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► To cite this version:

Kostas Beretis, Ieroklis Symeonidis. Experimental evaluation of end-to-end delay in switched Ethernet application in the automotive domain. SAFECOMP 2013 - Workshop CARS (2nd Workshop on Critical Automotive applications: Robustness & Safety) of the 32nd International Conference on Computer Safety, Reliability and Security, Sep 2013, Toulouse, France. pp.NA. hal-00848359

HAL Id: hal-00848359

<https://hal.science/hal-00848359>

Submitted on 26 Jul 2013

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Experimental evaluation of end-to-end delay in switched Ethernet application in the automotive domain

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Abstract. This article presents an approach for deriving upper bound for end-to-end delay in a double star switched Ethernet network. Four traffic classes, following a strict priority queuing policy, were considered. The theoretical analysis was based on network calculus. An experimental setup, which accurately reflects an automotive communication network, was implemented in order to evaluate the theoretical model. The results obtained by the experiments provided valuable feedback that redefined the analytical model.

Keywords: Switched Ethernet, Network calculus, Autosar, Real-time, Delay

1 Introduction

Even though Ethernet was not originally designed for real-time communication, the increasing need for available bandwidth has led the automotive industry to consider it as a possible alternative. All standards of Ethernet are widespread and non-proprietary (reduction of cost) and have become successful in other industrial domains such as avionics and industrial automation [1]. A major challenge for using Ethernet is to guarantee the real-time constraints (i.e. end-to-end delay) to ensure predictability in the time domain. Determining an upper bound for end-to-end delay on switched Ethernet networks has been examined by Loeser and Haerting for the case of a FIFO queuing policy [2]. Georges et al. evaluated the performance of switched Ethernet in an industrial context, comparing different queuing policies [3]. Finally, Rahmani et al. applied a similar approach in the automotive domain using simulation [4].

The purpose of this paper is the experimental evaluation of bounded end-to-end delay for an in-vehicle switched Ethernet network. This is achieved through comparison of theoretically obtained bounds with actual experimental data. In order to demonstrate that switched Ethernet can be used as a backbone based on existing technology; commercial off-the-shelf switches were used. All development boards used, were running an AUTOSAR operating system [5], in accordance to the automotive standards.

2 System model and traffic

In this section the system model and traffic types considered in this paper are presented. Traffic load and patterns, as well as timing constraints were provided by Volvo

Car Corporation. In the considered architecture, ECUs that serve similar functionality are grouped into the same domain. Communication among the domains is achieved through a double star switched Ethernet network (backbone), operating at 100 Mbps full duplex. In addition to the traffic generated by the five domains (as shown in fig.1), video and FTP traffic passes also through the backbone.

The highest amount of data is generated from the video source and the FTP server. As a consequence the worst case delay is observed in the frames going from left to right and the end-to-end delay is defined as follows: End-to-end delay is the time it takes for a frame to traverse the backbone once it is *received from* an input port of switch A until it is fully *transmitted from* an output port of switch B.

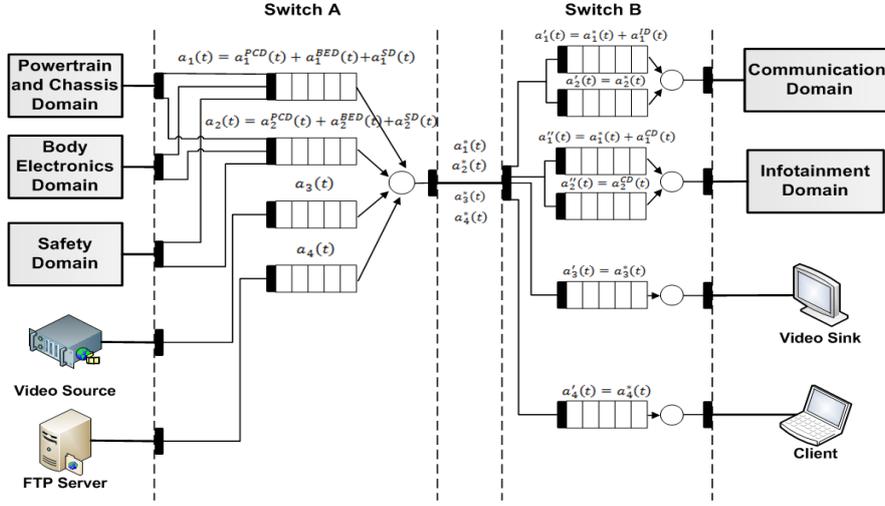


Fig.1. System model (Equations in this figure will be explained in section 3)

Traffic types. Traffic generated from a domain is usually destined for a subset of the domains (multicast). VLANs, as defined in IEEE 802.1Q, were used to enable multicasting. Additionally, up to eight priority levels can be assigned through the Priority Code Point (PCP) field located on the VLAN tag, as defined in IEEE 802.1p. However, due to switch limitations the following four priority classes are considered:

- **Hard real time messages:** This class has the highest priority and consists of control messages regarding the powertrain, chassis and body electronic domains. No packet loss is tolerated in this priority class.
- **Soft real time messages:** This class has second priority and consists of diagnostic messages. However, they are not as highly critical as the previous class and an amount of missed deadlines can be tolerated.
- **Video:** This class is the third priority and consists of video streams. One or more cameras stream video of MJPEG format. Losses $\leq 0.1\%$ can be tolerated [4].
- **Best effort data:** Finally the last class consists of best effort messages, for example, web browsing or file transferring. This class consists of non-critical traffic that has no real-time constraints.

