Performance Study of an In-Car Switched Ethernet Network without Prioritization

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Abstract. This paper presents the current state of our research in real-time communication of an IP-based in-car network. The Internet Protocol (IP) will serve as convergence layer of different specific in-car network protocols and IEEE 802.3 Ethernet will be the basic technology to transport IP. In this work, we evaluate a legacy switched Ethernet network without any Quality of Service (QoS) mechanisms. While there are arguments for not using QoS mechanisms, we give evidence that communication requirements and service constraints of a more and more streaming intensive in-car network cannot be met without. We argue for a setup with different traffic types: CAN and FlexRay like control messages, camera streaming, video and audio streaming, and bulk traffic. We will also argue for a simple double star topology as a valid assumption where the target architecture of the IP-based in-car network is not yet clear. Setup and simulation will serve as framework and motivation for future work: Analyzing IP-based real-time communication using QoS mechanisms - characterizing traffic classes after IEEE 802.1Q and IEEE 802.1 Audio Video Bridging (AVB).

Keywords: IP-Based In-Car Network, Switched Ethernet, Quality of Service Performance Evaluation.

1 Introduction

A current automotive network consists of more than 70 Electronic Control Units (ECUs) which are interconnected by different automotive specific network technologies such as the Controller Area Network (CAN), FlexRay, Media Oriented System Transport (MOST), and Ethernet. Due to the heterogeneous in-car network, different protocols are used and translated by an application layer gateway (see Fig. 1). Current automotive specific network technologies only provide low bandwidth. In the near future, the number of applications with high bandwidth demand will grow and thus imply the introduction of new technologies: Driver assistance camera applications will increase safety and comfort and the users' demand for high quality streaming data in the infotainment domain (e.g. BlueRay, HDTV) and bulk data due to back-end services is increasing. IEEE 802.3 Ethernet is a tested and proven standard that fulfills the high bandwidth

T. Strang et al. (Eds.): Nets4Cars/Nets4Trains 2011, LNCS 6596, pp. 165–175, 2011.

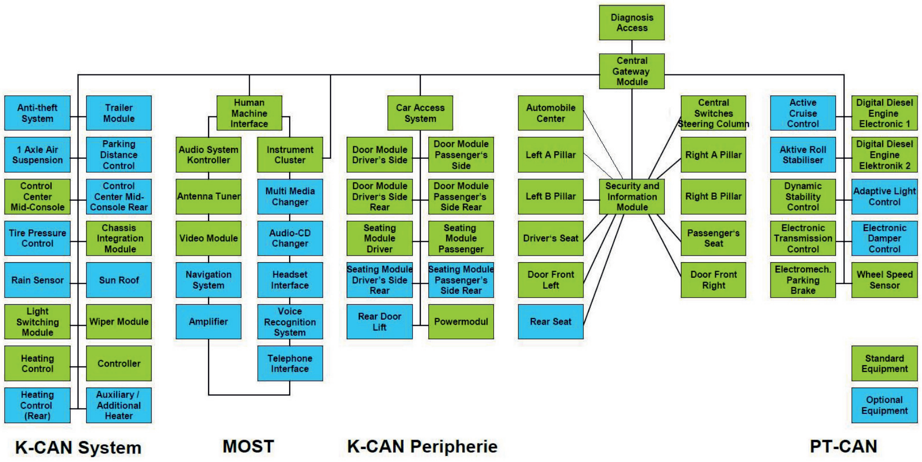


Fig. 1. Automotive network architecture [6]

demand. Several derivates of Ethernet exist that differ in connectors, cables, physical and medium access control layers. The automotive requirements for high bandwidth, low costs and good electromagnetic compatibility (EMC) can be met when the cable harness of Ethernet is realized with a 100 Mbit/s duplex unshielded derivate using a single twisted pair cable with adapted physical layer [1].

