基于OMNET++的INET库，评估了802.1Q的严格优先级，CBS(Credit based Shaper)，和TAS(Time aware Shaper)在低负载下的效果。

Performance assessment of the IEEE 802.1Q in automotive applications

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***Abstract*—Ethernet is nowadays a promising communication technology for automotive applications as, comparing with the existing in-vehicle networks, it offers high bandwidth and a significant reduction of cabling costs, while meeting the EMC/EMI requirements of automotive communications. The IEEE 802.1Q standard is one of the base standards of Time-Sensitive Networking. It offers several benefits, such as the real-time support, as it provides bounded latency to time-constrained traffic classes, with zero jitter and congestion-free transmissions, and the capability to handle multiple traffic classes on the same channel. The IEEE 802.1Q standard specifies multiple features, that support different ways to handle the transmission of Ethernet frames. In this paper a comparative performance assessment of three network configurations defined in the IEEE 802.1Q standard for automotive applications are presented. The assessment results are obtained using the OMNeT++ framework. The comparison between the results of these three different network configurations, using realistic traffic patterns, provides a quantitative evaluation of the network performance in terms of maximum end-to-end delays and absolute jitter.**

***Index Terms*—IEEE 802.1, Time-Sensitive Networking (TSN), Automotive Communications, Real-time networks, In-vehicle networks, Performance evaluation.**

I. Introduction

The introduction of novel applications in modern cars increased the level of in-vehicle connectivity among multiple functional domains. For instance, infotainment applications and advanced driver assistance systems (ADAS) may share the information acquired from, for instance, GPS or telematics. Hence, the concept of an in-vehicle backbone interconnecting different functional domains for cross-domain communication is accepted by automotive suppliers and car makers. These new applications require a network able to handle different kinds of traffic with multiple requirements, e.g., bounded latencies, zero jitter, low delays.

Ethernet-based networks are being considered as promising candidates [1] for automated driving applications and to support cross-domain communications, thanks to the high bandwidth and wide availability of suppliers on the market. In particular, the Time-Sensitive Networking (TSN) set of standards include several published standards and ongoing projects that provide deterministic services over bridged Ethernet networks for many application domains, such as, automotive and industrial control. The recent survey in [2] extensively deals with TSN standards for the above mentioned domains.

TSN offers time synchronization [3], guaranteed transmissions with bounded delays, reliability and deterministic communications with bounded ultra low delays [4]. To this aim, TSN provides a toolbox of features, mechanisms and protocols that can be selected and combined to design a network that meets the requirements of specific applications. However, the selection and design of a suitable configuration for a particular applications domain is a challenging task, especially for the automotive domain, in which hardware costs and network complexity are quite important issues and network reconfiguration is costly [5], due to the system down time that is required to perform reconfiguration operations.

This paper focuses on the comparative performance assessment of three network configurations in an automotive scenario to handle ADAS and multimedia/infotainment communications over the same IEEE 802.1Q [4] network. The aim of this work is to provide a quantitative evaluation, using realistic traffic patterns, of the network performance in terms of maximum end-to-end delays and absolute jitter. Moreover, some empirical insights on the network configuration and traffic mapping methods used for this kind of applications is presented.

This work is organized as follows. Section II overviews related work. Sect. III presents the basics of the IEEE 802.1Q standard. Sect. IV describes the assessed scenario and provides the reasoning used for the flow mapping of on the traffic classes under investigation, while Sect. V presents the assessment results. Finally, Sect. VI addresses the conclusions and gives hints for future work.

