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Spaceflex onboard digital transparent processor : a new generation of DTP with optical digital interconnects

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ABSTRACT

As high-speed digital signal processing has become a reality taking an increasing place in telecom satellite payloads for today, Thales Alenia Space has introduced the most advanced and disruptive technologies in his new generation of on-board digital transparent processor (DTP). DTP namely Spaceflex is an advanced repeater sub-systems having analogue-to-digital (ADC) and digital-to-analogue (DAC) channelizers on their input and output accesses and making extensive use of digital processing to support channel routing with fine bandwidth granularity.

The mechanical architecture of such advanced digital processor is based on input/output routing channel modules and switch modules interconnected together thanks to optical interconnect technology already implemented in a breadboard developed under the ESTEC contract Optical Inter-board Interconnects for High Throughput on-Board Processors (OI2) but showing higher performances requested by the application.

The optical interconnect is supported by optical transceiver, by optical connectors for inside and outside equipment interconnects, by optical cables and flexes. This optical interconnect solution is scalable to an overall throughput in excess of 15 Terabit/s with 150's of optical links.

In the frame of this development, Thales Alenia Space has identified and tested 3 different optical transceivers working at high speed data rate higher than 10 Gbps, compatible with GEO and LEO environment whose reliability is compatible with a lifetime of 15 years.

The paper will present in detail the tests on selected transceiver (radiation behaviour and temperature) as well as the overall architecture of such advanced digital on board processing equipment.

Keywords: Spaceflex, DTP, optical, interconnects, transceiver, radiation, architecture

1. INTRODUCTION

Satellite communication operators turn towards increasing capacity payloads, with higher number of beams and larger aggregate bandwidth to provide fast internet service to as many households as financially viable. Terrestrial cable and wireless techniques are being exploited to their physical maximum in Europe but white spots on the connectivity map, especially in Eastern and Southern Europe will be still seen in long-term future . This situation applies even stronger for other densely populated areas on the globe like South America and Africa, which will see a fraction of between 1 to a few percent of the population being left without high speed internet in the long term. Satellite communications from geostationary satellites (GEOs) can provide the required connectivity since it is not obstructed by any topological issues on ground. However, currently existing communication satellite transmission technology - High Throughput Satellite System (HTS) - cannot provide the required high throughput (which will easily exceed 1 Tbit/s per satellite) to serve such large amounts of the population. New technological approaches are necessary, known as Very High Throughput Satellite System (VHTS), together with optimized data transfer protocols like DVB-Sx-RTS, plus the user-link cells on ground must be optimized for maximum frequency re-use [1][2][3][4].
New satellite payloads need to be designed to meet such requirements of larger bandwidth, system transparency and flexibility. Broadband payloads will feature complex multi-beam active antennas, hundreds of channels to receive, route and transmit.

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2. ON BOARD DIGITAL TRANSPARENT PROCESSOR

Digital transparent processor (DTP) is the most typical example of such advanced telecom on-board repeater sub-systems. In particular, DTPs feature analogue-to-digital (ADC) and digital-to-analogue converters (DAC) at their input and output RF accesses and make extensive use of digital processing to provide flexible transparent connectivity and programmable bandwidth allocation. DTPs are particularly well-suited for routing channels or sub-channels with fine bandwidth granularity in telecom missions with multiple beam antenna coverage and offer reconfiguration flexibility when mission reorientation is needed.

