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Optical Wireless Interfaces for the MIL-STD 1553 bus

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ABSTRACT

The MIL-STD-1553B is one of the most used data buses for communication over aircraft and satellites. It requires a large amount of cables to connect all the onboard devices, therefore one of the most challenging issues in Spacecrafts (SCs) design is how to arrange all of them. Moreover, these wired communication systems represent up to 10% of the total mass of the satellite, introducing constraints on the cost of the mission launch and reducing the available room inside the satellite. We present here a novel system that can transport the MIL-STD-1553B signal over optical wireless, effectively removing wired connections. This can save weight and space while maintaining high performance and backward compatibility. We achieved these results by developing an innovative transceiver (TRX) board. The presented Optical Wireless Communication (OWC) system does not suffer from sniffing/jamming or from multipath interference. Moreover, it encompasses only Commercial Off-the-Shelf (COTS) components, so that no special technological development is needed and we can keep its cost low. Here, we first shortly summarize our approach and then discuss how it can be used to deploy OWC links over a SC. To this aim, our system can interface the MIL-STD-1553B data bus with the OWC devices without any modification of the protocol and of the bus architecture.

Keywords: Free-space optics, Optical Wireless communication, Spacecraft

1. INTRODUCTION

The onboard Spacecraft (SC) communication networks require a huge amount of cables that represent up to around 10% of the total satellite mass.[1,2] Moreover, this large quantity of wires takes a relevant fraction of the available space inside the SC and puts additional constraints on the cost of the mission launch and the fuel requirements. Therefore, reducing the onboard harness would be an attractive option to realize SCs that could be lighter, and smaller, with more room available for instrumentation, lower fuel consumption and lower costs.

This opportunity could be enabled by wireless technologies, i.e. transmitting data with no harness. The lower weight will reduce the use of fuel, giving a significant economic advantage and increasing the autonomy of the satellite for any possible steering operations in orbit.[1,3–5] Although Radio Frequency (RF) wireless technologies (e.g., WiFi or Bluetooth) can significantly simplify communication, they would introduce strong constraints in terms of Electro-Magnetic Compatibility (EMC) and security.[5–8] A solution to these issues is represented by Optical Wireless Communication (OWC). This transmission technology is attracting increasing interest and exploits modulated optical signals in the visible or Infrared (IR) spectral region. OWC has many advantages over RF wireless systems. As an example, it provides data links that do not produce Electro-Magnetic Interference (EMI).[5] Since light is naturally stopped by walls, it provides strong resilience to jamming/sniffing. Moreover, OWC has a high versatility, which makes it suitable for a wide range of different application scenarios.[9]

Depending on the choice of the optical components, we can design OWC systems with different values of data rate, link distances, and energy consumption. High-speed links (tens of Gbit/s) need high directionality of the light beam, and they were successfully implemented by means of a laser as the optical source.[10–12] On

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the other hand, lower rate (tens of Mbit/s) OWC systems can also use very diverging beams, even exploiting reflections/scattering from the walls. These configurations usually use Light Emitting Diodes (LEDs) as optical sources.[13] Noteworthy, thanks to the incoherent nature of this light, they are not impaired by multipath effects.[14]

In space scenarios, MIL-STD-1553B is one of the most used standards[15,16]: it is a military specification that defines a digital time division command/response multiplexed data bus. However, some of its features and the intrinsic nature of OWC links make it impossible to use the native MIL-STD-1553B straight for OWC[17] thus, in order to transmit this type of signals over a OWC link, the MIL-STD-1553B signal needs to be properly manipulated, both at the transmitter and receiver ends.

To demonstrate the feasibility of this solution, we realized an innovative OWC system able to replace the cabled communication bus in three different scenarios: Intra-Spacecraft (Intra-SC), Extra-Spacecraft (Extra-SC), Assembly Integration and Test (AIT). These scenarios present different characteristics in terms of link configuration, background ambient light, link distance, and required alignment. In order to make this system as simple as possible, we designed a flexible optical transceiver (TRX), so that it can perform transmission in a wide range of operating conditions, thus it is compatible with all scenarios. The TRX is the core of the OWC system and allows to establish a transparent transmission, hence avoiding the need for complex digital electronic devices such as Field Programmable Gate Arrays (FPGAs). It is made of three main sections: a Transmitter (TX), an Receiver (RX), and a passive signal adaptation circuit. The TX is based on an Infrared-LED (IR-LED) or a Vertical Cavity Surface Emitting Laser (VCSEL). On the other side, the RX is based on a low-cost PIN Photo-Diode (PIN-PD) with a large active area. The adaptation circuit shall make the signal suitable to be transmitted using optical wireless components.