II. Related Work

Many recent papers addressed the performance the IEEE 802.1Q standard for automotive applications. The paper in [6] addressed the performance assessment of the Credit-Based Shaper (CBS) defined in the IEEE Audio Video Bridging (AVB) standard and the use of the Time-Aware Shaper (TAS), as defined in IEEE 802.1Q, in automotive case studies. The papers in [7] and [8] deal with the AVB suitability for automotive applications. In particular, in [7] a comparative performance assessment of AVB and TTEthernet was addressed for ADAS, multimedia and infotainment traffic. The obtained results show that both AVB and TTEthernet meet the requirements of

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ADAS and multimedia flows. The paper in [9] presented a formal worst-case analysis for Ethernet networks using the Strict Priority policy and the CBS. The analysis provides upper bounds on frame delays. Several topologies were evaluated in industrial use cases. The evaluation showed that the CBS obtains higher delays than the Strict Priority, due to the additional traffic shaping delay. In [10] and [11] a new approach, called AVB_ST, introduced a separate traffic class on top of the AVB SR Classes A and B. The ST class handles high-priority time-sensitive traffic that has to be transmitted according to a fixed time schedule and has to be temporally isolated from other traffic. Simulation results obtained in automotive and industrial scenarios showed that the AVB_ST is able to support scheduled traffic, with low and deterministic latency values, without significantly affecting the SR traffic latency. A response time analysis for AVB_ST was proposed in [12]. The current version of the IEEE 802.1Q standard [4] provides support to scheduled traffic. The design of the schedule for ST traffic is challenging, so a recent work [13] addressed a formal description of scheduling constraints for building the ST schedule with the adoption of satisfiability modulo theories solvers for its synthesis.

III. Basics on the IEEE 802.1Q standard

This section focuses on the IEEE 802.1Q standard [4], which defines the mechanisms to handle multiple traffic classes on a bridged Ethernet network. In particular, here we focus on three traffic transmission mechanisms defined in the standard, i.e., the Strict Priority (SP), the Stream Reservation (SR), hereinafter called AVB (as the Stream Reservation Protocol and its classes were specified for the first time in the Audio Video Bridging set of standards) and the Enhancements for Scheduled Traffic, hereinafter called Qbv (as the IEEE 802.1Qbv is the amendment to the IEEE 802.1Q standard that originally introduced them).

In the IEEE 802.1Q standard each Ethernet port provides a maximum of eight queues ordered according to increasing priorities. Each time the channel is free, the Strict Priority algorithm selects for transmission the frame at the head of the highest priority queue. This mechanism allows up to 8 frame priorities.

The Audio Video Bridging set of standards introduced the Stream Reservation (SR) classes, which have guaranteed bandwidth. SR traffic undergoes traffic shaping, as the Credit-Based Shaper (CBS) is applied at the output ports of both switches (called bridges in the IEEE terminology) and end nodes, to prevent traffic bursts. The IEEE 802.1Q foresees multiple traffic classes, but it actually defines the configuration parameters for two SR traffic classes only. They are Class A, that provides a maximum latency of 2ms over 7 hops, and Class B, that provides a maximum latency of 50ms over 7 hops.

According to the CBS, each SR traffic class has an associated *credit* parameter. The frames that are pending in the SR queues can be transmitted only when their associated credit is non-negative. During the message transmission, the credit value decreases at the *sendSlope* rate defined for the class, while the credit increases at the constant rate *idleSlope* defined for the class when either the frames of that class are waiting for transmission on a busy channel or when no more frames of the class are waiting, but the credit is negative. If the credit is non-negative, but there are no frames of the class waiting for transmission, the credit is reset to zero.

Finally, the Enhancements for Scheduled Traffic specifications add to the previous classes the support for the Scheduled Traffic (ST) class. The ST traffic is periodically sent at specific instants. Transmissions are offline scheduled and ST traffic has to be transmitted at a specified time by the source and must be received at a specified time by the receiver. Such a behavior is achieved thanks to *gates* associated with each transmission queue. When the gate for a given queue is open, the pending frames within the queue can be selected for transmission (according to the Strict Priority rule and CBS, if the latter is enabled), whereas when the gate is closed, the pending frames within the queue cannot be selected for transmission. Gate Open/Close operations are specified in an ordered list (called a Gate Control List) and they are cyclically repeated. The duration of a cycle is called a *CycleTime*.

