Optical Wireless Communication in an Avionics Test Facility for Spacecrafts

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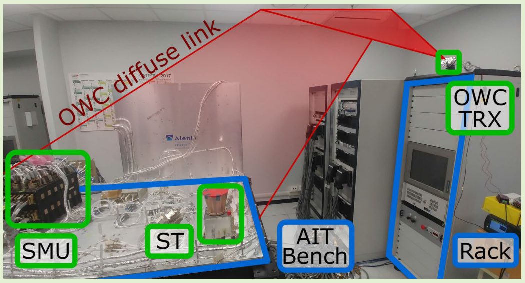

***Abstract*—We explore the evident benefits of introducing a new wireless technology in assembly integration and test (AIT), which is a key and demanding phase when commissioning a satellite. Namely, for the first time, we successfully tested an optical wireless communication (OWC) system in a real AIT room, demonstrating that it can effectively provide wireless transmission among the different units of a spacecraft (SC) and the test equipment. This environment is extremely challenging because it does not allow line-of-sight among the different units: as a result, OWC relies heavily on the diffuse illumination of the ceiling and the following light scattering. In addition to that, those test rooms present a strong ambient light that can reduce the transmission performance. The proposed system employs new OWC transceivers (TRXs) that we designed, realized, and optimized for this scenario. They adapt the native MIL-STD-1553B standard to the OWC transmission and vice versa, without any modification of the protocol. They effectively realize an OWC transparent connection, replacing the cabled connections with significant improvements in working time and costs. Mostly, they imply no modification of the existing protocol. The system is thoroughly tested by optical and communication measurements; to this aim, we emulated the usual communication measurements, placing the realized TRXs over a workbench for avionic tests. All tests showed no error and large system margins. These results prove that the OWC technology has a great potential for practical AIT applications, in the near future: this can also open the way to the wide deployment of the technology in real SCs.**

***Index Terms*—Assembly integration and test (AIT), avionics test, free-space optical communications, optical wireless communication (OWC), satellite communication.**

I. INTRODUCTION

TODAY, the space industry experiences an impressive exponential growth, thanks to several emerging applications, such as telecommunications, monitoring, and navigation [1], [2], [3], [4], [5]. To cope with this trend, the introduction of new technologies in the industry plays a crucial role. Namely, the assembly integration and test (AIT) phase should become faster and more effective [6], [7], [8], [9], [10], [11]. This phase consists of different tasks that take up to several months. Among them, the most demanding phase is the setup and test of all possible data connections among the avionic units: in this operation, all devices are first properly arranged on a workbench, then each of them is connected by electrical cable to the electrical ground support equipment (EGSE) so that these cables run through the room, from the EGSE to the units under test on the bench. Finally, the whole communication network is thoroughly tested. Therefore, the avionic industry would welcome it if one could exploit simple wireless links to replace the huge amounts of wires because can hugely speed up the verification phase and allow the production of satellites that are lighter and smaller [12], [13], [14].

Radio frequency (RF) wireless communications (e.g., Wi-Fi) might be an alternative to wired systems [15], [16], [17], [18], [19]. However, RF has severe security flaws because the signals can be easily received/jammed from outside the industrial area. Moreover, RF systems have a poor electromagnetic compatibility (EMC) with other instruments and systems. They can easily be affected by electromagnetic noise and they can in turn generate electromagnetic interference with the electronic equipment under test.

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A few years ago, it was proposed that optical wireless communication (OWC) could be an attractive solution for both AIT and onboard communications in spacecrafts (SCs) [17]. Although it is not yet commercial in space applications, OWC is an alternative to RF communications that have no EMC issue and do not generate electromagnetic interference (EMI). Moreover, OWC systems have negligible security risks and are less affected by jamming and sniffing issues since the light radiation is easily shadowed and confined. A wide range of different OWC systems can be designed to transmit signals of various data rates, over different link distances, in various environments, according to the application. As an example, high-data-rate links (tens of gigabits per second) use a collimated laser beam and line-of-sight (LoS) between transmitter (TX) and receiver (RX) [20], [21], [22].

However, in AIT, the wireless signal should cover a large area (about 10 m^2), and thus, a very different type of system is required. Furthermore, the links could suffer from shadowing effects: as LoS cannot be achieved, the light should reach the RX by exploiting reflection/scattering from spurious elements, e.g., the ceiling. Moreover, in AIT, we expect a significant background light, due to the needs of human operators. This brings the issues of eye safety and relevant white-light background.

Another key design issue is that OWC must be compatible with the data buses used for onboard communication. Among them, the most relevant is the MIL-STD-1553B, which defines a digital time-division command/response multiplexed data bus [23], [24]. Unfortunately, its main features and the nature of OWC links make it impossible to use the native MIL-STD-1553B straight for OWC [25]. A few years ago, complex OWC prototypes for onboard communication were realized; however, they proved to be bulky and heavy for practical requirements [26], [27], [28], [29], [30] and they were not considered for further studies. It was, however, clearly established that AIT could be the first scenario where the OWC will be implemented. This is mainly because a new technology can be quickly introduced in a conventional test lab, on Earth, where no space-grade test is required.

