Integrating Response-Time Analyses for Heterogeneous Automotive Networks in MPS-CAN Analyzer

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***Abstract*—MPS-CAN analyzer is a research tool that supports the Response Time Analysis (RTA) for Controller Area Network (CAN). It takes into account various queueing policies; buffer limitations in the CAN controllers; and mixed transmission patterns supported by the higher-level protocols. In this paper, we extend the MPS-CAN analyzer to support RTA of heterogeneous automotive networks. Within this context, first we implement RTA for Ethernet Audio/Video Bridging (AVB) messages in a single-switch architecture. We then integrate the analyses for CAN and Ethernet AVB by exploiting the analysis for CAN to Ethernet AVB gateway. With this integration, the MPS-CAN analyzer supports the analysis for heterogeneous messages that traverse through heterogeneous networks consisting of CAN and Ethernet AVB. We also evaluate the newly implemented analyses by conducting an automotive-application case study.**

I. Introduction

Modern vehicles contain nearly 100 Electronic Control Units (ECUs) that are connected to five or more different networks. This paper focuses on two of these networks namely CAN [1] and Ethernet AVB [2]. CAN is a multi-master, event-triggered, serial communication bus protocol supporting speeds of up to 1 Mbit/s. It has been standardized in ISO 11898-1 [3]. There are several higher-level protocols for CAN that have been developed for various industrial applications such as J19139, CANopen, HCAN and MilCAN. According to CAN in Automation (CiA) [4], more than two billion CAN controllers have been sold until today. Out of which, approximately 80% have been used in the automotive applications. For example, a modern heavy truck contains more than 20 CAN networks with over 6000 CAN messages [5].

Due to the limitation of network speed in CAN, some high data-rate networks have been proposed as alternatives for specific vehicular applications. For example, Ethernet AVB, that supports speeds of up to 100 Mbit/s, has been proposed for infotainment applications. Since both CAN and Ethernet AVB are used in real-time systems, they must be predictable. This means, it must be ensured that the messages that pass through these networks must meet their deadlines. There are several *a priori* schedulability analysis techniques that can provide such guarantees. Response-Time Analysis (RTA) [6], [7] is a powerful, mature and well-established schedulability analysis technique to calculate upper bounds on the response times of messages (or tasks) in a real-time network (or a system).

A. Authors' Previous Work

MPS-CAN analyzer [8] is a free tool that supports various RTA for CAN. It is the first and only free tool that supports RTA for periodic, sporadic as well as *mixed* messages in CAN. Mixed messages are partly periodic and partly sporadic. They are implemented by several higher-level protocols for CAN that are used in the industry. The first implementation of MPS-CAN, that includes the basic RTA for the messages in CAN [9], [10], [11], is reported in [8]. Since then, the tool has evolved over the last two years by integrating various extensions of RTA for periodic, sporadic and mixed messages in CAN. These extensions include RTA for messages that are scheduled with offsets; messages having arbitrary jitter and deadlines; CAN controllers implementing different queueing policies, e.g., priority and FIFO; and the controllers implementing abortable or non-abortable transmit buffers [12], [13].

B. Paper Contribution

In this paper[1], we extend MPS-CAN to support the end-to-end delay analysis of CAN-AVB heterogenous networks. The contributions in the paper are listed below.

- Implementation of RTA for Ethernet AVB.
- Implementation of RTA for CAN-Ethernet AVB gateway.
- Support for end-to-end delay analysis of global messages that traverse from CAN to Ethernet AVB. The analysis considers various types of transmission patterns, queueing polices and buffer limitations in the CAN controllers.
- Improved graphical user interface of the tool to support the specification of heterogeneous networks, various nodes and gateways, different types of messages, and analyses results for multiple networks.
- Extensive evaluation of the newly implemented analyses in the tool using an automotive-application case study.

II. Communication Architecture

The communication architecture is essentially a heterogeneous network consisting of CAN and Ethernet AVB. In this section, first we discuss practical limitations and constraints in CAN. Then we briefly discuss the Ethernet AVB architecture. Finally, we discuss the heterogeneous network architecture.

