Beware of the Hidden! How Cross-traffic Affects Quality Assurances of Competing Real-time Ethernet Standards for In-Car Communication

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***Abstract*—Real-time Ethernet is expected to become the core technology of future in-car communication networks. Following its current adoption in subsystems for info- and entertainment, broadband Ethernet promises new features in the core of up-coming car series. Its full potential will enfold when deploying Ethernet-based backbones that consolidate all automotive domains on a single physical layer at increased bandwidth but reduced complexity and cost. In such a backbone, traffic with a variety of real-time requirements and best-effort characteristics will share the same physical infrastructure. However, certain applications like online diagnosis, data- or firmware updates, and access to off-board backends will introduce bursty high traffic loads to the sensitive core of the cars communication network.**

In this work, we analyze the robustness against cross-traffic of real-time Ethernet protocols. Based on a realistic in-car scenario, we demonstrate that background cross-traffic can have significant impact on in-car backbone networks—even for real-time protocols with strict prioritization. By comparing the real-time approaches Ethernet AVBs asynchronous credit based shaping with the time-triggered and rate-constrained traffic classes of Time-triggered Ethernet (AS6802) we quantify how different media access policies suffer from low priority bursts of applications such as diagnosis, online updates or backend-based services. Our simulation study of a realistic in-car backbone design and traffic model reveals that in a realistic in-car network design, cross-traffic may increase end-to-end latency by more than 500 % while the jitter can become 14 times higher than for a network without background tasks. We discuss ways to mitigate these degrading effects.

***Index Terms*—In-car Networking, Automotive Backbone, Real-time Ethernet, Cross-traffic Analysis, Network Simulation**

I. Introduction

The in-car network of today's vehicles is a complex system consisting of different network technologies such as Controller Area Network (CAN), FlexRay, Local Interconnect Network (LIN) and Media Oriented Systems Transport (MOST). These technologies interconnect at a central gateway that translates between the specific in-car protocols. In a current premium car, there are up to 70 electronic control units (ECU) with more than 900 functions interconnected over this heterogeneous in-car network. While control loop applications have strong real-time requirements, other applications such as navigation, firmware updates or multimedia streaming demand high bandwidth at relaxed timing constraints. These applications are currently supported by heterogeneous network components. It is still an open question whether the traditional automotive architecture is able to cover the constraints of future in-car applications.

The inter- and intra-domain communication is growing and the amount of data exchanged within the car is heavily increasing. With the introduction of high quality sensors, high-resolution driver assistance camera systems and environment vectors, the future in-car network has to support high volumes of data while fulfilling rigid timing constraints. Especially autonomous driving requires timing and data rate to be strictly guaranteed by the in-car network. In addition to on-board systems, the car will receive off-board information by the backend or by other cars in the proximity using car-to-car (C2C) and car-to-infrastructure (C2I) communication.

One possible solution discussed by the major OEMs is the design of a homogeneous in-car network solely based on switched Ethernet [1]. Due to its high data rate—the 100 Mbit/s automotive certified physical layer is already available (commercially available as BroadR-Reach, standardization by the IEEE under P802.3bw [2]), 1 Gbit/s is under development [3]—its low cost of commodity components, and its large flexibility in terms of available protocols and topologies, Ethernet is a promising candidate to overcome the challenges of future in-car networking [4]. The network complexity can be reduced with such a flat design, consisting only of switches without a need for gateways between different technological domains in the car.

As opposed to previous studies that treat in-car networks as closed domains of fixed, offline configured traffic, we argue that the full benefit of an Ethernet based in-car backbone can only enfold when opening the network for applications with background traffic. Examples for such applications include online software updates, diagnosis' of the car conditions or updates of on-board databases (such as navigation maps or meta-data). Even the possibility to offload computational intensive services from the car to a data center is a use-case currently being discussed. With these perspectives the car becomes part of the Internet of Things (IoT) requiring the network to cope with a whole collection of new challenges, e.g. in the domain of security and safety.

With this paper, we contribute an evaluation of the impact of unshaped cross-traffic on the different real-time Ethernet technologies considered for future in-car backbones. We compare the event-based traffic-shaping concept of Ethernet AVB (IEEE 802.1Qav) [5] with time-triggered concepts from AS6802 [6] or the upcoming IEEE 802.1Qbv [7]. While the first solution originates in the multimedia domain using asynchronous event-triggered communication with over-provisioning and prioritization, the latter follows a synchronous approach with a coordinated Time Division Multiple Access (TDMA) strategy to achieve deterministic real-time behavior. Simulations using a system model with realistic in-car traffic pattern and cross-traffic evaluate both solutions. The models for the protocols under investigation are extensions of the INET-Framework [8] for the OMNeT++ [9] open-source discrete event-based network simulator.

The simulation uses a traffic model derived from real network configurations and traffic traces of BMW series cars. The model consists of unicast as well as multicast messages. It contains communication of the automotive application domains safety, driver-assistance, powertrain, chassis and entertainment. Our results reveal a significant impact of cross-traffic on the real-time traffic streams, that needs careful consideration in future designs. Based on our findings, we suggest strategies to overcome possible performance deficiencies.

