Next Generation Intra-Vehicle Backbone Network Architectures

(Invited Paper)

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***Abstract*—Increasing bandwidth requirements in vehicles are pushing the backbone architectures to use faster switching technologies like Ethernet. However, the traditional Ethernet cannot satisfy the strict latency requirements in a vehicle. As a solution, switched Ethernet variants like Time-Sensitive Networking (TSN) and Audio Video Bridging (AVB) are being standardized for automotive Ethernet. Moreover, it is expected that the intra-vehicle backbone architectures will shift to a zonal architecture for more centralizing the processing and decreasing the costs. In this paper, we present the recent trends, advances and challenges in intra-vehicle backbone networks. Moreover, we compare a TSN+AVB Ethernet backbone architecture with an alternative cut-through switching optical backbone network architecture by simulation and show that the cut-through switching optical architecture may achieve lower latency.**

***Index Terms*—Vehicle backbone, In-vehicle networks, Quality of service, Ethernet, Time-Sensitive Networking, Optical networks, Autonomous vehicles**

I. Introduction

Recent trends and advances in automotive systems have caused an explosive increase in the bandwidth requirements in vehicles. Due to the fierce competition in the automotive market, the manufacturers have been adding more and more services to sell the most advanced cars to take the lead in the competition. In the past the cars were merely a transportation device. However, the modern cars have become an entertainment and networking center with advanced functionalities. The consumers are expecting new features to buy new models of vehicles, so the manufacturers are striving to meet these expectations by developing new and exciting features continuously. Moreover, the mechanical parts of the cars that used to be controlled manually by the human drivers are being replaced with devices that are controlled automatically by computerized systems. For example, the automatic transmissions are now computer controlled. A computerized system determines when to shift and in what gear based on the information from the sensors. These new functionalities are being added to the vehicles by mounting embedded systems called electronic control unit (ECU). Today's cars carry as many as 150 ECUs [1]. As adding new ECUs increases the number of networking ports and the amount of data transferred inside the car, the burden on the backbone of the vehicles increase. Moreover, the introduction of faster wireless connection technologies like 5G networks to vehicles allow more interaction with the surrounding environment (V2X communication) and receiving better infotainment services in the car like watching high quality videos from online streaming services [2], [3]. Furthermore, the vehicles are becoming more and more autonomous [4]. The vehicle manufacturers are aiming completely self driving cars without any human intervention, which is very challenging. The increasing autonomy requires receiving more and more data with low latency and strict Quality of service (QoS) requirements from more sensors for a reliable operation. Therefore, the number and the resolution of sensors in a vehicle like video cameras, Lidar, sonar etc. have been increasing. The high resolution video traffic consumes a high amount of bandwidth, which can cause congestion in the backbone of the vehicles. Moreover, faster wireless connection technologies like 5G allows cars to exchange sensor and control information with each other and their environment for autonomous driving [4]–[6]. As a result, there is an explosive increase in the bandwidth requirements in vehicles.

The traditional intra-vehicle bus systems like CAN, Most, LIN etc. cannot satisfy with the high bandwidth requirements of many of the new services and features in intra-vehicle networks. Moreover, these bus systems are not expected to have a speed boost in the future. On the other hand, Ethernet technology has already reached a high speed of 100Gbps, and even faster variants are being standardized, so it is being shown as a candidate for the next generation intra-vehicle backbone networks. However, there are still many challenges in Ethernet like satisfying the QoS, resilience, cost requirements of future intra-vehicle networks. There is an active work on adapting and applying Time-Sensitive Networking (TSN) and Audio Video Bridging (AVB) [7] Ethernet standards to automotive networks for satisfying these requirements.