In this paper we provide the setup for analyzing the performance of a switched Ethernet based in-car network with different traffic classes and a general topology. This setup is used for simulation and interpretation of traffic characteristics where the IP traffic is modeled by using standard IP frames and packet sizes. The here-presented simulation using Ethernet without prioritization mechanisms shall motivate future work towards finally meeting automotive communication requirements.

The remainder of this paper is structured as follows: In section 2 we present performance studies with similar set-ups and the main differences compared to our work. Section 3 describes the setup by arguing for the modeling of Ethernet and a network topology, analyzing in-car traces of CAN and FlexRay for deriving a real-time communication model, and defining streaming and bulk data traffic models. Section 4 evaluates the performance of a switched Ethernet network without prioritization by simulation, presents the results, and reflects on the chosen setup. Section 5 concludes the paper as we define the tasks which have to be addressed on our research path.

2 Related Work

During the last years, researchers analyzed the applicability of a switched Ethernet network for automotive usage. Daoud et al. analyzed a switched Ethernet network based on 1000Base-T in a star topology without any QoS mechanisms for an in-car network, where two traffic classes were defined: control data and video streaming data [2]. The authors showed that service constraints are not violated, but they did not analyze the influence of other traffic classes (e.g. bulk data) towards the safety related control data. Furthermore, the authors modeled a gigabit Ethernet network. This is evidently a solution to easily address future bandwidth demand, but not a near-term option due to costs. We consider the usage of 100 Mbit/s Ethernet as a precondition.

A switched Ethernet network could have different topologies, e.g. star, double-star, daisy chain or combinations of different topologies. The effects of different topologies considering several automotive applications were analyzed by Rahmani et al. [3] [4]. The authors gave evidence that a ring based topology provides better performance than a double-star based topology concerning the need for traffic shaping mechanisms for variable bit rate (VBR) data traffics to avoid large bursts and packet losses. However, the proposed ring based topology is configured as a unidirectional ring only. Each connected device and switch has to be modified which objects our precondition to only use standard-conform components.

3 Performance Study Setup

In this section, we describe the setup for our ongoing research on analyzing Ethernet performance. The first part argues for the modeled Ethernet derivate and for not using prioritization mechanisms in the first step. Afterwards, the usage of a double-star topology is motivated and described. The network load has a strong influence on the service behavior, thus we consider different traffic classes for the simulation.

3.1 Usage of Ethernet

Our model uses Ethernet based on the 100Base-TX standard. In today's cars, 100Base-TX Ethernet as a point-to-point connector is used as isolated application for On-Bord Diagnostics (OBD) / Diagnostics over IP (DoIP) [5] where flashing time and available bandwidth are important factors to minimize time at the repair shop. The second use case is transmitting bandwidth-intensive map information for navigation applications.

In case of more than two nodes in a network, switched Ethernet is required as next expansion stage. The prospected Ethernet derivate for in-car communication over a single twisted pair cable with adapted physical layer does not differ from the 100Base-TX from the simulation point of view, as data rate and Medium Access Control (MAC) remain the same. A gigabit Ethernet is not a near-term option, because it is not sufficiently electromagnetic compatible, hardware is expensive, and most ECUs could not handle data at such high rates.

In a switched Ethernet network, the network has to be carefully dimensioned in order to support real-time applications with high service constraints. The standard though does not enforce Quality of Service (QoS) mechanisms that would deal with packet delays and packet loss at switches. Prioritization needs configuration of end devices and/or switches: The currently built-in Ethernet for Diagnostics over IP and Media-Oriented Bulk Traffic do not implement prioritization for simplicity reasons. Also QoS configuration strategies for switches and end devices are still an unsolved issue. For these reasons we want to analyze the applicability of off-the-shelf Ethernet technology by considering different traffic classes used in a vehicle.