We designed the TRX board to be light and compact in order to optimize the weight and footprint of the OWC system in the SC and to simplify the test operations during the AIT phase. Moreover, a great effort was devoted to reduce power consumption as much as possible. For the realization, we used only Commercial Off-the-Shelf (COTS) components to obtain an effective implementation, without any custom photonic components that would prevent fast development and large commercialization.

First, the boards were characterized at the Scuola Superiore Sant'Anna laboratories in Pisa to estimate the sensitivity of the receiver and to test the communication performance, both with a Non-Return-to-Zero (NRZ) and a MIL-STD-1553B signal.[18] After these preliminary tests, the whole communication system was installed and successfully tested in a relevant environment at the Thales Alenia Space facilities in Rome, exploiting a satellite mock-up and an AIT testing room. We shortly summarize the results and present a critical analysis of the key performance indicators that can be used to measure the potential for industrial development.

2. PROPOSED APPROACH AND TESTS

In order to prove this approach, we selected the MIL-STD-1553B, a military specification defining a digital time division command/response multiplexed data bus. The transmitter uses a Manchester II bi-phase bit encoding with a bit rate equal to 1 Mbit/s The MIL-STD-1553B electrical signal is sent over a shared bus, as a differential voltage on a pair of wires (a third wire is the ground). The bus conveys 20 bit data packets, named *words*, with a total length of 20 µs. Three types of devices are allowed on the bus: Bus Controller (BC), Remote Terminal (RT) and Bus Monitor (BM), each having different tasks. All of the developed OWC boards can be effectively interfaced to any of the above devices.

It must be stressed that some of the above features, as well as the intrinsic nature of the OWC links, make it impossible to transmit the native MIL-STD-1553B signal straight over a OWC link: to this aim, the MIL-STD-1553B must be adapted.[17] As an example, the signal bus uses a differential waveform that cannot be transmitted straight over OWC that uses only unipolar signals. Hence, to perform the signal adaptation, we realized an electronic adaptation stage able to convert the MIL-STD-1553B signal to one suitable to optical transmission.[17]

The core element of our OWC system is the TRX board. As shown in Fig. 1, the TRX is made of three logical parts: the signal adaptation stage, introduced above, the TX and the RX. The signal adaptation stage performs the conversion between a unipolar electrical signal, needed for the OWC transmission, and the MIL-STD-1553B differential signal. Moreover, it performs a flow control conveying the signals on the TX or RX section of the

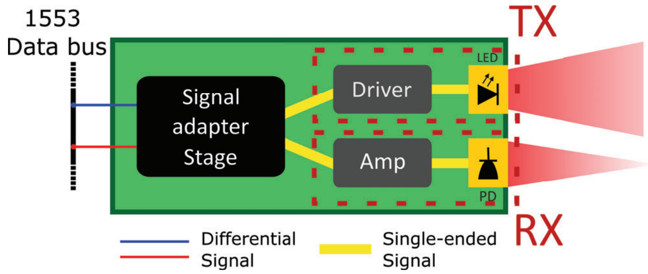
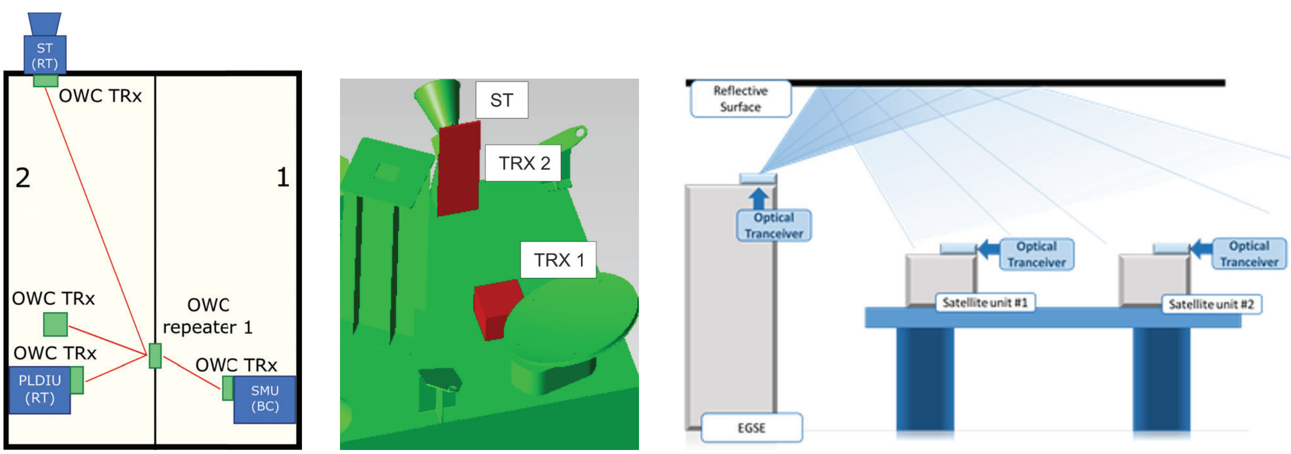


