Real-time Ethernet for Automotive Applications: A Solution for Future In-Car Networks

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Abstract—**Data networks of today's automobiles form a complex conglomerate of heterogeneously interconnected components. At the same time, high additional demands for future in-car communication systems are emerging from chassis control, camera based driver assistance and infotainment that cannot be accommodated by established technologies. A new approach towards a flexible highly scalable in-car network is real-time Ethernet.**

In this paper we discuss the upcoming requirements and argue why current in-car network designs are not suitable for future tasks. By demonstrating how a camera based time-critical driver assistance application can be integrated into a real-time Ethernet based in-car network, we present a typical use case for automotive broadband real-time communication and show application related design and configuration decisions.

I. INTRODUCTION

The innovation in automotive development is more and more driven by the progress of electronic components. Systems like driver assistance, info- and entertainment have already today a significant proportion of the cars value, especially in terms of development costs. From a computer science point of view, a car is a complex distributed real-time system with up to 60 microcontroller based electronic control units (ECUs) that communicate via approximately 2500 different signals with each other [1]. With the increasing number of electronic components, the demand for broadband high speed communication infrastructures grows. A trend that will hold on in the next years.

To satisfy the upcoming requirements, new in-car network architectures apply a centralised *backbone network* that connects the distributed control units. Such a centralised vehicle-backbone must provide a guaranteed deterministic message transport even under heavy load.

The new image recognition based diver assistance systems and high speed control loops of the chassis control drive the development of new data communication technologies in the automotive-domain. Currently, the communication technologies used are as heterogeneous as the applications that communicate over the in-car network. Different application domains use special bus systems. Examples are the Controller Area Network (CAN) [2] for the event-triggered communication of ECUs, FlexRay [3] for the ambitious control loops in chassis control or the Media Oriented Systems Transport (MOST) [4] for info- and entertainment. Gateways are required for communication between applications of domains that use different communication technologies. Such gateways act as translators that map messages between the different systems. This heterogeneous structure makes the in-car communication network complex and especially increase the price of development. Desirable is a technology that adapts the different aspects of the currently used systems like event-triggered and time-triggered communication or different levels of real-time requirements on a uniquely shared physical layer.

A new approach for an in-car communication backbone is the usage of switched Ethernet as communication infrastructure. Ethernet is a very flexible and scalable protocol, but it does not offer the required temporal characteristics which are necessary for the real-time communication of automotive applications. Real-time extensions for standard switched Ethernet promise reliable and deterministic transmission. In process automation real-time Ethernet technologies like the EtherCAT [5] or Profinet [6] protocol are well known.

Time-triggered Ethernet (TTEthernet) [7] is a real-time Ethernet extension that tries to satisfy the special demands of the airplane and automobile industry by combining concepts of different protocols like the time-triggered concept in FlexRay [3] or the rate-constrained traffic in the Avionics Full Duplex Switched Ethernet (AFDX) [8]. It offers three different traffic classes, each with special temporal characteristics. A failsafe synchronisation protocol distributes a globally valid time. All participants operate on a shared and predefined schedule that prevents collisions on outgoing linecards. This cooperative time-division-multiple-access (TDMA) approach extends the standard switched Ethernet protocol with the ability of transferring messages with hard real-time constraints.

This paper motivates the usage of real-time Ethernet for a future in-car backbone. It contributes design concepts and shows consequences of design decisions based on a typical in-car broadband real-time application.

The remainder of this paper is organised as follows. In section II the base techniques of current in-car networks and the TTEthernet protocol are introduced, the future challenges are demonstrated and related work and projects are shown. Section III outlines design concepts for future Ethernet-based in-car networks. In section IV the consequences of design decision in real-time Ethernet based networks is shown based on a typical broadband in-car application. Finally section V concludes and gives an outlook on further research.

II. FUTURE DIRECTIONS IN IN-CAR NETWORKING & RELATED WORK

A. *Challenges of In-Car Networking*

The biggest challenges for the design of future in-car communication architectures are the demand of massive scalability and the reduction of complexity. Today the network in cars is particularly heterogeneous. Different technologies are used, each for communication between a domain specific subset of ECUs. Communication beyond the edge of a domain specific group is realised through central or multiple decentral gateways. Although each subsystem is optimised for its specific field of application, the heterogeneity and the increasing need for communication beyond domain specific boundaries enhance development costs and system complexity [9].

