

International Conference on Space Optics—ICSO 2014

La Caleta, Tenerife, Canary Islands

7–10 October 2014

Edited by Zoran Sodnik, Bruno Cugny, and Nikos Karafolas



Application of photonics in next generation telecommunication satellites payloads

J. Anzalchi

P. Inigo

B. Roy



International Conference on Space Optics — ICSO 2014, edited by Zoran Sodnik, Nikos Karafolas, Bruno Cugny, Proc. of SPIE Vol. 10563, 105633O · © 2014 ESA and CNES
CCC code: 0277-786X/17/\$18 · doi: 10.1117/12.2304200

Proc. of SPIE Vol. 10563 105633O-1

APPLICATION OF PHOTONICS IN NEXT GENERATION TELECOMMUNICATION SATELLITES PAYLOADS

J. Anzalchi¹, P. Inigo², B. Roy²

¹ Airbus Defence and Space, Telecommunications Satellites Business Division, Stevenage UK.
Javad.anzalchi@astrium.eads.net,

² Airbus Defence and Space, Telecommunications Satellites Business Division, Toulouse, France
patricia.inigo@astrium.eads.net, bernard.roy@astrium.eads.net,

I. INTRODUCTION:

Next generation broadband telecommunication satellites are required to provide very high data throughput using complex multibeam architectures. These high throughput ‘Terabit/s’ Satellites will incorporate payloads with very large quantity of conventional RF equipment, co-axial cables, waveguides, harnesses and ancillary equipment, making the Assembly, Integration and Test (AIT) very complex. Use of ‘RF over Fiber’ and associated photonics equipment can make the process of AIT much simpler with the added benefit of significant reduction in number of payload equipment and inherent payload mass.

Application of multibeam concept with narrower beams and exploitation of the frequency reuse schemes have enabled a significant increase in the overall system capacity and instantaneous user data rates “as high as 100 Gbps” total capacity in the second generation of High Throughput Satellites (HTS) in Ka band (Ka-Sat, Viasat-1, ...). This important technology advance has allowed satellites to be back in the course of high throughput network access solutions and have improved their suitability for the current Internet requirements. Demand for higher and higher peak data rates continues to maintain pressure on communication infrastructures since Fiber to the Home (FTTH) has replaced Asymmetric Digital Subscriber Line (ADSL) as the new reference in terms of performances.

The satellite industry is now preparing for the next evolution of the HTS, the Terabit/s based architectures through various R&D studies during the past years funded by the European Space Agency, National Space Agencies and the European Commission.

Thanks to these studies it has been possible to carry out comprehensive end-to-end system assessment of such systems and propose innovative architectures capable of achieving the goal of a Terabit/s satellite capacity [1], [2].

Disruptive techniques and technologies have been applied in order to define such satellite, including very large platforms, highly efficient RF power amplification, large reflectors, and usage of new frequency bands including Q/V band and optical links as well as advanced air interface techniques.

The paper describes the photonics components that can be used to provide same functionality as fully RF payloads. Key features of RF and Photonic payload architectures are discussed. Free-space optical links in the forward link (FL) from Gateways to Satellite has also been investigated during the course of the study but is not covered in this paper and is the subject of separate paper.

II. SYSTEM DEFINITION:

The system under consideration is an evolutionary multibeam system with more than 250 beams, intended for the provision of Interactive Broadcast Satellite (IBS) services over a continental area, allowing the provision of Internet services with performance similar to that of ADSL in areas where the access to other terrestrial broadband connectivity is critical or non-existent.

A. Frequency Plan

Taking into account the regulatory constraints, the following frequency plan as shown in Fig 1 has been considered.

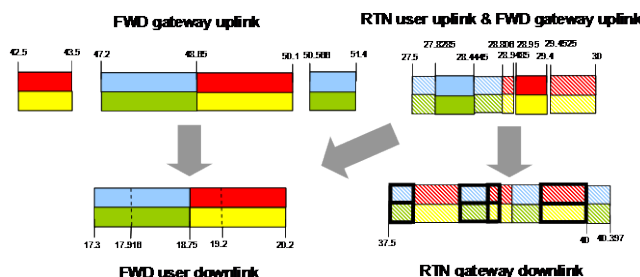


Fig. 1. Frequency Plan

The mission described in the present paper was studied under a programme of and funded by the European Space Agency. The view expressed herein can in no way be taken to reflect the official opinion of the European Space Agency.

The Ka band feeder link (FL) will share the Ka band user antenna on the satellite. The Q/V band feeder will use a dedicated antenna on the satellite.

This frequency plan allows connecting 1 gateway (GW) beam to 8 user beams instead of 6 user beams when using Q/V band feeder link spectrum only, or 4 user beams when using only the 47.2 – 50.1 GHz band. Hence, this reduces the number of required gateways by 2/3 or by 1/2 respectively.

B. User Beams and Gateways

The system scenario that has been investigated assumes a user beam layout of 260 beams of 0.21° over EU27 coverage area, as illustrated in Fig. 2.



