Optical Polymer and Polymer-Clad Silica Fiber Data Buses for Vehicles and Airplanes

Otto Strobel, Jan Lubkoll & Daniel Seibl

***Abstract*—The paper presents the state of the art and next-decade technologies for optical data buses in automotive applications. Nowadays, optical data buses in vehicles are almost exclusively used in the infotainment domain, MOST (Media Oriented Systems Transport). Current data rates are in the order of 150 MBit/s. In airplanes lightning strike protection raises new problems due to the future replacement of the metal fuselage by a carbon fiber one. Therefore, the use of LEDs and polymer-optical fibers (POF) has reached the uttermost limit of operation. For higher data rates, alternative solutions have to be found: The LED as transmitter has to be replaced by a vertical-cavity surface-emitting laser (VCSEL), and the plastic fiber (POF) will have to be substituted by a polymer-cladded-silica (PCS) one. Due to the smaller fiber core size the output spot diameter is also reduced and therefore the detector area of the well-known silicon photodiode diameter can be reduced considerably. As a consequence, data rates will be extended into the GBit/s-region. This situation then enables us to use the system for sensor applications as well, including safety-relevant operations like drive by wire, brake by wire and engine management, and may at last lead in the coming decades to autonomous driving.**

***Index Terms*—MOST, LED, FlexRay, Automotive, VCSEL, PCS.**

I. INTRODUCTION

Optical data transmission is nearly as old as the human race. A simple wave with a hand could be interpreted as an encrypted hint to gain attention. The smoke signals of the Native Americans are also a kind of optical data transmission. These signals were already complex and could transmit extensive information. A semaphore network invented by Claude Chappe operated in France from 1792 through 1846. Semaphore networks transmit single letters of the alphabet, thus, “real messages” could be sent. Optical data transmission is today mainly used in telecommunication areas. Long glass fibers conduct phone calls and internet data at high speed all around the world. Telecommunication applications nowadays reach data rates in the order of TBit/s. This technique is also used for recent application areas in the MBit/s region, e.g. in aviation, automobile and maritime industry; but in these areas data rates are rising as well. Furthermore, extending application areas in particular more challenging safety precautions recommend new solutions for several situations.

This paper shows two solutions mainly used in automotive applications: automobiles and airplanes. Electronics in nowadays cars has already reached a high complexity, even increasing in the future.

However, the integration of more and more multimedia and telematic devices in vehicles, in particular for luxurious classes led to a large increase in traffic demands, a relentless need for network capacity, and a higher complexity by integration of various applications. Although MOST is the optical data bus technology currently used; alternative solutions for higher data rates that satisfy current and future automotive applications are highly desirable.

By a rising complexity of these systems and their components, fault liability is also increasing. To avoid possible failures of the vehicles by disturbances of relevant electronics, highly sophisticated test procedures have been developed and matured. The basis of these test procedures is the MOST specification which is provided by the MOST Cooperation. This work deals with the improvement of an automated "MOST25 Full Physical Layer Compliance Test" for a measuring set-up at the MBtech Group. Tests are carried out for the MOST fiber-optic transmitter and receiver systems (Fiber-Optic Transceiver, FOT) which should proof of a perfect 25 Mbit/s-signal transmission [1].

Another serious challenge arises in protecting new generation aircrafts particularly against lightning strikes. New airplanes will be built using carbon-fiber to reduce the weight of fuselage. Therefore, these airplanes will loose a lot of protection against lightning, cosmic radiation and other electrostatic effects. In order to avoid failures in signal transmission on the physical layer the electrical copper wires should be extremely protected, but this solution is too expensive and increases the weight of cables [2]. A reasonable solution is to replace the electrical copper layer by polymer-optical fibers (POF) or polymer-clad-silica (PCS) fibers as transmission medium in new airplanes. On the physical side and on the software aspect the FlexRay bus protocol [3] is adequate for avionic applications and should be adapted for this transmission medium. Thus, this solution is cost-efficient and offers more safety in the aviation domain.

In this paper we propose an improvement for optical data bus systems that may satisfy the requirements on future automotive applications and safety-relevant operations. First, we give an overview on MOST bus systems. Then, we present the challenges of data transmission that arise in new aircraft

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Otto Strobel (Otto.Strobel@hs-esslingen.de) and Daniel Seibl (Daniel.Seibl@hs-esslingen.de) are from Esslingen University of Applied Sciences, Germany. Jan Lubkoll is from Erlangen Friedrich-Alexander University, Germany.

generations. Next, we discuss the deployment of the FlexRay bus protocol for optical data bus systems. After that, we propose two alternative solutions for optical data buses in avionic systems. Finally, we discuss the prototyping results and present open directions for future work.