Clearly, not all the possible OWC systems solutions can effectively bring real advantages with respect to a traditional wired system, without introducing further issues. First, an effective OWC alternative must work only at the physical layer without any modification to the communication protocol. Then, a valid OWC system needs to be as small as possible to minimize the weight and volume and have very low power consumption. Moreover, it should be realized using components that minimize the overall cost and improve its reproducibility.

In order to respond to these specific requirements, the project transmission of optical wireless signals for telecom satellites (TOWS) recently proposed an innovative, different approach, based on an optimized adaptation of the MIL-STD-1553B to OWC, without digital devices such as field-programmable gate arrays (FPGAs) or microprocessors [31]. We choose to design our OWC system to adapt the MIL-STD-1553B since this is one of the most used data buses currently in used onboard satellites [23]. TOWS includes the analysis and demonstration of MIL-STD-1553B over OWC in AIT tests as the most relevant application scenario. To this aim, the transceiver (TRX) was designed to work exclusively at the physical layer so that it is transparent to protocol information and ensures backward compatibility with the present standard: on each unit, a cable interface can be replaced by one TRX. With these assumptions, TOWS represents a breakthrough in data transmission onboard SC. It implements a novel, effective, and straightforward solution that simplifies the satellite communication system. Moreover, it is designed to be plug&play, and then, it can be easily implemented without requiring modifications to the current bus protocol.

These TRXs are based on commercial off-the-shelf (COTS) components and have limited footprint; they were designed, realized, and characterized in our laboratory [32], where we also emulated a first unidirectional transmission of MIL-STD-1553B [33]. The TRX prototypes were first deployed in a recent experimental demonstration of an MIL-STD-1553B transmission performed in the intra-SC scenario, i.e., in a dark environment with shadowing effects [34].

Here, we report on the subsequent demonstration in a real AIT room at the Thales Alenia Space facility (we highlight that these are restricted access areas and the procedure to employ these spaces to run tests and measurements is not simple). The specific optical characteristics here are very different: on one side, a relevant background light is present and, on the other side, we can exploit effective scattering from the ceiling. Also, all the SC equipment under test is distributed over a table and assessed using the EGSE equipment, which is well separated. We experimentally prove that the OWC successfully replaces the wired MIL-STD-1553B links, effectively providing communication between the EGSE and the other devices.

This article is structured as follows. First, in Section II, we briefly summarize the working principle of the optical TRXs used and discuss the choice of the optical components. In Section III, we describe the features of the AIT room. In Section IV, we describe the transmission tests and the results of complete communication among the devices. Finally, in Section V, we report the complete characterization of the testing bench for OWC transmission.

II. PROPOSED APPROACH

Here, we briefly recall the TOWS approach about the transmission of MIL-STD-1553B signals over OWC. The current MIL-STD-1553B data bus transmits a 1-Mb/s signal based on a time-division command/response scheme, over three electrical wires [23], [24]. The signal is encoded according to a Manchester II biphase code as a three-level digital signal. Over the bus, data are delivered in packets: those are defined as *words* and these words fall into three different categories, i.e., command word (CW), status word (SW), and data word (DW). Every word has a total length of 20 bits (20 μs).

The main challenge in establishing a novel OWC link in this scenario is meeting the strict requirements of the SCs design, rather than the transmission data rate. Here, it is crucial to maximize the adaptability of the proposed system to the existing bus. Moreover, the footprint of the communication

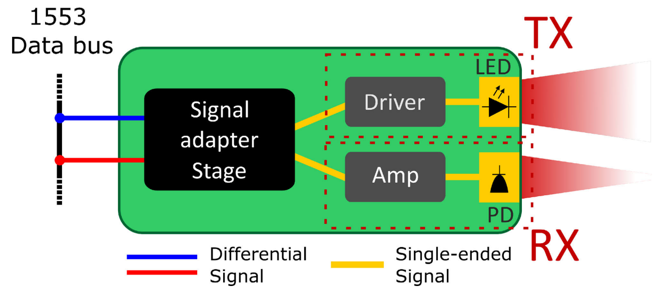


Fig. 1. Block scheme of the TRX board. TX: LED and driver. RX: PD and amplifier.

system should be minimized since mass, volume, and power consumption are key parameters when designing a satellite.

According to this goal, we realized an OWC solution that can be used to test the data network without deploying any physical wires; most importantly, this does not affect the other parts of the data network, i.e., it has no impact on the protocol that is not modified [31]. We designed a TRX board that can be directly connected to the MIL-STD-1553B bidirectional bus, effectively replacing the physical cables. Moreover, we realized these boards by implementing only analog solutions, without any digital signal processing (DSP), to minimize power consumption and to keep a low level of complexity. Finally, the TRXs are made exclusively of COTS components, so they do not require any new and special device, which can potentially allow for fast production and high reproducibility and versatility of the system.