In particular, DTP performs processing of the signal without demodulation and decoding and offers full spatial routing, channelization (with a granularity down to 400 kHz), spectrum equalisation on a port by port basis, gain control on each channel, multicast and broadcast capabilities. Second generation (SpaceFlex5) has been qualified and is flying since 2017. The (SpaceFlex5) presents up to 20 implemented I/O ports with bandwidth interface up to 250 MHz and up to 5 GHz of routing capacity. The qualification of current generation of DTP (SpaceFlex 24) is on-going as the development of its enhanced capacity version (SpaceFlex 64). The following table illustrates the capability of the successive processor generations including DBFN capabilities:

Products	SpaceFlex 2	SpaceFlex 5	SpaceFlex 24/28	SpaceFlex 64/76
Number of I/O	Up to 8/8	Up to 20/20	Up to 48	Up to 128
I/O bandwidth	Up to 250 MHz	Up to 250 MHz	500 MHz minimum up to 600 MHz	500 MHz minimum up to 600 MHz
Capacity (GHz) Useful bandwidth	Up to 2	Up to 5	24 minimum 28 maximum	64 minimum 76 maximum
Dynamic Management	Option	Option	Baseline	Baseline

SpaceFlex the current generation

For VHTS satellites, a powerful Digital Transparent Processor (DTP) SpaceFlex VHTS which allows to offer mobility customers extraordinary efficiency and unrivalled flexibility in bandwidth management capabilities is also currently under development.

Its main capabilities are summarized in the following table

Product	SpaceFlex VHTS
Number of I/O	Up to 160
I/O bandwidth	3 GHz
Capacity (GHz) Useful bandwidth	400/480
Embedded Digital BFN	Yes
Dynamic Management	Baseline

To achieve such high specification requirement, disruptive technologies have been implemented including optical interconnects at high data rate.

3. OPTICAL INTERCONNECTS

The optical interconnects are based on the introduction of optical multichannel transceivers with data rate higher than those developed in [4], interconnected by optical ribbons to the edge of the module and by ruggedized optical harness between modules. The following figure illustrates the optical interconnect architecture:

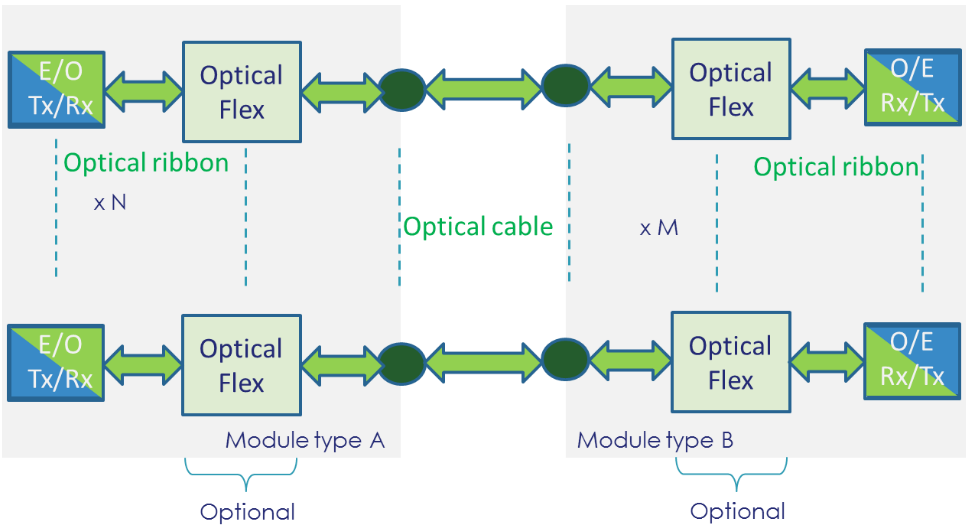


Figure 1 : optical interconnect topology

This modular architecture is easily scalable and is well defined to propose large or low bandwidth processing equipment.

Key technologies drivers are the optical transceivers and, in a lesser degree, optical cables, ribbons, connectors and flexes if any.

4. OPTICAL TRANSCEIVERS

Three different transceivers have been deeply evaluated regarding their overall performances including vertical cavity surface-emitting laser (VCSEL) reliability and power consumption, their radiation behavior (heavy ions and total ionizing dose) and their performances at cold, ambient and hot temperatures.

