Approaches for in-vehicle communication – an analysis and outlook

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Abstract. Electrical and electronic systems have been getting raising importance for innovations in the automotive industry. Networking issues are a key factor in this process since they enable distributed control functions and user interaction bringing together nodes from different vendors. This paper analyses available and emerging network technologies for in-vehicle communication from a requirements driven perspective. It reviews successful network technologies from other application areas regarding a possible deployment in vehicular communication and distinguishes passenger car and commercial vehicle sectors as far as possible. This contribution is oriented to the OSI reference model showing the state of the art and future opportunities at the level of the several communication layers with a focus on physical layer issues and medium access protocols and including information modeling aspects.

Keywords: in-vehicle networks; Controller Area Network; SAE J1939; Isobus; BroadR Reach; Reduced Twisted Pair Gigabit Ethernet; Time Sensitive Networking; OPC UA

1 Introduction

Automotive systems became complex systems of a reasonable number of distributed electronic control units (ECUs) with even more sensors and actuators attached. In passenger cars the number of ECUs reached 70, processing about 2500 signal points already ten years ago [1] and their numbers are still growing. From the late 1980s on standardized serial communication protocols have been used to interconnect the ECUs and signals. This approach provides several advantages, including the following. Subsystems of different vendors become able to interact with each other, sensor data can be shared by different functions and the number of wires in a vehicle can be reduced in comparison to parallel wiring of sensors, actuators and ECUs, which results in less costs for material and assembling, less weight and hence less fuel consumption of the vehicle.

There are many and various application functions utilizing the communication infrastructure of vehicles and new functions are evolving. For example, driver assistance systems improve towards autonomous driving, with truck platooning as a use case being deployed soon [2]. These functions impose requirements to both in-vehicle and car-to-X communication, where this paper focuses on in-vehicle networks. The application functions require different characteristics of the communication systems. For example, functions for driver assistance have a priority on determinism and functional safety, whereas other functionality, such as infotainment, has a priority on data throughput. As a consequence the communication structure consists of interconnected subsystems of heterogeneous technologies, which will be analyzed in this paper and opportunities for improvements will be discussed.

In other industries Ethernet-based technologies have been introduced successfully. For example in the industrial automation domain, Ethernet-based real-time protocols have been standardized and deployed in applications, where fieldbus protocols were used before. This development was primarily motivated by better capabilities for network management, maintainability and communication performance. In IEEE there are currently activities to specify extensions to the lower layers of the Ethernet protocol which may support its utilization at in-vehicle networks. The paper also aims to analyze where and under which conditions Ethernet-based technologies including their currently developed extensions can support in-vehicle communication and how a migration could be done.

This paper reviews the requirements for communication networks in the domains of passenger cars and of commercial vehicles. It gives an overview of available technologies and discusses their applicability in commercial vehicles. The focus of the paper will be on network technologies, which enable a broad range of vehicular applications while technologies for specialized applications will be only briefly dealt.

2 In-vehicle networks

2.1 Automotive networks and topologies

Vehicular networks started with the controller area network (CAN, ISO 11989-2), developed in 1983 and presented in 1987, defining layers 1 and 2 of the OSI reference model [3]. It basically offers a linear bus topology, which greatly reduces the wiring efforts in cars. In addition to CAN as a universal solution, other vehicular communication systems have been developed for more specialized applications. The local interconnect network (LIN, ISO 17987-1 to -7) focuses on small networks mainly for discrete I/O signals with low bandwidth requirements. LIN implements a master-slave-topology offering a low-cost, single wire solution compared to CAN-enabled devices. In the other direction, FlexRay was introduced 2000, offering benefits over CAN in means of bandwidth, real-time capability, redundancy and functional safety. The driving aspect was the advent of X-by-wire technologies, which needed a higher reliability and safety rating. FlexRay offers a redundant connection between nodes and supports both star and bus topology. The ability to support time-critical closed loop control application in conjunction the resulting higher cost and complexity of the components has preferred FlexRay's usage to engine, steering and advanced driver assistance systems (ADAS). Media Oriented Systems Transport (MOST) was developed exclusively for telematics and multimedia applications and is utilized only in the infotainment system. Comprehensive surveys about the outlined network technologies can be found in the literature [4], [3], [5], [6].

