

HIGH-THROUGHPUT OPTICAL INTERCONNECT TECHNOLOGY FOR FUTURE ON-BOARD DIGITAL PROCESSORS

Michel SOTOM⁽¹⁾, Norbert VENET⁽¹⁾, Pierre AUBRY⁽¹⁾, Jacques BERTHON⁽²⁾

⁽¹⁾ *ALCATEL SPACE, 26, avenue J-F. Champollion - BP 1187, 31037 Toulouse, France
e-mail: michel.a.sotom@space.alcatel.fr*

⁽²⁾ *CNES, 18, avenue E. Belin, 31401 Toulouse Cedex 4, France*

ABSTRACT :

Digital processing is expected to take place in many satellite payload sub-systems, including advanced telecom repeaters and antenna beam-formers, next-generation radar's and data handling units of remote sensors. The capabilities of integrated circuits and processors have been growing so rapidly over the last decades that the pressure is being now shifted to the interconnect function. Whereas the speed and pin count of IC's increases rapidly, the bandwidth and density of back-planes and connectors for space applications do not improve at the same pace. A breakthrough is needed in order to go on improving the overall system, and interconnects with commensurate performance have to be made available.

Alcatel Space is investigating optical interconnects as an enabling technology that may offer the high-throughput data communication capabilities required to the future on-board processors and digital equipment. Optical interconnects may constitute a generic solution for supporting both intra- and inter-equipment communications, with almost un-limited bandwidth, distance-independent performance, unprecedented connector density and low-mass cabling. Suppression of EM crosstalk issues and impedance mismatches, full isolation between transmitting and receiver ends, simplification of routing might, at the end, shorten the design and integration phases.

A proof-of-concept demonstrator was developed on the basis of a digital telecom processor that makes extensive use of digital processing in order to provide flexible connectivity and variable bandwidth allocation in missions with multiple-beam antenna coverage. The demonstrator was implemented with commercial-grade, 12-channel optical modules providing an aggregate rate of 30 Gbit/s. A flexible optical fibre circuit was developed so as to route the fibres from board to board, and connected to optical transmitter and receiver modules through multi-fibre connectors. The demonstrator was integrated and the overall processor functionality was successfully demonstrated with almost no difficulty, thereby confirming that these technologies may contribute to shorten the development cycle.

However, the adoption of optical interconnect technologies in digital processing units for space calls for new designs and developments in the packaging aspects before qualification. Specific developments have been recently carried out in order to make optical interconnect technologies compatible with space requirements; multi-channel transmitter and receiver optoelectronic modules upgraded for space have been prototyped and tested.

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1 - INTRODUCTION

Future satellite payloads including both telecom and remote sensing applications, will incorporate an increasing amount of high-speed digital processing hardware. Telecom operators anticipate the advent of broadband communications in the next five to ten years, providing high data rate connections to numerous low-cost terminals. Broadband payloads with multi-beam active antennas, will have to receive, route and re-transmit hundreds of channels ; they will likely incorporate large throughput digital processors for demultiplexing and switching telecom signals [1].

Digital transparent processors (DTP) are such advanced repeater sub-systems, particularly well-suited for routing channels with fine bandwidth granularity. They have analogue-to-digital (ADC) and digital-to-analogue converters (DAC) respectively on their input and output accesses and make extensive use of digital processing to provide flexible beam-to-beam transparent connectivity and variable bandwidth-to-beam allocation.

Digital beam-forming networks (DBFN) refer to processing architectures that collect and handle digital samples of the electromagnetic waves from many antenna array elements. By combining these samples with appropriate weightings, they enable to form multiple contemporaneous beams, and to control the beam shape and side-lobe level. This technique is very attractive for telecom missions calling for flexible multiple-beam antenna coverage. DBFN may also find application in next generation SAR (synthetic aperture radar) ; the antenna pattern can be dynamically controlled so as to implement various tracking or scanning modes, or to reduce the effect of directional jammers. Whereas in conventional radar architectures, only one high-speed link is required between the instrument output and the mass memory, there would be many links in DBFN-based architectures, namely from the ADC's to the central processor.

