Tomorrow's In-Car Interconnect? A Competitive Evaluation of IEEE 802.1 AVB and Time-Triggered Ethernet (AS6802)

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***Abstract*—Ethernet-based in-car communication is currently a hot topic in the automotive industry. Soon Ethernet will start to oust MOST bus in its domain of info- and entertainment applications. However, the full benefit of a technologically integrated in-car network will only become rewarding with the deployment of an Ethernet-based backbone that integrates all automotive domains on a single layer at increased bandwidth, reduced complexity and cost, while opening car intelligence for future innovations. Such backbone must transport critical control data in real-time. Standard Ethernet requires extensions to comply with the strict timing requirements of driver assistance and safety applications while simultaneously supporting broadband multimedia traffic.**

In this paper, we compare IEEE 802.1 AVB and Time-triggered Ethernet, two competing real-time approaches. While the first fosters over-provisioning and prioritisation, the second is based on a *coordinated* time-division-multiple-access (TDMA) policy for media access. By simulating a realistic in-car backbone design and traffic model, we reveal the strengths and weaknesses of both protocols and point to the diverging characteristics of event- and time-triggered policies. Our results show that in this in-car network scenario both protocols are able to meet the rigid timing requirements, while each has its unique benefits and disadvantages.

I. INTRODUCTION

A major source of complexity in current automobiles is the in-car network. Coping with next generation car intelligence strictly demands a simplified approach. Today, several technologies – CAN, FlexRay, LIN, MOST and LVDS – are interconnected in an inhomogeneous network that grew over the last three decades. All these technologies, that connect up to 70 electronic control units (ECUs) in premium cars, are highly application specific, and inter-domain coordination requires gateways that translate the messages from one technology to the other.

New in-car network architectures feature a flat backbone that allows intra- and inter-domain communication on a single access layer using switched Ethernet. Ethernet already has proven to be a flexible and highly scalable technology. Due to its vast deployment, Ethernet components have become inexpensive over the last years and many expert developers are familiar with the technology. Further, an extensive number of application-specific protocols (including distributed development platforms) is based on TCP/IP that adapts to Ethernet and thus offers an excellent basis for future innovation.

The ECUs in cars vary in size and performance, as the applications vary in requirements. Many control loops in physical processes require communication with hard real-time behaviour, while others, e.g., multimedia or camera based driver assistance, have high bandwidth requirements but elastic timing. A technology suitable for an in-car backbone must meet all these requirements.

Recently different approaches were proposed for achieving real-time communication in Ethernet-based in-car networks. In general they can be divided in two classes: The first class uses asynchronous event-triggered communication that is extended by over-provisioning and prioritising. The second class uses synchronisation and a time-triggered, TDMA-based media access to achieve real-time behaviour. In this paper we contribute a comparative evaluation of both approaches by simulating the same realistic in-car network with IEEE 802.1 AVB [1] and TTEthernet (AS6802) [2]. The simulation models are extensions of the INET-Framework [3] for the OMNeT++ [4] open-source discrete event-based network simulator.

Our simulation uses a traffic model derived from real in-car network configurations and traffic traces that are based on unicast and multicast messages. It contains communication of the automotive application domains safety, driver-assistance, powertrain, chassis and entertainment.

This paper is organised as follows: In section II, we introduce both protocols and present preliminary and related work. Section III presents our evaluation setup with a report and comparative discussion of the results. Finally, section IV concludes our contribution and gives an outlook on future research.

II. BACKGROUND & RELATED WORK

There are several approaches to extend standard switched Ethernet to achieve real-time behaviour. IEEE 802.1 AVB and TTEthernet are using diverging media access and prioritisation strategies.

A. IEEE 802.1 AVB

The IEEE 802.1 Audio/Video Bridging (AVB) standard consists of different mechanisms to enable time-synchronised low latency streaming services through 802 networks specified by the AVB task group [1]. The base of AVB builds the *IEEE 802.1AS* time synchronisation protocol which enables a synchronisation of distributed nodes in switched Ethernet with an accuracy of less than 1 µs over maximum seven hops by using hardware timestamping [5], [6]. AVB specifies queuing and forwarding rules for time sensitive applications in *IEEE 802.1Qav*. There are two different AVB classes depending on the latency requirement: stream reservation (SR) class-A with a maximum of 2 ms latency and SR class-B with 50 ms over seven hops. In addition to the AVB classes, there is a best-effort class which covers all other legacy Ethernet frames (see figure 1).