Future technologies will have different requirements concerning bandwidth and timing. Applications like control loops in the chassis control need low communication bandwidth but have tight temporal requirements in the microsecond range with cycle times in the unary millisecond range. On the other hand, camera based driver assistance systems lead to bandwidth requirements in the range over 100 Mbit/s.

In addition, future systems will offer non safety critical applications like video applications, Internet support and music on demand, which require high communication bandwidth with moderate timing constrains. Many driver assistance systems require communication across subsystem boundaries. This kind of inter subsystem communication requires a safe, well structured and efficient communication structure like a backbone network.

Future communication systems of cars must handle a wide range of traffic diversity concerning timing and bandwidth requirements in combination with efficient scalability (see figure 1).

B. *Time-triggered Ethernet*

TTEthernet is a possible candidate for future in-car backbones. It is a time-triggered real-time Ethernet extension that satisfies the special needs of automotive and avionic applications. It allows standard best-effort communication and hard real-time network traffic to share the same layer 2 infrastructure. The TTEthernet specification [7] was developed by TTTech and is currently proposed for standardisation by the Society of Automotive Engineers [10].

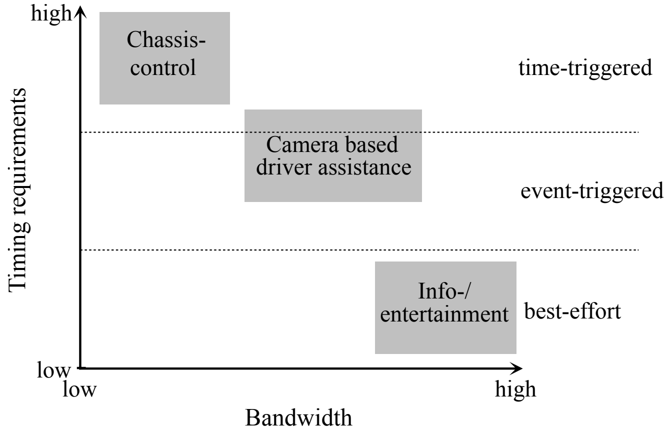

Fig. 1. Timing and bandwidth requirements of typical future in-car applications

Time-triggered Ethernet is a synchronised protocol extension based on standard switched Ethernet that is centered around periodic cycles. For real-time communication, each node is assigned to timeslots in an offline calculated schedule. This coordinated TDMA based access policy ensures predictable transmission delays without queuing, and therefore low latency and jitter. To allow each node to access its dedicated transmission slot, all components have their own globally synchronised local clock and transmission schedule. Since a global synchronised time across all participants is needed, the TTEthernet specification defines a fail-safe synchronisation protocol. Preliminary work shows that the time-triggered messages of TTEthernet are comparable to the static slots of FlexRay and share similar temporal attributes [11].

Besides the *time-triggered* traffic, TTEthernet defines two other traffic classes. *Rate-constrained* traffic adds support for real-time event-triggered communication. It is based on the AFDX-Protocol [8] and intended for communication with less rigid temporal requirements. *Best-effort* traffic is intended for traffic without hard real-time constraints and has the lowest priority. The messages are based on standard Ethernet frames. Therefore TTEther-Networks are capable of working with hosts that are unaware of the time-triggered protocol and thus remain unsynchronised. Those hosts only communicate by best-effort traffic.

C. *Related Work*

Multiple research projects on new communication infrastructures for cars exist. In 2007 BMW showed a technical demonstration of a IP-based car prototype [12]. Together with the Technische Universität München the CAR@TUM project was founded. Publications about switch based communication architectures show the benefits of an Ethernet-based communication backbone. In [13] and [14] a prototype for an Ethernet based switch for in-car application is shown. In contrast to the time-triggered architecture presented in this paper, the concepts used are based on standard Ethernet and use event-triggered strategies comparable to the AFDX-Protocol [8]. In [15] scheduling concepts for the coexistence of time-triggered and event-triggered traffic are shown. A genetic search algorithm for topologies in switched in-car networks is shown in [16]. By defining metrics like cabling effort, expected costs or energy consumption the quality of a topology is rated.

The SEIS project [17] is working on a universal and secure middleware concept for in-car communication based on the Internet protocol (IP). In [18] an analysis for the real-time capability of Ethernet is shown.