As high-speed digital processing is expected to be widely spread in future telecom repeaters and antenna beam-formers, in next generation SAR's as well as in data handling units of remote sensors, optical interconnects are regarded as the enabling communication technology for supporting the expected huge amounts of data [2].

2 - DIGITAL INTERCONNECTS WITH MULTI-GIGABIT THROUGHPUT

The advances of digital electronics over the last decades have been following the so-called Moore's law, stating that the complexity of integrated circuits (in terms of number of transistors per chip) doubles every eighteen months. As digital processing capabilities will continue to grow, the pressure will be shifted to the interconnect function. For future system performance continue to gain from transistor size reduction, interconnect technologies with commensurate data handling capabilities are required. In many on-board digital processors and equipment, interconnects between printed circuit boards (PCB) are becoming a bottleneck because of volume, mass, complexity, reliability and crosstalk issues. Whereas the operation speed and the number of pins of ASIC's and processors increase, PCB connectors for space applications remain limited in pin number and bandwidth, as a result of physical constraints such as pin spacing, insertion force, alignment ...

A technology breakthrough is required to support the expected huge amounts of data. Serial electrical links may partly solve some issues, by enabling to increase the bandwidth while reducing the number of connections between PCB's. They will provide gigabit-per-second data rates, feature higher connection densities, and may relax connector insertion forces. As transmission speeds reach a rate where electrical data transmission between racks is then becoming critical, extension technologies involving equalizing circuits may be necessary in order to restore degraded signals.

Fibre optics has become the technology of predilection for high-speed communications and interconnects [3]. In on-board applications, it will offer an almost unlimited bandwidth communication medium with extremely low mass and unprecedented connection density. It enables to transmit signals over longer distances, so that systems can be designed and tested without any distance constraint. Other important benefits should result from the suppression of electromagnetic interference and crosstalk in backplanes, suppression of impedance mismatches at the connector interfaces, as well as electrical isolation between transmitter and receiver ends. At the end, this much easier implementation is perceived as a factor of simplification and shortening of the definition and design, and the integration and test phases.

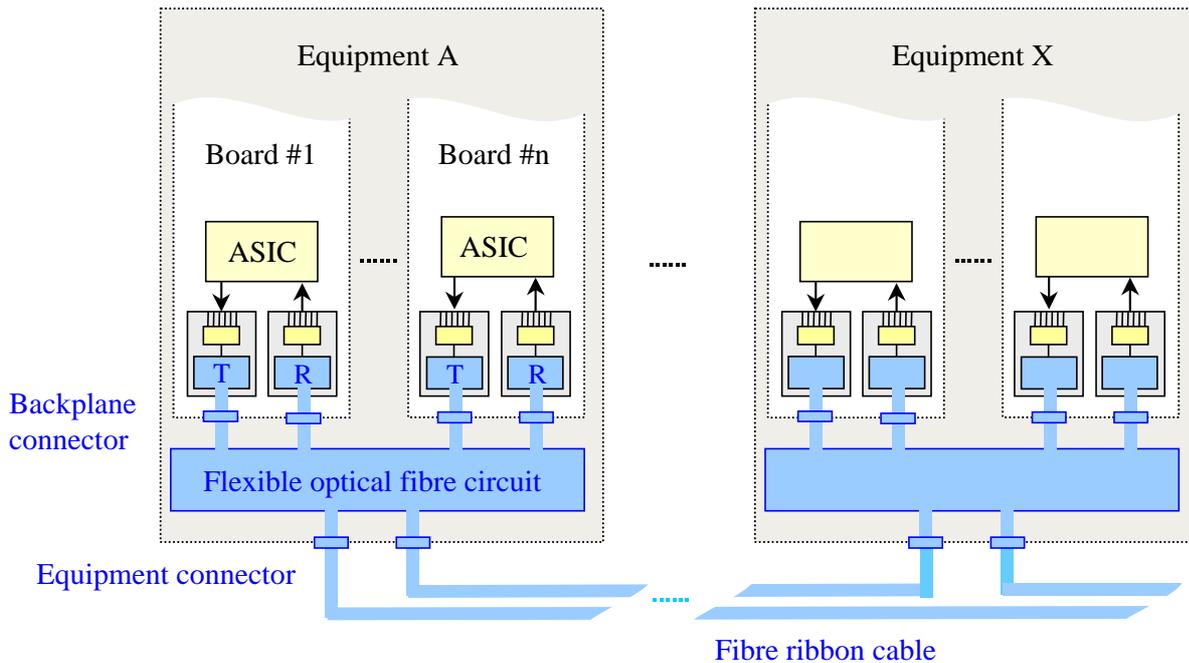


Fig. 1 : Optical fibre interconnects for high-speed intra- and inter-equipment communications

