The case for Ethernet in Automotive Communications

Lucia Lo Bello
Dipartimento di Ingegneria Elettrica,
Elettronica ed Informatica
University of Catania, Italy
Viale A. Doria, 6- 95125 Catania,
Italy
+39-095-7382386
lucia.lobello@dieei.unict.it

ABSTRACT

Several factors seem to favor the introduction of Ethernet technology in automotive communications. The spreading of Ethernet as an in-vehicle network for today's cars or for those in the near future is being broadly announced by spokespersons for major carmakers and automotive electronics companies. Even in the scientific community there is a growing interest in the topic, shown by the increasing number of studies on the performance of Ethernet-based technologies such as Switched Ethernet or Time-Triggered Ethernet in automotive embedded systems.

This position paper provides an overview on facts and trends towards the introduction of Ethernet in automotive communications and discusses how and to what extent Ethernet technology is likely to step in and provide benefits to the different automotive functional domains. The paper will also discuss which Ethernet technologies would be the possible candidates for the automotive industry.

Categories and Subject Descriptors

C.3.[Special-Purpose and Application-Based Systems] (J.7) [Computers in Other Systems].

General Terms

Performance, Design, Experimentation, Standardization.

Keywords

Automotive communications, in-car networks, Switched Ethernet, Time-Triggered Ethernet, Audio Video Bridging.

1. INTRODUCTION

A growing interest towards Ethernet as an in-vehicle network for cars of today and those in the near future has been recently shown by the industry. Several spokespersons for major carmakers (e.g. BMW, Daimler) and automotive electronics companies (e.g., Bosch, Continental, Micrel, etc.) explicitly addressed the case for Ethernet for automotive applications [1-3],[6],[41], providing examples of the current use of Ethernet in some applications and outlining what's next according to their companies' view. Stimulated by the interest shown by industries and supported by ongoing projects such as the SEIS project [3-4], academic research, often in collaboration with carmakers, is investigating the performance of Ethernet/IP [6-11], Ethernet ABV [12],[31], or Time-Triggered Ethernet [13] in automotive embedded systems.

Several factors seem to favor the introduction of Ethernet technology in the automotive communication systems arena. Some of them are similar to those that, ten years ago, motivated the interest towards the introduction of Ethernet in automation as either a complement or replacement of traditional fieldbuses. The automotive domain is, however, quite different from automation environments. An in-car embedded system is typically divided into several functional domains that feature different requirements and specific constraints [14].

In this context, this position paper discusses how and to what extent Ethernet technology is likely to step in and provide benefits to the different automotive functional domains. The potential for making Ethernet a complement or even replacement to other network technologies in their respective functional domains is also addressed.

The paper considers current Ethernet technologies summarizing significant results from related works. The aim is to assess which Ethernet technology may be suitable for which automotive functional domain.

The paper is organized as follows. Sect.2 elaborates on the motivations for introducing Ethernet in automotive communications. Sect.3 discusses which Ethernet technologies would be the possible candidates for automotive communications, while Sect.4 identifies which automotive functional domains would benefit from using such technologies and provides comparative assessments between Ethernet and the automotive networks currently used in the addressed domains. Finally, Sect.5 concludes the paper giving conclusive remarks and some directions for further investigation into the adoption of Ethernet in cars.

2. MOTIVATIONS FOR ETHERNET IN AUTOMOTIVE COMMUNICATIONS

The aim of this section is to discuss the motivations for using Ethernet as an in-vehicle network. The baseline of this discussion is an overview of significant facts that lean towards the adoption of Ethernet in automotive communications. Such facts are detailed in the following.

Fact 1: Traffic requirements are steadily growing, so there is a need for more bandwidth.

Premium cars today count more than 70 ECUs that implement hundreds of distributed functions to provide, e.g., comfort, safety, infotainment, and which produce many communication exchanges. Several new applications are bandwidth-intensive. For instance, to increase the ease of driving and safety, many applications, such as lane departure warning systems, signs/traffic lights recognition and collision avoidance systems, require enhanced picture image and sensor resolutions.

The demand for inter-ECU communication has also heavily increased and it is expected to continue growing in the future.

More bandwidth is also required by On-Board Diagnostics (OBD). The amount of software embedded in the cars of today is growing rapidly, due to the constant advancements of functionalities provided by in-car electronic systems. On-Board Diagnostic is needed by many vehicle functions such as, emissions monitoring, diagnosis of components and properties, service and maintenance with the possibility of downloading and updating software.

The time spent on the reprogramming (also called flash update or flashing) of automotive ECUs, which is necessary to upload new applications to the electronic control unit during the manufacturing of the car or at the repair shop, has already become a critical cost factor. Fast diagnostics and shorter update times are strongly required for efficiency and cost reduction.

The United Nations started an action towards the establishment of a legal global standard for the On-Board Diagnostics of cars and trucks and entrusted the International Organization for Standardization (ISO) with the creation of the World Wide Harmonized – OnBoard Diagnostics (WWH-OBD) standard. The aim of the global standard is to replace the regional standards for vehicle diagnosis for emission control [15]. The standard is also known as Diagnostics over Internet Protocol (DoIP) and uses Ethernet as the PHY. The DoIP standard, under specification as ISO 13400 [16], will therefore foster the use of Internet Protocol (IP) for diagnosis and of Ethernet as a replacement for CAN for the reprogramming and diagnostics of automotive Electronic Control Units. This replacement is necessary, as the CAN bus at 500 kbps has become a bottleneck today. Replacing CAN with 100 Mbps Ethernet significantly reduces the time needed to reprogram an ECU [15].