We highlight that, in this first version of the system, the TRX boards are separated from the equipment, yet they were designed so that, in the future, they could be directly integrated within the onboard units.

They are made of three main sections: TX, RX, and signal adaptation stage, as shown in Fig. 1. The TX section includes the optical source (i.e., an LED) and an electrical driver; the RX consists of a photodiode and an electrical amplification stage. The signal adapter plays a critical role, as it receives a differential MIL-STD-1553B signal directly from the bus (red and blue lines in Fig. 1) and converts that into a on–off keying (OOK) signal, which is the simplest modulation format and with the highest power efficiency for OWC transmission, and vice versa [32]. As an example, in the transmission from one device to another, the bipolar Manchester signal from the MIL-STD-1553B interface is first converted to an electrical OOK signal; this drives the LED producing the optical signal, which is then transmitted over free space. The OWC signal is then detected by the RX of the second TRX, producing an electrical signal and converted by the signal adapter back into a differential signal. The last is eventually transmitted to the receiving unit on the bus. These boards were characterized by measuring the RX sensitivity, i.e., the minimum received optical power to have a bit error ratio (BER) of 10^{-12}. In our case, the sensitivity was carefully measured and was found to be −37.5 dBm/cm^2. A deep description of the TRX board, the specific analog processing in the signal adaptation, and the characterization measurements can be found in [32].

The selection of the optoelectronics devices has to be optimized according to the transmission scenario. Here, the AIT application requires non line-of-sight (NLOS) links and a wide coverage area [35]. In this architecture, the OWC link exploits reflection and scattering from various surfaces (in our case, the ceiling) to achieve communication. Thanks to a diverging beam, the light intensity is thus diffused over a large volume and produces a wide coverage area; as we will see, the proper design of the TXs allows to reach the minimum required optical power at the RXs when one TRX is placed in any position over the whole working area and the other is on the rack.

TABLE I
SAFETY VALUES FOR THE EYE AND THE SKIN OF OUR TXS

Eye	Skin
1000 s at 30 mm	10 s at 5 mm

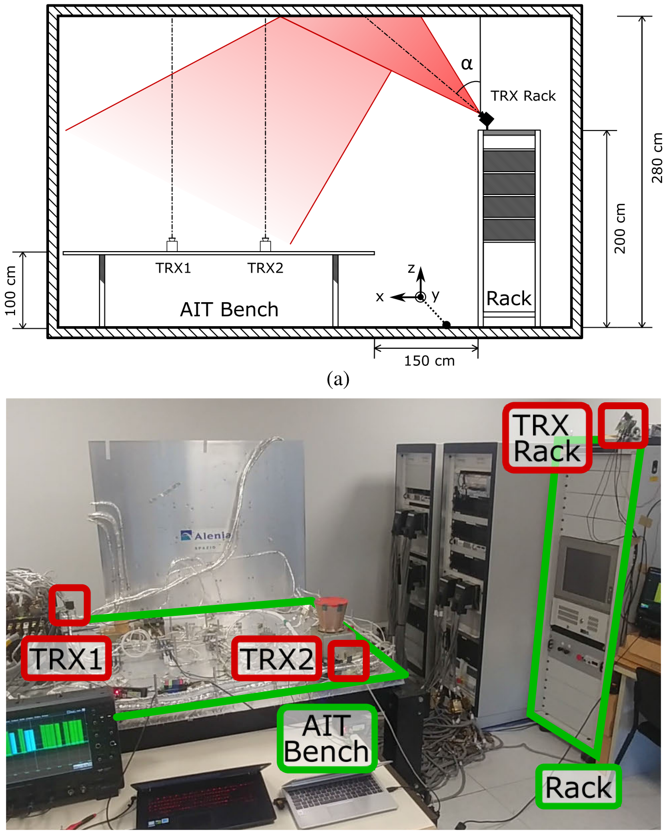
To this aim, the TX encompasses an array of four LEDs (850-nm peak emission wavelength, 50-nm spectral width of around, and 90° emission angle). Under modulation, the combined optical peak power is 1.2 W. We chose a source in the infrared (IR) spectrum, mostly because the AIT environment has human workers; thus, it has quite high visible illumination, and hence, visible-light OWC would be affected by strong noise, degrading the system performance. Using the IR light, we can filter out a large portion of this ambient noise. Moreover, the IR sources allow for much higher eye-safety levels. On the other hand, we did not use longer IR wavelengths, because in this region, the available COTS optical components for OWC do not reach the same performance as the components in the near-IR spectrum (<1000 nm). We also highlight that using an LED source (producing incoherent light) makes interference and multipath effects negligible. Moreover, in our case, the exposure time and distance between the operators and the optical sources satisfy the safety limits, thus implying no risk to the eyes and skin of the technicians. This is confirmed by the values in Table I, where we report the maximum acceptable exposure times for both eye and skin, at given distances. As indicated in [36], these values were estimated under worst case conditions, i.e., assuming a uniform intensity distribution in place of the real LED emission pattern and a continuous emission of radiation in place of the modulated signal.

