Network Calculus for the Validation of Automotive Ethernet in-Vehicle Network Configurations

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***Abstract*—Automotive functions require validation of the underlying network in advance. Especially driver assistance functions may require hard time bounds concerning their communication infrastructure. In several works analytical models have been introduced, enabling the calculation of worst case delays for real-time applications using Ethernet as communication technology. On the other hand considerable effort has been spend to evaluate Ethernet for the use in automotive in-vehicle networks using simulation tools and prototypes. Showing that Ethernet can be used in general for the automotive use, they did not make an assertion about what happens if the worst case occurs. In this work we show by means of an analytic model the worst case analysis of a sample automotive Ethernet network configuration. We show that this configuration satisfies a current set of automotive functions requirements – even for the worst case.**

I. Introduction

Watching the last decades the manufacturing and development process of premium cars was strongly affected by network technologies like the Media Oriented Systems Transport (MOST) Bus, Controller Area Network (CAN) Bus or FlexRay. Suffering from high per piece cost, incompatible standards or low bandwidth availability the automotive industry currently watches out for other solutions. One technology maybe fitting the automotive requirements is Ethernet. It comes with high bandwidth availability and with regards to the Internet Protocol (IP) with good compatibility to consumer electronics.

While the initial version of Ethernet lacks in providing adequate Quality of Service (QoS) support [1], the current version [2] brings a basic support of QoS with the Class of Service field. Benefiting from this extension Lim et al. showed in [3] that the performance provided by 100 Mbit Ethernet using a standard mixed scheduling mechanism (Strict Priority (SP) and Weighted Fair Queuing (WFQ)) would satisfy the requirements of current automotive applications.
Being confirmed that Ethernet can meet the requirements of current automotive electronic functions, one has to ask the question of how to validate the network against the communication requirements of the functions. The particularity about the validation of automotive in-vehicle networks is, that they require validation in advance. I.e. it has to be ensured during the design process that the communication requirements of every electronic function will be met.
There were already analysis concerning a statistically validation of automotive in-vehicle Ethernet networks done. In this work, a worst case validation of an Ethernet in-vehicle network is shown. Therefore, the model introduced in [4] is reviewed and adapted to the needs of the scenario considered in this work. Furthermore, a case study is presented showing up a worst case analysis of current automotive functions for a sample network configuration.
The remainder of this work is divided as follows: Section II gives an overview over the state of the art in validation methods of Ethernet for real-time applications. Section III presents the key data of the scenario which will be modelled in Section IV. Section IV reviews the model presented in [4] and further shows the adaptions made to make it fit to the scenario presented in III. Furthermore, in Section V the results received while applying the formulas presented in Section IV on the scenario described in Section III will be presented. The last part of this work summarizes and evaluates the results achieved in this work. Further, an outlook to our future research activities is provided.

II. Related Work

The validation of Ethernet for applications with real-time requirements has been considered in several works [1], [3]–[9]. In general one can distinguish between three methods: (i) validation by means of simulation, (ii) validation through analysis and (iii) validation on prototypes. However, every method has its advantages and disadvantages.
Simulation and analysis have the advantage that they can be done in advance. I.e. that one does not need to spend effort on building prototypes. Furthermore, simulation has the advantage that it often delivers realistic results. The major disadvantages of simulation are that the computational costs are very high and that the stimulation of the worst case may be very difficult if not impossible. Despite of this, it abstracts from real hardware respectively software. Nevertheless, simulation is used for the validation of Ethernet for real time applications. In [1], [3] Lim et al. showed that the communication requirements of current electronic vehicle functions can be met using standard 100Base-TX Ethernet. But they also showed that prioritization is needed. They used the simulation framework OMNet++ [10].