A. Practical Limitations and Constraints in CAN

The timing behavior of CAN messages may vary depending upon different types of queueing polices implemented by the CAN device drivers and communications stacks, internal organization, and hardware limitations in the CAN controllers. The most common queueing policies implemented in the CAN controllers are priority and FIFO. For example, the Microchip PIC32MX and Infineon XC161CS controllers implement FIFO policy [14]. In the case of a FIFO queue, the response times of CAN messages can be significantly higher

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due to large buffering delays and priority inversion. If an ECU transmits more messages compared to the number of transmit buffers, the messages may be subjected to extra delay and jitter due to priority inversion. The amount of the delay varies depending upon whether or not the CAN controllers support transmission abort requests. For example, the Microchip MPC2515 controller implements abortable transmit buffer; whereas, the Philips 82C200 controller implements non-abortable transmit buffer [14], [15], [16]. RTA for the mixed messages varies depending upon the method of their implementation by the higher-level protocol. For example, CANopen [17], HCAN [18] and AUTOSAR [19] use different implementations for mixed messages [12].

In crux, the RTA for CAN should match the limitations and constraints in the CAN controllers and higher-level protocols. Otherwise, the calculated response times can be optimistic.

B. Ethernet AVB

Ethernet AVB is a set of technical standards developed by IEEE. It supports clock synchronization, bandwidth reservation and traffic shaping services. The messages must have priorities and they can share a priority level. A set of messages with the same priority belong to the same traffic class. Within a traffic class, the messages are treated according to the FIFO policy. The standards define two traffic classes for real-time messages, known as classes A and B, where class A has a higher priority than class B. A Credit-based Shaping Algorithm (CBSA) is defined for each class of traffic to forward the messages. The messages in the traffic class can be forwarded if the credit for the class is zero or positive. During the transmission, the credit is reduced with a defined rate. The credit is replenished at a particular rate when there is no message in the buffer for transmission, or when the credit is negative. Note that the non-real-time messages are transmitted when there are no messages in classes A and B, or when the credit for them is negative.

C. Heterogeneous Architecture

Several network technologies including CAN, FlexRay and Local Interconnect Network (LIN) are simultaneously used in a vehicle. Such a heterogeneous network is connected via a gateway, which is an essential component for a seamless communication among different network protocols. In this work, we focus on the CAN-Ethernet AVB heterogeneous network, in which the CAN bus is connected to the AVB switch via a gateway. In order to increase the efficiency of the bandwidth usage in Ethernet AVB, the gateway collects several CAN messages and encapsulates them into a single Ethernet message. The message transformation in the CAN-Ethernet AVB gateway is proposed in [20] that considers the features of Ethernet AVB including its periodic transmission. A buffer is defined in the gateway to collect CAN messages. Also, a timer is defined for the buffer. Once the timer expires, a fixed number of CAN messages are picked and inserted in an Ethernet message. This assures the periodic transmission of the Ethernet message, where the timer value is the period of the message. The buffer can follow three types of transmission, FIFO, priority-based, or earliest deadline first. In this version of the tool, we consider the priority-based policy for the buffer inside the gateway. Note that the generated Ethernet message may belong to class A or class B. It is solely a design decision. In this version of the tool, we use an Ethernet message from class A to forward the global CAN messages to Ethernet AVB.

The worst-case end-to-end delay for a global message (CAN-AVB) is equal to the sum of its response time in CAN, gateway delay and the delay experienced by it in Ethernet AVB. The worst-case delay of a message crossing the gateway includes three elements. The first element is the delay of the gateway buffer, which is upper bounded in [20]. The second delay is related to the encapsulation of the Ethernet message, which is a constant value. The third element is the queuing delay in the output port of the gateway that contains the Ethernet AVB shaper. The last delay element can be computed using the analysis presented in [21].

III. Related Work and Implemented Analyses

A. Related RTA

Tindell et al. [9] developed the first RTA for CAN with priority queues, which is later revised by Davis et. al [10]. Davis et al. further extended their RTA to support the FIFO and work-conserving queues while supporting arbitrary deadlines of messages [22], [14], [23]. Khan et al. [24] integrated the overhead of the copying delay in abortable transmit buffers with the RTA of CAN [10]. RTA of CAN is extended to support non-abortable buffers in the CAN controllers [16], [15]. The RTA for CAN messages with offsets has been developed in several works, e.g., [25], [26], [27], [28]. However, none of these analyses support the mixed messages. Mubeen et al. [11], [29] extended the seminal RTA [9], [10] to support mixed messages in CAN with priority and FIFO queues respectively. RTA for mixed messages in CAN is extended in [30], [31], [32] to support the CAN controllers that implement abortable and non-abortable transmit buffers. RTA for CAN is further extended to support periodic and mixed messages that are scheduled with offsets [33], [34], [35].

