Vehicle Networks

CAN-based Higher Layer Protocols

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Outline

- Introduction

- General-purpose HLPs
  - ISO TP
  - TP2.0

- Special-purpose HLPs
  - Vehicle-Operational Purposes:
    - CANopen
    - SAE J1939
  - Diagnostics Purposes:
    - ISO 15765-3 (KWP2000/CAN)
    - Unified Diagnostic Services
    - On-Board Diagnostics
Introduction

“Pure CAN” provides fast, prioritized, reliable, broadcast message transmission with sophisticated error detection and error handling.

Pure CAN can fulfill all requirements of small closed systems.

Pure CAN cannot satisfy the requirements that have to be fulfilled within large, extendable, interconnected networks from different manufacturers.

Higher Layer Protocols (HLP) required that enable the interconnection of these networks.

Inter-manufacturer connection is of major importance for all kinds of utility vehicles:
- Trucks
- Tractors
- Snowcats
- Harvesters
- Foresters
- Cranes

Extension:
- Fixed attached components: blue lights, information systems, taximeter
- Dynamic attached components: trailers, seeders, dozer blades
- Highly dynamic attaches components: Fleet management system
Introduction

Functions that have to be fulfilled by HLPs:

- Definition of common message identifiers, their meaning, format and respective data types to enable **interoperability**
- **Flow control**
- **Transportation** of messages > 8 bytes
- Node **addressing** to address a specific device
- **Networking** via gateways
- **Network management:**
  - Startup, maintenance and shutdown behavior
  - Status reporting, diagnosis

Interconnecting Higher Layer Protocol

<table>
<thead>
<tr>
<th>Application</th>
<th>Application</th>
<th>Application</th>
<th>Application</th>
</tr>
</thead>
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<tr>
<td>CAN Low Speed</td>
<td>CAN Low Speed</td>
<td>CAN High Speed</td>
<td>CAN High Speed</td>
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<tr>
<td>CAN High Speed</td>
<td>CAN High Speed</td>
<td>Other Protocols</td>
<td></td>
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</table>
## Introduction

**CAN in ISO/OSI Reference Model**

<table>
<thead>
<tr>
<th>No. of layer</th>
<th>ISO/OSI ref model</th>
<th>CAN protocol specification</th>
</tr>
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<td>6</td>
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<td>5</td>
<td>Session</td>
<td>Optional: Higher Layer Protocols (HLP)</td>
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<tr>
<td>4</td>
<td>Transport</td>
<td>CAN protocol (with free choice of medium)</td>
</tr>
<tr>
<td>3</td>
<td>Network</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Data Link</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>Physical</td>
<td></td>
</tr>
</tbody>
</table>
**Introduction**

Protocol messaging

- Protocol Data Unit (PDU) of layer $N$ becomes Service Data Unit (SDU) of layer $N-1$
- $(N-1)$-SDU extended with Protocol Control Information (PCI) and Footer becomes $(N-1)$-PDU

**Terminology**
- Layer 1 PDU: bits
- Layer 2 PDU: frame
- Layer 3 PDU: packet
- Layer 4 PDU: segment
Introduction
Protocol service primitives

- Service Access Points (SAP) provide services to upper and lower layers
- SAP to layer (N-1)
  - Request
  - Confirmation
- SAP to layer (N)
  - Response
  - Indication
Introduction
Network Layer

- Transmission of packets over multiple intermediate hops
- Protocols: IPv4, IPv6, ICMP, IGMP
- Main functions:
  - Global addressing
  - Routing, e.g.:
    - Flooding
    - Link State Routing
    - Distance Vector Routing
    - Hierarchical Routing
  - Fragmentation
  - Quality of Service
Introduction
Transport Layer

- Data exchange over a logical connection between end-to-end systems
- Protocols: TCP, UDP, DCCP, SCTP
- Main functions:
  - Reliability management:
    - Reliable communication (e.g. TCP by acknowledgements)
    - Unreliable communication (e.g. UDP)
  - Segmentation with (un)ordered delivery
  - Flow control: Overload at receivers
  - Congestion control: Overload of the network
  - Connection management:
    - Connection-oriented (e.g. TCP)
    - Connectionless (e.g. UDP)
  - Error Control
  - Multiplexing of concurrent services
General-purpose HLPs

