Optical Interconnects for Intra-Vehicle Networks: Opportunities and Challenges

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***Abstract*—Intra-vehicle networks for autonomous driving require high bandwidth. Optical interconnects can provide several advantages over electrical cables in the application, but face many challenges, especially due to the harsh environment.**

Keywords—Autonomous Driving Vehicles, Intra-vehicle Networks, Optical Interconnect

I. Introduction

In recent years, autonomous driving vehicles have attracted extensive attention from governments, academia and industry. In 2020, both China and US governments issued documents stating that they would take a leadership position in the research, development and integration of autonomous driving vehicle technologies through a series of measures [1, 2]. At the same time, traditional car manufacturers, new forces in car manufacturing, leading Internet and telecommunication equipment companies are all fully invested in the research and development of autonomous driving vehicles, hoping to participate in this huge market.

Table 1 Data rate demands for autonomous driving vehicles

Sensor	Qty.	Parameters			Data rate demands / sensor [1]
		Pixels	Frame rate	Color	
Camera	5~14	2Mega	30fps	12bit	0.7Gbps
		4Mega	30fps	12bit	1.4Gbps
		8Mega	60fps	14bit	6.5Gbps
LIDAR	1~2 [2]	32 Lines			15Mbps
		64 Lines [4]			30Mbps
		128 Lines [5]			48Mbps
Millimeter-wave RADAR	5 [3]	76~77GHz [6]			400~600 kbps
Total data rate demands	4Gbps [4] to 91Gbps [5]				

1 Communication overhead is not included.
2 Quantity may increase with the cost reduction of LIDAR.
3 1 long range and 4 short range millimeter-wave RADAR.
4 Based on sensors of minimum numbers with the lowest performance.
5 Based on sensors of maximum numbers with the highest performance.

Autonomous driving requires a large number of sensors to perceive the surrounding environment, such as high-definition (HD) cameras, LIDAR (LIght Detection And Ranging), millimeter-wave RADAR (RAdio Detection And Ranging), etc. Moreover, the data generated by these sensors must be transmitted to the vehicle's processor with the lowest latency within the car. Then the processor will instruct various actuators to make the car respond quickly to the surrounding changes, so as to achieve safe driving with little or no human intervention. As the autonomous driving technologies grow, the number and performance of in vehicle sensors and processors continues to increase, and the bandwidth required to communicate with each other has increased dramatically. For example, NIO's first autonomous driving vehicle, ET7, released in January 2021, is equipped with 33 high-performance sensors, including seven 8-megapixel HD cameras and four 3-megapixel surround view cameras [3]. With a frame rate of 30 frames per second and a color depth of 12 bits per pixel, the data rate requirement of cameras alone can be calculated a 26Gbps without accounting for communication overhead. Future fully autonomous vehicles will use more sensors to improve the detection capability of surrounding targets, and the accuracy of sensors will be further improved, and their bandwidth requirements will be increased to 100Gbps or beyond, as detailed in Table 1 [4-6].

II. Opportunities

The intra-vehicle network, which enables high-speed and reliable information exchange inside vehicles, simplifies wiring, reduces costs, and improves reliability by sharing communication wires and equipment. Under the trend of using sensor fusion technology in autonomous driving, the conventional stand-alone electronic control units (ECU) are no more preferable. All sensors need to directly transmit uncompressed data to the processor for the coordinative computing. Consequently, the intra-vehicle network evolves from gateway architecture to domain and zone architectures [7]. This will increase the data rate demand as well, especially in the backbone of intra-vehicle networks. However, traditional intra-vehicle networks mainly rely on electrical cables with low data rates, such as local interconnect networks (LIN) of 19.2Kbps, control area networks (CAN) of 1Mbps, and FlexRay of 20Mbps [8].