The remaining paper is organized as follows. In Section II, we introduce the technological background and relate to preliminary and related work. Section III presents the network scenario and the utilized simulation environment. We present the simulation results in section IV along with a comparative discussion of the findings. Section V suggests strategies to overcome the problems of cross-traffic induced network degradation. Finally, Section VI concludes our work and gives an outlook on future research.

II. Background & Related Work

Several approaches extend standard switched Ethernet to achieve real-time behavior. In this assessment, we compare diverging media access and prioritization strategies. These are bandwidth limiting as in IEEE 802.1Qav [10] or TTEthernets rate-constrained/AFDX [11] traffic as well as time-triggered such as the time-triggered traffic class of AS6802 [12] or the upcoming IEEE 802.1Qbv (Enhancements for Scheduled Traffic) [7].

A. *IEEE 802.1 AVB*

The IEEE 802.1 Audio/Video Bridging (AVB) [5] standard enables low latency streaming services and guaranteed data transmission in switched Ethernet networks. The real-time Ethernet extension originates from the multimedia domain where synchronization, jitter and latency constraints of the applications are high. Ethernet AVB guarantees latencies under 2 ms over seven hops for its best traffic class. The IEEE 802.1 AVB standard consists of different sub-standards required to guarantee the latency, synchronization performance, as well as a coexistence with legacy Ethernet nodes (see Fig. 1).

One key mechanism in an AVB network is the *IEEE 802.1AS* [13] time synchronization protocol providing a common view of time by all systems. It allows an accuracy of less than 1 µs by using hardware time stamping. *IEEE 802.1Qav* [10] specifies queuing and forwarding rules to guarantee the latency constraints for AVB and the support of legacy Ethernet frames. AVB defines two service classes with different guarantees: Stream reservation (SR) class-A with a maximum latency of 2 ms and SR class-B with 50 ms over seven hops. An AVB network is also able to deal with non-AVB frames. These frames are mapped to the best-effort class (see Fig. 2).

Prioritization, queuing and scheduling mechanisms realize a guaranteed data transmission of AVB frames within bounded latency. A transmission of an AVB frame is controlled by using a credit based shaper (CBS) approach: Transmission of an AVB frame is allowed when the number of available credits is greater or equal 0. Implicitly, the CBS has a lower and upper bound to limit the data rate and burstiness of AVB data. The remaining bandwidth is available for non-AVB nodes. To ensure that AVB traffic always has the highest priority, the priority of legacy Ethernet frames by non-AVB

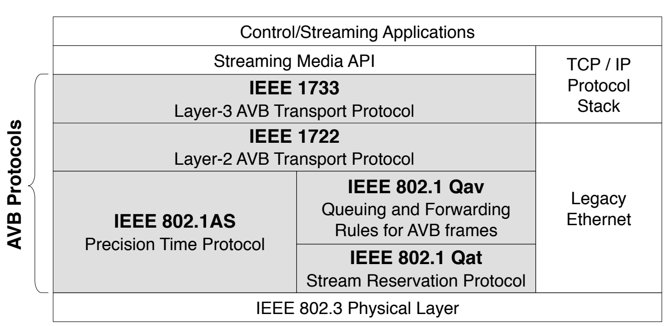

Fig. 1. Overview of the IEEE 802.1 AVB Standard

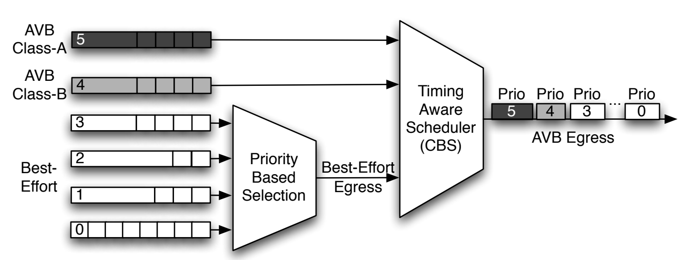

Fig. 2. IEEE 802.1Qav: Transmission Selection Algorithms

nodes is re-mapped to the priorities of the best-effort traffic class. Furthermore, there is a signaling protocol specified in *IEEE 802.1Qat* [14] to reserve the required resources for AVB frames along the entire path between source and sink. The standard recommends that at most 75 % of the total bandwidth is reservable for AVB data while the remaining resources are free for best-effort traffic. In a cross-layered design, AVB specifies application framing for synchronized media streams (IEEE 1722 [15]) and synchronized RTP over AVB (IEEE 1733 [16]).

B. Time-triggered Ethernet

Another possibility of traffic shaping and media access policy for real-time communication in switched networks is time-triggered Ethernet. Time-triggered Ethernet extensions such as PROFINET [17], TTEthernet (AS 6802) [12] or the upcoming IEEE 802.1Qbv [7] standard use a similar media access strategy and thus share their real-time characteristics. Time-triggered Ethernet variants are operating on an offline configured schedule with dedicated transmission slots for all real-time messages shared among all network participants. This enables a *coordinated* time-division-multiple-access (TDMA) media access strategy with deterministic transmission and predictable delays. TDMA prevents congestion on outgoing line cards and thereby enables isochronous communication with low latency and jitter. To allow for this access scheme, a failsafe synchronization protocol has to provide a precise global time among all participants.