For the assessment presented in this paper, we will focus on the following three traffic classes that are defined in the IEEE 802.1Q standard [4]:

- **Scheduled Traffic (ST).** A high priority traffic class that is transmitted according to a time schedule, so as to ensure no interference from other traffic classes.
- **Stream Reservation (SR).** Traffic classes with reserved bandwidth. This traffic undergoes traffic shaping (CBS). Two SR classes are defined, i.e., SR class A and Class B. Class A has higher priority than Class B.
- **Best-Effort (BE).** Low-priority traffic, that is handled without time and delivery guarantees. BE traffic does not undergo traffic shaping. When the Enhancements for Scheduled Traffic are used, the BE traffic queues implement the gate mechanism.

The other features provided by the IEEE 802.1Q standard are not addressed here, as they are not relevant to the assessment that this work proposes.

IV. Simulation Scenario

The scenario here considered, shown in Fig. 1, consists of two different automotive functional domains, i.e., Advanced Driver Assistance Systems (ADAS) and multimedia/infotainment, supported by an IEEE 802.1Q Ethernet backbone.

The ADAS system includes four cameras, here called Cam1, Cam2, Cam3 and Cam4, which transmit video streams to a specialized Electronic Control Unit (ECU), here called DA-Cam. The DA-Cam processes the video streams and produces both an aggregated video, e.g., the bird-eye view, and navigation warnings. The processed video and warnings are displayed on the monitor of a Head Unit (HU) to give visual assistance to the driver. Moreover, warnings are also sent to a Control Unit (CU) that sends real-time control messages to the DA-Cam

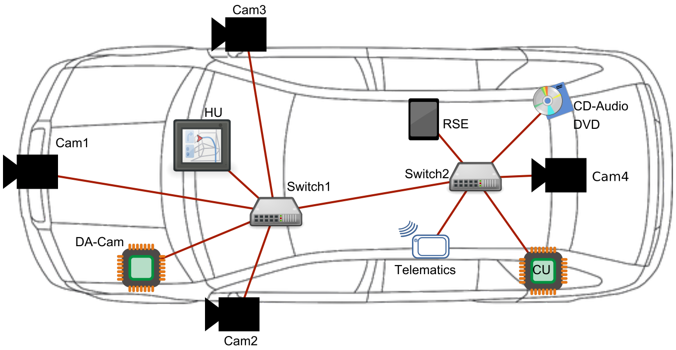

Fig. 1. The simulated network scenario.

and to the Head Unit. In the considered scenario, the cameras operate at a frame rate equal to 60 frames per second (fps) and they generate compressed video frames of 48.38 kbytes [6].

The scenario also includes a multimedia/infotainment system. The Audio-CD/DVD node transmits both one high-quality audio stream and one video stream to the Rear Seat Entertainment (RSE) system, which consists of monitors and speakers to display video and to play audio. The multimedia video stream is transmitted at a rate of 30 fps. Finally, the scenario under study provides a telematics subsystem (Telematics in Fig. 1) that transmits information, such as GPS data, traffic alerts, maps, etc. to the HU and to the RSE system. Multimedia/infotainment and telematics systems are real-time, but not safety-critical.

The following three configurations were simulated:

- **Case A: ST Config.** This configuration implements the enhancements for scheduled traffic and provides support for Scheduled Traffic, SR class A, SR class B, and best-effort traffic.
- **Case B: AVB Config.** This configuration provides support for SR class A, SR class B and best-effort traffic.
- **Case C: Strict Priority (SP) Config.** This configuration handles the simulated traffic flows using only the Strict Priority selection algorithm defined in the IEEE 802.1Q standard that was explained in Sect. III.

A. Mapping flows over the IEEE 802.1Q traffic classes

This Section describes the mapping of the traffic flows of the considered scenario on the traffic classes of an IEEE 802.1Q switch.

The traffic flows and their mapping on the available traffic classes are shown in Table I.

In the case A, i.e., IEEE 802.1Q implementing the Enhancements for Scheduled Traffic, the video streams used by the ADAS system are mapped onto the SR Class A, as these flows do not require very low jitter, but they should be received within few milliseconds (less than 16ms). Conversely, the control messages are mapped onto the ST Class, as they typically require a jitter close to zero. The multimedia/infotainment flows are transmitted in Class B, as their deadlines are typically higher than those of ADAS traffic and within the upper bound of 50ms provided by this class. The telematics flow delivered to RSE is transmitted in Class A, as it may handle gaming control messages, which require a shorter deadline than other multimedia/infotainment flows. Finally, the flow no. 32 (from Telematics to HU) is mapped onto the best-effort class, as it does not require any guaranteed upper bound on delay.

