Challenges in a Future IP/Ethernet-based In-Car Network for Real-Time Applications

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ABSTRACT

In current vehicles, a large number of control units are connected by several automotive specific communication buses, facilitating innovative distributed applications. At the same time, computers and entertainment devices use IP and commodity communications technology like Ethernet to connect to the Internet, allowing for innovative solutions and maintaining fast innovation cycles. Today, one can see first applications of Ethernet for in-vehicle communication in contemporary cars. In next generation vehicles, many innovative applications could benefit from the increased bandwidth Ethernet can offer. Therefore, a examination of Ethernet usage for additional in-vehicle communication use cases is needed. In this paper, we show simulation results of promising use cases for in-car Ethernet, while looking at different realistic topologies, types of traffic, and configurations.

Categories and Subject Descriptors

C.2.1 [**Computer-Communication Networks**]: Network communications, Network Topology; C.4 [**Computer Systems Organization**]: Performance Evaluation

General Terms

Performance

Keywords

In-vehicle communication, Ethernet, QoS, Simulation, Performance Evaluation

1. INTRODUCTION

The traditional in-car network consists of different network technologies like CAN, FlexRay, and MOST [1, 2]. All of them being optimized solutions for specific use cases. While CAN has been used since the late 1980s to connect different Electronic Control Units (ECUs) with a cost-efficient but relatively slow bus, FlexRay was designed for dependable real-time communication and somewhat higher bandwidth requirements (10 Mbit/s). MOST was designed for transporting high quality audio data between entertainment ECUs with a maximum data rate of 25 (optical), 50 (electrical), and 150 Mbit/s (again optical) in the latest version. Just a couple of years ago first vehicle manufactures started to include Ethernet in their cars for two applications [3]:

- Diagnosis and updates.
  When considering the increasing amount of data in the vehicle, it becomes clear that the traditional CAN-based access to the car becomes too slow to update the data of the navigation system, for example. This data can easily reach a couple of Gigabytes. For updating the increasing amount of data and software, faster access to the vehicle is required. While the newer versions of MOST could provide sufficient bandwidth for this use case, adding MOST to a diagnosis plug seemed difficult due to MOST's ring topology and, in the optical case, sophisticated plugs. Adding 100 Mbit/s electrical Ethernet to the diagnosis plug was clearly an easy and cost-efficient way to provide the bandwidth required.

- Entertainment use cases.
  Even in the Entertainment domain, which is the main focus of MOST, Ethernet is used today to connect the Rear Seat Entertainment system (RSE) to the Head Unit to provide high-speed access to the mass storage located in the Head Unit. Ethernet proves to be the perfect fit for implementing a network file system, since it was designed for such applications originally.

While these use cases have been the first applications of Ethernet in the car, it is the next logical step to consider Ethernet also for other in-car applications [4]. Currently, we consider three additional applications of Ethernet:

- LVDS replacement to connect digital video cameras.
- MOST replacement for all Infotainment and Communication use cases.
- Additional high speed data communication between larger ECUs, for instance for future driver assistance applications.

All of these applications have in common that the requirements are somewhat stronger than in the current applications of Ethernet in the vehicle: As MOST replacement Ethernet, must prove to deliver audio and video streams in a timely and dependable fashion. As camera connection, Ethernet in combination with video codecs must prove to transport the video data with minimal latency, and for high speed data communication Ethernet must prove that latency and jitter requirements are achieved. In this paper, we examine Ethernet as a solution for these challenging areas of application. We consider up to four different traffic aggregate on the same switched 100 Mbit/s Ethernet, while examining the influence of different topologies and configurations. Our results can be used as basis for future in-vehicle network design.

This paper is structured as follows: In Section 2, we present existing performance studies for switched Ethernet topologies. Section 3 describes the setup, the proposed topologies and traffic characteristics in a switched Ethernet in-car network. It evaluates the performance of the in-car applications in a final step. Section 4 concludes our work and sketches out future research path.