II. POLYMER-OPTICAL-FIBER DATA BUS TECHNOLOGIES FOR MOST APPLICATIONS IN VEHICLES

The integration of more and more multimedia and telematic applications in vehicles, in particular for the premium class led to a fast increase of the complexity by the integration of various applications. The development started with a car radio and simple loudspeakers. Today there is an ingenious sound system; DVD- and CD-changer, amplifier, navigation and video functions are included. Voice input and Bluetooth complement these packages. Important and basic logical links of these single components are already well known from a simple car radio. Everybody probably knows the rise of the volume in case of traffic announcements.

In a complex infotainment system there is a huge number of such links. If these functions have to be guaranteed, a large transmission bandwidth is demanded for the system. From this requirement, a special infotainment communication system was developed, the “Media Oriented Systems Transport”, abbreviated MOST. The manufacturer spanning MOST technology offers not only a synchronous transmission for audio and video data, but also makes available the application framework for the control of the system complexity. This procedure defines interfaces and functions for infotainment systems at a high abstraction level. MOST connects the different multimedia components in a ring (Fig. 1). For wireless integration of headsets or mobile phones Bluetooth is used. In the future this could also be used for a wireless diagnosis interface [4].

A. *Focus on the physical layer of a MOST system*

MOST meanwhile exists in three implementations: The first generation (MOST25) is based on a bit rate of 25 Mbit/s and the use of an optical physical layer (oPhy). With a frame length of 512 bits a data rate of 22.58 Mbit/s is achieved. The data of the different MOST bus components are transmitted using a 1-mm-Polymethylmethacrylat fiber (PMMA), often named polymer-optical fiber (POF). As transmitter an LED (Light-Emitting Diode) is used converting the electrical signal to an optical one using a driver circuit. The receiver converts the optical signal into an electric current by means of a Si-photodiode. Transmitters and receivers form a unity in MOST devices, called Fiber-Optic Transceiver (FOT). This is shown in Figure 2.

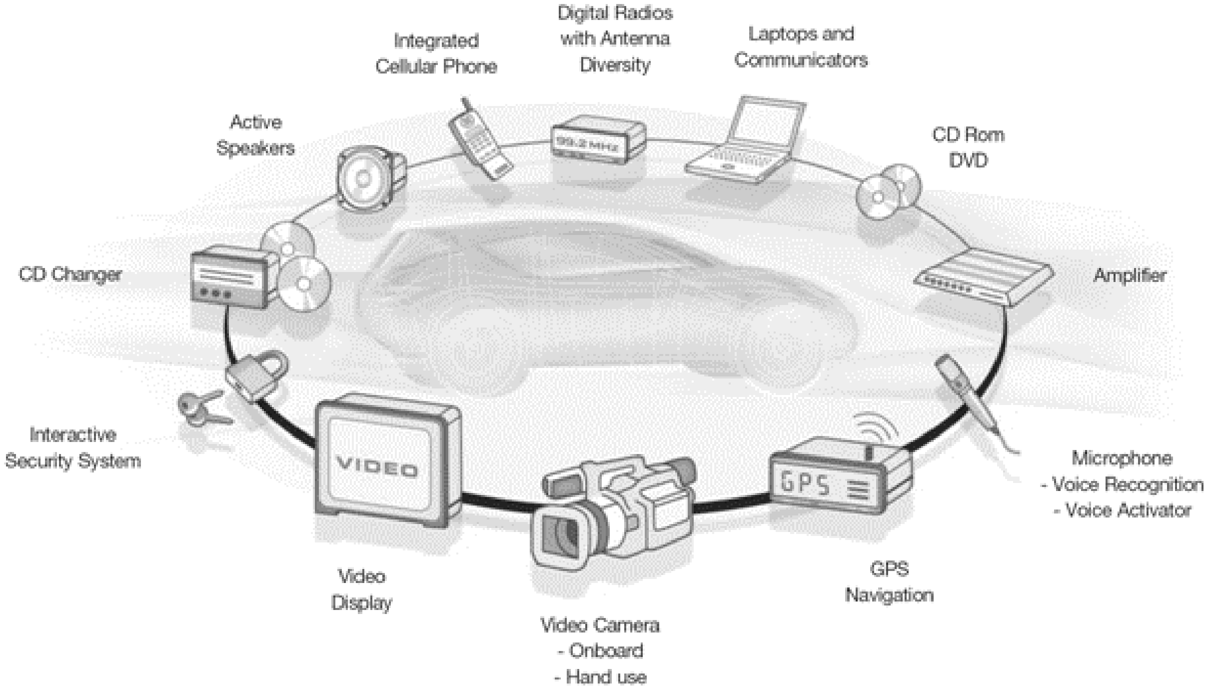

Figure 1. MOST network with ring topology [1].