The transmission selection algorithm for AVB frames is controlled by a credit based shaper (CBS). Transmission of an AVB frame is only allowed if the amount of available credits is greater or equal than 0. The credit shaper has an upper and lower bound to limit the AVB bandwidth and burstiness. In case non-AVB capable nodes transmit messages, the priority of these frames are re-mapped to the priorities of the best-effort traffic class to ensure that the AVB traffic always has the highest priority. A signaling mechanism is specified in *IEEE 802.1Qat* to ensure that AVB frames will have the required resources on the entire path between source and sink, where at most 75% of the total bandwidth can be reserved. The remaining ressources are used for best effort traffic. In an additional cross-layered design, AVB specifies application framing for synchronized media streams in IEEE 1722 and for synchronized RTP over AVB (IEEE 1733).

B. Time-triggered Ethernet

The TTEthernet (AS6802) specification [7] was standardised in 2011 by the Society of Automotive Engineers (SAE) [2]. It is a compatible extension of IEEE switched Ethernet and uses topologies formed of full-duplex links.

TTEthernet defines three different traffic classes: For *time-triggered* (TT) communication, offline configured schedules assign dedicated transmission slots to each participant. This *coordinated* time-division-multiple-access (TDMA) media access strategy allows deterministic transmission at predictable delays. It prevents congestion on the outgoing linecards and enables isochronous communication with low latency and jitter. To allow for the TDMA access scheme, a failsafe synchronisation protocol implements a global time among all participants.

In addition to synchronised time-triggered messages, two event-triggered message classes are defined: *Rate-constrained* (RC) traffic is intended for the transmission of messages with relaxed timing requirements. It limits bandwidths and prioritises according to the strategy of the *ARINC-664 (AFDX)* protocol [8] and is thus comparable with AVB Classes A and B. *Best-effort* (BE) traffic conforms to standard Ethernet messages that are transmitted with the lowest priority. The latter allows the integration of hosts that are unaware of the time-triggered protocol and remain unsynchronised. These nodes can only use best-effort messages. Figure 2 shows the media access policy for messages of different traffic classes.

C. Related Work

The simulation models for IEEE 802.1 AVB and TTEthernet are both based on the INET-Framework [3] for OMNeT++ [4] and have been introduced and validated in previous work [9], [10]. The source code of the TTEthernet model is published [11]. In [12] an overview of different approaches to Ethernet-based automotive communications is given. This work argues for deploying IEEE 802.1 AVB and TTEthernet in different application domains. In [13] typical requirements for in-car communication are defined. Soft requirements demand the end-to-end latency below 10 ms. For control loops, hard requirements defined in [14] require the latency below 100 µs. The analysis of [15] reveals that these requirements are not easily met by using Ethernet as a backbone in a prioritised network. It was shown that the requirement can be achieved with a probability of 99% over a single overprovisioned switch with limited in-car foreground traffic. The partitioning of a network and the forground load strongly influence the performance of control information. In [16], [17] different topologies based on a switched Ethernet network with in-car applications have been analysed, where the hard latency requirements of control frames are only achieved with a tree based topology [17]. In this work we assume a tree based topology for the in-vehicle network and focus on the transmission of control information to determine whether the application constraints are fulfilled.