The optical interconnect technology tool box now includes vertical-cavity surface-emitting laser arrays (VCSEL) at 850 nm, laser driver arrays, PIN photodiode arrays, transimpedance amplifier arrays, graded-index multimode optical fibres (GI-MMF), multiple-fibre ribbon cables, multiple-fibre optical connector, blind-mate backplane connectors, flexible optical fibre circuits... These latter enable to route optical fibres in pre-determined paths and to fix them on a flexible substrate. Thus, this solves the physical fibre management issue and allows accurate and automated manufacturing of custom optical circuits. Fig. 1 shows how all these technologies may be combined together so as to provide a generic, unique communication solution to both intra- and inter equipment high-speed connections.

Advanced interconnects under study embed optical waveguides in various forms (optical fibres, polymer waveguides, glass waveguides) into PCB's. However, none has emerged yet due to technical issues relating to optical coupling efficiency, materials, and manufacturing.

Most of commercially available high-speed optical transmitter/receiver modules have been developed for ground telecom or data communications; they are generally based on non-hermetic molded-resin packages that are unsuitable for operation in space environment. However, there is now an increasing demand from various industry segments (avionics, defence, space, transportation, nuclear industry...) for devices designed or ruggedised for harsh environments.

3 - PROOF-OF-CONCEPT OPTICAL INTERCONNECT DEMONSTRATOR

A backplane interconnect demonstrator was developed in order to assess optical technology under the system environment and constraints of a digital processor for space application. Commercial-grade optical components were selected among ground telecom products. Parallel optical interconnect transmitter and receiver modules providing 12 channels running at up to 2.5 Gbit/s were purchased, and extensively tested.

In order to minimise the development efforts, existing prototype rack and boards were re-used instead of developing entirely a new equipment with an optical interconnect. The equipment selected as study case was a digital transparent processor that performs channel routing from 8 input to 8 output ports. The optical transmitter and receiver modules were inserted by using additional mezzanine boards as shown in Fig. 2. Serialisers at 1 Gbit/s were used to feed the transmitter modules; conversely, deserialisers were implemented at the output of the receiver modules.