RTA for the traffic in Ethernet AVB should consider the effect of the CBSA as well as the FIFO queues. The analysis for the messages in the Ethernet AVB architecture is given in [36]. The work presented in [21] shows that the analysis in [36] considers only one blocking factor that results from lower priority messages, which is not the case in Ethernet AVB due to the traffic shaper. Thus, they propose a new RTA that takes the new blocking term into account. However, the analysis is limited to the constrained deadline traffic model and a single-switch architecture. All of the above analyses are within the scope of the implementation in MPS-CAN.

B. Related Tools

VNA [37] is a communication design tool that implements RTA for CAN [9]. CANalyzer [38] supports the simulation, analysis and data logging for CAN-based systems. CANoe [39] provides simulation of functional and timing behavior of ECU networks. SymTA/S [40] is a tool by Symtavision for model-based timing analysis and optimization. It supports RTA of various vehicular networks including CAN, Flexray, AFDX, and Ethernet AVB. RTaW-Sim [41] supports the simulation and performance evaluation of CAN. Rubus-ICE [42] supports model- and component-based development

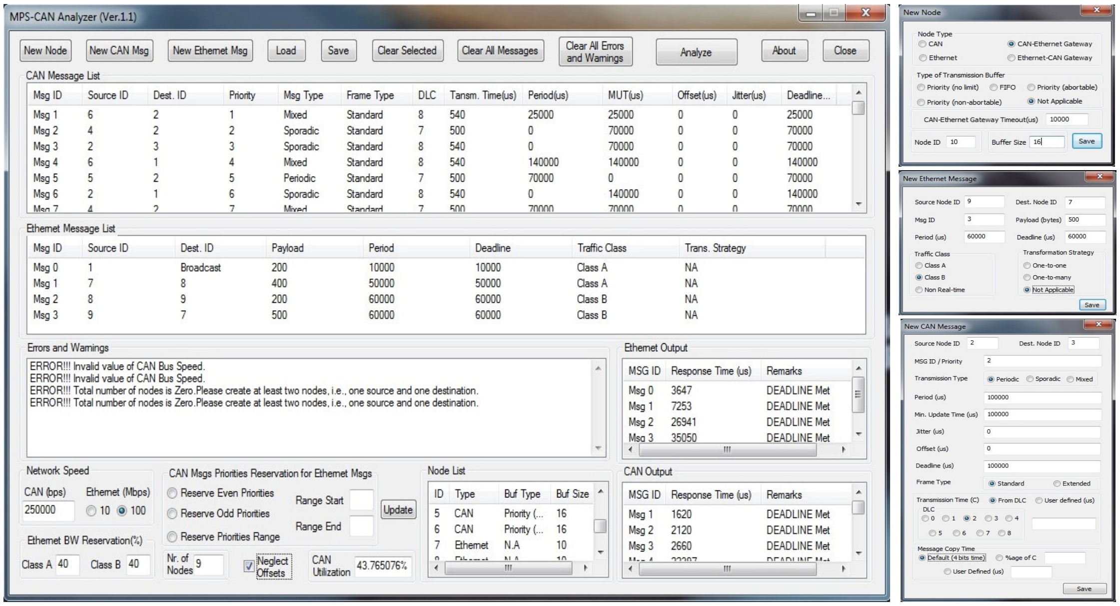

Fig. 1. Graphical user interface of the extended MPS-CAN analyzer.

of real-time embedded systems [43], [44]. It implements the seminal RTA of CAN [10] as well as RTA for mixed messages in CAN [11]. To the best of our knowledge, there is no free tool, other than MPS-CAN, that implements RTA of CAN for periodic, sporadic as well as mixed messages in CAN while taking into account different queueing policies and buffer limitations in the CAN controllers. With the implementation of RTA for Ethernet AVB and CAN-AVB gateway, MPS-CAN now supports the analysis of heterogeneous networks.