Figure 1: Block diagram of the TRX board. The differential electrical signal coming from the MIL-STD-1553B data bus is conveyed to the signal adaptation stage, its output is a unipolar electrical signal. It drives the transmitter to produce an optical signal. In the RX section, the incoming signal is detected and sent to the MIL-STD-1553B bus following a reverse adaptation.

OWC part, depending on the communication direction. The TX section is mainly composed of an electrical driver and an optical source. It receives a unipolar electrical signal from the adaptation stage that is converted to an optical signal and sent to another TRX. Finally, the RX section is composed of a photodiode and an amplification stage.

The TRX boards were designed and successfully tested in three different application scenarios. These scenarios were chosen to test the proposed OWC communication system for data transmission inside a satellite, outside the satellite among devices belonging to the same SC and during the AIT phase.

A schematic representation of all three scenarios is shown in Fig. 2. Top view of the satellite mockup is reported in Fig. 2a. The satellite is divided into four separate rooms, of which two can be seen in the figure. The TRXs were placed at various onboard devices (blue boxes in figure), all connected via OWC, also exploiting reflections/scattering from the walls. The second scenario is shown in Fig. 2b, showing an external view of the satellite. Here, the two TRXs involved in the Extra-SC scenario should be placed over the surfaces depicted in red. Finally, Fig. 2c presents a side view of the AIT testing room, where the involved TRXs are placed at the Electrical Ground Support Equipment (EGSE) on a rack and on two devices on a bench.



(a) (b) (c)

Figure 2: Application scenarios. (a) Intra-SC: top view of the SC mock-up with the onboard devices. In red we indicate the shortest optical path; (b): Extra-SC, view of the SC mock-up with TRXs devices; (c): AIT, view of the testing room with one TRX at the EGSE and two devices on the bench.

Each scenario has unique features that require a dedicated OWC configuration, which is either Non Line-of-Sight (NLOS) or Directed Line-of-Sight (DLOS). In a DLOS configuration, TX exploits a low-divergence beam and the RX shows a low acceptance angle, to maximize the received power. This is the good candidate for the Extra-SC scenario to counteract the effect of the strong background light, minimizing the transmitter power. On the other hand, in the NLOS configuration, an optical link can be established without a direct line of sight between TX and RX, as it indeed also can exploit reflections from the walls. NLOS configuration needs much higher transmitted optical power, wider emission angle at TX and wider Field-of-View (FoV) at RX. Both Intra-SC and AIT scenarios work in this configuration.

We developed an OWC system that can be used for onboard communications, in all scenarios. This was experimentally confirmed by several tests in different system mock-ups, which are not reported here: the communication performance showed that the prototypes were perfectly replacing MIL-STD-1553B electrical wires with no modification of the connected units.

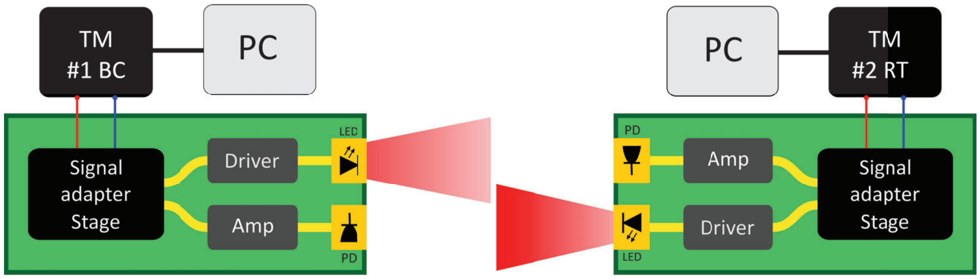


Figure 3: Communication setup involving two optical TRX.