3.2 Topology

The trend towards integration of functionality from several small ECUs onto one combined, powerful device will generate the need for more communication bandwidth. This integration can be motivated by functional similarity, spatial proximity or other means. To prepare the migration, general concepts are needed that will later-on be adopted to a certain migration scenario. The topology in a switched Ethernet in-car network directly influences the service properties. While the future network topology is not foreseeable, the double-star topology we assume for our simulations is suitable for our analysis. Looking at the geometrical arrangement of ECUs in a vehicle, most of them are located either at the front or at the rear, as there is only little installation space inside or under the passenger cabin. Therefore they can easily be mapped to a double-star topology with a front and a rear switch (see Fig. 2). Future detailed consideration may lead to a multi-star topology which we see as a variant only. Star-based topologies lead to a less complicated cable harness compared to e.g. daisy chain topologies, especially if some of the nodes are optional. Furthermore star-based topologies are confirmed with the IEEE 802.3 and IEEE 802.1 Ethernet standards, so that no modifications on the MAC layer are required. In our system model there is

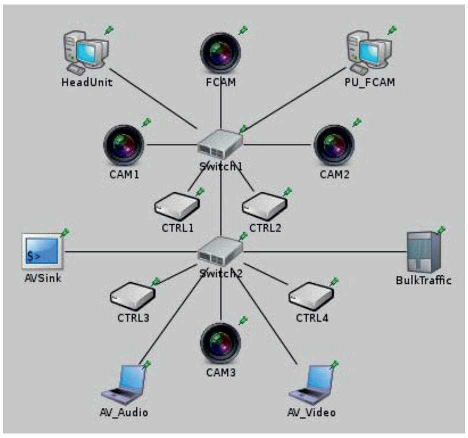


Fig. 2. Reference simulation topology

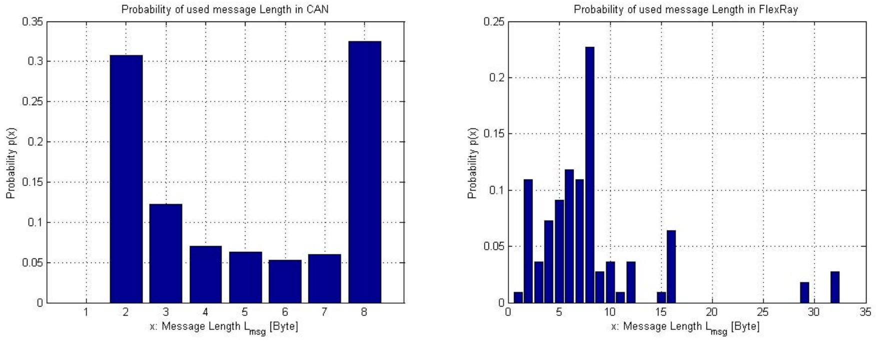
a processing unit (Head Unit) connected to the front switch which operates as the sink of control data, camera data and bulk data. There are two side-cameras and one rear-camera which generate and transmit the driver assistance related video data to the Head Unit. The Head Unit calculates a bird's eye view from these three video streams. Another camera generates video streaming data for the front view system terminated at a dedicated processing unit ('PU_FCAM'). In the rear part the 'AVSink' represents a rear seat entertainment (RSE) system. Audio and video streaming data from end nodes located in the rear part of the network are transmitted to the RSE. The 'BulkTraffic' node represents open connections to the internet which transmit bulk data to the Head Unit.

3.3 Traffic Characteristics

The simulation scenario contains four different traffic types: control data, driver assistance camera streaming, video and audio streaming, and bulk traffic data. First, an analysis of CAN and FlexRay serves as reference for the modeling of the control data traffic type. Afterwards the other traffic types are discussed.

Control Message Traffic Type - CAN and FlexRay Real-Time Communication. The analysis of real data traffic gives evidence on traffic characteristics of a current in-car network with focus to real-time control communication. Therefore the analysis concentrates on the CAN- and FlexRay bus systems. We used CAN and FlexRay message traces derived from a BMW car.