These core standards are still a subject for improvements. For example for CAN there are SAE J2284/3 (High-Speed CAN for Vehicle Applications at 500 kbit/s) aiming at high transmission rate and higher allowable node count, and SAE J2411 (Single Wire CAN Network for Vehicle Applications) providing a simplified variant for low requirements regarding bit rate, bus length and robustness. As a disadvantage, sometimes compatibility issues arise, such as for CAN FD (flexible data-rate) [7].

Upon these communication layers, a number of protocols and standards have been developed for network control and data exchange. For CAN, this includes general purpose protocols like ISO 11898-4 (TTCAN, Time-Triggered Communication on CAN), industry-specific protocols like CANopen, SAE J1939 and ISOBUS [4] [3] and protocols for special purpose vehicles, mainly derived from CANopen like EnergyBus (pedelecs, E-bikes), CleANopen (municipal vehicles) and FireCAN (DIN 14700, for external firefighter equipment). LIN does not comprise diverse higher layer protocols, but is most often terminated with a gateway to connect to an overlying CAN network. FlexRay, as a safety-critical subsystem, allows a diagnostic function via gateway, but also includes no diverse higher layer protocols. An outstanding application layer protocol is On-board Diagnostic (OBD) specifying self-diagnostic and reporting capability to assist the vehicle owner and repair technician. The development of OBD began in the 1980s driven by legal requirements for continuous emission surveillance during the entire lifetime of a vehicle. There are several standards for OBD, some of them contain both protocol and data object definitions. At the beginning ISO 14230 (Road vehicles - Diagnostic communication over K-Line, DoK-Line) gain importance, also known as KWP2000 and referring to ISO 15031-5 (Road vehicles - Communication between vehicle and external equipment for emissions-related diagnostics). Its CAN-based version ISO 15765-3 (Road vehicles - Diagnostic communication over Controller Area Network, DoCAN) has been widely implemented but never released by ISO. The most recent standard for OBD is ISO 14229 (Road vehicles - Unified diagnostic services, UDS). It focuses on application data and services, decoupling them from the lower layers. UDS provides data and services with the same semantics as the ODB standards based on KWP2000 and extend them but the representation is not compatible. This collection is not complete, there are additional standards about OBD, such as definitions by SAE or about communication to external equipment.

The different areas of preferred application for each bus system has led to a heterogeneous network structure, so far with only few needs for interconnection; each segment is mainly designed to work standalone, exchanging mainly status information with other networks. Nowadays the bus segments are usually connected by a centralized gateway. A typical network architecture is shown in figure 1, while additional topology examples can be found in [3]. Other approaches focus on the introduction of backbone networks for different application areas and different positions in the vehicle as described in [8] and [5].

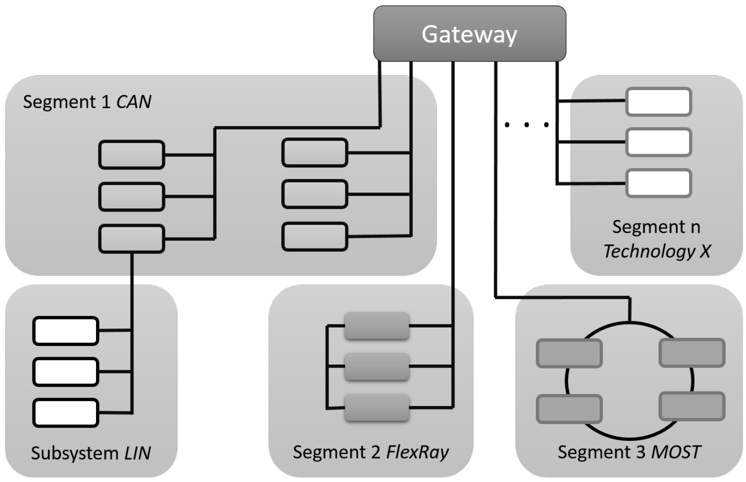

Fig. 1. Typical vehicular network architecture

Almost all available literature about vehicular network architectures aims at passenger cars, while the commercial vehicles sector is inadequately represented in the related work.