C. Implemented Analyses in the Tool and its Distribution

The newly implemented analyses in MPS-CAN are shown in Fig. 2. The figure also shows the relationship among the new and already implemented analyses for CAN in [8], [13], [12]. The tool is implemented in the C language. Its graphical user interface is developed using the Windows Application Programming Interface (WinAPI). Each RTA, supported by the tool, is implemented as a separate C file which is accessed using the function calls. Hence, the tool supports a simple and easy mechanism for further extensions and implementations of other related analyses in the future. The layout of the tool along with its inputs and outputs are shown in Fig. 1. The tool, its user manual, and test cases can be downloaded at https://github.com/saadmubeen/MPS-CAN.

IV. Evaluation of RTA for CAN and Ethernet AVB

In this section, first we discuss the experimental setup for a heterogeneous CAN-Ethernet AVB case study. Then, we use the extended tool to analyze and evaluate the case study.

A. Experimental setup

We adapt and extend the case study of the experimental vehicle [45] by introducing Ethernet AVB and a CAN-AVB gateway. The vehicle contains a heterogeneous architecture consisting of one CAN and one Ethernet AVB network. The two networks are connected via a gateway. There are five ECUs that are connected to the CAN bus. Each ECU implements a priority queue and has 16 abortable transmit buffers in the CAN controller. The network speed for CAN is set to 250 Kbit/s. On the other side of the gateway, three Ethernet nodes are connected to one Ethernet AVB switch which is connected to the gateway. The network bandwidth for Ethernet AVB is set to 100 Mbit/s. In this case study, we generate both local and global messages. The local messages are transmitted within the same network. They do not traverse through the gateway. Whereas, the global messages traverse between the networks via the gateway. The global messages are assumed to traverse from CAN to AVB and not vice versa.

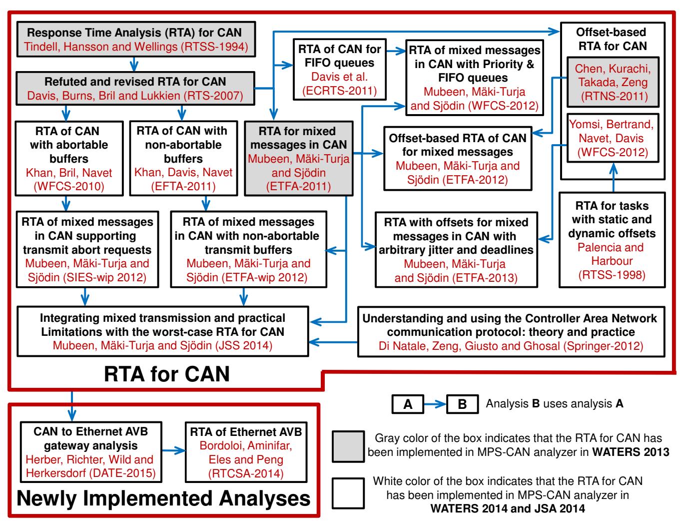

Fig. 2. Graphical representation of RTA for CAN and its extensions along with the analysis for Ethernet AVB implemented in MPS-CAN.

There are 50 CAN messages that are generated using the NETCARBENCH tool [46] which is a benchmark for the design of automotive embedded systems. Out of these 50 messages, 10 are selected as global messages, i.e., their destination nodes are connected to the Ethernet AVB network.

Since NETCARBENCH cannot generate mixed messages, we randomly assign mixed, periodic, and sporadic transmission types to 40%, 30%, and 30% of the generated messages respectively. The messages are equally distributed among the ECUs, i.e., each ECU sends 4 mixed, 3 periodic and 3 sporadic messages. Moreover, each ECU sends two global messages that are randomly selected from its set of 10 messages with respect to their transmission types.

The attributes of the messages, shown in Fig. 3, are identified as follows. The priority, sender node ID, transmission type, size of data in bytes, period, minimum update time, deadline, and type showing local (L) or global (G) are represented by P, CC, ξ, S, T, MUT, D and $Type$ respectively. The priority of a CAN message is assumed to be equal to its ID. The offset and jitter for all messages are assumed to be zero. The messages with priorities 4, 6, 10, 14, 16, 24, 28, 29, 31, 50 are global, whereas the rest of the messages are local.

