COURSE 7
COMMUNICATION SYSTEMS IN VEHICULAR NETWORKS
PART 1

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CONTENT

- Introduction
- In-vehicle communication networks
- Automotive ETH
- V2X, V2V, V2I – covered in Part 2

INTRODUCTION

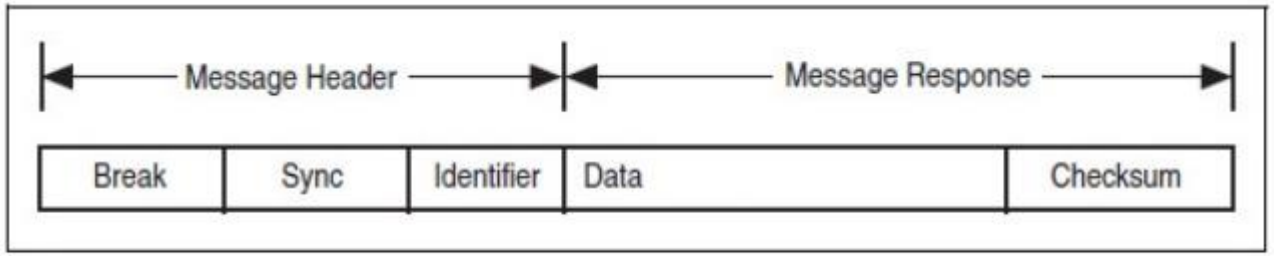
- The purpose of vehicular communication systems is to increase road safety and reduce accident costs
  - Annually, road accidents cause 1.2 million deaths worldwide
  - The number of injured is around 50 million
- A distinction can be made between:
  - In-vehicle communication systems
    - Modern vehicles can have up to 70 ECUs (Electronic Controller Unit)
  - Vehicle-to-everything (V2X) communications systems is a growing field
    - Includes V2V (Vehicle-to-Vehicle)
    - V2I (Vehicle-to-Infrastructure)
    - V2X (Vehicle-to-Everything): V2P (Vehicle-to-Pedestrian), V2R (Vehicle-to-Roadside), V2D (Vehicle-to-Device), V2G (Vehicle-to-Grid) communication systems

LOCAL INTERCONNECT NETWORK – LIN

- It is a serial network protocol used for communication between vehicle components
  - It offers lower performance than CAN (Controller Area Network) but also has much lower costs
- It was introduced in 2002 and it is used in almost all modern cars
  - Comfort: temperature, humidity, light sensors
  - Air conditioning: motors, control panel
  - Doors: side mirrors, electric windows, locks and other applications
- The network topology includes a maximum of 16 nodes (1 master, 15 slaves)
- A single wire with 19.2kbps speed at a maximum distance of 40m is used for communication

LOCAL INTERCONNECT NETWORK – LIN

- LIN can be implemented using UART (Universal Asynchronous Receiver/Transmitter)
- Communication on the LIN bus is controlled by the master
- LIN frames are divided into header and response
  - The header is transmitted by the master node
    - The master performs a query of the slave nodes
  - The response is transmitted by a slave node



LOCAL INTERCONNECT NETWORK – LIN

- The header consists of:
  - Break: 13+1 bit length, indicates the beginning of the LIN frame
  - Sync: 8-bit length, has the default value 0x55 hex, used for node synchronization
  - ID: formed of 6 bits + 2 parity bits, identifies LIN messages and the nodes that need to respond
    - Each slave listens to LIN messages, checks parity, and determines if it needs to repond
- The response consists of:
  - Data: contains 1-8 bytes of data
  - Checksum: 8-bit length, cand be computed based only on data or based on data and identifier

LOCAL INTERCONNECT NETWORK – LIN

- Six types of LIN frames are defined:
  - Unconditional: are the most used, carry data, have ID between 0-59
  - Event-triggered: the master requests a response from several slave nodes, the response includes the ID in the data (sequence), the response is sent only if the data has been updated
  - Sporadic: it is transmitted by the master when it knows that the data has been updated
  - Diagnosis: IDs 60-61 are used to read diagnostic data from master and slave nodes; frames always have 8 bytes of data
  - User defined: has ID 62 and can contain any information
  - Reserved: has ID 63 and should not be used