2.2 Communication requirements and applications

With more driver assistance, autonomous driving and other integral functionality, there are variable applications demanding information exchange between the ECUs, sensors and actuators. These applications also require diverse qualities of service, mainly determined by the update rate of information. In [9] update interval requirements at commercial vehicles are given, such as tire pressure: 10 s, battery current: 1 s, cruise control information: 100 ms and electronic transmission controller information: 10 ms. This fact of variable requirements in conjunction with the large number of communication nodes and the limited bus capacities led to a functional separation of bus segments into subsystems. The most typical subsystems comprise the power train bus (engine and gear control), the chassis system (e.g. anti-lock brake system) and driver assistance (e.g. electronic stability program), the body and comfort electronics (e.g. air condition), and the infotainment (audio and navigation). The power train bus needs to be generally accessible for diagnostics including emission monitoring to fulfill legal regulations, while all other bus system diagnostics is depending on manufacturer-specific tools.

The requirements imposed by the applications on the communication network comprise determinism, fault tolerance, data throughput and functional safety. Security requirements have to be managed for components, which grant access from outside components. This becomes a raising issue since car-to-X communication and infotainment connectivity pose growing challenges. In [10] an overview about the subsystems and their priorities of communication requirements is given. Table 1 extracted from this source summarizes the assignment of the different requirements to the subsystems.

Table 1. Automotive subsystems and their major requirements acc. to [10]

	Fault tolerance	**Determinism**	**Bandwidth**	**Flexibility**	**Security**
Chassis	YES	YES	SOME	NO	NO
Airbag	YES	YES	SOME	NO	NO
Powertrain	SOME	YES	YES	SOME	NO
Body and comfort	NO	SOME	SOME	YES	NO
X-by-wire	YES	YES	SOME	NO	NO
Multimedia / Infotainment	NO	SOME	YES	YES	NO
Wireless / Telematics	NO	SOME	SOME	YES	YES
Diagnostics	NO	SOME	NO	YES	YES

An advantage of the segmented topology is, that dependability of the communication for critical applications can be achieved by taking into account only a small number of components interconnected by a single segment. Additionally, every single bus segment can be configured in a way that is exactly matching the specific application requirements. On the other hand, the application functions of the vehicles become more complex and require information exchange across several bus segments. The therefore necessary communication paths involve segment transitions, which lead to an additional, resource demanding load for those ECUs acting as gateways between the bus segments. The number of cross-segment functions and gateways influences the efficiency of the overall network topology.

2.3 Influences by upcoming power concepts on in-vehicle networks

Vehicles like heavy duty road trains, buses and equipment for forestry and agriculture are characterized by a big number of auxiliary aggregates. These auxiliaries comprise compressors, fans, hydraulic pumps for servo-assisted steering, lifts etc. Nowadays they are usually driven directly by the combustion engine. The available power budget is coupled to the speed of the engine and cannot be steered on demand. Therefore the aggregates have to be scaled in a way that they can be operated at low engine speed. As a consequence, weight and size of the aggregates raise, decreasing the efficiency of the vehicle and resulting in a higher fuel consumption. In contrast to this, electrically powered drives allow a flexible power supply management which can adjust the power to operate an aggregate depending on the individual demand. Hence, the introduction of electric drives for the auxiliaries has a high potential to increase their efficiency. An accompanying effect of this concept is a significant increase of the number of communication nodes and signal points of the in-vehicle network, since the power management will require information exchange among the electrically powered auxiliaries and between the auxiliaries and other vehicle equipment. In contrast to the passenger cars with a mostly static configuration, in the context of commercial vehicles the communication topology is more dynamic due to the often changing of truck/trailer or tractor/implement combinations. Especially upon the initial composition of such a combination the exchange of device descriptions of the auxiliaries can become necessary which will cause a high amount of data to be transferred. Even this scenario does not happen very often, it is a some minutes lasting procedure when realized by conventional in-vehicle networks. Additionally there is the challenge of introducing many instances of the same or at least of a similar device type to the vehicle network. This opportunity will become important especially for modular devices and it shows a lack of scalability of the current communication standards. Requirements coming from this use case may exceed not only the number of physical nodes but also the number of logical addresses of a network segment when the modules shall be addressed individually. Another issue is about the information model. The standardized information models for commercial vehicles, for example SAE J1939 [9] describe only the common available data objects and do not allow a dynamic management of the object pool. Currently, additional objects can only be described in a proprietary way, which increases the engineering effort for the information exchange.

