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A cost-effective ultra-high throughput space-based optical link

A Cost-Effective Ultra-High Throughput Space-Based Optical Link

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Abstract

High capacity throughputs are more and more requested by satellite owners, even before launching the first generation of optical constellations. MPB is developing a commercially-competitive photonics subsystem that increases the data throughput of a "free-space" optical link in a space environment. The objective is to build and demonstrate an optical subsystem suitable for deployment in space with a target capacity of ≥100Gbit/s having a scalable architecture optimized for cost per Gbit, while maintaining acceptable (e.g. 10-4) pre-FEC bit error ratio (BER), high reliability, design flexibility.

The two most promising solutions for the 100Gbps links use either a suitably-adapted commercial 100 Gbps x 1ch transceiver (e.g. commercial Dual-Pol 28Gbaud, 4 bits/symbol) or wavelength-agile WDM 10 Gbps x 10ch, or similar system (e.g. 12.5 Gbps x 8ch). The subsystem is based on the selected optimal architecture, convenient for space environment, and potentially comprising one or more of the "throughput-enhancing" possible approaches; such as the Modulation bitrate, Wavelength multiplexing (WDM), and Spectral efficiency. A large number of the performance parameters are also involved in the evaluation of the optimal solution, including: OSNR, Power at Rx, Mass and Volume, Cost, Complexity of the Software and Hardware to develop, Reliability/Redundancy, Power-Consumption and wall-plug Efficiency (W/Gbps), Signal Modulation, BER, and Stimulated Brillouin Scattering.

MPB plans to verify that the 100G commercial transceiver, a coherent module optimized for terrestrial use, is compatible with the harsh space environment. Moreover, its design needs to be modified (in collaboration with the manufacturer) in order to employ distinct Tx and Rx wavelengths. Although such an approach enables all data to be sent over a single wavelength, in the event of an e.g. Tx optical-amplifier failure all transmission capability would be lost. The coherent transceivers themselves are very complicated in design, but this development has already been carried out by the manufacturer for terrestrial applications.

The WDM option 10 G x 10ch has a larger mass, volume, and power per Gbps, however, the technology is based on MPB-developed boosters for space applications and offers higher redundancy (i.e. if one optical Tx amp fails, the other nine channels can still transmit). This option adds more complexity and cost since it needs to develop more software and hardware items. This development is useful for the other amplifiers with similar requirements from space primes. In addition, we are including a detailed study and prototyping of a space-borne Reconfigurable Optical Add-Drop Multiplexer (ROADM), which would enable greatly enhanced dynamic bandwidth allocation.

The two approaches (single-channel high BW vs multi-channel medium BW) have respective advantages and disadvantages.

Keywords: 100 Gbps Transmitter Optical Intersatellite link- satellite-Ground link, High power EDFA,
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1. INTRODUCTION

Satellite Constellations are launched in space mainly at Low Earth Orbit (LEO). In 2015, three main groups were competing to provide the internet from satellites through optical communications; Google, Facebook, SpaceX-Airbus, with a plan to have a global 5000-6000 satellites in a few constellations. Now they are about a dozen major players planning to populate the space with about 55,000 to 60,000 satellites by 2029 [1].

In parallel, the studies of intermediate liaisons between satellites and Earth such as balloons, airplanes, or drones are now assembled within a group called HAP(S) High Altitude Platforms or High-Altitude Pseudo-Satellites. Satellite primes are testing airplanes high at about 25-35 km in space (e.g. Zephyr from Airbus) as HAP. The market for optical inter-satellite communications has evolved based on the growth in demand for bandwidth capacity.

RF communications is still a bottleneck for moving data at Internet speeds in space. The centimeter-long wavelengths of microwaves in high-frequency RF transmission bands result in widely diffracting beams that spread over hundreds of kilometers on the Earth when transmitted over 39,000 km from a satellite above in geosynchronous orbit (GEO). Increasing data transmission to speeds in excess of 100 Gb/s requires a more concentrated signal at the target and higher transmit powers to deliver the same energy per bit to the receiver. Satellite services based on RF, offer limited bandwidth and have high latency, and they require licensing of the extremely crowded frequency spectrum.

Fiber optic cables provide the capacity and latency. However, the installation of fiber optic infrastructure is often impractical, inaccessible, and/or uneconomical in underserved or remote geographical regions. It is also not an option for transport vehicles such as aircraft and ships where the demand for internet access and associated services is also growing. Therefore, optical inter-satellite links offer the potential for "affordable terrestrial fiber quality service with global coverage" for:

- Remote geographical areas, where fiber optic technology is inaccessible or impractical to deploy
- Aircraft, where on-board demand for internet access and "Netflix" type broadcasts are desirable
- Marine, from internet and "Netflix" type access to travellers on cruises to mariners aboard fleets is desirable
- Disaster stricken areas, when hardwired infrastructure is critically damaged and it is necessary to restore services such as mobile phones and critical broadcasting in the shortest interval.