LOCAL INTERCONNECT NETWORK – LIN

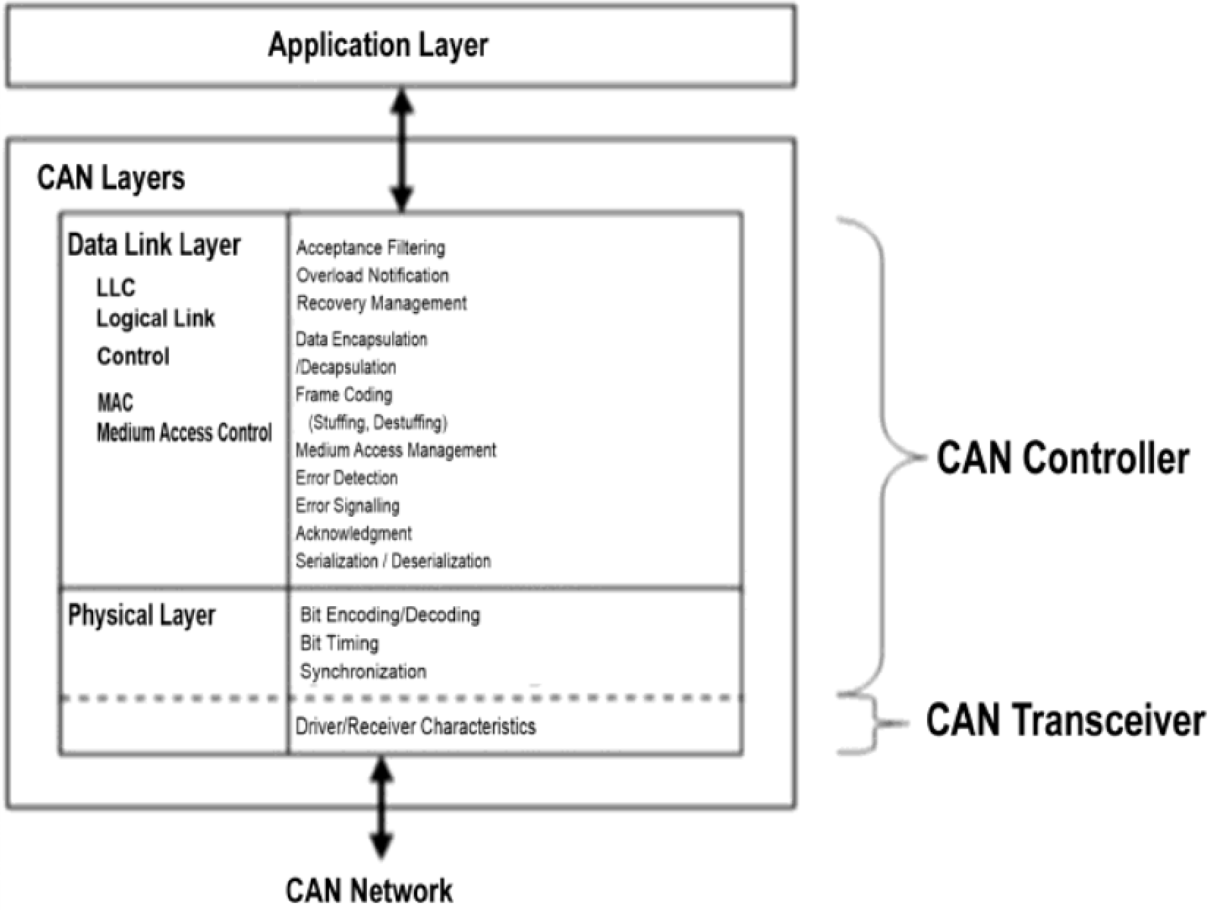
- Error detection takes place at the slave nodes
  - At the first erroneous bit in the frame, frame processing stops
- LIN provides a sleep wakeup mechanism
  - Sleep:
    - The master sends a diagnostic frame with the first data byte equal to 0, upon receipt of this message the slave nodes go into sleep mode
    - After inactivity of at least 4s the slave nodes go into sleep mode
  - Wakeup:
    - It can be initiated by any node by transmitting a specific message
    - Upon receipt of the message, the nodes must be able to process the headers in 100ms

CONTROLLER AREA NETWORK – CAN

- CAN (ISO 11898) was developed by Robert Bosch GmbH and launched in 1986
- It allows communication without a central node
- The CAN bus ensures serial communication with reduced delays with data rates depending on the length of the bus:
  - 1Mbps for d < 40m
  - 125kbps for d < 500m
  - 50kbps for d < 1000m
- Messages are broadcast to all nodes in the network
- Network access takes place through CSMA/CA (Carrier Sense Multiple Access with Collision Avoidance)

CONTROLLER AREA NETWORK – CAN

- The transmission takes place on pairs of twisted wires with the characteristic impedance of 120 Ω
- NRZ (Non Return to Zero) encoding is used
  - Bit 0 is encoded as the dominant state
  - Bit 1 is encoded as the recessive state