3 Physical Layer aspects

In this chapter, the state of the art technologies which are most widespread in the automotive domain will be described. These are CAN (ISO 11989-2) for the passenger car sector and SAE J1939 as a CAN-based adaptation for the commercial vehicle sector. In contrast to this, a state of the art technology which is widespread in other domains will be introduced, Ethernet 100BASE-TX. Relevant criteria are robustness, bit rate, number of nodes, network extension and topology in order to fulfill application requirements on fault tolerance, bandwidth and scalability. With Ethernet 100BASE-T1 and Ethernet 1000BASE-T1 two emerging technologies will be described, which are promising candidates to enable Ethernet based protocols on a physical layer being as simple and reliable as nowadays solutions.

Currently used in-vehicle networks have different physical layer characteristics because of their design and application area. Upcoming technologies and concepts like ADAS or in-vehicle power concepts require network systems with a higher bandwidth to handle the amount of data. Ethernet is generally regarded as a next in-vehicle network for future development. A comparison of physical layer characteristic between CAN and Ethernet is shown in Table 2.

Table 2. Physical layer characteristic of CAN and Ethernet based communication

	CAN 2.0	**SAE J1939**	**Ethernet 100BASE-TX**	**BroadR-Reach® (100BASE-T1)**	**Ethernet 1000BASE-T1**
Standardization	ISO 11898-2	SAE J1939	IEEE 802.3 Clause 25	IEEE 802.3bw	IEEE 802.3bp
Possible topologies	bus	bus	star	star	star
Max. transfer speed	1 Mbit/s	250 kbit/s	100 Mbit/s	100 Mbit/s	1 Gbit/s
Max. cable length	40 m for 1 Mbit/s	40 m	100 m	15 m	15 m
Transmission media	copper, twisted pair	copper, shielded twisted pair	copper, 2 unshielded twisted pair	copper, single unshielded twisted pair	copper, single unshielded twisted pair

Typical CAN applications range from engine control and diagnostics to comfort electronics, with different bandwidths being employed. Typically, the range below 125 kbit/s is regarded as low-speed CAN oder CAN B, and the range from 125 kbit/s up to 1 Mbit/s is regarded as high-speed CAN, or CAN C. The CAN A class defines a bandwidth of 10 kbit/s or lower, historically used for diagnostic purposes. The maximum line length is depending on the chosen bandwidth. This limitation arises from the propagation time of the signal on the medium combined with the need for CAN to sample the received data exactly bit-synchronously. All bus nodes need to see the same bit value at the same point in time. Fault-tolerance is achieved by the use of differential signaling and the insertion of stuff-bits after 5 consecutive identical bit values, guaranteeing a state transition occurrence for synchronization. For commercial vehicle, the Society of Automotive Engineers (SAE) defines a communication protocol standard named J1939. It uses CAN as physical layer and is widely in use. Compared to CAN 2.0, SAE J1939 sets some limitations for the physical layer. The standard defines a maximum transfer speed of 250 kbit/s with a maximum cable length of 40 meters, being below the allowed rating of up to 1 Mbit/s on 40 m distance for CAN, and a bus topology with a maximum number of 30 physical nodes.