In the case B, i.e., IEEE 802.1Q supporting the AVB SR classes, the control messages are mapped onto the SR Class A, as they require the lowest delay, while the other flows are mapped in the same way as case A.

Finally, in the case C, i.e., IEEE 802,1Q supporting only Strict Priority, the flows are assigned a priority according to their timing requirements. In fact, the control messages are assigned the highest priority, i.e., priority 7, the video streams used by the ADAS system and the telematics flows delivered to RSE are assigned priority 6, the multimedia/infotainment flows have assigned priority 5, and the flow no. 32 (from Telematics to HU) is assigned the lowest priority, as it does not require any guaranteed upper bound on delay.

B. Network Configuration

Simulations were performed in a scenario that models an IEEE 802.1Q switch supporting the Credit-Based Shaper (CBS) for SR Class A and SR Class B and the Enhancements for Scheduled Traffic. The nodes support 8 queues per port and the simulated datarate is 1 Gbps, i.e., the highest datarate supported for automotive Ethernet communications.

1) Case A: In the case A, ST flows are scheduled offline using an offset-based scheduling. The Greatest Common Divisor (GCD) among all the ST flow periods is equal to 5ms, therefore, assigning an offset lower than 5ms, the ST transmissions will never interfere with each other. As a result, an offset increasing with steps of 200μs is assigned the to ST flows, so that, between two consecutive ST transmissions there will be enough time for non-ST transmissions.

The SR traffic goes through traffic shaping and needs to be configured according to specific parameters, given in the IEEE 802.1Q standard [4], that limit the frame size for each flow. SR flows are typically made of samples that are transmitted at specific rates. In the scenario here considered, we chose to map periodic data messages with no jitter requirements on the SR class A and class B, as these classes provide bounded latencies. However, as these periodic data messages are not made of small samples, the messages are segmented so as to meet the Stream Reservation Protocol specifications [4]. In fact, according to the IEEE 802.1Q standard [4], the *idleSlope* values for an SR flow f are calculated for each port as

$$idleSlope_f = \frac{(MFS + PFO) \times MIF}{CMI} \times \frac{CT}{GCT} \quad (1)$$

where *CT (CycleTime)* is the duration of an ST scheduling cycle (as explained in Sect. III), *GCT (GateClosedTime)* is the total amount of time during a CycleTime in which low priority frame transmissions are frozen due to the ST frame transmissions, *MFS (MaxFrameSize)* is the maximum assumed payload

TABLE I
FLOW PARAMETERS AND MAPPING

No.	Talker	Listener	Period (ms)	Size (Bytes)	Class (Case A)	Class (Case B)	Class (Case C)
1	DA-Cam	HU	1000	46	ST	A	BE (Prio 7)
2	DA-Cam	HU	200	46	ST	A	BE (Prio 7)
3	DA-Cam	CU	1000	46	ST	A	BE (Prio 7)
4	DA-Cam	CU	200	46	ST	A	BE (Prio 7)
5	HU	CU	5	46	ST	A	BE (Prio 7)
6	HU	CU	50	46	ST	A	BE (Prio 7)
[7-8]	HU	CU	100	46	ST	A	BE (Prio 7)
9	HU	CU	200	46	ST	A	BE (Prio 7)
10	HU	CU	500	46	ST	A	BE (Prio 7)
[11-12]	HU	CU	1000	46	ST	A	BE (Prio 7)
13	HU	DA-Cam	100	46	ST	A	BE (Prio 7)
[14-15]	HU	DA-Cam	200	46	ST	A	BE (Prio 7)
16	CU	HU	100	46	ST	A	BE (Prio 7)
17	CU	HU	200	46	ST	A	BE (Prio 7)
[18-19]	CU	HU	500	46	ST	A	BE (Prio 7)
20	CU	HU	1000	46	ST	A	BE (Prio 7)
21	CU	DA-Cam	10	46	ST	A	BE (Prio 7)
22	CU	DA-Cam	1000	46	ST	A	BE (Prio 7)
[23-26]	Cam[1-4]	DA-Cam	16.66	43380	A	A	BE (Prio 6)
27	DA-Cam	HU	16.66	43380	A	A	BE (Prio 6)
28	Telem.	RSE	0.625	600	A	A	BE (Prio 6)
29	Telem.	HU	5	400	B	B	BE (Prio 5)
30	cd/dvd	RSE	33.33	43380	B	B	BE (Prio 5)
31	cd/dvd	RSE	0.25	80	B	B	BE (Prio 5)
32	Telem	HU	1000	250000	BE (Prio 0)	BE (Prio 0)	BE (Prio 0)

