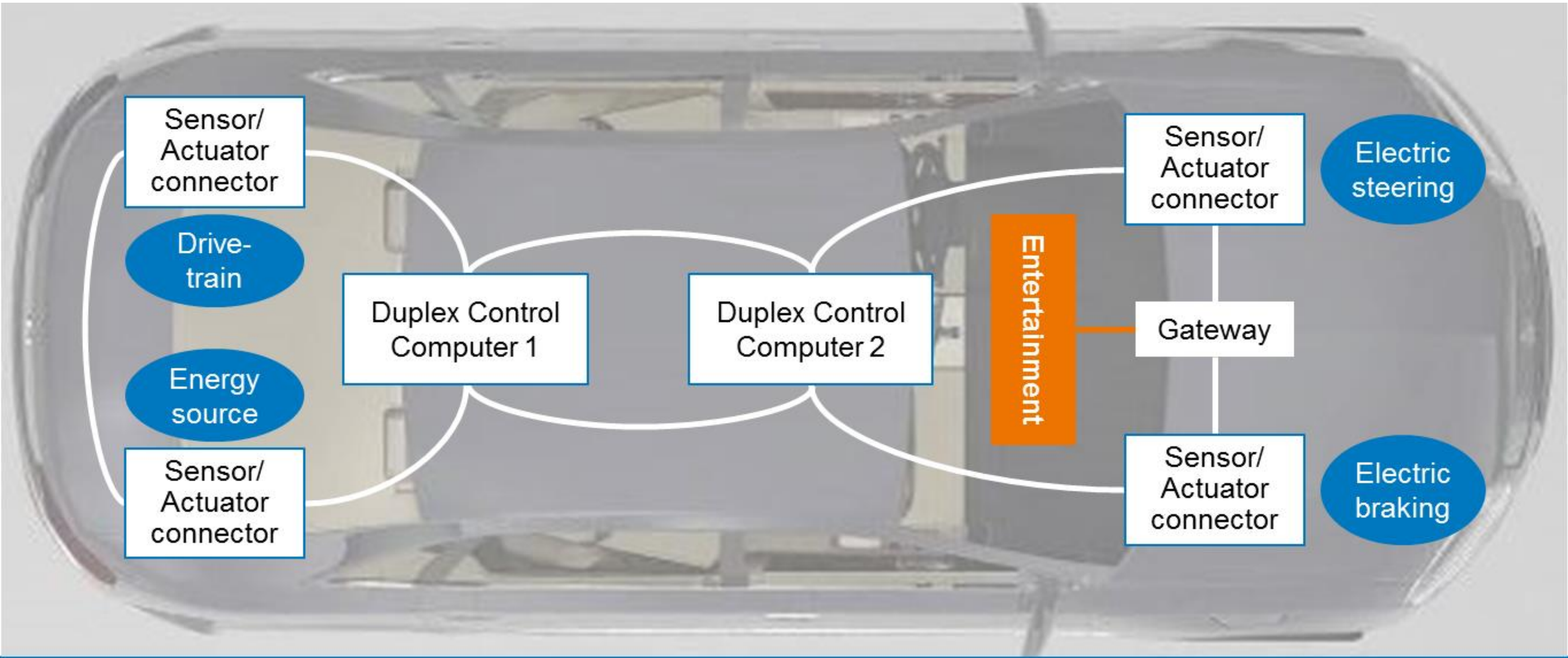
- Roding Roadster Electric



Chassis
- *Carbon/Alloy Light Weight Construction*
- *Weight: 1.250 kg*

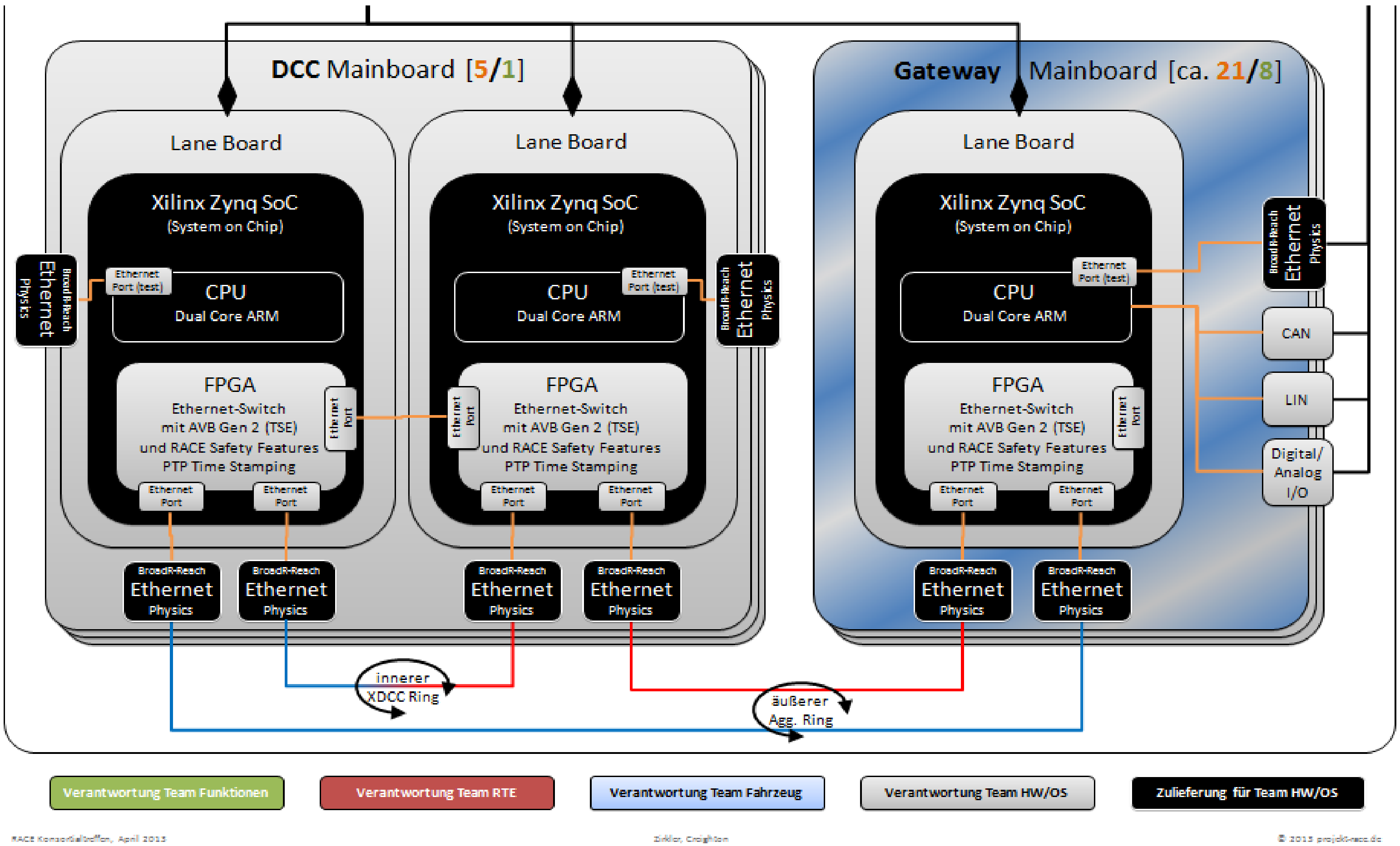
Hub Motors
- *Performance overall: 126 kW (330 kW max.)*
- *Torque overall: 1.000 Nm (2.500 max.)*

Battery
- *Voltage Level: 720 V*
- *Charge: 27 Ah*
- *Capacity: 19.44 kWh*



- Ethernet: AVB Gen 2/Time Sensitive Networking
- Based on IP from Siemens Industry
- Ingress/Egress rate limiting to isolate faulty components (babbling idiot)
- Big buffers to reduce / eliminate interrupts
- Hardware support for Precision Time Protocol (PTP)
- Redundancy by ring structure
  - Inner ring for DCCs
  - Outer ring for sensors / actuators
- Mixed criticality

Use case: Automotive



Summary

- A large variety of communication protocols exist
- Suitable protocol has to be selected based on requirements of application (e.g. costs, hard/soft real-time, etc.)
- Time-sensitive Networking (TSN) is the future!
  - Automotive
  - Automation
  - Industry 4.0
  - Robotics
  - Medical
  - …

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