The growing internet market is driving the interest in optical satellite telecom, following the plans of Google, Facebook, SpaceX, Airbus, Telesat, and others, to invest in the development of large constellations using optical telecom. There are tremendous potential commercial applications, in particular, to connect a considerable percentage of the Earth's population to the Internet.

The first generation of satellite constellations using optical communications is planned for deployment in 2022 with service in 2025. While these constellations will offer Gbit capacity, there is already a desire to see terabit/s capacity, in order to seamlessly integrate with the existing terrestrial infrastructure.

It is expected that the 10 W optical amplifier based on Erbium and Erbium-Ytterbium Doped Fiber (EDFA) will permit more than 100 Gbps data transfer. The EDFAs are key devices in the optical communications in space with the following examples of applications:

- Optical Telecom satellite communications. Recently, there is a large increase in the importance of investment, Google, Facebook, SpaceX, Airbus are investing Billions$:
- Satellite to HAP, the HAP being the liaison between the satellite and the ground segment
- Optical inter-satellite Link (LEO-LEO) and (LEO-GEO)
- Fast transfer of data close to real-time data from Earth Observation satellite images (a few minutes instead of 90 minutes currently with RF signal)

- Intra telecom satellite optical applications- Flexible telecom repeater with microwave photonic MxN cross-connect. The Optical Wideband Receiver (OWR) contract from ESA to Thales-Alenia-Space (TAS) led to the experimental definition of the parameters and then building the components (e.g. minimum amplification needed and maximum Noise acceptable). MPB participated in OWR as a subcontractor to TAS, the major task was to build a Medium Level Optical Amplifier (MLOA), containing 4 amplifiers with a 20-21 dB gain each, and ± 1 dB flatness requirement over 10 nm 1540-1558 nm. Two MLOAs were built and delivered to TAS/ESA

- Sensor application in non-Telecom satellites. MPB installed Fiber sensors demonstrator on Proba-2 to measure the temperature (Fiber-wireless multiplexing). It uses the first Erbium Doped Fiber Laser in space

- Various Instruments where very low noise is a must (e.g. MIRAS on SMOS)

- Non-Telecom Communication links in non-Telecom satellites, for example, a next-generation SMOS.

- Boost the optical signal in Photonics payloads

- Processing applications in non-Telecom satellites (mm-wave generation e.g. EO or THZ on Fiber).

2. OPTICAL INTERSATELLITE LINK BUDGET

To validate the functionality of a transmitter for a fast data transfer, one main item to find is the number of photons getting in the unit time, e.g. 10^{-11} second for the 100 Gbps, is high enough to have an acceptable small Bit Error Rate (BER). This leads to the estimation of the link budget between the transmitter and the receiver. A simplified schematic of the inter-satellite link is presented in Figure 1.

It starts with a transceiver sending a small signal in the high gain amplifier called usually a "booster". For the Optical Intersatellite link and Optical to ground link the booster output power is between 1 and 10W (1550 nm). The signal is reduced by a large factor due to the dispersion in long distances in free space called the "Isotropic Space Loss" which is about -260 dB for LEO links (1300 km) and -290 dB for a GEO Link (39770 km) [2] Although these values are very large the signal is getting at the receiver point is a very small signal (down to -48 dBm). A Low Noise Amplifier (called pre-amplifier) regenerates the signal and sends it in the input of the transceiver to repeat the transmission.
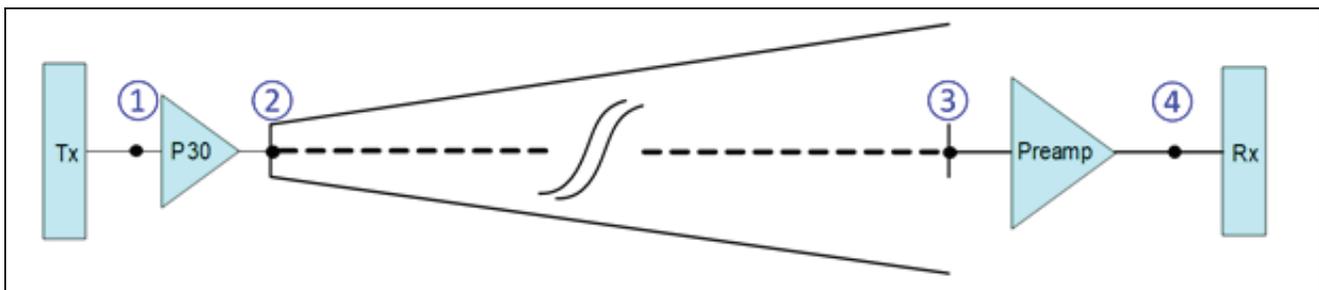

Figure 1. Simplified schematic of an Optical Intersatellite Link (OISL)