The first tests performed were heavy ions. On the three references, no latch-up and no SEFI as well, have been found for a LET of lower than 60 MeV.cm²/mg , and a fluency of 1E7 ions/cm².

Pictures hereafter show the device under test (DUT) for the three references A,B or C.

Figure 2 : References A,B,C

By implementing the right parameters in B&C registers, no SEE having an impact on the mission were found. These results were quite positive as any of these B or C optoelectronic modules could be selected for the mission.

As optoelectronic modules could not be selected on the radiation behavior alone, other parameters as general performances have been used to choose the best compromise for the forecasted mission.

Each optoelectronic module has been characterized in its typical configuration (recommended by the supplier).
This characterization consists in:

- BER measurements
- Eye diagram measurements
- Optical power measurements
- Sensitivity measurements
- Power supply measurements

All these measurements were performed in different configurations at ambient temperature but also changing the temperature from -30°C to +85°C, using several pseudo random binary sequence (PRBS), varying VCSEL currents and different input voltages.
To perform the comparison, internal specifications have been defined such as minimum eye diagram profile necessary to guarantee proper operations of the equipment. It was decided to compare the results at a very high data rate superior to the one tested in [5] with a BER better than 10^{-12}.

The test set-up made use of a BER tester to feed the demonstrator with high-speed binary sequences and measure the BER and eye diagram openings. The BER equipment delivered the maximum data rate of the high speed serial links (HSSL) to the optoelectronic module. Electrical signals recovered at the output of the optoelectronic modules were fed back to the BER equipment to calculate a BER after more than 10^{12} sent bits, or sent to an oscilloscope to draw an eye diagram. Measurements were all done using the bias and modulation current settings recommended by the supplier for all the modules.
Fig. 3 represents the used test bench to assess the performances of the optoelectronic modules.

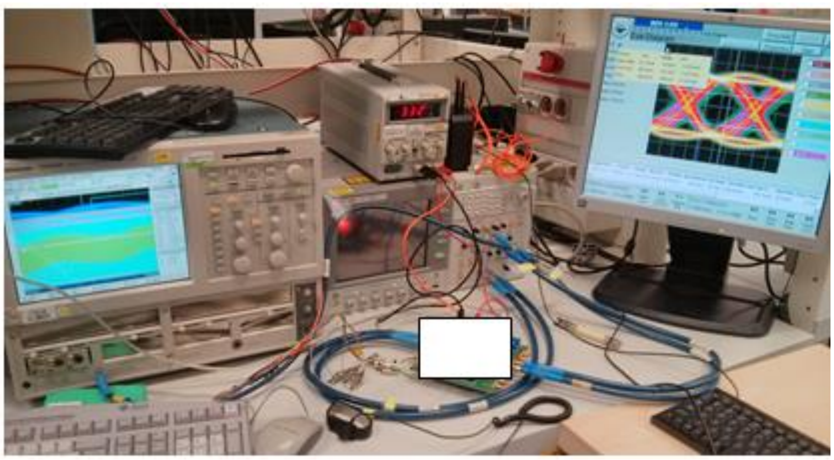


Figure 3 : optoelectronic modules assessment test set-up

The following table shows the test performed on each type of optoelectronic modules in order to select the one which will be used in our equipment

