Simulative Assessments of IEEE 802.1 Ethernet AVB and Time-Triggered Ethernet for Advanced Driver Assistance Systems and In-Car Infotainment

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***Abstract*—Investigations into the usage of Ethernet in automobiles is in progress in academia, the car industry and companies producing automotive electronic devices. The interest in Ethernet is motivated by the high bandwidth and scalability provided. It is a well experienced technology with support for the Internet Protocol (IP) suite. Ethernet as in-car network is expected to breakthrough in Advanced Driver Assistance Systems (ADAS) involving cameras and in the multimedia domain. Both the IEEE Audio Video Bridging (AVB) standard and Time-Triggered Ethernet (TTE) are promising candidates. This paper presents a simulation study aimed to investigate the behavior of these technologies when supporting ADAS and multimedia traffic on star-based networks under varying workload. The performance under different operating conditions is presented and discussed.**

I. Introduction and Motivation

Ethernet is nowadays considered as a promising candidate for in-car communications, thanks to the high bandwidth provided (100 Mbps onwards) that paves the way for applications such as Advanced Driver Assistance Systems (ADASs), which make the volume of exchanged data in automotive communication continuously grow. Other strengths of Ethernet are the well-experienced technology, that allows for better testing, maintenance and development, and the wide use and open standardization, that entail a large availability of high-quality chips on the market and therefore low production costs. In addition, Ethernet is a scalable technology, that meets the requirements imposed by today's automotive systems, where the number of nodes to interconnect steadily increases. The compliance of the physical layer with automotive requirements is already addressed [1], allowing the usage of unshielded twisted single pair connections.

Another strong point in favor of Ethernet is the support for the Internet Protocol (IP) stack that opens the way to enhanced navigation functionalities, remote diagnostics and location-based services.

Investigations into the usage of Ethernet in automobiles is in progress in academia, the car industry and companies producing automotive electronic devices. Attention is paid to the IEEE AVB standard family [2] for multimedia, infotainment and driver assistance. AVB is attractive for the enhanced QoS provided, the IEEE standardization, no need for license fees and its cost and quality, comparable to those of standard Ethernet. Another suitable candidate to support driver assistance systems and multimedia is TTEthernet [3] (SAE standard AS6802) that also offers high bandwidth and guaranteed data rates for audio/video.

Among the automotive functional domains in which AVB and TTE might step in, here we focus on ADAS, multimedia and infotainment systems. This is because 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 due to wiring complexity, that affects maintenance, reliability, weight and costs. In-vehicle infotainment networking is today dominated by the Media Oriented Systems Transport (MOST) technology [4] which, however is only used in the automotive domain, and the smaller market penetration entails higher production costs. Moreover, with MOST the total network bandwidth is shared among all connected devices, while switched networks like Ethernet AVB and TTE utilize bandwidth more efficiently. Ethernet provides higher throughput than a MOST network operating at equivalent bit rates [5]. In addition, when using AVB or TTE for ADAS and infotainment, both systems could be integrated into the same network in a cost-effective design.

This paper, motivated by the findings in [6] about the suitability of AVB and TTE for automotive communication, presents an assessment of the two above mentioned technologies to investigate their behavior when supporting ADAS and multimedia traffic on star-based networks under a high and varying workload.

The paper is organized as follows: Section II deals with related work, while section III gives an overview about AVB and TTE. Section IV describes the experimental environment, while section V addresses the simulation setup. Section VI presents the network topologies investigated, while section VII discusses the performance obtained by the two networks. Finally, section VIII provides our conclusions and outlook.

II. Related Work

Several recent studies addressed the performance of Ethernet as in car-network. The work in [7] focuses on audio and video communications and compares several network topologies in terms of Quality of Service (QoS) and cost. In [8] the performance of an IP-based in-car network with a double star topology under intensive streaming flows is assessed. The results showed the need for QoS mechanisms. The same authors then addressed the QoS offered by three different network topologies, i.e. a star, a daisy-chain and a tree-based one, in a mixed traffic scenario that encompasses the traffic generated by several vehicle functions. The results showed that the star topology offers the best performance in terms of end-to-end delay. In [9] the performance of AVB and TTE are proven to be comparable in a network with a tree-based structure and a mix of control traffic and streaming traffic. Such a scenario significantly differs from the one in this paper, both for the topologies investigated and for the type and amount of traffic exchanged on the network.

In [10] Ethernet is investigated as a common networking technology to be used not only in a single functional domain, but also as in-car backbone for interdomain communications. This way, gateways would be used to connect to the Ethernet backbone the different types of networks used in today's cars [11]. According to the work in [10] the double star is, again, the topology that offers the best performance in terms of end-to-end delay and packet loss.