However, new technologies and concepts need an enhancement of the physical layer. Nowadays, Ethernet is a widely used point to point communication technology. With 100BASE-TX it is possible to transfer data with 100 Mbit/s over a maximum cable length of 100 meters. Due to the requirements on electromagnetic interference (EMI) and radio frequency interference (RFI) in the automotive market, Ethernet 100BASE-TX could not be used as an in-vehicle communication network. In addition to that limitation, 100BASE-TX uses 2 unshielded twisted pair cable, which would increase the overall cable weight and cost. To compensate the disadvantages of Ethernet in physical layer for automotive, new PHY's are ready for operation or in development. BroadR-Reach® supports 100 Mbit/s transfer speed over a single unshielded twisted pair cable which meets automotive EMI requirements [11] and is standardized as 100BASE-T1 in IEEE 802.3bw-2015 [12]. BroadR-Reach® has been used in a real-time Ethernet in-car backbone project, where BroadR-Reach® became a part of the Ethernet backbone system [13]. Also the applicability of BroadR-Reach for use with an industrial Ethernet protocol has been approved in [14]. But future challenges like uncompressed video for ADAS would need more bandwidth [15]. Hence, the next generation for Ethernet in the automotive field is under development. The standardization of a 1000BASE-T1 PHY in IEEE 802.3bp is currently in progress [16]. The 1000BASE-T1 PHY supports a maximum transfer speed of 1 Gbit/s in full duplex mode over a single unshielded twisted pair cable with a maximum length of 15 meters. First PHY's on the basis of IEEE802.3bp draft are introduced [17]. Another point for the trend of Ethernet as in-vehicle communication system is the possibility to support voltage and current levels over a single twisted pair Ethernet link. Currently the 1-Pair Power over Data Lines (PoDL) Task Force defines under IEEE802.3bu a standard for that feature [18]. The deployment of these Ethernet based physical layers in the commercial vehicle sector is more challenging in comparison to passenger cars. A main reason is the topology extent beyond 15 meters which requires components for signal refreshing. Beside this, the harsher environment induces higher requirements for ingress protection and overall robustness of connectors and may cause signal refreshing too.

4 Medium Access Control aspects

Medium access control is most relevant to fulfill application requirements on determinism, transmission latency and data throughput. Here, the data link layer methods for medium access control of CAN and Ethernet as state of the art technologies will be briefly discussed. Time sensitive networking (TSN) targets to the real-time capability of Ethernet. Relevant TSN specifications will be described, as they can contribute to cover a broad range of vehicular requirements.

4.1 State of the art protocols

CAN specifies an asynchronous, event based medium access protocol. The communication is message-oriented, with a given identifier being assigned to a certain information, but not to a specific device. The number of devices on a bus is theoretically not limited, while the number of possible message identifiers depends on the their length. Two types of identifiers, 11 bit and 29 bit, are available to choose. CAN follows the Carrier Sense Multiple Access Collision Resolution (CSMA/CR) scheme, where each network node is allowed to send data when it detects an idle state at the medium. The messages are prioritized by their identifier, i.e. in case of conflicts an arbitration occurs and the message coming up with the higher order identifier being sent successfully. The arbitration reduces the number of retries and avoids a stop of data transfer due to congestions [3]. Although CSMA/CR represents a non-deterministic method, determinism can be reached for messages holding the highest priority. To fulfill application requirements on latency of transmission, a serious engineering effort regarding the assignment of priorities and update intervals of data objects is necessary and simulation and test of the network configuration is recommended. A detailed analysis about schedulability in CAN Networks is provided in [19].

The IEEE 802.1 Ethernet standard utilizes Carrier Sense Multiple Access with Collision Detection (CSMA/CD) for medium access and was originally not designed to transport any time sensitive traffic and hence does not provide determinism. After introduction of the IEEE 802.1Q, providing the possibility to assign a defined priority level to a particular message by using the Virtual LAN (VLAN) field, many proprietary industrial protocols were developed, e.g. Ethernet/IP, PROFINET RT, SERCOS and many other, which were build upon this feature. Due to limits of the priority based communication, some additional functionalities to further improve the real-time efficiency were introduced. These are: TDMA based communication (e.g. PROFINET IRT), polling based communication (Powerlink) or summation frame communication (EtherCAT). All mentioned approaches, allow to achieve high real-time performance, however it require modification of the original IEEE Ethernet MAC [20]. Beside this development of industrials protocols for Ethernet to transfer sensitive traffic a pool of establishments from the automotive area, like BMW and Daimler AG, developed a in-vehicle communication protocol, known as FlexRay, to handle the requirements like real-time communication.

