WIRELESS INTRA-SATELLITE LIFI DUAL CAN BUS NETWORKS FOR REDUNDANCY AND THROUGHPUT

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Abstract

The SatelLight project focuses on the development of wireless Light Fidelity (LiFi) for nano-satellite intra-satellite communication. LiFi can provide several advantages over physical or wireless radio-spectrum based communication including a reduction in harness mass, improved reliability by removing connectors, immunity to electromagnetic interference, enhanced protection against eavesdropping, and powering of low power sensors. As part of the SatelLight project a LiFi transceiver has been developed that functions in low levels of ambient light and supports the Controller Area Network (CAN) and Universal Asynchronous Receiver Transmitter (UART) protocols. This transceiver has been shown to support communication between groups of nodes using CAN of up to 4 nodes over distances of $12\,\mathrm{cm}$ between each node at a baud rate of $1\,\mathrm{Mbit\,s^{-1}}$ and using UART at distances of up to $30\,\mathrm{cm}$ at baud rates of $4\,\mathrm{Mbit\,s^{-1}}$. However, in real world satellite bus networks, redundancy is a vital requirement for most if not all space missions. This paper presents a redundant wireless intra-satellite LiFi CAN network. The network is composed of two independent CAN physical layers transmitting on different wavelengths of light. Each physical layer is implemented as a set of LiFi transceivers where each node in the network is connected to two transceivers. This allows for the redundancy concept to be configured on the fly. The redundancy can be configured as a dual network where both networks are communicating concurrently which increases the throughput of the network. It can also be configured as a cold redundant network where only one physical layer is communicating at a time. This can also be used as a power saving method where network throughput can be reduced to conserve the power consumed by the transceivers. In addition, this can be configured on a per-node basis where high priority nodes use the dual physical layers while other nodes only use a single physical layer. The results presented in this paper show the distances and error rates are the same when only a single wavelength is transmitted or multiple wavelengths are transmitted. It also includes power measurements showing the power required for each physical layer and the trade-off between power usage and network throughput.

Keywords

Intra-satellite Communication, LiFi, CAN, Nano-satellite, Redundancy

1. INTRODUCTION

A significant factor in the mass of a satellite is the harness used for power delivery and communication. This accounts for approximately 8% of the total satellite mass [1] which is composed of 55% for the data harness, approximately 20% for the mechanical fasteners and shielding, and the rest is power distribution cables [2,3]. Reduction in satellite mass allows for reduced launch costs, more fuel to be added to the satellite to extend its life, or additional payloads or systems to be added to the satellite. Wireless optical and radio frequency technologies can both be used to replace wired communication harness, however, optical communication does not cause electro-magnetic interference.

LiFi is a wireless optical communication system that is capable of transmitting data over the visible light, ultraviolet, and infrared spectrum. A transmitter such as a Light Emitting Diode (LED) transmits visible light through free space using diffuse broadcast or point to point links that is received by a sensor such as a photo resistor or a photodiode as shown in Figure 1.

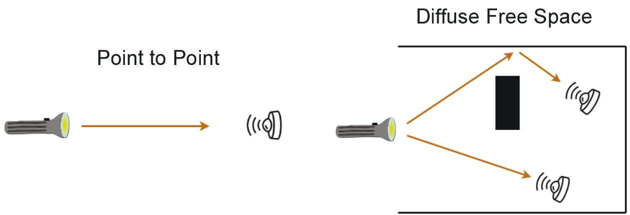

FIG 1. Point to Point and Diffuse Free Space Links

The main advantages for using wireless optical communication for intra-satellite communication are:

- Reduction in satellite mass and complexity by reducing the satellite harness.
- Increase in reliability by removing cables and connectors.

- Communication in unregulated spectrum with large available bandwidth.
- The energy of light can be used to power small components.
- Does not cause electromagnetic interference.
- Increase in eavesdropping and interference immunity.