The first two classes generate periodic traffic; the third is bursty by nature while the fourth class is event-triggered. The first three classes use UDP while the fourth uses TCP. The end-to-end delay for the first three is guaranteed through modeling (see Section 3) while reliable transfer for the fourth class is guaranteed through TCP.

Switch model. Collisions are completely avoided in full duplex switched Ethernet. Upper bounds of delays introduced by the switch can be calculated in a deterministic way. The total delay of a frame passing through a switch can be expressed as [6]:

$$D_{\text{switch}} = D_{\text{proc}} + D_{\text{queue}} + D_{\text{trans}}$$

where D_{proc} is the processing delay of a frame by the switch (often referred to as switch fabric); D_{queue} represents the queuing delay by the output port and has the greatest impact on the switch delay; and finally D_{trans} is the transmission delay and can be calculated as $D_{\text{trans}} = L/C$ where L is the frame length and C is the link capacity.

Figure 2 shows a conceptual model of the switch. A frame is received by Rx port and is then processed by the switch fabric and placed in the appropriate priority queue. The queue scheduler decides which frame will be transmitted based on the queuing policy and finally, transmitted through the Tx port.

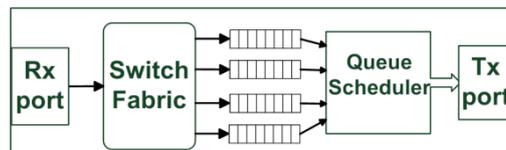


Fig.2. Switch Model (notice the four different queues for the four priority traffic flows)

3 End-to-End delay modeling

Network calculus (originally introduced by Cruz [7] and extended by Le Boudec and Thiran [8]) allows the calculation of end-to-end delay using the notions of *arrival* and *service* curves. We applied this method to derive guaranteed upper bounds.

Arrival Curves. The traffic generated on the vehicle's backbone network is known beforehand both in terms of size and period. The arrival curve for the first two flows can be expressed as $a(t) = b + rt$, where b is the maximum frame size of the given flow and r is its average data rate. Consequently, $a(t)$ is a deterministic upper bound of the specific incoming traffic. Also, because this curve is an affine function [8], the arrival curves of different data flows can be merged by simply adding them to obtain the cumulative traffic load from different domains.

The third priority class which consists of MJPEG video data can be modeled in a similar way. Each frame is a JPEG picture which is compressed individually and then transmitted. A typical configuration consists of a resolution of 640X480 and a rate of 30 frames per second. The arrival curve of this flow can be expressed as $a(t) = b + rt$ where b is the frame size of a JPEG picture and r the average data rate. The traffic of the fourth priority class is random by nature. Therefore, a simple token bucket traffic shaper, similar to [2], was applied at the source to ensure predictable behavior.

However, the data arrival on a physical network is limited by its link capacity C . As a consequence each arrival curve is expressed as:

$$\alpha(t) = \min\{Ct, b + rt\}$$

Service Curves. In our model, strict priority policy is considered to determine which class of traffic to service first: *any frame of a given priority class is served only if there are no other frames of higher priority class present in the queues*. Therefore, the service offered by the switch is not the same for all priority classes. As shown by Georges et al [4], the service curve offered to each flow can be expressed as:

$$\beta(t) = R * (t - T)^+$$

where R is the rate at which data will be served expressed in bits/sec and T is the total delay suffered by a flow before being actually served. The total delay parameter T is computed based on two factors: (i) the interference from higher priority flows, and (ii) the blocking delay due to a non-preemptive transmission of lower priority flows.

Traffic scenario. There are four different flows from left to right (fig. 1). The end-to-end delay was calculated for each of them. Flow $a_1(t)$ is the sum of all flows of first priority messages generated from the powertrain/chassis domain, body electronics domain and safety domain. Flow $a_2(t)$ is the sum of all flows of second priority messages generated from the powertrain/chassis domain, body electronics domain and safety domain. Flow $a_3(t)$ is the flow of third priority video data destined for the video sink. Finally, flow $a_4(t)$ is the flow of fourth priority best effort data sent from an FTP server to a client. System traffic is exchanged on both directions.