In contrast to simulation the advantages of worst case analysis[1] are that the computation cost are moderate and that the determination of the worst case delay is easy. The disadvantages of worst case analysis are that the results may be too pessimistic since they represent worst case delays and – like simulation – it also abstracts from real hardware respectively software. In [9] Fan et al. presented a novel mathematical model enabling the computation of worst case delays for real-time applications assuming a periodic traffic model. The key idea of the model is that the calculation of the worst case delay consists in determining the critical instant when queuing delay is biggest. They have shown that this critical instant occurs when all functions are sending the first message simultaneously. However, the model did not consider strict priority (SP) nor weighted round robin (WRR) scheduling. Loeser et al. presented in [8] a Network Calculus (NC) [11] approach describing traffic sources with arrival curves and switches using service curves. They did not model SP nor WRR scheduling. Furthermore, the analysis of cascaded switches was not considered. Introducing another NC model Georges et al. presented in [4] a model which is very similar to the work shown in [8]. However, it differs in the fact that they considered SP as well as WRR scheduling. Furthermore, they showed how to calculate delays considering cascaded switches.

The strengths of the measurement on prototypes are the realistic results since the behaviour of the test-hardware may be very similar to that of the target-hardware. The disadvantage of measurement on prototypes are the big effort of implementation and the difficulty of stimulating the worst case. In [5], [6] Rahmani, Steffen et al. presented a prototypical implementation of an Ethernet based car. They showed that it is possible to build an Ethernet based in-vehicle network into a real car and that this network satisfies the requirements of current electronic automotive functions. Furthermore, Kern et al. showed in [7] different implementation variants of an embedded IP network stack and compared them.

The approach adapted in this work is based on the results presented in [4]. The decision to adapt this approach is based on the following reasons:

- The model considers worst case. Thus, assertions about the worst case behaviour of the network are possible.
- It supports prioritization. As Lim et al. have shown in [1], [3] the use of prioritization seems to be necessary in Ethernet based automotive in-vehicle networks.
- It supports arbitrary topologies.

III. Case Study

The scenario presented here was chosen according to two aspects. First of all, the scenario should enable to determine the limits of the Ethernet technology within the car. Therefore, a special topology was chosen. Furthermore, the scenario shall be realistic. Hence, the electronic functions were chosen according to current automotive vehicles.

[1]In this work only Network Calculus worst case analysis is considered. However, there are several approaches to validate packet based networks using statistical methods.

A. Topology

To emphasize the effect of aggregation the double star topology was chosen as depicted in Figure 1. It shows two switches (”Switch Front” and ”Switch Back”) interconnected with a full duplex 100 Mbits Ethernet link. Further, there are several Electronic Control Units (ECU) connected via full duplex 100 Mbits links to the switches. For the switches store and forward mode and four priority queues using SP scheduling are assumed. The role of every ECU is described in the following.

The *Headunit (HU)* enables the driver as well as the co-driver

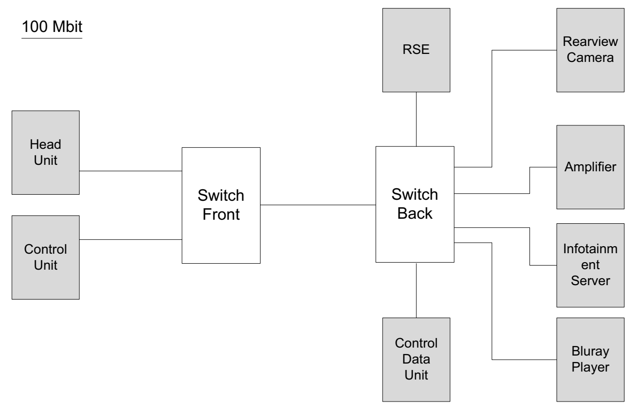

Fig. 1. Reference Topology showing several electronic control units and two switches interconnected through 100 Mbits links

to watch entertainment video originating from the *Infotainment Server (IS)* respectively the *BluRay Player (BP)*. Furthermore, it can display a video stream originating from the *Rearview Camera (RVC)*. Another feature is the calculation and presentation of navigation data originating from the Infotainment Server. The *Control Unit (CU)* receives and processes data originating from the *Control Data Unit (CDU)*. The *Rear Seat Entertainment (RSE)* enables the rear seat passengers to watch entertainment video originating from the Infotainment Server respectively the BluRay Player. The *Amplifier* receives digital audio streams from the IS or from the BP and plays them on the local loudspeakers.