① Transceiver Transmitter output (Tx) – input to MPB Amplifier-Booster (named P30)
② MPB Amplifier-Booster **Output** into Free Space 1W to 10W optical output at 1550 nm is needed
③ MPB Preamp –Low Noise Amplifier **Input** from Free Space for very low signal down to -48 dBm
④ MPB Preamp **Output** is the **Input** to the Transceiver Receiver (via Optical Band-Passing filter)

Various parameters need to be known in o evaluate the link budget we consider various involved parameters:

A) Power related parameters

- Bit/Symbol -depends on the modulation used (see Table 1)
- Number of photons/symbol received at the next relay point ③
- Transmitter electrical power/symbol (mW_e/Gbps) (Wall plug efficiency) at ③
- Transmitter Optical signal power (dBm) at ③ (compare with a commercial 100Gbps transceiver at -28 dBm)
- Optical Signal to Noise Ratio (OSNR) at ④ (compare with a commercial 100Gbps transceiver at 12 dB)
- Total electrical power/symbol (mW_e/Gbps) at ④
- BER/SER (depends on the modulation type and rate)

B) Other parameters

- Redundancy
- Optical Cross Connection (case of 10λ x10Gbps)
- Stimulated Brillouin Scattering (at high power: 10 W)
- Size, Weight, and Power (SWaP)
- Reliability – Failure In Time (FIT)
- Compatibility with space environment (outgassing, thermal cycling, radiation)

To note, the term "GigaBit Per Second" or Gbps is used, the important parameter for the data transfer is the "Giga Symbol Per Second". The Bit/Symbol depends on the used modulation technique. Table 1 gives the number of Bit/Symbol for some frequently used modulation techniques. For example, most of the current commercial fast transceivers claiming the capability of 100 Gbps rate, are in fact at 28 Gbps, with a DP-QPSK modulation transferring at 112 Giga-Symbol per second.

Table 1: Number of Bit/Symbol for some frequently used modulation techniques

Modulation Techniques	On-Off Keying (OOK)	Binary phase-shift keying (BPSK)	Differential Phase Shift Keying (DPSK)	Differential Quadrature Phase Shift Keying (DQPSK)	Dual-polarization Quadrature Phase Shift Keying (DP-QPSK)
Number of Bit/Symbol	1	1	1	2	4

The link budget relates the power at the Receiver is related to the Transmitter power, its evaluation is needed to verify the required power at the transmitter level, to determine the number of photons per unit time (bit), arriving at the entrance of the receiver (pre-amplifier). The following equation is commonly used by the satellite primes to evaluate the required transmitter power, the size of the transmitter and receiver telescopes, and the requirement of the preamplifier:

$$P_R = P_T\, G_T\, \eta_T\, \eta_{ATM}\, L_{FS}\, L_p L_{SI}\, G_R \eta_R\, \eta_C$$

P_R is the received optical power, detected at distance L

P_T is the transmitted average optical power with wavelength λ

$G_T = (\pi D_T/\lambda)^2$ and $G_R = (\pi D_R/\lambda)^2$ are the transmitter and receiver gains, respectively

   (D_T and D_R are the diameters of the transmitter and receiver telescope, respectively)

η_T , η_R, and η_C are the transmitter, receiver, and fiber coupling efficiencies, respectively,

η_{ATM} is the atmospheric attenuation in the case of Satellite Ground or Ground-Satellite;

$L_{FS} = (\lambda/4\pi L)^2$ is the free-space loss, L is the distance Transmitter-Receiver

$L_p = \exp(-G_T\theta^2_{BW})$ corresponds to the pointing errors, θ_{Bw} is the pointing jitter

L_{SI} is the scintillation-induced errors when the light is transmitted through the Earth Atmosphere

For a fixed distance, to increase the signal at the receiver (P_R) we can increase the transmitter power, (P_T), the diameter of the transmitter telescope (D_T), and that of the receiver (D_R). In most cases, they are the other parameters related to the efficiencies and pointing errors

In 2019 and 2020 ESA accorded two contracts in parallel, "High Throughput Optical Network (Hydron), Artes ScyLight" within Hydron subprogram (ESA AO/1-9814/19/UK/AB); to study the feasibility of 100 Gbps with 10 wavelengths each at 10 Gbps. The final objective is to compare the advantages and disadvantages of the two methods:

- One transmitter at one channel (wavelength) 10 W, 1λx100Gbps
- Many transmitters (e.g. 10) at lower powers and different wavelength (10x 1W, 10λx10Gbps)

3. OPTION-1- ONE TRANSMITTER (10W, 1λx100Gbps)

3.1 Review of current fast transfer with one wavelength

To achieve image transfers from satellites, close to real-time, with low Bit Error Rates-(BER), a data transfer rate should be of the order or higher than 100 Gbps. To achieve this level of transfer speed the number of photons per unit time (10^{-11} second) should be high enough to permit a low Bit Error Rate (BER)
Table 2 gives an example of current studies of space-related optical link and their date rate transmission.