A common protocol for intra-satellite communication is the CAN protocol [4–6]. To communicate using CAN, all nodes in the network need to see the transmissions from all other nodes. This can be problematic in nanosatellites when using optical free space communication, where tightly packed components can cause shadowing between nodes. In addition, satellite bus sub-systems are often implemented on a stack of Printed Circuit Boards (PCBs). This illustrates some of the challenges of the implementation of free space optical communication; how to transmit light between stacks of PCBs, how to transmit light between sub-systems on different sides of the satellite, and how to implement a shared satellite communication bus between all sub-systems without always having a direct line of sight between all sub-systems.
In real world satellite missions, redundant satellite communication busses are a common requirement for most if not all space missions. In a wired satellite bus, this can be implemented by duplicating the CAN transceivers and the communication harness as shown in Figure 2.

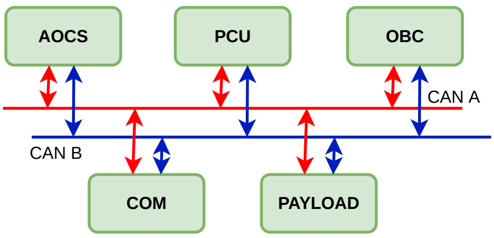

FIG 2. Redundant Wired CAN Satellite Bus

For LiFi satellite busses, this is implemented by having duplicate transceivers but having these transceivers functioning at different wavelengths as shown in Figure 3. To provide isolation between the wavelengths the receiving sensor will also require a filter to limit the wavelengths that the transceiver can receive.

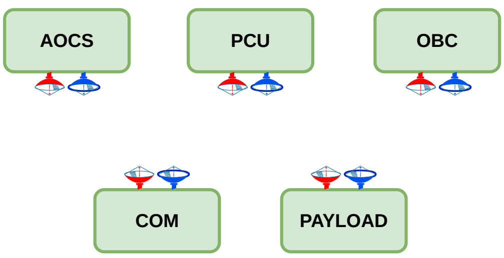

FIG 3. LiFi CAN Satellite Bus

While duplicate satellite busses provide redundancy, they can also be used to increase the bandwidth available on the bus. For example, two busses running at $500\,\mathrm{kbit\,s^{-1}}$ can be used to implement a bus running at closer to $1\,\mathrm{Mbit\,s^{-1}}$ provided that the micro-controller has multiple CAN controllers.

For LiFi transceivers the dominant power consumption comes from the power required to run the LED so the duty cycle has a significant impact on the power usage. To conserve power, the satellite busses can be turned on or off based on the communication requirements of the satellite. For example, when there is a large amount of payload data to transfer to the communications subsystem to transfer to ground the number of busses used can be scaled up, but in normal operation they can be scaled down dynamically. In addition, nodes can be activated on additional busses selectively so only the nodes required to do the high bandwidth data transfer have their redundant bus transceivers activated.
In this paper, we implement and test dual CAN satellite busses that operate in infra-red and the visual red spectrum. The transceiver and filters are initially validated with tests between two transceivers to examine the possible baud rates over different distances between the transceivers and the angle between them. The transceivers are then tested concurrently where the red and infrared light is transmitted in the same physical space. These tests validate the possible combined baud rates and distances as well as confirming any possible interference caused.

2. RELATED WORK

In the Würzburg Universität's Skip The Harness (SKITH) project wireless satellite infrastructure has been developed. It uses fault-tolerant and robust software running on Realtime Onboard Dependable Operating System (RODOS) that uses the $2.4\,\mathrm{GHz}$ band with up to $19\,\mathrm{dBm}$ transmit power [7]. Although the project aims to reduce interference and increase electromagnetic compatibility, there remains a potential risk that Radio Frequency (RF) transmissions will be disrupted or in turn disrupt other satellite systems. The SKITH wireless satellite infrastructure has been deployed on the InnoCube satellite being developed by Technische Universität Berlin (TUB) and the Würzburg Universität [8] launched in January 2025.
The Optical Wireless Links to Intra-Spacecraft Communications (OWLS) project was a long running project by Spain's National Institute of Aerospace Technology [9]. The goal of the project was to develop optical wireless communication for intra-satellite communication in the range of between 0.1 to 2-3 meters using diffuse free space transmission. It is intended to be a physical layer substitution that enables commonly used satellite bus communication protocols to still be used (e.g. MIL-STD-1553 or CAN [10]). They have developed optical wireless transceivers based on Commercial Off-The Shelf (COTS) components that have been tested for radiation resistance. In addition, they also reported on the results of a technology demonstrator in-orbit test of their transceivers where they showed errors in the order of 10^{-6} due to single event transients and negligible effects due to displacement damage [11].
The project culminated in the launch of the 3U Cubesat OPTOS [5]. OPTOS did not use data lines and all sub-systems communicate using wireless CAN with a dif-