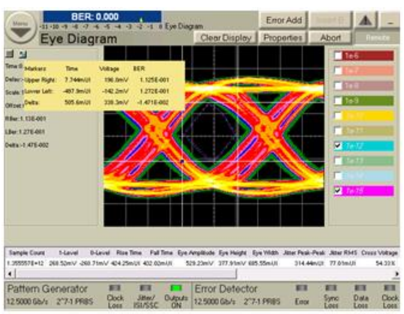
Table 1 : tests condition description

Tests \ Operating conditions	Influence of PRBS variations		Influence of electrical input data levels				Influence of VCSEL average current		
	PRBS A	PRBS B	Vin = a Vpp	Vin = b Vpp	Vin = c Vpp	Vin = d Vpp	Iavg = x mA	Iavg = y mA	Iavg = z mA
BER measurements	3T	Only 25°C	Only 25°C	3T	Only 25°C	Only 25°C	Only 25°C	Only 25°C	Only 25°C
Eye diagram at RX output	3T	Only 25°C	Only 25°C	3T	Only 25°C	Only 25°C	Only 25°C	Only 25°C	Only 25°C
Sensitivity measurements	3T	Only 25°C	Only 25°C	3T	Only 25°C	Only 25°C	-	-	-
Optical power measurements	3T	Only 25°C	Only 25°C	3T	Only 25°C	Only 25°C	Only 25°C	Only 25°C	Only 25°C
Eye diagram at TX output	3T	-	-	3T	-	-	-	-	-
Crosstalk measurements	3T	3T	-	3T	-	-	-	-	-
Power consumption measurements	3T	Only 25°C	Only 25°C	3T	Only 25°C	Only 25°C	Only 25°C	Only 25°C	Only 25°C

There were two test phases :

- A phase in nominal conditions at ambient temperature
- A phase where operating conditions and transceiver settings were changes

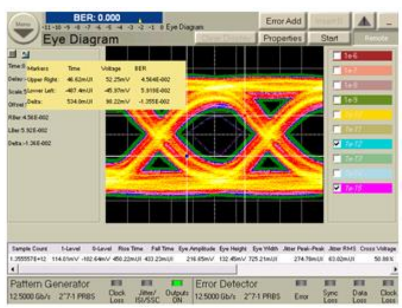
Following figures hereafter show some examples of the eye diagram measured in nominal conditions. BER testing and eye diagram showed better performances at 25°C for manufacturer A's module than for manufacturer B's modules or than manufacturer C's. Nevertheless, manufacturer A's module presents more deterministic jitter.



Amplitude 0,34V

Width 0,5 UI

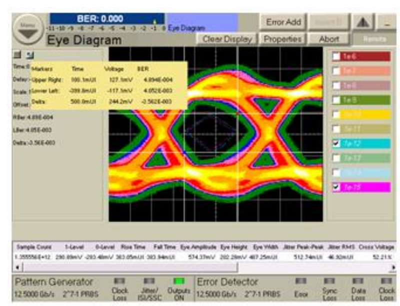
Figure 4 : manufacturer A eye diagram



Amplitude 0,1 V

Width 0,53 UI

Figure 5 : manufacturer B eye diagram



Amplitude 0,24V

Width 0,5 UI

Figure 6 : manufacturer C eye diagram

No error during 1E15 bits counting occurred for the three manufacturers.

The sensitivity curves for all the manufacturers are plotted on the graphics below for all channels. At the right side of the x-axis are plotted vertical bars corresponding to the Tx output optical power.

Vertical bars marking the Rx input average optical power to get a 10^{-12} BER are drawn and the available optical link budget can be seen on the plot showing the worst case corresponding to the worst Tx link with the worst Rx link