CONTROLLER AREA NETWORK – CAN

SOF	11-BIT ARBITRATION ID	SRR	IDE	18-BIT ARBITRATION ID	RTR	r0	DLC	0...8 BYTES DATA	CRC	ACK	EOF

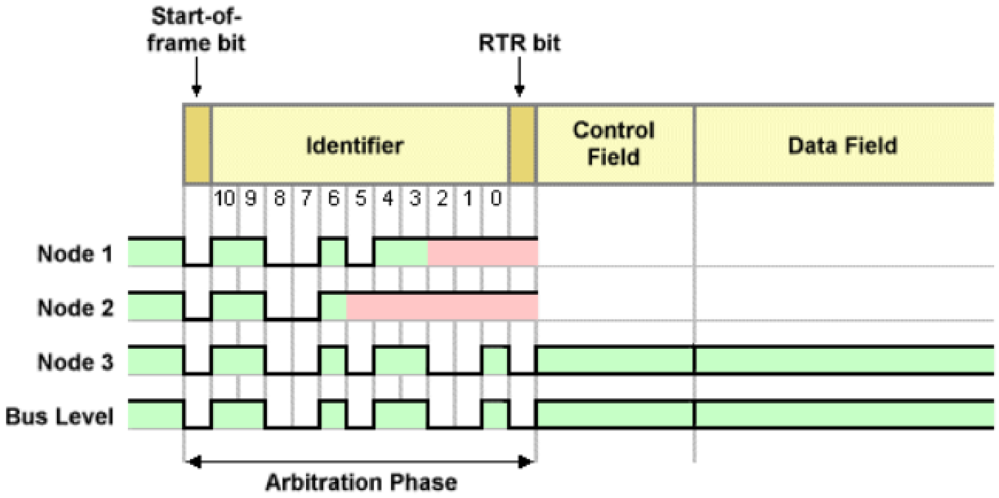
- CAN frame structure
  - SOF: 1 bit, frame start identifier
  - ID: identifies the message and indicates it's priority
  - Two formats are defined: standard with 11-bit arbitration ID, and extended with 29-bit arbitration ID
  - IDE (Identifier Extension): 1 dominant bit means that the standard ID is transmitted
  - RTR (Remote Transmission Request): 1 dominant bit when information is requested from another node

CONTROLLER AREA NETWORK – CAN

- r0: 1 reserved bit
- DLC (Data Length Code): 4 bits, contains the number of transmitted bytes
- Data: 64 bits of data can be transmitted
- CRC: 15 bits for error detection
- DEL: 1 bit CRC delimiter
- ACK: 1 acknowledgement bit, at correct reception of a message this recessive bit from the original message is overwritten with a dominant bit
- DEL: 1 bit ACK delimiter
- EOF (End Of Frame): 7 bits that mark the end of the frame
- ITM/IDLE: at least 3 bits for spacing between consecutive frames

CONTROLLER AREA NETWORK – CAN

- If 2 nodes transmit simultaneously, the arbitration process takes place according to the priority of the message given by the ID
  - The message with the highest priority will be sent
  - If a node receives a dominant bit when it transmits a recessive bit, the node will stop transmitting



- Message IDs must be unique on a CAN bus
- Low value ID means high priority
- There are also extended frames with 29-bit ID

CONTROLLER AREA NETWORK – CAN

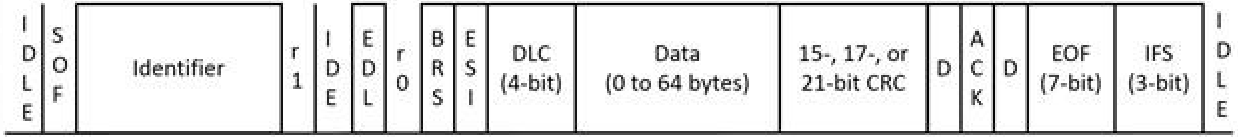
- CAN message types
  - Data
    - Most used for data transmission up to 64 bits using simple or extended frames
  - Remote
    - The destination node can request information from the source node by transmitting a remote message
    - In the remote frame RTR=1 and there is no data field
  - Error
    - Any CAN node that detects an error sends an error message
    - It is a message that contains 6 consecutive bits of the same level
  - Overload
    - It is similar to the error message and it is transmitted when a node becomes overloaded
    - It is used to ensure a delay between two consecutive messages

CONTROLLER AREA NETWORK – CAN FD

- CAN FD (Flexible Data rate) - ISO 11898-1:2015
  - Supports flexible message payload, ranging from 0, 8, 12, 16, 20, 24, 32, 48, 64 bytes per frame
  - Supported data rates are 2, 5 and 8 Mbps
  - Has two independent bit rates for the arbitration and data phases:
    - The arbitration phase uses the same bit timing as the Classical CAN
    - The data bit rate is either similar or higher than the arbitration bit rate
  - Downward compatible with Classical CAN
  - Advantages of CAN-FD:
    - Flexibility to switch between faster and slower data rates
    - Better reliability
    - Up to 30 times more efficient and faster communication between multiple ECUs
    - Decreased number of undetected errors with advanced CRC

CONTROLLER AREA NETWORK – CAN FD

- CAN FD message format



  - Extended Data Length (EDL): the reserved bit after the IDE or after the RTR bit in a standard CAN frame that is transmitted recessive
  - r1, r0: r1 is reserved for future protocol expansion and r0 is used for resynchronization before the optional bit-rate switch. Both bits are transmitted dominant
  - Bit Rate Switch (BRS): A dominant transmission means the bit-rate in the data phase is the same as the arbitration phase while a recessive transmission signifies a faster bit-rate for the data phase
  - Error State Indicator (ESI): a dominant transmission for error active and recessive transmission for error passive
  - Data Length Code (DLC): DLC values ranging from 1001 to 1111 are used to specify the data lengths of 12, 16, 20, 24, 32, 48, and 64 bytes
  - Cyclic Redundancy Check (CRC): The length of the CRC depends upon the length of the DLC and EDL. The CRC is 15-bits for CAN messages and either 17 or 21-bits for CAN FD