An other important aspect in the intra-vehicle networks is the network architecture. Even if a very high speed link layer technology is used, the network may not satisfy the latency requirements of intra-vehicle networks if the architecture is not adequate. Moreover, it is necessary to minimize the cost by optimizing the architecture. Recently, the industry has

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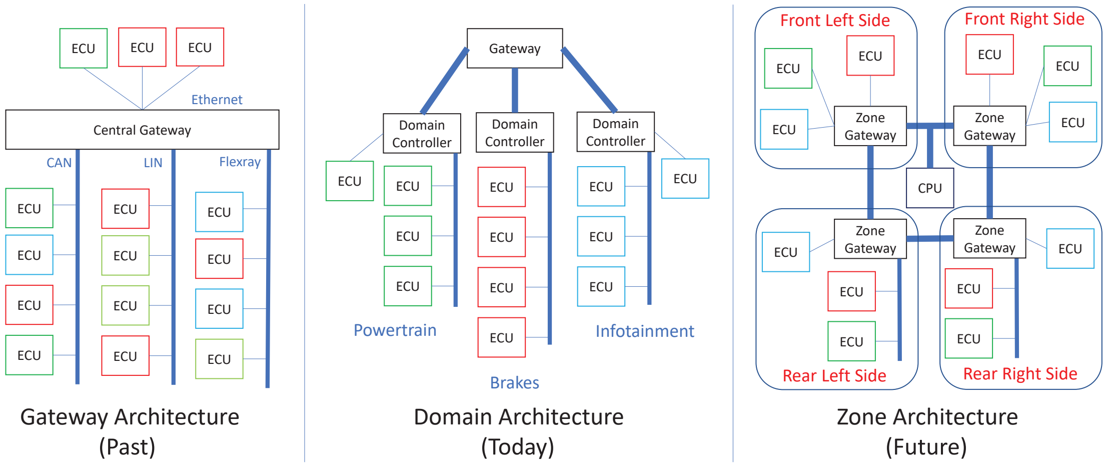

Fig. 1. The evolution of intra-vehicle architectures.

shifted from a gateway architecture, where few number of gateways are used for only data switching between ECUs, to a domain architecture, where related ECUs are connected to the same domain controller that controls the operation of ECUs to increase the efficiency and decrease the costs. In the future, the industry is planning to shift to a zonal architecture that groups and connects ECUs to zone gateways based on the spatial distance, which further decreases the costs by decreasing wiring and centralizing the processing. However, the zonal architectures will require high capacity intra-vehicle networks to carry the high amount of data transfer between the ECUs and the centralized processor.

In this paper, we investigate the backbone network architectures and technologies for intra-vehicle backbone networks. We present simulation results on a zone-based TSN+AVB Ethernet based architecture and an alternative zone-based optical ring-based architecture. We show that optical ring-based architecture with cut-through switching can achieve lower end-to-end delays than TSN+AVB Ethernet.

The remainder of this chapter is organized as follows. Section II introduces the recent technologies and trends in intra-vehicle network architectures, Section III describes the simulation scenario and presents the simulation results, Section IV describes the challenges and future works and concludes the paper.

II. Intra-vehicle Networking

A. Architectures

Traditionally, the vehicles use a gateway architecture, where ECUs with the same bus technology are grouped and connected to few number of gateways, which handles only the protocol translation and data switching data among different ECUs with different bus technologies as shown in Fig. 1. The gateways do not control the ECUs. However, with the increasing number of ECUs it becomes difficult to manage all ECUs by connecting all of them to a central gateway. Moreover, wiring all ECUs to a central gateway greatly increases the length of wires, which has a big impact on the weight of the car. Wires are the third heaviest element of a typical vehicle, after the engine and chassis [8]. Moreover, many ECUs have overlapping functionalities and sensors, which unnecessarily increases the cost.

Recently, the vehicle manufacturers are shifting to a domain-based architecture [9] as shown in Fig. 1. In this architecture, the related ECUs are connected to the same domain controller. The dedicated domain controller replace several functionalities in multiple ECUs. The processing and control functions move from individual ECUs to the domain controller, so it is no longer necessary to put a high speed processor to each ECU for processing. As the domain controller gives decisions by collecting information from multiple ECUs, overlapping functionalities and sensors in multiple ECUs can be avoided. As a result, the wiring, cost and complexity in a vehicle can greatly decrease.