The work [6] addresses the suitability of Ethernet for automotive communications and indicates AVB and TTE as possible candidates. In [12] encouraging simulation results obtained with the IEEE 802.1AS standard for in-car networking are provided. The work [13] highlights open issues in AVB worst case latency analysis, pointing out some limitations of current theoretical formulations used for AVB latency estimation in [14]. Basically, starting from the findings in [15], the Authors explain two effects that affect the latency estimation of AVB, that are not encompassed in the formulas provided by the AVB standard [14]. The first of these effects is the so-called "own-priority and higher-priority blocking", that occurs when several streams share the same port. In this case, bursts can accumulate over multiple hops, thus eventually interfering with other streams and increasing their latency. The second effect is called "shaper blocking" and refers to the large blocking times that a flow may experience in certain scenarios (i.e., in daisy-chains) due to traffic shaping. Such a blocking may get worse when combined with priority inversion and the priority blocking described above.

As it will be shown in this paper, our simulation results are compliant with these findings, although these effects are limited, as in our topology we do have traffic bursts, but we have at most two cascaded switches. The work [16] reports preliminary performance assessments of AVB for ADAS, multimedia and infotainment traffic in a double-star topology. This paper extends the work [16] in several aspects. First, here we address different topologies, i.e. both a single and a double star. Second, the simulation scenarios are very different, as we used cross-domain flows here, that were not present in the other work, and a highly varying workload with significant traffic bursts, while in [16] the traffic distribution was constant. Last, but not least, the work [16] deals with AVB only, while this paper deals with both AVB and TTE and provides comparative assessments.

III. Overview on the Technologies under Study

In the following, we summarize the features of the IEEE AVB standard and TTE, respectively.

A. The IEEE 802.1 Audio Video Bridging Standard

The AVB standard defined by the IEEE 802.1 Audio/Video Bridging Task Group [2] provides the specifications for time-synchronized low-latency streaming services through IEEE 802 networks and includes three specifications:

- IEEE 802.1AS Timing and Synchronization for Time-Sensitive Applications, that specifies the synchronization process.
- IEEE 802.1Qat Stream Reservation Protocol, that specifies the three-step signalling process (i.e., stream advertisement, registration and de-registration). The purpose is reserving resources within switches (buffers, queues) along the path between sender and receiver.
- IEEE 802.1Qav. Forwarding and Queuing Enhancements for Time-Sensitive Streams. These specifications extend the IEEE 802.1Q standard splitting traffic into two classes, i.e., the time-sensitive AVB traffic and the non-AVB best-effort traffic. The document also specifies the different scheduling mechanisms, i.e., strict priority (for non-AVB classes) and credit-based shaper transmission selection algorithm (for AVB classes).

B. The Time-Triggered Ethernet

TTE [3], SAE standard (AS6802), supports three different traffic types: Time-triggered (TT), rate-constrained (RC) and best-effort (BE). Time-triggered (TT) messages are transmitted at predefined points in time and have precedence over the other traffic classes. They are suitable for safety critical and highly time sensitive applications such as X-by-wire. Rate-constrained (RC) messages are sent at a bounded transmission rate, that is enforced in the network switches, so that for each application a predefined bandwidth, together with delays and temporal deviations within given limits, is guaranteed. 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 switches, leading to increased transmission jitter. Rate-constrained messages are suitable for multimedia or ADAS automotive applications, like the ones addressed in this paper. Best-effort (BE) messages use the spare bandwidth left from the higher priority classes and thus have no guarantee on the delay and on the delivery at the destination.

C. Protocols in Comparison

While TTEthernet offers fully deterministic synchronous transmission with jitter in the magnitude of microseconds in its best traffic class, Ethernet AVB only supports event-triggered traffic. Thus TTE is more suitable for the transmission of control traffic whereas Ethernet AVB is optimized for the transmission of video and audio streams. In contrast to TTE, Ethernet AVB offers an online stream reservation protocol to reserve bandwidth when required. This increases flexibility and allows to adapt the configuration based on the actual bandwidth demand. Especially for traffic of multimedia applications this is highly attractive. A detailed comparison of the protocols was done in previous work [6].

IV. Simulation Scenario

In the scenario under study, shown in Table I, different traffic types are present:

- Advanced Driver Assistance Systems (ADAS).
- CD Audio.
- DVD Video entertainment.
- Cross-domain traffic.

The ADASs considered are based on a system composed of 6 cameras that generate video streams (one for each camera) and send them to a specialized Driver Assistance (DA) Electronic Control Unit (ECU), named DA-Cam, that processes them. According to the services provided, we divide the cameras in the following two groups [17]:

- Indirect services, aimed to improve road safety, that support the driver with navigation warnings derived from the processed video streams. The camera used for indirect services, i.e. Lane Departure Warning/Traffic Sign Recognition (LDW/TSR) is positioned on the windshield close to the rear mirror. LDW is a mechanism devised to warn the driver when the car crosses a road lane marking or the edge of the road. TSR is a technology that enables a vehicle to recognize the traffic signs on the road.
- Direct services, that support the driver with visual information in the form of views. In our scenario, there are five direct service cameras: Front, NightVision, Left, Right, Rear (see figure 1).

