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Vehicle-to-Vehicle Optical Wireless Communication with the Smart Corner™ Automotive Headlamp

Bastien Béchadergue¹, Carlos Dominguez¹, Arunkumar Pesala², Preethi Chandra²,
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Abstract—Optical wireless communication (OWC) is seen as an interesting technology to complement radio-based systems for vehicular communication. Along with sensors like radar, lidar or cameras, vehicular communication is a cornerstone of the future autonomous vehicles. Automotive Lighting - Magneti Marelli has thus gathered all these technologies into a single automotive light called Smart Corner™. This paper details the architecture, integration and performances of the OWC system used in the third generation Smart Corner™ presented at the 2019 Consumer Electronic Show (CES). Based on an orthogonal frequency division multiplexing (OFDM) modulation combined with channel estimation and bit loading, this system maintains a null packet error rate (PER) over 2 m at more than 100 Mbps and over 15 m at 14 Mbps, which shows it could provide a vital redundant communication link in several automotive use cases.

I. INTRODUCTION

Vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communication is a keystone of vehicle automation. Radio-based technologies like dedicated short-range communication (DSRC) are already deployed and tested worldwide. However, these technologies suffer from serious performance degradations in dense traffic use cases like traffic jam or platooning [1] so that redundant technologies like optical wireless communication (OWC) could be useful [2], [3]. In OWC, the data signal is carried in free space by lightwaves generated by light emitting diodes (LED) or lasers rather than radiowaves. Thanks to the massive deployment of LED headlamps and taillights, OWC could thus be integrated in most new cars.

Numerous experimental studies on V2V and V2I-OWC have been carried out. Most of the systems proposed are based on simple pulse modulations like on-off keying (OOK) and reach data rates of at most a few Mbps [4]. In [5], however, an orthogonal frequency division multiplexing (OFDM) modulation is used in conjunction with an advanced custom made photo-receiver to reach 55 Mbps over 1.5 m indoor. On the other hand, tests in real driving conditions have been detailed in [6], where a V2V-OWC link is established and maintained over 40 m despite lateral shifts of around 4 m between the vehicles. However, the data rate is limited in this case to 2 kbps.

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Fully autonomous vehicles will also rely on several different sensors to understand their environment and then take the best decision they can. These sensors have progressively been deployed in advanced driver-assistance systems (ADAS) over the past few decades so that most new vehicles are already equipped with cameras or ultrasonic sensors. In parallel, automotive radar and lidar are now being commercialized [7]. Automotive Lighting - Magneti Marelli, as one of the major automotive set makers, has thus developed the Smart Corner™, an automotive light integrating advanced lighting functions along with radar, ultra short-range radar, far infrared (IR) cameras, ADAS cameras and solid state lidar for a 360° coverage [8].

Presented at the 2019 Consumer Electronic Show (CES), the third generation Smart Corner™ also brings connectivity to the vehicles by integrating an OWC system, which makes Automotive Lighting - Magneti Marelli the first set maker to ever present publicly an OWC-enabled car light. The design of this OWC system, made by the start-up Oledcomm, as well as its integration in the Smart Corner™ are thus detailed in this paper. This system relies on an advanced modem compatible with Ethernet input frames and implementing OFDM modulation with channel estimation and bit loading to optimize the data rate while maintaining a constant quality of service (QoS). Therefore, a null packet error rate (PER) is demonstrated over 2 m at more than 100 Mbps and over 15 m at 14 Mbps, so that Automotive Lighting - Magneti Marelli was able to demonstrate flawless real-time video streaming at CES 2019. These results also show this system could be used as a reliable redundant communication link in several automotive use cases.

Section II describes the architecture of the OWC system whereas Section III presents its integration into the Smart Corner™ and Section IV its experimental performance evaluation. Finally, Section V provides some concluding remarks and relevant future works.

II. OWC SYSTEM ARCHITECTURE

The demonstrator exhibited at CES has to transmit by OWC a real-time video stream taken from a camera from a vehicle to a podium where the received video stream has to be displayed on a screen. The architecture of the corresponding OWC system is represented on Fig. 1. It is composed of three main blocks: the data generation/display block, the OWC modem block and the OWC analog front-end (AFE) block.