A problem of domain based architecture is that some of the related ECUs may be far away from each other, so wiring to each of them from a domain controller may be costly. For example, the video cameras usually generate the highest amount of traffic in a car, but they are usually placed at the edges of the car, far away from each other to maximize the total field of view. A zone architecture, which is software-driven centralized processing architecture, is now being proposed as a solution by the automotive industry for future intra-vehicle networks [9]. In this architecture, different areas of a vehicle is divided into zonal areas and a zone gateway is assigned to each zone. Fig. 1 shows an example zone architecture with four zones. The ECUs are connected to the closest zone gateway based on the spatial distance. The zone gateway provides the network connectivity and power distribution to the nearby ECUs. Compared to domain based architecture where each domain gateway has a processing platform for a specific type of ECUs, the zone based architecture is being proposed to have few number of central processing units (CPU) for running and controlling the

ECU-specific features implemented in software. As a result, the processor redundancy and the related costs can be further decreased employing a zone based architecture. However, a fast intra-vehicle network becomes necessary to carry the data between the ECUs and the centralized processor.

B. TSN and AVB Ethernet

In the next generation intra-vehicle architecture, the zonal gateways and CPUs should be connected to the backbone via a high speed and low latency backbone network with QoS guarantees to exchange the data and the control information between the ECUs and the CPUs. Today, Ethernet standard has reached very high link speeds like 100Gbps, so it is being proposed as a strong candidate for the backbones of automotive networks. The original Ethernet was a best-effort datagram service with no guarantees with regards to delivery. Later it was extended by IEEE 802.1p (later 802.1Q [10]) standard in 1998 with some limited QoS capabilities. However, automotive networks carry critical devices like safety and driver assist functions with strict QoS requirements like ultra-low latency and packet drop that cannot be satisfied by traditional Ethernet. Moreover, to prevent accidents the network should guarantee a fast recovery in case of a failure. To satisfy these wide-range of requirements, automotive Ethernet is being extended and standardized based on the TSN and AVB Ethernet standards.

The AVB Ethernet standard was initially developed for audio/video applications by a task group in IEEE, which started in 2006. The AVB reserves a fraction of the available bandwidth to registered multimedia traffic. The AVB defines the two Stream Reservation classes (Class A and B) with a fixed upper bound for latency of 2 ms for Class A traffic and 50 ms for Class B traffic over a maximum of 7 hops, with a transmission period of 125μs for Class A and 250μs for Class B traffic. The AVB shapes the traffic by Credit Based Shaper (CBS) leaky buckets to prevent bursts and guarantee the QoS. The AVB makes sure that the total bitrate of reserved Class A and B flows is limited to maximum 75% of the bandwidth, so they do not overutilize the links. The AVB gives strict priority to registered multimedia flows over the best-effort traffic, so a congestion due to best-effort traffic do not penalize the multimedia flows. While AVB is enough for satisfying the QoS requirements of most multimedia traffic, it is not enough for satisfying the strict QoS requirements of some flows in autonomous self-driving intra-vehicle networks [11].

In 2012, the AVB Task Group was renamed to Time-Sensitive Networking Task Group for extending the AVB standards for time-sensitive transmission of data over deterministic Ethernet networks. The new standard, which is called TSN Ethernet, divides the transmission on the links to time slots based on time-division multiple access (TDMA) to separate high priority control packets from other traffic. The slots have a cycle (period) of 500μs. There are a maximum number of eight priority levels and each priority level has a dedicated queue for buffering and shaping the traffic. The TSN uses a Time-Aware Shaper (TAS) scheduling table that shows which queues can transmit in a time slot. As the TSN separates the high priority control packets and the other packets by TDMA, the control packets do not collide with other packets.

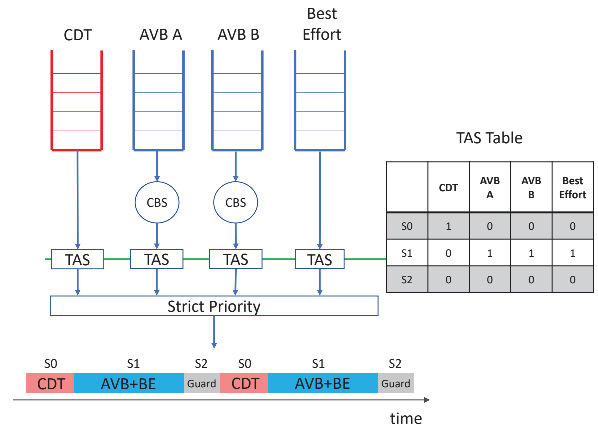

Fig. 2. The TSN and AVB Ethernet scheduling.