size, *PFO (PerFrameOverhead)* is the frame overhead (i.e., Ethernet header, FCS and IFS), *MIF (MaxIntervalFrames)* is an integer representing the maximum number of frames of a flow that can be transmitted in one *CMI (classMeasurementInterval)*.

The *classMeasurementInterval* values are defined in the IEEE 802.1Q standard [4] for both class A and class B: $125\mu s$ for SR class A and $250\mu s$ for SR class B. As a consequence, class A streams should transmit frames at a rate multiple or equal to 8000 frames/s (i.e., MaxIntervalFrames / 0.000125s) and class B streams at a rate multiple or equal to 4000 frames/s (i.e., MaxIntervalFrames / 0.000250s). Also, in the case of lower message transmission rates, the same bandwidth for 8000 or 4000 frames/s has to be reserved. Such an over-reservation is very pessimistic when the rate is lower than the one provided by the SR class. A good way to limit such an over-reservation is to split a message (at the application level) into multiple frames in order to obtain low idleSlope values.

Table II shows the configuration parameters for each SR flow. The last column shows the number of frames the message is split into, while the fourth column shows size of each segment in bytes.

Finally, the Network configuration parameters are shown in Table III. In particular, the *idleSlope* parameters, calculated using Eq. (1), for each link are presented. The highest SR workload is handled over the link between the Switch1 and the DA-Cam, the bandwidth assigned to Class A flows approaches 184 Mbps, that is the 18.4% of the bandwidth available for a link.

TABLE II
CASE A: SR FLOWS CONFIGURATION PARAMETERS

Flow no.	SR Class	Message Length (B)	Max payload length according to the SRP (B)	Num. of frames
[23-27]	A	43380	678	64
28	A	600	120	5
29	B	400	50	8
30	B	43380	334	130
31	B	80	80	1

TABLE III
CASE A: NETWORK CONFIGURATION PARAMETERS

Parameter	Value
Port transmit datarate	1 Gbps
Switch traversing delay	5 μs
Cam[1-3] $\rightarrow$ Switch1 idleSlope(A)	46.08 Mbps
DA-Cam $\rightarrow$ Switch1 idleSlope(A)	46.48 Mbps
Switch2 $\rightarrow$ Switch1 idleSlope(A)	46.09 Mbps
Switch1 $\rightarrow$ DA-Cam idleSlope(A)	184.34 Mbps
Switch1 $\rightarrow$ HU idleSlope(A)	46.09 Mbps
Telem. $\rightarrow$ Switch2 idleSlope(A)	10.37 Mbps
Switch2 $\rightarrow$ RSE idleSlope(A)	10.37 Mbps
Telem. $\rightarrow$ Switch2 idleSlope(B)	2.95 Mbps
Switch2 $\rightarrow$ Switch1 idleSlope(B)	2.95 Mbps
cd/dvd $\rightarrow$ Switch2 idleSlope(B)	15.94 Mbps
Switch2 $\rightarrow$ RSE idleSlope(B)	15.94 Mbps

2) Case B: In the case B, the SR traffic goes through traffic shaping and needs to be configured according to specific parameters, given in the IEEE 802.1Q standard [4]. In this