For example, BMW has already been using Ethernet technology to reprogram the calibration software for the engine control modules since early 2008 [1]. In [17] a few figures regarding Vehicle Flashing Times are given that are quite interesting. In the 4th-generation BMW 7 series, to upload 81 MB via CAN 10 hours were required. In the 5th-generation BMW 7 series, to upload 1 GB via Ethernet only 20 minutes were required. The potential savings through faster reprogramming exceeds the costs due to the introduction of Ethernet.

Among bandwidth-demanding applications there are those related to telematics and infotainment that also require support for IP/Web-based applications' need to become more open for non-automotive devices.

Similar considerations also hold for communication between vehicles and the external world, due to applications such as remote monitoring, fleet management, Internet-based automotive applications and Car-to-X communications.

Fact 2: A common network technology would reduce the communication complexity.

Multiple and heterogeneous networks support the different automotive functional domains [14][18]. Table 1 summarizes the different functional domains to be found in a car today and the kind of communication they generate.

Table 1. Functional domains and relevant communications

Functional domain	Communication
Powertrain	Data for the control of engine, transmission, gearbox, etc.
Chassis	Data for the control of car stability and dynamics, i.e., suspension, steering and braking
Body & Comfort	Driving unrelated data concerning the comfort of both driver and the passengers (climate control, windows lifts, seat control, mirrors, doors..)
Driver assistance	Data for driving support operating without user intervention (rear-view, side-view and top-view services, night vision service, speed limit information, lane departure warning,etc.)
Telematics/Infotainment/HMI	Interactive systems presenting data about car operation and driving conditions (navigation systems, route and traffic related information, dashboard, head-up display, etc.)
Entertainment	Driving unrelated data such as audio and video programs, rear seat entertainment, hand-free phones, personal connectivity, etc.

The communications are quite different from one functional domain to another. In some domains, such as powertrain, the main requirement is real-time communication, as the traffic consists of exchanges of small real-time packets. Other domains have more relaxed time constraints, but require more bandwidth. This difference is also reflected in the different network technologies adopted, that span from the low-bandwidth Local Interconnect Network (LIN) [19], used mainly for low-speed communications in the body and comfort domain, to the Controller Area Network (CAN) [20], used in various flavors over different domains (i.e., bandwidth ranging from 100 to 500 Kbps) and to FlexRay [21] that provides 10 Mbps. In the entertainment and infotainment domains as well as in camera-based driver assistance systems the situation is also quite heterogeneous, as here communication is supported by point-to-point Low-Voltage Differential Signaling (LVDS) wires or by analogue Color Video Blanking Signal (CVBS) cables or, more recently, by the Media Oriented Systems Transport (MOST) protocol [22] with data rates of 25 Mbps, 50 Mbps and 150 Mbps. Traffic shaping mechanisms for IP-based in-car switched Ethernet networks, implemented in the switching device [23] or in the video source [24], were investigated for camera-based driver assistance services.

The communications may be quite different even within the same functional domain when several functions are present that feature different data rates and constraints. As a result, several network types are also found within the same domain, with different characteristics in terms of bandwidth, real-time support, etc. Moreover, when a new network technology providing, for example, a higher bit rate is introduced, it is usually intended for supporting novel applications. As a result, it usually does not replace, but complement the already existing networks. The reason for this is that in the automotive environment as long as a (sub)system works properly, there is no willingness to change it, for the sake of keeping the costs low.

This network heterogeneity complicates the communication exchanges, so the usage of a single network technology, where applicable, would be beneficial to avoid the need for gateways. Moreover, it has to be considered that many new applications also require communications between functions belonging to different domains. For instance, in new hybrid vehicles, intelligent battery management systems located in the powertrain domain will optimize charging and discharging strategies based on navigation data from the telematic domain.

In-car interdomain communications between multiple not directly compatible networking technologies requires the support of complex gateways. The gateway functionality may be either centralized in one ECU to which every bus is connected, or distributed over several ECUs, each one acting as "sub gateway". These are complex gateways that require application knowledge. For example, as explained in [4], if a device connected to MOST has to send a request to configure a parameter to a device connected to FlexRay, the communication requires multiple steps that involve a mediating gateway. To correctly perform these steps, such a gateway requires knowledge about the application. This means that every time a change in the application is made, the gateway has to be adapted. This is not a desirable property. A common networking technology for in-car control units would solve the problem and simplify the electronic architecture of the vehicle.

2.1 The Ethernet suitability for Automotive Communications

Ethernet is a promising candidate for in-car communications. The main motivation for this is the higher bandwidth provided by Ethernet (100 Mbps onwards) as compared to current in-car networks. Such an increased bandwidth paves the way for applications, like Advanced Driver Assistance Systems (ADASs), which make the volume of exchanged data in automotive communication continuously grow.

Another enabling factor for using Ethernet as a common networking technology for in-car communications is the assessed technology, which entails that there is a large knowledge already available that allows for better testing, maintenance and development. Thanks to the Ethernet's wide use, standardization and openness, a large availability of high-quality chips on the market and therefore low-cost product development and manufacturing can be expected/predicted. On the contrary, the main competitors of Ethernet, MOST and FlexRay, are only used in the automotive domain, and this entails a smaller market penetration and thus higher costs for products based on these technologies [25].