Table 2: Example of studies and the relative data transfer for 1 wavelength transmitter

Reference Work	Modulation Technique	Link	Tx Power (W)	Max transfer Symbol/sec	Distance (km)
Optical Link Study Group OLSG (2012); [2]	OOK,	LEO-Ground	0.5	10	1300
Optical Link Study Group OLSG (2012); [2]	DPSK,	GEO-Ground		10	39,770
DLR, Barrios et al. (2018); [3]	DPSK or BPSK	Small LEO-GEO Relay	3	10	40,000
DLR, Barrios et al. (2018); [3]	DPSK or BPSK	Big LEO- GEO Relay	5	10	45,000
DLR, Barrios et al. (2018); [3]	DPSK or BPSK	UAV to GEO Relay	50	10	35,980
DLR, Barrios et al. (2018); [3]	DPSK or BPSK	GEO Relay to Ground	10	10	38,394
DLR, Giggenbach et al. (2018); [4]	OOK	LEO (Earth Observation) to Ground	1	10	700-1000
DLR, Giggenbach et al. (2018); [4]	OOK	Ground to LEO (Earth Observation)	10	10	700-1000
EDRS-Copernicus –Sentinel-1 (2019); [5] **Demonstrated on satellite**	O-QPSK	LEO-GEO	2.5	1.8	45,000
NASA, Warner et al. (2019); [6]	DPSK	GEO-GEO	5	55	73,000
NASA, Warner et al. (2019); [6]	DPSK	GEO-GEO	1	11	73,000
NASA, Warner et al. (2019); [6]	DPSK	LEO-GEO	5	200	42,880
NASA, Warner et al. (2019); [6]	DPSK	LEO-GEO	2.5	100	42,880
NASA, Warner et al. (2019); [6]	DPSK	GEO-Ground	5	1,524	35,790
NASA, Warner et al. (2019); [6]	DPSK	GEO-Ground	2.5	762	35,790
NASA, Warner et al. (2019); [6]	DPSK	GEO-Ground	0.5	152	35,790
Padhy et al. (2018); [7]	DPSK + Manchester coding	LEO-MEO	1	40	19,100
Sivakumar (2019); [8]	PDM-QOSK with coherent detection and DSP	LEO-GEO	1	160	40,000

NASA had performed studies [6; 9] evaluating the Maximum Data Rate Achievable and Power Requirements for three cases of optical links: Relay to Ground (35,790 km), LEO-GEO (42,880 km), and GEO-GEO (73,000 km). For each link three levels of transmitter power were considered; 0.5W, 1 or 2.5W, and 5 W (1550 nm). Four sets of transmitter and receiver telescopes were considered for each study, their diameters were selected based on previous or proposed telescopes for NASA missions. The 100 Gbps was possible for the LEO GEO only with the set of largest telescopes, and the highest transmission was 55 Gbps (5W transmitter) for the GEO-GEO Link. The studies show the need for a higher power (10W) transmitter to have a reliable 100 Gbps at LEO-GEO or GEO-GEO link

It was not possible to push for a quantitative comparison between the various studies, each having its own assumptions and estimation of the efficiency parameters and pointing errors, in addition to very different telescope diameters considered.

3.2 Development of the 10 W Amplifiers in the 1550 nm range at MPB

For the method with one Transmitter at 10W (1λx100Gbps), a simple diagram of the demonstrator with the 100 Gbps transceiver is:

Transceiver-Output (0-1 dBm) => MPBC 10 W Amplifier => VOA(s)

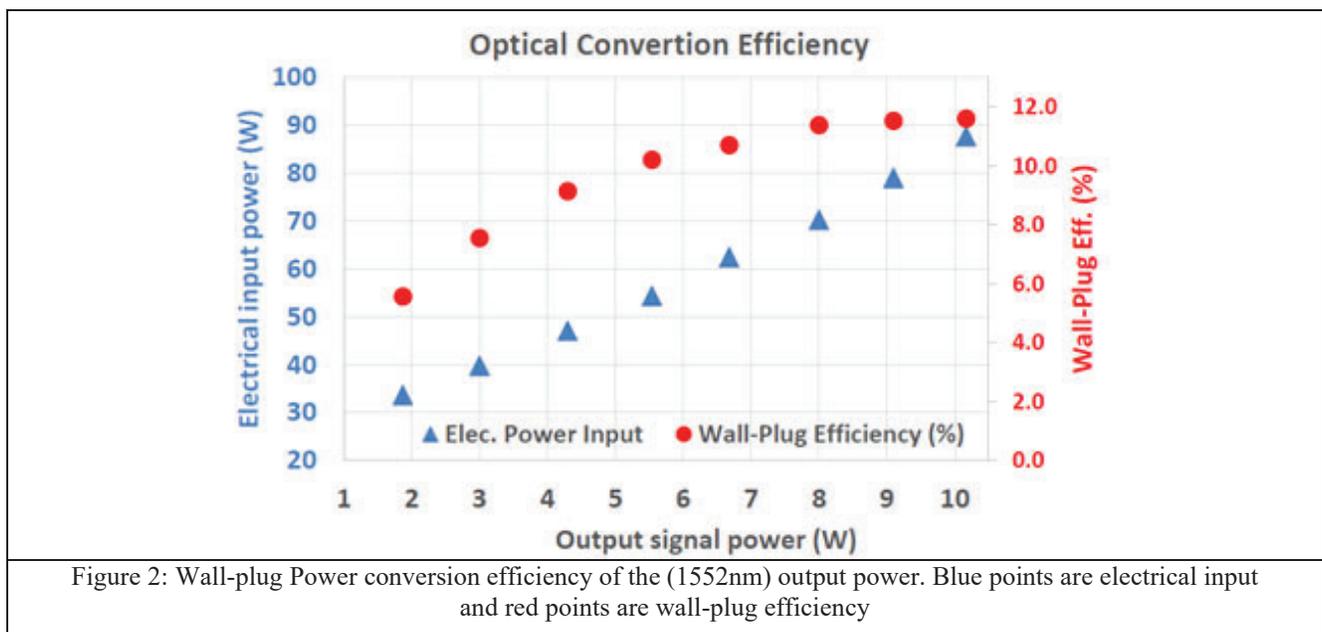**=> MPBC Low-Noise-Amplifier => Input-Transceiver**