fusion cavity that stretches the length of the satellite. The satellite operated successfully in orbit for more than 3 years. The OWLS project shows the potential for the use of LiFi for intra-satellite communication.

Included in the payload of the INSPIRE-SAT 7 2U Cubesat was a LiFi test module [12]. The module aims to demonstrate point-to-point communication at $5\,\mathrm{Mbit\,s^{-1}}$ over a distance of 1 to $2\,\mathrm{cm}$. This is a commercial module developed by oledcomm for which little information has been released.

In addition to the INSPIRE-SAT 7 mission, oledcomm also conducted a LiFi test on the Arianne 6 launcher [13]. This test involved two 'SatelLiFe' modules $80\,\mathrm{cm}$ apart fitted under the fairing. When lift-off was detected, the modules communicated to test the resiliency of the communication during launch. This is a very interesting mission and extends the advantages of LiFi, such as reduced mass, to launchers, but no information has yet been released by oldecomm on the success or results of the mission.

Cossu et al have demonstrated an optical wireless system with 4 nodes using a mock-up of the Cosmo-SkyMed satellite [1]. The system uses the MIL-STD-1553B protocol at $1\,\mathrm{Mbit\,s^{-1}}$ using the free space medium. The mock-up has several separate compartments. To send signals between them they make use of cutouts in the structure of the satellite and some active regenerator nodes that receive signals and re-send them.

The OCC4SAT project uses optical cameras to receive the optical signal rather than the more commonly used photodiodes [14]. The use of cameras means that a single receiver can differentiate signals from different senders based on the location on the image of the signal. The cameras are able to detect signals with a very low intensity which also enables a relaxation of any alignment requirements. However, the target data rate is in the range of $3\,\mathrm{kbit\,s^{-1}}$

A wireless visible light based MIL-STD-1553 system was presented by Das et al [15]. This system focused more on avionics considering distances of up to $4.5\,\mathrm{m}$ and using line of sight transmission. It uses Field-Programmable Gate Arrays (FPGAs) to modulate and demodulate the MIL-STD-1553 signaling in to on-off-keying to transmit via light.

Other works also dealt with light transmission for intra-satellite communication [16] and showed advantages for applications with high bandwidth requirements, such as telecommunications satellites [17]. This second work has been extended to implement both the MIL-STD-1553 and CAN protocols [10]. The transceiver developed uses an array of LEDs and photodiodes and is capable of transmitting CAN at data rates of $500\,\mathrm{kbit\,s^{-1}}$. The system was developed to work on the physical layer and not require any modification to existing hardware.

Two relevant Institute of Electrical and Electronics Engineers (IEEE) standards cover LiFi communication:

- IEEE 802.15.7: IEEE Standard for Local and metropolitan area networks–Part 15.7: Short-Range Optical Wireless Communications [18].
- IEEE 802.11bb: IEEE Standard for Information Technology–Telecommunications and Information Exchange between Systems Local and Metropolitan Area Networks–Specific Requirements Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications Amendment 6: Light Communications [19].