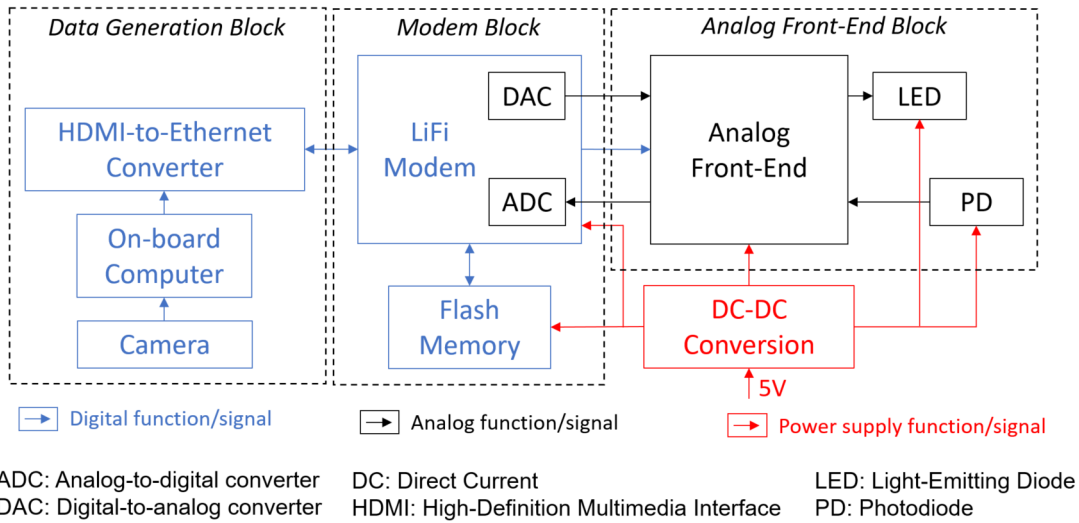


Fig. 1. Block diagram of the OWC system for V2V video transmission.

A. The Data Generation/Display Block

The video transmitted by OWC is a real-time 640x480 video taken by an IR camera installed on the front of the vehicle. The real-time video stream captured by this camera is first processed by an on-board computer that performs object classification and adds marks around the pedestrians and vehicles detected so that they can be clearly identified, as represented on Fig. 2.



Fig. 2. Example of video stream to transmit by OWC.

A high-definition multimedia interface (HDMI) output is then used to get this processed video stream and to transmit it to the next vehicle via OWC. However, a protocol conversion is first operated from HDMI to Ethernet using a HDElite ProHD HDMI extender. This converter cuts the video stream into moving picture experts group transport

stream (MPEG-TS) packets that are encapsulated in user datagram protocol/internet protocol (UDP/IP) packets and then Ethernet packets. These Ethernet packets are finally transmitted to the OWC modem that will be described next.

Note, however, that on the receiving vehicle, the data generation block is replaced by a data display block composed of an equivalent Ethernet-to-HDMI converter connected directly to a screen so that the video transmitted can be displayed in real-time. Note also that this data generation/display block is supplied by external power sources.

B. The OWC Modem Block

The role of the OWC modem is, on the emission side, to convert the Ethernet frame into a format compatible with transmission through light. The modulation selected here is the direct current biased optical OFDM (DCO-OFDM) modulation, which has a high spectral efficiency and thus allows to reach data rates up to 2 Gbps with a limited modulation bandwidth of 100 MHz.

The modem also implements advanced channel estimation from pilot symbols in order to know the channel state for each subcarrier and then apply bit loading. Bit loading is here used to optimize the data rate while maintaining a constant QoS. Once modulated, the data frames are turned into a continuous analog signal by an embedded digital-to-analog converter (DAC) and sent to the AFE for emission by light.

On the reception side, the modem can demodulate the data signal collected by the AFE and digitized by an analog-to-digital converter (ADC). In this case, the channel estimation is also used to adjust the gain of the AFE and thus maintain a rather constant signal amplitude at the ADC input.

The modem is used for emission and reception at both the vehicle and the podium sides. In the downlink direction, from the vehicle to the podium, Ethernet frames containing the video data are transmitted, whereas on the uplink direction, acknowledgment frames are sent back by the podium. Therefore, even though the downlink bandwidth needed is much

larger, the communication channel is bidirectional. Note also that the system described here could actually be connected to any Ethernet network and not only to an HDMI extender.

C. The OWC AFE

The AFE is, as the modem, used for both the emission and reception of OWC signals. The emission part of the AFE is composed of an amplification stage and a DC bias in order to set the mean value of the analog data signal at a fixed working point of the transmitting LED while maintaining its peak-to-peak amplitude in the linearity region of the LED. Pre-equalization is added to extend the modulation bandwidth of the LED to 30 MHz so that, when combined with the modem previously described, a maximum data rate of 250 Mbps has been measured in laboratory tests. In addition, a focusing lens is added after the LED to reduce the field of emission to $\pm 10^\circ$ and thus increase the power collected at the receiver side.