In addition to the above mentioned features, Ethernet technology is scalable, thus meeting the scalability requirement imposed by today's automotive systems, where the number of nodes to interconnect steadily increases.

Another strong point in favor of Ethernet is the support offered to the IP stack. With Internet connectivity, the IP protocol will be used in-car, opening the way to enhanced navigation functionalities, remote diagnostics and location-based services. Investigations into usage of the Internet Protocol (IP) and the Ethernet in automotives is in progress in academia, the car industry and companies producing automotive electronic devices (BMW [1], Bosch [2], Continental [3], Daimler [6] to mention just a few). Providing the basis for IP as a common networking technology for control units in the car to reduce the complexity of the car electronic architecture is the aim of the SEIS project [4][5], a German project coordinated by BMW Forschung und Technik GmbH in Munich. The SIES project investigates IP-based communication both inside the car and between the car and the environment. The target is not to replace all the technologies currently in use, but to keep using them on an IP-based network and to resort to alternative technologies, selected among those already well established in other industrial contexts, when needed. Among alternative technologies, Ethernet and its real-time variants are addressed and suitable physical layers and network topologies for the automotive domain are investigated. Attention is paid to the IEEE 802.1 AVB protocol and its extensions [26-29] to transfer multimedia data in real-time over IP.

In [6] Daimler's view on the usage for Ethernet in automation is summarized. Basically, the company sees Ethernet as a good solution to have higher bandwidth for future automotive applications at reasonable costs, through a well-proven and widely used technology that has been tested in other domains (such as industrial automation, avionics and telecommunications). Another advantage they mention is the support to IP, which is valuable, as IP is a natural candidate for applications like vehicle diagnostics, in-car internet access, smart charging in electric cars, etc.

Also BMW is really towards the use of Ethernet in cars. In [1] a roadmap is drawn, where unshielded Ethernet was introduced as a diagnostic interface in 2008, while shielded Ethernet was introduced for Rear Seat Entertainment in 2008 and for the Park Assist Camera for the new X5 (pilot expected in 2013).

2.1.1 Ethernet Electromagnetic Compatibility issues

Automotive networks typically operate under high temperature and high electromagnetic radiations, so the question is whether Ethernet can correctly operate in these conditions. Temperature is not an issue for Ethernet, which performs well under high temperatures, thanks to the low power consumption. As far as Electromagnetic Compatibility (EMC) issues are concerned, two aspects have to be considered. The first is the Electro-Static Discharge (ESD), which consists of the unwanted short-duration electric current that flows when two charged objects come into close proximity or even in contact and may cause damage to electronic equipment. Many new Ethernet devices have improved their Electro-Static Discharge performance thus meeting the limits. The second aspect refers to Electro-Magnetic Interference (EMI) i.e., the unwanted effects of unintentional generation, propagation and reception of electromagnetic energy. While Standard Ethernet 100 Base TX unshielded exceeds the typical limit for EMC emission, Standard Ethernet 100 Base TX shielded technology does not exceed the limit, but unfortunately requires expensive cable and connectors. Plastic Optical Fiber can be used for 100 Mbps Fast Ethernet with a reach of 100 m, but it is a costly solution and cost is an issue in the automotive field. The most effective solution, as reported in [1] and [30], is Ethernet Unshielded Twisted Single Pair (UTSP) at 100 Mbps, that successfully passes the EMC immunity test. The UTSP is unshielded, provides for one pair of wires at 100 Mbps with full duplex operation and requires standard inexpensive cables and connectors. Automotive qualified Ethernet devices currently available on the market, e.g., from Micrel (transceiver, switches) and from Broadcom® (transceiver), are designed to meet automotive EMC specifications.

As the cable lengths in cars is limited and never reaches 100 m (this is the maximum length specified by the IEEE 802.3), assuming a lower maximum cable length, for instance 10 meters, the Ethernet transmitter drive strength can be reduced accordingly, thus also reducing the output signal amplitude and therefore emissions.

3. OVERVIEW OF AUTOMOTIVE-RELEVANT ETHERNET TECHNOLOGIES

Recent Ethernet technologies provide support for real-time behavior and QoS. Real-Time support is provided by Industrial Ethernet protocols in IEC 61784 [32][33], that improve real-time capabilities of Ethernet-based networks for industrial scenarios. However, IEC 61784 technologies are not as widely-used in the mass market as standard Ethernet and are too costly for the automotive domain. The main challenge for the automotive industry will instead be to transfer and extend standard IP and Ethernet into cars and still fulfill the automotive requirements. Moreover, no intention to use any Industrial Ethernet for the automotive case is in place. PROFINET, for instance, addresses trains (train profile for PROFINET IO), not cars.

QoS support is offered by the IEEE 802.1 Audio/Video Bridging (AVB) standard [26-29], that provides for highly reliable audio and video applications over IEEE 802 networks.

Another promising candidate is the TTEthernet technology (TTEthernet) [34], which is marketed by TTTech Computertechnik AG for use in avionics, in aerospace applications and in other real-time domains. TTEthernet enables deterministic time-triggered communications, rate-constrained and event-triggered communications over the same network interface [42]. The technology is compatible with legacy Ethernet (ARINC 664 Part 7 Standard, 802.3) [35]. Integration with AVB would also be possible [36].