The IEEE 802.15.7 standard defines a physical layer and a media access control layer. The media access control layer is compatible with using TCP/IP as a higher layer. The standard defines six physical layers:

1) PHY 1 is for outdoor application and works from $11.67\,\mathrm{kbit\,s^{-1}}$ to $267.6\,\mathrm{kbit\,s^{-1}}$.
2) PHY 2 is for indoor applications and works from $1.25\,\mathrm{Mbit\,s^{-1}}$ to $96\,\mathrm{Mbit\,s^{-1}}$.
3) PHY 3 is used for sources with multiple lights and detectors and uses color shift keying modulation. It works from $12\,\mathrm{Mbit\,s^{-1}}$ to $96\,\mathrm{Mbit\,s^{-1}}$.
4) PHY 4 is for discrete light sources and works up to $22\,\mathrm{kbit\,s^{-1}}$.
5) PHY 5 is used for diffuse light sources and works up to $5.71\,\mathrm{kbit\,s^{-1}}$.
6) PHY 6 is intended for video speeds and works in the $\mathrm{kbit\,s^{-1}}$ range.

The standard includes some extensions to support both dimming and flicker mitigation for use in homes and offices that are not required for intra-satellite communication.

IEEE 802.11bb defines a line of sight based high speed LiFi protocol. It uses near-infrared light in the 800 to $500\,\mathrm{nm}$ range and supports speeds from $10\,\mathrm{Mbit\,s^{-1}}$ to $9.6\,\mathrm{Gbit\,s^{-1}}$.

The approaches in previous work can be divided into RF based solutions [7], high bandwidth commercial tests [12, 13], IEEE standards [18, 19], or optical LiFi solutions [1, 5, 9, 10, 14, 15].

SatelLight belongs to the group of optical LiFi solutions as it will develop actual hardware and software and will not use RF solutions due to electromagnetic interference, the use of licensed spectrum, and the potential increase in security available through LiFi. The SatelLight project concentrates on nano-satellites with satellite sizes in the range of 2U to 6U. In contrast to previous optical solutions for intra-satellite communication, SatelLight is not pursuing an isolated solution, but rather a holistic approach towards fully optical satellite platforms including the satellite bus, communication with sensors, and the powering of low power sensors. The investigated basic principles for free-space communication inside the satellite structure form the basis for this.

3. TRANSCEIVERS

As part of the SatelLight project a LiFi transceiver has been developed that can support both CAN and UART [20]. The transceiver currently consists of three stages in the signal processing path: a trans-impedance amplifier to convert the current generated by the photodiode to a voltage, an edge detection stage that detects edges or changes in the output of the trans-impedance amplifier, and a Schmitt trigger that converts output to a binary signal. It supports CAN baud rates of up to $1\,\mathrm{Mbit\,s^{-1}}$ and UART baud rates of up to $4\,\mathrm{Mbit\,s^{-1}}$. The transceiver acts as a transparent plug and play replacement for a wired CAN transceiver to the micro-controller with the TX and RX connections from the micro-controller being directly connected to the transceiver. A logical 1 is translated to the LED being off. This is required for the arbitration procedure so that a dominant signal is visible to all nodes if they are currently sending a recessive signal. The transceiver PCB is shown in Figure 4 with the LED highlighted on the left hand side and the photodiode on the right.

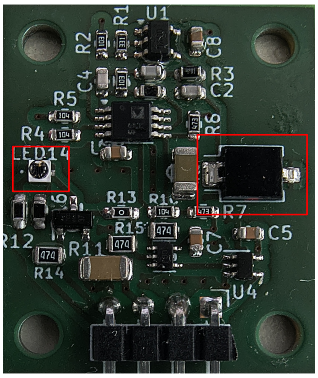

FIG 4. CAN Transceiver PCB

The transceiver has been tested with multiple different LEDs with different properties. Table 1 shows the two LEDs used in this paper. They are selected to have similar power usage and half viewing angles but different wavelengths.

LED	Half Viewing Angle (°)	Wavelength (nm)
SFH 4247 [21]	65	950
CH DELSS1.22 [22]	60	655

TAB 1. Transceiver Test LEDs

The tests also use two closely related photodiodes as listed in Table 2. Both are of the BPW 34 series of photodiodes but one has an inbuilt daylight filter. The other photodiode is used with a $660\,\mathrm{nm}$ filter with a half peak bandwidth of $20\,\mathrm{nm}$.