We show results for time-triggered communication using the TTEthernet protocol that was standardized in 2011 by the Society of Automotive Engineers (SAE) [6] under AS6802 [12]. It is a compatible extension of IEEE switched Ethernet and uses topologies formed of full-duplex links. As both media access strategies are similar, the results obtained in this paper will be transferable to future versions of IEEE 802.1Qbv (Enhancements for Scheduled Traffic) that is under development by the IEEE Time Sensitive Networking (TSN). Besides the time-triggered traffic class, TTEthernet defines two other event-triggered message classes: *Rate-constrained* (RC) is comparable to the link layer of the *ARINC-664 (AFDX)* protocol [11]. Bandwidth limits for each stream and sender enable the real-time guarantees. So-called bandwidth allocation gaps (BAGs) implement the bandwidth limits. The BAGs define the minimum distance of two consecutive frames of the same stream (called virtual link). The rate-constrained traffic is comparable with Ethernet AVBs stream reservation classes A and B. Similarly it uses strict priorities for traffic with different real-time requirements.

The *Best-effort* (BE) traffic conforms to standard Ethernet messages transmitted with the lowest priority. The presented assessment uses the best-effort class for the transmission of cross-traffic. It allows the integration of hosts that are unaware of the time-triggered protocol and remain unsynchronized. Figure 3 shows the media access policy for messages of different traffic classes while forwarding concurrent packets on a single link: The time-triggered traffic – in this example shown as a chassis control loop – is forwarded strictly in compliance with its schedule. It has the highest priority in the network. Afterwards traffic of the rate-constrained traffic class is forwarded with the second highest priority. The best-effort cross-traffic is transferred in the gaps between the real-time messages using the remaining bandwidth.

C. Related Work

A simulation based performance comparison between the IEEE 802.1 AVB and the TTEthernet was realized in previous work [18]. It assesses a next generation topology based on switched Ethernet using current traffic patterns. The results show that both solutions are able to meet the high timing requirements of control data transmitted over several hops. However, the influence of additional cross-traffic on the application performances was not addressed. The work concludes that a mix of time-triggered scheduling and AVBs credit based shaper (CBS) would probably combine the best of both approaches. In [19] such an approach was developed and analyzed, showing that a mixed scenario would have significant influences on the performance guarantees given for AVBs services classes. Despite including background traffic in the simulation, a comprehensive analysis of realistic cross-traffic was not given.

Several real-time protocols are under investigation for in-car communication networks [20]. Lo Bello [21] motivates the use of Ethernet for in-car applications and recommends AVB and TTEthernet for covering applications in the different automotive domains. The evaluation of the domains and the inter-domain communication with Ethernet as a high performance backbone is considered in [22]. The authors show that the constraints of control data are met with a probability of 99 % over a single network with limited in-car foreground traffic. The performance of control information strongly depends on the foreground load and the network design.

Recent publications around Ethernet AVB focused on improving the end-to-end latency for challenging applications in the areas of automotive and industrial networking. Imtiaz, Jasperneite and Weber [23] argue in favor of smaller frames to reduce the impact of congestion. In the work of Thangamuthu et. al. [24], three new traffic shaping mechanisms – Burst Limiting, Time Aware and Peristaltic – are compared to meet end-to-end latency requirements below 100 µs. The authors conclude that without further restrictions, only the

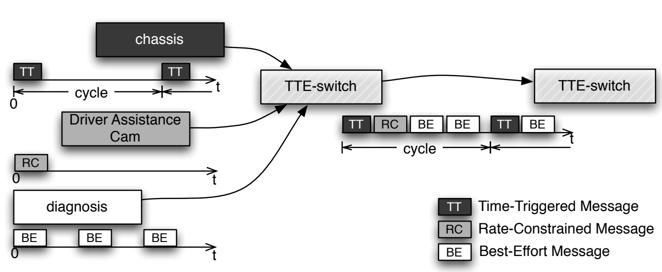

Fig. 3. Prioritising and time-triggered media access in TTEthernet

TABLE I
CHARACTERISTICS OF TRAFFIC MODEL AND CONFIGURED TRAFFIC/PRIORITY CLASSES

Type	Bandwidth [Mbit/s]	Payload [B]	Service Rate [ms]	IEEE 802.1 AVB Class (Priority)	TT and RC Class (Priority)
Control, 42 Streams (multicast + unicast)	$(3.68\ldots736)\cdot10^{-4}$	46	5…1000	AVB SR Class A (Prio. 5)	TT + RC (Prio. 0…5)
Driver Assistance Camera (unicast)	25	390	0.125	AVB SR Class A (Prio. 5)	RC (Prio. 6)
TV (unicast)	10…20	1428	0.56…1.12	AVB SR Class B (Prio. 4)	RC (Prio. 7)
Media Audio (unicast)	8	1428	1.4	AVB SR Class B (Prio. 4)	RC (Prio. 7)
Media Video (unicast)	40	1428	0.28	AVB SR Class B (Prio. 4)	RC (Prio. 7)
Best-effort cross-traffic (Total 1 MB)	Bursts	0…1500	Bursts	Best-effort (Prio. 2)	Best-effort

(time-triggered) time aware shaper can guarantee the required deadlines. Usually analytical worst case timing analysis is used to assess the behavior of real-time Ethernet networks (e.g. [25]–[28]). We use network simulation instead and apply realistic traffic streams to prevent over-pessimistic results.