The demonstrator with the 100 Gbps transceiver is being built in collaboration with the supplier of such a commercial product. This product is still in the prototype stage, MPB will perform its space qualification during the collaboration.

MPB developed a family of EDFA amplifiers (1550 nm) at 1-3W output power, presented at ICSO-2018 [9]. Recently a preliminary space-qualified 10 W Polarization Maintaining Amplifier based on Erbium-Ytterbium Doped Fiber. The amplifier characterization (Table 3, Figure 2) is presented in a paper at ICSO 2020 [10]. At the 10 W level, the thermal dissipation of the heat generated by the electronics and the laser diode pumps at 940 nm becomes the main challenge for a space-qualified amplifier, with limited surfaces, volume, and mass. To have the amplifier functional between -20°C and 50°C MPB had to use an Innovative Proprietary Method of the spool design for the active fibers. Work is progressing to have a larger range, at least between -35°C and + 65°C.

The optical loss signal in space of the order of 60-72 dB, estimated from the Link budget (previous section) can be represented by Variable Optical Attenuators (VOA).

Table 3: Experimental Efficiency 10 W-PM EDFA

Loss Power (W)	Loss Power (W)	Last (2020)
Nominal output Power(W)	-	10.4
Er:Yb-doped fiber efficiency	25	32%
Combiner efficiency signal	0.07	93%
Combiner pump transmission	1.5	95%
Isolator efficiency	1	89%
Laser Diode Pump power	35.5	51.5%
Driver and control board efficiency	15	83%
Total electrical power needed(W)	-	87
Total Loss (W)	77	89.6%
Wall-plug efficiency	-	11.4 %

Figure 2: Wall-plug Power conversion efficiency of the (1552nm) output power. Blue points are electrical input and red points are wall-plug efficiency

4. OPTION-2- 10 TRANSMITTERS (1W,10λx10Gbps)

4.1 Review of current fast transfer with many wavelengths

Table 4 gives some studies examples of very high data transfer rate up to Terabit/second (Tbps) and the modulation techniques used to reach such rates. The EDRS relatively lower data rate is the one proposed to be used on satellites.

Table 4: Example of studies and the relative data transfer for lower power amplifiers with many wavelengths

Reference Work	Modulation Technique	Link	Tx Power (W)	Max transfer Symbol/sec	Distance (km)
EDRS-Copernicus – Sentinel-1 (2019) [5]	O-QPSK	LEO-LEO, LEO-GEO, UAV-GEO	5	4 λ x1.8 =5.6Gbps	1000-45000
Sumathi (2020) [12]	Hybrid WDM–PDM with orthogonal modulation scheme CSRZ–DQPSK - PolSK	LEO -GEO	1	16 ×2 SOP ×120 Gbps = 3.84 Tbps	58,000
Kaur et al. (2018) [13]	WDM link with Alternate mark inversion (AMI) scheme	LEO-LEO	1	64λ x 40 Gbps =2.56 Tbps	2,500
Gill et al. (2019 [14]	Mode Division Multiplexing (MDM) with DQPSK scheme	LEO-LEO	1	64 spatial modes x40 Gbps = 2.56 Tbps	3,750
Poliak (2018) [15]	DWDM channels	Uplink Ground-GEO	1.7	40 λ x 43Gbps =1.72 Tbps	40,000

A detailed comparison of various modulation techniques, with some explanation, an estimation of BER and their capabilities up to 400 Gbps are given by Mohapatra et al. [16]

4.2 Present Development of 10λx10Gbps at MPB

For the method with 10 transmitters: MPB completed a detailed optical design of Reconfigurable Optical Add-Drop Multiplexer (ROADM) for Space Optical Cross Connection Links (OXC), based on DWDM, having 10-ITU channels for a total 100Gbps.