In the following we will examine the features of both the IEEE AVB standard and TTEthernet and discuss their possible application domains for automotive usage.

3.1 The IEEE Audio Video Bridging standard

AVB is a common name for the set of technical standards defined by the IEEE 802.1 Audio/Video Bridging Task Group. The AVB standards provide the specifications for time-synchronized low latency streaming services through IEEE 802 networks.

AVB includes three specifications:

- IEEE 802.1AS: Timing and Synchronization for Time-Sensitive Applications (gPTP) [29].
- IEEE 802.1Qat: Stream Reservation Protocol (SRP) [28].
- IEEE 802.1Qav: Forwarding and Queuing Enhancements for Time-Sensitive Streams (FQTSS) [27].

The IEEE 802.1as Time Synchronization provides precise time synchronization of the network nodes to a reference time. It synchronizes distributed local clocks with a reference that has an accuracy of better than 1 us. The IEEE 802.1Qat Stream Reservation allows for the reservation of resources within switches (buffers, queues) along the path between sender and receiver. The IEEE 802.1Qav Queuing and Forwarding for AV Bridges separates time-critical and non time-critical traffic into different traffic classes extending methods described in the IEEE 802.1Q standard and performs traffic shaping at the output ports of switches and end nodes to prevent traffic bursts.

For seven hops within the network, the AVB standard guarantees a fixed upper bound for latency. Two QoS classes are defined, i.e.

- Class A, that provides a maximum latency of 2ms

- Class B, that provides a maximum latency of 50ms.

With a careful planning of periodic execution and mapping to the high priority queues within switches, AVB is able to guarantee low jitter. As the resource reservation protocol is able to dynamically handle QoS, new devices can join the network at any time and QoS can be maintained through a combined design approach, where a QoS configuration made at the end of the production line is adapted on the field afterwards.

The work in [31] addresses the accuracy of the time synchronization mechanism of Ethernet AVB under varying temperature conditions. The measurement results provided are encouraging.

3.2 The Time-Triggered Ethernet

TTEthernet [34][36][42] combines the determinism, fault-tolerance properties and real-time behavior of the time-triggered technology with the flexibility, dynamics and legacy of “best effort” Ethernet. TTEthernet offers several advantages. First, it offers higher bandwidth compared to FlexRay or CAN (100 Mbps onwards). Second, it supports communication among applications with diverse real-time and safety requirements. Finally, TTEthernet provides three different traffic types: time-triggered (TT) traffic, rate-constrained (RC) traffic and best-effort (BE) traffic.

Time-triggered (TT) messages are transmitted at predefined times and have precedence over the other kinds of traffic. They are suitable for brake-by-wire, steer-by-wire systems (avionics). Rate-constrained (RC) messages do not follow a sync time base, so multiple transmissions may occur at the same time and messages may queue up in the network switches, leading to increased transmission jitter. RC messages are sent at a bounded transmission rate that is enforced in the network switches, so that for each application a max predefined bandwidth, together with delays and temporal deviations within given limits, are guaranteed. Rate constrained messages are suitable for multimedia or safety-critical automotive and aerospace applications that need highly reliable communication, but do not feature strict temporal constraints. Best-effort (BE) messages use the remaining bandwidth and have less priority than TT and RC messages. BE messages have no guarantee on whether and when they can be transmitted, i.e., on the delay and on the delivery at the destination. These messages are suitable for all legacy Ethernet traffic (e.g. Internet protocols) without any QoS requirement.

TTEthernet is used as the backbone system in the NASA Orion spacecraft, the successor of the Space Shuttle [37]. TTEthernet is also a SAE standard (AS6802).

More details on TTEthernet and its properties can be found in [34].

4. WHICH ETHERNET TECHNOLOGY FOR WHICH DOMAIN

The question we attempt to answer here is which Ethernet technology is suitable for the automotive environment. The choice really depends on the functional domain. In the following, we will consider possible application scenarios for Ethernet AVB and TTEthernet.

4.1 Application scenarios for AVB in cars

The IEEE AVB standard [26-29] has recently attracted attention as a potential in-vehicle network technology for multimedia, infotainment and driver assistance. There are multiple reasons for this interest in AVB, such as the enhanced QoS provided, the IEEE standardization, no need for license fees and, last but not least, prices and quality comparable to those of standard Ethernet.

In-car audio/video systems, in addition to common playback functions, also handle content that requires a timely delivery. For instance, turn-by-turn navigators continuously present directions to the users in graphics or speech and dynamically update the path to the destination taking into account traffic and road conditions. Moreover, these systems give the user step-by-step vocal advices about the street name, the distance to the turn and whether to turn left or right.

The Audio/Video content associated with infotainment systems is steadily increasing, but the usage of point-to-point dedicated connections for audio and video content, such as the currently adopted shielded LVDS cables, has to be discontinued for many reasons. Among them, wiring complexity, that also affects maintenance, reliability and weight, and costs, in terms of wires, connectors and fuel consumption.

In-vehicle infotainment networking is today dominated by MOST technology [22]. However, according to the Nov.2008 Hansen Report [40], MOST is not "open enough" compared with CAN, LIN and FlexRay. For this reason, in several years alternatives, including Ethernet with AVB extensions, might step in [39].