2. RELATED WORK

The analysis of a double star and an unidirectional based ring topology was performed by M. Rahmani et al. [5, 6] who used typical in-car services with statistical models. They showed that the unidirectional ring based topology offers a better performance in terms of throughput, packet loss and they thus recommended the use of traffic shaping mechanisms to avoid large bursts of variable bit rate (VBR) data traffics. However, the proposed ring topology was configured as an unidirectional ring which does not conform to the IEEE 802.1 and IEEE 802.3 standard, so that a modification of end nodes and switches is required. In our work, we assume a legacy Ethernet Medium Access Control (MAC) without any modifications.

S. Rüping et al. analyzed the cycle times and the latencies for automation systems in different topologies based on a switched Ethernet network: daisy chain, ring and tree [7]. They showed that the ring based topology performs better than the daisy chain, but state that a special routing strategy and redundancy management mechanisms are required which are unlikely to be implemented in a realistic in-car network due to the costs.

Ramez M. Daoud et al. [8] assumed a 1Gbit/s network for the in-car network in a star-based topology without any QoS mechanisms where only two traffic classes were defined: control data and video streaming data. The considered network is not a near-term option due to the costs and the problems of electromagnetic compatibility (EMC). Independent of the costs, they showed the given applications fulfill the constraints and requirements in terms of the end-to-end delays, but the influence of other traffic classes to control data are not analyzed. The influence of different traffic classes to each other in a switched Ethernet in-car network was shown in our recent analysis [9] where applications, especially control data violated their constraints and requirements. We recommended a prioritization mechanism to avoid violation of the highest service constraints at least.

3. PERFORMANCE EVALUATION

The topology of a switched Ethernet network has a strong influence on the applications provided in a vehicle. A badly configured and partitioned network results in high network load so that applications cannot meet their requirements. In the worst case, safety critical control messages are transmitted delayed or get lost. In this work, we analyze a switched Ethernet network with typical in-car applications to evaluate the network load based on three different topologies. The evaluation uses the simulation tool OMNeT++ [10] and the INET-framework [11]. First, we analyze a legacy switched Ethernet network without any QoS or prioritization mechanisms. Afterwards, we prioritize the data traffics and configure the switches with four queues per port to determine the influence of prioritization mechanism to the provided applications.

3.1 Topology

We propose three different topologies for the in-car network with the given applications: a star-based (Topo1), daisy-chain based (Topo2) and a combination of both topologies realized as a tree structure (Topo3). These topologies can be used in a switched Ethernet network without any modifications of the IEEE 802.3 [12] and the IEEE 802.1Q [13] standard. The star-based topology of a switched Ethernet network in a vehicle reduces the complexity of cable harness and therefore the installation, maintenance costs especially when optional ECUs are connected to the network. In contrast to the star-based topology, the daisy-chain based topology is the simplest configuration with 3-port switches and fixed in-car equipments. We can assume that there are only 3-port switches in a vehicle which are integrated in the ECUs. The combination of both topologies realized as a tree structure could be an option for the in-car network to have a good trade-off between performance and installation maintenance costs.

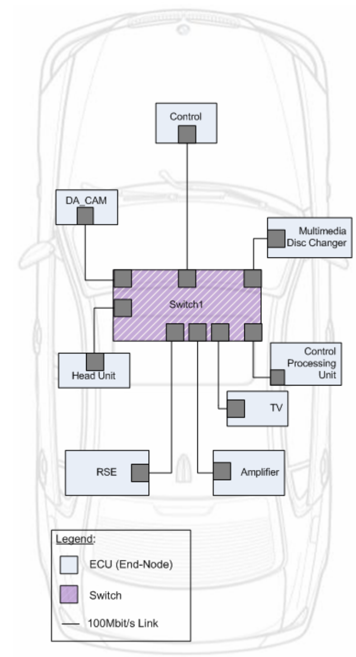

Figure 1: Star-based Topology (Topo1)

3.2 Traffic Characteristics

We chose typical in-car applications with high bandwidth demands to evaluate the network load and the influence of