Photodiode	Spectral Range (nm)	Filter Wavelength (nm)
BPW 34 S [23]	420 - 1120	660
BPW 34 FS [24]	780 - 1100	Daylight Filter

TAB 2. Transceiver Test Photodiodes

FIG 5. 2 Node Transceiver Test

4. TEST SETUP

4.1. 2 Node Transceiver Test

To provide a baseline for later results an initial test is done using just the visual or infrared spectrum transceivers. They are set up facing each other and then the Bit Error Rate (BER) and distance is measured for 0°and 20°. The results of these tests will then be compared with later tests when the different spectrum transceivers are run concurrently.

4.2. Filter Validation Test

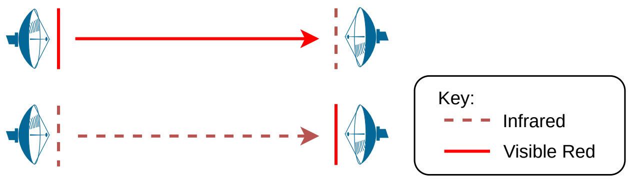

FIG 6. Filter Validation Test

To validate the filters in a simple test case, visible red light is transmitted at the transceiver with the visible light filter and infrared light is transmitted at the light with the red filter as shown in Figure 6. This test will confirm that no signal is received by either of the transceivers to confirm the correct functioning of the filter.

4.3. 4 Node Multiple Wavelength Test

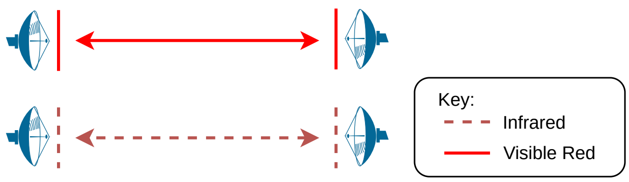

FIG 7. 4 Node Multiple Wavelength Test 2

The four-node test has the transceivers of the different spectrum placed horizontally opposed as shown in Figure 7. The intention of this test is to have a strong signal from each spectrum received on the photodiode of the opposing spectrum. This will test the efficacy of the filters and the impact of any interference from the signals of the opposing spectrum on the distance of the transmission and achievable baud rates.

4.4. Power Usage

To have an accurate measurement of the power usage of the LiFi transceivers when transmitting CAN, we take a measurement of the power usage when the LED is on and when it is off. This corresponds to the power usage when a dominant bit is sent (LED on) and a recessive one (LED off). CAN has a number of bits within the data frames that have to be dominant, such as the reserved bit, or recessive, such as the cyclic-redundancy-check delimiter. In addition, there are frame spacing bits that have to be recessive and bit stuffing bits that are the opposite polarity of the preceding bits when required. As an estimate for the power usage of the transceiver when at 100% duty cycle we assume that 50% of the bits are dominant and 50% are recessive.

