Opportunities and Challenges of Optical Communications in Autonomous Driving Vehicles

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Abstract: Autonomous driving vehicles require high bandwidth due to the increased sensors and improved architectures. Optical communications provide several advantages over copper cables in intra-vehicle networks, but face many challenges, especially because of the harsh environment.

1. Introduction

In recent years, autonomous driving vehicles have attracted extensive attention from governments, academia and industry [1,2]. Traditional automobile factories, new electric car manufacturers, and leading Information Technology companies are all fully involved in the research and development of autonomous driving vehicles, hoping to participate in this huge market.

Autonomous driving requires a large number of sensors to perceive the surroundings, such as high-definition (HD) cameras, LIght Detection And Ranging (LIDAR), millimeter-wave RAdio Detection And Ranging (RADAR), etc [3]. The data generated by these sensors must be transmitted to the vehicle's processor with the lowest latency. Then the processor will instruct various actuators to make the vehicle respond quickly to the surrounding circumstance, so as to achieve safe driving with little or no human intervention. Currently, the sensing system of a Level-2 autonomous driving vehicle is equipped with 3 LIDARs, 6 millimeter-wave RADARs, 13 HD cameras, and 12 ultrasonic RADARs [4]. Future Level-4/5 autonomous vehicles will use more sensors with higher accuracy to improve the detection capability, and the data rate requirements for those sensors can be as high as 91Gbps, even without considering the communication overhead, as detailed in Table 1 [5-7].

Table 1 Data rate demands for autonomous driving vehicles

Sensor	**Qty.**	**Parameter**			**Net data rate / sensor**
		Pixel	Frame rate	Color	
Camera	5~14	2Mega	30fps	12bit	0.7Gbps
		4Mega	30fps	12bit	1.4Gbps
		8Mega	60fps	14bit	6.5Gbps
LIDAR	1~3	32 Lines [5]			15Mbps
		128 Lines [6]			48Mbps
MMW RADAR	5	76~77GHz [7]			400~600 kbps
Total sensor data rate	4Gbps (min numbers & lowest accuracy) to 91Gbps (max numbers & highest accuracy)				

2. Opportunities

The intra-vehicle network (IVN) enables high data rate and reliable information exchange inside vehicles. By sharing communication wires and equipment, IVNs simplify wiring, reduce costs, and improve reliability. With the trend of using sensor fusion in autonomous driving vehicles, the conventional stand-alone electronic control units (ECU) are no more desirable. All sensors need to transmit uncompressed data directly to the processor for collaborative computing. As a result, the electrical/electronic architecture (EEA) evolves from gateway architecture to domain architecture first and zone architecture later [8]. In the zone architecture, the network will be further divided into the access part and the backbone part. Such an architecture evolution will also increase the data rate demand, especially in the intra-vehicle backbone networks. However, traditional IVNs mainly rely on copper cables with low data rates, such as local interconnect networks (LIN) of 19.2Kbps using a single wire, control area networks (CAN) of 1Mbps by a twisted pair, and FlexRay of 20Mbps with a twisted pair [9]. Copper cables have the limitations of high cost, large size, heavy-weight and susceptible to electromagnetic interference (EMI).

Compared with copper cables, optical fibers have the advantages of high bandwidth, small size, light weight and good electromagnetic compatibility. In response to the demand for higher data rate, optical interconnects consisting of light sources (LS), optical fibers and photodiode (PD) have become a trend in IVNs. In 1998, with the high-speed interconnects demand coming from automotive infotainment systems, the industry proposed the Media Oriented

Systems Transport (MOST) using plastic optical fiber (POF), which supports data rate from 25Mbps to 150Mbps [10]. Recently, IEEE has formed 802.3cz Task Force in 2020 and 802.3dh Task Force in 2022 to develop multi-gigabit optical Ethernet standards for IVNs to support Advanced Driver Assist Systems (ADAS) [11,12]. The data rate being standardized ranges from 2.5Gbps to 50Gbps and two required interconnect lengths are 15 meters and 40 meters. Higher data rate can be expected for the Level-4/5 autonomous driving vehicles. Therefore, optical fiber communication will be the overwhelming solution for future intra-vehicle networks. In turn, since the shipment volume of automotive is approaching 100 million per year, IVNs will be a huge market for optical communication.

3. Challenges

Data center interconnects based on 850nm Vertical Cavity Surface Emitting Laser (VCSEL) and Multimode Fiber (MMF) can easily support the above-mentioned data rate and interconnect length. However, optical interconnects used in data centers cannot be used directly for intra-vehicle networks. Because the working environment in vehicle is much worse than the one in data centers, intra-vehicle optical communication requires higher reliability.