CONTROLLER AREA NETWORK – CAN DATABASE FILES

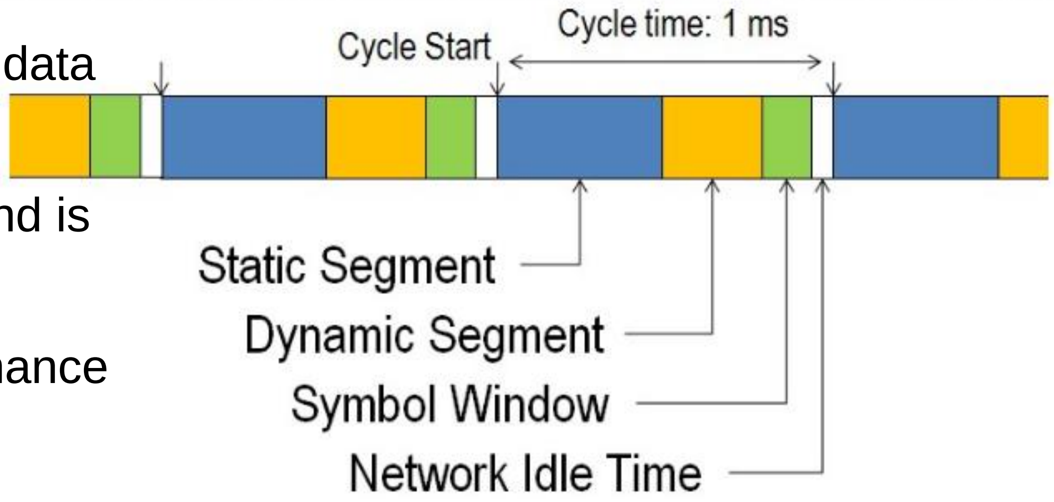
- CAN database files are text files that contain scaling information for CAN frames and signal definitions
- For each signal, CAN databases define rules for conversion to engineering units.
- The following data is stored in databases:
    - Channel name
    - Location (start bit) and size (number of bits) of the channel within a given message
    - Byte order (Intel/Motorola)
    - Data type (signed, unsigned, and IEEE float)
    - Scaling and units string
    - Range
    - Default value
    - Comment
- This information to easily convert the "raw" frame information (usually bytes) to a "real world" value
- CAN database files may contain frame and signal definitions for an entire vehicle
    - The database files are vendor-specific and usually confidential.

FLEXRAY

- Flexray allows speeds up to 10Mbps and uses one or two twisted pairs
- It was first used in 2009
- Possible network topologies are:
  - Linear
    - A single cable connects all nodes, the same topology as LIN, CAN
  - Star
    - There is a central node, similar to a hub
  - Hybrid
- Network access takes place with TDMA

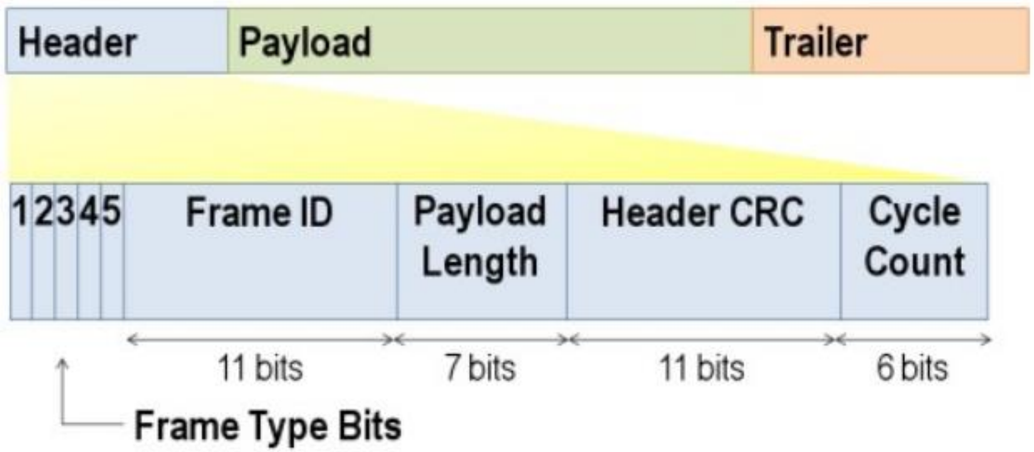
FLEXRAY

- Flexray provides communication cycles for static and dynamic data transmission, one cycle lasts 1-5ms
  - The static segment is reserved for deterministic data that are transmitted at fixed time periods
  - The dynamic segment works similarly to CAN and is used for event-based data transmission
  - The symbol window is used for network maintenance
  - Network Idle Time is used to maintain synchronization



