Revolutionizing Spacecraft Communication: Optical Wireless Technology for Reduced Weight and Cost

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ABSTRACT

The current on-board communication network in spacecrafts requires a significant amount of wires, leading to relevant issues in cost and occupied volume . Optical Wireless Communication (OWC) can eliminate the need for physical cables, reducing installation and maintenance costs and improving system flexibility. We propose and demonstrate an OWC system that provides wireless data transfer among the electronic units within the satellite. The system is now successfully operated with two popular wired communication protocols on satellites, i.e., CAN-bus and MIL-STD-1553B. It has complete backward compatibility with existing protocols. Moreover, as it requires no DSP, it results in an extremely small footprint and low power consumption. It can effectively reduce the overall weight and cost of the spacecraft data network, offering the potential for a groundbreaking change in spacecraft technology.

Keywords: Optical wireless communication, Spacecraft communication, Satellite communication, Light Emitting Diodes

1. INTRODUCTION

Today, the intra-spacecraft data communication in any satellite relies on physical wires that connect all the onboard units (equipment and other devices) to the System Main Unit (SMU). These cables represent a relevant percentage of the total mass of a satellite (e.g., 8%[1,2]); thus, they contribute to the fuel consumption, the high occupancy inside the spacecraft, and also pose relevant issues during the Assembly Integration and Test (AIT) phase[3,4] (e.g., long installation and testing times). In the future, wireless technologies could help to reduce this harness[2,5–7] by substituting the physical cables. Among them, Radio Frequency (RF) systems could represent an alternative to wired links,[7–11] however, they have severe security issues[6] and a low Electro-Magnetic Compatibility (EMC) with the other electronic systems.

Optical Wireless Communication (OWC) technology can solve most of the issues of the wired and RF systems.[10,12,13] This type of system does not generate Electro-Magnetic Interference (EMI) that can cause issues to the onboard equipment. Moreover, they have negligible security risks being intrinsically robust to jamming and sniffing, thanks to the fact that the light radiation is easily shadowed and confined by physical obstacles.

Recently, the project Transmission of Optical Wireless signals for telecom Satellites (TOWS) proved the OWC transmission of the military standard MIL-STD-1553B by proposing an innovative approach, based on an optical transceiver (TRX) and a Signal Adaptation Stage (SAS) for the signal adaptation of the MIL-STD-1553B to/from OWC.[14] The SAS is a transparent solution that works only at the physical layer without digital devices, such as field programmable gate arrays (FPGAs) or microprocessors.[15] This ensures backward compatibility with the present standard. The prototypes were designed to be plug&play so that they do not require modifications to the MIL-STD-1553B bus protocol; indeed, the proposed interfaces should be plugged directly into the current connectors, where the cable is usually inserted. Furthermore, the OWC system was based on Commercial Off-the-Shelf (COTS) components to reduce the final cost and improve the reproducibility of the system. They also were designed to have a very low power consumption, weight, and dimensions.

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The optical TRXs were designed, realized, and characterized in the laboratory of Telecommunications, Computer Engineering, and Photonics Institute (TeCIP), in Pisa. A recent paper described the architecture of the TRX and the experimental results for the first version of the boards.[14] As said, this version of the optical TRXs was developed to demonstrate a MIL-STD-1553B transmission in a realistic intra-spacecraft scenario, i.e., in a dark environment with shadowing effects,[16] as well as in an AIT environment.[17] After these tests, they were updated and optimized to increase the dynamic range and to be employed in different application scenarios.

MIL-STD-1553B was selected as it is a bus type that was traditionally deployed on spacecrafts.[18–20] However, recently, CAN-bus also emerged as a high-potential solution:[21] in future spacecrafts, the two protocol options can be alternatives or even coexisting. Therefore, it is important to prove that the previously developed solution can be adapted so that they and also support CAN-bus. This is not taken for granted, because the two bus types are very different in signal features and data flow processes, then, clearly, the original TRX architecture was only able to transport MIL-STD-1553B signals and cannot be used for CAN-bus.

Therefore, we had to realize a new board for the CAN-bus: however, we wanted to keep it modular, i.e., with minimum changes. Thus, the new board was required to have a new SAS block, but we designed it so that all other parts stayed untouched. This provides a strong value in terms of hardware flexibility.