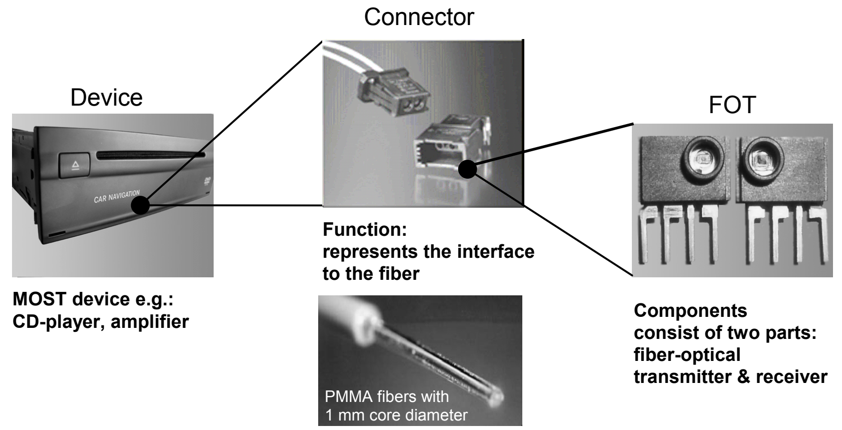

Figure 2. MOST physical layer components [5]

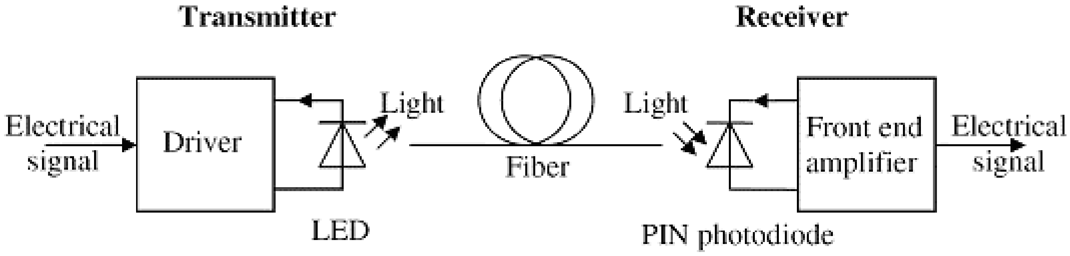

Figure 3. Schematic model of transmitter-receiver link and the MOST FOT (Fiber Optic Transceiver)

Beside MOST25, since 2006, the second generation of MOST, MOST50 is also ttspecified. In this case the frame amounts to 1024 bit and the signal is transmitted by an electrical physical layer (ePhy).

To fulfill future demands, the third generation (MOST150) of MOST was also specified recently. The bit rate now amounts to 150 Mbit/s and uses again an oPhy. Therefore, the LED/POF solution has reached the uttermost limit of operation. For higher data rates, alternative solutions have to be found: The LED as transmitter has to be replaced by a vertical-cavity surface-emitting laser (VCSEL), and the pure plastic fiber (POF) will have to be substituted by polymer-cladded silica (PCS) fiber.

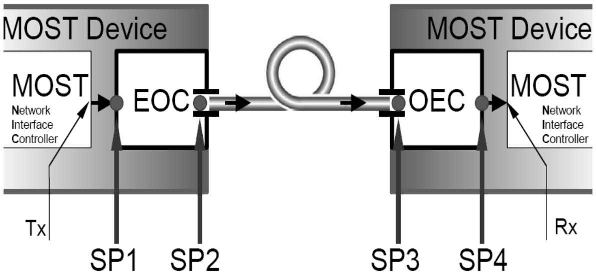

Figure 4.Location of specification points along a point-to-point-link between neighboring FOT

According to the ISO/OSI layer model the lowest level is the physical layer in a network. In our case it represents the physical connection between two neighboring MOST controllers, the MOST NICs (Network interface controller, NIC). This connection is divided into four points – SP1 to SP4 – (Fig. 4).

The specification points SP1 and SP4 define the interface between MOST network interface controllers in different MOST devices. The specification points SP1 and SP4 describe the electric parameters of the converters. The electric-optical converter (EOC) works on the transmitter side and the optical-electric converter (OEC) on the receiver side. The SP2 and SP3 define the connection between the MOST device plugs and the optical fiber (POF).

The limit values of the specification points SP1 to SP4 which are defined in the MOST specification are an essential criterion for the proper function of the physical layer and therefore also for the whole functionality of the MOST network.