The ROADM is connecting in bi-direction, with Add/Drop. We consider 4 satellites each in one direction noted East (E), South (S), West (W), and North (N), with a fifth option to the Add/Drop to Ground (Figure 3). The OXC design permits switching signals from one direction to any other for two channels having the same ITU wavelengths or two different wavelengths. The Add/Drop signals – can add one or two ground data signals or drop one or two ROADM data signals into and from any direction and any DWDM (wavelength) channel among the ten λ-channels, respectively (Figure 4).

The optical signal power flatness between the λ-channels is controlled by power monitors, including a 2-5% tap photodetector (PIN-photodiode) and VOAs. For 10λx10Gbps, various suppliers were contacted.

Although all the optical components are available as commercial products, the price of optical components (Optical switches, MUX/DEMUX, couplers, VOAs, channel-power-monitor, DFB-transmitters, and photodetectors) is of the order of 200 K€, without the electronics that monitor these components.

MPB reduced the number of components (e.g. wavelengths) to build a simplified prototype significantly representative of ROADM-OXC at an acceptable cost. This exercise permits MPB to keep a minimum of know-how to stay within the best international companies providing the ROADM-OXCs.

Figure 5 illustrates the demonstrator to build, it was reduced to 2x2 Cross Connection in all direction between two satellites e.g. satellite East (E) and Satellite West (W).
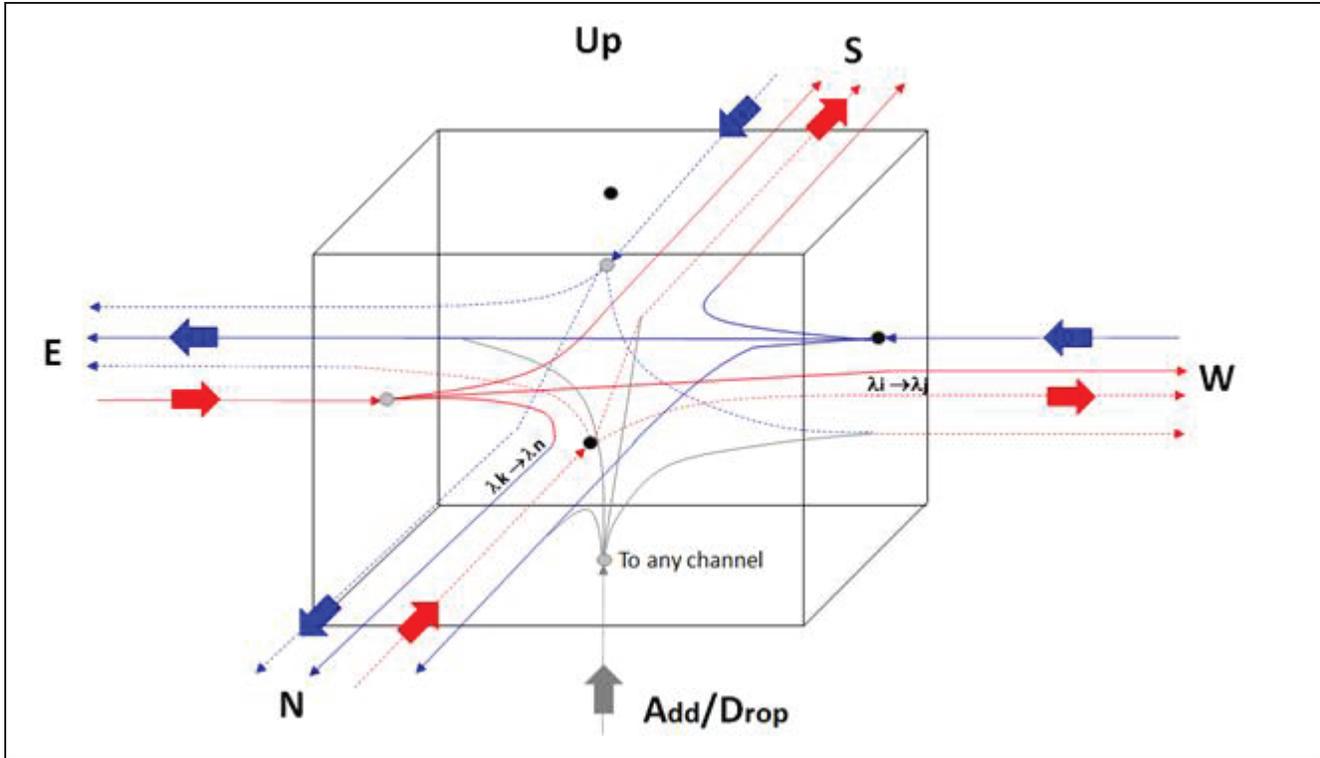
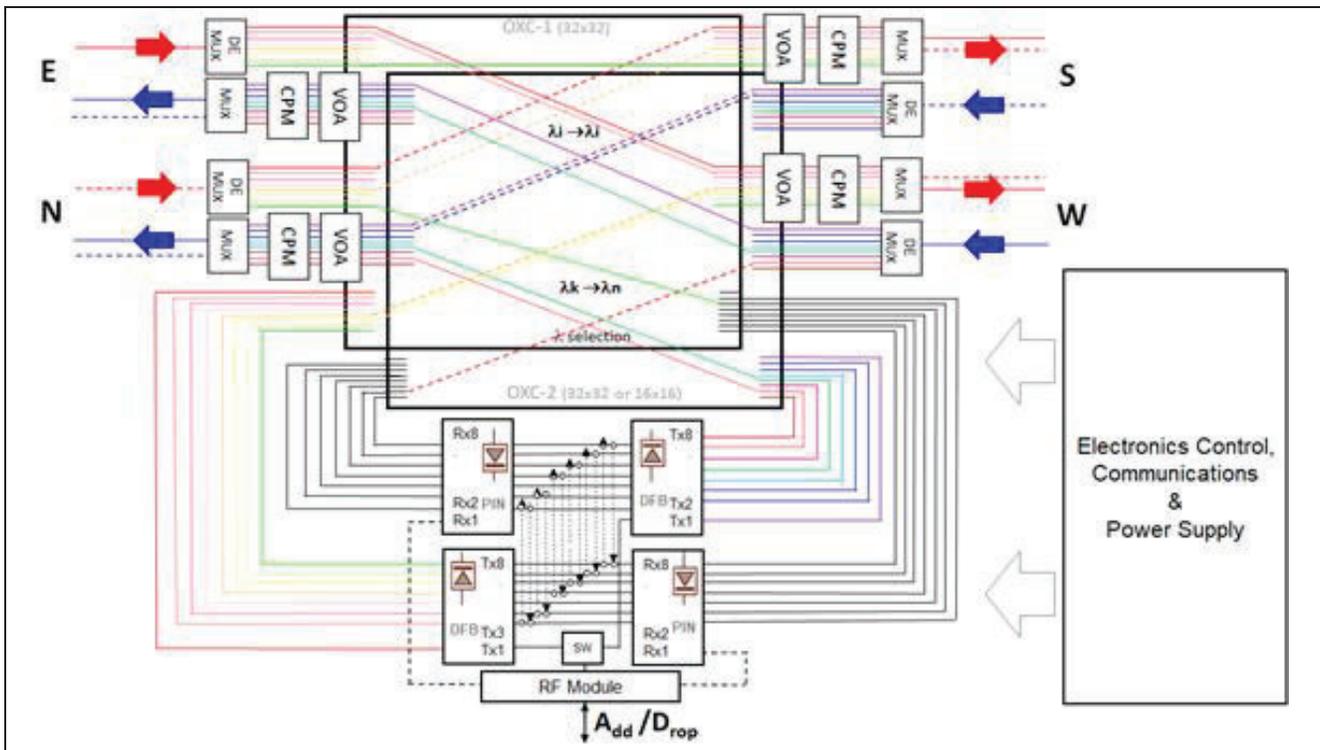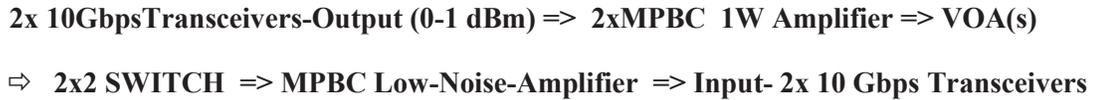Figure 3. Space Reconfigurable Optical Add-Drop Multiplexer (ROADM) Design

Figure 4. Space ROADM Design- Connection of the channels (wavelengths)

For the method with 10 Transmitters at 1W (10λx10Gbps), MPB will develop a 2x2 demonstrator to verify the technology and compare the experimental results to available satellite data at close rate e.g. those from EDRS, and works developed at the NASA or ESA.

 A simple diagram of the demonstrator with 2x2 Cross Connection, and 10 Gbps Transceivers is:

2x 10GbpsTransceivers-Output (0-1 dBm) => 2xMPBC 1W Amplifier => VOA(s)