Here, we present results that extend and enhance our OWC system so that it shows that it can support the transmission of both the MIL-STD-1553B and the CAN-bus, by only changing the SAS. Also for this case, the solution is transparent and neither of the protocols needs any modifications, the system is realized only by using COTS components, analog processing, and by minimizing dimension and power consumption. In the following, We report the system characterizations and the bidirectional transmission tests for both standards. This paper is structured as follows. First, in Section 2, we briefly describe our starting system used for the transmission of MIL-STD-1553B and the results achieved. In Section 3, we summarize the main features of the CAN-bus protocol and the working principle of the systems used for the CAN-bus adaptation. In Section 4, we describe the experimental setup used for the system characterization and the transmission test. Finally, in Section 5, we report the results for the characterization and the OWC data transmission of the CAN-bus bus.

2. THE MIL-STD-1553B OWC SYSTEM

The OWC system was initially designed to work with the MIL-STD-1553B, one of the most common data buses for communication onboard satellites.[19,20] The MIL-STD-1553B defines a digital time division command/response multiplexed data bus employing three electrical lines.[18] The signal has a Manchester II biphase code with a bit rate of 1 Mb/s. Data transmission is performed using data packets, which are defined as ”words”. Each word comprises a synchronization sequence (SYNC) made of 3 bits, a 16-bit long sequence, and an additional parity bit (P), for a total length of 20 bits. Therefore, each word lasts 20 µs.

For the OWC transmission, we designed and realized a board that consists of three main sections: the OWC-transmitter (TX), the OWC-receiver (RX), and the SAS (see Fig. 1). The TX comprises a current driver and a Light Emitting Diode (LED). The driver converts a unipolar electrical signal with an amplitude between 0 and 5 V into the current driving the OWC source, which is made by a 4-infrared-LEDs (IR-LEDs) array to improve the emitted optical power (each with the emission peak at 850 nm, an emission angle of 150°, and an average emitted optical power of 0.6 W). On the other side, the RX comprises a photo-diode (PD), a Transimpedance Amplifier (TIA) stage, and an electrical filter. We chose a PIN photo-diode (PIN-PD) with the responsivity peak at 850 nm and a field-of-view (FoV) of 135° and we employed an array of 4 PDs to increase the collected optical power.

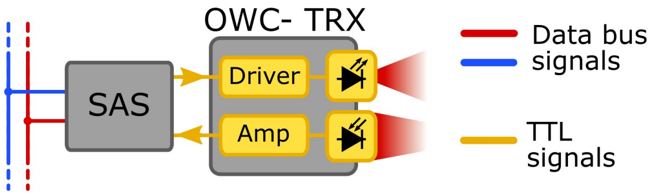


Figure 1. Functional scheme of the OWC transceivers.

The third stage is the SAS, which allows the optical transmission of the bus signals. The MIL-STD-1553B protocol cannot be transmitted straightforwardly over OWC: on the electrical bus, there are differential bipolar signals that run over three electrical lines, all used for bidirectional transmission over the shared bus. On the other hand, any OWC system can be seen as two independent unidirectional links, which both exploit positive unipolar signals. Therefore, to perform an OWC transmission the signals need to be adapted both at the transmitter and at the receiver. The main task of this SAS is to convert the electrical signal from the format of the standard to Transistor-Transistor Logic (TTL) format for the OWC transmission and vice-versa. In addition, the SAS manages the data direction by performing a flow control.

In Fig. 2, we present the block scheme of the typical transport of MIL-STD-1553B over OWC. To simplify the explanation, we included as insets the examples of the waveforms of the electrical signals taken at the main points of the link. The electrical signals A and B on the MIL-STD-1553B bus (blue and red in inset 1) are sent to the SAS that converts them into the TTL format (inset 2). The TTL signal is used to drive the current on the LEDs, modulating them. After the free space transmission, the optical signal is received by the RX and converted back into the electrical domain (inset 3), sent to the SAS, and adapted according to the MIL-STD-1553B format. Once the second TRX receives the message, it replies with another message directed to the first TRX, which follows all the previous steps in reverse.