B. Communication Relations and Traffic Characteristics

The communication relations, their traffic characteristics as well as their communication requirements are listed in Table I. The first column shows the name of the corresponding function. Whereas column two and three show the source respectively the destination ECU. The fourth and the fifth column are showing the traffic characteristics of the function. The (ρ, σ) representation as shown in (1) was chosen. The variable ρ represents the average rate and σ represents the maximum one time burst. The values assigned have been taken from [3] whenever applicable. As variable bit rate (VBR) is assumed for all video transmitting functions, some assumptions according their burst values had to be made. For *RearviewHU* the maximum frame size was taken as stated in [3]. This is valid since the token refresh rate for a 24 Mbits stream at 33.33

ms refresh rate is 99990 octet. For *BluRayHU*, *BluRayRSE* (BluRay video) the token refresh rate was calculated using the maximum bandwidth of 40 Mbits and a frame interval of 33.33 ms. For *ISHU* and *ISRSE* (entertainment video) a current video trailer was analysed and the maximum frame size of 62500 octet was taken. For *RearviewHU*, *BluRayHU*, *BluRayRSE*, *ISHU* and *ISRSE* additional protocol overhead has to be added. This originates from the fact that the mentioned traffic characteristics are on application layer. For *ISAmp* and *BluRayAmp* the transmission of uncompressed audio data was assumed. For *ISAmp* 16 bit stereo audio transmitted via IP/UDP/RTP using 946 octet packets (884 octet payload + 62 octet overhead) was presumed. For *BluRayAmp* five channel audio (2 × 946 octet + 1 × 504 octet) was assumed.

The communication requirements have been determined according to the categories presented in [1], [3].

IV. Network Calculus Model

The Network Calculus model used in this work is based on the model presented in [4]. Georges et al. presented a model of a minimal Ethernet switch which basically consists of a scheduler serving multiple queues according to a specific scheduling discipline. They presented strict priority (SP) and weighted round robin (WRR) scheduling policies.

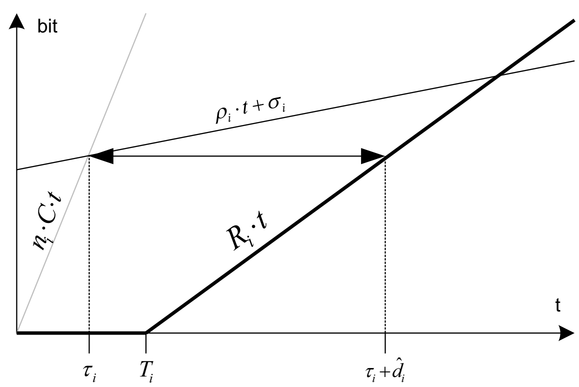

Fig. 2. The left side of the graph (to the left of τ_i) is showing the first part of the arrival curve $b_i(t)$ (with $n_i \times C$ as slope) in grey. To the right of τ_i one can see two lines. The upper one represents the second part of the arrival curve. The lower one (solid drawn) with slope R_i represents the service curve β_i. The arrowed line shows the maximum horizontal distance between the arrival curve $b_i(t)$ and the service curve β_i which represents the maximum delay $\hat{d}_i$ introduced through the corresponding network element.

A. Arrival Curves

In a first step the arrival curves of the different network streams have to be defined. In [4] Georges et al. used the model shown in (1). It bounds the bits arriving from a network stream $b(t)$ which has a long term average rate ρ and a burst value σ. Furthermore, the stream is upper bounded by the capacity C of the Ethernet link.

$$b(t) = min\{Ct, \sigma + \rho t\} \tag{1}$$

B. Service Curves

In Network Calculus the behaviour of a serving network element (e.g. a switch or a router) is modelled by a service curve. A widely used service curve for modelling the behaviour of a network element is the rate-latency function (2) which depends on the parameters R and T. The variable T represents the initial delay induced by the network element. R represents the rate of the network element serving the considered data stream. The difficulty of defining a service curve for a given network element consists in the determination of these parameters. As already mentioned, Georges et al. defined service curves for SP and for WRR. Differently to the work of Georges et al. in this work it is assumed that a higher numerical priority value means a higher priority.