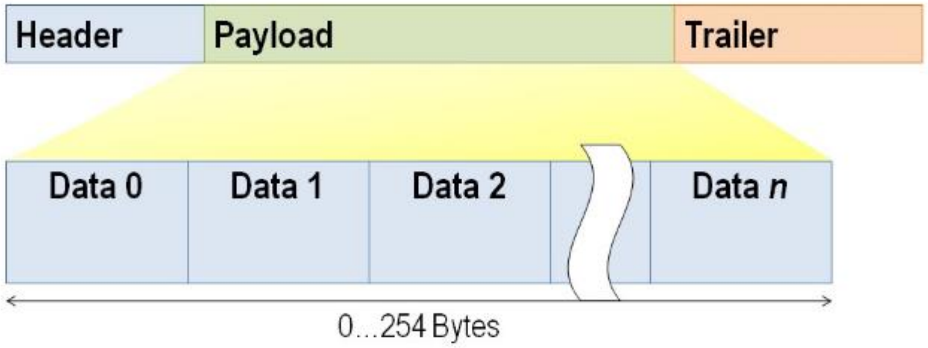
FLEXRAY

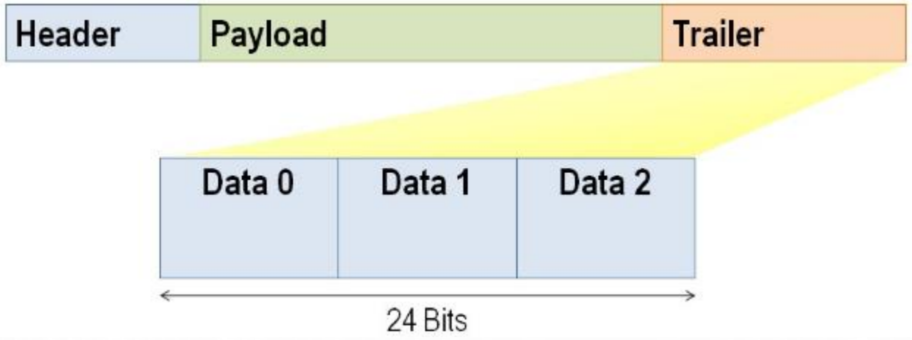
- Flexray frames are divided into 3 segments:
  - Header
    - Consists of 5 bytes
      - Frame type bits: 5 bits
      - Frame ID: 11 bits – used for prioritization
      - Payload length: 7 bits – the number of words transferred to the frame
      - Header CRC: 11 bits – for error detection
      - Cycle count: 6 bits – incremented at the beginning of a new communication cycle



FLEXRAY

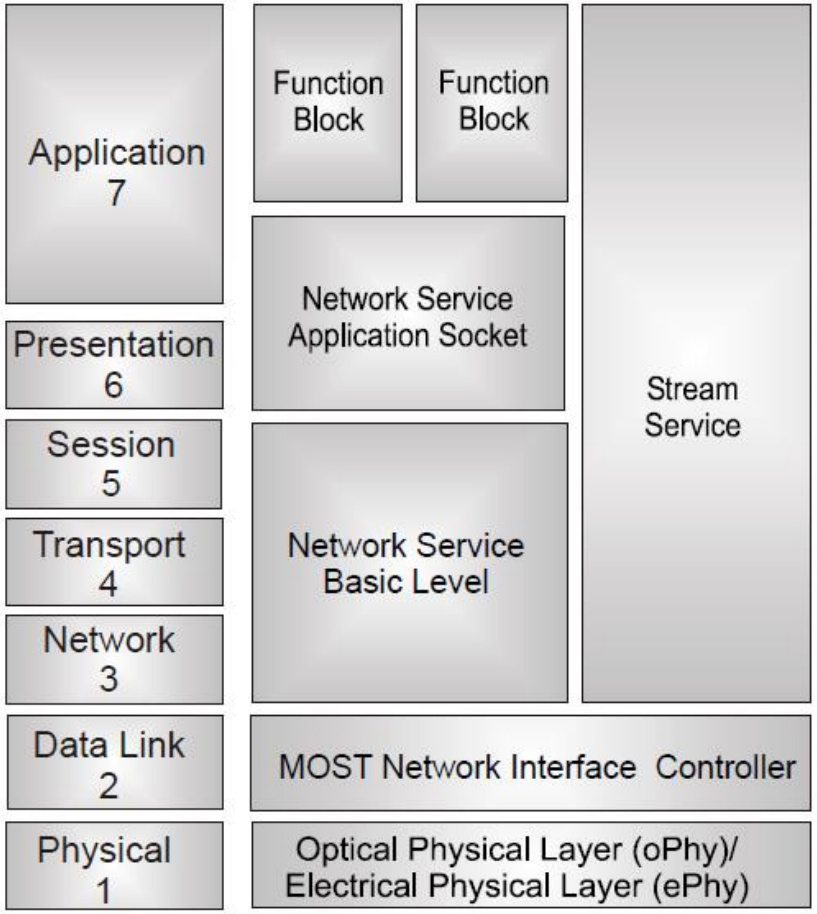
- Payload
  - Contains the data transferred in the frame
  - Can hold up to 256 bytes of data (127 words)
- Trailer
  - Contains 3 8-bit CRCs for error detection





MEDIA ORIENTED SYSTEM TRANSPORT – MOST

- It is a protocol developed for multimedia transmissions introduced in 2001
- Uses synchronous streaming and asynchronous packet data communications
- The topology is ring type with a maximum of 64 devices
- It can work using:
  - Optical fiber (MOST25, MOST150)
  - Electrical conductors (MOST50, MOST150)