The flows processed by the DA-Cam are sent to a ECU called Head Unit that is equipped with a monitor, installed on the cars dashboard, on which the received streams are displayed. The output flows produced by the DA-Cam are new flows, either augmented with additional graphics to assist the driver or resulting from processing multiple camera flows to produce single views (e.g., Top view, Side view, etc.). A flow streamed to the Head Unit therefore consists of either a single view, or multiple views aggregated in a single flow in such a way that the Head Unit can select and extract the needed view. The DA-Cam ECU also produces the navigation warnings that are displayed at the Head Unit.

To obtain a realistic scenario, we had to decide how to model both the traffic generated by cameras and the streaming of the flows displayed on the Head Unit monitor, taking into account current practices and state of the art. Some previous work [7] considered MPEG-2 Transport Stream compression (MPEG-2/TS) for both IP cameras and multimedia video. This can be considered as a conservative approach, as MPEG-2 traffic has been thoroughly analyzed and modeled and hardware compression is available at reasonable costs. On the other hand, MPEG-2 has been recently replaced by more effective codecs based on the MPEG-4 standard for a number of reasons. In most cases recent IP cameras for video surveillance adopt MPEG-4 SP (Simple Profile) for video coding as a trade-off between encoding/decoding complexity and bitrate/quality combination. Compared to other standards for video compression, MPEG-4 SP requires a smaller bandwidth (a few Mbps in our case) while offering higher quality, thus we chose MPEG-4 SP. In our simulation scenario, the video frame rate generated by a camera is 30 frames per second (fps), while the video resolution selected for displaying the stream on the Head Unit monitor is 640×480 pixels. To model an increasing video traffic workload, we used two DA-Cam aggregated flows. The first one, indicated in table I as *DA-Cam Aggregated 4-flows*, starts at $t = 0\,s$ and stops at $t = 400\,s$. The second one, named *DA-Cam Aggregated 5-flows*, models the workload increase corresponding to turning on the fifth direct camera (i.e. the Night Vision one). It starts at $t = 400\,s$ and continues until the end of the simulation at $t = 600\,s$. This way we could assess the behavior of the network when the video traffic workload increases over time.

The car is also equipped with a CD audio and a DVD video entertainment system. The DVD video stream, encoded with the MPEG-2 Program Stream standard (MPEG-2/PS), is directly sent to the rear seats monitor, while the audio stream is encoded with AC3 (Dolby Digital) and sent to the in-car digital audio amplifier. Alternatively, instead of the DVD audio stream, the audio stream produced by the CD player can be sent to the in-car audio digital amplifier. The features of the CD Audio and DVD video flows are shown in table I.

Our scenario also regards cross-domain traffic, consisting of periodic data coming from the car control network which is gathered from a gateway device and injected in our network, directed to a Cross-Domain Processing Unit which extracts relevant data useful to the navigation and driver warning functions. If a given condition is detected, which requires a driver warning, the Cross-Domain Processing Unit turns on the corresponding dashboard indicator. Here we model an increasing cross-domain traffic using two flows. The first one, indicated as *Cross-domain 1st flow* in table I, starts at $t = 0\,s$ and stops at $t = 300\,s$. The second one, named *Cross-domain 2nd flow*, uses twice the bandwidth of the first one. It starts at $t = 300\,s$ and continues until the end of the simulation.

In addition to the characteristics, the traffic flows table I also shows the mapping on the traffic classes provided by AVB and TTE, respectively. The first column gives the corresponding workload for each traffic type. For instance, the interval $[5, 15]$ for cameras means that the overall amount of video traffic generated by all the cameras varies between 5 and 15 Mbps. The second column shows the payload generated at

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

Type	Bandwidth [MBit/s]	Appl. Payload [Byte]	Service Rate [ms]	Activation interval [s]	IEEE 802.1 AVB Class (Priority)	TTE Priority
Cameras (4+1)	[5,15]	uniform(303, 910)	2.426	4x[0,600] + 1x[400,600]	SR Class A	RC (Prio 3)
LDW/TSR camera	[2,6]	uniform(303, 910)	1.213	[200,600]	SR Class A	RC (Prio 3)
DA-Cam Video traffic Single flow	[1,3]	uniform(303, 910)	2.426	[0,600]	SR Class A	RC (Prio 3)
DA-Cam Video traffic Aggregated 4-flows	[4,12]	uniform(303, 910)	0.6065	[0,400]	SR Class A	RC (Prio 3)
DA-Cam Video traffic Aggregated 5-flows	[5,15]	uniform(303, 910)	0.4852	[400,600]	SR Class A	RC (Prio 3)
DA-Cam Warning traffic	0.016	100	50	[200,600]	SR Class A	RC (Prio 2)
DVD player	10.08	1400	1.11	[500,600]	SR Class B	RC (Prio 4)
CD Audio Player	1.41	1400	7.94	[0,600]	SR Class B	RC (Prio 4)
Cross-Domain traffic 1st flow	0.0736	46	5	[0,300]	SR Class A	TT (Prio 1)
Cross-Domain traffic 2nd flow	0.147	92	5	[300,600]	SR Class A	TT (Prio 1)