The overall power consumption is in line with the power budget of a satellite. Taking into account the Manchester modulation and the typical data traffic on the bus, we estimated that the average electrical power is estimated around 0.6 W, in the present prototypes.

At the RX, the NLOS configuration requires a large-area photodetector, which can work at very low irradiance values. Therefore, on all our boards, the RX encompasses an array of four Hamamatsu p-i-n photodiodes (PIN-PDs), each with a photosensitive area of 26 mm^2, 0.55-A/W responsivity, and 120° field-of-view (FoV).

III. EXPERIMENTAL ENVIRONMENT

After the preliminary characterization in our laboratory [33], we performed tests and measurements in a real industrial



(a)

(b)

Fig. 2. AIT room. (a) Experimental setup, where two TRXs are on the bench (left) and another is on the EGSE rack TRX (top right). (b) Room picture, where the actual positions of the TRXs are highlighted in red.

environment, i.e., the AIT facilities at Thales Alenia Space, in Rome. We set up and assessed our OWC solution in a room where the subsystem avionics (AVS) test is routinely performed in the AIT phase. The routine procedure requires that all subsystems are connected by a network of electrical cables, exactly as they would be on the SC. The devices under test are placed on the bench and they are then connected to the EGSE, which is used to monitor the signals on the bus and placed on a separate rack.

In the OWC scenario, various TRXs should be closely connected to different pieces of equipment on the bench and another TRX should be closely connected to the EGSE. All data should be transmitted by OWC so that no communication cable should be present. In Fig. 2, we present the scheme of the setup and a picture of the testing room. In order to provide excellent signal coverage in the AIT setup, our NLOS OWC links exploit light scattering from the ceiling and highly diverging beams. This link architecture allows illuminating the whole table from the EGSE (and vice versa), obtaining a uniform irradiance distribution on/from the bench. We highlight that the table was populated with real satellite devices, using an experimental environment similar to the real testing setup. Here, many onboard subsystems of the satellite are simultaneously tested on the bench: however, assembling a complete AIT setup was unfeasible, because of limitations in time and equipment.

In order to simulate an AVS test using OWC, we used three optical TRXs. The first (TRX-Rack in Fig. 2) was placed on the top of the rack of the EGSE and it is assumed to provide OWC connectivity to the EGSE. As shown in Fig. 2(b), the other two TRXs (TRX1 and TRX2) were placed on the bench at typical locations of the two most representative units: the system main unit (SMU) and star tracker (ST), at 300 and 175 cm from the rack, respectively.

In Fig. 2(a), we show the EGSE on the rack and two units on the bench. The height values of the room ceiling, the rack, and the bench are 2.8, 2, and 1.5 m, respectively, and the horizontal distance between the rack and the bench is 1.5 m. For the sake of clarity, in Fig. 2(a), we only show the transmission beam from the TRX placed on the EGSE rack (TRX-Rack) to the TRXs placed at units on the bench. In the other communication direction, similar beams are emitted by the boards on the bench, illuminating the TRX-Rack.

As we can see, the TRX-Rack is tilted by an angle $\alpha = 45°$, while the TRXs at the tested devices point directly to the ceiling.

The indoor lighting in the room is provided by white LEDs: the measured illuminance on the bench is about 600 lx. Therefore, combining the NLOS configuration and this high background light, this configuration results to be very challenging. An optimized design led us to use a wide emission angle at TX and wide FoV at RX, as said above. These choices allow us to reach the RX sensitivity, hence effective communication, only thanks to the quite high optical power.

In this environment, we performed two sets of measurements, which will be described in Sections IV and V.

IV. OPTICAL TRANSMISSION TEST

A. Transmission Setup

First, we set up the OWC boards and tested the MIL-STD-1553B communication over the wireless links. As already mentioned, any real test phase involves various devices connected to the communication bus; however, because of the complexity of the setup, we performed the communication involving two onboard devices in the most significant positions. Nevertheless, the transmission with two devices is enough to verify the proper functioning of the overall bus. This is possible because the same type of issues related to propagation, crosstalk, return loss, and time-division multiple access (TDMA) would be present in a network with a higher number of nodes.

We present in Fig. 3 the scheme of the experimental setup for the communication experiment. We used three test modules (TMs) (two for the devices on the bench and one for the EGSE) to simulate the MIL-STD-1553B bus and the proper interactions among the devices on the bus [bus controller (BC), remote terminals (RTs), and bus monitor (BM)]. The TMs are specific equipment by Avionics Interface Technologies and they are the most frequently used electronic devices to test the communication among MIL-STD-1553B units. The TM at the EGSE controls and monitors the transmission on the bus so that it was configured as both BC and BM, while the TMs at the testing devices were set as RTs.