TABLE IV
CASE B: SR FLOWS CONFIGURATION PARAMETERS

Flow no.	SR Class	Message Length (B)	Max payload length according to the SRP (B)	Num. of frames
[1-22]	A	46	46	1
[23-27]	A	43380	678	64
28	A	600	120	5
29	B	400	50	8
30	B	43380	334	130
31	B	80	80	1

TABLE V
CASE B: NETWORK CONFIGURATION PARAMETERS

Parameter	Value
Port transmit datarate	1 Gbps
Switch traversing delay	5 μs
Cam[1-3] $\rightarrow$ Switch1 idleSlope(A)	46.08 Mbps
DA-Cam $\rightarrow$ Switch1 idleSlope(A)	51.72 Mbps
HU $\rightarrow$ Switch1 idleSlope(A)	5.64 Mbps
Switch2 $\rightarrow$ Switch1 idleSlope(A)	51.72 Mbps
Switch1 $\rightarrow$ DA-Cam idleSlope(A)	189.98 Mbps
Switch1 $\rightarrow$ HU idleSlope(A)	51.72 Mbps
Switch1 $\rightarrow$ Switch2 idleSlope(A)	51.72 Mbps
Telem. $\rightarrow$ Switch2 idleSlope(A)	10.37 Mbps
Switch2 $\rightarrow$ RSE idleSlope(A)	10.37 Mbps
Telem. $\rightarrow$ Switch2 idleSlope(B)	2.95 Mbps
Switch2 $\rightarrow$ Switch1 idleSlope(B)	2.95 Mbps
cd/dvd $\rightarrow$ Switch2 idleSlope(B)	15.94 Mbps
Switch2 $\rightarrow$ RSE idleSlope(B)	15.94 Mbps

case, as there is no ST traffic, the gates are always open. Therefore, according to the IEEE 802.1Q standard [4], the *idleSlope* values for an SR flow f are calculated for each port as in Eq. (1), but without considering the gate-related parameters, i.e.,

$$idleSlope_f = \frac{(MFS + PFO) \times MIF}{CMI} \quad (2)$$

Table IV shows the configuration parameters for each SR flow.

The Network configuration parameters are shown in Table V. In particular, the *idleSlope* parameters, calculated using Eq. (2), for each link are presented.

3) Case C: In the case C, the Network configuration parameters used are shown in Table VI.

C. Assessed metrics

The metrics assessed in this scenario are the end-to-end delay and the absolute jitter. The end-to-end delay is calculated as the difference between the message reception time (RxTime), i.e., the time at which the message is received by the application layer of the destination and the message generation time (GenTime), i.e., the time the message has been generated by the application. The end-to-end delay (E2EDelay) is calculated as,

$$E2EDelay = RxTime - GenTime \quad (3)$$

TABLE VI
CASE C: NETWORK CONFIGURATION PARAMETERS

Parameter	Value
Port transmit datarate	1 Gbps
Switch traversing delay	5 μs

The second assessed metric is the Absolute Jitter of a flow f, calculated as the difference between the maximum and the minimum end-to-end delay of f, i.e.,

$$AbsJitter_f = max(E2EDelay_f) - min(E2EDelay_f) \quad (4)$$

V. SIMULATION RESULTS

In this section, the maximum end-to-end delays and the absolute jitter results obtained through simulations are presented. The simulations were run through the OMNeT++ framework. The TSN simulation model was implemented from scratch based on the INET library implemented for OMNeT++.

Table VII shows the maximum end-to-end value for each flow and the absolute jitter in all the three cases. In the assessed network, when the control traffic (flow no. 1-22) is mapped onto the scheduled traffic class (Case A), the lowest possible maximum delays were obtained. In fact, the ST frames are transmitted according to a fixed time-schedule and thanks to their highest priority and to the offset-based scheduling, their transmissions do not suffer from any interference or blocking due to other frames.

The delays obtained by the ST flows in Case A are quite similar, as the delay difference between the flows only depends on the frame size and the number of hops traversed by each flow. In particular, in Case A two groups of delays can be identified. The flows with 3-hop path always obtain delays equal to 12μs, while the flows with 2-hop path always obtain delays equal to 6μs.