4.2 Time Sensitive Networking

Due to the rapid evolution of the IT technology, especially the entertainment sector, such as high quality audio and video streaming, demands for real-time communication followed to the establishment of a new IEEE working group, Audio Video Bridging (AVB). The aim was to further enhance the real-time capabilities of the Ethernet standard. The suitability of AVB for particular vehicular use cases already has been proven by simulation [21]. Due to the high interest of the industry in this activity, the focus of the group has been broadened by including industrial application requirements [22]. At the same time, the name of the working group has been changed to more generic Time Sensitive Networking (TSN). An important aspect for this activity was to offer low costs devices, which require a minimal configuration effort to achieve plug-and-play functionality [23]. In case of in-vehicle communication, the plug-and-play functionality is not of major importance. It is due to the fact that in opposite to the industrial automation, in cars, the installed in-vehicle network infrastructure remains unchanged. More important is the spectrum of traffic classes that can be supported by the TSN technology. It allows to satisfy demands in terms of high throughput required by multimedia or infotainment systems, but also provide high determinism and availability, thus enabling support of control loops and safety critical functions. Having one system supporting different traffic flows, would help to significantly reduce the complexity of the current in-car communication infrastructures, and open the possibility for the future functionalities, such as highly sophisticated ADAS. The focus of TSN is very broad, therefore multiple sub-groups has been established to deal with a particular aspect. The most relevant for in-car communication are listed below:

- Timing and synchronization aspects:
  - timing and synchronization IEEE 802.1.AS
- Quality of service aspects and resource reservation:
  - stream reservation protocol IEEE 802.1Qat and the further extension IEEE 802.1Qcc
  - path control and reservation mechanisms IEEE 802.1Qca
- Forwarding and queuing mechanisms
  - forwarding and queuing enhancements for Time-Sensitive streams IEEE 802.1Qav
  - deterministic communication through time aware shaper IEEE 802.1Qbv and cycling queuing and forwarding shaper IEEE 802.1Qch
  - frame pre-emption IEEE 802.1Qbu
- Reliability
  - seamless redundancy IEEE 802.1CB
  - redundancy mechanisms included in IEEE 802.1Qca

There are several papers currently available, which try to evaluate some of the TSN amendments in the in-car communication context. In [24], authors investigated the worst case behavior of three different shapers, namely *Burst Limiting Shaper (BLS)*, *Time Aware Shaper (TAS)* and *Peristaltic Shaper (PS)* using analytical calculation and simulation. According to the authors in [24], the best performance in terms of latency and latency jitter had the *TAS*, however require a lot of configuration efforts. *BLS* offers a compromise between performance and configuration efforts. The *PS* offers the easiest configuration, however the worst performance as comparing to other shapers. An additional deep investigation of the worst case latency provided by *BLS* in a typical automotive setup was conducted in [25]. Authors shown that in some cases it is better to use the IEEE

802.1Q than TSN + *BLS*. In order to efficiently use *BLS* some additional filtering functionality is required. The same authors analysed the effect of TSN with frame preemption (IEEE 802.3br) to worst-case end-to-end latency in [26]. Their experiments in a typical automotive setup show, that latency guarantees for time-critical traffic can be significantly improved while preemptable traffic only slightly degrades. In [27], authors investigated bandwidth allocation ratio for the scheduled traffic (IEEE 802.1Qbv), while adjusting the Maximum Transmit Unit (MTU). They have shown that using two time sensitive flows it is possible to achieve cycle times of $250\mu s$ for the MTU size of 109 bytes. A survey in [28] provide a broad overview about the Ethernet-based communication with the focus on IEEE AVB. It discusses especially the scheduled traffic and presents simulation results, where offset scheduling *TAS* were combined to achieve an temporal isolation from other kinds of traffic. The fault-tolerance aspects of TSN were investigated in [29]. Authors compared two different approaches aiming to guarantee seamless redundancy. They pointed out that the current seamless redundancy mechanisms provided by TSN lacks of flexibility in terms of stream reconfiguration and mechanisms for automatic stream reservation. Despite of all advantages, TSN increases the configuration overhead of a network. In [30] an ontology-based approach to support automatic network configuration of TSN is presented. The authors demonstrated the approach by modeling the *TAS* and came to the conclusion that the expressiveness of the ontology has to be further investigated. The several papers demonstrate that TSN is actually in focus, but it also shows a gap in the field of implementation to simulate the behavior of TSN. An easily accessible implementation of single protocols would be a benefit to gain insight of TSN and whose performance. After all it can be concluded that TSN is a prominent candidate for in-vehicle communication to handle future requirements. It supports different real-time classes, offers determinism and high reliability via seamless redundancy.

As a wrap-up of this chapter, table 3 gives a summary about the access methods of the discussed communication technologies.