4.1.1 Comparative assessments between MOST and AVB

MOST was originally designed for automotive infotainment. It therefore exploits the available bandwidth optimally for all kinds of media streaming. Despite MOST outperforming Ethernet in payload efficiency (PE=Payload data/Sent data) [12], with MOST the total network bandwidth is shared among all connected devices, while Ethernet AVB is a switched network that multiplies the available bandwidth [12]. As AVB utilizes bandwidth only between source and destination node connections, there is a significant bandwidth saving that allows a higher throughput over an AVB network compared with a MOST network, even when they operate at equivalent bit rates [39].

Some works see a potential for AVB for time-triggered-like communications, thanks to the support provided in terms of time synchronization and synchronous data transport [25]. However further work has to be done in this direction to improve performance.

4.2 Application scenarios for Time-Triggered Ethernet in cars

Chassis and powertrain functions operate mainly as closed-loop control systems and their implementation is moving towards a time-triggered (TT) communication, as this approach is able to provide a deterministic communication service. TTEthernet would be a good candidate for these subsystems, especially for the chassis domain, whose behavior has a strong impact on the vehicle's stability, agility and dynamics, and so is very critical from a safety standpoint.

Deterministic communication overcomes the problem of interdependencies between components, which is a major issue and cost factor in today's automotive distributed systems. A deterministic communication system significantly reduces the integration and test effort, as it guarantees that the cross-influence is completely under the control of the application and is not introduced by the communication system. Moreover, determinism facilitates the system composability (i.e., ability to integrate individually developed components) and real-time behavior.

As stated in [36], the introduction of TTEthernet as in-car network would allow to reduce the number of end systems and to integrate several distributed functions on a small number of ECUs. This is because TTEthernet meets the requirements that this approach imposes, i.e. that bandwidth be apportioned exactly and deterministically without statistical fluctuation (jitter) of the network traffic, and that bit rates be guaranteed.

Other possible scenarios for TTEthernet in automotive applications are:

- Advanced Driver Assistance Systems (ADAS), thanks to the combination of high bandwidth and TT communication.

- Multimedia, thanks to the reliable communication and guaranteed data rates for audio and video. Moreover, by using TTEthernet for both ADAS and infotainment, driver assistance systems and infotainment could be integrated into the same network.

- X-By-Wire, thanks to its real-time, fault-tolerant and fail-operational behavior that meets the communication requirements typical of these systems.

4.2.1 Comparative assessments between FlexRay and TTEthernet

The paper [13] offers a competitive analysis of FlexRay and TTEthernet. Based on a mathematical model, the analysis provides comparative results for real-time relevant metrics like latency, jitter and bandwidth. The general eligibility of TTEthernet for in-vehicle applications is shown in a scenario where a fully utilised FlexRay system is replaced by a time-triggered Ethernet. The paper also discusses the utilization benefits offered by a switched system, like TTEthernet, when using group communication, while FlexRay is limited to broadcast communications. The analysis in [13] shows that FlexRay real-time traffic can be supported by TTEthernet. Jitter and latency are comparable. The sample configuration used is shown in Table 2, while the results obtained are given in Table 3 (redrawn from [13]).

Table 2. Sample configuration (source [13])

	FlexRay	TTEthernet
Bus speed	10 Mbps	100 Mbps
Max payload size	254 bytes	1500 bytes
Min payload size	1 byte	46 bytes
Topology	Two active stars/switches	
Wire length	72 m	
Divergence of quartz	220 ppm	
Cycle time	16 ms	

Table 3. Jitter and latency results (source [13])

	FlexRay	TTEthernet
Latency min payload	12.2 us	24 us
Latency max payload	265.2 us	372 us
Jitter bounds	6.4 us	<10 us

FlexRay and TTEthernet share very good properties for automotive communications. Both of them provide support for fully deterministic data communication for time-critical applications and have built-in fault-tolerance and safety mechanisms. While FlexRay is qualified for automotive, TTEthernet does not have this property yet. FlexRay controllers have the ISO 26262 (ASIL-D) certification, not yet available for TTEthernet.

TTEthernet provides higher bandwidth than FlexRay (100 Mbit/s vs. 10 Mbit/s). Software stacks as well as development and configuration tools are available for both technologies. The two technologies currently differ as far as costs are concerned, being TTEthernet more expensive due to the lack of a mass production of TTEthernet products till now. This difference may be overcome with increasing market penetration.

Both FlexRay and TTEthernet support a number of network nodes and network topologies that are adequate for the needs of automotive applications. In particular, FlexRay supports bus, star and mixed topologies. TTEthernet supports star and star bus, while bus and ring are possible with special switch components. FlexRay is a de facto standard in automotive and TTEthernet is a SAE standard (SAE AS6802). While the EMC of FlexRay has been proven in automotive, TTEthernet EMC for automotive is currently under test.

4.3 Ethernet in automotive communications: evolution or revolution?

Ethernet was recently introduced in several car models as cost-efficient high-speed data access for diagnostics, software updates and multimedia for entertainment (Rear Seat Entertainment Systems). As reported in [1], the pilot applications for Ethernet according to the BMW view are Driving Assistance Functions. The BMW plan is to use Ethernet instead of shielded Low-Voltage Differential Signaling (LDVS) video transmission for the surround view system to provide good overview during maneuvering. The company target is to accomplish this by 2013 [1] and significant cost reduction is expected.

Other targeted applications are night vision with person recognition, speed limit information, entertainment video transmission (TV, DVD, etc.).