The OWC system for the transmission of the MIL-STD-1553B was characterized by measuring its sensitivity, we already provided an in-depth description of the first version of the TRX board and the specific analog signal processing.[14] These boards were then optimized with several modifications; among them, the most relevant was the improvement of the dynamic range, a key parameter for the application in any environment with a large range of received optical power. After this optimization, the system was also tested by performing a complete OWC transmission of the bus in different scenarios: inside a satellite mockup for an intra-spacecraft configuration[16] and in an AIT environment.[17] In all cases, the OWC bus transmission was performed successfully and no error was observed.

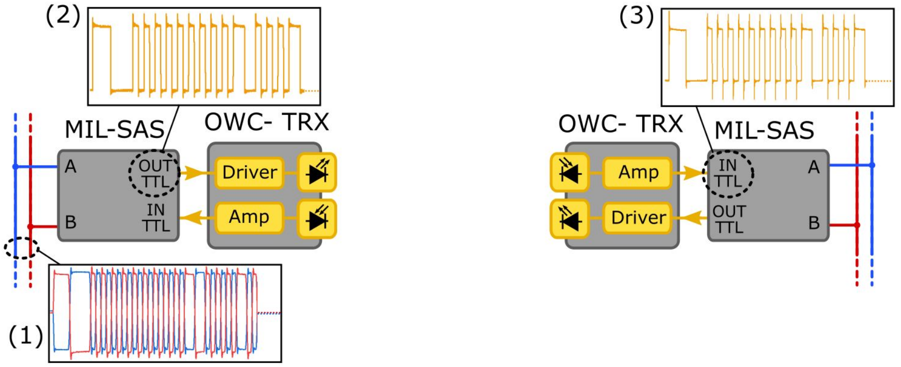


Figure 2. Block scheme of the OWC link in the case of a MIL-STD-1553B SAS with the electrical waveforms at the main steps of the transmission. (1) MIL-STD-1553B signals on the bus; (2) Electrical signal after the conversion into TTL format; (3) Electrical TTL signal after the OWC transmission. (1) CAN-High (CANH) and CAN-Low (CANL) signals on the bus; (2) Electrical signal after the conversion into TTL format; (3) Electrical TTL signal after the OWC transmission. (4) CANH and CANL signals received on the bus (5).

3. THE CAN-bus OPTICAL SYSTEM

The CAN-bus was introduced in 1983 for the automotive industry and extended in 2015 for spacecraft onboard applications.[21] Due to the increased use of this standard on satellites, we adapted the OWC system originally designed only for the MIL-STD-1553B to the transmission of the CAN-bus. This upgrade was achieved by maintaining the fundamental blocks of the TRX and by designing a new SAS to work with the CAN-bus.

The CAN-bus defines a multi-master serial bus that efficiently supports distributed real-time control with a very high level of security. It works according to a broadcast system: when a node transmits data, the data are available on the network to all other nodes. The CAN-bus transmits data using two separate lines for the electrical signals (indicated as CANH and CANL). The data are encoded using two logical states that result from the difference between CANH and CANL signals: a logic ’1’ and a logic ’0’. Data are transmitted on the bus as messages. The most common type of message is the data frame that consists of four main sections: the arbitration field (12 bits), the data field (from 0 up to 64 bits), the Cyclic Redundancy Check (CRC) field (15 bits), and last the Acknowledgment (ACK) slot. The bit rate depends on the transmission length, with a maximum of 1 Mb/s. We tested the system at a bit rate of 500 kb/s since this data rate is typically used in intra-spacecraft communications.

The setup for the OWC transmission of the CAN-bus has a very similar structure as in the previous case of MIL-STD-1553B. The CAN-bus signal cannot be directly converted to OWC signal and thus needs to be adapted. Actually, in this case, the CAN-bus features are very different from the MIL-STD-1553B, so we designed and realized a new version of SAS. We outline that the CAN-bus-SAS is the only difference compared to the MIL-STD-1553B OWC systems, as the OWC-TRX is the same. Indeed, the RX and the TX sections exploit only signals having single-ended logic (TTL), so that they are independent of the employed protocol and can be used with both MIL-STD-1553B and CAN-bus without any further modification. In Fig. 3, we depicted the transmission setup and the details of the CAN-SAS. Also in this case, we reported a portion of the electrical signal waveforms corresponding to the main steps of the communication process.