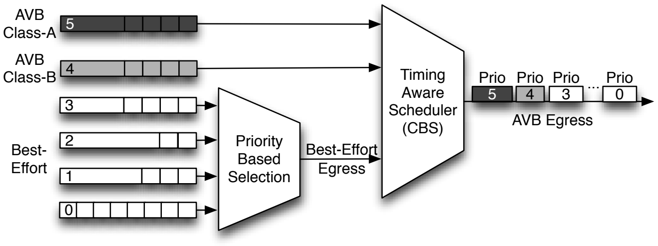

Fig. 1. IEEE 802.1Qav: Transmission Selection Algorithms

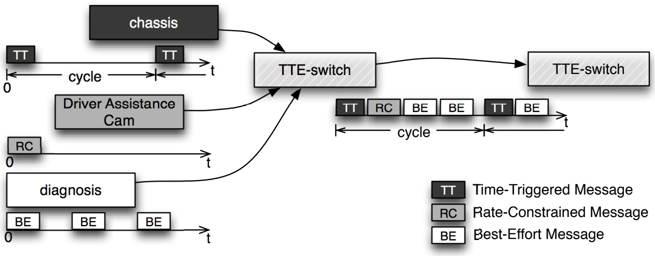

Fig. 2. Prioritising and time-triggered media access in TTEthernet

TABLE I

CHARACTERISTICS OF TRAFFIC MODEL AND CONFIGURED TRAFFIC/PRIORITY CLASSES

Type	Bandwidth [MBit/s]	Payload [Byte]	Service Rate [ms]	IEEE 802.1 AVB Class (Priority)	TTEthernet Class (Priority)
Driver Assistance Camera (unicast)	25	390	0.125	AVB SR ClassA (Prio 5)	RC (Prio 6)
TV (unicast)	10…20	1428	0.56…1.12	AVB SR ClassB (Prio 4)	RC (Prio 7)
Media Audio (unicast)	8	1428	1.4	AVB SR ClassB (Prio 4)	RC (Prio 7)
Media Video (unicast)	40	1428	0.28	AVB SR ClassB (Prio 4)	RC (Prio 7)
Control (multicast + unicast)	$(3.68\ldots736)\cdot10^{-4}$	46	5…1000	AVB SR ClassA (Prio 5)	TT + RC (Prio 0…5)

III. PERFORMANCE EVALUATION & COMPARISON

For the performance evaluation, the simulation models of both protocols are applied to the same in-car network model.

A. In-car Network Simulation Scenario

The simulated in-car network consists of 7 switches and 15 hosts. The topology uses a tree structure with a maximum of four hops between sender and receiver (see figure 3). Tree-based topologies offer a good trade-off between performance and installation maintenance costs [17].

The links are assumed to carry 100 MBit/s as this allows the utilisation of a physical layer and cables optimised for automotive systems. To further reduce the complexity of the simulation setup and amount of configuration, the network and traffic model was carefully downsized. Varying transmissions due to different cable lengths are in the order of approximately 5 ns per meter and neglected in the simulation. The propagation delay is set to 25 ns (≈5 meters) for all links.

The traffic model is derived from configurations and traces of the communication of a BMW series car. The messages are defined by applications from the domains safety, driver-assistance, powertrain, chassis and entertainment, that currently use communication technologies such as MOST, CAN, FlexRay or LVDS. Table I shows the characteristics of the traffic model that is applied to the simulation. It consists of synchronous messages that are transferred periodically with a cycle time between 5 ms and 1 s, and asynchronous messages with a uniformly distributed distance between 5 and 200 ms.

The Ethernet AVB network consists of two AVB classes: SR-Class A and B. We transmit 42 different control frames with small frame sizes modeled as SR-Class A to the different ECUs in the network. In addition, driver assistance camera data is also transmitted by SR-Class A, while multimedia streaming data is modeled by SR-Class B (see table I). We assume that the clock drift is 50 ppm and the best master clock algorithm (BMCA) is not performed so the port roles are set manually. The synchronisation error is less than 1 µs as specified in IEEE 802.1AS [18].

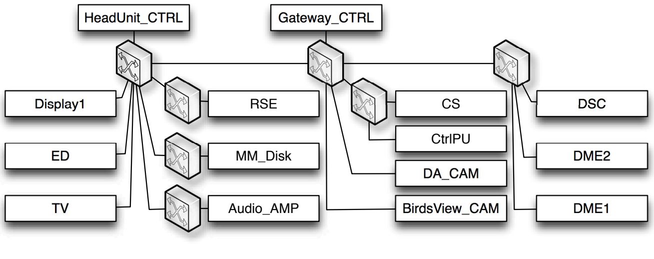

Fig. 3. Simulated tree-based topology

The TTEthernet configuration uses a cluster cycle of 100 ms and has a total of 142 statically configured routes, so called virtual links; 130 time-triggered virtual links for synchronous and 12 rate-constrained virtual links for asynchronous frames. Table I shows the traffic class and priorities applied to the different streams. All multimedia streams are transferred asynchronously (event-triggered), thus the TTEthernet configuration uses rate-constrained messages for the transmission.

The imprecision of synchronisation is simulated based on hardware experiments [19] with 500 ns and a clock drift of 50 ppm. In the schedule, the time-triggered messages are grouped in several blocks of approximately 30 µs. The arrangement in such blocks is a tradeoff between the maximum usable bandwidth and the lowest end-to-end delay for event-triggered (rate-constrained and best-effort) messages.

B. Results

For the evaluation, the most significant traffic flows were extracted from the simulation results of each protocol and compared against each other.