The introduction of Ethernet in cars looks more an evolution than a revolution: In the next few years, Ethernet will not replace existing automotive networks completely, but a "migration path" to facilitate the communication between the existing automotive networks and Ethernet is needed [25]. This is the motivation behind some effort to investigate how to realize gateways between AVB networks and the automotive networks currently in use, such that the QoS offered can be maintained across the network borders. For instance, the work [25] proposes both a MOST/AVB gateway and a FlexRay/AVB gateway to support synchronous data transport, and uses an evaluation system built within the SEIS project [3] activities to validate the proposed gateway concepts.

The paper [43] addresses a migration concept for transferring CAN traffic over Ethernet/IP. The idea is to use full duplex switched Ethernet connections for multiplexing data originating from CAN ECUs and streaming data coming from co-located high bandwidth sensors over one Ethernet connection, for the sake of reducing packaging, weight and system costs.

5. CONCLUSIONS

Ethernet usage in cars is expected to spread in several domains. The first one is diagnostics, where Ethernet is already in use and will replace the bottleneck CAN. Ethernet usage will further grow thanks to the DoIP standard that allows for seamlessly interfacing the car to a service centre network or remote laptop.

Another success story of Ethernet in cars is expected in the multimedia and infotainment domains. In today's cars Ethernet already connects the Rear Seat Entertainment system to the Head Unit, thus providing high speed access to the mass storage located in the head unit. The AVB standard will compete with MOST which, in turn, is expected to fast displace the LDVS data transfer technology.

Advanced Driver Assistance Systems involving cameras represent another use-case for Ethernet, as these applications require high bandwidth to support high speed data communication and FlexRay is not suitable for this. ADAS may therefore be the right use-case for Ethernet, especially for TTEthernet.

In terms of timeline, Ethernet is expected to enter the non-safety critical domain first. While Ethernet definitely has a bright future for video, audio and infotainment, its usage in automotive domains with hard real-time constraints depends on some critical factors. For real-time control, the car industry is (slowly) moving from CAN to FlexRay, so it could take time for Ethernet to step in. FlexRay is used for some time-critical and safety-critical applications and will likely continue to be used in the powertrain and vehicle dynamics management domain. An aspect to consider is that there are not so many Ethernet COTS components suited to cars, due to EMC issues. Currently, Broadcom is launching the Broadcom BroadR-Reach™ PHYs family of transceivers, while

Micrel offers automotive qualified Ethernet devices (PHY transceivers, integrated MAC/PHY controllers, switches) that reduce the drive strength via internal software registers or via a modification in hardware. Assuming that there are some proprietary technologies, the question is whether the automotive industry will rely on a product/standard that is proprietary.

An open question regards the topology to be used in cars. One could think about a single Ethernet backbone supporting all the kinds of traffic (safety-critical, multimedia), but the study in [8] showed that different traffic classes over a switched Ethernet in-car network influence each other, causing the violation of critical data constraints. The work in [8] showed that a Switched Ethernet with a star-based topology may support different traffic types while providing satisfying QoS only if the network is managed in such a way that overload never occurs and a prioritization mechanism is used.

One possible option foresees an infotainment architecture centered around an AVB Ethernet backbone conveying all the traffic, i.e. in-vehicle data and control traffic, together with audio/video streaming for passenger entertainment, driver assistance, mobile interconnect connectivity. However, for the sake of integrity, reliability and safety, it is probably better to keep safety-critical communications separate from infotainment ones. Some companies, like Micrel [41] envisage a single standard Ethernet for multimedia applications and non-critical data traffic and an AVB cloud (i.e., a kind of sub-network where all devices must support AVB capabilities) for time-critical traffic. As reported in [41], it was suggested that only the so-called Audio Video Bridging for Automotive (AVA) subset of the AVB specification, including the IEEE 1722 AVB packet and the PTPv2 Time Synchronization (IEEE 802.1as) would be required for the automotive needs.

The separation between different traffic types is definitely possible with TTEthernet, that provides a native support for deterministic communication while also allowing for rate-constrained and best-effort exchanges.

As far as new visions and new possibilities for Ethernet in the automotive field are concerned, according to the Bosch and BMW view, in a future architecture based on the deployment of Domain Control Units (DCUs) and a backbone connecting those domains, Ethernet will be the ultimate choice (expected start 2020).

Another possible scenario for Ethernet is relevant to electric cars. The next generation of electrical vehicles represents a unique opportunity for a significant rethinking of current automotive network architectures. A shift from proprietary solutions to a novel network architecture, based on an established standard technology, would allow for faster design and analysis of the network transmission schedule, better quality and performance assessments. The adoption of a common communication network architecture would simplify the task of ECU suppliers allowing for component reusability across different car manufacturers shortening the time to market of their products.

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7. REFERENCES

[1] Bruckmeier, R. 2010. Ethernet for Automotive Applications. Freescale Technology Forum (Orlando, FL, US, June 23, 2010).http://www.freescale.com/files/ftf_2010/Americas/WBNR_FTF10_AUT_F0558.pdf.

[2] Hammerschmidt, C. 2011. Ethernet to gain ground in automotive applications, Bosch predicts. *EETimes Europe*. (4 Feb.2011). http://electronics-eetimes.com/en/ethernet-to-gain-ground-in-automotive-applications-bosch-predicts.html?cmp_id=7&news_id=222905757

[3] Noebauer, J. 2011. *Is Ethernet the rising star for in-vehicle networks?* Invited Talk at the 16th IEEE Conference on Emerging Technologies in Factory Automation (Toulouse, France, Sept.7, 2011). ETFA 2011.