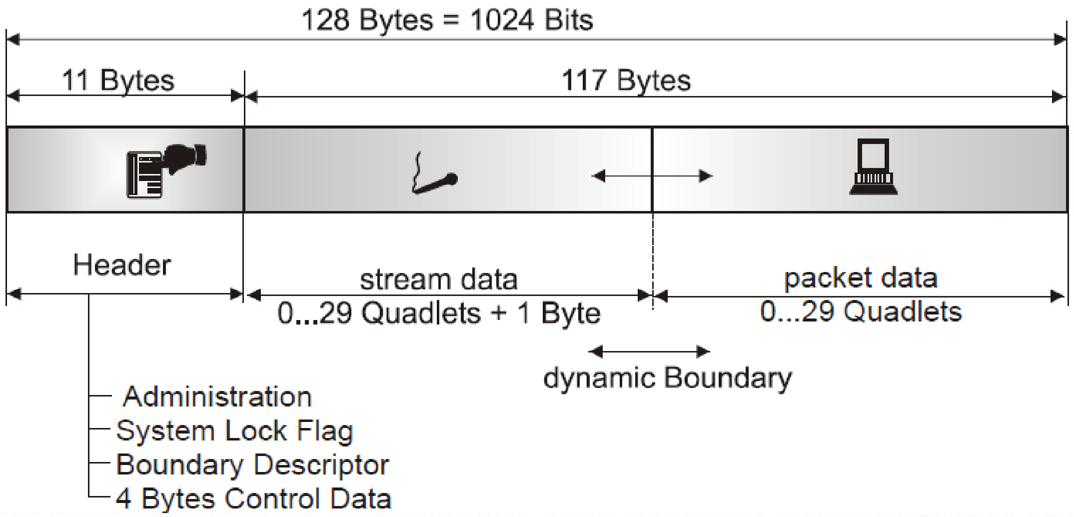


MEDIA ORIENTED SYSTEM TRANSPORT – MOST

- The bit rates provide by MOST are: 25, 50, 150Mbps and there are 3 variants of MOST
- MOST25
  - The transmitted blocks consists of 16 frames
  - The length of the frame is 512 bits
    - 60 bytes are used for data transmission
    - 2 bytes are used for the network control message, which is distributed in 16 frames
    - The first and the last byte contain the control information of the frame
  - The sampling frequency is 44.1kHz

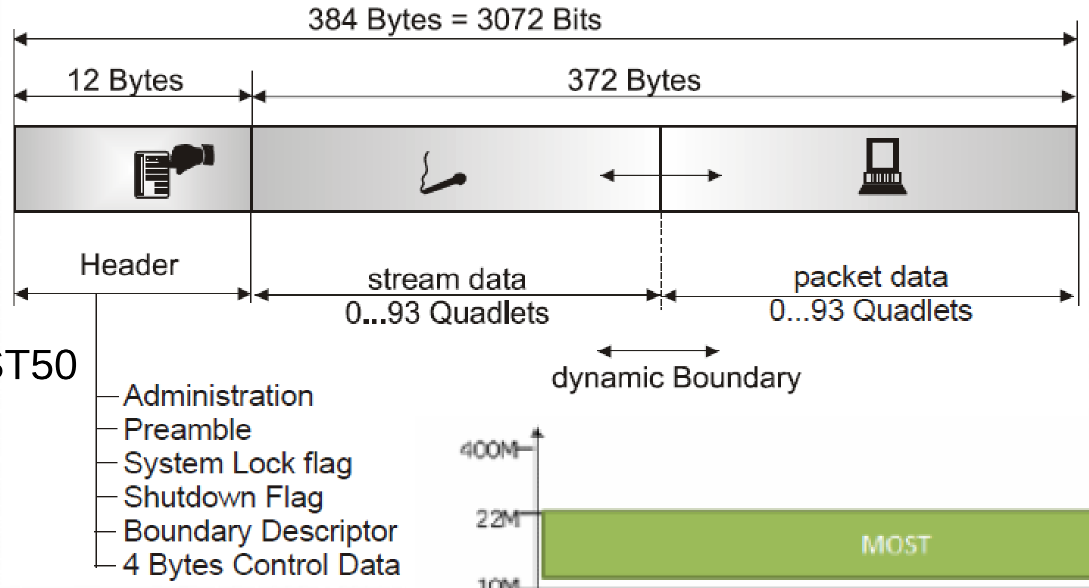
MEDIA ORIENTED SYSTEM TRANSPORT – MOST

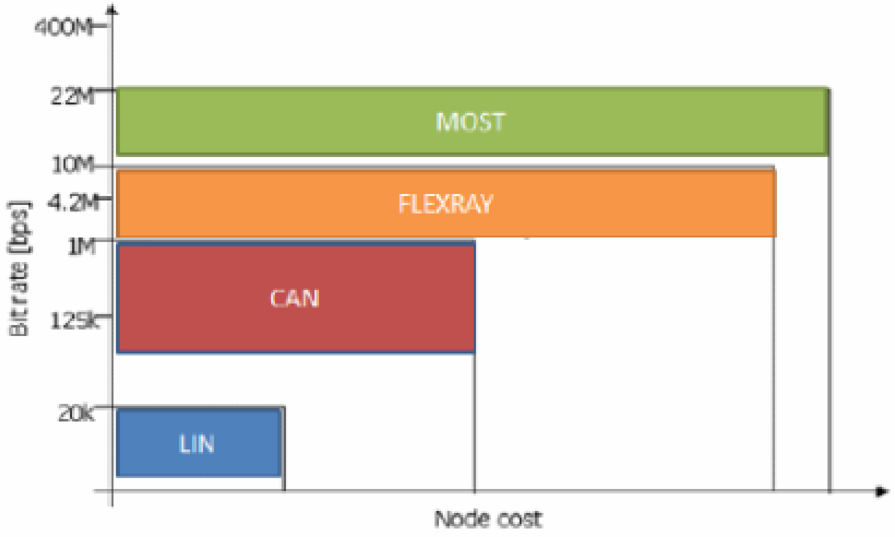
- MOST50
  - The blocks consist of 6 frames
  - The length of the frame is 1024 bits
    - 11 bytes represent the header
    - 4 bytes from the header are used for control data
    - Packet and streaming length can be adjusted dynamically
  - The sampling frequency is 48kHz