The TSN requires minimum three time slots in one cycle (period). An example configuration is shown in Fig. 2.

1) In the first time slot (CDT slot), only the control data traffic (CDT) can be sent to the link.
2) In the second time slot (AVB slot), the queues of lower priority traffic can send packets to the link. However, CDT packets cannot be sent to the link. There is a strict priority among these queues. AVB queues can send traffic only if they have enough credit, which is controlled by CBS.
3) In the third slot (guard-band slot), all the gates are closed before the transmission of control data traffic to prevent contention of control and other packets. The duration of this time slot is set to the transmission time of a maximum size frame.

In a TSN configuration, there may be multiple AVB and CDT slots with different lengths in the same cycle. Each switch and node may have a different scheduling table. In a mesh topology, calculating the optimum number of CDT and AVB slots and their lengths is an NP-hard problem. If CDT slot length is too short, the control packets may get blocked by TAS and not arrive their destination in a single period (500us), which can greatly increase the delay of CDT packets. If CDT slot is too long, AVB slot may not be long enough to carry the video and best effort traffic, which limits the efficiency of the network. There are many works in the literature [12], [13] on optimization of routing and scheduling parameters of TSN by using Integer Linear Programming (ILP) and heuristics.

C. Optical backbone network

In this paper, we investigate an alternative optical cut-through intra-vehicle backbone architecture composed of a single master node and multiple zonal gateway nodes. The architecture is called Si-based In-vehicle Photonic Network (SIPhoN). In SIPhoN, the nodes are connected by an unidirectional optical ring topology as in Fig. 3. The optical backbone

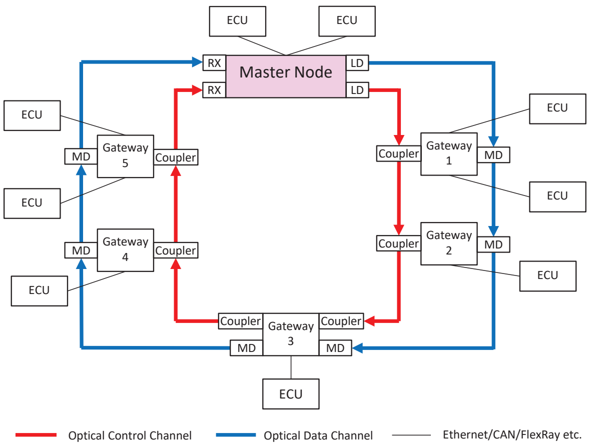

Fig. 3. The optical intra-vehicle backbone architecture.

links carry a single control channel for control packets and one or more data channels for data packets. The data channel is divided into fixed length time slots. Each slot is assigned to the transmission of data to or from a node in the backbone ring topology as in Fig. 4. The master node decides and controls the assignment of slots to the gateways. The master node informs the zonal gateway nodes about the assignment of a data slot by sending a control packet on the control channel before sending the associated data slot. There is a guard band between the data slots to account for the switching time. As cut-through switching is used in both control and data channels, the time difference between a control packet and its associated data slot is fixed to the length of the guard band throughout the path in the backbone.

There are three types of actions defined in control packets. They are

- Listen: The zonal gateway selected by the master node may listen (receive) data from the master node in the associated data slot.
- Talk: The zonal gateway selected by the master node may talk (send) data to the master node in the associated data slot.
- Idle: The associated data slot is unused (empty).

The control and data channels are carried in parallel on different fibers or wavelengths. Only the master node carries wavelength transmitter laser diodes (LD) for the control and data channel, which decreases the cost of the network. The data slots are generated by the master node. The gateways use modulation and detection optical circuits (MD) for reading and updating the information in the data channel. When an optical control packet arrives to a gateway node, the node gets a copy of the optical control packet via an optical coupler and processes the information in the control packet. If the corresponding data slot is assigned to a Listen or Talk operation in this gateway node, the node updates its switching configuration for forwarding the upcoming data slot to its modulation and detection optical circuit.