Both the CAN-bus electrical signals (CANH and CANL, red and blue curves in the inset (1) in Fig. 3) arrive at the SAS, which then produces the TTL signal (inset (2)) that is sent to the LED driver to be transmitted in free space. After the wireless transmission, the optical signal is received by a second TRX and sent to its CAN-SAS (3). This SAS, in addition to the adaptation of the CAN-bus signal to/from the TTL, is responsible for the isolation of the ACK bit. This bit is sent back from the bus when the received message has no error, to confirm the receipt of the data (the last bit in (4)). In a typical wired transmission, all the units are connected to the bus so that when the RX transmits the ACK on the bus, it is read instantaneously by the TX since it is connected directly to the bus. In a OWC transmission, we employ a signal adapter that converts all the signals from the CAN-bus to TTL and vice versa. Therefore, when the RX transmits the ACK, the output of the CAN-TTL adapter will be both the received message and the ACK. This type of signal would cause an error in the transmission since the TX is expected to receive only the ACK. This is a key issue for the bidirectional transmission of the CAN-bus and for this reason the CAN-SAS has to isolate the ACK bit (inset (5)) to send only it back to the TX side.

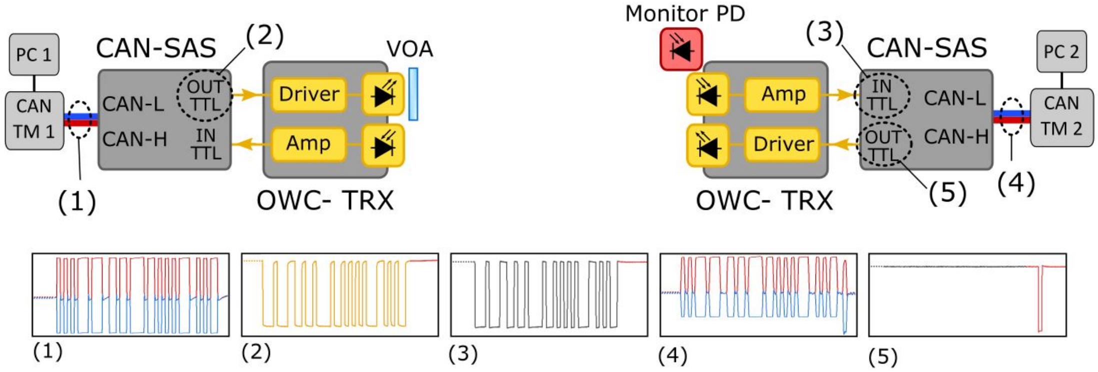


Figure 3. Block scheme of the communication setup in the case of a CAN-bus adaptation, with reported the electrical waveforms of the main steps of the transmission. CANH and CANL signals on the bus before the transmission (1); TTL signal after the adaptation (2); TTL received signal (3); CANH and CANL signals on the bus after the transmission (4); isolated ACK bit sent back to the TX (5).

4. EXPERIMENTAL SETUP

In Fig. 4 we present the experimental setup of OWC transmission of the CAN-bus. During the measurements, the CAN-bus signals were handled by the CAN-bus Test Modules (CAN-TMs), one at the TX side and one at the RX side. Each one of these is made up of an Arduino One board coupled with a board that provides the CAN-bus controller. This controller implements the specification of the CAN-bus message version 2.0B with a data rate of 500 kbps. This board also adopts a high-speed transceiver that acts as an interface between the CAN-bus protocol controller and the physical bus. The CAN-bus differential signal, generated by the Arduino assembly, needs to be converted into a format suitable for the optoelectronic devices present on the TRX boards (see Section 3). This conversion between the differential and the TTL signal is performed by the CAN-SAS. As mentioned in Section 3, the isolation of the ACK bit has to be performed at this stage. During the tests, this operation was emulated using software operations that would be integrated into the next version of the SAS board. Both the CAN-TMs were connected to the PC where it is possible to observe the status of the sent and received messages using the Arduino IDE software, and at the same time, the related waveforms are observed using real-time oscilloscopes.