ISO-TP
ISO-TP
Overview

- ISO-TP = ISO Transport Protocol
- Designed to run existing diagnostics protocols (ISO 14230) on CAN
- Unreliable connection-oriented transport protocol enabling:
  - Segmentation (transmission of up to 4095 bytes)
  - Flow Control
  - Broadcast and unicast addressing
- Uses CAN on Data Link layer
- Standardized under ISO 15765-2
- E.g. used with diagnostics protocols KWP2000 and UDS
ISO-TP Frames

Frame Types:

- **Single Frame:**
  Standard frame for unsegmented data
  ```
  0x0 | Data Length | 0..7 Data Bytes
  ```

- **First Frame:**
  Initial frame in a sequence of frames
  ```
  0x1 | Data Length | Data Length | 0..6 Data Bytes
  ```

- **Consecutive Frame:**
  Subsequent frame in the sequence (SN modulo 2⁴)
  ```
  0x2 | Seq Number | 0..7 Data Bytes
  ```

- **Flow Control Frame:**
  Response of the receiver specifying min. timing and max. buffer size (=block size) for consecutive frames
  ```
  0x3 | Flow Status | Block Size | Separation Time
  ```

- In case of error (timeout or wrong sequence number) application layer is informed but not sender of the message

- No inherent reliability, application layer has to handle errors

![Diagram showing the frame types and their structures](image)
ISO-TP Addressing

- Flow control requires unicast communication
- Addresses have to be predefined and statically assigned
- Addressing schemes:
  - Normal Addressing:
    Source and destination address are encoded in CAN identifier
  - Extended Addressing (for gateways):
    Additional Transport-PCI Byte (= first byte of CAN payload) with gateway address
    → CAN payload reduced to 0..6 bytes
General-purpose HLPs

TP2.0
TP2.0
Overview

- Designed to allow existing diagnostics protocols on CAN2.0A
- Mainly used by Volkswagen Group
- Connection-oriented transport protocol enabling:
  - Segmentation of arbitrary size
  - Flow control with handshake
  - Dynamic assignment of CAN identifier per channel (vs. static assignment of CAN identifiers in ISO-TP)
  - Automatic recovery after timeout
- Addressing:
  - Unicast
  - Multicast, e.g. all ECUs on the powertrain
  - Broadcast
TP2.0
Broadcast communication

- Allows usage of gateways (specified by Logical Address)
- Broadcast messages with and without required response
TP2.0
Connection-oriented unicast communication

Connection setup request/response message:
- CAN Identifier
- CAN Payload
- Opening ID
- Address
- Opcode
- RX ID
- TX ID
- APP Type
- Destination ID
- Sender ID
- ID of application e.g. 0x01 Diagnostics
- Request 0xCO
- Positive Response 0xD0
- Negative Response 0xD6-0xD8

Data message:
- Opening ID
- Opcode
- 1..7 Data
- Includes Sequence Number, Receive Ready (for Flow Control), etc.
- ACK

Connection shutdown message:
- Opening ID
- Opcode
- Connection Test 0xA3
- Positive Response 0xA4
- Negative Response 0xA8
TP2.0
Message sequence

1. Channel Setup
2. Data Exchange
   - Block-wise data transmission
   - Cumulative acknowledgements
3. Channel Shutdown
Special-purpose HLPs

CANopen
CANopen
Overview

- Developed by CAN in Automation (CiA) since 1995
- Originally developed for motion-oriented machine control networks, by now it is also used to network:
  - medical electronics, automotive-, industrial- and rail-vehicles, laboratory automation systems,
  - building automation systems,
  - embedded networks such as passenger information systems, gambling machines and professional coffee machines,
  - vehicle add-ons (blue lights, taximeter, etc.)
- Standardized in 2002 under EN 50325-4
- Features:
  - CAN 2.0A on Data Link layer (optional CAN 2.0B)
  - Network auto-configuration
  - Access to all device parameters
  - Device synchronization
  - Cyclic and event-driven data transfer
  - Synchronous reading or setting of inputs, outputs or parameters
CANopen Overview