Figure 3 shows the schematic model of a transmitter, a receiver and their connection. Transmitter, receiver and their connection describe the physical layer in MOST networks. For the entire description of the transmitter a driver circuit must be added to the LED. This driver circuit is in close association with the LED. The LED converts the digital electrical signal into an optical one. The fiber transmits the light to the receiver. The receiving diode converts the light into an electrical current. A following circuit called front end amplifier converts the small and noisy electrical current into a significant digital output voltage signal. For MOST applications PMMA fibers are used. According to the attenuation curve (Fig. 9) the visible spectrum is used. A wavelength of 650 nm is chosen. At 500 nm the fiber attenuation is even lower but the power of 650 nm LEDs is much higher. Taking into account the required temperature range from -40 °C to 85 °C, the wavelength of the LED varies and therefore the worst case fiber attenuation is approximately 0.4 dB/m [6]. Using LEDs with 650 nm wavelength, a 1-mm-diameter POF and large Si-photodiodes are sufficient for present typical demands. The short transmission distances of about 10 m as well as a bandwidth of 100 MHz are adequate for actual MOST25- and even MOST150-systems.

B. Physical layer compliance test

The document “MOST Compliance Test of Physical Layer” of the MOST specifications describes the approach to the measurement concerning physical interfaces. Moreover, beside the “Full Physical Layer Compliance Test” there is also the “Limited Physical Layer Test” dealing with the FOT implemented in the MOST devices, the “Core Compliance Test” concerning with the manufacturer’s software and the “Profile Compliance Test” concerning the whole MOST system with all its devices. The “Full Physical Layer Compliance Test” deals only with the components, i.e. the optical transmitter and receiver. This test describes the parameters and the limit values defined at the well-chosen specification points SP1 to SP4 of the FOT, in order to guarantee the system functions after the integration of the FOT.

III. FLEXRAY WITH POLYMER-CLAD-SILICA FIBER AS TRANSMITTING MEDIUM IN AVIATION ELECTRONICS

In order to reduce the weight of new generation aircrafts, design engineers are going to use more and more carbon-fiber fuselage. By using this material the weight will be decreased up to 30% compared to aluminum. Considered over the economic lifetime of an airplane, every saved kilogram affects a fuel economization of several thousand liters of kerosene.

But in this case many advantages of a closed metal fuselage get lost, like the Faraday's cage inherent lightning strike and cosmic radiation protection. If lightning strikes an aircraft, the current will travel on the exterior skin. Figure 5 shows a typical lightning strike development at an airplane. In Fig. 5b it is seen that the charge channel of the lightning hits the nose of the plane, travels along the skin and leaves through the rear. In Fig. 5c the return bolt follows the charge channel. This could induce transients into wires or equipments beneath the skin. Those transients are called indirect lightning effect. Therefore, some components could possibly drop out but the situation is handled by system redundancy and special protections.

In contrast, without the completely closed Faraday's cage the situation would be fatal. Lightning strikes could possibly take different paths through the plane. Thus, more wires and electrical components could be affected by its indirect effects. If standard copper wires were in an affected area, the indirect lightning effects could possibly harm or even destroy electrical components. In particular, if a lightning strike caused current travels parallel to the wires, the effect is fatal. Consequently, the internal data transmission of the aircraft has to cope with the above described issues. The problems can be solved by complex electrical protection [2]. Therefore, the consequences of a lightning can be handled very well. But this solution causes higher costs and higher weight of the cables. By choosing a galvanic separation, e.g. optical wires, the sources of the problems themselves would be avoided. Thus, we initiated projects to analyze, specify and build a prototype using an optical solution.

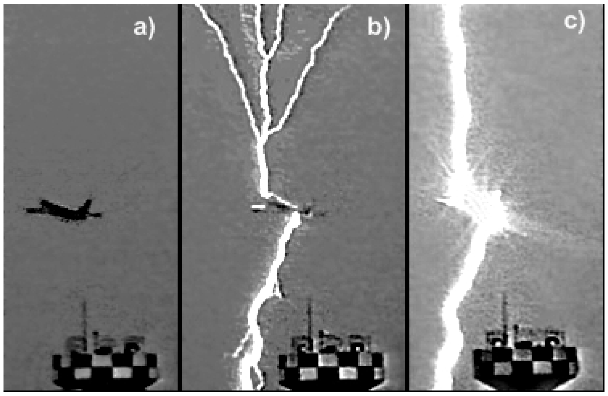

Figure 5. Lightning strikes an airplane

A. FlexRay Characteristics

The FlexRay bus system was founded by the FlexRay Consortium, which is composed of automotive manufacturers, semiconductor manufacturers and several system vendors [3]. Actually it was planned for the automotive industry, but many of the characteristics and advantages can perfectly be integrated in avionic systems.