5. RESULTS

5.1. 2 Node Transceiver Test

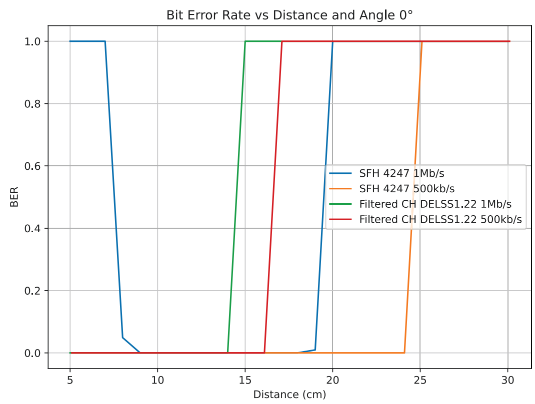

FIG 8. Bit Error Rate vs Distance and Angle 0°

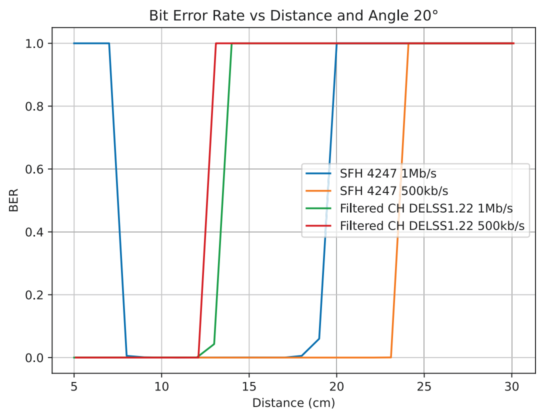

FIG 9. Bit Error Rate vs Distance and Angle 20°

The results in Figures 8 and 9 show the BER of the transceivers without interference over different distances and at the angles of 0° and 20°. The results show that while both are able to have reliable transmissions at both $500\,\mathrm{kbit\,s^{-1}}$ and $1\,\mathrm{Mbit\,s^{-1}}$ the SFH 4247 has a greater range than the CH DELSS1.22. Errors can be seen at lower distances for the SFH 4247 at $1\,\mathrm{Mbit\,s^{-1}}$. This is caused by the over-saturation of the trans-impedance amplifier of the transceiver which causes delays in the response. Currently, a single value of resistor is used in series with the transmitting LED. If the design requires lower distances, this series resistor can be increased to prevent over saturation.

5.2. Filter Validation Test

The filter validation tests did not show any reception of the infra-red transmission by the red visible light transceiver or reception of the red visible light by the transceiver with the daylight filter. This simple test validates that the filters are correctly filtering out the wavelength sent by the other transceiver.

5.3. 4 Node Multiple Wavelength Test

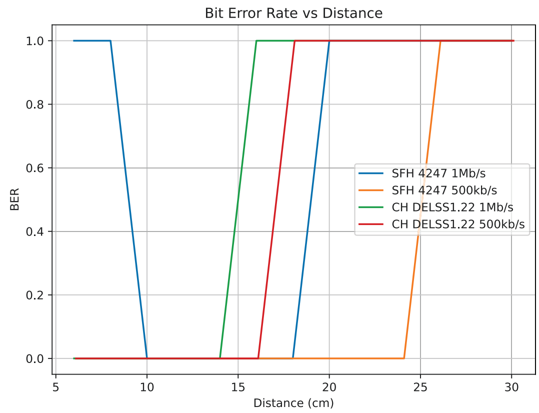

FIG 10. 4 Node Multiple Wavelength Test

Figure 10 shows the results of the 4 node multiple wavelength test where the transceivers are horizontally opposed. The results show that the baud rates, distances, and error rates do not show any impact of interference with the multiple wavelength transmissions. This is expected provided the filters of the photodiodes are functioning correctly. Although some loss is expected due to the filters. For example, the $660\,\mathrm{nm}$ filter has a peak permeability of 90%.

5.4. Power Usage

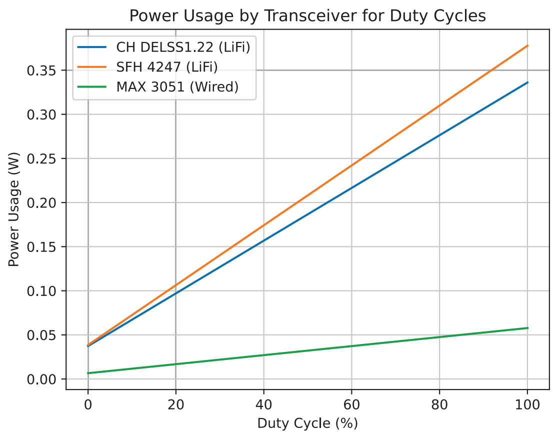

FIG 11. Power Usage by Transceiver for Duty Cycles

The main power usage of the LiFi transceiver is the LED when this is activated. This scales linearly with the duty cycle as shown in Figure 11. The power usage of the LiFi transceivers is more than the corresponding power usage of a common wired transceiver. This shows that being able to power down the transceivers when they are not in use can be a useful function. It also shows that as the network bandwidth increases linearly by adding extra wavelengths, the power usage will also scale linearly. However, it is worth noting that this power usage is below or in the range of low power sensors used in nanosatellites such as accelerometers or magnetometers.