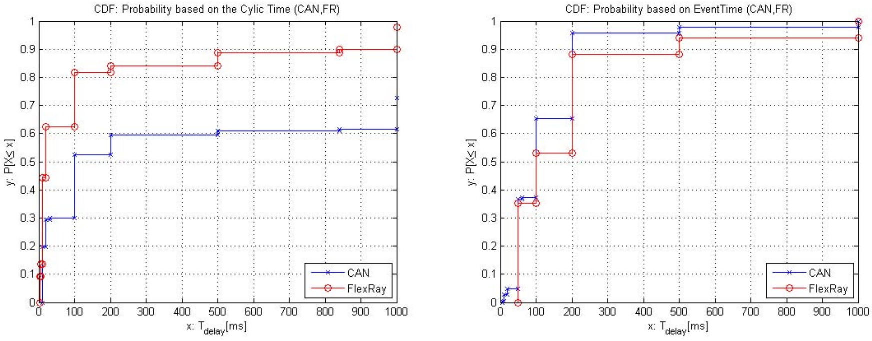
Packet size. CAN has a maximum message size of 8 byte while FlexRay is able to transmit data with a maximum payload size of 254 byte. The results give an indicator for the traffic characteristics of control and regulation messages in a current automotive network. Figure 3(a) and figure 3(b) show the distribution of CAN and Flexray payload sizes as used for the probability density functions (PDFs).



(a) CAN (b) FlexRay

Fig. 3. PDF of data length based on CAN and FlexRay

Cycle Times. The cyclic messages on CAN have higher cycle times than those on FlexRay. ECUs which generate messages with high cycle times are likely on a CAN bus while messages with low cycle times are likely on FlexRay. The cycle times are less than 100ms for more than 80% of the transmitted FlexRay messages and approximately 52% of the CAN messages (see Fig. 4(a)). The situation is quite similar in case of event-based messages, while these are mostly sent on CAN (see Fig. 4(b)).



(a) CDF cyclic

(b) CDF event-based

Fig. 4. Cumulative Distribution Function (CDF) of cyclic and event-based messages in CAN and FlexRay

Following this analysis, we chose a service rate based on an uniform distribution from 10ms to 100ms with a UDP payload size of 20 bytes, which is a reasonable size, because it works for virtually all CAN and FlexRay messages - shorter UDP payloads would be padded to at least 18 byte anyway. The control data has the highest latency and service requirement. It is sent to the Head Unit.

More Traffic Types - Driver Assistance Streaming, Infotainment Streaming and Bulk Traffic. In a vehicle, different driver assistance cameras capture high quality video streaming data from the outside of a vehicle. The Head Unit aggregates the different video streams to derive environment information. We assume that the driver assistance camera data is based on MPEG2-TS video streaming data which has a bit rate of approximately 25Mbit/s [11]. This traffic type has the highest bandwidth and a medium end-to-end delay requirement. A single camera generates and transmits UDP frames with a service rate of 0.25ms. The infotainment streaming data is characterized by multimedia data, where a rear seat entertainment (RSE) is simulated. The RSE ('AVSink') node receives video and audio streaming data transported by UDP frames from the video and audio source nodes within a vehicle. The audio streaming data is based on a Stereo Audio CD with a sampling rate of 44.1khz while video streaming data is based on a DVD. Audio and video streaming data have a medium bandwidth and end-to-end delay requirement. The bulk data is modeled with assumed 15 TCP connections between the source node and the Head Unit, where the source node could, for instance, be an antenna module managing internet connections. Bulk traffic is transmitted using TCP's flow control mechanism to dynamically use the available bandwidth. Table 1 presents a detailed overview of the different kinds of traffic.

Table 1. Traffic characteristics of the simulation

Node Name	**UDP/TCP Packet Length [byte]**	**Service Rate [ms]**	**Bandwidth**	**Destination Node**
CTRL1 .. CTRL4	20	uniform(10, 100)	1.6Kbit/s - 16Kbit/s	Head Unit
CAM1 .. CAM3 [11]	786	0.25	25.1Mbit/s	Head Unit
FCAM [11]	786	0.25	25.1Mbit/s	PU_CAM
Audio	1472	8.4	1.4Mbit/s	AVSink
Video	1472	1	11.8Mbit/s	AVSink
Bulk Traffic	1400	uniform(1,10)	1.12Mbit/s - 11.2 Mbit/s	Head Unit