Fig. 4 shows an example of incoming and outgoing control packets and data slots in gateway 1. The left side of the gateway 1 shows the incoming control packets and data slots after they are generated in the master node, while the right side shows the output after processing in the gateway. The first control packet is a Talk packet for gateway 1, which means that the gateway 1 use the associated data slot for sending data packets from its ECUs to the master node. The gateway 1 configures the data channel switching fabric and injects data to the data slot through MD circuit and then forwards to its output backbone link. There is strict priority queuing that gives high priority to the packets of control flows and low priority to the other flows when sending the packets to the optical backbone. The second control packet is a Listen packet for gateway 1, which means that its associated data slot contains data for this gateway sent from the master node. Therefore, the gateway node forwards the data slot to itself and extracts the data packets in the slot by converting the optical signal to electronic domain by MD circuit and forwards the extracted data packets to the destination ECU. As the optical signal in the data slot is forwarded to MD circuit, the power of the optical signal in the data slot becomes very low in the output backbone link. The third control packet is a Talk packet for gateway 5. As the destination of the data slot is another gateway node, this node forwards the incoming data slot directly to its output backbone link without processing it. In case a gateway node wants to send data to another gateway node, the data is first sent to the master node and the master node forwards the data to the destination gateway node in the next cycle.

The ECUs can be connected to gateways by different communication bus standards like Ethernet, CAN, FlexRay etc. Therefore, the architecture can be implemented without changing the ECUs in the market. The granularity of the data channel can be further increased by using multiple data channels by using multiple wavelengths or fibers so that a data slot can carry multiple subframes destined to different gateways.

Optical fiber links have many advantages over traditional copper wires. Optical fibers are resistant against environment factors like electromagnetic waves and mechanical/chemical stress. They have been used in military and commercial avionics successfully for a long time, which has proven their reliability. As a result, Multi-Gigabit Automotive Optical PHYs (OMEGA) Study Group has been established to standardize high speed optical fiber links for Ethernet networks in intra-vehicle networks [14]. The OMEGA is expected to standardize optical links with a speed of 50Gbps or more to satisfy the high bandwidth requirements of zonal architecture, connected car, and autonomous car. OMEGA can allow establishing an optical Ethernet backbone network with a ring-based topology as in our architecture. However, one important difference is that the optical links in our architecture apply optical cut-through switching and processing in the gateways. The cut-through optical switching and processing can greatly decrease the transmission delays in the backbone. Moreover, SIPhoN greatly decreases the number of laser diodes in the network

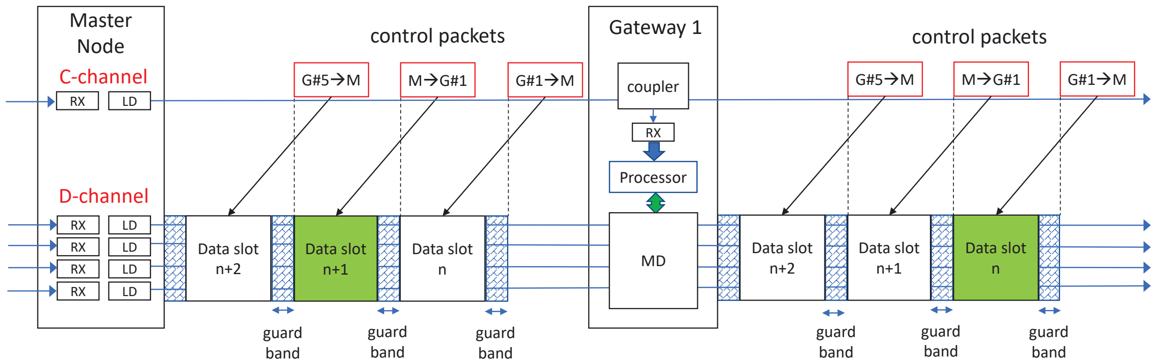

Fig. 4. An example of incoming and outgoing control packets and data slots in gateway 1.