MEDIA ORIENTED SYSTEM TRANSPORT – MOST

- MOST150
  - The blocks consist of 6 frames
  - The length of the frame is 3072 bits
    - The frame structure is similar with MOST50
  - The sampling frequency is 48kHz
- The access of the nodes is based on a token
  - It is sent from one node to the other
  - Only the node which has the token can transmit data



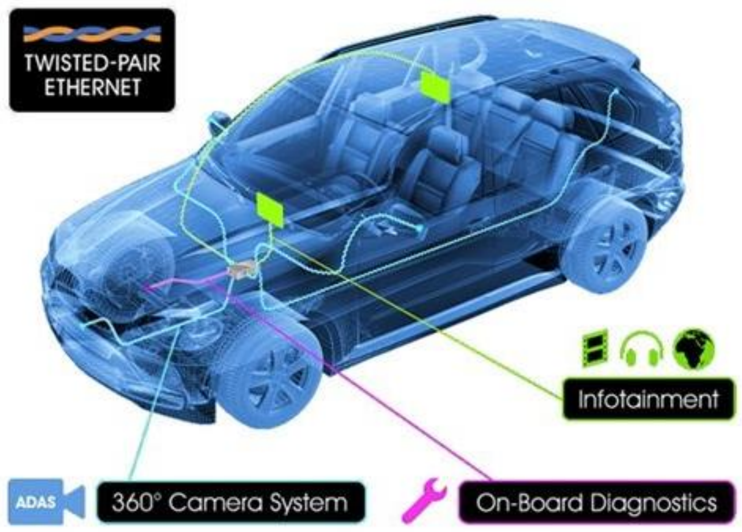


AUTOMOTIVE ETHERNET – ETH

- There are 3 different ETH standards, with differences mainly related to physical layer:
  - IEEE 100BASE-T1 (IEEE 802.3bw)
  - IEEE 100BASE-TX (IEEE 802.3u)
  - IEEE 1000BASE-T1 (IEEE 802.3bp)
- ETH provides high throughput and low implementation costs and allows simultaneous access to information for different systems:
  - Infotainment
  - Diagnosis
  - ADAS (Advanced Driver Assitance Systems), etc.

AUTOMOTIVE ETHERNET – 100BASE-T1

- 100BASE-T1 requirements:
  - 100Mbps bit rate
  - Provides MAC compatible with standard Ethernet
  - Full-duplex data transmission
  - BER ≤ 10^{-10}
  - Fast power management states transitions
  - Minimum operating distance 15m
  - Resistant to vehicle environment: temperature, electromagnetic compatibility (EMC), over- and undervoltage, etc.



AUTOMOTIVE ETHERNET – 100BASE-T1

- A twisted pair cable on which symmetrical differential voltages are applied is used for the physical connection
  - The voltages represent symbols that the sender encodes
- The same band and the same pair of wires are used for transmission and reception
  - The separation of the transmission directions is done by the echo cancellation technique
    - The sender adds its own differential voltage to the two wires
    - The receiver subtracts its own voltage from the applied total voltage
    - The result is the voltage that was sent by the opposite node
- Only two nodes are connected to one cable, only point-to-point topology is available
  - More nodes can be connected using a coupling element, e.g. switch