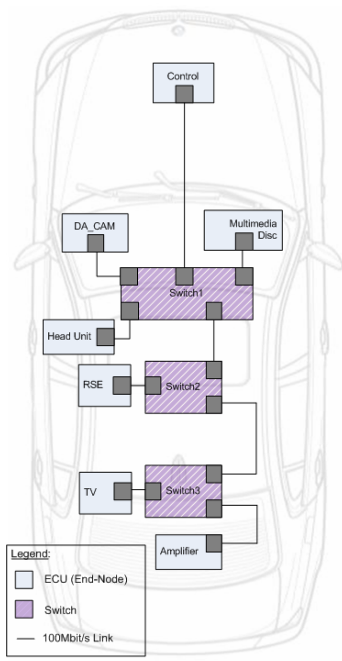

Figure 2: Daisy chain-based topology (Topo2)

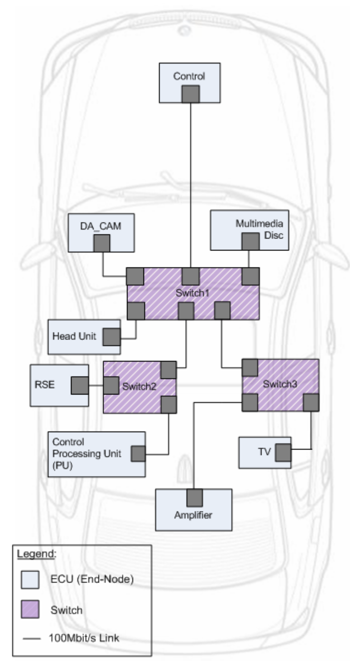

Figure 3: Tree-based topology (Topo3)

bandwidth intensive applications to the control data in a network. Four service classes are considered in our analysis: control data (according to existing CAN and FlexRay traces, see below), driver assistance camera data, navigation data and multimedia audio/video data streamed by an internal device (e.g. BlueRay player) and by a TV module (see Tab. 1). In our recent analysis of in-car CAN and FlexRay control data, we gave evidence that most of the data had a packet size of less than 18 Bytes [9]. Based on the results we chose a UDP payload size of 18 Bytes for control data which is the minimum packet size without any paddings of an Ethernet frame. The control data are transmitted from the control node the processing unit ("Control Processing Unit") and the RSE node. Several driver assistance cameras (not shown) are directly connected to the "DA CAM" node, which aggregates the data and streams it to the "Head Unit". The packet size of the video data is based on an uniform distribution according to the current Ethernet camera prototypes. For each 100ms, navigation bulk data are transmitted from the Head Unit to the rear seat entertainment unit ("RSE") with a packet size of 20000 bytes (e.g., map segments). In addition to that, multimedia data are streamed from a BluRay disc player ("Multimedia Disc") to the RSE which traffic characteristics are based on a BluRay specification [14]. Live TV data is streamed from the "TV" node to the "Head Unit". We assume a DVB-T streaming data with a bit rate from 10Mbit/s to 20Mbit/s. In reality, the bit rate depends on the modulation and the coding rate [15].

Table 1: Characteristics of In-Car applications

Traffic Type	UDP Packet Size [byte]	Service Rate [ms]	BW [Mbit/s]	P
Control	18	uniform (10,100)	$1.44 \cdot 10^{-3}$ ... $14.4 \cdot 10^{-3}$	3
Driver Assistance CAM	uniform (41663,99990)	33	10 - 24	2
Navigation	20000	100	16	1
MM Video	1400	0.28	40	0
MM Audio	1400	1.4	8	0
TV Video	1400	uniform (0.56,1.12)	10 - 20	0
TV Audio	1400	2.33	4.8	0

3.3 Assumption and Metrics

For the entire simulation we make following assumptions:

- Ethernet Link Bandwidth: 100 Mbit/s.
  We assume a switched Ethernet network based on the 100Base-TX standard, which is already used for some use cases in current vehicles (software update and diagnosis). The next generation of vehicles will most likely still use 100Mbit/s-Ethernet, but exchange the physical layer to allow for unshielded twisted pair cables [3]. Gigabit Ethernet is currently not used in the car since it would need expensive shielding. In addition to that, most current ECUs cannot handle data at such high rates anyway.

- QoS with prioritization mechanism.
  The in-car data traffic is classified into four priority classes as defined in IEEE 802.1Q [13]. Data packets with the highest priority are scheduled based on a strict priority queuing so that a transmission is started as soon as it arrives at a queue. Other priorities are

scheduled based on a weighted fair queuing (WFQ) with a weight value.