III. SCENARIOS FOR REALISTIC SIMULATIONS

The in-car network design used for the evaluation was based on real-world data from a BMW series car as developed for previous performance assessments [18] and design decisions for future in-car backbones. To analyze the impact of cross-traffic, we integrated different scenarios for background tasks.

A. In-car Network Scenario

The network topology consists of 7 switches and 15 hosts representing ECUs in the car. The topology forms a tree structure with a maximum of 4 hops (see Fig. 4) between each sender and receiver. Tree-based topologies offer a good trade-off between performance and installation maintenance costs [29].

Links with 100 Mbit/s are used in the physical layer. This represents the upcoming IEEE 802.3bw (100BASE-T1) standard, also known as BroadR-Reach technology. 100BASE-T1 is specifically designed for the harsh environment in cars and features full duplex 100 Mbit/s operation over a single balanced twisted pair cable. To include the propagation delay a maximum of 5 m was assumed, resulting in an additional latency of ≈25 ns (≈5 ns/m)

The model of the traffic flows was generated using network configurations as well as traces from a BMW series car. The model contains messages from applications of the domains safety, driver assistance, powertrain, chassis and entertainment. Table I shows the most relevant aspects of the traffic model.

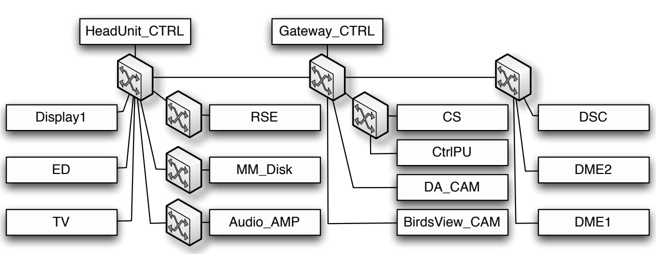

Fig. 4. Tree-based Topology of the Simulated In-Car Network

The flows of the control traffic consist of synchronous messages, periodically transmitted using a cycle between 5 ms and 1 s, as well as asynchronous messages. The asynchronous traffic uses intervals between 5 ms and 200 ms. To model jitter in the sending applications execution time, a uniform variance is added to the interval. As some signals are required by multiple receivers, multicast is used for those messages.

The network hosts several high bandwidth media streams. The driver assistance camera stream sent from the DA_CAM ECU to the display transports a birds or top view generated by the DA_CAM ECU using multiple cameras directly connected to the ECU. It requires low latency for a minimally delayed view. The streams of the entertainment domain – TV, Audio and Video – are transmitted from the TV and the MM_Disk ECU to the Rear Seat Entertainment System (RSE) or the Amplifier (Audio_AMP). For the data rates of the media streams we applied the technical specification of Blu-ray and assumed high definition audio and video.

For the cross-traffic, we consider different scenarios, which involve interaction between ECUs in the car and systems that are off-board. These include online software updates, online diagnosis, map-updates or off-board navigation as well as backend-based services. The External Data (ED) ECU implements the gateway, representing a router to a wireless network. The bursts are sent periodically with a total size of 1 MB. To visualize the impact of the packet size, we vary the MTU for all packets in the burst from 46 B to 1500 B.

B. Network Configuration

1) Ethernet AVB: The Ethernet AVB configuration uses both standard AVB classes—Stream Reservation A and B. The control traffic is configured in 42 streams with minimal frame size and assigned to SR-class A. The driver assistance camera data is also transmitted in SR-class A to allow for a minimal latency and jitter. The multimedia streams of the entertainment domain are assigned to SR-class B (see table I). We assume that the clock drift is 50 ppm. The synchronization error is less than 1 µs as specified in IEEE 802.1AS [30].

2) Time-triggered and Rate-constrained: The configuration for the time-triggered messages uses a cluster cycle of 100 ms. The synchronous signals of the control traffic are assigned to 30 time-triggered virtual links with a cycle time between 5 ms and 1 s. The schedule consists of several blocks of consecutive time-triggered messages. Each block has a length of approximately 30 µs. The scheduling of such blocks is a trade off between the maximum usable bandwidth and the lowest end-to-end delay for event-triggered (rate-constrained and best-effort) messages [19]. The asynchronous control traffic utilizes 12 rate-constrained virtual links. Table I shows the traffic class and priorities applied to the different streams. The multimedia streams are all transmitted using event-triggered messages. The configuration assigns this traffic to the rate-constrained class. Based on previous hardware assessments [31], the configuration of the synchronization imprecision is 500 ns with a maximum clock drift of 50 ppm. This models realistic attributes obtained with typical automotive hardware. The synchronization is required for the schedules that enable the time-triggered media access.

C. OMNeT++ Simulation Environment

All simulations are performed using the OMNeT++ [9] open-source discrete event-based network simulator. The simulation models base on the INET-Framework that provides the implementation for the physical and MAC layer. The traffic shapers and real-time media access policies were developed at BMW (Ethernet AVB) [32] and the Hamburg University of Applied Sciences (AS 6802/Time-Sensitive Networking) [33]. Large part of the implementation is open-source and can be downloaded for simulation experiments and reviewing [34].