Compared with electrical cables, optical fibers have the advantages of high bandwidth, light weight and good electromagnetic compatibility. In response to the demand for higher data rate, optical interconnects constituted by light source, optical fiber and photodetector have become a development trend in intra-vehicle networks. 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 of 150Mbps [9]. 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 intra-vehicle networks to support Advanced Driver Assist Systems (ADAS) [10, 11]. The data rate under standardized is from 2.5Gbps to 50Gbps and two required interconnect lengths are 15 meters and 40 meters. Higher data rate can be expected for the autonomous driving applications. Therefore, optical interconnects will be the overwhelming solution for future intra-vehicle networks. On the other hand, since the shipment volume of automotive is approaching 100 million per year, intra-vehicle networks will be a huge and promising market for optical interconnects.

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III. CHALLENGES

Data center optical 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 directly used in intra-vehicle networks because intra-vehicle optical interconnects require lower cost, lower latency, and more importantly, higher reliability in harsh environment.

In order to ensure the easy installation and working stability of the intra-vehicle network, optical fiber needs to meet the requirements of small bending loss, high tensile and compressive strength, insensitivity to vibration, wide temperature range and humid working condition [12]. 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), resonant cavity light-emitting diodes (RC-LEDs) with bandwidth less than 300MHz are commonly used in MOST. But the maturity of high-bandwidth VCSELs at 650nm is much lower than that at 850nm, resulting in the lack of suitable high-speed light sources in 650nm. Moreover, as a step index POF, PMMA POF suffers stronger modal dispersion. Therefore, PMMA POFs are not suitable for the high-speed intra-vehicle optical interconnects. The performance of perfluorinated (PF) POF with graded-index (GI) can be greatly improved. The study of PF GI-POF with a core diameter of 50μm shows that its bandwidth distance product can reach >30GHz×100m [13]. However, its stability at the wide working temperature of -40 - +125 ºC, especially at the high temperature of +125 ºC, has to be further investigated, due to the low glass transition temperature of PF polymer [14]. Glass optical fiber (GOF) such as OM3 fiber and large core MMF is another promising candidate with better transmission performance [15]. Compared with POF, GOF has worse mechanical characteristics. But with strong coating, its robustness has been proven in optical access networks.

The ambient temperature strongly affects the performance of VCSEL as well. Modeling simulations of temperature-dependent modulation characteristics of a 20 GHz VCSEL show that the VCSEL carrier lifetime at +85 ºC is reduced by 50% compared to that at +20 ºC [16]. Relative intensity noise (RIN) increases at +60 ºC leads to significant degradation of NRZ modulation performance at 25Gbps [17]. At the same time, the high temperature affects the slope efficiency and then leads to bandwidth degradation of VCSEL [18]. Therefore, the reliability and wavelength selection of VCSEL is an important topic discussed in IEEE 802.3cz and 802.3dh.

Vibration is another key environment factor to degrade the performance of optical interconnects. During vehicle driving, continuous vibration exists with the frequency smaller than 300Hz. It will cause coupling offset between butt coupling connectors (BCCs), and cause additional coupling loss and received power variation. To avoid such a power variation, expanded beam connectors (EBCs) will be a possible selection in intra-vehicle optical interconnects since EBCs have larger aperture and higher coupling offset tolerance [19]. Moreover, EBC has low sensitivity to dust. It is another advantage over BCC since the connector end face is easily contaminated by dust and grease during the use and maintenance of vehicles. But comparing with BCCs, EBCs has higher insertion loss and sensitive to liquid contamination. Additionally, the cost of EBCs will be higher than that of BCCs. Due to the short length of fiber in vehicles, in-lines connectors account for a higher proportion of the overall cost, compared with the case in data centers. Therefore, the connector selection is an open question for intra-vehicle optical interconnects.

IV. CONCLUSIONS

With the development of autonomous driving, intra-vehicle networks require high bandwidth. Optical interconnects can provide several advantages over traditional electrical cables. But due to the demands of low cost, low latency, and high reliability in harsh environment, intra-vehicle optical interconnect still face many challenges.

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