the application level. For camera flows, it is known that the workload is highly dependent on the specific video, i.e. on the scene being captured. Here we are interested in evaluating the performance of the two addressed networks under highly varying workload. We took the typical workload ranges of the adopted encoding as reference. Hence, we derived the parameters of statistical distributions able to generate such workloads. For the sake of simplicity, we chose a uniform distribution after evaluating several options. All the other traffic types are periodic, with a period equal to the service rate shown in table I and have a constant payload. Table I also shows the activation interval of each traffic type. Every device in the network has in fact an activation interval that indicates when the stream with the relevant traffic starts.

V. SIMULATION SETUP

The network performance was evaluated using the OMNeT++ [18] simulation toolchain and the INET-Framework [19]. We simulated a protocol stack on top of layer 2. The protocol overhead is therefore 18 bytes for both TTE and AVB. For each topology two cases were investigated.

- Case A: the DA-CAM sends a single flow to the Head Unit (with a workload varying in the range of $[1, 3]$ Mbps);
- Case B: DA-CAM sends a flow resulting from the aggregation of flows from the cameras that provide direct services (with a workload varying in the range $[4, 12]$ Mbps for the first 400 s, and in the range $[5, 15]$ Mbps for the last 200 s of simulation).

Given the high variability of the video payload, traffic bursts are present in both scenarios. All the other traffic flows are the same in both cases and the relevant values are shown in table I.

A. AVB Setup

In AVB simulation, all the traffic is mapped on the Stream Reservation (SR-AVB) classes. A priority value is associated with each SR-AVB class, that is, '3' for SR-AVB Class A, '2' for SR-AVB Class B. As shown in Table I, all the video flows from the cameras to the DA-CAM, the video flows and the navigation warnings from the DA-CAM to the Head Unit and cross-domain traffic are mapped onto class A, while the entertainment traffic is mapped to SR-AVB class B.

The rationale behind this mapping is that AVB supports only two classes of time-sensitive traffic (i.e., class A and class B), and camera video, DA-Cam video, navigation warnings and cross-domain traffic are relevant to the driver safety. We could have divided those flows onto class A and B, but doing so, we should have mapped entertainment traffic either onto class B, to the detriment of the safety-related flows in that class, that would have experienced interference from very bandwidth-greedy entertainment flows at the same priority level, or on best-effort traffic, without any guarantee on quality of service. With our mapping we do not mix safety-critical with non-safety critical flows, while providing QoS guarantees to the entertainment flows as well. This choice therefore reflects the different criticality of the flows from the users perspective (being safety-related traffic more critical than entertainment). Bandwidth is reserved using the Stream Reservation Protocol (SRP) and the related signaling protocol, the Multiple Stream Registration Protocol (MSRP).

According to the IEEE 802.1Qat Standard [2] only 75% of the total bandwidth can be reserved to class A and class B, to leave room for best-effort traffic. Although in our scenario there is no best-effort traffic, we followed the specifications. The bandwidth percentage reservable is 40% for AVB SR class A and 35% for AVB SR class B. The medium access scheduling algorithm for both classes is credit based fair queuing. For each stream, SRP specifies the bandwidth that can be consumed through the traffic specification parameter TSpec, that defines the maximum number of bits per frame (MaxFrameSize) and the maximum frame rate (MaxIntFrms) in frames per class. Here MaxFrameSize is assumed equal to the application payload in table I for constant frame size streams, while for variable frame size streams MaxFrameSize is equal to the maximum of the interval of the uniform distribution in table I.

According to the standard [2], the actual bandwidth $actBw$ needed to support a given stream is calculated as in equation 1:

$$\begin{aligned} actBw &= (PFO + APlSize) \times maxFrmRate \\ maxFrmRate &= MaxIntFrms \times (1/classMsIntv) \end{aligned} \quad (1)$$

where PFO = 18 Bytes is the per-frame overhead, the assumed payload size (APlSize) is set equal to MaxFrameSize and maxFrmRate is the maximum frame rate. For each stream,

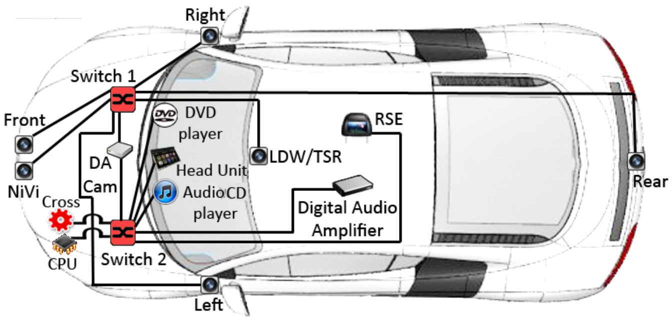

Fig. 1. Single Star Topology

MaxIntFrms is the ratio between the class measurement interval and service rate in Table I.