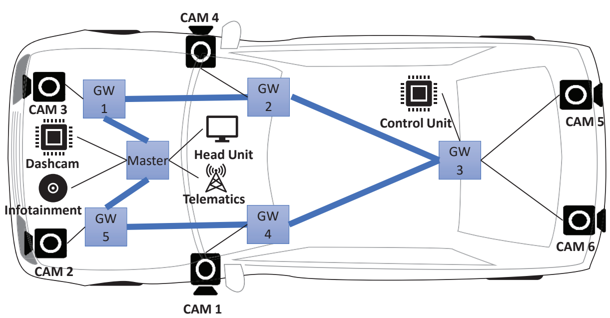

Fig. 5. Simulated intra-car network topology.

by generating the optical packets and slots only in the master node and applying cut-through switching in the gateway nodes. Laser diodes have a failure time of around 10^6 hours under typical conditions [15]. Using many laser diodes in a network increases the overall failure probability, so decreasing the number of laser diodes in the network by using cut-through switching can greatly decrease the failures and repair costs in the optical backbone.

III. Simulation

We simulated an intra-vehicle network as shown in Fig. 5 with traffic matrix inspired from [16]. The propagation delay between the links is 20ns. We simulated the TSN+AVB Ethernet scenario by using CoRE4INET simulator [17], then our architecture by a simulator that we implemented on OMNeT++ framework.

We simulated a traffic matrix with 13 flows (7 video flows, 2 background flows and 4 control flows). The flows are as follows:

1) Six video cameras send uncompressed 4K60p smooth video traffic (11.9 Gbps) to Dashcam.
2) The Dashcam sends uncompressed 4K60p smooth video traffic (11.9 Gbps) to Head Unit. As Dashcam and Head Unit are connected to the same GW, this traffic does not use the backbone so it does not affect the main simulation results.
3) Infotainment unit sends 10 Gbps background multimedia traffic to the Head Unit.
4) Telematics unit sends 2Mbps background information, such as GPS data, traffic alerts, maps, etc. to the Head Unit.
5) The Control unit sends warnings to the Dashcam. This control flow sends 46 Bytes data packets with a uniform distribution of 0.5ms.
6) The Dashcam unit sends warnings to the Control Unit. This control flow sends 46 Bytes data packets with a uniform distribution of 0.5ms.
7) The Head Unit sends real-time control messages to the Control Unit. This control flow sends 46 Bytes data packets with a uniform distribution of 0.5ms.
8) The Control Unit sends real-time control messages to the monitor of Head Unit. This control flow sends 46 Bytes data packets with a uniform distribution of 0.5ms.

The parameters of TSN+AVB Ethernet simulation are as follows. The nodes are connected in a ring topology by 100Gbps optical links. All links have transmitters/receivers at both ends that can lead to sever degradation of car's lifetime as the transmitters are active laser devices. All data packets except the packet of control flows have 1518 Bytes size. The gateway switches have 8μs Ethernet packet processing time, which is the default value in CoRE4INET simulator. There are three slots in one TSN cycle using the configuration explained in II-B. The length of the CDT time slot in the gateways is set to 35μs because the maximum end-to-end transmission, propagation and Ethernet processing delay is around 33μs in the network. This guarantees that a CDT packet sent at the beginning of CDT slot always in the same CDT slot without contending with AVB and guard-band slots on the path to the destination. The duration of the guard band time slot is set to around $1.2 * 10^{-7}$ seconds, which equals to the transmission time of a maximum-size frame of 1518 Bytes. The rest of 500μs TSN cycle time is assigned to AVB slot. The video

TABLE I
END-TO-END DELAYS (μS)

	Control		Video	
Backbone	Min	Max	Min	Max
TSN+AVB Ethernet	32	32	34	90
SIPhoN	1.1	4	3.5	12

flows are assigned to AVB A priority.