Three parts:
- Application Layer
- Object Dictionary
- Communication Profile

Based on: Zeltwanger 2007, CANopen
CANopen
Object Dictionary and Profiles

- Every CANopen device has a standardized device specification, the *Object Dictionary (OD)*
  - It includes general objects (ID, manufacturer, etc.) and status objects (temperature, speed, etc.)
  - Semantics of the OD-objects are defined in the *Electronic Data Sheet (EDS)*
  - Objects are addressed by 16-bit index + 8-bit subindex
    - 1000-1FFF: Communication profile area (CiA DS-301)
    - 2000-5FFF: Manufacturer-specific profile area
    - 6000-9FFF: Standardized device profile area (e.g. CiA DS-401)
    - A000-AFFF: Network variables (NWV)
- CANopen defines:
  - Communication profiles: definition of fundamental communication mechanisms
  - Device profiles: unambiguous definition of manufacturer-independent OD-parameters describing the device and its network behavior (i.e. input/output modules, drives, encoders, etc.)
- Devices become interoperable and interchangeable between manufacturers
CANopen
Communication Profile

- Process Data Objects (PDO): Transport of real-time data (=operational data)
- Service Data Objects (SDO): Read and write OD entries (=system parameters)
- Special Object Messages:
  - Synchronization (SYNC)
    Cyclic time synchronization
  - Time Stamp (TIME)
    Adjustment of global network time
  - Emergency Object (EMCY)
    Indicate device internal errors
- Administrative Messages:
  - Network Management (NMT)
    Node state monitoring
  - Error Control:
    Cyclic heartbeat, Node/Life guarding
CANopen
Device and Application Profiles (extract)

- **CiA 301**: CANopen application layer and communication profile
- **CiA 401**: Device profile for generic I/O modules
- **CiA 402**: Device profile for drives and motion control (servo controller, stepper motor controller, frequency inverter)
- **CiA 404**: Device profile for measuring devices and closed-loop controllers
- **CiA 406**: Device profile for encoders (rotating and linear)
- **CiA 413**: Set of device profiles for truck gateways
- **CiA 415**: Application profile for road construction machine sensors
- **CiA 418**: Device profile for battery module
- **CiA 419**: Device profile for battery charger
- **CiA 422**: Application profile for municipal vehicles (e.g. garbage trucks)
- **CiA 423**: Application profile for power drive systems (e.g. diesel engine)
- **CiA 424**: Application profile for rail vehicle door control systems
- **CiA 447**: Application profile for special-purpose car add-on devices
CANopen
CiA DS-447 Car add-on devices

- Attachment of add-on devices, such as blue light, siren, taximeter, etc.
- Standardization finished in 2008
CANopen
CiA DS-413 Device profiles for truck gateways
CANopen

ISO 11783 (ISOBUS) for agricultural and municipal vehicles, based on J1939 and NMEA-2000

Source: Zeltwanger 2005: J1939-based application profiles
Special-purpose HLPs

SAE J1939
SAE J1939

- Specified by *Society of Automotive Engineers (SAE)* heavy trucks and bus division
- The SAE J1939 set of profiles is based on the CAN data link layer (ISO 11898-1) using the extended frame format (CAN2.0B) with 29-bit identifier
- Features
  - Unicast and broadcast communication
  - Network management
  - Transport protocol functions: data segmentation, flow control
  - Definition of parameter groups
  - Support of real-time close loop control
- Applications
  - Light to heavy trucks
  - Agriculture equipment e.g. tractors, harvester, etc.
  - Engines for public work

![Diagram showing a network with bridge connections between truck bus and trailer bus, including engine, transmission, brakes, and lighting components.](image-url)
SAE J1939 Standards

**SAE J1939-71 Truck and bus power-train network**
Defines all parameters as well as assembled messages called parameter groups