P	CC	ξ	S (bytes)	T (ms)	MUT (ms)	D (ms)	Type	P	CC	ξ	S (bytes)	T (ms)	MUT (ms)	D (ms)	Type
1	5	M	8	25	25	25	L	26	2	M	7	70	70	70	L
2	3	S	7	0	70	70	L	27	1	S	8	0	70	70	L
3	1	S	8	0	70	70	L	28	2	S	8	0	140	140	G
4	5	M	8	140	140	140	G	29	2	P	8	160	0	160	G
5	4	P	7	70	0	70	L	30	2	P	5	60	0	60	L
6	1	S	8	0	140	140	G	31	4	S	8	0	140	140	G
7	3	M	7	70	70	70	L	32	1	P	5	70	0	70	L
8	3	P	8	70	0	70	L	33	4	P	1	80	0	80	L
9	5	S	5	0	60	60	L	34	3	P	8	80	0	80	L
10	5	P	8	140	0	140	G	35	4	M	0	70	70	70	L
11	4	S	8	0	60	60	L	36	2	M	1	70	70	70	L
12	4	M	0	70	70	70	L	37	1	P	1	70	0	70	L
13	1	M	6	60	60	60	L	38	4	S	8	0	80	80	L
14	3	P	8	110	0	110	G	39	5	S	8	0	70	70	L
15	5	M	8	70	70	70	L	40	3	M	2	80	80	80	L
16	4	M	8	140	140	140	G	41	3	S	4	0	70	70	L
17	2	S	8	0	80	80	L	42	1	M	8	70	70	70	L
18	2	M	8	70	70	70	L	43	5	S	8	0	20	80	L
19	5	P	8	70	0	70	L	44	1	M	8	70	70	70	L
20	5	P	7	70	0	70	L	45	2	M	7	70	70	70	L
21	4	M	8	70	70	70	L	46	2	P	6	70	0	70	L
22	1	M	0	60	60	60	L	47	5	M	2	60	60	60	L
23	2	S	0	0	70	70	L	48	4	P	1	80	0	80	L
24	3	S	8	0	140	140	G	49	3	M	6	70	70	70	L
25	3	M	8	70	70	70	L	50	1	P	8	140	0	140	G

Fig. 3. Attributes of the CAN message set under analysis.

We also generate five messages in the Ethernet AVB network as shown in Fig. 4. The attributes of an Ethernet message m_i include the size of payload (S_i); period (T_i), deadline (D_i); source node ID (Sr_i); destination node ID (Ds_i); and class ($Class_i$) with 'A' or 'B' as a possible value. Note that there is another Ethernet message with ID 0 that is generated by the gateway and is part of the global traffic. It belongs to Class A. It encapsulates all the CAN messages that are part of the global traffic. We are interested in calculating response times of all local messages and end-to-end delays of the global messages respectively.

B. Experimental Evaluation

We perform a number of experiments on the generated message set for CAN and Ethernet AVB. In the first set of experiments, we calculate the response times of all local messages and end-to-end delays of all global messages for different settings in the gateway. The variation parameters in the gateway include the timer and buffer size (i.e., the number

ID	S (bytes)	T (ms)	D (ms)	Sr	Ds	Class
1	400	40	40	1	2	A
2	200	50	50	2	3	B
3	400	60	60	2	1	A
4	500	50	50	3	1	B
5	600	70	70	1	3	A

Fig. 4. Attributes of the Ethernet AVB message set under analysis.

of CAN messages). In the second set of experiments, we focus on the global messages by calculating their end-to-end delays in different settings in the gateway.