Fig. 2. User Beam Layout

This number of beams has been selected through a top-down approach so as to approach the Terabit/s capacity based on the selected frequency plan and assuming realistic spectral efficiencies. According to the frequency plan presented above, this leads to 33 active gateways.

To mitigate the propagation attenuation for the Q/V band feeder links, a diversity solution called N+P [3] has been selected. In this scheme, in a given feeder beam, only one gateway is deployed. However, the system implements more feeder beams and deploys more gateways than the required active gateways. It is assumed that for N active gateways, P additional gateways are deployed as back-up, leading to a total of N+P gateways. The additional gateways are deployed sufficiently far apart from other gateways in order to ensure full decorrelation of rain events.

After assuming full-decorrelation of rain events between sites, the problem has been modelled by a random variable following a binomial law. In order to ensure a single feeder link availability of 99.99%, a total of 4 back-up gateways have been identified.

III. PAYLOAD ARCHITECTURES:

A. Antenna Configurations:

Various antenna configurations have been considered for the system design, such as:

- 3xSFPB (Single Feed Per Beam) configuration with 4.8m Tx/Rx
- 4xSFPB configuration with 4.8m Tx/Rx
- 2xMFPB (Multi Feed Per Beam) configuration with 6.3m Tx and 4.8m Rx

The above list is not exhaustive but aims to illustrate that feasible antenna configurations exist. Each of the above configurations has different advantages/disadvantages in terms of intrinsic RF performance (directivity, Carrier/Interference (C/I)), cost, Technology Readiness Level (TRL) and accommodation constraints on the satellite platform. This paper presents the performance results based on 2xMFPB antenna configuration.

In order to implement a Terabit satellite we have assumed a transparent bent-pipe payload. The proposed repeater architecture assumes 110W Ka band Travelling Wave Tube Amplifiers (TWTA) shared by 2 beams and 60W Q/V band TWTA's per gateway and per polarization.

B. Payload Implementation Using Conventional RF Equipment:

A generalized top level block diagram for a typical conventional payload architecture that can satisfy the payload requirements of the mission outlined in the previous sections, identifying the major elements in

conventional bent-pipe architecture is presented in Fig. 3 and a typical payload panel showing equipment layout complexity for such payload architecture is shown in Fig. 4.

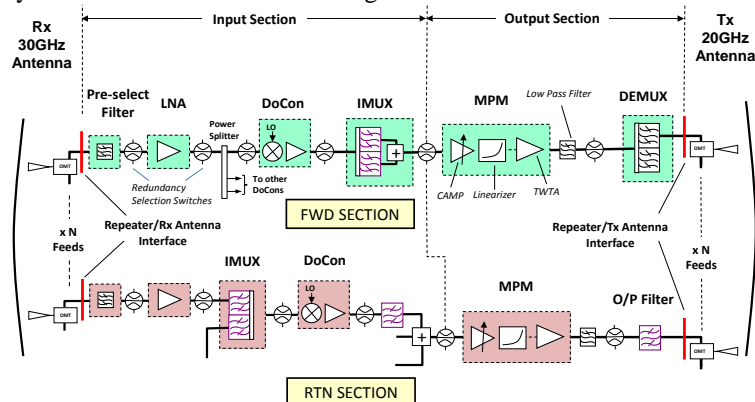


Fig. 3. Simplified Payload Block Diagram Using Conventional RF Equipment

The main elements as highlighted in the block diagram of Fig. 3 are briefly described as follows:

The Receive Antenna:

This provides coverage over a specified area, with a defined gain and cross-polarization performance.

The Pre-select Input Filter:

This is a wideband filter included at the antenna output prior to the Low Noise Amplifier (LNA) input. Its purpose is to reject signals outside the wanted receive band, suppress unwanted image signals, protect the LNAs from high power spill-over from the payload transmit section and assist in preventing ring-around instability of the overall payload transponder. This filter will still be manufactured using conventional RF technology and not photonics.

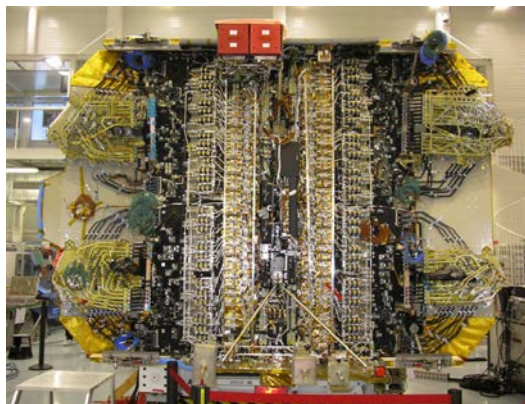


Fig. 4. Typical Payload Panel Equipment Layout (Eurostar E3000 Platform) Using Conventional RF Equipment

The Low Noise Amplifier (LNA):

This provides high gain amplification (typically 35dB to 45dB) with low noise and high linearity. The effects of LNA non-linearity are relatively small but can become significant if the amplifier is driven by high level leakage from the transmit section and high level uplinks which could emanate from outside the system. Waveguide switches are used at the input and output of LNAs in a redundancy network to provide the facility to select a redundant LNA in case of failure of any of the LNAs. The LNA and the redundancy network at the input and output of the LNAs will still be manufactured using conventional RF technology.