6. FILTERS

To easily adopt multiple wave length LiFi transmission for redundancy, bandwidth, and even the usage of multiple different protocols within the same physical space filters are required for the photodiodes. When these are built in to the photodiode such as the daylight filter on the BPW 34 FS this is trivial. If a separate filter is required then this has to be tested for radiation hardness and sizing and mounting the filter in such a way that it can withstand the vibration of launch while still being aligned over the photodiode can be a difficult problem. The material selected for the mount and the filter also needs to be checked to make sure out-gassing does not occur in orbit. Additionally, filters must be selected that function over the entire viewing angle range required for the placement of the transceivers. Another option is to select photodiodes that have different spectral sensitivities considering the wavelengths of the light chosen for the communication. However, the usage of different photodiodes can create problems with the circuit design with the transimpedance amplifier having to be customized for each photodiode depending on its electrical characteristics.

7. COMPLETE CONCEPT

The complete concept of a satellite using LiFi wireless transmission is shown in Figure 12. The concept illustrates a satellite with several sub-system nodes with some being redundant. Connected to the nodes are a variety of sensors and actuators.

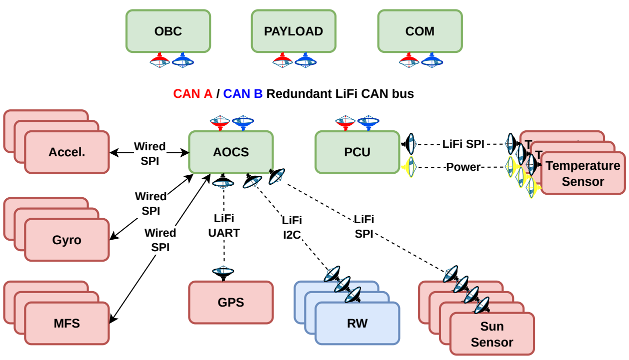

FIG 12. Complete LiFi Wireless Optical System

The main components of a complete system are:

- A dual redundant CAN network as demonstrated and validated in this paper.
- Wireless LiFi connections to sensors using a variety of common protocols including UART, Serial Peripheral Interface (SPI), and Inter-Integrated Circuit (I2C). Currently in the SatelLight project previous work has demonstrated UART connections with baud rates up to $4\,\mathrm{Mbit\,s^{-1}}$.
- Wireless LiFi connections to actuators. Based on the actuators these will also make use of the same set of common protocols as the sensors.
- Physical connections to sensors where little mass is saved. In this example, the accelerometers, gyroscopes, and magnetic field sensors are all placed on the same PCB as the Attitude Orbit and Control System (AOCS) making a physical connection the best option.
- Low power sensors such as some temperature sensors will have not just the data but also the power delivered via LiFi. This has the big advantage of removing both the communication and power harness to the sensors.
- An Electrical Ground Support Equipment (EGSE) connection optionally via LiFi to allow for testing, debugging, and flashing of software to the nodes. A powerful LiFi EGSE connection can have advantages for testing on equipment such as an air bearing table.

8. CONCLUSIONS

The results of the tests in this paper show that multiple wavelength LiFi transmissions can be used to implement redundancy and increase bandwidth for wireless optical satellite busses. The results can be generalized to not just implementing redundancy for a single protocol but also having multiple different isolated protocols transmitting within the same physical free space. Care must be taken when selecting the filters to use for the photodiodes to ensure they are radiation hard and will effectively filter the required wavelengths at all required angles. The power usage of the LiFi transceivers is mostly impacted by the power usage of the LED used and scales linearly with the duty cycle.

8.1. Future Work

In the SatelLight project the following are some of the main items of future work:

- Perform radiation, thermal vacuum, and vibration and shock tests on the transceivers to raise them to Technology Readiness Level (TRL) 6.
- Improve the baud rate and supported ranges of the transceivers and active repeaters. A higher baud rate for CAN will be tested using a CAN FD controller.
- Testing with more realistic satellite mock-ups with realistic components and more nodes.
- Develop software-based simulations to optimize the placement of transceivers based on the components and wavelengths.
- Proof of concept for powering low power sensors using light.
- Implementing more protocols using LiFi such as SPI and I2C.

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