For each set of parameters we simulate 150 s of simulation time. The simulation time must be sufficiently long to allow for the clock drift to influence the timing and thus to randomize the transmission of the event-triggered traffic. Our experiments show that 150 s suffice to have a stable state in the simulation. We also drop the results from an initial warm-up period. We simulate each configuration with 10 random seeds resulting in 180 different simulation runs. The simulation of the time-triggered model requires in total approximately 6 h for all configurations on a current generation 4 core system (simulating 8 configurations in parallel) and generates over 60 GB of data for the simulation results.

IV. Comparative Evaluation

In the following evaluation, performance results of the event-triggered traffic classes in Ethernet AVB and the rate-constrained class, as well as the scheduled time-triggered traffic are compared for varying cross-traffic loads and frame sizes. We quantify the effect of competing cross-traffic on the prioritized classes.

A. Results

1) Control Traffic: Control traffic is the most sensitive data transferred within the car. It must comply with the tightest temporal and reliability requirements, since all coordination messages for driving are transmitted therein. In this scenario, we compare Ethernet AVBs SR class A with the rate-constrained traffic class (for acyclic messages) and the time-triggered traffic (for cyclic messages). The worst-case timing was obtained with messages sent from the HeadUnit to the DME1 ECU (see figure 4) in parallel with best-effort cross-traffic from the external data ECU (ED) to DME1. Accordingly, the real-time and best-effort streams share three of their four hops from source to sink. Realistic applications for cross-traffic in this scenario are software updates or diagnosis.

TABLE II
Overview Results for Control Traffic using different real-time Ethernet Technologies and Cross-traffic Frame sizes: Maximum latency and absolute jitter

Size	**IEEE 802.1 AVB**		**Time-triggered**		**Rate-constrained**	
Cr. Tr.	**Latency**	**Jitter**	**Latency**	**Jitter**	**Latency**	**Jitter**
[B]	[μs]	[μs]	[μs]	[μs]	[μs]	[μs]
0	75.69	7.23	82.02	1.17	42.26	19.12
100	142.97	10.58	82.03	1.16	70.95	47.81
800	344.64	69.60	82.02	1.15	162.57	139.43
1518	484.27	112.82	82.02	1.16	258.48	235.34

Table II gives an overview of the end-to-end performance for control-traffic in the different real-time traffic classes and cross-traffic bursts at varying frame sizes. As expected, the time-triggered traffic class admits the best results, both for end-to-end latency (<82.03 μs) and jitter (<1.17 μs) when increasing the frame size of the cross-traffic. Due to the coordinated TDMA approach, the performance is independent of the best-effort traffic. The slight variance in the jitter (<20 ns) is due to the inaccuracy by the clock. The rate-constrained traffic class performs slightly better than time-triggered traffic up to a cross-traffic frame size of approximately 200 B, but congestion increases latency and jitter for larger frames. Within the scenario, the maximum end-to-end delay for rate-constrained control messages is 258.48 μs with cross-traffic of 1518 B. Ethernet AVB shows the lowest performance for control-traffic with concurrent cross-traffic with a maximum end-to-end latency of 484.27 μs (with cross-traffic of max. frame size).

Figure 5 visualizes the dependency between the cross-traffic frame size and the maximum end-to-end latency of the real-time control traffic for the unscheduled traffic classes (AVB and rate-constrained). The time-triggered end-to-end latency remains unaffected by the cross-traffic. In the average case, rate-constrained traffic exceptionally suffers from larger packets. This is due to the increased probability of two packets residing at the same time in the output queue of outgoing line cards. For Ethernet AVB the absolute latency is even larger, but due to the dominance of the delay of the credit-based shaper we see a more linear increase for larger packets.

2) Camera Streams of Driver Assistance: The driver assistance camera stream composed by the DA_CAM ECU consists of a stitched surround image stream with 25 Mbit/s. The stream is forwarded to the Display1-ECU. The external data ECU (ED) sends concurrent cross-traffic representing e.g. media streaming or off-board navigation data. In this case only one hop suffers from concurrency of real-time and cross-traffic, thus the influences on the end-to-end latency and jitter are smaller than for the control traffic. As the media streams are not synchronized and thus not suitable for time-triggered traffic we compare AVBs class A with rate-constrained traffic.

The Ethernet AVB traffic class performs much better in this scenario compared to the control traffic (see table III). For cross-traffic with 1518 B, the maximum end-to-end latency is bounded at 211.70 μs compared to 311.37 μs for

TABLE III
OVERVIEW RESULTS FOR DRIVER ASSISTANCE CAMERA TRAFFIC USING DIFFERENT REAL-TIME ETHERNET TECHNOLOGIES AND CROSS-TRAFFIC FRAME SIZES: MAXIMUM LATENCY AND ABSOLUTE JITTER

Frame Size	**IEEE 802.1 AVB**		**Rate-constrained**	
Cross-traffic [B]	**Latency** [μs]	**Jitter** [μs]	**Latency** [μs]	**Jitter** [μs]
0	108.71	17.51	211.34	111.43
100	140.27	20.75	214.75	114.83
800	167.77	38.87	255.98	156.06
1518	211.70	59.30	311.37	211.45

TABLE IV
OVERVIEW RESULTS FOR MULTIMEDIA AND ENTERTAINMENT USING DIFFERENT REAL-TIME ETHERNET TECHNOLOGIES AND CROSS-TRAFFIC FRAME SIZES: MAXIMUM LATENCY AND ABSOLUTE JITTER