4 Simulation Results and Discussion

4.1 Methodology and Assumptions

The influence of the network load on the availability of application services is evaluated based on a simulation with reduced complexity. We set up the simulation by using certain assumptions and selecting a specific scenario. This specific scenario describes the in-car network situation where ECUs are placed at the front and at the rear of a vehicle, so that the double-star based topology is a first and logical approach to analyze the influence of typical automotive applications. In this work, we use the OMNet++ simulation tool with the INET framework which contains the required networking protocols IP, TCP, UDP and Ethernet [7]. Following assumptions were made for the simulation:

1. Switch processing time: 3μs [4].
2. MAC transmission Queue size (TXQueue length): 1000 packets.
3. Static IP-address configuration.
4. Ethernet Link Bandwidth: 100Mbit/s.

4.2 Metrics

The network load in a switched Ethernet network has a strong influence to the service behaviors in an in-car network. A packet delay or packet loss of control data would negatively influence driving stability and safety which is not tolerable. Packet delay and packet loss result from overloaded networks. We define the following metrics in order to evaluate the network, its load situation and the influence of different traffic characteristics.

- The **End-to-End Delay** is calculated by the time difference between the generated packet time at a source node and the receiving packet time in the application layer at the sink node.
- The **Inter-Arrival Times (IATs)** are determined by measuring the arrival time of two subsequent data frames at the sink. It is used to see how the network load influences the packet arrival time at the sink node. Furthermore it indicates a packet loss at the sink node.

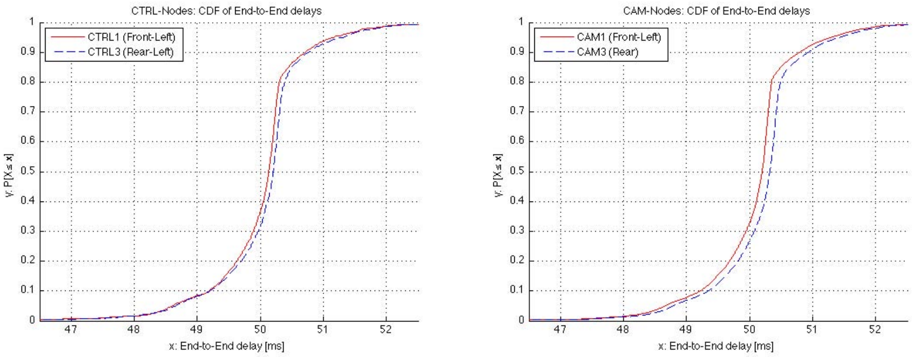
Service Constraints. The service constraints are used in order to evaluate the switched Ethernet in-car network and to verify if the services fulfill the requirements in terms of end-to-end delays. For safety-relevant control systems (e.g. engine control system, dynamic stability control), the maximum end-to-end delay is 10ms. This value is currently used for a typical hard real-time communication in a vehicle [3]. The data transmitted by a driver assistance camera must have an end-to-end delay of 45ms [3]. In case of multimedia audio and video streaming data the latency should be less than 150ms [13]. The service constraints of different traffic types are listed in Table 2. In addition to the end-to-end delays, the IATs are compared with the service rate of each traffic class to determine the load situation on the network.

Table 2. Service constraints

Traffic Number	**Traffic Type**	**Max. End-to-End Delay [ms]**
1	Control Data	$\leq$ 10 [3]
2	Driver Assistance Camera Data	$\leq$ 45 [3]
3	Multimedia Audio Data	$\leq$ 150 [13]
4	Multimedia Video Data	$\leq$ 150 [13]