$$\beta_{R,T}(t) = R(t-T)^+ \tag{2}$$

1) Strict Priority: Using (2) Georges et al. defined the service curves for a SP scheduler serving three priority queues. In this work a scenario with more than three queues is considered. Thus, a generic definition of the SP service curve given in (3) is used, where i denotes the currently considered priority and i_{max} represents the highest possible priority. Basically, the rate of the service curve is affected by the rates of higher priority streams. Furthermore, the initial delay is generated by $\delta_{hol,i}$ and $\delta_{burst,i}$. The variable $\delta_{hol,i}$ represents the delay that can be induced by lower priority streams (head of line blocking), where $L_{j,max}$ is the maximum frame size of stream j. Head of line blocking can occur due to the fact that Ethernet does not support the interruption of the transmission of Ethernet frames (in particular lower priority frames). The value of $\delta_{burst,i}$ is the delay caused by the transmission of bursts from higher priority streams.

$$\begin{aligned}
\beta_i &= R_i(t-T_i)^+, 0 \le i \le i_{max} \\
R_i &= \begin{cases} C - \Sigma_{k=i+1}^{i_{max}} \rho_k & i < i_{max} \\ C & i = i_{max} \end{cases} \\
T_i &= \delta_{hol,i} + \delta_{burst,i} \\
\delta_{hol,i} &= \begin{cases} 0 & \text{i=0,} \\ \dfrac{max\{L_{j,max}\}}{C}, j < i & \text{else.} \end{cases} \\
\delta_{burst,i} &= \begin{cases} 0 & i = i_{max}, \\ \dfrac{\Sigma_{k=i+1}^{i_{max}} \sigma_k}{C - \Sigma_{k=i+1}^{i_{max}} \rho_k} & \text{else.} \end{cases}
\end{aligned} \tag{3}$$

2) Weighted Round Robin: Furthermore, Georges et al. presented a service curve for a WRR scheduler which is given in (4), where ϕ represents the weight of the corresponding traffic class. As the focus of this work lays on SP scheduling, WRR is not further considered in this work.

$$\begin{aligned}
\beta_i = \quad & R(t-T)^+ \\
& R = C\frac{\phi_i - L_{i,max}}{\Sigma_j \phi_j - L_{i,max}}, \\
& T = \frac{\Sigma_{j \ne i} \phi_j}{C}
\end{aligned} \tag{4}$$

TABLE I
TABLE SHOWING THE COMMUNICATION RELATIONS, THEIR TRAFFIC CHARACTERISTICS AND THEIR COMMUNICATION REQUIREMENTS

Function Name	Source ECU	Target ECU	Average Rate [Mbits]	Burst Size [octet]	Max. Packet Size [octet]	Requirement Max. End-to-End Delay [ms]
ControlData	CDU	CU	0.0512	6400	64	$\leq$ 10
RearviewHU	RVC	HU	24.8390	103496	1522	$\leq$ 45
BluRayHU	BP	HU	41.6419	173508	1522	$\leq$ 150
BluRayRSE	BP	RSE	41.6419	173508	1522	$\leq$ 150
ISHU	IS	HU	15.7070	65446	1522	$\leq$ 150
ISRSE	IS	RSE	15.7070	65446	1522	$\leq$ 150
ISAmp	IS	Amplifier	1.5136	946	946	$\leq$ 150
BluRayAmp	BP	Amplifier	3.8336	2396	946	$\leq$ 150
NaviHU	IS	HU	1.7046	21308	1522	$\leq$ 100

C. Worst Case Delay Calculation

As Georges et al. considered real time applications in their work, they developed (5) allowing the calculation of an upper bound delay of a single bit of a specific traffic class crossing a scheduler of an Ethernet switch.

$$\begin{aligned} \hat{d}_i = \quad & (T_i - \tau_i) + \frac{\sigma_i + \rho_i \tau_i}{R_i}, \\ & \tau_i = \frac{\sigma_i}{C_{in} - \rho_i} \end{aligned} \tag{5}$$

D. Modifications

Due to the differences of the scenario modelled in [4] and the scenario considered in this work, the model presented in [4] has to be adapted. Taking into account the fact, that the scenario considered in this work includes aggregated traffic streams, it is necessary to adapt this in the arrival curves and the worst case delay calculation. Furthermore, this work considers a setup with four traffic classes respectively traffic queues. Thus, the service curves have to be adapted. Finally, this work considers the calculation of end to end delays, namely application to application respectively function to function delays. Thus, (5) has to be expanded.