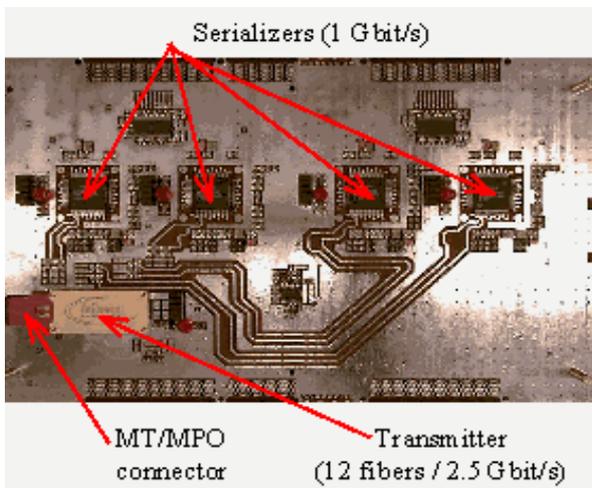


Fig. 2 : E/O transmitter module on mezzanine board

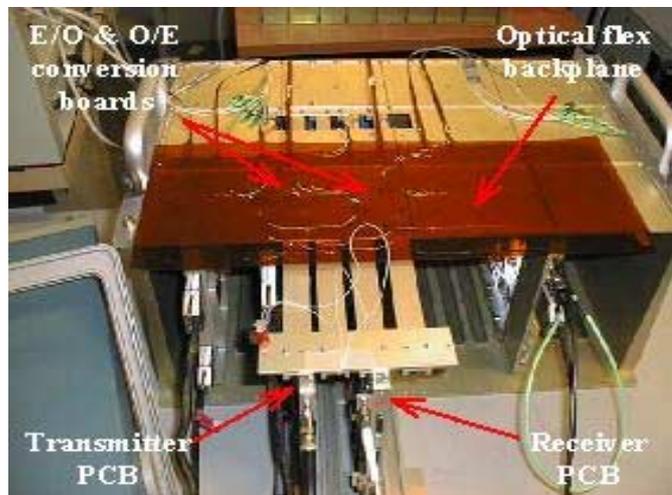


Fig. 3 : Integrated optical backplane interconnect demonstrated

A flexible optical fibre circuit was developed so as to route the optical signals from board to board. It was connected to the multi-channel transmitter and receiver modules through MPO connectors based on the industry-standard 250-micron pitch MT ferrule. Average optical connector loss was found to be about 0.25 dB. The insertion of the flexible optical circuit was shown to introduce no performance degradation. Bit error rate (BER) performance were recorded for a number of links going through the flexible optical circuit. There was no impact on the shape of BER curves, no BER floor, no penalty on the detection threshold. For each of the 19 optical fibre routes, the BER was measured to be less than 10^{-11} . One of these links was tested and ran error-free over more than two days, thus demonstrating a cumulated BER figure at least lower than 10^{-14} .

The building blocks were tested separately [4], assembled and integrated in the breadboard demonstrator composed of the processor rack unit and the optical fibre interconnect. Fig. 3 gives an overview of the integrated breadboard demonstrator. The integration of the optical backplane interconnect was validated by successfully demonstrating the overall digital processor functionality. It was checked that an analogue signal could be properly routed from an input access board with a transmitter PCB, through the optical interconnect to an output access board with a receiver PCB. One of the most striking aspects of the integration phase was that very few difficulties were encountered. This reinforced our perception that optical interconnect technology, operating with

large system margins, may bring error-free operation without any tuning. This is expected to have a beneficial impact in shortening the industrial development cycle.

4 - SPACE-QUALIFIABLE OPTICAL INTERCONNECT TECHNOLOGY

The adoption of optical interconnect technologies in space-borne digital processing units however requires design upgrades and further developments before qualification. In this respect, the optoelectronic interface modules and the multi-fibre optical connectors are regarded as the most critical items. The present section is focused on the testing of new multi-channel transmit and receive optoelectronic modules, specifically developed by the French manufacturer D-Lightsys [5] for space applications, starting from devices already designed for demanding environments.

Multi-channel transmitter modules were designed to transmit 12 independent channels at up to 2.5 Gbit/s data rate per channel. Transmitter modules incorporate state-of-the-art 850-nm GaAs VCSEL arrays, and implement a D-Lightsys proprietary algorithm for controlling the laser output power within an extended temperature range. Similarly, multi-channel receiver modules receive high data rate signals on 12 independent channels. They include state-of-the-art GaAs PIN photodiode arrays. Both transmitter and receiver modules come in a small-size, hermetic ceramic package with multimode fibre ribbon pigtail, that is shown in Fig. 4. Both transmit and receive modules are optimised for low power consumption.

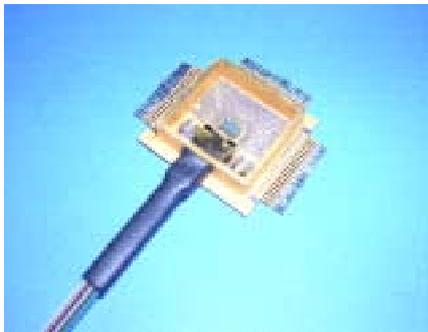


Fig. 4 : Multi-channel optoelectronic module prototype (after D-Lightsys)