Queuing delay. For a given arrival curve $a(t)$ and service curve $\beta(t)$, Le Boudec and Thiran [8] have shown that the maximum end-to-end delay D is the maximum horizontal distance between the two curves. The point where the arrival curve changes slope, denoted by g , is the point where $Ct = b + rt$ and is given in [2] as follows:

$$g = \frac{b}{c-r}$$

As shown by Georges et al. (equation (7) in [3]), the expression for the calculation of the end-to-end delay of a given flow is the following:

$$D = \frac{b + rg}{R} + (T - g)$$

The theoretically calculated end-to-end delay values were compared with the values obtained experimentally, through the setup described in the following section.

4 Experimental Setup

Five development boards, equipped with a Freescale MPC5567 processor, were used during the experiments. Two Netgear GS108Tv2 switches were also deployed. Video source and sink as well as FTP server and client were represented by four laptop

computers running Linux. Besides the traffic generated by the domains, an MJPEG video stream of 32 Mbps and a file transfer with a rate of 8Mbps were used. The system was loaded using the provided traffic patterns by Volvo Car Corporation.

In order to experimentally measure the end-to-end delay of a frame, the frame has to be time-stamped while entering and exiting the network. For the measurement of the first priority message delay, one network tap was connected on the link between the powertrain/chassis domain and switch A while the other tap was connected to the link between switch B and the infotainment domain. This was done since the rate of the first priority data traversing that path is the highest for the system. Since all diagnostic messages are destined to the communication domain, the second priority message delays were measured between the powertrain/chassis domain and the communication domain. The two taps were then connected to an experimental computer through a Vector VN5610 network interface, which captured and time-stamped the frames for experimental measurement. The same approach was applied to the third priority flow between the video source and sink. The fourth priority flow is not considered since it is best effort.

The development boards were running ArcCore's [9] implementation of AUTOSAR with an extended IP Stack supporting IEEE 802.1p and 802.1Q. AUTOSAR 4.1 also specifies such support for these two protocols.

5 Results and discussion

The calculated theoretical bound was not exceeded by any experimentally measured delay value in all three cases. Due to space limitation only the results for the first two priorities are presented. The x-axis in each graph represents the captured frames and the y-axis represents their respective delay. The solid horizontal line is the theoretical delay. It can be easily observed that the vast majority of the end-to-end delay values for our experimental results are much smaller than the theoretical bound. However, the maximum (worst-case) measured delays were close to the theoretical bound.

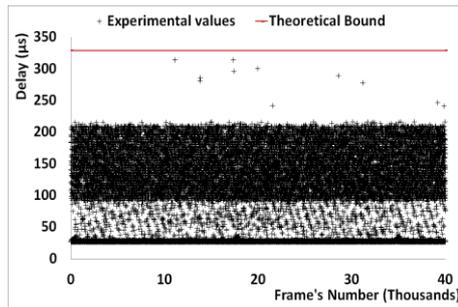


Fig.3. Delays for first priority traffic

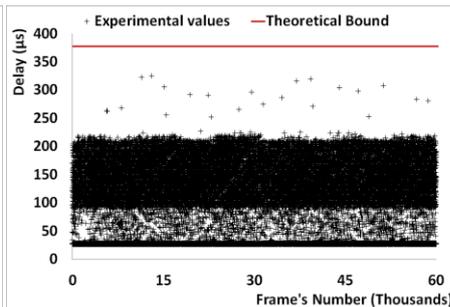


Fig.4. Delays for second priority traffic

Although in theory a high priority frame can be blocked by one lower priority frame, during our experiments it was observed that the blocking point due to a non-preemptive transmission consists of *two* frames due to the way the queue scheduler dispatches the traffic. This was used as feedback to the theoretical model resulting in

higher delay values than originally anticipated. The delay calculated was the end-to-end network delay. The application-to-application delay, as well as the CPU utilization due to the IP stack, has to be further investigated and it is left as future work.

6 Conclusions

In this paper, a theoretical model of a double star switched Ethernet network topology was presented. Network calculus was used to calculate the upper bound of end-to-end delays and experiments were performed to evaluate those bounds. The experimental results confirmed the validity of the theoretical analysis. This clearly demonstrates that for *a priori* known traffic, such as a vehicle's backbone traffic, network calculus can be applied to derive deterministic guarantees for end-to-end delay using switched Ethernet. Consequently, switched Ethernet can be considered an alternative for future vehicles backbone architecture. Taking into consideration that 1Gbps Ethernet will become available for automotive and the fact that AUTOSAR 4.1 and its future versions will support 802.1Q and 802.1p, great potential is being presented for the designers of future vehicular communication networks.

Acknowledgements. We would like to thank Prof. Johan Karlsson and Postdoc researcher Risat Pathan from Chalmers University for their helpful guidance. We are also sincerely grateful to Samuel Sigfridsson and Jerker Fors from Volvo Car Corporation, as well as Michael Svenstam from ArcCore for their insightful advice.

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