The forwarding process provides one or more queues for a given switch port, each corresponding to a distinct traffic class. Each traffic class is assigned a distinct priority level, so there is one queue for each priority level.

B. TTE Setup

TTE supports three traffic classes. As here we have cross-domain, cameras and DA-Cam video, navigation warnings and multimedia flows, we use the time-triggered traffic class for the first traffic type and the rate-constrained traffic class for the others. Four priority levels, with different queues, are used. Cross-domain traffic has the highest priority, i.e. level 1, as it has a small payload and introduces a light workload, so we preferred to provide it with a preferential handling. For the same reason, the second priority level, i.e., level 2, is given to navigation warnings, while cameras and DA-Cam video have the third priority level, i.e. level 3. Finally, CD audio and DVD video streams have the fourth priority level, i.e. level 4. Strict priority scheduling is used between the priorities, FIFO within the same queue.

The TT traffic is sent at regular time intervals. To support this traffic it is necessary to configure a complete schedule. In the cycle time, i.e., the period after which the schedule is repeated, we define the slots in which every network device can send TT messages. In the offline planned slots no other traffic can be sent. TT traffic is actually generated at a well-defined time at the sending device and it must be received at a known time by the receiving device. A different receiving time of the frame could cause incorrect scheduling.

The RC traffic is based on the concept of Virtual Links (VL), i.e., a logical unidirectional connection from one source to one or more destinations. The use of VL allows full-duplex communication channels on which multiple streams, each one identified by a CT-ID (Critical Traffic-Identifier), can be sent. Each RC-VL is associated with a Bandwidth Allocation Gap (BAG), that is the minimum delay between two consecutive frames on the same VL. The application sending the message has to respect the constraint of the relevant configured BAG, otherwise the Ethernet frame will be considered invalid and will be dropped [3]. For RC traffic, we configured the BAG values according to the service rate in table I.

The TTE simulation is published as open source [20] and was evaluated using analytical methods and real-world measurements using TTE hardware [21].

In the simulation shown, the switches are characterized by a switch processing time of 8 µs. The model allows to consider the propagation delay, that in our case has been fixed equal to 5 ns per meter and varies according to the length of the connections between the devices in the interval $[0.3, 3.2]$ m.

VI. Topology

In this paper we investigate two different topologies. In the first one, called a single-star topology (Figure 1), we use two separate switches, while in the second one, called a double-star topology (Figure 2), we have two interconnected switches.

A. Single-star Topology

In the single-star topology (Figure 1), the first switch connects the ADAS cameras to the driver assistance cam ECU (DA-Cam).

This choice, that differs from the approach in [22], where point-to-point connections are used between cameras and ADAS, is motivated by the need to reduce wiring complexity, weight and costs (as explained in section I) replacing the current point-to-point Low-Voltage Differential Signalling (LVDS) wires with a switched network. The second switch connects the Head Unit with the DA-Cam, the Cross-domain Processing Unit (CPU), the DVD player with the Rear Seats Entertainment (RSE) system, and an audio player (CD-Audio) with the relevant digital audio amplifier. The reason for two switches is to separate the flows originating from the cameras and directed to the DA-Cam from the rest of the traffic, to avoid that entertainment and cross-domain traffic on the same switch could affect the performance of ADAS traffic.

In the single-star topology, the DA-Cam is therefore a specialized ECU, equipped with two ports to be connected to two separated networks, respectively. It produces new traffic flows (resulting from processing the ones received from the cameras and traversing the first switch), that are sent through the second switch to be displayed at the Head-Unit. The second switch handles, in addition to the flows sent by the DA-Cam to the Head Unit, the multimedia video traffic sent by the DVD player to be displayed at the Rear Seat Entertainment (RSE) system, the multimedia audio flow that the CD player streams to the digital audio amplifier and the cross-domain traffic that is processed by the Cross-domain Processing Unit (CPU).

B. Double-star Topology

The second topology under study here, called a double-star topology, is shown in figure 2.