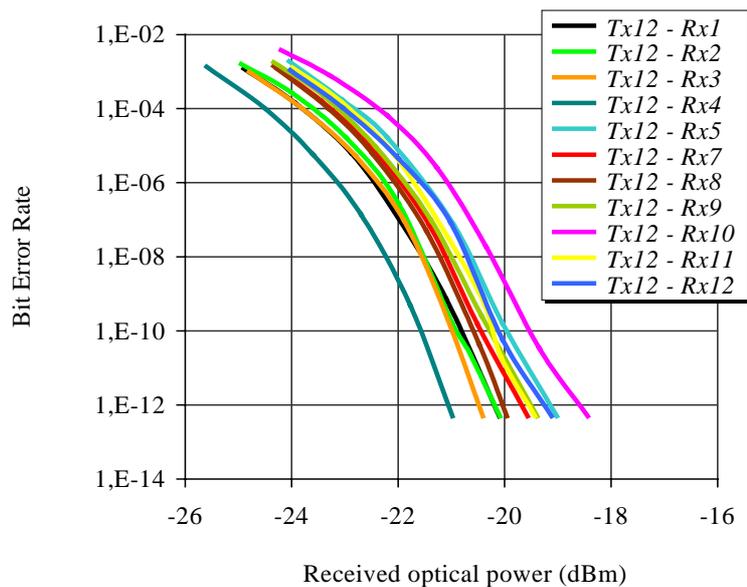


Fig. 5 : BER performance of the multi-channel receiver module under 2.5 Gbit/s PRBS modulation

Prototype modules have been designed, assembled by D-Lightsys and delivered for extensive testing. A special attention was paid to the channel performance distribution. Since such modules are to support many links in parallel, it is important that performance be maintained over the whole set of channels.

Transmitter channels were fed by PRBS (pseudo-random binary sequence) signals at 2.5 Gbit/s. The BER curve recorded for each of the 12 receiver channels is given in Fig. 5. These curves are very close to each other, proving that all the receivers perform similarly. The transmitter module was tested in a similar way. The transmit optical power as well as the detection threshold are given

for each of the 12 transmitters in Fig. 6. Detection threshold was defined as the optical power required at the receiver for achieving a given BER channels. The detection threshold at 10^{-9} ranges from -19 to -21 dBm. Fig. 7 shows an eye-diagram as typically observed at the receiver output; it is well-shaped and perfectly open, thus indicating that the signal integrity is maintained.

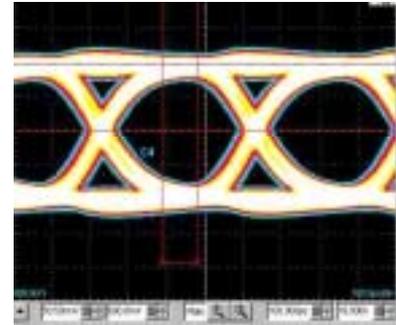
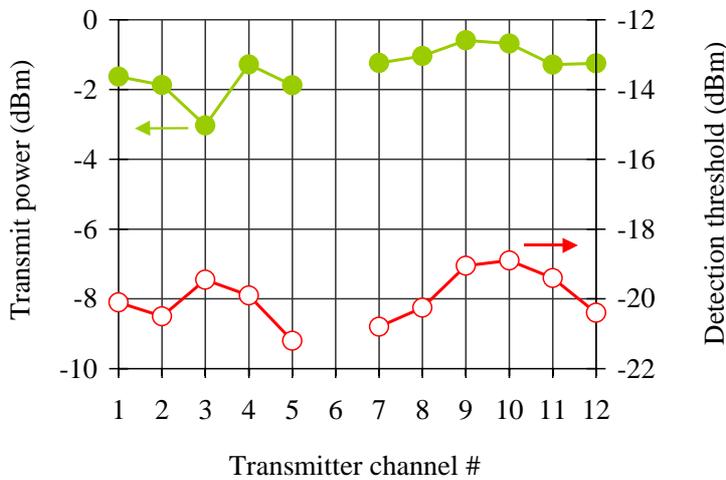


Fig. 6 : Transmit optical power and detection threshold vs transmitter channel

Fig.7 : Eye diagram under 2.5 Gbit/s PRBS modulation

Fig. 6 also allows for a first estimate of the available optical link loss budget, namely up to 16 dB. Of course, this figure neither accounts for all possible connections, nor includes margins, but it is well beyond what is strictly needed for straight point-to-point connections. So, this might be used to create safe operating margins or to include additional functionality such as broadcasting.

The behaviour of the prototype modules was also assessed under varying thermal conditions. As shown in Fig. 8, the transmitter optical output power can be maintained within ± 1 dB over a wide temperature range, thus confirming that the built-in algorithm to control the output laser power without cooling performs efficiently. Similarly, the receiver detection threshold is preserved over the same temperature range, as demonstrated in Fig. 9. Together, these results confirm the feasibility of high-performance, high-speed optical interconnect interfaces with an extended operating temperature range compatible with space environment.