⇨ **2x2 SWITCH => MPBC Low-Noise-Amplifier => Input- 2x 10 Gbps Transceivers**

MPB is in the process of building the 1W (2λx10Gbps), demonstrator using MPB amplifiers of 1W at the transmitters and the Low Noise Amplifier at the receivers
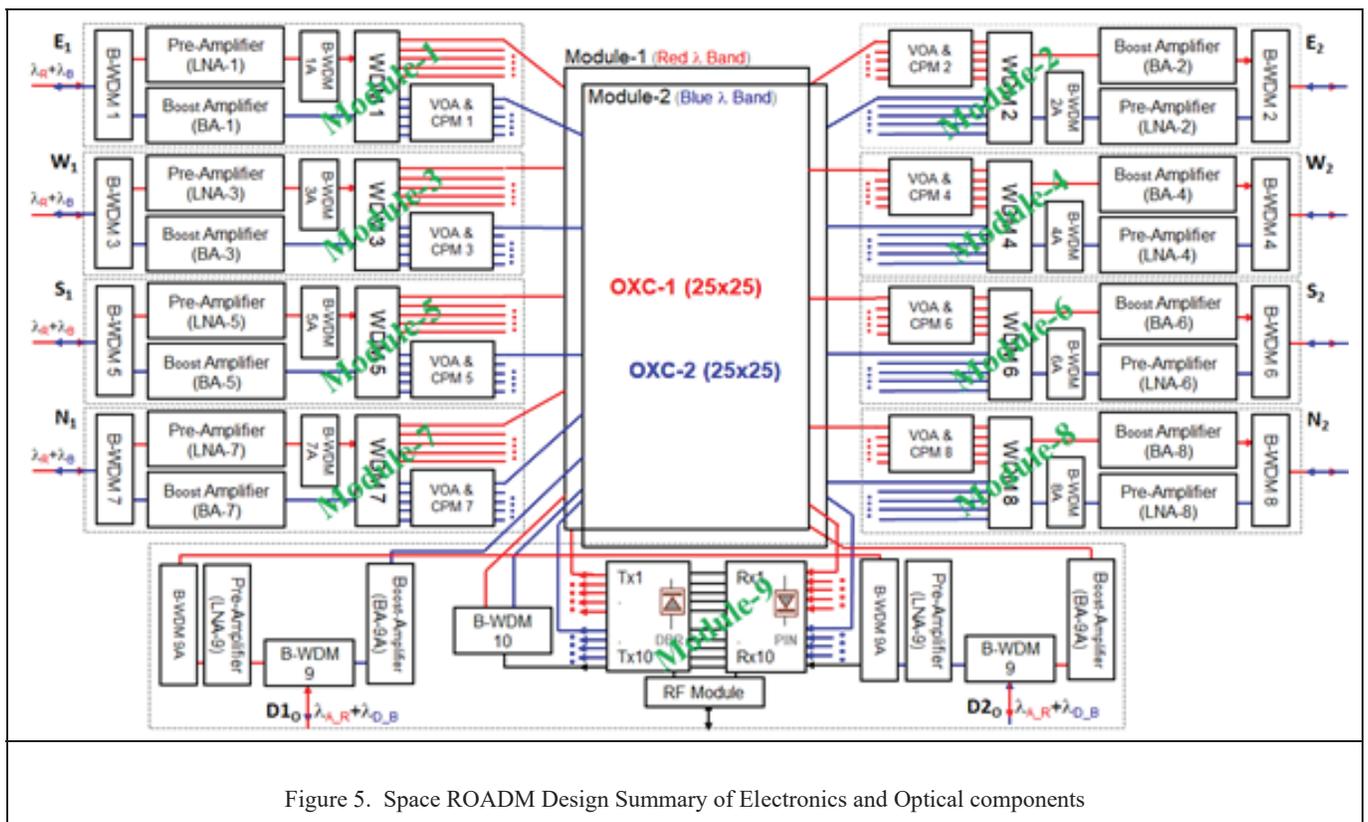

Figure 5. Space ROADM Design Summary of Electronics and Optical components

5.   COMPARISONS OF TRANSMITTERS: 1X(10W,1λX100GBPS) VS 10X(1W,10λX10GBPS)

In the next step, we will compare the performance of the two methods (1λx 10Wx100Gbps) and (10λ x 1Wx 10Gbps). A preliminary comparison is given in Table 5. The 10W version seems very well needed unless the telescope diameters at the receiver and transmitters are increased to > 20 cm each.

Table 5: Comparison of the two methods 1λx 10Wx100Gbps with 10λ x 1Wx 10Gbps

Parameter	1λx 10Wx100Gbps	10λ x 1Wx 10Gbps
Redundancy	Only one transmitter	10 transmitters, if one fails the others continue to be functional
Bit Error Rate or Symbol Error Rate	Lower	Higher
Modulation techniques	Simple techniques are convenient in most applications	Complex techniques with increased bit/symbol are needed
Max Distance	More convenient as distance increase e.g. for GEO-GEO 73,000km	Less convenient as the distance increases LEO-LEO and some LEO-GEO
Other application than	Lidar (CO_2), Ranging, 3D-Imaging, Altimetry, Topology,	MxN intra-satellite optical link (e.g. Optical Microwave cross-connection [17]
Space qualification status	To complete the space qualification of the 10W transmitter Space qualify the 100 Gbps transceiver	We can find suppliers of space-qualified components included in the demonstrator

ACKNOWLEDGMENTS

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