Optical TDM technology for N+1 redundant systems in high resolution optical earth observation satellites

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Abstract: Optical remote sensing has been greatly expanded by the construction of satellite constellations and improving the performance of the optical sensors. As the data throughput of earth observation satellites increases, photonic technology is expected to be used for the interconnections within the payload in order to reduce its overall size, mass, and power consumption, and to improve its immunity to EMI. Here, we propose an optical time division multiplexing technology for N + 1 redundancy in the payload, which is able to improve reliability by reducing the number of active components in the satellites, and present a feasibility study on its transmission efficiency.

Keywords: optical time division multiplexing, digital payload, N + 1 redundancy, Barrel shifter, remote sensing, earth observation satellite

Classification: Sensing

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1 Introduction

Optical remote sensing from space for earth observation has been applied widely to various fields, such as land observation, weather observation, disaster prevention, etc. Furthermore, achieving higher spatial resolution thanks to the improvement of the image quality of the charge coupled device (CCD) image sensors [1] and more frequent observations using multiple satellite constellations [2] are allowing this field to expand steadily into agriculture, fisheries, and forestry.

Recently, the Complementary Metal-Oxide Semiconductor (CMOS) image sensor, which is popular for consumer Digital Cameras, has been introduced to earth observation satellites [3]. Improvement of the readout speed and reduction of the power consumption were achieved by using CMOS image sensors, which are voltage driven devices.

Digital signal processing technology using application specific integrated circuits (ASIC) and field-programmable gate arrays (FPGA) has been in development for realizing higher data throughput for the payload as improving the spatial resolution and readout speed of the image sensors. Additionally, interconnections using optical fibers have been introduced in order to further increase the data throughput, to reduce the size, mass, and power consumption, and to improve the immunity to EMI [4]. 40 Gbps (4 channels × 10 Gbps) optical modules for space conditions have been developed for the optical interconnections [5].

Here, we propose optical time division multiplexing (TDM) technology for an N + 1 redundant system in earth observation satellites. The redundant configuration, which requires twice the number of interconnections, has been applied to payloads in satellites due to the requirements for fault tolerance and higher availability. Optical TDM is a well known and mature technology used for passive optical network (PON) systems, which reduce the cost by sharing the optical fiber among multiple users in terrestrial telecommunications [6]. The proposed N + 1 redundancy system, which can be implemented with a smaller number of active components than conventional systems, will make it possible to reduce the cost, size, mass, and power consumption, and to improve the reliability of the satellites.
2 Redundancy systems in earth observation satellites

Fully redundant payload systems with cross strapping have been applied in order to maximize the availability of satellites while maintaining flexibility [7]. Figure 1(i) shows an example of a redundant configuration for an earth observation satellite with three image sensors. The parallel image data from the three image sensors are separately converted to digital form by the A/D converters (ADC), processed by the digital signal processors (DP), compressed (Comp), stored in the memories (STR), processed for transmission (TX), and then transmitted to ground via the antennas. The units from DP to antenna for each sensor are fully redundant and the connections between the primary and standby units from DP to TX are cross strapped. The standby units are only activated in the event of failure of the associated primary units in order to reduce the power consumption.

![Image of redundant system configuration](image)

(i) Block diagram of fully redundant configuration

Recently, an N + 1 redundant system with the Barrel shifter configuration shown in Fig. 1(ii) has been applied in order to reduce the size and mass of the satellites [8]. There are three primary units and one set of redundant units from DP to antenna. The connections from DP to TX are in a Barrel shifter configuration. The standby units are also inactive until a failure occurs in a primary unit. Note that a 1 + 1 redundant system is the same as the cross strapped configuration shown in Fig. 1(i).

![Image of redundant system configuration](image)

(ii) Block diagram of 4+1 redundant configuration

Fig. 1. Examples of redundant system configurations for earth observation satellites.
3 N+1 redundant system by using optical TDM technology

The block diagrams of a conventional Barrel shifter configuration with optical connections are shown in Figs. 2(i) and (ii). The digital signals from the serializer (Ser) are converted to optical signals by the E/O and split out by the optical coupler at the sender side (Units 1 to 4). At the receiver side (Units 5 to 8), two optical signals are separately converted to electrical signals by each O/E and selected by an electrical switch (E-SW) for Fig. 2(i). One of the two optical signals is selected by an optical switch (O-SW) and then converted to electrical signals by the O/E for Fig. 2(ii). Either the electrical or optical switches are required for the conventional Barrel shifter configuration.

![Fig. 2. Proposed optical N + 1 redundant system.](image)

The block diagram of the proposed Barrel shifter configuration using optical TDM technology and the timing chart of the signals at points (a) and (b) are shown in Figs. 2(iii) and (iv). The differences between this configuration and Fig. 2(ii) are the functions for forming burst packets at the serializer for TDM signals (SerT) and gating them at the deserializer for TDM signals (DesT), and the substitution of
optical couplers (CPL) for the optical switches (O-SW) at the receiver side (Units 5 to 8). The signals are formed into burst packets by SerT, converted to optical by the E/O, and split out by the optical coupler at the sender side (Units 1 to 4). The optical bursts from the odd and even numbered units are alternated within the duration of a given signal block. At the receiver side, the two optical bursts are combined in the optical coupler, converted to electrical by the O/E, and then gated by DesT. Note that the optical burst packets become time interleaved when combined in the optical coupler, and the primary packets or the redundant packets can be selected by the DesT at the receiver side as required. The components used for generating and gating optical burst packets in terrestrial telecommunications [9] could be used to provide these functions in the proposed system.

As the proposed optical N + 1 redundant system requires a smaller number of active optical components compared to the conventional configurations shown in Figs. 2(i) and (ii), it can be expected to reduce the size, mass, and power consumption, and to improve the overall reliability.

4 Performance of proposed optical N+1 redundant system

As the proposed optical N + 1 redundant system has chains of optical bursts, each optical burst packet should have a guard time, which includes the laser on/off times, the synchronization time, and the payload data, as shown in Fig. 3(i).

We verified the transmission efficiency, an important factor for an optical TDM system, which is defined as the ratio of total payload data within the duration of a signal block. Figure 3(ii) shows the calculated transmission efficiency as a function of the duration. The guard time and the synchronization time were 128 ns and 1200 ns, respectively [6]. The calculated transmission efficiency was greater than 96% even when the duration was only 70 μs, and it was greater than 99% when the

![Model of optical burst signals](image)

![Transmission efficiency and timing error](image)

**Fig. 3.** Calculated transmission efficiency and timing error.
duration was more than 300\,\mu s.

The difference in transmission time of the fibers in the primary and redundant paths can cause a time interleaving error, but this should be small enough because even a 1\,m difference in the fiber lengths causes less than a 5\,ns timing error as shown in Fig. 3(iii). Although, the data rates of the E/O and O/E are required to be twice that of the original electrical signals due to the multiplexing of two signals, 40\,Gbps (4 channels \times 10\,Gbps) optical modules suitable for space conditions have already been developed [5], in addition to which, up to 400\,Gbps products are available for terrestrial telecommunications.

5 Conclusions

We have proposed an optical N + 1 redundancy system for a satellite payload using optical TDM technology that can realize a redundant configuration with a smaller number of active components than a conventional configuration. A basic configuration and an example of its operation were introduced. A study to verify the transmission efficiency demonstrated the feasibility of this system. We showed that it has the potential to reduce the cost, size, mass, and power consumption, and to improve the reliability of high resolution optical earth observation satellites.