1) Camera and Entertainment Streams: Table II shows the maximum end-to-end latency and the absolute jitter for the video stream of the driver assistance camera and the entertainment streams (audio, video and TV). Due to the higher priority and the smaller frame size (see table I), the driver assistance camera has a lower end-to-end latency (below 115.4 µs for IEEE 802.1 AVB and 209.77 µs for TTEthernet) than the entertainment streams that use large frames (IEEE 802.1 AVB: 674.32 µs and TTEthernet: 725.37). In an AVB network, the media audio stream is not highly influenced by the media video stream which becomes apparent by small jitter values. The transmission of both streams is started in a random manner, so that both streams do not affect each other. The cumulative distribution functions (CDFs) of the end-to-end latencies (see figure 4) illustrate the different priorities

TABLE II

OVERVIEW RESULTS FOR MULTIMEDIA AND CAMERA STREAMS: MAXIMUM LATENCY AND ABSOLUTE JITTER

Type of Stream	IEEE 802.1 AVB Latency [µs]	IEEE 802.1 AVB Jitter [µs]	TTEthernet Latency [µs]	TTEthernet Jitter [µs]
Driver Assistance Camera	115.40	6.69	209.77	90.98
TV	674.32	135.80	485.18	117.27
Media Audio	497.67	6.11	610.49	117.28
Media Video	503.68	130.70	725.37	232.15

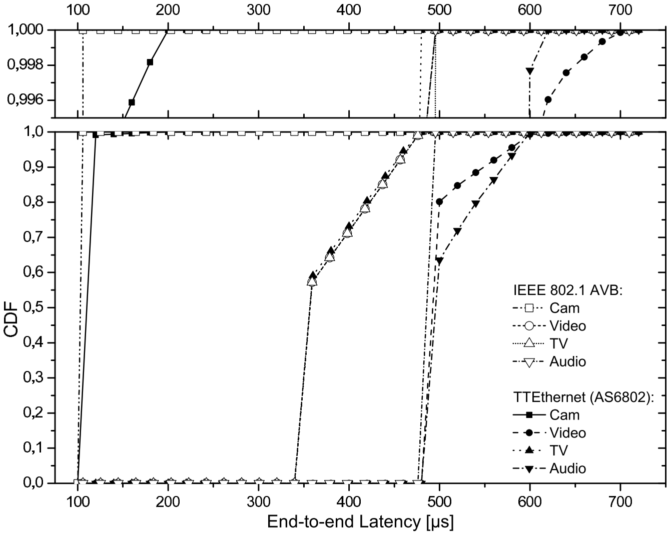

Fig. 4. Cumulative distribution function (CDF) for the camera and entertainment streams

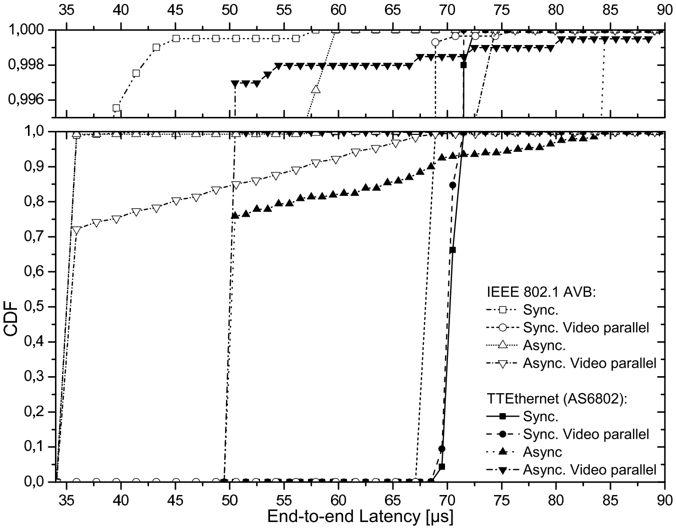

Fig. 5. Cumulative distribution function (CDF) for the control data: synchronous and asynchronous over 4 hops with and without parallel videostream

of the driver assistance camera and the multimedia streams. While the camera has low jitter, the joint traffic of the streams of the multimedia domain lead to network congestion.

2) Control Data: Table III shows latency and jitter for the control data. In the simulated in-car network, both protocols conform to the desired maximal end-to-end latency of 100 µs (IEEE 802.1 AVB: 75.69 µs, TTEthernet: 72.08 µs (time-triggered traffic) 89.61 µs (rate-constrained traffic)). In both protocols, we can observe that the influence of driver assistance camera data on the end-to-end latency of control data depends on the number of hops which have to be passed from the source to the destination node. The highest latency value is recorded for control data which is transmitted from a DSC node to the HeadUnit_Ctrl node in parallel with the driver assistance data. Furthermore, there is no significant difference between synchronously and asynchronously transferred messages.

The TTEthernet protocol uses different traffic classes for the synchronous (periodic) and asynchronous (event-triggered) communication. The cyclic synchronous messages are transferred as time-triggered messages, the asynchronous messages as rate-constrained traffic. Due to the scheduled forwarding of the switches in TTEthernet, the absolute jitter for the synchronous messages is very low ($\leq$3.25 µs). The time slot concept of TTEthernet allows for a communication without congestion at the outgoing linecards. Thus the end-to-end latency is only affected by the precision of the synchronisation and the clock drift. Parallel traffic such as the video stream of the driver assistance camera has no impact on the end-to-end latency (see figure 5).