- Priority 3 (highest): Strict priority Queuing
- Priority 2: Weighted Fair Queuing (weight = 100)
- Priority 1: Weighted Fair Queuing (weight = 10)
- Priority 0: Weighted Fair Queuing (weight = 1)

- MAC Transmission Queue size: 100 packets.
The transmission queue size of a medium access control (MAC) is limited to 100 packets, so that each priority class has an own queue to store maximum 100 packets.
- Switch processing time: $3\mu s$ [6].

We use following metrics throughout the performance evaluation:

- *End-to-End delay* quantifies the total time required for a transmission of a data frame from the source to the sink node. This value indicates if the in-car applications fulfill their constraints.
- *Throughput* gives information about the network load and the link load. Most of the in-car applications are sent to the “Head Unit” and “RSE”. Therefore, we concentrate on the link load between the switches and the two most important nodes “Head Unit” and “RSE”.

3.4 Requirement of the applications

The evaluated system model contains four traffic types, where each of them has different constraints. We measure the end-to-end delay of these applications to verify if they fulfill their requirements. The maximum end-to-end delay for the highest traffic type should be less than 10 ms, while multimedia streaming data require an end-to-end delay of up to 150 ms. The provided in-car applications and their constraints are listed in Table 2.

Table 2: Application constraints [9]

Priority Value	Traffic Type	Max. End-to-End Delay [ms]
3	Control	$\leq$ 10 [16, 5]
2	Driver Assistance CAM	$\leq$ 45 [5, 17]
1	Navigation	$\leq$ 100
0	Multimedia	$\leq$ 150 [18]

3.5 Results

The results of the simulation based performance evaluation show us that all of the provided in-car applications fulfill their constraints stated in Tab. 3. The prioritization mechanism can only improve the two highest priority classes (Prio3 and Prio4) while other priority classes do not improve the end-to-end delays. This result is expected due to the priorization of data; higher priority data are processed and scheduled faster in a switch. In case of control data which are transmitted and scheduled with the highest priority, we could show that a prioritization mechanism can improve the end-to-end delay to 8% in average and 40% in a worst case (see Fig. 5 and Fig. 4). The best performance related to the end-to-end delay is achieved with a star-based topology

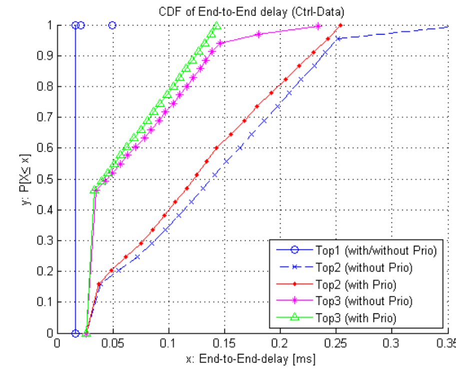

Figure 4: CDF of End-to-End delay (control data)

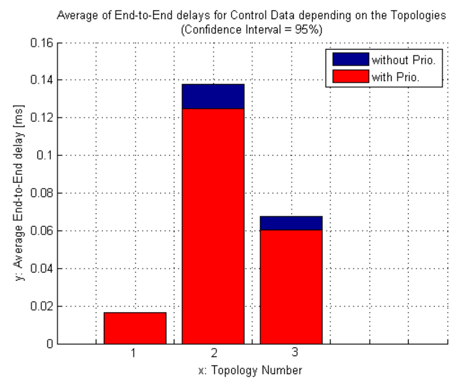

Figure 5: Average of End-to-End delay (control data)

(“Topo1”) because packets from the control node to the sink node are pass a single switch.
In case of driver assistance camera data, the situation is quite different (see Fig. 6). All of the topologies have similar results due to the fact that the data of all driver assistance cameras passes only a single switch in all of the topologies. Furthermore, the results show that prioritization mechanisms improve the end-to-end delay by approximately 1% in average. The network load in all of the topologies is medium so that the provided applications fulfill their constraints (see Tab. 4 and Fig. 7). A link between the head unit (“Head Unit”) and the switch (“Switch”) of more than 30 Mbit/s is required to enable applications (e.g. DA-CAM, navigation, control) without any violation of the constraints. Multimedia applications with high bandwidth demands are transmitted to the RSE node so that a link of more than 55 Mbit/s is required to fulfill the multimedia constraints.