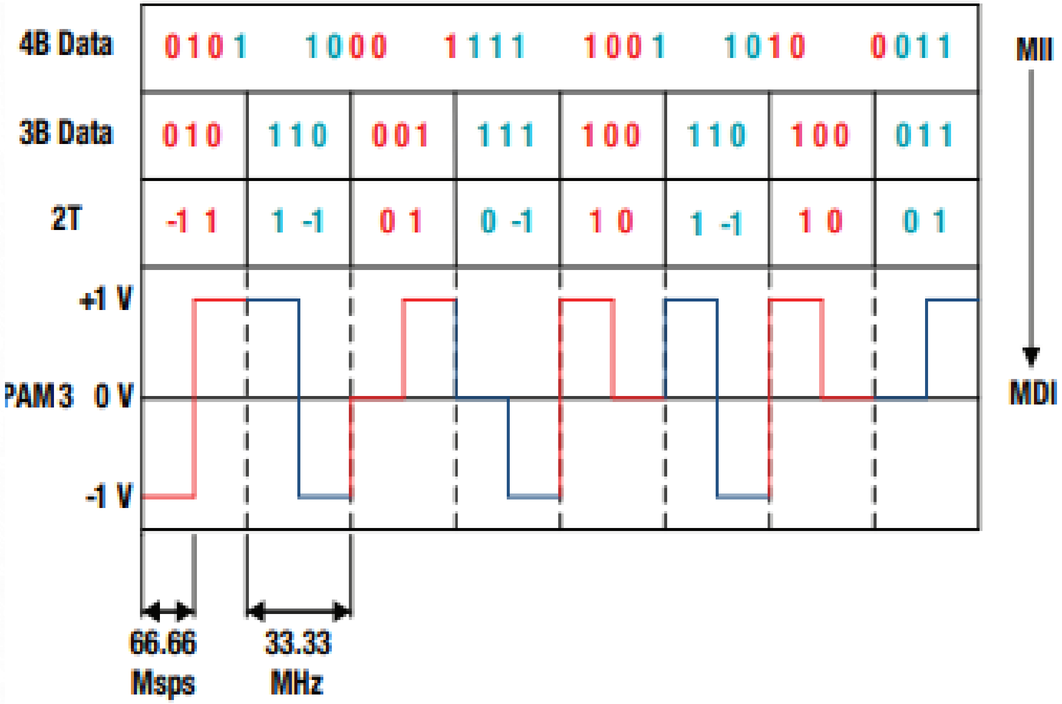
AUTOMOTIVE ETHERNET – 100BASE-T1

- At the PHY layer ETH works with a combined encoding scheme 4B3B (4-bit to 3-bit), 3B2T (3-bit to 2-ternary pair) and PAM3 (3-level Pulse Amplitude Modulation)
  - PHY handles scrambling and coding
  - 4 bits received in parallel at the 25MHz clock frequency are converted to 3 bits, and the clock frequency increases to 33.3MHz
    - If necessary, justification takes place
  - Using each 3-bit group a ternary pair is generated
  - The ternary pair vector is transmitted using PAM3 at the fundamental frequency of 66.6MHz

3-bit data	TA	TB
0 0 0	-1	0
0 0 1	0	1
0 1 0	-1	1
0 1 1	0	1
1 0 0	1	0
1 0 1	0	-1
1 1 0	1	-1
1 1 1	0	-1

AUTOMOTIVE ETHERNET – 100BASE-T1

- 100BASE-T1 encoding example



AUTOMOTIVE ETHERNET – 100BASE-TX

- For the physical connection 2 channels are needed, each of which has two twisted wires
  - The wire pairs are used to transmit symmetrical differential voltages that represent previously encoded symbols
  - Standardized Cat5 or Cat5e cables are typically used
  - The assignment of the wire pairs is specified in EIA/TIA-568A and EIA/TIA-568B
- A combination of NRZI, 4B5B, and MLT-3 methods for coding and decoding
- Only two nodes are connected to one cable, only point-to-point topology is available
- Information can be transmitted bidirectionally at 100 Mbit/s
  - One channel is used for sending and the second channel for receiving the information
  - If a PHY supports only fixed channel assignments, a crossover cable must be used, but most modern PHYs have an auto negotiation mechanism to automatically detect the channel usage

AUTOMOTIVE ETHERNET – 1000BASE-T1

- For the physical connection four channels are needed, each with two twisted wires
  - The wire pairs are used to transmit symmetrical differential voltages that represent previously encoded symbols
  - Standardized Cat5e cables are used, all 8 available wires are necessary for the 4 channels
  - The assignment of the wire pairs is specified in EIA/TIA-568A and EIA/TIA-568B
- A combination of 8B1Q4, Trellis, Viterbi, and PAM5 methods is used for coding and decoding
  - Due to the PAM5, two nodes can send and receive simultaneously on four channels (full duplex)
- Only two nodes are connected to one cable, only point-to-point topology is available

AUTOMOTIVE ETHERNET – DOIP

- Diagnostics over IP (DoIP) is specified in ISO 13400
- ETH has been used for a few years for diagnostics, in particular, for flashing ECUs
  - It enables flash cycles to be significantly reduced in production and car repair shops
- DoIP is not a diagnostic protocol according to ISO 13400 but a transport protocol
  - The transmission of diagnostic packets is defined in DoIP
  - The contained diagnostic services are specified by diagnostic protocols, e.g. UDS
- DoIP must support UDP and TCP
  - UDP is used for transmission of status or configuration information
  - TCP enables transmission of actual diagnostic packets via a fixed communication channel
  - TCP and UDP must be implemented in the diagnostic tester, each ECU with DoIP diagnostic capability (DoIP Node) and in each diagnostic gateway (DoIP Gateway or DoIP Edge Node).

AUTOMOTIVE ETHERNET – DOIP

- A diagnostic tester enables the sending of diagnostic requests
  - Testers can be external devices, such as in repair shops, or on-board testers in the vehicle
  - The receiving ECU must process requests and return an associated response to the tester
    - This requires that DoIP as well as underlying layers be implemented in each directly diagnosable ECU
- DoIP allows the use of diagnostic gateways, a separate implementation is not needed for each ECU
  - The gateway assumes the role of the intermediary
  - Requests of the tester are forwarded to internal networks
  - When a response from the ECU is available, the gateway routes this back to the tester