In case of our architecture, the optical backbone links carry a 100Gbps data channel and a 1.25 Gbps control channel. The links in the backbone are unidirectional and the transfer is in the clockwise direction. In the data channel we used a set of 7 slots as Listen, Talk GW1, Talk GW2, Talk GW3, Talk GW4, Talk GW5, Talk GW3 that repeats in cycles. The first Listen slot is used by the master node to send data to one of the gateways nodes in case there is a packet destined to one of ECUs connected to the gateways. The other Talk slots are used for transferring data from the indicated gateways to the master node. There are two video CAMs are connect to the gateway 3, so two slots are assigned to transfer data from this gateway, which effectively makes the assigned link capacity to this gateway twice the other gateways. We used a repeating cycle of slots in this example only for the sake of simplicity. Unlike TSN, the slots do not have to be repeating. There is a 100ns guard band size between the slots. As we are using a set of 7 repeating slots, each slot and its guard band is assigned around 100/7=14.28 Gbps link capacity. Four of the gateways send data of a CAM to the master node over a single slot in a cycle, so each slot should have enough size to support a minimum capacity of around 11.9 Gbps after the overhead of a 100ns (1250 Bytes) guard band per slot. As a result, the minimum optical slot size should 6375 Bytes. We chose 9000 Bytes as the slot size, because this value also allows carrying jumbo ethernet frames in the optical network without fragmentation. As the maximum slot size is 9000 Bytes, we also set the maximum video packet size to fully use the 9000 Bytes slot capacity in the simulation of our architecture.

In the simulation study, we evaluated the end-to-end delay of control and video data packets and compared the results of TSN+AVB Ethernet and SIPhoN. The overall simulation results are shown in Table I. Fig. 6 shows the end-to-end delay of control packets from Control Unit to Dashcam in TSN+AVB Ethernet. The x-axis is the arrival time of the packet to the destination in terms of seconds. The y-axis is the end-to-end delay of the packet in terms of μs. As the control packets are carried over a dedicated TDMA channel without contention with video flows, the delays of the control packets have a fixed value. The delay is around 32μs mainly due to 8μs Ethernet processing delay per hop.

Fig. 7 shows the end-to-end delay of control packets from the Control Unit to Dashcam in SIPhoN. The plotted simulation duration is longer than in Fig. 6 to show the delay distribution of packet more clearly. The minimum delay in the simulation result was around 1.1μs and maximum delay was around 4μs, which is around 8 times less delay than TSN+AVB Ethernet.

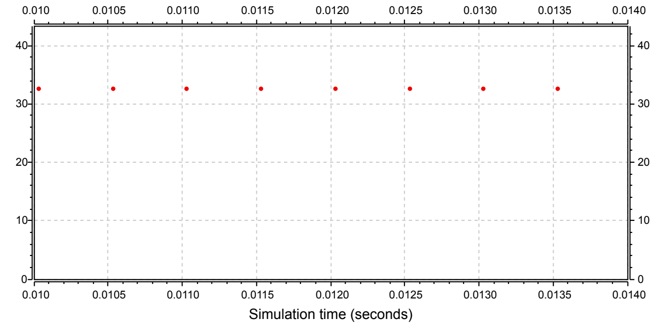

Fig. 6. Delay of control packets from Control Unit to Dashcam in TSN+AVB.

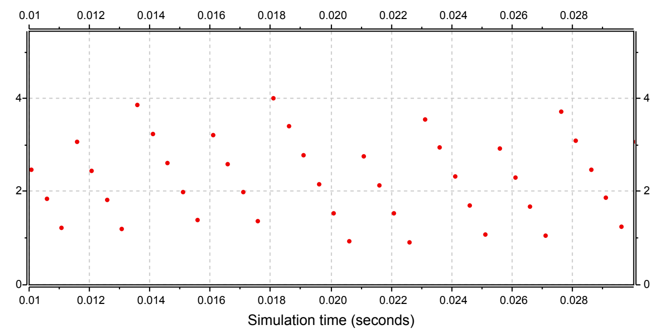

Fig. 7. Delay of control packets from Control Unit to Dashcam in SIPhoN.

Fig. 8 shows the end-to-end delay of video data packets from CAM 6 node to DASHCAM node in TSN+AVB Ethernet. 0.004s of simulation time is plotted to show the result of 8 TSN cycles, where each cycle is 500μs. The figure shows that the minimum end-to-end delay is around 34μs and maximum delay is around 90μs. The minimum delay of 34μs is mainly due to 8μs processing time of Ethernet switches and the packet queuing that occurs because of the rate control of AVB. The maximum delay of 90μs is mainly due to the build up of AVB queues when the video and best effort traffic are blocked by TAS while control packets are transferred in CDT slot by TDMA-based TSN Ethernet.