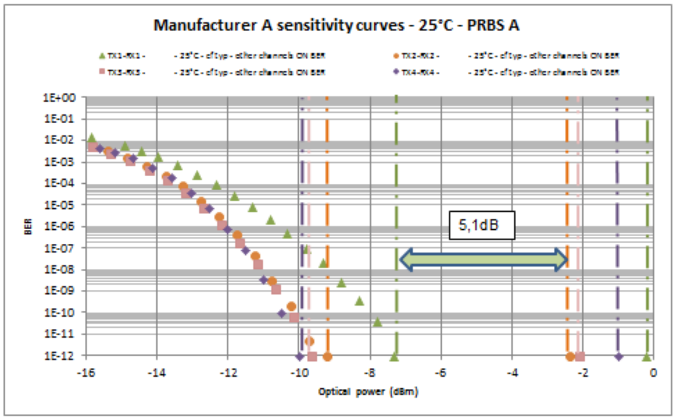


Figure 7 : Manufacturer A sensitivity curves

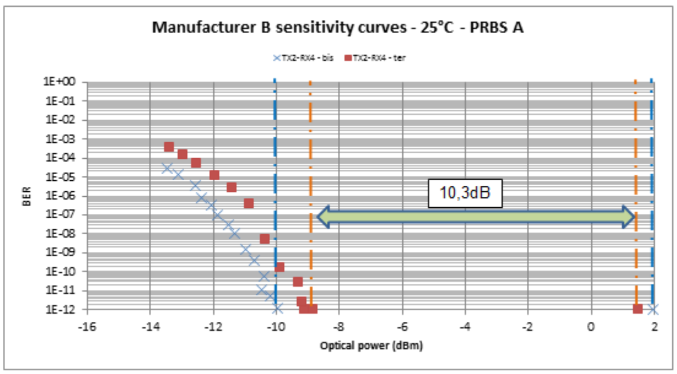


Figure 8 : Manufacturer B sensitivity curves

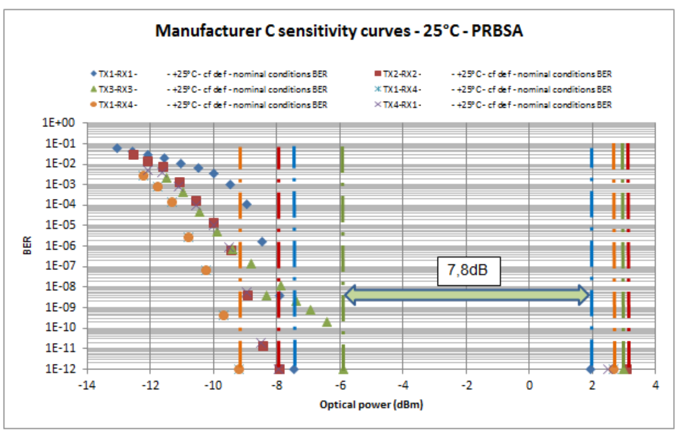


Figure 9 : Manufacturer C sensitivity curves

Due to set-up problems, we have tested only one link for the module B. However, the link budget is comfortable with around 10dB for this looped-back channel, which leaves margin to cover dispersions between channels.

During the second phase, some parameters were swept : PRBS, input data voltage level and VCSEL average current.

For the three suppliers, no modification was seen on the BER level and we reached and repeated at any time 10^{12} transmitted data without any error.

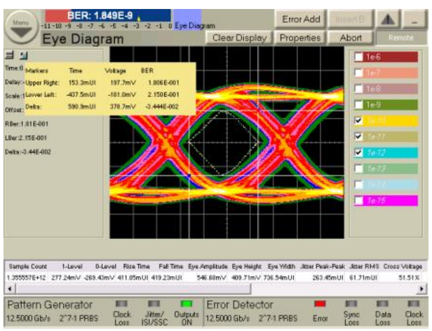
However, we have noticed for all modules a degradation of the jitter by changing the PRBS sequence from A to B as well as a degradation of the budget link by roughly 2 dB without any change in the optical power and in power consumption. This sensibility of the modules to pseudo random sequences has been then taken into account in our equipment test activity.

Power supply levels of electrical input data have very low impact on the overall performances of the optical modules. On the contrary, VCSEL average current have been identified, not surprisingly to us, during our testing as having high impact on the overall performances. The ratio performance/reliability of the VCSEL is a key driver and the configuration of registers have to be well defined to answer our requirements.