Here, in contrast to the single-star topology, the two switches are directly connected. The DA-Cam ECU is a one-port device. The flows that traverse both switches originate from DA-Cam and go to the Head Unit. As in the single-star topology, these flows consist of either single views (case A in section V), or multiple aggregated views (case B in section V), in addition to the navigation warnings present in both

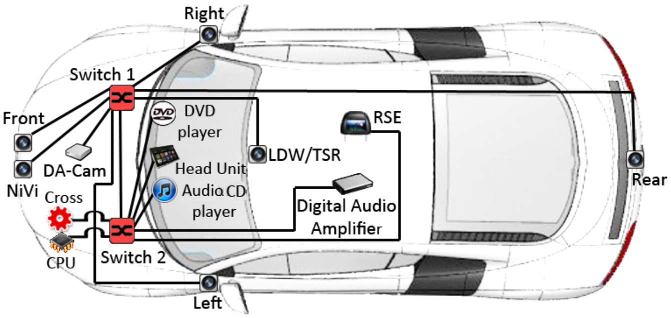

Fig. 2. Double Star Topology

cases. The cross-domain and entertainment flows traversing the second switch in the double star topology are the same that traverse the second switch in the single star topology.

We investigate the double star topology to assess the network performance when the traffic of the three domains, i.e. cross-domain, ADAS and entertainment, is transmitted on the same physical infrastructure, and the network operates under a high workload. In this case, in fact, the first switch is also traversed by the ADAS traffic generated by DA-Cam, so its workload is higher than in the single-star topology.

VII. Simulation Results

In this Section, we present the results of the AVB and TTE simulation under the same operating conditions in the two presented topologies.

Our performance metrics are:

- Latency (L), defined as the one-way end-to-end frame delay, i.e., the time from the source sending a packet to the destination, measured at layer 2.
- Latency Relative Deviation (LRD), here defined as the absolute value of the difference between two consecutive interarrival times. The interarrival time is defined as the difference between the arrival times of two consecutive frames of the same stream at the destination. LRD is calculated at the destination as shown in equation 2:

$$LRD(n) = |(a_n - a_{n-1}) - (a_{n-1} - a_{n-2})|\,, n > 2 \quad (2)$$

where a_n is the arrival time at the destination of the n^{th} Ethernet frame.

Here we present latency and LRD results, measured in both topologies addressed for all traffic flows in our scenario. Measurements are taken at the MAC level based on the Ethernet data frame transmission and reception instants. The network load increases over time, according to the activation interval column in table I.

A. Latency Assessment - Single Star topology - Case A

Table II shows the results for Ethernet AVB and TTE for Ethernet frames. Mean latency values for both protocols are in the same order of magnitude, although AVB has slightly higher values than TTE, with the exception of cameras and DVD flows. As far as maximum latency is concerned, TTE has slightly higher values for cameras, LDW/TSR and navigation flows, but lower values for the other traffic flows. For both protocols, we observed that latency increases, during simulation, whenever devices are dynamically activated. For example, when the LDW/TSR and NiVi cameras are added (at $t = 200\,s$ and $t = 400\,s$), the latency increases about 80 µs at every device.

TABLE II
Mean and maximum latency and LRD of the Ethernet frames in Single Star - Case A, for each traffic class.

Traffic Type	Latency [µs]				LRD [µs]			
	AVB		TTE		AVB		TTE	
	Mean	Max	Mean	Max	Mean	Max	Mean	Max
Cameras	109	441	169	469	411	852	148	689
LDW/TSR camera	209	443	121	459	414	852	86	734
DA-Cam	122	245	111	166	67	481	57	192
Navigation warnings	62	113	33	163	32	189	6	173
DVD	399	1400	794	1350	526	2100	0	0
CD-Audio	412	489	238	238	637	971	0	0
Cross-domain 1	160	170	60	61	0	2	0	1
Cross-domain 2	160	175	60	61	0	2	0	1

LRD is high in cameras and LDW/TSR flows for both protocols, as several video streams at the same priority level are sent from the cameras to the same receiver (DA-Cam). The Ethernet frames are delayed in the relevant switch outgoing queue. The slightly different LRD between the two protocols is due to the different frame scheduling in TTE (FIFO) and AVB (Credit-Based Fair Queuing). The LRD values equal to 0 for Audio CD and DVD in TTE are because both these flows do not suffer from interference from other flows in the relevant queues. This behavior is observed with TTE in all topologies and in all cases addressed.

About AVB results, the LRD for the audio traffic flow has some peaks (about 971 µs) due to shaping management (we recall that audio flow is in class B). These peaks, however, seldom occur and for this reason do not significantly impact on the average value. We also observed a slight increase in the latency value at simulation time $t = 200\,s$, due to the activation of the navigation traffic flow. This increase is about 2 µs and thus does not significantly impact the overall performance.

For the navigation flow in AVB, the LRD depends on the presence of large frames of other class A traffic, i.e. DA-Cam flows, in the same switch output queue.

The maximum LRD for the DA-Cam flow shows that this flow is sometimes affected by the navigation warning traffic, that determines rare peaks starting from 200 s onwards. Average LRD values are instead very close to TTE results.

Here we underline that TTE benefits from using different priorities for navigation warnings and DA-Cam, while in AVB these traffic flows have the same priority level, as both flows are mapped onto class A, so they mutually interfere. Cross-domain traffic also obtains the best results in terms of latency and maximum latency deviation with TTE, thanks to the mapping onto the highest priority class and especially the time-triggered scheduling.