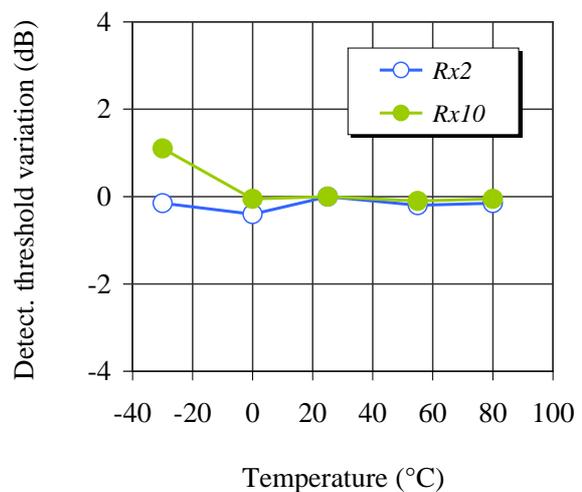
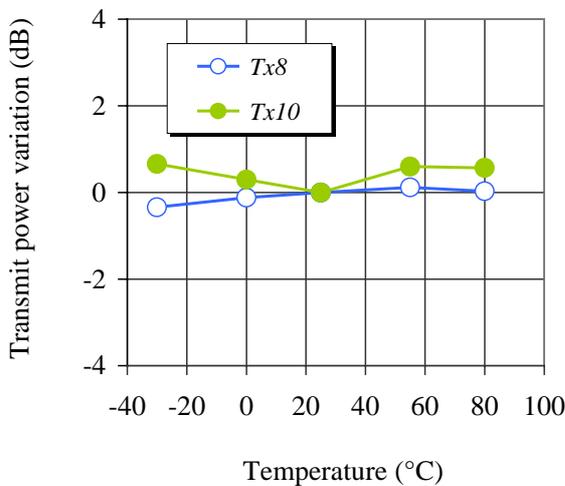


Fig. 8 : Temperature dependence of transmitter optical power

Fig. 9 : Temperature dependence of receiver detection threshold

5 - CONCLUSIONS

The massive introduction of digital processing in future satellite payload sub-systems calls for a disruptive interconnect and data communication technology in order to go on improving the overall performance. Optical fibre interconnects can meet this target; they provide a generic medium supporting both intra- and inter-equipment communications, with almost unlimited bandwidth, distance-independent performance, unprecedented connector density and low mass cabling. Other benefits for on-board applications stem from the suppression of crosstalk issues, suppression of impedance mismatches, full isolation between transmitting and receiver ends, simplification of routing. All in all, this is expected to substantially simplify and shorten both the design and integration phases.

A proof-of-concept demonstration based on a digital processor prototype enabled to assess the suitability and practicality of these technologies from an industrial point of view. An important finding was that almost no difficulty was encountered during the integration phase, thereby confirming that such a technology may contribute to shorten the development cycle. In addition, it was found that, by incorporating optical interconnect technology in that equipment, the designer would have been able to reduce the connector footprint and accommodate more functionality on the same board, as well as to extend the connectivity (number of input/output ports) of the equipment.

However, the adoption of optical interconnect technologies in future on-board digital processing units calls for new designs and further developments before qualification. Specific efforts have been devoted to the upgrade of optoelectronic devices designed for harsh environments into space-qualifiable modules. A pair of transmitter and receiver multi-channel modules was prototyped in an hermetic housing. With 12 channels operating at up to 2.5 Gbit/s, such a module supports an aggregate rate of 30 Gbit/s over a multi-fibre ribbon cable. Preliminary testing on multi-channel transmitter and receiver module samples revealed good performance with low distribution, which is taken as an evidence of maturity. In addition, these samples were shown to keep their performance over the temperature range from -30 to $+80^{\circ}\text{C}$. Optical link loss budgets in excess of 10 dB are anticipated to be ultimately available. In addition to guarantee safe operating margins, this may allow for the implementation of additional functionality such as broadcasting or redundancy.

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