TABLE III
OVERVIEW RESULTS FOR CONTROL DATA: MAXIMUM LATENCY AND ABSOLUTE JITTER

Hops	Type	Video parallel	IEEE 802.1 AVB Latency [µs]	IEEE 802.1 AVB Jitter [µs]	TTEthernet Latency [µs]	TTEthernet Jitter [µs]
4	sync.	yes	75.69	6.58	71.53	2.70
		no	58.49	21.97	72.08	2.82
	async.	yes	75.07	39.19	84.79	33.81
		no	60.09	26.03	89.61	38.64
3	sync.	yes	42,67	16.04	52.08	3.21
		no	42.52	15.89	51.78	2.20
	async.	yes	42.75	6.55	78.05	33.81
		no	42.71	6.19	77.50	33.26
2	sync.	yes	31.90	5.50	31.37	3.25
		no	33.19	6.55	31.48	2.53
	async.	yes	32.83	6.19	30.31	15.57
		no	33.19	6.55	29.50	14.75

The asynchronous messages are transferred in TTEthernet as rate-constrained messages and can be delayed by other messages. Thus the results show a higher maximum end-to-end latency and jitter. The messages are delayed by the parallel video stream of the driver assistance camera (408 Byte message → max. 32,64 µs delay) or the scheduled time-triggered messages.

C. Discussion

The results show that in general both protocols are able to fulfill the initially determined strict requirements for in-car communication (see section II). All messages of the control data are transferred within the desired maximum end-to-end latency of 100 µs. The maximum delay of 10 ms for the video stream of the driver assistance camera is not exceeded. Furthermore, the available capacity easily satisfies the requirements of in-car entertainment applications.

In the traffic model derived from a current in-car network configuration, most of the control data uses small payload (8 - 16 Byte) that is padded to the Ethernet minimum of 46 Byte. By a careful aggregation of different messages that join the same sender and receivers – into one message that better takes advantage of the available payload – end-to-end latency as well as bandwidth utilisation could be further optimised.

The performance of the messages in IEEE 802.1 AVB and the TTEthernet rate-constrained traffic class are closely correlated to the size of the frames that share the path between sender and receiver. As the messages are transferred event-triggered, they might arrive at a busy linecard and thus be delayed. The simulated traffic model does not contain best-effort background traffic, thus corresponding effects of congestion do not appear in our results. Still the usage of unscheduled background best-effort traffic is highly attractive for various applications, such as diagnosis or entertainment, and should be enabled without affecting real-time behaviour.

Previous work and empirical results show that under heavy load of full size frames, event-triggered communication, such as IEEE 802.1 AVB or the rate-constrained traffic class of TTEthernet, is inferior compared to synchronous time-triggered communication. In worst case, the congestion delays the event-triggered messages up to 490 µs, whereas the end-to-end latency of time-triggered frames remains constant independent of the applied load. Therefore, an analysis with detailed cross-traffic scenarios is part of our future work.

The time-triggered configuration in TTEthernet requires a complex schedule for the whole network and thus has a higher configuration effort than the IEEE 802.1 AVB network. But for the same reason, the time-triggered communication offers the best results in terms of determinism and predictability of latency and jitter.

IV. Conclusion & Outlook

Ethernet is an emerging technology for in-car applications. While domain-specific implementations for info- and entertainment are ready for deployment, a unified in-car Ethernet backbone is subject of ongoing research.

With this work we presented a competitive simulation-based performance evaluation of IEEE 802.1 AVB and TTEthernet – two promising candidates for future in-car networks – based on a relevant subset of the traffic and topology model of a premium car. The results show comparable results for both technologies for the simulated scenario. We found the end-to-end latency of Ethernet AVB to be directly affected by the maximum frame size of other traffic flows in the network, which is in contrast to time-triggered traffic of TTEthernet. Thus, our ongoing work will extend to comparative evaluations that use background cross traffic with large payload.

The results show that IEEE 802.1 AVB is especially useful for in-car multimedia streams. It offers the option of frame synchronous playback and allows due to its signalling protocol the dynamical registration of data flows. TTEthernet uses an offline configured schedule that offers the best performance in terms of determinism and precision of the communication. Thus it perfectly suits the requirements of mission critical control data.

To share the benefits of IEEE 802.1 AVB and time-triggered communication, an interesting subject of future work is an in-car network that uses both protocols on the same physical layer using time-triggered messages for critical control data and AVB for the forwarding of time sensitive streams.

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