On the contrary, the maximum delay values obtained in Case B are the highest ones, as in this case the control traffic is transmitted in the same class of video traffic (flow no. 23-27) and it is also subject to shaping. Moreover, in Case A the flows mapped onto the SR classes obtained the same maximum end-to-end delays than the one obtained in Case B. The interference of ST traffic in this case is not significant, as the network operates at 1 Gbps and with such a datarate the ST interference has a very short duration, i.e., about 0.7μs.

As far as Case C is concerned, the control traffic obtained very low delays, i.e., always lower than 40μs, but higher than the ones in Case A, as in Case C transmissions are not isolated.

It is important to highlight that in the assessed scenario the workload is low, as it never exceeds the 20% of the available datarate, and the transmission time of a maximum-sized Ethernet frame (i.e., 1530 bytes) at 1 Gbps is equal to 12.24μs. Such a time is short if compared with the flow periods that are orders of magnitude larger.

In Case C, the best-effort flow (flow no. 32) obtained a higher maximum delay value than in both Case A and Case B, as in the latter cases the CBS leaves the bandwidth left

TABLE VII
END-TO-END DELAY AND ABS. JITTER

Flow no.	Max E2EDelay (μs)			Abs. Jitter (μs)		
	Case A	Case B	Case C	Case A	Case B	Case C
1	6	150	30	0	16	22
2	6	164	32	0	17	24
3	12	261	24	0	0	12
4	12	511	26	0	374	13
5	12	1135	19	0	1124	7
6	12	1011	18	0	999	6
7	12	761	16	0	749	4
8	12	1135	18	0	998	5
9	12	636	15	0	624	3
10	12	761	16	0	749	4
11	12	886	17	0	874	5
12	12	1010	17	0	873	4
13	6	880	12	0	749	4
14	6	1005	13	0	998	6
15	6	1130	13	0	999	5
16	12	650	35	0	530	23
17	12	525	34	0	405	22
18	12	288	33	0	168	21
19	12	413	34	0	279	21
20	12	538	32	0	418	20
21	12	697	30	0	685	18
22	12	697	29	0	627	16
23	7891	7891	1399	0	0	14
24	7897	7897	1411	0	0	14
25	7922	7921	1422	0	0	14
26	7953	7951	1446	0	0	2
27	7891	7902	385	5	11	11
28	508	520	34	1	13	11
29	1769	1797	395	7	34	370
30	32261	32262	374	1	2	5
31	198	198	380	192	191	273
32	1123	1118	1433	50	45	365

apart from SR traffic for the transmission of best-effort frames, while in the Case C best-effort frames are transmitted only when there are no higher priority frames pending.

Table VII also shows the obtained absolute jitter values. In the Case A, the values obtained for ST traffic are always close to zero (i.e., lower than 1 nanosecond). In the case B, the jitter is higher only for the control traffic, as control messages are short (i.e., 46 bytes) and they are transmitted in single Ethernet frames, so the delays of these messages obtain a higher variability. Conversely, when the messages are split into multiple Ethernet frames, the flows subject to the CBS (i.e., flow no. 23-31) obtain very low jitter values, as the CBS is able to compensate for the delay experienced by a frame belonging to an SR class. In fact, if a frame belonging to an SR class is delayed due to an on-going transmission of non-ST frames, the credit value grows, thus allowing multiple consecutive transmissions from the same SR queue. The delays are calculated at the application layer, so what is accounted for is the delay of the entire message, that consists of multiple Ethernet frames (not of one single Ethernet frame).

VI. CONCLUSIONS

The comparative performance assessment of three network configurations over an IEEE 802.1Q network in the realistic automotive scenario here addressed showed that, under a low workload, when low jitter values are tolerated, Strict Priority is enough to meet the communication requirements of the considered applications. Conversely, when jitter matters and ultra low delays are required, the adoption of the Enhancements for Scheduled Traffic is mandatory. Future work will address the performance assessment of automotive networks using frame preemption. The work in [14] demonstrated that in specific scenarios preemption is very beneficial to control traffic on plain Ethernet, while the work in [15] proved that preemption can reduce the jitter, but not enough to meet strict jitter requirements. We will investigate this aspect even further.

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