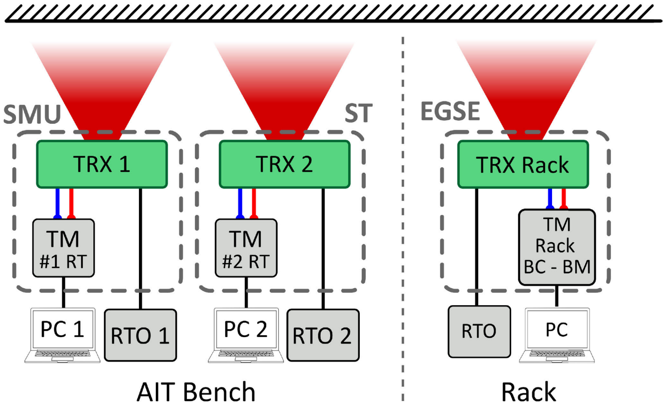


Fig. 3. Setup for the OWC experiment. Each TRX board is connected to an RTO to probe the signals and to a TM for the MIL-STD-1553B bus, and the TM is controlled by a PC.

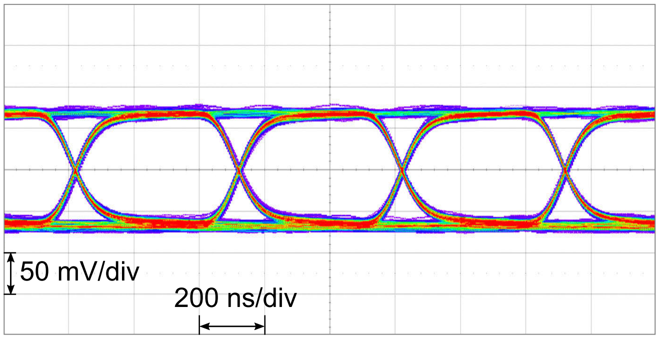


Fig. 4. Electrical waveforms probed by the RTO at the three positions: (a) EGSE, (b) SMU, and (c) ST. At each TRX, the RTO detected either the transmitted signal and the received signals. 4.

Let us first recall the flow of the data packets transmitted on the bus, according to the protocol. The communication starts with the generation of a query by the BC (TM Rack in Fig. 3). It sends a Manchester bipolar electrical signal to the signal adapter of a first TRX, and this signal is converted to OOK format and then transmitted over OWC [32]. On the other side of the optical link, the OOK optical signal is received by the PDs of the various RXs, and the single-ended electrical signal is converted back into a bipolar signal by the signal adapter. The electrical query is then received by all the RTs (TMs #1 and #2 in Fig. 3), but, according to the protocol, only the queried RT replies with the requested data. The other RT remains silent.

At each TRX, the transmission was analyzed by means of software running on a PC and a real-time oscilloscope (RTO). Using the PC, we monitored the BM logbook, which contains all the information about the data exchanged on the bus and keeps track of the transmission errors. Simultaneously with the data transmission, the RTO recorded the RX output to monitor and analyze the electrical waveforms.

B. Transmission Results

The first insight about the quality of the transmission was obtained by the eye diagrams of the received signals, obtained from the waveforms probed by the RTO after the PD. As an example, we report in Fig. 4 the eye diagram of the signal received by the TRX2, taken with the signal irradiance of -19.5 dBm/cm^2 and a Q-factor $\ll 20$, We can see that the eye was well open and symmetric; moreover, the jitter was far below the MIL-STD-1553B tolerance of 25 ns.

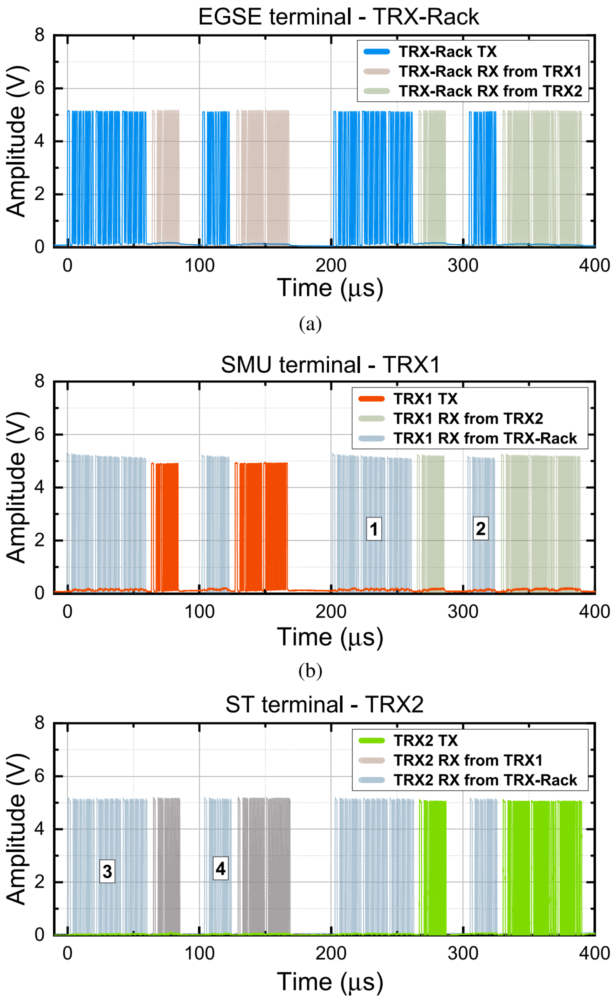
In Fig. 5, we present the typical Manchester waveforms received at each device and the communication steps, according to the working principle of the MIL-STD-1553B explained previously. Each of these waveforms was taken by the corresponding RTO. Here, we see the data sequences exchanged among the devices. As can be noted, all the received waveforms are equal because the MIL-STD-1553B is a bus protocol where all units receive all packets: indeed, all devices detect all the transmitted signals on the bus. In order to better distinguish the behavior of the different units, we indicated the signals by each device with different colors. We can clearly see that each device transmits one or more words of 20 μs.