The TRX used for these tests is the same for all scenarios and involved two or more TRX, depending on the configuration. A schematic representation of the link between two TRX is shown in Fig. 3. To simulate the bus MIL-STD-1553B and the proper interactions among the devices allowed on the bus, at each device we used a Test Module (TM) by Avionics Interface Technologies, compliant with the MIL-STD-1553B standard. An electrical signal is generated using a first TM (in this particular example working as BC) and it is sent to a first TRX. Here, the signal is adapted (as explained in Sec. 2) and transmitted optically to a second TRX. With a reverse process, the optical signal is received by the PIN-PD, amplified, converted to a MIL-STD-1553B signal and sent to a second TM box (in this example used as RT). Both the TM boxes were connected to a PC with their proprietary software: thus, the PCs controlled the transmission and analyzed the quality of the received signal. By means of this software, we monitored the ongoing transmission, collected all the information about the bus traffic and the receiving messages and performed accurate error analysis. As an example, in Fig. 4 we report a small portion of the log, as we can see from the last column of the display there are no errors reported.

The transmitted and received electrical signals were also probed to be shown on an RTO for further analysis. The results from the RTO analysis are shown in Fig. 5. In Fig. 5a, we present the waveforms corresponding to the OWC signals transmitted (blue) and received (orange) by the BC TRX. As expected for a command-response data bus, we see the transmission of a query to a RT and its response with the requested data. Different queries bring different responses, as we can see by the different number of words between the two RX messages.

In Fig. 5b, we report the eye diagram of the received signal (NRZ format). As expected, the eye is open and well-defined.

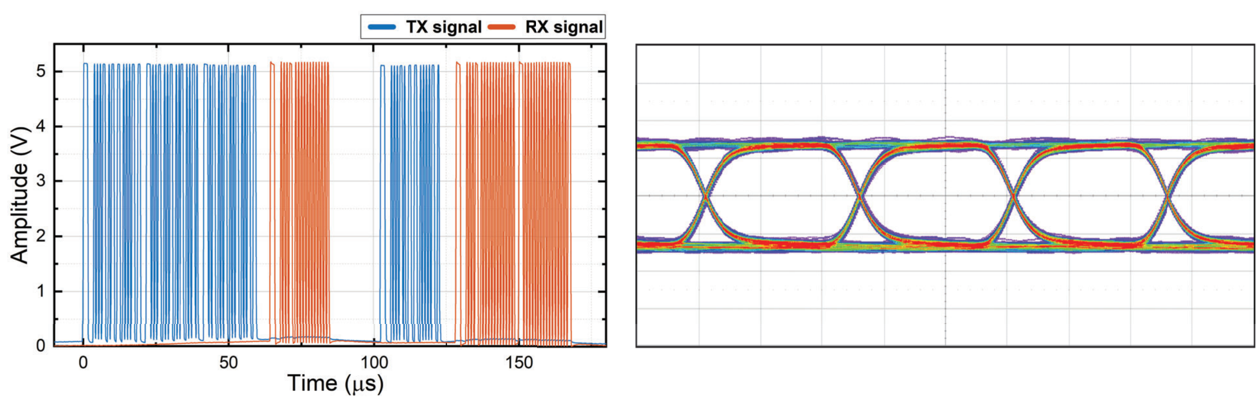
3. SYSTEM SPECIFICATIONS AND PERFORMANCE PARAMETERS

We discuss in this section the key features of our interfaces. First of all, in order to make the system as flexible as possible, we considered a key requirement that the boards design and the electrical components remain unchanged in all three scenarios. The only minor modification is indeed due to the TX source, which in NLOS is a LED and in DLOS is a VCSEL, in order to adapt the system to the link architecture.

Another key feature, which is critically important, is backward compatibility. The proposed approach assumes that the adoption of the OWC will cause the removal of transmission medium only, i.e. the data bus cables, bus couplers and connectors, but the SC units will continue to use all the current pin layout, voltages, type of coding