Due to high safety requirements in the aviation domain, special bus functions have to be implemented. E.g. redundancy functions, limited latency and jitter are necessary. The FlexRay protocol supports several characteristics demanded for data transmission in aviation:

- Application area: engine control, gearing control, safety
- Deterministic bus, with a static and a dynamic segment for time and event triggered information (scalable)
- Variable topologies possible (passive bus, active/ passive star)
- Data rate up to 2 x 10 MBit/s (redundancy ↔ performance)
- Error detection via CRC (cyclic redundancy check) and Bus Guardian (still in development) for the static segment
- global data consistency
- low overhead (5% to 10%)
- guaranteed latency and jitter
- global clock with internal synchronization → no master, no slaves
- because of guaranteed latency and redundancy (2 channels) suitable for safety critical systems.

B. FlexRay Time-Division Multiple Access (TDMA) structure

As shown in Figure 6, each communication cycle is divided into a static segment, dynamic segment, symbol window and the network idle time. To ensure a continuous latency, all these partitions do have a given runtime. In the static segment the slots "Slot 1" to "Slot n" are assigned in an adjustable order to the transceiving nodes.

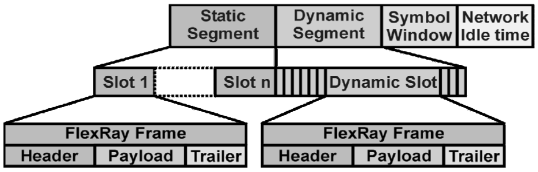

Figure 6. FlexRay frame structure [7].

Therefore, these signals appear in a constant time slice and could be used for safety critical systems. The dynamic segment can be used e.g. to transmit analog signals like temperature or additional information concerning the data of the static slots. In the dynamic segment the slots do not have to be used, but the maximum time of the whole segment is given in the adjusted settings. For bus intern signals, like a media test pattern, the "Symbol Window" can be used optionally. During the "Network Idle time" the bus can run its clock synchronize algorithms and calculate the correction values.

All in all it seems reasonable to test and analyze this flexible protocol for possible future aviation applications.

C. Solutions

Within two projects we have worked out a fully functional prototype solution for the internal communication between up to eight nodes. This prototype has to fulfill several specifications (Table 1). To avoid too many special shielded components in the network, all units except the transceiver have to be passive/non electrical. Thus, the chosen passive optical star opens two options (see 3.3.2 VCSEL & PCS), one with a duplex fiber and a transmissive star and another with a simplex fiber and a reflexive star.

TABLE I. PROTOTYPE SPECIFICATIONS

Parameter	Value
Data rate	10 MBit / s
Operating temperature	-40 °C… +85 °C
Number of Nodes	Up to 8
Passive optical star	8×8, 8 in; 8 out
Distance between two nodes	100 m (50 m ↔ optical star ↔ 50 m)
Low cost, low weight	Two solutions, see 3.2.2 VCSEL & PCS

1) Polymer-optical Fibers

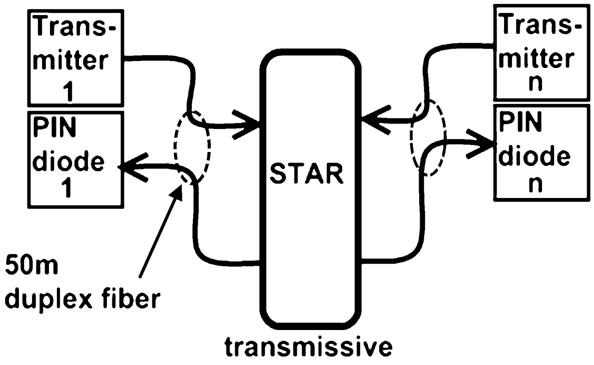

Figure 7. Transmissive star.

To accomplish the mentioned challenges concerning lightning, copper cables are exchanged by a 1-mm-diameter step-index polymer-optical fiber. Because of its low price, robustness and simple connector fitting, this optical waveguide seems to be suitable for the aviation domain. With a bandwidth of more than 100 MHz, data rates of 10 MBit/s of the FlexRay-protocol are easily achievable. Due to the attenuation minimum of the POF at 650 nm (approximately 0.19 dB/m, Fig. 9) and its simple electrical control, a red LED is used as transmitter. To fulfill the specifications, the network is designed by using a transmissive star coupler (Fig. 7). Problems in achieving the demands are caused by the huge attenuations: There are twice 50 meters POF (transmitter → star coupler and star coupler → PIN diode). Thus, the installed POF shows an attenuation of 19 dB (Fig. 8). Furthermore, a four-in, four-out (4 x 4) transmissive star has an attenuation of about 13 dB. As shown in the optical power budget of a POF prototype (Fig. 8), the output power (incl. 3 dB margin) would be about -50 dBm. Thus, the optical output power is much too low to satisfy the necessary -28 dBm receiver sensitivity. Several options are possible to reach the necessary power budget. The LED could be improved, to reach a higher fiber input power (-7 dBm, Fig. 8). This would require a complex electrical circuit and special LEDs. Furthermore, a proper receiver with sufficient sensitivity is not available. Therefore, fiber and transmitter have been exchanged by more sophisticated components.