During the experimental measurements of the Bit Error Ratio (BER), a unidirectional transmission was used, and the analysis was performed using a custom MATLAB routine uploaded into the oscilloscope. For this scope, a Variable Optical Attenuator (VOA) was used to obtain signals of variable amplitude, while the received optical power was measured using a monitor PD.

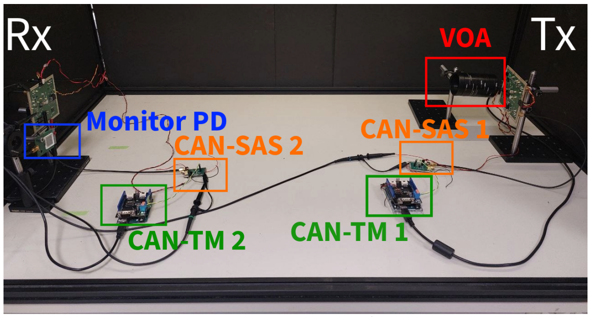


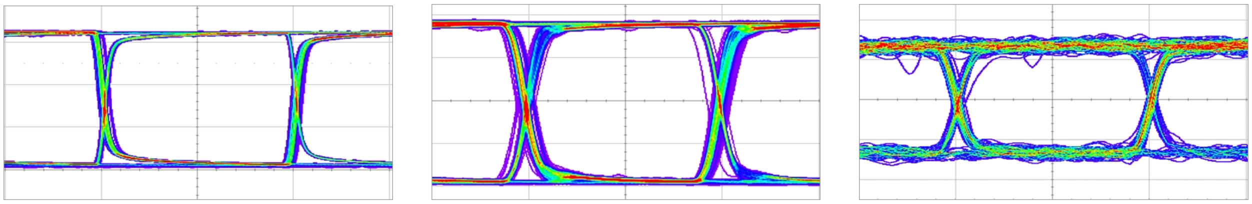
Figure 4. Picture of the experimental setup for the CAN-bus-OWC system transmission tests.

5. EXPERIMENTAL RESULTS

In order to obtain an in-depth evaluation of the quality of the digital signal, we first report in Fig. 5 the eye diagrams taken at three different levels of received optical power. To obtain the eye diagrams, we probed and analyzed the CAN-bus signal at the output of the TIA of the receiving node. We report in Fig. 5 the three different eye diagrams corresponding to -16 dBm (Fig. 5a), -26 dBm (Fig. 5b) and -34.5 dBm (Fig. 5c) of optical received power. Obviously, the performance degrades with the decrease of the optical received power, but all the eyes are well-opened, proving the good quality of the transmission. In all three cases, no error was detected.

We report in Fig. 6 the results of the BER measurements. Here, the optical power values are presented on a logarithmic scale on the Y axis and are directly proportional to the log(BER), as expected by the optical communication theory. This proportionality between the optical power and the log(BER) allows us to estimate the sensitivity of the RX, now related to the use of the CAN-bus protocol. Considering a target BER value of 10^{-12}, the value of the sensitivity extrapolated from the graph is equal to -33.7 dBm.

After the first characterization of the system, a bidirectional OWC link was established to perform a transmission test, enabling both the involved TRX to transmit and receive. In fact, for a correct bidirectional transmission using CAN-bus, the receiving node needs to transmit the ACK bit. To this aim, we used the setup shown in Fig. 3. The transmitted frame had the arbitration field set to 0x0 and the data field consisted of one byte of data corresponding to the sequence “K”, “Z”, “X”, “3”, “T”, “F”, “H”, “J”. The resulting frame was composed of 112 bits, with a total duration of 224 µs. The CAN-bus transmitted signal is shown in Fig. 7a, and it was perfectly reconstructed at the receiving node with the addition of the ACK bit. As can be seen in Fig. 7b, the last bit that corresponds to the ACK bit presents different levels of voltage compared to the rest of the frame, because of the operation made by the SAS related to its extrapolation. However, the voltage levels of the frame



(a) (b) (c)

Figure 5. CAN-bus eye diagrams probed after the TIA at −16 dBm (a), −26 dBm (b) and −34.5 dBm (c). The horizontal scale is 1 µs. The vertical scale is 500 mV/div (a); 50 mV/div (b); 10 mV/div (c).