Arrival Curves: As the aggregation of several streams and links is considered, the arrival curve has to be modified as stated in (6). The variable i is the number of the corresponding traffic class, n is the number of aggregated switch ports and m is the number of aggregated streams in traffic class i. Figure 2 depicts such an arrival curve.

$$\begin{aligned} b_i(t) = \quad & min\{nCt, \sigma_i + \rho_i t\}, \\ & \sigma_i = \Sigma_{j=0}^{m-1} \sigma_{ij}, \\ & \rho_i = \Sigma_{j=0}^{m-1} \rho_{ij} \end{aligned} \tag{6}$$

Service Curves: In first place switches with four queues and SP scheduling are assumed. This results in the service curves defined in (7).

$$\begin{aligned} & \beta_3 = \\ & C\left(t - \frac{max\{L_{0,max}, L_{1,max}, L_{2,max}\}}{C}\right)^+ \\ & \beta_2 = \\ & (C-\rho_3)\left(t - \frac{\sigma_3}{C-\rho_3} - \frac{max\{L_{0,max}, L_{1,max}\}}{C}\right)^+ \\ & \beta_1 = \\ & (C-\rho_3-\rho_2)\left(t - \frac{\sigma_3+\sigma_2}{C-\rho_3-\rho_2} - \frac{L_{0,max}}{C}\right)^+ \\ & \beta_0 = \\ & (C-\rho_3-\rho_2-\rho_1)\left(t - \frac{\sigma_3+\sigma_2+\sigma_1}{C-\rho_3-\rho_2-\rho_1}\right)^+ \end{aligned} \tag{7}$$

Worst Case Delay Calculation: After the definition of the service curves the formulas for the calculation of the worst case delay can be adapted. Using (5) one gets (8).

$$\begin{aligned} \hat{d}_3 = \quad & \left(\frac{max\{L_{0,max}, L_{1,max}, L_{2,max}\}}{C} - \tau_3\right) \\ & + \frac{\sigma_3 + \rho_3\tau_3}{C} \\ \hat{d}_2 = \quad & \left(\frac{\sigma_3}{C-\rho_3} + \frac{max\{L_{0,max}, L_{1,max}\}}{C} - \tau_2\right) \\ & + \frac{\sigma_2 + \rho_2\tau_2}{C-\rho_3} \\ \hat{d}_1 = \quad & \left(\frac{\sigma_3+\sigma_2}{C-\rho_3-\rho_2} + \frac{L_{0,max}}{C} - \tau_1\right) \\ & + \frac{\sigma_1 + \rho_1\tau_1}{C-\rho_3-\rho_2} \\ \hat{d}_0 = \quad & \left(\frac{\sigma_3+\sigma_2+\sigma_1}{C-\rho_3-\rho_2-\rho_1} - \tau_0\right) \\ & + \frac{\sigma_0 + \rho_0\tau_0}{C-\rho_3-\rho_2-\rho_1} \end{aligned} \tag{8}$$

Similar to the modifications of the arrival curve in (6), τ_i has to be modified as stated in (9). Here, it has to be taken into account again that aggregated traffic streams originating from different switch ports are considered. This results in the fact that the burst values as well as the average rates are summed up and instead of taking the capacity of one link, the capacity of all links transmitting to the considered port is taken.

$$\tau_i = \frac{\Sigma_{j=0}^{m-1} \sigma_{ij}}{nC - \Sigma_{j=0}^{m-1} \rho_{ij}} \quad (9)$$

Resulting from the fact, that this work considers end to end delays and formula (5) respectively (8) deliver the delay experienced by one single bit, the delay caused by the transmission of one maximum sized application layer frame (+ protocol overhead) has to be added to the worst case delay of the concerning traffic class. Furthermore, this work considers store and forward switches. Thus, the delay induced by the transmission of one Ethernet frame per crossed switch (n_{cs}) has to be added.