In process automatisation the deployment and evaluation is already further advanced. Although the requirements and assumptions differ in this application domain, performance evaluation concepts [19] can be adopted to in-car networks.

III. DESIGN CONCEPTS AND CONSTRAINTS FOR FUTURE ETHERNET-BASED IN-CAR NETWORKS

Future designs of In-Car networks are expected to meet the objectives of high scalability in bandwidths and the number of active controllers, and at the same time of reducing complexity in passive and active components. The most promising way to fulfill these requirements is by a hierarchical network structure that relies on a scalable multi-service multi-protocol backbone. Switched real-time Ethernet currently is the hottest candidate for a future backbone technology. TTEthernet in particular supports such a new design paradigm by providing a single, domain overlapping communication infrastructure that can carry the three different traffic classes, time-triggered, rate-constrained and best-effort.

TTEthernet conforms to the 802.3 Ethernet standard [7] and allows for the simple integration of clients without real-time extension. Those clients remain unsynchronised and communicate via best-effort messages. This compatibility supports the use of off-the-shelf components e.g., for consumer applications where the Ethernet standard is already widely deployed. Thus a car network design with a TTEthernet-based backbone can profit from re-utilising well deployed protocols on top of the layer 2 infrastructure. In particular, the IP protocol family contributes advanced communication for info- and entertainment that seamlessly connects to an Ethernet-type backbone.

There are several noteworthy aspects when designing an Ethernet car backbone. While it is conceptually clear that regional control units and gateways for networked subsystems will connect to the backbone, the design space remains large.

A. Scheduling and Traffic Planning

Even though TTEthernet shares concepts with established automotive technologies like the slot concept of FlexRay, there is an important difference for the traffic planing. A bus system that attains a single physical collision domain for all participants requires one schedule to be shared among all end systems. TTEthernet is based on switching and splits the collision domain of the entire network into small congestion domains at the outgoing linecards of each link. Besides the higher bandwidth on the physical layer, this is the reason why it is possible to transfer more data simultaneously. The schedules must be designed for each link separately, while the resulting overall timing must be continuously verified [20]. It is desirable to hide as many messages with individual schedule from the backbone as possible and keep these local to subsystems.

On the contrary, the advantage of scalable point-to-point connections is its variable transmission speed. While connections in the network core can be run with high transmission speed of 1 or even 10 Gbit per second, peripheral units can be connected depending on their actual bandwidth demands with lower transmission speeds.

In addition, TTEthernet inherits the minimum payload size of 46 Byte from the 802.3 standard. Thus minimal packets are larger those of today's automotive technologies. Especially for gateways between those technologies and TTEthernet, a deliberate aggregation strategy that joins messages for the same domain in one message can prevent bandwidth wastage because of message padding.

B. Backbone Topology

Typically, the physical structure of an in-car network is characterised by two classes of network elements. The first class are local control unit clusters that handle most of the communication within a limited range. These local clusters are connected with each other to allow for inter domain communication. The second class are widely distributed control units of the same application domain that need to communicate with each other.

An in-car backbone may be designed as a collapsed or a fully distributed network, or may admit any level of hybrid architecture. A collapsed TTEthernet backbone relies on the star topology. Although there are already automotive technologies that offer support for star topologies like FlexRay, this wiring concept is relatively new in the automotive industry. First results of switch based automotive network planning promise a possible reduction of cabling effort mainly because of the usage of a unified physical infrastructure [16], which is particularly promising in a distributed approach.

This concept could be realised in a hierarchical switch structure that uses a tree or snowflake topology. Such topology allows to transfer the traffic of clusters through the switches at the edges of the network, and only relays part of the traffic through the core backbone. However, such a multi-component distribution system raises issues of error resilience and redundancy.

C. Fault Tolerance

A switched system is more tolerant against faults than a wired bus. While in bus-structures only one faulty participant is able to break the communication on the whole system, the fault propagation in switched technologies is by design limited to the link between the faulty node and its neighbor switch.

Although redundancy of in-car communication networks is currently not used since all safety relevant systems like steering or breaking have mechanical fallback systems. Future x-by-wire applications will demand stricter security levels. In avionics systems such as AFDX redundancy is already implemented. For in-car applications redundancy must be implemented cost efficiently. The redundancy concept must scale with the necessary safety level. A real-time Ethernet based in-car backbone must support redundant links between components and redundancy over complete parts of the network. Safety critical end systems are then connected with redundant ports. During network design the impact of failure of each component must be regarded and where appropriate redundancy must be included. Lightweight redundancy can be achieved for example by a ring topology. In contrast to standard Ethernet, ring topologies are allowed for critical traffic because of the static routing of time-triggered or rate-constrained messages.