In Fig. 5(a), we report the packets received and transmitted by the TRX-Rack, i.e., the traffic on the BC: in particular, the bright blue waveforms are the queries by the TRX-Rack itself, while the light red and light green waveforms are the RT replies by the TRX1 and TRX2, respectively. In Fig. 5(b), we present the probed electrical signals at the TRX1. Here, the bright red waveforms indicate the packet replies by the RT-TRX1 to the BC query; on the other side, the light blue and light green waveforms are the received signals from the TRX-Rack and the TRX2, respectively. Similarly, in Fig. 5(c), we show the signals at ST terminal: the bright green waveforms are the replies of the RT-TRX2 to the BC and the light blue and light red waveforms are the signals from the TRX-Rack and TRX1.

We highlight that, as in usual MIL-STD-1553B communications, although each RT received all packets, it replied only to the queries addressed to it and ignored all the others. This primary–secondary mechanism is inherited by the MIL-STD-1553B protocol. This can be seen in Fig. 5(b) and (c): TRX1 receives the queries from the BC [#1 and #2 in Fig. 5(b)], but no replies are transmitted by the RT itself, and similarly happened in Fig. 5(c) for the TRX2, placed at the ST [#3 and #4 in Fig. 5(c)].

The final analysis of the whole communication system was performed by means of the BM. This only listens to all messages on the bus recording all the information about devices and data (e.g., addresses and subaddresses of the RTs involved, transmitting status, received and transmitted data by each device, devices status, responses time, numbers, and type of errors). In Table II, we present a portion of the BM logbook corresponding to a 30-min acquisition time window. Here, we can see the key information about the transmission: address and subaddress of the queried RT, the transmitted data, and the number of words transmitted. The last column reports the observed errors: as we can see, this column is empty, indicating that, in the considered transmission, no error was observed.

The report of the BM definitely confirms that a perfectly working communication was established between the BC and the RTs. This transmission occurs with no detected errors (the last column in the BM log) and it meets all the



(a)

(b)

(c)

Fig. 5. Electrical waveforms probed by the RTO at the three positions: (a) EGSE, (b) SMU, and (c) ST. At each TRX, the RTO detected either the transmitted signal and the received signals. 4.

TABLE II

SECTION OF THE BM LOGBOOK OF THE COMMUNICATION AMONG THE THREE UNITS, DETAILING THE EXCHANGED DATA. WE HIGHLIGHT THAT THE LAST COLUMN SHOWS NO ERROR

Time (µs)	Type	Rx Rt	Tx Rt	Rx Sa	Tx Sa	TR	Data	Word Count	Error
0	BC-RT	1		10		R	BC10:BC11	2	
94	RT-BC		1		10	T	1101	1	
168	BC-RT	2		20		R	BC20:BC21	2	
261	RT-BC		2		20	T	2201:2202	2	
500	BC-RT	1		10		R	BC10:BC11	2	
594	RT-BC		1		10	T	1101	1	
668	BC-RT	2		20		R	BC20:BC21	2	
761	RT-BC		2		20	T	2201:2202	2	
1000	BC-RT	1		10		R	BC10:BC11	2	
1093	RT-BC		1		10	T	1101	1	
1168	BC-RT	2		20		R	BC20:BC21	2	
1261	RT-BC		2		20	T	2201:2202	2	
1500	BC-RT	1		10		R	BC10:BC11	2	
1594	RT-BC		1		10	T	1101	1	
1668	BC-RT	2		20		R	BC20:BC21	2	
1761	RT-BC		2		20	T	2201:2202	2	