**SAE J1939-21 Data link layer**
Defines commonly used messages such as Request, Acknowledgement and Transport Protocol

**SAE J1939-31 Network layer**
Defines repeaters, routers, gateways and bridges

**SAE J1939-73 Application layer diagnostics**
Defines diagnostic messages

**SAE J1939-11 Physical layer**
Physical layer based on ISO 11898-2 at 250 kbit/s with up to 30 devices and a maximum of 40 m bus length (twisted shielded pair)

**SAE J1939-81 Network management**
Defines message sequences for initialization and constraints on the use of addresses (e.g. address claiming)
**SAE J1939**

**Message Format**

- **Priority**: Priority during the arbitration phase (lower value = higher priority)
- **Reserved**: Reserved for future usage (always 0)
- **Data Page selector**: Expands parameter groups (for future usage)
- **PDU Format**:
  - **Global PGNs for broadcast parameter groups**
    - PDU Format $\geq 0xF0 = 240_{10}$
    - PDU Specific: Group Extension (further PDU type specification)
  - **Specific PGNs for unicast parameter groups**
    - PDU Format $\leq 0xEF = 239_{10}$
    - PDU Specific: Destination Address


**SAE J1939 Example**

**Engine Temperature message:** Broadcast transmission with 1 Hz

- CAN 2.0B Frame

- Priority: 6
- Res: 0
- DP: 0
- PDU Format: 254 = 0xFE
- PDU Specific: 238 = 0xEE
- Source Address: ???

- Data Field:
  - Coolant Temperature
  - Fuel Temperature
  - Engine Oil Temperature
  - Turbo Oil Temperature
  - Engine Intercooler Temp.
  - Not defined

**Torque/Speed Control message:** Unicast transmission

- to Engine (=00) with 100 Hz
- to Engine-Retarder (=15) with 20 Hz

- Priority: 3
- Res: 0
- DP: 0
- PDU Format: 0
- PDU Specific: 15 (= Engine-Retarder)
- Source Address: 11 (= ABS/TC)

- Data Field:
  - Control Bits
  - Requested Speed / Speed Limit
  - Requested Torque / Torque Limit
  - Not defined
The Transport Protocol specifies the breaking up of large amounts of data into multiple CAN-sized frames, along with adequate communication and timing to support effective frame transmission between nodes.

Two types:

- **Broadcast Announcement Message (BAM)**
  - Broadcast communication
  - Connection-less (e.g. no handshake)
  - Unreliable
  - No flow control

- **Connection Mode Data Transfer (CMDT)**
  - Unicast communication
  - Connection-oriented (2-way handshake)
  - Reliability by cumulative ACKs
  - Flow control by windowing
SAE J1939
Addressing

**Address:**
- Unique identity within a session
- Every device requires a unique address (0-253)
  - 254: zero address
  - 255: broadcast address
- Included in every message
- Can change during re-configuration

**Name:**
- Probably unique identifier within the network
- Provides functional identification of ECUs
- Used to arbitrate in the case of an address selection conflict

<table>
<thead>
<tr>
<th>Name</th>
<th>Arbitrary Address Capable</th>
<th>Industry Group</th>
<th>Vehicle System</th>
<th>Reserved</th>
<th>Function</th>
<th>Function Instance</th>
<th>ECU Instance</th>
<th>Manufacturer Code</th>
<th>Identity Number</th>
</tr>
</thead>
</table>
SAE J1939
Network management

- Dynamic address allocation (address claiming)
- Address conflict detection
- Address conflict resolution

Address Claim
DA=255, SA=B

Address Claim
DA=255, SA=C

Address Claim
DA=255, SA=D

Address Claim
DA=255, SA=A

Address Claim with no complications.
SAE J1939 Application
SAE J1939
Fleet Management System (FMS)