Time	Type	Bus	Rx Rt	Rx Sa	TR	Data	Cmd Word 1	Rx Status	Rx Response Time	Word Count	**Error**
40d 15h 25m 15s 12316us	BC-RT	PRI	1	10	R	1111:2222	C01_R_0A_02	S01_0_0...	6.00us	2	
40d 15h 25m 15s 12816us	BC-RT	PRI	1	10	R	1111:2222	C01_R_0A_02	S01_0_0...	6.00us	2	
40d 15h 25m 15s 13316us	BC-RT	PRI	1	10	R	1111:2222	C01_R_0A_02	S01_0_0...	6.00us	2	
40d 15h 25m 15s 13816us	BC-RT	PRI	1	10	R	1111:2222	C01_R_0A_02	S01_0_0...	6.00us	2	
40d 15h 25m 15s 14316us	BC-RT	PRI	1	10	R	1111:2222	C01_R_0A_02	S01_0_0...	6.00us	2	
40d 15h 25m 15s 14816us	BC-RT	PRI	1	10	R	1111:2222	C01_R_0A_02	S01_0_0...	6.00us	2	
40d 15h 25m 15s 15316us	BC-RT	PRI	1	10	R	1111:2222	C01_R_0A_02	S01_0_0...	6.00us	2	
40d 15h 25m 15s 15816us	BC-RT	PRI	1	10	R	1111:2222	C01_R_0A_02	S01_0_0...	6.00us	2	
40d 15h 25m 15s 16316us	BC-RT	PRI	1	10	R	1111:2222	C01_R_0A_02	S01_0_0...	6.00us	2	
40d 15h 25m 15s 16816us	BC-RT	PRI	1	10	R	1111:2222	C01_R_0A_02	S01_0_0...	6.00us	2	
40d 15h 25m 15s 17316us	BC-RT	PRI	1	10	R	1111:2222	C01_R_0A_02	S01_0_0...	6.00us	2	
40d 15h 25m 15s 17816us	BC-RT	PRI	1	10	R	1111:2222	C01_R_0A_02	S01_0_0...	6.00us	2	
40d 15h 25m 15s 18316us	BC-RT	PRI	1	10	R	1111:2222	C01_R_0A_02	S01_0_0...	6.00us	2	
40d 15h 25m 15s 18816us	BC-RT	PRI	1	10	R	1111:2222	C01_R_0A_02	S01_0_0...	6.00us	2	
40d 15h 25m 15s 19316us	BC-RT	PRI	1	10	R	1111:2222	C01_R_0A_02	S01_0_0...	6.00us	2	
40d 15h 25m 15s 19816us	BC-RT	PRI	1	10	R	1111:2222	C01_R_0A_02	S01_0_0...	6.00us	2	

Figure 4: BC transmission log with error report TRX; no error appears in the last column.



(a) (b)

Figure 5: Experimental results from the RTO: (a) Transmitted (blue) and received (orange) electrical signal by the BC. (b) Eye diagram of the received electrical signal

(e.g, Manchester coding) according to the current MIL-STD-1553B. This implies backward compatibility with the existing standards, which is dramatically important: all existing interfaces should not be changed.

Finally, all the electrical and optical components used to realize the boards are COTS components, including VCSEL, IR-LED and PIN-PD, and no custom elements are present. These features allow obtaining low-cost boards and a system that allows large availability since we rely upon well-consolidated components.

Finally, the system tests were completed by estimating the communication specifications and the most relevant physical features of the TRXs boards. The specification values are summarized in Tab. 1. Here, we first report the RX sensitivity, the tolerance to ambient light and misalignment and the power consumption for both the link configuration, NLOS and DLOS.

We measured a RX sensitivity of $-32\,\mathrm{dBm/cm^2}$, this value is compatible with the optical intensity values observed in the three scenarios that always were higher than $-30\,\mathrm{dBm/cm^2}$. We also obtained a good tolerance to ambient light, an important parameter in both Extra-SC and AIT scenarios, where light can come either from Sun or from artificial lighting sources. The tolerance to misalignment is a key parameter in the Extra-SC since this scenario exploits a DLOS architecture: a proper tolerance makes the system robust to possible misalignment effects. A tolerance up to $\pm 15\,\mathrm{mm}$ is considered to be well above the possible misalignment values. Furthermore, we measured that we have a very low (average) power consumption in all link architectures. This is a key parameter in all scenarios since the introduction of this technology must come with limited power consumption.

Besides the data communication, the other main objective of this study was to realize a OWC system smaller and lighter than a traditional wired system and that at the same time has low cost and high reproducibility.