1) Analysis of CAN Messages: We calculate response times of all messages in three different scenarios with respect to the buffer size and timer in the gateway: (i) buffer size is 10; while the timer is 10ms, (ii) buffer size is 20; while the timer is 10ms, and (iii) buffer size is 20; while the timer is 20ms. The response times of all local CAN messages that are calculated in the three scenarios are illustrated in Fig. 5. The end-to-end delays[2] of the CAN messages that are part of the global traffic are also depicted in Fig. 5. The end-to-end delays of the global messages are larger than the response times of the local CAN messages due to different types of delays experienced by the former at the gateway and Ethernet AVB. Another aspect that is obvious from Fig. 5 is the variation in the end-to-end delays of the global messages with respect to the gateway buffer size. The end-to-end delays are slightly decreased by increasing the buffer size. The response times of local messages in different experiments remain constant as the effect of the gateway parameters does not influence them.

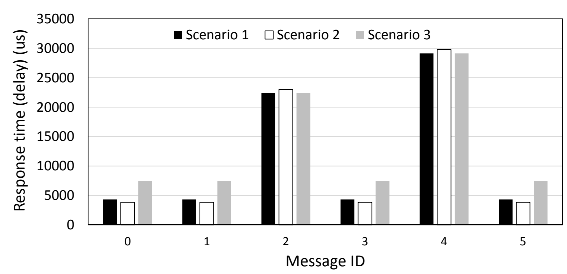

Fig. 6. Response times/delays of Ethernet local/global messages respectively.

The delay of Ethernet message with ID 0; and response times of Ethernet messages with IDs 1,2,3,4 and 5 are shown in Fig. 6. The delay of message 0 in Scenarios 2 is slightly lower than Scenario 1 due to larger size of the data that is encapsulated in this message. Note that the size of the buffer corresponds to the number of CAN messages that are encapsulated in the Ethernet message at the gateway. We assume that multiple instances of each global CAN message may be queued at the gateway. The variations in the gateway parameters directly influence the period and size of the Ethernet message that is transmitted from the gateway. Consequently, the response times of other Ethernet messages are also affected. Since the messages from the gateway belongs to Class A, their effects are different on the other Ethernet

[2]We attribute response times to all local CAN and local Ethernet messages; delays to all Ethernet messages that are part of the global traffic; and end-to-end delays to all CAN messages that are part of the global traffic.

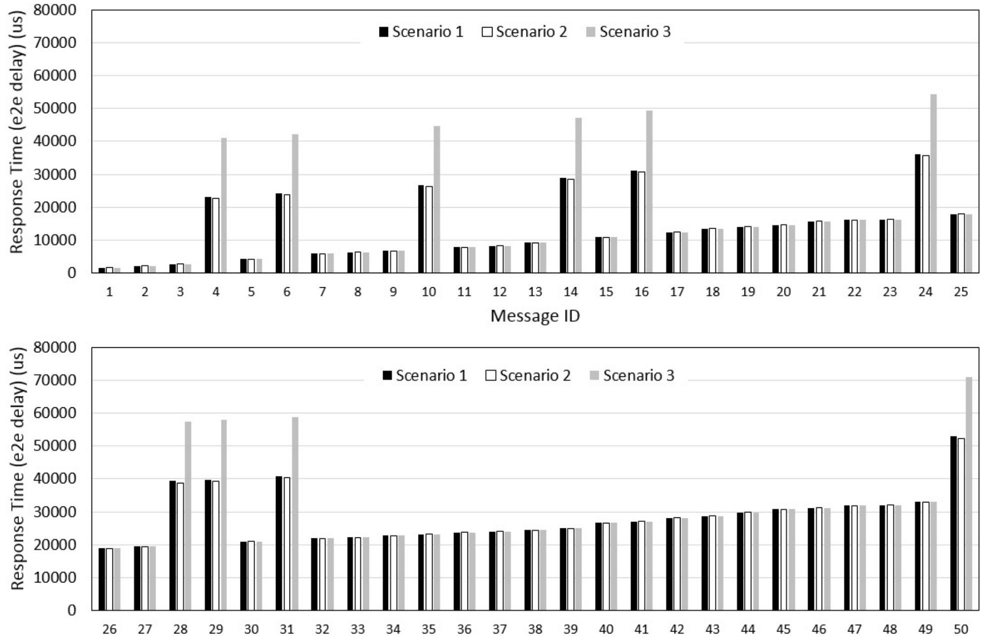

Fig. 5. Response times and end-to-end (e2e) delays of local and global CAN messages respectively.

messages belonging to Class A and B. For instance, the size of an Ethernet message from the gateway affects the response times of other class A messages; whereas, its period and size both effect the response times of other class B messages [21].