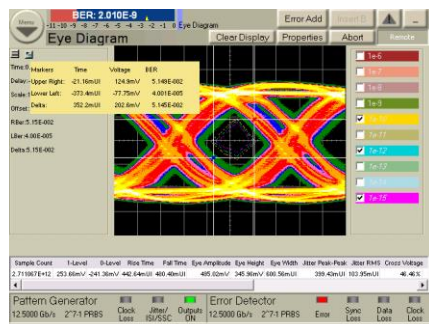
All the optoelectronic modules have demonstrated high performances at hot and cold temperature using standard settings of the register. Yet, all of them had to be tuned in order to fit with our requirements. Especially the eye width had to be improved for three of them at 85°C even if we still had a BER level better than 10^{-12}.

Figures hereafter illustrate the eye diagram plotted for the three optoelectronic modules at cold and hot temperature.

Cold Temperature

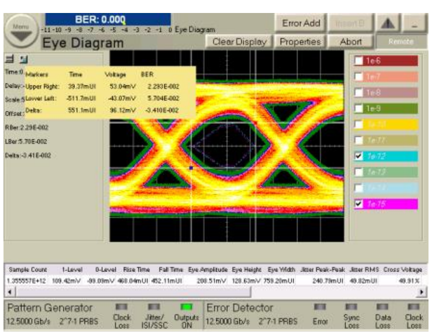


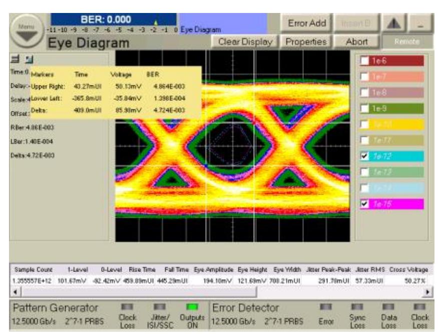
Hot temperature



Amplitude	0,38 V	Amplitude	0,2 V
Width	0,59 UI	Width	0,35 UI

Figure 10 : Manufacturer A eye diagrams at cold and hot temperatures





Amplitude	0,1 V	Amplitude	0,09 V
Width	0,55 UI	Width	0,41 UI

Figure 11 : Manufacturer B eye diagrams at cold and hot temperatures

Amplitude	0,15 V	Amplitude	0,14 V
Width	0,53 UI	Width	0,42 V

Figure 12 : Manufacturer C eye diagrams at cold and hot temperatures

5. CONCLUSION

Thales has extended his Spaceflex DTP family by introducing a new generation for VHTS services implementing advanced optical interconnect technologies. Key optoelectronic modules enabling to interconnect and route an overall throughput in excess of 15 Terabit/s have been deeply assessed. The selected candidates are finally all in line with the required performance even if some discrepancies exit in few parameters but could be optimized by tuning the register settings taking in mind the power consumption minimizing.
Passive optical interconnects have been identified and ruggedized for space constraint applications.
In summary, the tests performed pass the whole environmental testing campaign including radiation testing, permitting the introduction of optical interconnect technology in the new generation of highly-demanding on-board digital processors.

6. ACKNOWLEDGEMENTS

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REFERENCES

[1] E. Lutz, "Towards the Terabit/s Satellite - Interference Issues in the User Link", International Journal of Satellite Communications and Networking, 2015
[2] A. Salvatori, "Satellite broadband Future technology roadmap," SABER 5th Workshop, Toulouse, 23 Jan. 2014. http://www.project-saber.eu/cms/documents/workshops-and-meetings/workshop-5
[3] E. Lutz "Achieving a Terabit/s GEO satellite system", 19th Ka and Broadband Communications", Navigation and Earth Observation Conference: Florence, Italy, Oct. 14-17, 2013; 509-516
[4] ESA Artes projects UTMBeam, Terasat, at http://artes.esa.int/projects/
[5] N. Venet and al "HIGH-THROUGHPUT OPTICAL INTER-BOARD INTERCONNECTS FOR NEXT-GENERATION ON-BOARD DIGITAL TRANSPARENT PROCESSORS" ICSO2014 conference, Tenerife, Spain, Oct.7-10 , 2014