Frame Size	**IEEE 802.1 AVB**		**Rate-constrained**	
Cross-traffic [B]	**Latency** [μs]	**Jitter** [μs]	**Latency** [μs]	**Jitter** [μs]
0	497.67	30.23	582.58	117.20
100	518.66	36.39	592.49	127.11
800	539.12	90.42	646.66	181.28
1518	561.51	105.60	713.24	252.13

the rate-constrained traffic. In the average case both, traffic using AVBs credit based shaper and rate-constrained traffic performs equally well. For Ethernet AVB, the average end-to-end latency increases with larger frames by approximately $3\,\%$ from $108.70\,\mu s$ to $112.05\,\mu s$. For rate-constrained traffic the increase is approximately $6\,\%$ from $100.34\,\mu s$ to $106.38\,\mu s$. This shows that the probability of cross-traffic delaying frames of the camera stream is low. Figure 6 shows a comparison of the maximum and average end-to-end latency of both classes.

3) Multimedia and Entertainment: For the multimedia domain we exemplarily show the traffic of the audio streams between the multimedia streaming ECU and the amplifier. Again, the asynchronous characteristics of the traffic make the usage of time-triggered messages inadequate.

Due to the lower priorities chosen for the streams of the entertainment domain, the end-to-end latency and jitter is higher than in the other scenarios. For Ethernet AVB the end-to-end latency is between $497.67\,\mu s$ and $561.51\,\mu s$ depending on the cross-traffic configuration. For rate-constrained traffic with strict priorities the end-to-end latency ranges from $582.58\,\mu s$ to 713.24 Both, latency and jitter are higher for rate-constrained traffic than for Ethernet AVB. Table IV shows a comparison of the results for selected frame sizes of cross-traffic.

4) Cross-traffic Performance: In all scenarios the best-effort cross-traffic heavily suffers from the concurrent real-time messages in the network. The highest latencies were simulated on the path between the ED and DME1 ECUs. The maximum latency of individual background cross-traffic frames is at minimum $146.55\,\mu s$ for minimum size frames and goes up to $755.23\,\mu s$ for frames with $1500\,B$ of payload. For the whole burst the latency decreases with larger packets, starting with $18.85\,ms$ for the smallest packets going down to $11.26\,ms$ for bursts with the largest frames. This decrease is due to the lower overhead when using larger frames. Compared to the latencies obtained in cellular and wide area networks, the simulated cross-traffic latencies are still low. Though it is well suitable for the projected applications in the domains of diagnosis, firmware updates or functions deployed off-board.

5) Buffer Sizes: Another challenge for in-car networks with cross-traffic bursts is the required buffer size in the forwarding switches. When only smallest frames are used for cross-traffic in this scenario, the queues in the switches are required to host at maximum 1764 frames or $110.25\,kB$. With only maximum sized frames for cross-traffic the largest fill level of the buffers in the network is 55 frames or $81.53\,kB$. For real-time frames (that use dedicated queues for each stream) the buffers remain small. Due to the shaping, the maximum sizes for the event-triggered traffic classes remains below 3 frames. For time-triggered messages the maximum buffer size in the switches is by definition between 0 frames and 1 frame.

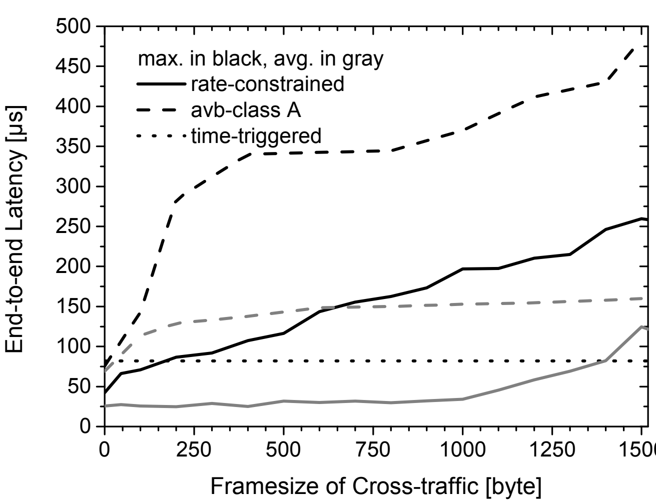

Fig. 5. Maximum end-to-end latency of real-time control traffic in relation to the maximum frame size of concurrent best-effort cross-traffic

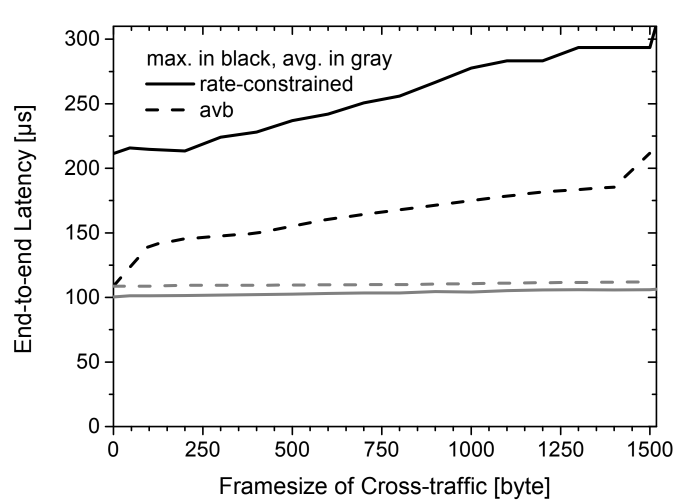

Fig. 6. Maximum end-to-end latency of real-time driver assistance camera traffic in relation to the maximum frame size of concurrent cross-traffic