In order to ensure the easy installation and stable operation of the intra-vehicle network, optical fiber needs to meet the requirements of small bending loss, high tensile and compressive strength, insensitivity to wide temperature range and humid working condition. Moreover, during vehicle driving, there are continuous vibration and severe dust contamination. Therefore, the appropriate fiber connection of IVN should have large tolerance to coupling misalignment and dust contamination. Polymethacrylate (PMMA) POFs with a core diameter of 500μm or 1mm have been used in MOST for more than 20 years. Since the attenuation of POF at 850nm (about 3dB/m) is much higher than that at 650nm (about 0.15dB/m), 650nm resonant cavity light-emitting diodes (RC-LEDs) with bandwidth less than 300MHz are commonly used in MOST. However, even introducing the spatial division multiplexing (SDM) and multi-input multi-output (MIMO) equalization, only 2.4Gbps can be transmitted over 15m multi-core POF via RC-LED [13]. Moreover, the maturity of high-bandwidth VCSELs at 650nm is much lower than it at 850nm, resulting in a lack of suitable high-speed light sources in the 650nm range [14]. In addition, as a step index POF, PMMA POF suffers stronger modal dispersion. Therefore, PMMA POFs are not suitable for the high-speed intra-vehicle optical communication. The performance of perfluorinated (PF) POF with graded-index (GI) is much higher. The study of PF GI-POF with a core diameter of 50μm shows that its bandwidth distance product can reach >30GHz×100m [15]. However, due to the low glass transition temperature of PF polymer, its stability at the high temperature of +125 ºC has to be further investigated [16]. Glass optical fiber (GOF) such as OM3 fiber is another promising candidate with better transmission performance. Compared with POF, GOF has worse mechanical characteristics. But with a strong coating, its robustness has been proven in optical access networks. Recently, a bend-insensitive MMF with 100-μm core diameter is proposed for short distance communication [17]. We have further demonstrated that such a large core MMF has large tolerance to coupling misalignment and dust contamination, make it suitable for IVNs [18].

The ambient temperature also strongly affects the VCSEL performance. Simulations with temperature dependent modulation characteristics of a 20 GHz VCSEL show a 50% reduction in VCSEL carrier lifetime at +85 ºC compared to that at +20 ºC [19]. Relative intensity noise (RIN) increases at +60 ºC leads to significant degradation of NRZ modulation performance at 25Gbps [20]. At the same time, the high temperature affects the slope efficiency, resulting in bandwidth degradation of VCSEL [21]. To tackle the high temperature induced laser degradation, on the one hand, the industry proposes to employ 980nm VCSEL in IVNs [11] which has better reliability. On the other hand, some optical communication signal processing algorithms are introduced to enhance the transmission performance [22]. Moreover, a silicon photonics (SiPh) based optical network architecture is proposed by sharing lasers at a single master node. Temperature insensitive SiPh integrated Mach-Zehnder Interferometer (MZI) and PD are placed at distributed gateway nodes to modulate and receive the optical slots sending from the master node [8].

To support such DSP algorithms and Media Access Control (MAC) protocols for new intra-vehicle optical networks, the real time signal processing is required. Nevertheless, since autonomous driving is still in the early stage, many relevant architectures and protocols have not been standardized and evolve frequently, making many enterprises hesitate to develop the dedicated ASIC. Fortunately, most autonomous vehicles have already equipped with the high-performance heterogeneous FPGA-GPU processing platform for the services such as lane detection and obstructive identification. Utilizing the abundant computing power of heterogeneous FPGA-GPU platform, the real time optical communication algorithms can be carried out [23]. The software-defined MAC protocols such as dynamic bandwidth allocation (DBA) can also be implemented in such a platform [24]. Comparing with ASIC, FPGA and GPU have lower development costs and shorter deployment times. Therefore, the heterogeneous FPGA-GPU platform will be a good candidate for conducting optical communications in IVNs. In our experiment, the maximum data transfer rate between an ADC daughter card and an FPGA baseboard is limited by the FPGA

Mezzanine Card (FMC) interface, which is 32GByte/s, or 256Gbps. Therefore, the maximum data rate which can be handled by the heterogeneous platform mainly depends on the data acquisition rate of ADC. Note that the intra-vehicle optical network is highly asymmetric since most of the traffic is coming from sensors to the central computing. Only the instructions with low data rate are sent from the controller to sensors. An exemplary system block diagram of an intra-vehicle optical network can be shown in Fig. 1, where only one heterogeneous FPGA-GPU platform is depicted in the central node and the type of LS or modulator depends on the specific solution.

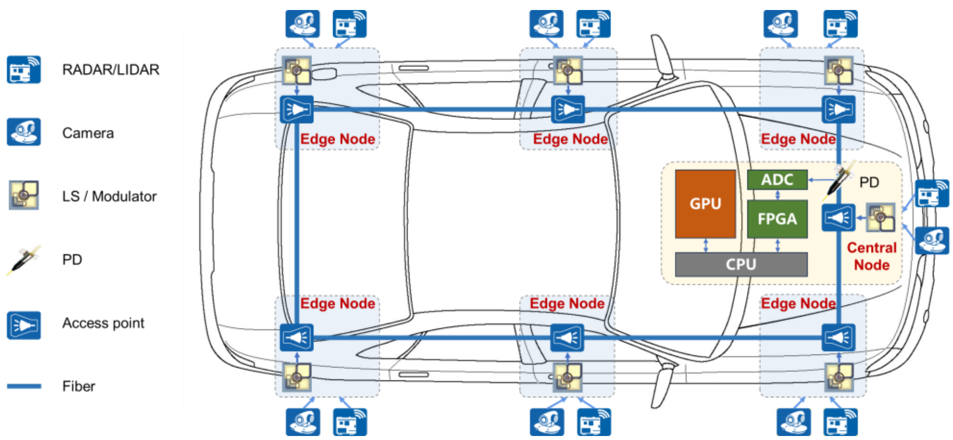

Fig. 1. An exemplary system block diagram of an intra-vehicle optical network.

4. Conclusion and Outlook

With the development of autonomous driving, intra-vehicle networks require high bandwidth data transmission. Optical communication can provide several advantages over traditional copper cables. But due to the demands of high reliability in harsh vehicle environment, the intra-vehicle optical communication still faces many challenges and deserves to be further studied. Additionally, vehicle-to-everything (V2X) communication plays an important role in future autonomous vehicles by providing improved road safety and traffic efficiency. Compared with the traditional RF-based V2X technologies, the optical wireless communication has the advantages of high-speed transmission in a spectrum without license constraint, and could be a promising way to be investigated.

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