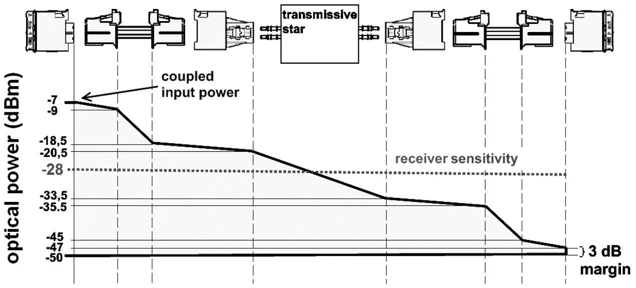

Figure 8. Optical power budget of POF.

2) *Vertical-Cavity Surface-Emitting Lasers & Polymer-Clad-Silica Fibers.*

Though standard silica fibers have a significant low attenuation we did not decide to use it. This is due to some advantages of the POF compared to silica fiber, e.g. its robustness, easy connector fitting and low price. But unfortunately in this case the demanded power budget cannot be achieved (Fig.8). Therefore, the POF is exchanged by a 200 µm step index PCS-fiber. The polymer-clad-silica fiber combines the advantages of the glass fiber and the POF (Fig. 9).

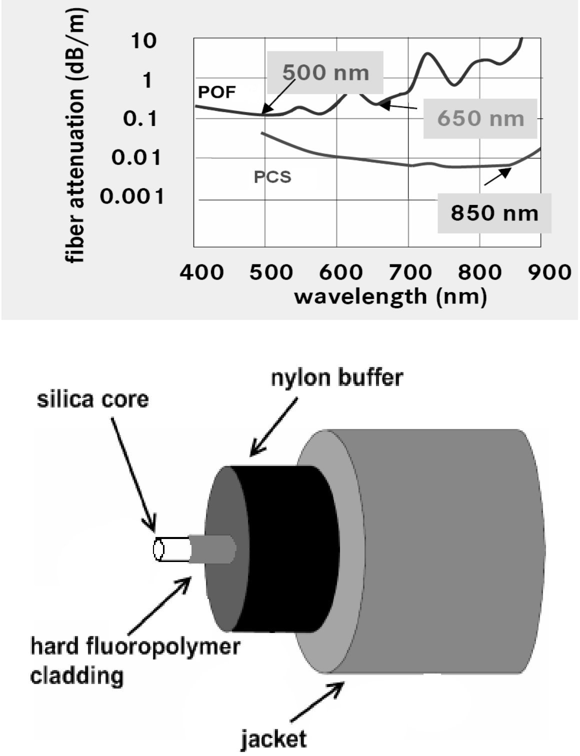

Figure 9. Attenuation and body of PCS-fiber

At a wavelength of 850 nm the attenuation amounts to only 0.008 dB/m. Thus, the necessary link budget can be achieved. Furthermore, the LED is exchanged by a vertical-cavity surface-emitting laser (VCSEL). As shown in Figure 10, a VCSEL has a significant smaller output beam divergence as a common LED. Thus, the achieved coupling efficiency is much higher. In addition, a VCSEL offers a low current consumption. Due to these characteristics a coupled fiber input power above 0 dBm will definitely be achieved. By choosing an 850 nm light source in addition higher relative receiver sensitivity is gained. Instead of a responsivity of about 0.47 A/W at 650 nm we get approximately 0.63 A/W at 850 nm (Fig. 11). Hence, in this constellation, the receiver responsivity is about -30 dBm. The complete link budget is 30 dB. Therefore, components with an attenuation of up to 27 dB (3 dB margin) can be used.

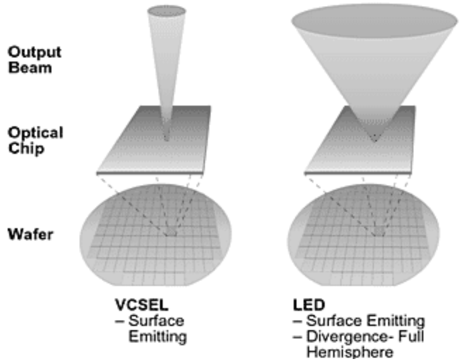

Figure 10. VCSEL output beam.