Table 3: Average of End-to-End delays

Traffic Type	Topo1		Topo2		Topo3	
	without Prio [ms]	with Prio [ms]	without Prio [ms]	with Prio [ms]	without Prio [ms]	with Prio [ms]
Control	0.0165	0.0165	0.1377	0.1251	0.0674	0.0602
Driver Assistance CAM	3.4141	3.3656	3.4108	3.3597	3.4108	3.3597
Navigation	1.2153	1.7362	1.3415	1.8912	1.3415	1.8912
MMVideo	0.2476	0.2476	0.3679	0.3679	0.3679	0.3679
MMAudio	0.2409	0.2409	0.4816	0.4816	0.3614	0.3614
DVB-T (Video)	0.2650	0.2650	0.3853	0.3853	0.5056	0.5056
DVB-T (Audio)	0.2507	0.2507	0.2505	0.2505	0.2505	0.2505

Table 4: Average of Link Load based on the measured bandwidth

Measured Link	Topo1		Topo2		Topo3	
	without Prio [Mbit/s]	with Prio [Mbit/s]	without Prio [Mbit/s]	withPrio [Mbit/s]	without Prio [Mbit/s]	with Prio [Mbit/s]
Switch1 → HeadUnit	28.7754	28.7733	29.1889	29.1866	29.1889	29.1866
Switch2 → RSE	55.3968	55.3968	55.4090	55.4090	55.3984	55.3984
RSE → Switch2	x	x	1.6959	1.6959	1.6960	1.6960
Switch2 → RSE	55.3968	55.3968	55.4090	55.4090	55.3984	55.3984

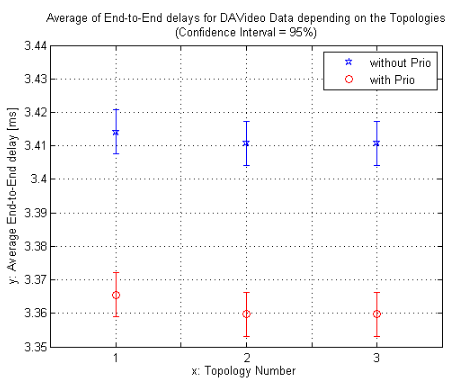

Figure 6: Average of End-to-End delay (DA-CAM)

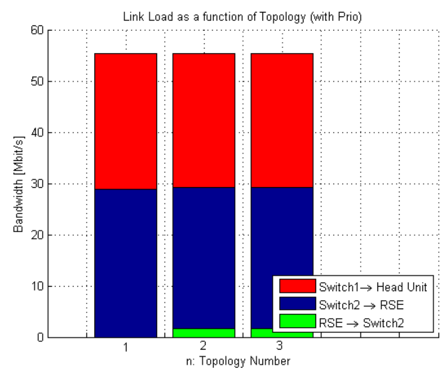

Figure 7: Average of Link Load

4. CONCLUSION AND FUTURE WORK

In this paper, we have shown that Ethernet cannot only be used to transport the traffic of a single vehicle function, but also a traffic mix of different vehicle functions, while achieving satisfying Quality of Service. Also, the influence of different realistic topologies and the usage of prioritization have been examined: The star-based topology ("Topo1") has the best performance in terms of the end-to-end delay, but it has to be assured that optional ECUs are connected carefully to avoid an overloaded network. A prioritizsation mechanism is required to improve the performance of in-car applications in a worst case scenario.

As future work, we will analyze the in-vehicle network in overload situations with many high bandwidth applications in addition to high bandwidth bulk traffic. In addition, we will examine the usage of the IEEE 802.1Qav mechanism [19], which enhances queues and schedulers of an Ethernet switch. 802.1Qav is a part of the IEEE 802.1 Audio/Video Bridging (AVB) standard [20], which aims on delivering high quality audio/video streaming data in multi-hop Ethernet networks with very low latency and synchronized play-out at different nodes.

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