- Supervise a whole fleet - consisting of vehicles from different manufacturers - over the Internet
- Developed by the 6 major European truck manufacturers Daimler, MAN, Scania, DAF, IVECO, Volvo/Renault
- Based on J1939
- Vehicle data shall be available for third parties but internal vehicle busses shall be untouched
- Secure and legal solution for the remote download of data e.g. from the digital tachograph
Special-purpose HLPs
Diagnostics
Interchange of digital information between an on-board ECU and an off-board diagnostic tester to facilitate inspection, test, diagnostics and configuration.
Diagnostics
ISO 15765-3 Diagnostics on CAN

- *Diagnostics on CAN* standardized in ISO 15765-3 in 2004
- Enables interoperability between off-board diagnostic tester and on-board ECU
- ISO 15765-3 is based on the *Keyword Protocol 2000 (KWP2000)* protocol
- Client-Server with simple request-response communication
Diagnostics
ISO 15765-3 Diagnostics on CAN

- Client-Server communication:
  - Client (=diagnostic tester) initiates request and waits for confirmation
  - Server (=ECU) receives indication and sends response

- Services
  - Diagnostic Management: Control of diagnostic sessions
  - Network Layer Protocol Control
  - Data Transmission: Read from and write to ECUs
  - Stored Data Transmission: Read Diagnostic Trouble Codes (DTC)
  - Input/Output Control: Control of ECU I/O
  - Remote Activation of Routines: ECU program startup
  - Upload/Download: ECU Flashing
Diagnostics
ISO 15765-3 Diagnostics on CAN

Message formats:

Service Request

<table>
<thead>
<tr>
<th>SID</th>
<th>Request Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>SID</td>
<td></td>
</tr>
</tbody>
</table>

Positive Response

<table>
<thead>
<tr>
<th>SID</th>
<th>Response Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>0x40</td>
<td></td>
</tr>
</tbody>
</table>

Negative Response

<table>
<thead>
<tr>
<th>Error ID</th>
<th>SID</th>
<th>Error Code</th>
</tr>
</thead>
</table>
**Diagnostics**

Unified Diagnostic Services

- **Unified Diagnostics Services (UDS)** standardized by ISO 14229
- Advancement of *Diagnostics on CAN* for general usage
- Whereas ISO 15765-3 relies on CAN, UDS is independent of lower layer protocols
- Technically UDS is almost identical to *Diagnostics on CAN*, advancements are mainly the restructuring of SIDs and unification
- UDS also defines, as one of the first protocols, a security layer in order to encrypt data

![Diagram of Diagnostics](image)
Diagnostics
On-Board Diagnostics

- Self-diagnostic and reporting capability of modern vehicles
- Guarantees standardized access to vehicle information for:
  - fault diagnostics by repair shop and
  - emission inspection by technical inspection agencies ("TÜV")
- Mandatory in Europe for:
  - gasoline vehicles manufactured since 2001
  - diesel vehicles manufactured since 2003

- OBD provides diagnostic data on:
  - Emission-related components
    (e.g. lambda sensor, catalytic converter)
  - Engine
  - Vehicle electronics
Diagnostics
On-Board Diagnostics

Service Request

<table>
<thead>
<tr>
<th>Service ID SID</th>
<th>Parameter ID PID</th>
<th>0..6 Byte Request Parameters</th>
</tr>
</thead>
</table>

- **Service Identifiers (SID):**
  - Fault memory
    - 0x03 Request emission-related diagnostic trouble codes
    - 0x02 Request powertrain freeze frame data
    - 0x04 Clear emission-related diagnostic information
  - Test of emission-related components
    - 0x05 Request oxygen sensor monitoring test results
    - 0x06 Request control of on-board system, test or component
  - Read ECUs
    - 0x01 Request current powertrain diagnostic data
    - 0x09 Request vehicle information

- **Parameter Identifier (PID):**
  - 0x04 Calculated Load Value
  - 0x05 Engine Coolant Temp
  - 0x0A Fuel Pressure (gage)
  - 0x0C Engine RPM
  - 0x0D Vehicle Speed
  - 0x11 Absolute Throttle Position
Questions

- Why are Higher Layer Protocols (HLP) required?
- What are the main functions of HLP in automotive environments?
- Why almost all HLPs introduce unicast communication?