Taking into account this power budget, we get additional optical design options. The first solution, which uses a transmissive star (Fig. 7), needs two fibers or one duplex cable.

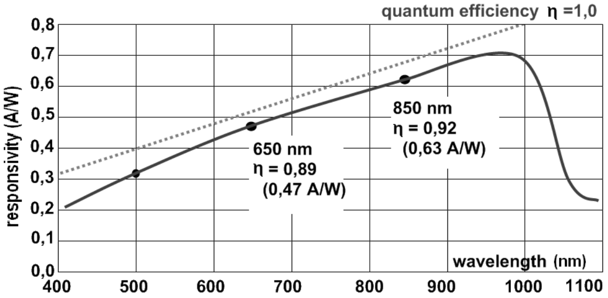

Figure 11. PIN diode responsivity.

Because weight is a significant factor in aviation, we also can choose a second prototype solution. The transmissive star is exchanged by a reflexive one. Thus, inputs are as well outputs. Therefore, we only need one simplex fiber per transceiver: In addition Y-couplers have to be integrated to connect transmitter and receiver (Fig. 12).

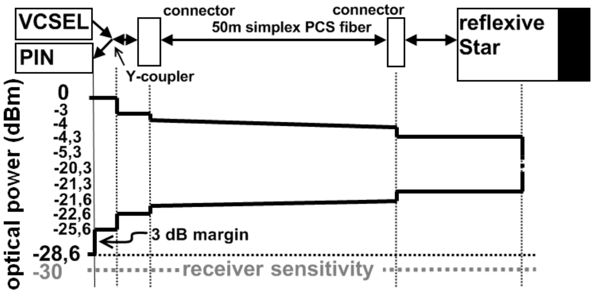

Figure 12. Optical power overview of PCS-fiber

Taking into account the optical components, we achieve a proper solution. The silica-cored PCS-fiber shows a very low attenuation. Moreover, connectors can be easily fitted and a low cost solution is still possible. Due to the smaller core of 200 µm, the PCS provides a bandwidth significantly larger than 1 GHz, which enables the system to higher data rates. Because the VCSELs and PIN-diodes are operated far below their limit the distance and the amount of passive optical components are free to rise [8].

As shown in Figure 13 the digital input signal of the first node (Tx1) is transmitted, converted into an optical pulse, by the VCSEL. The receiver/PIN-diode of the second node (Rx) hands the correct signal, reconverted into an electrical digital signal, to the microcontroller. Thus, the principal operational reliability of an application of FlexRay in the aviation domain has been demonstrated. Next investigations have to deal with the quality description of the transmitted signal in terms of signal-to-noise ratio and bit error rate.

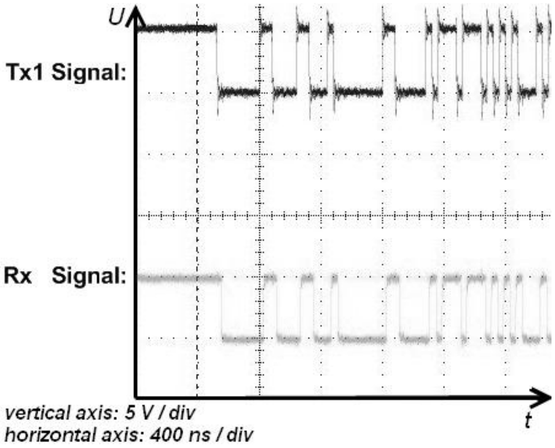

Figure 13: Demonstration of a typical FlexRay data communication.

The upper trace shows the 5 V TTL data signal coming from the microcontroller and sent to the transmitter. Data rates up to 10 Mbit/s have been demonstrated.

The lower trace shows the receiver signal, already converted into a 5 V TTL level.

IV. CONCLUSIONS

In this paper we presented the state of the art and next-decade technologies for optical data buses in automotive applications. MOST is the optical data bus technology currently used in cars. The principle operation and a test set-up for polymer-optical-fiber data busses have been described. The MOST data bus with ring topology implemented in today's vehicles is designed in particular for infotainment. MOST25 is the actual standard with a bandwidth of 25 Mbit/s. FOT and POF are the most important components of the physical layer of a MOST system which was tested using a measurement set-up at MB-technology. MOST150 is the third generation and the next step into the future. The actual technology is capable to achieve 150 Mbit/s and will preliminarily remain as solution in the car [9]. The cross linking of onboard video cameras, laptops, GPS and cell phones is perfectly realized. MBtech owns a measurement set-up for the "Physical Layer Compliance Test" of MOST devices. Defined values of four specification points of this point-to-point link can be measured using this set-up [10]. MOST150 is an adequate solution for optical multimedia data transmission in today's automobiles. However, to provide the next step to autonomous driving new bus systems with higher data rates are desirable [11].