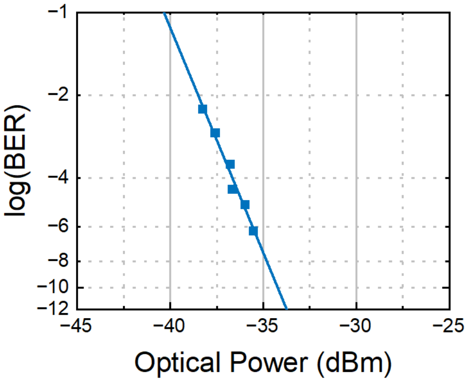
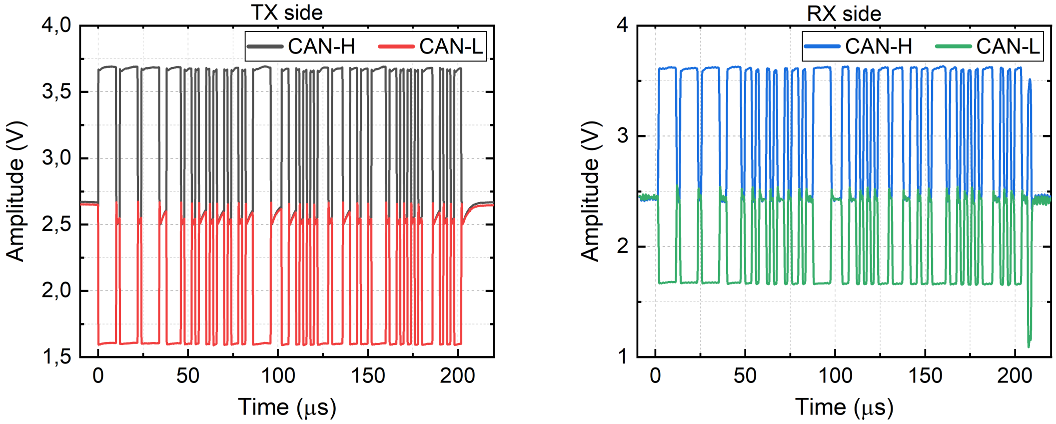


Figure 6. BER curve for the 500 kb/s CAN-bus signal transmission over OWC



(a) (b)

Figure 7. Electrical CANH and signals on the bus at the transmitter side (a) and at the receiver side (b)

are compliant with the requirements of the protocol. The transmission test has thus demonstrated the feasibility of a bidirectional OWC link using CAN-bus.

6. CONCLUSION

Here, we presented an innovative OWC solution for the optical wireless transmission of two data buses used for the data transmission on satellites: the MIL-STD-1553B and the CAN-bus. This system relies on an optical TRX and a SAS to substitute the physical cables of the buses, implementing a transparent adaptation of the standards with no need for modification of the protocols and with no digital signal processing (DSP). Substituting the data cables with wireless links would allow for a reduction in the weight of the satellites and the occupancy inside the spacecraft. Therefore, the system was designed to minimize its weight, volume, and power consumption. Moreover, the electronic boards were realized only using COTS components to minimize the overall cost of the system and to improve its reproducibility.

The system was originally designed for the OWC transmission of the MIL-STD-1553B bus and successfully characterized and tested in an intra-spacecraft scenario[16] and an AIT environment.[17] To enhance the versatility of the system, we adapted it also for the transmission of the CAN-bus, which is recently gaining popularity in the space sector. As for the MIL-STD-1553B, also for the CAN-bus transmission, we characterized the OWC system by estimating the RX sensitivity. We also performed a transmission test where we successfully established OWC bidirectional links with no observed error.

The CAN-bus protocol has some key differences from the MIL-STD-1553B. However, even with these differences, the proposed system was effectively adapted to both standards only by changing the signal adaptation stage while using the same TRX. In the future, the minor changes needed to switch between the two standards could allow for the realization of a single board with the connectors for both standards that could be directly plugged into the desired units.

This ease to be adapted to different communication standards is a key promising feature of our system, as it allows for high versatility. Therefore, this adaptable OWC solution can be improved for the transmission of other protocols as well, allowing a faster spreading of the OWC technology on satellites.

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