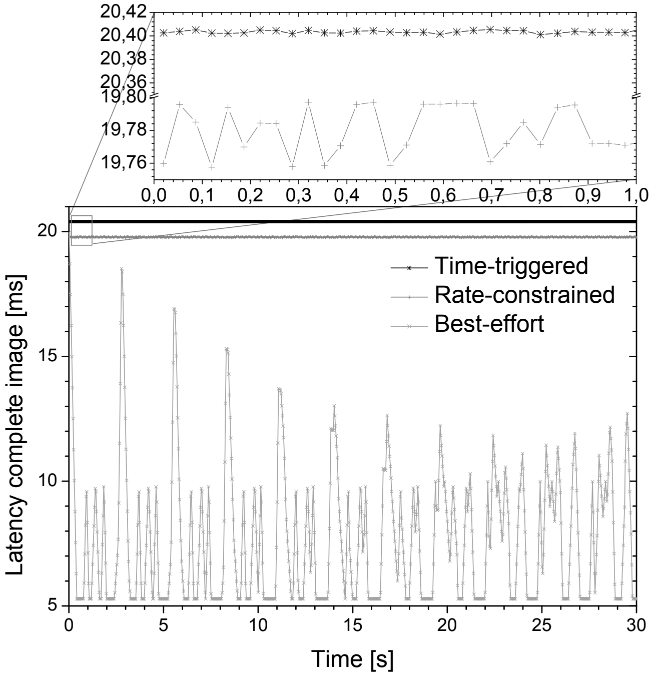

Fig. 2. Latency for the image transmission with different traffic classes

IV. IN-CAR NETWORK DESIGN USE-CASE

This section shows the consequences of design decisions based on a typical broadband real-time application.

A. Camera based vehicle-environment detection

Active driver assistance systems, that include the current vehicle-environment in decisions, become more important to further reduce the amount of road casualty. In current upper class vehicles there are already four or more cameras used in conjunction with other sensors to detect the vehicle environment. Special ECUs use the sensor data to build a virtual image of the surrounding area. Today, proprietary protocols based on Low Voltage Differential Signaling (LVDS) are used over point-to point connections to transport the huge amount of data from the camera to the image processing unit. Because of the huge cost saving potential when replacing LVDS links first Ethernet based solutions are expected for rear-view cameras soon.

B. Use-Case Scenario & Application Requirements

For the evaluation of the camera based vehicle-environment detection we considered a scenario with four cameras. After capturing, the image data is relayed to one or more ECUs that are responsible for image processing and feature extraction. Currently the image resolution of the cameras used is in VGA range (640x480 pixels) and will soon exceed the megapixel class. The required refresh rate (cycle time) is 30 pictures per second. The allowed latency is one picture (≈33.3 ms) and the maximum acceptable jitter is 10 % of the cycle time (≈3.3 ms). The application requirements were provided by the Ingenieurgesellschaft Auto und Verkehr (IAV GmbH) and are based on current automobile designs. We calculated a future bandwidth demand of ≈150 MBit/s for each camera.

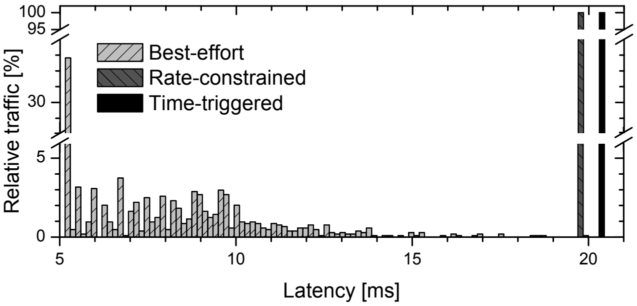

Fig. 3. Latency distribution for the image transmission with different traffic classes

C. Network Design, Configuration & Scheduling

We did experiments with different abstract topologies that used between one and three switching hops between sending and receiving end systems and evaluated all three traffic classes of TTEthernet for this scenario. For time-triggered communication, a schedule with precise action times for each frame at each relaying unit must be created. In contrast the configuration of rate-constraint traffic does not require this detail since it does not operate scheduled. Best-effort traffic does not require any configuration, a drawback of best-effort traffic arises for the capturing of images that cannot be synchronised on all cameras.