Table 1: Specifications of the TRX board

RX sensitivity	$-32\,\mathrm{dBm/cm^2}$
Tolerance to ambient light	$0\,\mathrm{dBm/cm^2}$
Tolerance to misalignment in Extra-SC	$\pm 15\,\mathrm{mm}$
Power consumption	0.6 W (NLOS) 0.5 W (DLOS)
Dimensions	$10\,\mathrm{cm} \times 10\,\mathrm{cm} \times 0.5\,\mathrm{cm}$
Weight	40 g (with connectors)

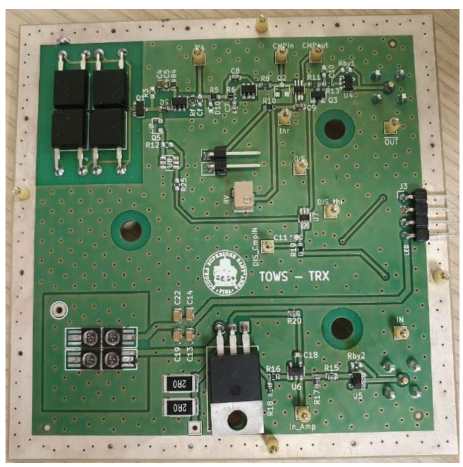


Figure 6: Pictures of the TRX board

Finally, we report in the following the critical analysis of the parameters of the developed boards, to assess preliminarily the benefits of this technology.

Physical features correspond to the weight and dimensions of the communication system. They take into account connectors, boards, cables, and physical interfaces. As we can see from Tab. 1, the physical parameters of the developed boards indicate a volume of $50\,\mathrm{cm^3}$ and a weight of around 40 g. To implement a complete OWC system a board needs to be installed at each onboard device connected to the data bus. Both these values refer to a test version of the board that includes all the connectors for signals and supplies and testing points. Moreover, the actual layout was defined to allow testing and debugging operations. As shown in Fig. 6, the space among the components is quite large and with proper space and layout optimization, the boards can be made smaller. These values are already acceptable for some applications, but it is clear that both of them can be significantly improved when integrated boards will be produced, without the testing points.

A second parameter is the time needed to implement an adopted technology. As an example, the requested time to deploy the harness of the MIL-STD-1553B instead of an optical wireless link. Indeed, the installation time of the proposed system is quite short: we realized the transceiver with a plug-and-play device to be easily connected to the onboard instruments. Concerning the production time, they can be greatly shortened compared to what is required for in-lab realization if industrial processes are used.

The cost parameter accounts for both the effective costs of all the components of the system and the man-hours needed to physically realize and implement the system itself. As mentioned before, all the electrical and optical components of the TRX boards are COTS components. According to the acquisition costs, it is possible to estimate safely that the total cost of the hardware transceiver is quite moderate and should be fully acceptable.

Another important parameter measures the capability to reuse the harness or technology in multiple phases or multiple programs. A strong point of these boards is their high reusability. A big effort was made to design a transceiver able to be used at each onboard device and in all the application scenarios without the need for any or minimal modification.

Finally, we have found a high grade of commonality of the given physical interfaces (connectors) among the onboard equipment involved in the analyzed applications. This is directly related to the fact that we will have a single type of OWC interface types for all different units onboard.

4. CONCLUSION

We realized and successfully tested an innovative wireless communication system that can seamlessly transport the consolidated MIL-STD-1553B data bus over optical wireless. The proposed solution is a transparent OWC system that exploits only analog operations with no need for any digital device, such as FPGAs or microprocessor. It works only at the physical layer, making the onboard units not affected by, nor sensible to, the replacement of the wires.

The core of the system is the transceiver board that performs the adaptation with the MIL-STD-1553B, transmits and receives the optical signal. The system was experimentally tested in various mock-ups and complete optical transmissions were established with no observed errors, between different MIL-STD-1553B standard TMs. The communication tests were carried out in three different application scenarios: Intra-SC, Extra-SC and AIT. This system results be much lighter and smaller than a traditional wired communication system, still achieving the required performance for the data transmission. Moreover, being made of COTS components, the TRX boards have high reusability, compatibility with all the onboard devices and application scenarios and low costs. Here, we shortly summarized the implementation of this system and the demonstration results obtained by means of the prototype boards of the transceivers. In a final deployment stage, both size and weight can be further improved without affecting system performance.

As an industrial prospect, it is expected that the use of the OWC system is especially attracting for the AIT phase. In this scenario, replacing cables by OWC links involves a simple system that can likely reduce significantly the time requested for set-up and tests. Moreover, the AIT phase is an attracting candidate for wireless link deployment in the near future, since the involved devices do not need to undergo the same complex procedures associated with the SC launch. Later on, OWC can become a practical alternative to wired onboard communications, reducing the cable mass and power consumption and increasing the autonomy of the satellite.

Finally, we note that we had been concerned with MIL-STD-1553B signals, but we are confident that our approach can be extended to other types of protocols currently used on SCs, which could also be transported over optical wireless signals.

ACKNOWLEDGMENTS

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