4.3 Results

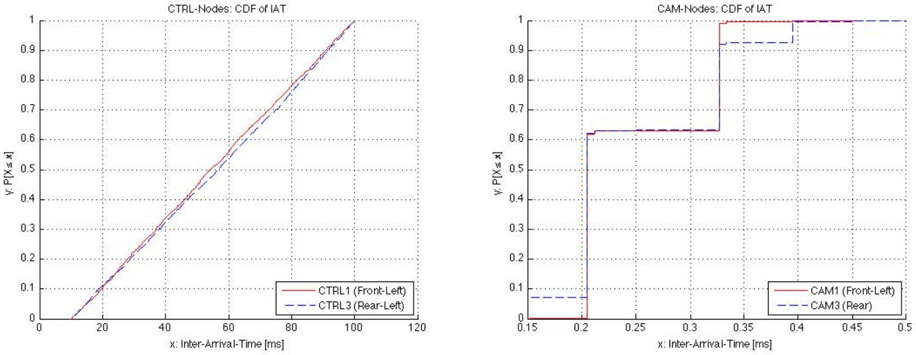
End-to-End Delay. The cumulative distribution function (CDF) of the end-to-end delay by transmitting control data to the Head Unit (HU) is represented in figure 5(a) while figure 5(b) shows the CDF for camera data transmitted to the HU. In both cases, we can observe that the end-to-end delays decrease, if the number of intermediate switches along the transmission path is low. This result is expected, because the end-to-end delay increases with each intermediate switch in the entire path from the source node to the sink node. The end-to-end



(a) Control Data (b) Camera Data

Fig. 5. CDF of End-to-End delays on the HU

delay of camera data and control data have quite similar characteristics where the CDFs vary between 47 ms to 53 ms. For both cases, the service constraints are not fulfilled and the QoS constraints of the applications are violated.



(a) Control Data (b) Camera Data

Fig. 6. CDF of IAT on the HU

Inter-Arrival Time (IAT). The service rate of the control nodes is uniformly distributed over 10ms to 100ms and we would expect that the CDF of inter-arrival times reach a probability of 1 for a value of 100ms. Figure 6(a) indicates that all control data packets are transmitted to the Head Unit so that no packet loss is occurred. In case of camera data, the situation is quite different. The camera data which are sent with a service rate of 0.25ms have an IAT of approximately 0.5ms in a worst case (see Fig. 6(b)). This would mean that half of the transmitted data have a packet loss. Furthermore we can observe that IAT of the front CAM node (CAM1) is lower than of the rear node (CAM3). This is due to the intermediate switch ('Switch2') which has to be passed for packets generated by the rear end node.

4.4 Summary

The simulation based on a double-star topology gives evidence that the service constraints of typical automotive applications are not fulfilled. The end-to-end delay of control data is five times higher than allowed. The inter-arrival time of camera data gives further evidence for an overloaded network where service constraints of driver assistance cameras are violated.

5 Conclusion and Future Work

A switched Ethernet network without any prioritization mechanisms cannot guarantee the service requirements of the presented IP-based in-car communication scenario with a double star topology and several traffic types relevant to future in-car communication. In order to avoid violation of the highest service constraints, services must be classified and prioritized. Our research continues evaluating two different QoS mechanisms to do so: Characterizing traffic classes after IEEE 802.1Q and IEEE 802.1 Audio Video Bridging (AVB).

The IEEE 802.1Q standard defines VLAN tagging within the Ethernet header which provides a prioritization on Layer 2 and a scheduler in a switch to treat different types of packets. Four priority queues per output port per switch are configured for the next analysis: Control Data for Hard Real-Time traffic, Driver Assistance Camera Data for Soft Real-Time traffic, Multimedia Video/Audio Data for MM Streaming traffic, and Bulk data.

The second QoS mechanism for supporting QoS on Layer 2 is the IEEE 802.1 Audio Video Bridging (AVB) draft standard [9]. It specifies a latency less than 2ms over 7 hops for synchronized time sensitive streams [8]. We will look at the following mechanisms of AVB:

- IEEE 802.1AS [10]: Time synchronization of distributed Ethernet nodes
- IEEE 802.1Qat [11]: Stream reservation protocol for AVB streaming data
- IEEE 802.1Qav [12]: Scheduling, Queuing and Forwarding rules on switches

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