The receiving part of the AFE is composed of a positive-intrinsic-negative (PIN) photodiode (PD) followed by a trans-impedance amplifier (TIA) and an adaptive amplification stage which gain is adjusted by the modem according to the channel estimation results. The overall bandwidth of this receiving chain is 48 MHz. In addition, three PD have actually been used to increase the sensitive surface of the receiver and thus the power of the signal collected. Each PD has field-of-view (FOV) of $\pm 35^\circ$, which is large enough to collect the incoming data signal at different positions while limiting the exposition to interfering light sources.

The AFE components, as well as the modem, are supplied by a DC-DC conversion stage that generates from a single 5V source all the power supplies needed. Note, however, that this power stage does not supply the components of the data generation/display block.

III. INTEGRATION OF THE OWC SYSTEM

After implementing the three main blocks previously described on discrete electronic cards, the integration of the whole system on the Smart Corner™ and on the podium has been made.

A. Smart Corner™ Integration

On the vehicle side, only the AFE, the LED and the PD are integrated directly inside the Smart Corner™, as the space available is rather restrained. The other components are directly embedded in the car. Fig. 3 represents the three electronic cards corresponding respectively to (a) the LED, (b) the PD and (c) the AFE.

The LED board includes only the LED and connectors to bring the power and data signals so that its form factor remains small enough for an easy integration. Similarly, the PD card is only composed of the three PD with their respective TIA, whereas the AFE board embeds the various amplification and power supply stages. The three boards are eventually integrated into the Smart Corner™ as represented on Fig. 4. Note that the emitting and receiving cards are situated at opposite locations in order to reduce their mutual

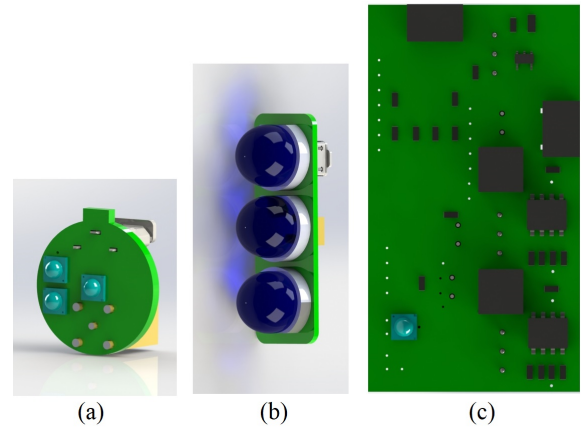


Fig. 3. (a) LED, (b) PD and (c) AFE cards integrated into the Smart Corner™.

interferences and that an IR optical filter was added in front of the receiving card to further limit the impact of the interfering ambient light, but also for aesthetic reasons.

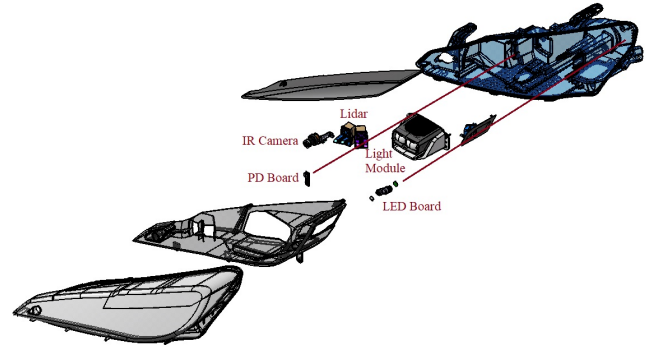


Fig. 4. Exploded view of the electronic cards integration into the Smart Corner™.

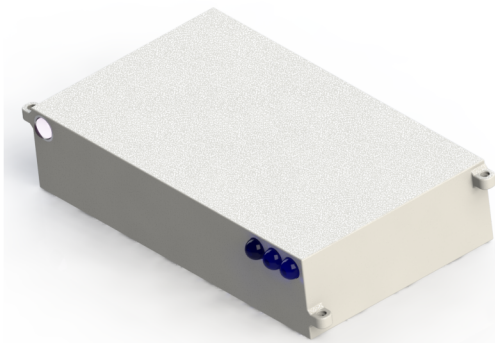
B. Podium Integration

On the podium side, the integration is much easier as there are no specific space constraints. Therefore, a box including all the system components has been designed and integrated directly into the podium, as represented on Fig. 5. This box is then hidden behind an IR optical filter, which allows at the same time to reject most of the ambient light and thus improve the quality of the signal received.