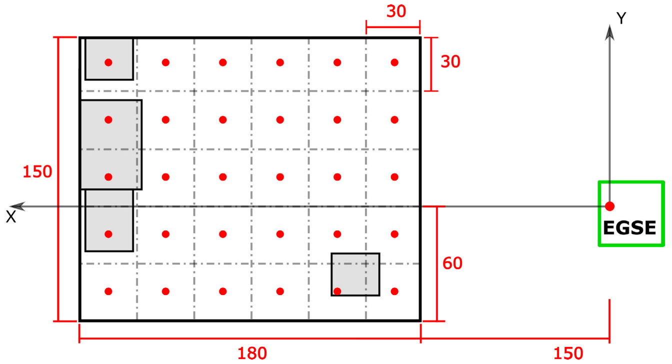


Fig. 6. Top-view configuration of the irradiance measurements. In the table, data were taken at the center of each square (red dots) of a grid. The gray areas represent actual equipment.

MIL-STD-1553B standard requirements, proving the transparency of the signal adapting system [25].

V. OPTICAL IRRADIANCE DISTRIBUTION

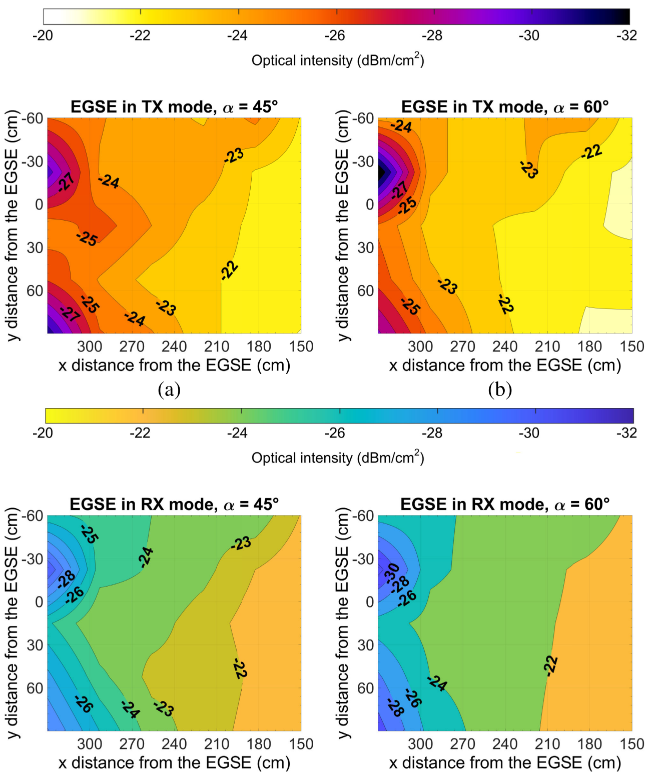
As said, the previous tests were performed with two units on the bench. In order to extend the validity of these measurements, we experimentally investigated the robustness of the link over the whole surface of the bench, by estimating the power budget for the different positions of the devices, in both transmission directions. First, we set the TRX at the EGSE in transmitting mode and measured the received optical irradiance (I_{opt}) over the whole AIT bench. Then, we measured I_{opt} at the EGSE rack when a TX on the bench was transmitting.

Let us introduce this measurement by referring to Fig. 6: here, we divide the bench into 5×6 squares with 30 cm side.

First, when the TX was at the EGSE, we measured the I_{opt} value at the center of each square. In each measurement, both the optical source and the PD were connected to a sourcemeter for the LED power supply and for the photocurrent measurement. The sourcemeter was controlled by a PC using a homemade routine. The photodetector was a Si-PD from Hamamatsu (324-mm^2 photosensitive area and 0.47-A/W responsivity at 850 nm). For this measurement, the optical source was the same as the OWC TRX.

At any point, we first measured the background photocurrent (i_{bkg}) when the LEDs were off. Then, the LEDs were switched on and we measured the output photocurrent (i_{ON}). The photocurrent due to only the LED signal was $\Delta i = i_{\mathrm{ON}} - i_{\mathrm{bkg}}$. From this value and the PD specifications, we estimated the I_{opt} value. This operation was repeated in all 30 positions. At each point, we measured the I_{opt} value for 45° and 60° α angles [see Fig. 2(a)] of the TRX at the EGSE.