Fig. 9 shows the end-to-end delay of video data packets from CAM 6 node to DASHCAM node in SIPhoN. The minimum delay is around 3.5μs and maximum delay is around 12μs. Most of the delays are between 3.5μs and 6.8μs, which is mainly due to slot and packet transmission times and slot waiting time. The delays higher than 6.8μs occur when there is a contention with the packets of CAM 5 or the packets of control flow from Control Unit to Head Unit. The maximum delay video data packets was around 7 times less than the maximum delay in TSN+AVB Ethernet.

IV. CONCLUSION

There are many challenges in realizing the next generation intra-vehicle networks. The intra-vehicle networks are becoming increasingly complex with the deployment of new

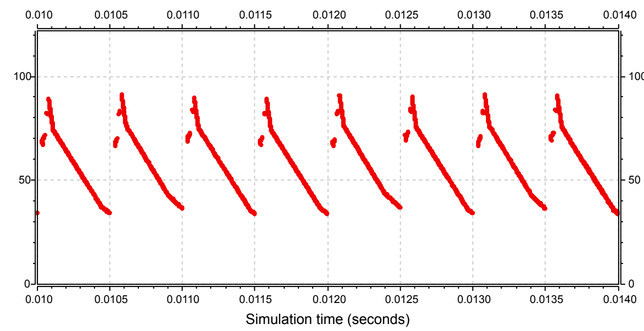

Fig. 8. Delay of video packets from CAM 6 to Dashcam in TSN+AVB.

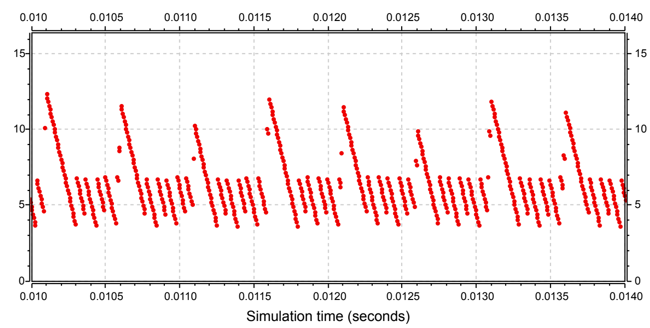

Fig. 9. Delay of video packets from CAM 6 to Dashcam in SIPhoN.

technologies and services. Moreover, satisfying the bandwidth and delay QoS requirements of new services like autonomous driving, ultra high resolution video etc. both in terms of hardware and software is still difficult. Moreover, the resilience against failure of devices like laser diodes, links, sensors, ECUs etc. in the intra-vehicle network has not been investigated in detail in the literature. Furthermore, there are many open research topics like optimizing the utilization efficiency and latency of the network by designing packet/slot scheduling algorithms for optical intra-vehicle networks.

In this paper, we investigated the future backbone network technologies like zonal gateway architecture and TSN+AVB Ethernet for intra-vehicle backbone networks. By a simulation study, we compared a zonal TSN+AVB Ethernet backbone architecture with an alternative zonal ring-based cut-through optical backbone network architecture called SIPhoN and showed that SIPhoN may achieve lower latency. SIPhoN has also some advantages in terms of cost and reliability, because cut-through switching decreases the number of laser diodes that have a limited lifetime.

As a future work, we will extend SIPhoN by carrying multiple frames to different destinations in parallel in the same slot by wavelength switching. We will work on scheduling algorithms for optimum distribution of subframes to wavelengths in slots to maximize the link efficiency. To maximize the resilience of the network, we will investigate the failure scenarios and try to estimate the requirements like maximum number of laser diodes that should be used in order to have a low failure rate. Moreover, we will work on protocols that will carry out the wake-up and initialization of the network and the ECUs so that the car becomes ready to drive in a short time after starting the engine.

Acknowledgment

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