[4] SEIS - Security in Embedded IP-based Systems. www.strategiekreis-elektromobilitaet.de/projekte/seis/.

[5] Glass, M., Herrscher D., Meier H., Piastowski M., and Schoo P., 2010. SEIS – Security In Embedded IP-Based Systems. *ATZ Elektronik* 5, (01-2010), 36-40.

[6] Kern, A., Zhang, H. and Teich, J. 2011. Testing switched Ethernet networks in automotive embedded systems. In *Proceedings of the 6th IEEE International Symposium on Industrial Embedded Systems* (Vasteras, Sweden, 15-17 June, 2011) SIES 2011. IEEE Industrial Electronics Society, Piscataway, NJ, 150-155. DOI=10.1109/SIES.2011.5953657

[7] Lim, H.T., Volker L., Herrscher, D. 2011. Challenges in a future IP/Ethernet-based in-car network for real-time applications. In *Proceedings of the 48th ACM/EDAC/IEEE Design Automation Conference, 2011.* (San Diego, California, June 5-10, 2011). DAC 2011. IEEE, New York, NY, 7-12.

[8] Lim, H.-T., Weckemann, K., Herrscher, D. Performance Study of an In-Car Switched Ethernet Network without Prioritization. In: *Communication Technologies for Vehicles (Lecture Notes in Computer Science 2011)*, Springer, Heidelberg, 2011.

[9] Lim, H.T., Krebs, B., Völker, L., and Zahrer, P. 2011. Performance Evaluation of the Inter-Domain Communication in a Switched Ethernet Based In-Car Network. In *Proceedings of the 36th IEEE Conference on Local Computer Networks* (Bonn, Germany, Oct. 04-07, 2011). LCN'11. IEEE, Piscataway, NJ.

[10] Rahmani, M., Steffen, R., Tappayuthpijarn, K., Giordano, G., Bogenberger, R., and E. Steinbach.2008. Performance Analysis of Different Network Topologies for In-Vehicle Audio and Video Communication. *In Proceedings of the 4th International Telecommunication Networking WorkShop on QoS in Multiservice IP Networks*. (Venice, Italy, Feb.13-15, 2008). IT-NEWS 2008. IEEE; Piscataway, NJ, 179-184. DOI=10.1109/ITNEWS.2008.4488150.

[11] Hintermaier W., Steinbach, E. 2010. A System Architecture for IP-camera based Driver Assistance Applications. In Proceedings of the IEEE Intelligent Vehicles Symposium (IV), (San Diego, CA, June 21-24, 2010). IEEE, Piscataway, NJ, 540-547. DOI= 10.1109/IVS.2010.5548103.

[12] Noebauer J,. Zinner H. 2011. Payload efficiency and network considerations of MOST and Ethernet. *Elektronik automotive. Special issue MOST*. March 2011, 14-17. http://www.elektroniknet.de/automotive/most-spezial/technik-know-how/article/77135/2/Friend_or_Foe/.

[13] Steinbach, T., Korf, F., and Schmidt, T. C. 2010. Comparing Time-Triggered Ethernet with FlexRay: An Evaluation of Competing Approaches to Real-time for In-Vehicle Networks. In *Proceedings of the 8th IEEE Intern. Workshop on Factory Communication Systems.* (Nancy, France, May 18-21, 2010). WFCS'10. IEEE Industrial Electronics Society, Piscataway, NJ.

[14] Navet, N., Simonot-Lion, F. 2009. Trends in Automotive Communication Systems. *Embedded Systems Handbook, 2nd Edition, Part three*. *Dr. R. Zurawski, Ed.* CRC Press, Taylor and Francis Group, Boca Raton, FL. 13-1, 13-24.

[15] Lang, J. 2010. ISO 13400 – Diagnostics over Internet Protocol (DoIP) at EB, *EB Automotive Software Newsletter,* 2010. http://www.elektrobit.com/

[16] ISO 13400-1:2011 - Road vehicles -Diagnostic communication over Internet Protocol (DoIP) -Part 1: General information and use case definition. Published on Oct.18, 2011.

[17] Thomsen, T., Drenkhahn, G. 2008. Ethernet for AUTOSAR. *1st AUTOSAR Open Conference & 8th Premium Member Conference* (Detroit, MI, Oct. 23, 2008). http://www.autosar.org/download/conferencedocs/07_Elektrobit_Ethernet_for_Autosar.pdf

[18] Nolte, T., Hansson, H., Lo Bello, L. 2005. Automotive Communications - Past, Current and Future. In *Proceedings of the 10th IEEE International Conference on Emerging Technologies and Factory Automation* (Catania, Italy, Sept. 19-22, 2005). ETFA '05. IEEE Industrial Electronics Society, Piscataway, NJ, 1, 985-992. DOI=10.1109/ETFA.2005.1612631.

[19] LIN Consortium, *LIN Specification Package Revision 2.0*, Motorola GmbH, Schatzbogen 7, 81829 Munchen, Germany, Sept. 2003.

[20] *CAN Specification Version 2.0*, Robert Bosch GmbH, Postfach 50, 70049 Stuttgart, Germany, Sept. 1991.