In Fig. 7(a) and (b), we report the optical irradiance distribution obtained by interpolating the measured values to cover the whole bench. As can be seen, in both cases, the received irradiance is higher than the RX sensitivity (–37.5 dBm/cm^2) [32] since the lowest measured value is –32 dBm/cm^2. Thus, we can assume that TRX 1 and TRX 2 can safely receive data at any position on the bench. We also note that there are a few small differences between the two α, but there is no substantial discrepancy; yet, when $\alpha = 45°$, the distribution is slightly more uniform over the table. These experimental results can be compared to the theoretical values of the incident irradiance on the bench when the ceiling works as a perfect reflector. In this ideal scenario, irradiance on the



(a) (b) (c) (d)

Fig. 7. Measured irradiance distribution for the two TRX-Rack communication modes: transmitting mode at (a) 45° and (b) 60°, and receiving mode at (c) 45° and (d) 60°.

bench would be between −27 and –21 dBm/cm^2, with the maximum value on the side of the bench closer to the rack. Our results report the irradiance values between −32 and –22 dBm/cm^2. However, the minimum value of –32 dBm/cm^2 is due to the shadowing produced by the dummy units so that, if we remove the shadowing unit, the minimum value is around –25 dBm/cm^2. As can be expected, with respect to the case of an ideal reflector, we have a lower maximum irradiance and the distribution on the bench is more uniform, namely with a spread of about 3 dB, and this increases the robustness of the communication links.

We then tested the link robustness in the reverse communication direction. To this aim, we measured the optical irradiance at the TRX-Rack when the light source was placed at the centers of the squares on the table. The obtained distributions are reported in Fig. 7(d), which reports the irradiance received at the TRX-Rack. Again, the I_{opt} values are in a range from −32 to –20 dBm/cm^2, and thus, they are always higher than the RX sensitivity. Over most of the bench surface, the irradiance values have only small and negligible differences when the configuration parameters change and they are quite higher than the sensitivity (by at least 5 dB). This difference makes us confident that optical links can be established also in other AIT rooms when the ceiling is made of different materials since the system can accept a reduction of the received irradiance down to 30% with no noticeable degradation of the performance. This would correspond to a reflectivity of around 0.18%, which is lower than all values reported in [37] for a wide range of different materials. Moreover, the margin of 5 dB (with respect to the RX sensitivity) can allow the effective use of ceilings of different materials, with the present optoelectronic components.

These results confirm that a TRX placed anywhere on the bench can establish high-quality wireless bidirectional communication. This means that the TRXs can be connected directly to the respective unit, without the need for additional cable.

VI. CONCLUSION

We presented the ever-first experimental demonstration of MIL-STD-1553B optical wireless transmission in a real avionics test facility. In order to operate an OWC link in this environment, we designed and realized novel bidirectional TRXs; they were placed in the most relevant positions of the tested devices over a real workbench: we proved that the system can successfully replace the communication cables to/from the EGSE, thus significantly simplifying the AIT operations. The TRXs are based on common COTS components, and thus, they need no special photonic technology, and they are designed to maintain backward compatibility with the existing MIL-STD-1553B standard. Moreover, they encompass no DSP, which makes them very simple to deploy. The results indicate that the OWC technology can find a relevant application in the space industry, to make the test phase much faster and more effective. Moreover, thanks to the wide use of MIL-STD-1553B in avionics, the same solutions can also be exploited in aeronautics.

Although the bit rate is quite lower than in other OWC demonstrations (e.g., [38]), the AIT environment is extremely challenging to any optical wireless system because it does not allow line-of-sight among the different units; therefore, the communication relies heavily on the diffuse illumination of the ceiling and the following light scattering. No error was observed in the various transmission tests, as all devices always worked according to the MIL-STD-1553B requirements. A deep characterization of the signal intensity distribution shows that all over the bench the optical links had at least 5-dB margins in both transmission directions. Thus, OWC bidirectional links can be established for any arbitrary position of the devices.

We note that the realized system can be further optimized, producing a very compact TRX board to further reduce footprint and weight. Moreover, in the future, the TRXs will be connected directly to the respective unit, without any additional cable or, in the long term, directly integrated into the electronic units. The direct connection will be used for the power supply and to convey data to/from the OWC TRX. Another future research line will be about designing the signal adaptation stage to work with other bus standards (e.g., CAN-bus and SpaceWire) among those that are currently used onboard. Furthermore, the design of the system can be enhanced to be employed in many different AIT environments, in addition to the specific avionics test room where we tested this first version of the OWC system. From a long-term perspective, the establishment of the OWC technology and the improvement of its reliability of OWC systems onboard satellites and during the AIT phase could eventually lead to the development of specific standards for the OWC data transmission on satellites. This is partly similar to what happened with the release of a communication standard for the transmission of OWC Ethernet signals in indoor (terrestrial) environments [39].

Furthermore, introducing OWC in the AIT phase is commonly viewed as the first step toward the widest deployment of this new technology for onboard communications on flying SCs: the test environment is indeed simple to control and does not involve space-graded subsystems, and thus, an innovative technology can be quickly adopted and operated. Once the technology is established in terrestrial labs, it could be then moved to a very challenging space environment, with high standards for reliability and performance.

As publicly stated by European Space Agency (ESA) [40], these results represent indeed a significant innovation in the area of wireless systems for space applications, indicating a realistic path toward the development of cable-free satellites.

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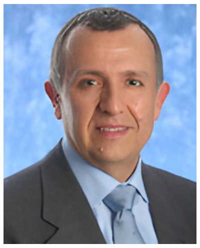

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