Table 3. Summary on medium access methods

	CAN	**Ethernet**	**TSN**
Basic access protocol	CSMA/CR	CSMA/CD	CSMA/CD
Additional measures	priority based arbitration	–	scheduling
Determinism	restricted	no	yes

5 Transport protocol and efficiency aspects

In this chapter, the considerations are mainly driven by the application requirement of bandwidth. The state-of the-art technologies are compared regarding their performance to transfer different qualities of user data. For this communication layer no emerging technology is discussed, but new mappings with established protocols at higher layers open future opportunities.

The standard ISO 11898 for CAN does not specify higher protocol layers of the OSI reference model. CAN is limited to a maximum data object length of 8 octets and provides message oriented broadcasting without address information about the sender and receiver. This simplicity enables a small protocol overhead and allows short transmission times. Consequently, user data rates of approximately 7,5 KB/s for 1 octet payload and approximately 28 KB/s for 8 octets payload are possible, supposing a bus workload of 100 %, according to [3] and [31]. Although this throughput statement is not very impressive, it is sufficient for many applications regarding the update intervals of the required number of communication objects. In the domain of commercial vehicles, the widespread standard SAE J1939 defines transport protocols for segmented transport for both message-oriented broadcasts and node-oriented unicasts on top of the CAN layers. The transport protocols define an initial frame to announce the transmission and the user data length of a data frame is reduced to 7 by taking the first octet of the CAN payload for protocol information. The protocols shall not strongly interfere in the plain message exchange, therefore the standard defines a low CAN priority and a minimum frame gap of 50 ms. All these measures reduce the user data rate to below 140 bit/s and limit the application range to very low demanding functions.

While CAN based protocols show constraints which the upper limit of the payload size, Ethernet based protocols show a lack of efficiency considering the lower limit of the payload size. The payload size of an Ethernet frame is defined from 42 to 1500 octets, if the VLAN tag is used. When transferring control data of sensors and actuators, the user data length often will be between 1 and 4 octets and the remaining payload size needs to be filled by padding octets. Considering the overall Ethernet protocol overhead and the inter frame gap the gross ratio of net data becomes 1:84 for a single octet. When using a Ethernet bit rate of 100 Mbit/s, the net data rate in this worst case is still above 1 Mbit/s, again supposing a network load of 100 %, which is significantly higher than CAN communication.

Consequently, the substitution of CAN based protocols by Ethernet based protocols can overcome bandwidth limitations for in-vehicle communication when transferring big sized data objects. In [32] an approach is published, where the SAE J1939 application protocols are mapped on top of a TCP/UDP stack. The authors claim the applicability for the power train segment in heavy duty vehicle networks, which still needs further investigation. Nevertheless, this contribution shows, that a changeover to more powerful network technologies is possible without essential modifications at the application interface.

6 Information model aspects

In this section, a well established information model of the commercial vehicle domain is discussed. To enable the easy integration of future application function a possible extension of this model, which preserves the existing application interface, is described in the second subsection.

6.1 Consideration about available information models

The application layer protocol standards for in-vehicle communication SAE J1939 and ISO 11783, which are nowadays the mostly utilized standards for commercial vehicles, contain detailed information models to address vehicle components and their parameters. For example, one part of SAE J1939 comprehensively specifies parameters concerning typical components (e.g. engine, steering, collision sensors) and functions (e.g. speed control, air suspension control, aftertreatment) of an vehicle. The parameter description includes the unambiguous parameter identifier, information about name and acronym, data type, data range, affiliation to records for transmission and update intervals. This document provides a valuable contribution for the interoperability of the typical, widespread components and functions. On the other hand, the approach of SAE J1939 is difficult to manage in case of extending the model for new information object types or even for adding new instances of already existing object types. Currently such a extensibility is rarely required, but upcoming application concepts like introducing modular electrical drives for auxiliaries will tighten the problem.