Additional challenges arise in new generation aircrafts. Due to safety problems in data transmission, an optical solution is highly needed. We have shown that conventional LED/POF solutions could only perform simple structures, like ring or multimedia point-to-point connections. For more complex or long ranged structures like a 100 m optical network, LED/POF solutions will exceed their limits. The high attenuation of up to 30 dB, a typical temperature range demand between -45 °C and +85 °C and strong vibration influences cause problems. Consequently, components to fulfill higher demands should be used. In particular low attenuation PCS-fibers combined with less temperature critical VCSELs are necessary. Thus, the receiving photodiode diameter can be smaller and the transmission data rates increase into the range of GBit/s. This combination paves the way for the new generation aircrafts covered by carbon fiber fuselages, having a much better lightning protection and EMC-compatibility.

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V. REFERENCES

[1] MOST Cooperation: "MOST Brand Book" vol. 1.1, Aug. 2007, www.mostcooperation.com, last accessed date 12/07/09
[2] R. Majkner: "OVERVIEW - LIGHTNING PROTECTION OF AIRCRAFT AND AVIONICS", Sikorsky Corp., 2003, http://ewh.ieee.org/r1/ct/aess/aess_events.html, last accessed date 12/07/09
[3] FlexRay Consortium, www.FlexRay.com, last accessed date: 08/07/09
[4] Andreas Grzemba: "MOST: das Multimedia-Bussystem für den Einsatz im Automobil", Poing: Franzis 2007, ISBN-10: 3772341497
[5] Photographs provided by MBtech Group, Sindelfingen, Germany
[6] T. Kibler et al.: "Optical Data Buses for Automotive Application"s, Journal of Lightwave Technol., vol.22. pp. 2184-2199, Sept. 2004
[7] TZM FlexRay-Training 2005, FlexRay-Protokoll, TZM, Robert-Bosch-Straße 6 – D-73037 Göppingen
[8] J. Lubkoll et al.: "FlexRay with Polymer-Clad-Silica Fiber as Transmitting Medium in Aviation Electronics", ICTON MW 2008, Marrakech, Morocco, Dec. 2008, ISBN: 978-1-4244-3484-8
[9] D. Seibl et al.: "Polymer-Optical-Fiber Data Bus Technologies for MOST Applications in Vehicles", ICTON MW 2008, Marrakech, Morocco, Dec. 2008, ISBN: 978-1-4244-3484-8
[10] R. Reiter, A. Schramm: „Verfügbarkeitsrisiko senken – Neue Physical-Layer-Spezifikation für MOST150", WEKA Fachmedien GmbH, 2008
[11] O. Strobel: "Optical Data Bus Technologies for Automotive Applications", in Proc. ICTON MW 2007, Sousse, Tunesia, Dec. 2007, pages 1-1.

Otto Strobel is Head of the Physics Institute and Director of Physics Laboratory, Faculty of Basic Sciences at Esslingen University of Applied Sciences in Germany and Honorary Chair of the IAER group. He received his Dr.-Ing. degree from Technical University of Berlin and his Dr. h.c. degree from Moscow Aviation Institute, Technical University of Moscow in Russia. He published about 50 papers in the field of fiber-optic technologies and optoelectronics and performed more than 30 visiting professor stays worldwide. He is author of the textbook (in German language) "Technology of Lightwave-Guides in Transmission and Sensing" (VDE 2002, 2nd edition). Furthermore he is chair member of the "International Conference on Transparent Optical Networks ICTON" and "ICTON - Mediterranean Winter ICTON-MW" and of the "International Workshop on Telecommunications ITW, Brazil" and also member of the Construction Consultative Committee of Wuhan Optics Valley of China. He has more than 10 years experience in companies' R&D, as member and consultant of Daimler, Alcatel-Lucent, HP, Agilent and Siemens.

Jan Lubkoll received his Bachelor of Engineering degree from Esslingen University of Applied Science, Germany. He has some years of experiences in fiber-optic data buses (FlexRay) in the aviation field. His major research interests include technologies of micro systems, optoelectronic (systems and sensors) and optical communication. Now he is studying at Erlangen Friedrich-Alexander University towards his Master degree in Advanced Optical Technologies.

Daniel Seibl completed his diploma studies in Electrical Engineering, in the field of Micro-Electro-Mechanical Systems and specialized in Micro Optics and Laser Technology in October 2008 at Esslingen University of Applied Sciences. His major research interests are in the fields of fiber-optic technologies. He already has experience in automotive fiber-optic data buses (MOST) and fiber-optic sensors. Now he is working as research associate at Esslingen University of Applied Sciences. His actual research work is dealing with optical 3D measurement.