B. Discussion

The simulation results show a diverse behavior of the different technologies when stressed with cross-traffic. For the control traffic the best results are undoubtedly obtained with time-triggered traffic. It was shown that time-triggered traffic proves its promise of determinism and independence of concurrent traffic streams. Also, it was the only traffic class able to comply with the highest end-to-end latency requirements of below 100 µs that are under discussion in the automotive industry [24]. There is a controversy whether such low-latency requirements will be really required in the near future. For applications with less rigid timing requirements, Ethernet AVB or its counterpart rate-constrained traffic that use strict priorities along with traffic shaping, still perform sufficiently well with latency bounds below 500 µs. For control-traffic the rate-constrained message class slightly performs better than Ethernet AVB due to the absence of credit-based shaping. While rate-constrained traffic with the highest priority only has to wait until the line card is idle, Ethernet AVBs credit based shaper adds a delay in situations where a frame has to wait for enough credit. As the additional delays for real-time messages due to cross-traffic occur for each hop, the penalty of best-effort background traffic increases with the length of the path from sender to receiver.

When utilized for multimedia traffic, Ethernet AVB can provide best results. Especially for the driver assistance camera that is transferred in the highest service class A, the latency influence of cross-traffic is low. Also, the rate-constrained traffic is a possible candidate for driver assistance applications, although adding a delay compared to Ethernet AVB. An even bigger difference between rate-constrained and Ethernet AVB traffic was obtained for the streams of the entertainment domain. With cross-traffic the end-to-end latency of AVB is almost one third lower than for the same streams using rate-constrained traffic. One reason for the performance advantage of Ethernet AVB in the camera and entertainment domain is the concurrent time-triggered traffic in the rate-constrained scenario. In relation to the requirements for audio and video streams both technologies offer sufficient performance.

V. Performance Improvements

Multiple strategies improve the real-time performance of Ethernet based networks. In the following we show possible techniques and their impact on real-time performance and efficiency of in-car networks with cross-traffic.

A. Limiting MTU

As shown in section IV, the frame size has significant impact on the latency and jitter of real-time traffic in in-car networks. While control traffic of most in vehicle applications – historically due to the limitation of today's fieldbusses – contains small payloads and thus has only small impact on latency and jitter, traffic of the entertainment domain and best-effort cross-traffic as shown in this paper can utilize up to maximum size frames. Especially for large traffic bursts this makes sense as it significantly reduces overhead. Transferring data with minimum size frames (46 B payload) produces almost 23 times more overhead than with the maximum MTU of 1500 B. Thus limiting the maximum frame size in real-time networks can significantly improve real-time performance at the cost of available net bandwidth. This trade off must be carefully considered when designing the network. As shown in section IV-A5 a limited MTU also has disadvantages for the required buffer sizes. Further, limiting the MTU can degrade the performance of media streams, e.g. in the domain of advanced driver assistance systems as it may provoke excessive frame fragmentation.

B. Limiting Cross-traffic & Optimized System Design

Our performance study shows the strong influence of the cross-traffic to the performance of the in-car applications. Especially if the network load is increased by non-controlled best-effort cross-traffic, the performance is degraded. To avoid this behavior and to guarantee the application constraints independent of the background traffic, cross-traffic has to be limited in the network. This can be realized by using traffic shapers on the network (e.g. at the gateway where cross-traffic enters the car) or by specifying design rules for cross-traffic applications. While the first solution is a dynamic process that is mainly implemented on the network and end devices, the latter is a static approach providing design rules on how much traffic to transmit in a limited time interval.

C. Increased Bandwidth

Besides lowering the frame size, the influence of a blocked line card due to lower priority traffic can be reduced by improving the transmission delay – the time that is required for the transmission of one frame on the wire. As previously calculated, the worst-case blocking time of a frame on an outgoing link at 100 Mbit/s is at maximum 123.36 µs. By increasing the bandwidth of the link from 100 Mbit/s to 1 Gbit/s, also the blocking time decreases to 1/10th. Although an automotive enabled Reduced Twisted Pair Gigabit Ethernet (RTPGE) supporting 1 Gbit/s (IEEE P802.3bp – 1000BASE-T1 PHY) is under development [3], we will most probably see gigabit links solely connecting high bandwidth sensors and for uplinks that would be otherwise saturated. Nevertheless, gigabit links should be also considered in situations where the other presented strategies could not satisfy the challenging real-time requirements with concurrent cross-traffic.

D. Topology

The topology is important for the influences of cross-traffic in in-vehicle networks. For all event-triggered traffic classes the latency and jitter increase is proportional to the number of hops a real-time message shares with the cross-traffic. Thus, considering cross-traffic while designing the network topology can significantly improve performance. In general the entry of background messages should be near the ECUs with the most inbound cross-traffic. Further, if possible the cross-traffic should be planned orthogonally to real-time messages with challenging timing requirements.