IV. EXPERIMENTAL EVALUATION OF THE SYSTEM

A. Preliminary Analysis of the Data Packets

As explained in Section II.A, the data transmitted are MPEG-TS frames generated by an HDMI-to-Ethernet converter from a 640x480 real-time video stream. The MPEG-TS protocol has first been studied using the network protocol analyzer software Wireshark in order to understand its structure. This prior analysis shows that the HDMI-to-Ethernet converter outputs a data stream with a constant bit rate of 14 Mbps, whatever the input image. Therefore, our OWC system must support a minimum data rate of 14 Mbps to



(a)



(b)

Fig. 5. (a) OWC box integrated into the podium and (b) view of the final integration.

transmit in real-time and without loss of quality the video stream captured by the camera.

B. Data Rate Performances

The data rate performances have then been evaluated by simulating Ethernet frames at the input of the system and then measuring the effective data rate at which they are output. Note that given the QoS target of the modem, the Ethernet frames reconstructed are error-free.

Fig. 6 shows the evolution of this data rate with the distance between the vehicle and the podium, when the podium is in the reference axis of the OWC transmitter of the vehicle. It shows that the data rate is larger than 100 Mbps at short distance (less than 2 m) and then experiences an exponential decay with the distance. However, it remains larger than 14 Mbps up to 15 meters.

Note that the maximum uplink data rate has not been measured since only the downlink performances are critical

in real-use. The uplink is indeed only used periodically to send acknowledgment frames at a few kbps.

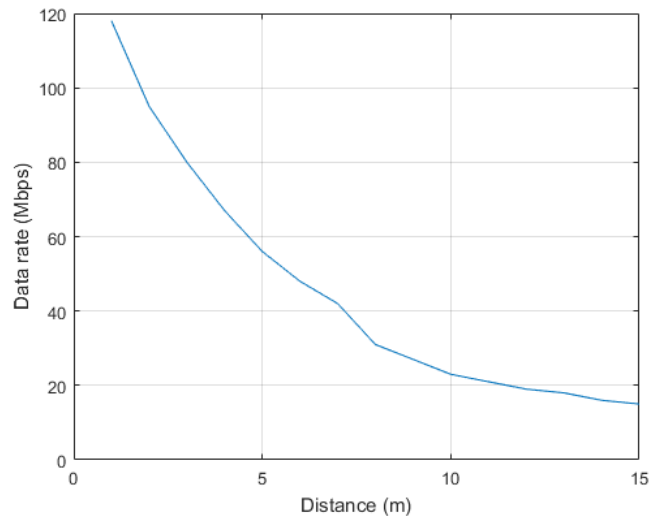


Fig. 6. Evolution of the data rate against the vehicle-to-podium distance.

From these results, we can expect the demonstrator to provide flawless real-time video transmission over at least 15 m. More importantly, these performances show that our system could provide a high-capacity redundant channel to conventional radio-based systems like DSRC systems for V2V or V2I communication, especially in dense traffic scenario like traffic jam, platooning or toll approach phases.

C. Final Demonstration

The demonstrator was publicly revealed for the first time at the Consumer Electronic Show (CES), in Las Vegas, from January 8th to 11th 2019. It ran during the whole duration of the show without any issues, while the podium was placed 10 m away from the vehicle, as shown on Fig. 7. In particular, the strong ambient lighting did not cause noticeable performance degradation thanks to the interference rejection capabilities provided by both the limited FOV and the optical filters. A video of the demonstration can be found in the following reference [9].



Fig. 7. General set-up of the demonstration at CES 2019.

V. CONCLUSION AND FUTURE WORKS

In this work, the design and implementation of a high data rate OWC system that can be connected to any Ethernet network is detailed, along with its integration into the Smart Corner™ developed by Automotive Lighting - Magneti Marelli. To the authors' knowledge, this work is the first integration of a high-speed OWC system by an automotive set-maker for public demonstration. Tests show that a data rate larger than 100 Mbps is reached up to 2 m and that this data rate remains larger than 14 Mbps up to 15 m, while transmitting Ethernet packets without errors. Such performances are promising for medium-range V2V and V2I communication use cases such as platooning, toll approach phases or during traffic jam, where a redundant communication link would be useful. Therefore, future works will consist in testing the system presented here outdoor, in real driving scenario and under various weather conditions.

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