Due to the completely scheduled time-triggered transmission, it is possible to transfer the pictures of different cameras that were captured at the same time serial, or parallel with frames of different cameras alternating. An alternating schedule, where all pictures are transferred in parallel is optimal for a parallel image processing chain. For a sequential image processing unit a configuration where the images are transferred serial is the better decision.

A potential advantage of an Ethernet based solution – compared to a LVDS based point-to-point connection – is the possibility to send the different image streams to multiple receivers. This way tasks may be shared among multiple ECUs or the same stream may be used for different applications at the same time.

D. Evaluation Results & Discussion

The following results (table I) were recorded in simulation [21]. To show the effects of different design decisions, we simulated worst case scenarios for different configurations. The recorded transfer time starts with the transmission of the first frame at the camera and ends with the complete reception of the last frame at the ECU.

The best results in terms of real-time behaviour were achieved using time-triggered traffic. Because of the fully deterministic media access, a transmission with fixed temporal bounds could be achieved. Additional switching hops do not have a significant impact on the timing. Each hop must be calculated with an additional 25 µs for message forwarding. When using rate-constrained messages the jitter slightly increases because of the unsynchronised media access. The latency is shorter than with time-triggered messages due to the enlarged interframe gap – for inaccuracies in synchronisation – for

TABLE I
CAMERA BASED VEHICLE-ENVIRONMENT DETECTION – OVERVIEW OF SELECTED RESULTS WITH DIFFERENT DESIGN DECISIONS

Traffic class	**Configuration of transmission order**	**Switch-hops**	**Maximum latency, picture first camera**	**Maximum latency, picture last camera**	**Maximum jitter**
time-triggered	serial transmission	1	5.1 ms	20.4 ms	9.68 µs
time-triggered	serial transmission	3	5.2 ms	20.5 ms	10.04 µs
time-triggered	parallel transmission	1	20.0 ms	20.0 ms	36.98 µs
rate-constrained	parallel transmission	1	19.8 ms	19.8 ms	39.85 µs
best-effort	parallel transmission	1	20.0 ms	20.0 ms	14,671.16 µs
	Requirements		33.3 ms	33.3 ms	3,333.33 µs

time-triggered frames that is not necessary for rate-constrained traffic. The transmission with best-effort messages does not comply with the requirements of the application. Although the latency is low enough the jitter exceeds the temporal bounds.

Figure 2 shows the latency for the transmission of one picture with the different traffic classes of TTEthernet. The best-effort graph in figure 2 shows the interference that occurs due to the differences in clock speed of the different senders. The latency distribution (figure 3) shows the temporal undeterministic transmission when using best-effort traffic, while the real-time traffic classes offer a high precision.

The use-case shows that it is possible to meet the ambitious bandwidth and timing requirements of the camera based vehicle-environment detection, leaving capacity for further applications. The advantage of the Ethernet based solution in contrast to point-to-point connections using e.g. LVDS is the flexible topology with potentially less cabling and the possibility of distributing a videostream to multiple endsytems. It was shown that both real-time traffic classes of TTEthernet are suitable for the transmission. For the temporal requirements in this application the topology has small impact.

V. CONCLUSION & OUTLOOK

This paper pointed to major design challenges of future in car communication: high complexity in combination with a large amount of communication between subsystems, a wide range of traffic diversity concerning timing and bandwidth, and efficient scalability. We examined in-car communication designs based on real-time switched Ethernet systems, which support different traffic classes for event- and time-triggered communication. Central design decisions for this kind of backbone design have been discussed, the design space for a camera based driver assistance systems has been explored, and the measurements of different solutions using simulation tools have been taken. The results show that real-time Ethernet systems are adequate candidates to solve the upcoming challenges for future in-car communication structures.

To preserve the huge amount of research in current technology, a migration process of todays in-car communication structures – like CAN, MOST or FlexRay – to a real-time Ethernet based in-car backbone must be supported. Additional work of our group focuses on gateway designs and consolidation of current automotive technologies using real-time Ethernet backbones. Static scheduling algorithm and heuristics that take care for the event- and time-triggered traffic classes of TTEthernet must be reviewed for a successful integration of real-time Ethernet into in-car communication structures.

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