2) End-to-end Delays of Global Messages: In another set of experiments, consisting of six scenarios as shown in Fig. 7, we evaluate the effect of variations in the gateway parameters on the end-to-end delays of global messages. The end-to-end delays, calculated in the six scenarios, are shown in Fig. 8. It can be seen in the scenarios SCN 4, SCN 5 and SCN 6 that the end-to-end delays of global messages increase by increasing the timer. This is due to the fact that the messages wait more in the gateway for their transmission in the case of a large timer value. Whereas, the end-to-end delays of global messages decrease with an increase in the number of packets in the Ethernet frames that originate at the gateway as shown in the scenarios SCN 1, SCN 2 and SCN 3. The values of the timer and buffer size in the gateway may have contradicting effect on the end-to-end delays of global messages. This aspect requires further investigation and is left for the future work.

Scenario	SCN 1	SCN 2	SCN 3	SCN 4	SCN 5	SCN 6
Timer (ms)	10	10	10	5	10	15
Buffer Size	1	10	20	5	5	5

Fig. 7. Six scenarios used for the experiments.

V. Conclusion

In this paper, we have implemented the Response Time Analysis (RTA) of Ethernet AVB in a free tool called the MPS-CAN analyzer. Further, we have integrated the existing RTA for CAN with the RTA for Ethernet AVB by implementing the timing analysis of CAN-Ethernet AVB gateway in the tool. The MPS-CAN analyzer already supports various extensions of RTA for CAN while taking into account mixed messages (implemented by the higher-level protocols), messages scheduled with offsets, messages with arbitrary jitter and deadlines, various queueing policies (e.g., priority- or FIFO-based), and limitations of transmit buffers in the CAN controllers (e.g., abortable or non-abortable). With the newly implemented analyses, MPS-CAN is able to analyze communications in the heterogeneous automotive networks.

We have shown the usability of the extended tool by conducting an automotive-application case study that contains a heterogeneous network. Using the case study, we have performed a number of experiments for the evaluation of the newly implemented analyses. The tool is structured in such a way that it provides ease for further extensions and implementations of other related analyses. Since, the tool is freely available, we believe, it may prove helpful in the research-oriented projects that require the analysis of the systems that use CAN, Ethernet AVB or both for network communication.

The timing behavior of the heterogeneous traffic, that traverses from CAN to AVB, is affected by the gateway configurations. The gateway may use a fixed-size buffer to collect the CAN frames. In addition, Ethernet frames can also be generated upon the expiry of a timer. These two parameters affect the delay of the messages in the gateway. An interesting future work is to implement an algorithm to find the most suitable values for setting the gateway parameters in order to decrease the end-to-end delays of global messages.

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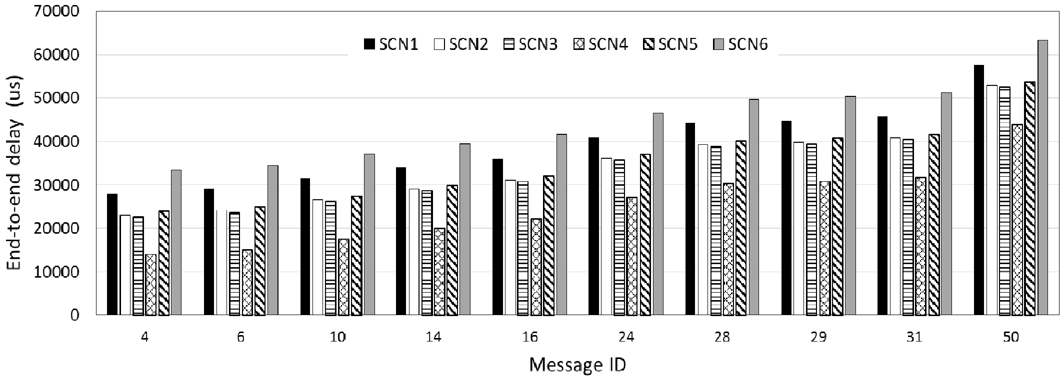

Fig. 8. End-to-end delays of the global messages.

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