[21] FlexRay Consortium, *FlexRay Communications System Protocol Specification Version 2.1 Revision A*, Altran GmbH & Co. KG, Schillerstr.20, 60313 Frankfurt am Main, Germany, Dec. 2005.

[22] MOST Media Oriented System Transport, Multimedia and Control Networking Technology, Rev. 2.4, OASIS Silicon Systems, 2005. http://www.mostcooperation.com/publications/Specifications_Organizational_Procedures/index.html?dir=291

[23] Rahmani, M. Tappayuthpijarn, K., Krebs, B., Steinbach, E., and Bogenberger, R. 2009. Traffic Shaping for Resource-Efficient In-Vehicle Communication. *IEEE Transactions on Industrial Informatics*, 5, 4, 414-428, 2009.

[24] Hintermaier W., Steinbach, E. 2010. A System Architecture for IP-camera based Driver Assistance Applications. In *Proceedings of the IEEE Intelligent Vehicles Symposium (IV)*, (San Diego, CA, June 21-24, 2010). IEEE, Piscataway, NJ, 540-547. DOI= 10.1109/IVS.2010.5548103.

[25] Zinner, H., Noebauer, J., Gallner, T., Seitz, J. and Waas, T., 2011. Application and realization of gateways between conventional automotive and IP/Ethernet based networks. In *Proceedings of the 48th ACM/EDAC/IEEE Design Automation Conference* (San Diego, CA, Jun 05-09, 2011). DAC'11. ACM, New York, NY, 1-6.

[26] IEEE, Inc. Audio Video Bridging Task Group. IEEE Standard 802.1 edition. October 2010.

[27] IEEE, Inc. Forwarding and Queuing Enhancements for Time-Sensitive Streams. IEEE802.1Qav/D7.0 edition. October 2009.

[28] IEEE, Inc. Stream Reservation Protocol. IEEE 802.1Qat/D6.1 edition. June 2010.

[29] IEEE, Inc. Timing and Synchronization for Time-Sensitive Applications in Bridged Local Area Networks. IEEEP802.1AS/D7.5 edition. October 2010.

[30] Jones, M. 2009. *EMI Challenge to Ethernet in the Car. White paper.* Micrel Inc., San Jose, CA. Feb. 2009, p.1-6. http://www.micrel.com/applications/auto/automotive_ethernet_emi.pdf

[31] Kern, A., Zinner, H., Streichert, Noebauer, J. and Teich, J. 2011. Accuracy of ethernet AVB time synchronization under varying temperature conditions for automotive networks. In *Proceedings of the 48th ACM/EDAC/IEEE Design Automation Conference.* (San Diego, California, June 5-10, 2011). DAC 2011. IEEE, New York, NY, 597-602. DOI=10.1145/2024724.2024862

[32] International Electrotechnical Commission, IEC 61784-1, Digital data communications for measurement and control - Part 1: Profile sets for continuous and discrete manufacturing relative to fieldbus use in industrial control systems, 2008. http://www.iec.ch.

[33] International Electrotechnical Commission, IEC 61784-2, Industrial communication networks- Profiles, Part 2: Additional fieldbus profiles for real-time networks based on ISO/IEC 8802-3, 2010, http://www.iec.ch.

[34] TTA-Group: TTEthernet-Spezifikation. 2008. http://www.ttagroup.org/ttethernet/specification.htm

[35] ARINC: Specification 664P7-1. 664P7-1 Aircraft Data Network, Part 7, Avionics Full-Duplex Switched Ethernet Network. 2009. https://www.arinc.com/cf/store/catalog_detail.cfm?item_id=1269

[36] TTTech Computertechnik AG. 2011. TTEthernet in Motion. TTTech White paper.2011. http://www.automationworld.com/whitepapers/TTTech-TTEthernet_in_Motion.pdf

[37] Walko, J. TTTech, NASA Team on TTEthernet for Space Apps. *EETimes,* Apr.14, 2009. http://www.eetimes.com/electronicsnews/4195051/TTTech-NASA-team-on-TTEthernet-for-space-apps.

[38] SAE: AS6802 - SAE Standards. 2010. http://www.sae.org/servlets/works/documentHome.do?comtID=TEAAS2D&docID=AS6802&inputPage=wIpSdOcDeTaIlS

[39] Kreifeldt, R.. 2009. AVB for automotive use. *AVnu Alliance White paper*. http://www.avnu.org.

[40] The Hansen Report on Automotive Electronics. Nov. 2010.

[41] Jones, M. *Automotive Ethernet Diagnostics and Beyond!*. *White paper*, Micrel Inc., San Jose, CA. Dec. 2010, p.1-10.

[42] Kopetz, H., Ademaj, A., Grillinger, P. and Steinhammer. 2005. The Time-Triggered Ethernet (TTE) Design. In *Proc. of the 8th International Symposium on Object-Oriented Real-Time Distributed Computing* (Seattle, WA, May 18-20, 2005). ISORC'05. IEEE, Piscataway, NJ, 22–33. DOI=http://doi.ieeecomputersociety.org/10.1109/ISORC.2005.56

[43] Kern, A., Streichert, T., Teich, J. 2011. An automated data structure migration concept - From CAN to Ethernet/IP in automotive embedded systems (CANoverIP). In *Proceedings of the Design, Automation & Test in Europe Conference & Exhibition* (Grenoble, France, March 14-18, 2011). DATE 2011. IEEE, Piscataway, NJ. 1-6. URL: http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=5763027&isnumber=576299