Daisy chains are discussed for some areas of in-car networking. A motivation behind those chains is to easily add optional ECUs without having to provide the required uplink ports also for entry configurations. Due to their structure, even without cross-traffic, daisy chains cannot provide the best performance. The higher number of hops used in chained network designs foster congestion. Due to the increased probability of congested line cards generated by background traffic bursts this effect is even more dominant when cross-traffic is added. Previous work [22] already showed the influences of daisy chain compared to star topologies in Ethernet-based in-car networks. For AVB SR class-A the analytical penalty for each hop is $250\,\mu s$. For time-triggered messages the additional delay of each hop can be reduced to the propagation delay plus the switches forwarding delay. Depending on the time-triggered schedule, the cumulative delay for each hop with current $100\,\mathrm{Mbit/s}$ store-and-forward hardware can be reduced down to $25\,\mu s$ to $135\,\mu s$ (depending on the frame size) as shown in [35]. Though, in cases where a daisy chain should be used, the requirements of the real-time traffic should be carefully analyzed.

E. Frame Preemption

Frame preemption is together with scheduled traffic (IEEE 802.1Qbv) a new topic under development in the IEEE 802.1 Time-Sensitive Networking Task Group under PAR 802.1Qbu [36]. In fact the requirement for frame preemption was actively driven by the introduction of scheduled traffic. As shown in section IV, time-triggered communication introduces a guard-band before each scheduled transmission slot to prevent delays due to line cards that are not idle at the configured action time. This guard band has to match the largest possible frame with lower priority. IEEE 802.1Qbu suggests splitting large messages on demand in chunks of at least $64\,\mathrm{B}$. As a result, the largest not splittable frame is $127\,\mathrm{B}$ or in transmission time (containing preamble, delimiters and interframe gap) $11.76\,\mu s$, what is comparable to the worst-case transmission time of a full size Ethernet frame at $1\,\mathrm{Gbit/s}$ (see section V-C).

Besides its benefits for scheduled traffic, frame-preemption would also improve event-triggered traffic, such as streams scheduled in the SR classes of IEEE 802.1Qav or the rate-constrained traffic defined in TTEthernet (and also ARINC-664) as it reduces the maximum time a high priority frame has to wait for the media access. The effect on latency and jitter is similar to reducing the maximum MTU, but in contrast the overhead of required bandwidth does only increase when preemption happens.

VI. Conclusion & Outlook

Real-time Ethernet is expected to become the favored solution for meeting the challenges of future in-car communication networks. While early deployments cover applications in the domain of advanced driver assistance and entertainment, future in-car network designs are likely to devise Ethernet in the backbone. Such a real-time Ethernet core will consolidate applications of a variety of domains both with rigid and relaxed timing and safety requirements. New applications such as firmware updates, diagnosis, or functionality deployed off-board will benefit the most from a homogeneous broadband communication infrastructure. Such applications add concurrent streams to the system and we demonstrated that particular knowledge and care is needed to shield the real-time and the best-effort classes. Accordingly, a careful evaluation of cross-traffic scenarios is of vital importance for the design of in-car network concepts.

With this work, we contributed a competitive performance evaluation of real-time Ethernet standards currently considered for in-car backbone networks under heavy cross-traffic. By simulating a realistic network design using traffic streams obtained from a current series-car, we analyzed the suitability of credit-based shaping, rate-constrained shaping and time-triggered traffic. Our results for the sensitive real-time control traffic show that event-triggered traffic classes such as IEEE 802.1Qav or rate-constrained traffic exceptionally suffer from cross-traffic bursts. End-to-end latency can increase by over $500\,\%$, while the jitter may rise up to a factor of 14. Nevertheless, all technologies in our analysis admit sufficient performance when compared to current fieldbusses (e.g. CAN and FlexRay). The worst-case end-to-end delay is still 10 to 20 times below today's requirements. Future applications of sophisticated control loops, though, may pose more rigid timing requirements (e.g., automated driving). For Infotainment, we found a lower influence of cross-traffic. This is due to the typical in-car topologies with reduced number of hops between sources and sinks. Further, applications in these domains typically have more relaxed timing requirements.

Based on these results, we propose different strategies to improve the real-time performance of networks with coexisting real-time and cross-traffic. While most strategies require a trade-off between real-time performance and other network or design metrics, we see a huge potential to reduce the impact of cross-traffic in frame preemption as proposed in PAR 802.1Qbu [36]. Still, frame-preemption requires significant changes of the Ethernet MAC and support on multiple layers, and needs careful analysis and justification. In our future work, we will implement a model for frame preemption and assess its potential. Further, we will confirm our simulation results by real-world measurements on a series-car that we extended by a prototypic Ethernet backbone [37].

Another important area of research and development are heterogeneous Ethernet-fieldbus designs. In such systems legacy busses, such as CAN or FlexRay will be attached to an Ethernet backbone instead of a central gateway [38]. Those heterogeneous mixed designs will increase the performance of in-car networks while keeping costs reasonable. We are currently working on simulation models to cover Ethernet-fieldbus designs. In future work we will include those heterogeneous networks in our performance assessments.

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