6.2 Potential future information models

An object oriented modeling of application specific information structures can be used to improve the rigid information modeling provided by the current technologies for in-vehicle communication. OPC UA, a technology widely used mainly in the domain of industry automation, provides such an object oriented modeling. Currently, the OPC UA specification is being enhanced by PubSub, a new communication pattern according to the publisher/subscriber model enabling so called server based subscriptions [33]. In IEC 62541-3 the Address Space Model of OPC UA is defined. It can be considered as a meta model providing objects as the basis for any information model. The object elements are represented by nodes. These nodes comprise variables, methods or references to other objects. Additionally, IEC 62541-5 specifies nodes to be used for diagnostics and as entry points to server-specific nodes. As a result, an information model of an "empty" server is defined and the vendor of the component which is represented by the OPC server can customize it. As optional specification elements, predefined models for data access, alarms, history and others are available. Moreover, the information model can be changed during runtime of the server by adding or removing nodes. By this means, the OPC UA information model is independent from transport protocols and enable domain specific extendibility. For the deployment in in-vehicle networks, OPC UA needs the ability to be implemented on physical nodes with low resources. For this reason, OPC UA components need to be scaled down. In order to support this, the OPC UA specifications provide profiles, for example the OPC UA Nano Embedded device profile. Based on this profile, it is possible to scale down an OPC UA server to 15 kB RAM and 10 kB ROM [34], thus allowing implementation at the chip level of a resource limited device such as a sensor or an actuator.

To provide interoperability beyond this general information model and to ease the use of OPC UA in several domains, Companion Standards have been developed. For example, the specifications for building automation (in co-operation with BACnet), energy systems and management (participating in IEC TC 57 "Power systems") or railways transportation shows that OPC UA already has been approached by applications outside the industrial automation. The utilization of the OPC UA Address Space Model as a wrapper of data models provided by the in-vehicle communication standards could be a step ahead to the required extendibility of the models. The existing information structures can be preserved and transformed into an object oriented approach as it is shown in [35] for building automation. At the same time the co-existence with information models of upcoming components and functions, which are not covered by the available standards in the vehicle domain, becomes possible. For example, SAE J1939 data in parallel to data according to the standard CAN in Automation DS402 for electric drives could be modeled and transferred on the same network.

7 Conclusion

This paper shows the current status of in-vehicle communication networks in the field of passenger cars as well as for commercial and heavy duty vehicle, and points at upcoming challenges. It depicts the future of Ethernet as in-vehicle communication system related to several parts of the OSI reference model. In summary, Ethernet will take place in the automotive market, see also [36]. However, ongoing developments and implementations show, that new network systems will not immediately replace, but rather supplement them. This strategy is beneficial especially for critical systems, where proven-in-use concepts contribute to the functional safety.The evolution of automotive Ethernet, according to [8], propose the implementation of Ethernet in three generations. The first generation already exist in high class vehicles. It uses 100BASE-TX Ethernet with Diagnostics over IP (DoIP) for on-board diagnostics and ECU's updates. Figure 2 given by the author of [37] illustrates the next generations. Second generation uses Ethernet as additional in-vehicle network to transfer the amount of data from camera systems for drive assistance and infotainment. Finally, the 3rd generation with the possibility to transfer 1 Gbit/s will implement Ethernet as a backbone system and change automotive wiring harness from heterogeneous to hierarchical homogeneous network by introducing a new network topology level.

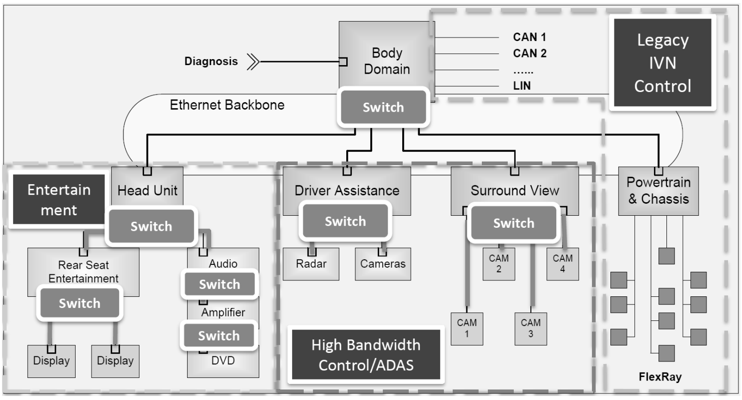

Fig. 2. Future architecture with Ethernet backbone acc. to [37]

In future, Ethernet in connection with TSN will be a possible approach for time relevant communication beside ADAS and infotainment. At the layer of information modeling, concepts incorporating dynamic and instantiable information object presentation like OPC UA can support the integration of new application functions.

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