B. Latency Assessment - Single Star topology - Case B

In this scenario, instead of a single flow, DA-Cam streams an aggregated video to the Head Unit. Here we refer to DA-

Cam 4 and DA-Cam 5 to indicate the aggregated flow before and after the activation time of the night vision camera at time $t = 400\,s$ (see table I). The results are shown in table III.

TABLE III
MEAN AND MAXIMUM LATENCY AND LRD OF THE ETHERNET FRAMES IN SINGLE STAR - CASE B, FOR EACH TRAFFIC CLASS.

Traffic Type	Latency [µs]				LRD [µs]			
	AVB		TTE		AVB		TTE	
	Mean	Max	Mean	Max	Mean	Max	Mean	Max
Cameras	100	441	169	469	411	852	148	689
LDW/TSR camera	209	443	121	459	414	852	86	734
DA-Cam 4-flows	203	225	111	161	308	340	57	191
DA-Cam 5-flows	204	228	171	389	330	372	57	193
Navigation warnings	89	154	42	168	67	200	20	178
DVD	399	1400	794	1350	526	2100	0	0
CD-Audio	412	489	238	238	644	971	0	0
Cross-domain 1	160	170	60	61	0	2	0	1
Cross-domain 2	160	175	60	61	0	2	0	1

With TTE, there is almost no difference in the latency results for DA-Cam 4-flows as compared to the single DA-Cam flow in case A (see table II). For DA-Cam 5-flows, in TTE we see a slight latency increase, while the LRD is still very close to the single flow in case A (see table II). This means that TTE offers a more stable behavior than AVB for DA-Cam flows. AVB results, in fact, show an increase in the mean latency values and a significant increase in the LRD for both DA-Cam 4-flows and DA-Cam 5-flows. Similar results for the two protocols are obtained for the latency and LRD of navigation warnings between case A and case B, with AVB providing slightly higher values. Even in this case, the cross-domain flow obtains the best results with TTE, because it is scheduled as time-triggered traffic.

LRD values are generally better in TTE, as mentioned before. In AVB, the maximum value of LRD for the traffic sent by DA-Cam to the Head Unit (see table III) is less than in the previous case, and this occurs at the expense of the maximum LRD of navigation warnings, that is larger than the one in case A. These results confirm the mutual interference between these two traffic flows in our AVB settings, and show that a larger amount of traffic with big-size frames, such as DA-Cam one, affects the performance of competing traffic in the same class with small-size frames, such as navigation warnings.

C. Latency Assessment - Double star topology - Case A

For the double star topology in case A (with a single flow) the latency increases, as compared to the single star, for both the DA-CAM and navigation warnings flows with both AVB and TTE, albeit more significantly with AVB (see table IV).

This is due to the increased amount of traffic that traverses switch 1 in this topology. As cross-domain, audio and video flows are not affected by the double star topology, their results remain the same as in the single star (case A). From the results we see that the frames that are forwarded through two switches now experience a higher latency. Also in this scenario the activation of navigation warning traffic affects the AVB latency of DA-Cam flow, from $t = 200\,s$ onwards, by introducing rare peaks up to 912 µs. This is because these two flows have the same priority and content for transmission in the same queue.

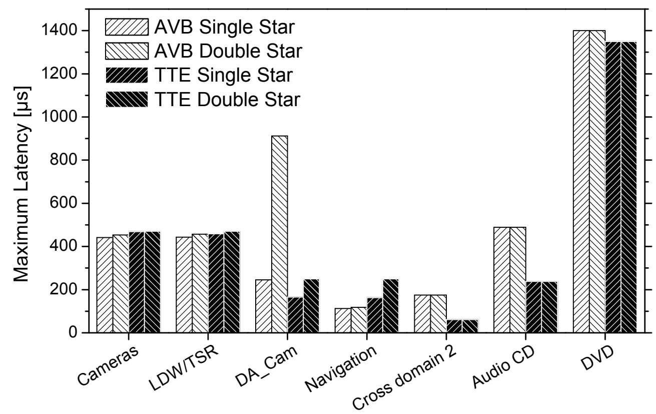

Fig. 3. Comparison of maximum latency of all flows in Case A

Under certain circumstances, own-priority blocking and traffic shaping may determine very high latency for some frames. The LRD values increase in TTE for cameras, LDW/TSR, DA-Cam, navigation warnings as this traffic directed to the Head Unit must cross both switches. Further, switch 1 is traversed by more traffic compared to the single star topology.

D. Latency Assessment - Double star topology Case B

For TTE in the double star topology, there is no significant latency increase for the DA-Cam 4 aggregated flow as compared to DA-Cam single flow, while for DA-Cam 5 there is a latency increase, although the LRD remains stable. Conversely, AVB latency is larger for both DA-Cam 4 and DA-Cam 5 (see table V).