$$\hat{d}_{app_{ij}} = \hat{d}_i + \frac{maxAppFrameSize_{ij}}{R_i - \Sigma_{k \neq j} \rho_{ik}} + \frac{n_{cs} L_{max,ij}}{C} \quad (10)$$

V. Results

Figure 3 and 4 are showing the link utilization of the considered links. As shown in Figure 3 the link between the two switches is nearly 84 percent utilized. The link between switch back and the RSE has a load of 57.35 percent. Whereas the link to the amplifier has a load of only 5.35 percent. Table II shows the results of the case study presented in this work. As one can see, the calculated End-to-End delays of the functions are all below their requirements. In particular, the worst case delay of *RearviewHU* is almost 80 percent below the requirement. Nevertheless, compared with the delay measured in the simulation done in [3] it is about three times bigger. This origins mainly in the fact, that Lim et al. measured the average delay. Further, the traffic trace of the driver assistance scenario used in [3] could not be analysed. Therefore, assumptions had to be made. It was assumed that the arrival curve of this traffic trace would be bounded by a function with an average rate of 24 Mbits and a burst value which is as big as the biggest frame size, while Lim et al. assumed a stream varying from 10 to 24 Mbits. Obviously, the bound of 24 Mbits – which was chosen for this paper – is not tight.

As a matter of fact constant delays like switch processing time and the calculation of buffer requirements in the switches and ECUs have been omitted. This important task will be considered in our future research activities.

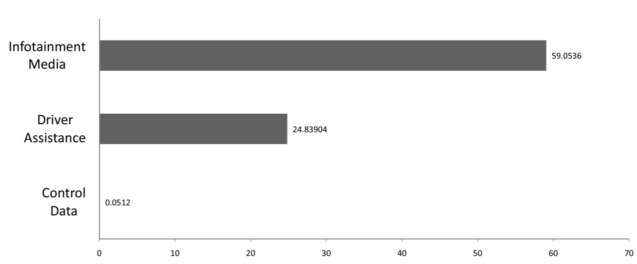

Fig. 3. Graph showing the link utilization between the two interconnected switches. Infotainment data (NaviHU, BluRayHU, ISHU) consumes 59.05, driver assistance (RearviewHU) 24.84 and the control application 0.05 percent of the available bandwidth. The link is nearly 84 percent utilized.

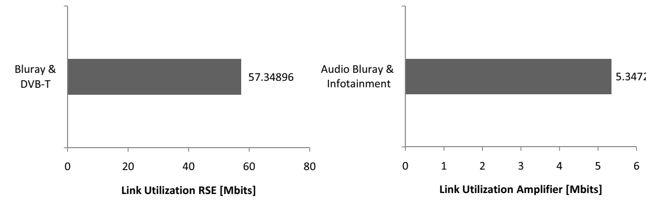

Fig. 4. Graphs showing the link utilization of the links between Switch Back and (i) the RSE (BluRayRSE, ISRSE) and (ii) the amplifier (BluRayAmp, ISAmp). The former link is 57.35 percent utilized and the latter link has a load of only 5.35 percent.

TABLE II

Table showing the results calculating the worst case delays according to the functions listed in Table I. The middle column shows the assumed queue assignment of the corresponding function.

Function Name	Assigned Queue [0..3]	Worst Case Delay [ms]
ControlData	3	0.137
RearviewHU	2	9.167
BluRayHU	1	60.569
BluRayRSE	1	30.111
ISHU	1	52.995
ISRSE	1	22.616
ISAmp	1	0.364
BluRayAmp	1	0.480
NaviHU	1	46.109

VI. Conclusion and Future Work

In this work a case study has been presented, exploring the possibilities of an Ethernet based in-vehicle network. Differentiating from other works, this scenario was examined using a NC worst case model. The communication requirements of all considered functions could be met – even though considering the worst case. It became clear that the quality or tightness of the results depends on the quality of the traffic descriptions.

As already mentioned it will be part of our future work to calculate – at least as a rule of thumb – minimum buffer sizes for switches and ECUs. Furthermore, methods will be investigated, enabling an efficient use of the network resources within an in-vehicle network.

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