No latency peaks as in case A are found with AVB for DA-Cam aggregated flows in this configuration, thus showing that in this case the own priority effect affected more navigation traffic than DA-Cam one. In fact, with AVB, the navigation traffic obtained higher latency values than in case A, due to the increased amount of interfering DA-Cam traffic at the same priority. As far as DA-Cam LRD is concerned, AVB suffers from significant increase for the mean value, but not for the maximum. Conversely, TTE for DA-Cam obtained results are quite close to the ones found in case A, thus showing a more stable behavior.

E. Discussion

Figure 3 summarizes the maximum latency results for all flows for TTE and AVB in all scenarios in case A. The

TABLE IV
MEAN AND MAXIMUM LATENCY AND LRD OF THE ETHERNET FRAMES IN DOUBLE STAR - CASE A, FOR EACH TRAFFIC CLASS.

Traffic Type	Latency [µs]				LRD [µs]			
	AVB		TTE		AVB		TTE	
	Mean	Max	Mean	Max	Mean	Max	Mean	Max
Cameras	131	453	169	471	432	852	148	718
LDW/TSR camera	209	457	121	471	432	852	87	757
DA-Cam	189	912	170	250	103	1400	85	287
Navigation warnings	77	118	57	250	47	119	12	241
DVD	399	1400	794	1350	526	2100	0	0
CD-Audio	412	489	238	238	637	971	0	0
Cross-domain 1	160	170	60	61	0	2	0	1
Cross-domain 2	160	175	60	61	0	2	0	1

TABLE V
MEAN AND MAXIMUM LATENCY AND LRD OF THE ETHERNET FRAMES IN DOUBLE STAR - CASE B, FOR EACH TRAFFIC CLASS.

Traffic Type	Latency [µs]				LRD [µs]			
	AVB		TTE		AVB		TTE	
	Mean	Max	Mean	Max	Mean	Max	Mean	Max
Cameras	130	442	169	469	411	852	148	710
LDW/TSR camera	203	457	121	459	417	852	86	743
DA-Cam 4-flows	223	265	170	246	401	434	85	288
DA-Cam 5-flows	237	279	231	537	410	482	85	289
Navigation warnings	129	339	70	252	77	224	34	243
DVD	399	1400	794	1350	526	2100	0	0
CD-Audio	412	489	238	238	637	971	0	0
Cross-domain 1	160	170	60	61	0	2	0	1
Cross-domain 2	160	175	60	61	0	2	0	1

best results for both protocols are obtained by the single star topology, but both topologies are suitable to fulfill the requirements of the traffic considered, that is, 33 ms for all the video flows from cameras and DA-Cam and 100 ms for audio and multimedia video flows [7], [8]. The results for cross-domain traffic are also adequate. Throughput and workload mean values, measured at Ethernet layer in the interval $[500, 600]$ s, i.e. under the maximum workload, are almost the same in all topologies and cases, thus confirming that there is no packet loss (see table VI). As stated in [7], the maximum packet loss should be less than 0.1 %, so both protocols performed well in our scenario.

TABLE VI
TOTAL WORKLOAD AND THROUGHPUT FOR EVERY SWITCH IN DOUBLE STAR TOPOLOGY FOR AVB AND TTE

	Workload [Mbps]		Throughput [Mbps]	
	AVB	TTE	AVB	TTE
Switch 1 A	16.923	16.493	16.923	16.493
Switch 2 A	14.013	13.931	14.013	13.931
DA-Switch 1 B	23.899	24.731	23.899	24.731
DA-Switch 2 B	21.024	22.169	21.024	22.169

VIII. CONCLUSIONS & FUTURE WORK

This work assessed the performance of IEEE 802.1 AVB and TTE for ADAS and in-car multimedia. The simulation results showed that both protocols fit the latency requirements of future ADAS systems and multimedia entertainment, albeit with slight differences. TTEthernet offers the most precise communication with very low jitter and thus is perfectly suitable for the cross-domain control traffic. Thanks to the time-triggered traffic, the transmission is completely deterministic in this traffic class. The event-triggered (rate-constrained) traffic of TTE is comparable to Ethernet AVB but, thanks to the broader range of priorities and the strict priority scheduling, it also shows slight advantages over AVB.

The two protocols are complementary. TTEthernet must be scheduled offline, while Ethernet AVB allows for online stream reservation. TTE allows for completely deterministic transmission and offline verification of time-triggered messages for safety-critical applications, while AVB allows for online stream reservation, that fits entertainment applications with varying bandwidth demand. In future work we will therefore investigate the case for integrating the two protocols in the same infrastructure to combine their benefits. We will also address more detailed traffic models and topologies. In particular, we will analyze the effect on the protocols performance of increasing bandwidth demand due to, for example, cameras with higher resolution.

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