The Down-converter:

This equipment provides down-conversion of the Receive RF signal to the Transmit frequency bands. It also provides high level amplification (typically 25dB). Because of the relatively high input levels (from the LNA output), linearity becomes an important issue for this equipment, particularly as it is a wideband element and may be driven simultaneously by a number of signals of greatly differing power levels. If signals of widely different levels are present, then those at the lower end of the power range may suffer significant interference from intermodulation products resulting from the higher power carriers. In addition there is the possibility of

interference from spurious signals resulting from the mixing process. Another critical parameter for the converter is phase noise or spurious modulation. The down-converter may also introduce additional thermal noise into the system, albeit at a much lower level than introduced by the LNA, but still of significance.

The down-converter is the first element of the payload where photonic technology will provide significant benefit.

The Channel Filter or Input Multiplexer (IMUX):

This equipment provides filtering of the converter output and defines the channel bandwidth. It protects the wanted signal from adjacent channel interference and out of band spurious signals and intermodulation products generated within the LNA and down-converter. Ideally the filter should provide filtering without distortion of the wanted signal. However, because of the need to provide adequate out of band rejection to protect the wanted signal, the in-band performance, that is the gain and group delay versus frequency is degraded and results in some impairment of the signal.

Channel filtering is potentially another function which can be performed using photonic technologies. However for implementation of narrowband filters for missions such as, Fixed Satellite Service (FSS) and Broadcast Satellite Service (BSS) the technology or techniques are not yet mature. Description of how channel filtering could be achieved using photonic technologies is provided in later part of the paper.

The High Power Amplifier and Output Multiplexer:

For the payload architecture proposed in Fig. 3 above, the high power sections such as TWTA and output multiplexer (OMUX) will still be performed using conventional RF equipment.

C. Payload Implementation Using Photonic Equipment:

A simplified top level payload architecture using photonic technology and satisfying the mission requirements described in section II is provided in Fig. 5. In this figure, the payload equipment functions which can be implemented using photonic technologies are highlighted.

Payload elements such as frequency down/up-converters, Frequency Generation Unit (FGU), Optical Switching and Optical interconnecting elements are the main beneficiaries of photonic technologies.

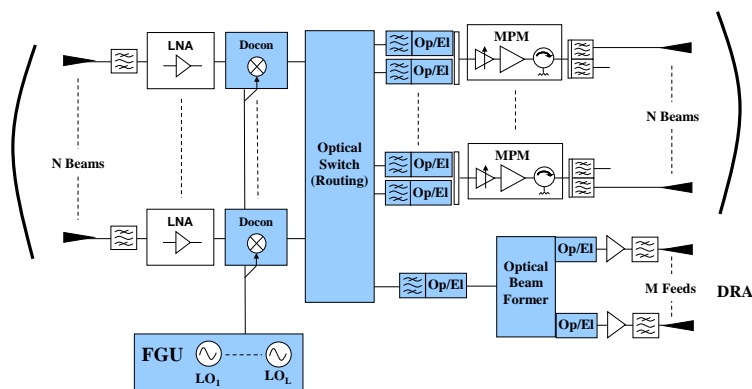


Fig. 5. Simplified Payload Block Diagram Using Photonic Equipment

The main elements as highlighted in the block diagram of Fig. 5 are briefly described as follows:

Photonic-RF-Conversion Equipment:

Photonic-RF-Conversion (PRC) refers to the frequency conversion of the RF multi-beam signals using the optical domain. Fig. 6 below illustrates a building block schematic of the photonic equipment. The equipment is illustrated with the option of multi-frequency conversion which provides the advantage of multi-band and multiple simultaneous conversions which enhances the equipment flexibility and functionality.

The basic optical components required for the implementation of the PRC equipment are:

- Electro-optic (EO) Mach-Zehnder modulators (MZMs): to realize frequency conversion in the optical domain
- Wavelength Division Multiplexer (WDM)/Demultiplexer: to multiplex/demultiplex the optical channels in case of multi-frequency conversion
- Mid-power Optical Fiber Amplifiers (OFAs): to boost the power of the optical signals and compensate photonic-RF mixing losses. The OFA is deployed depending on the architecture and power budget.
- High-speed photodiodes: for opto/electronic up/down conversion of the optical signals.

Electro-optic (EO) Mach-Zehnder modulators (MZMs) are widely used in terrestrial communications in long distance Radio-over-fiber (RoF) as well as metro and long-haul optical transport systems. In the PRC equipment MZM arrays are used as the "front end" and are integrated together with their RF driver circuits. The optical performance requirement is the wide modulator electro-optic bandwidth to accommodate frequency conversion of the high frequency RF signals.

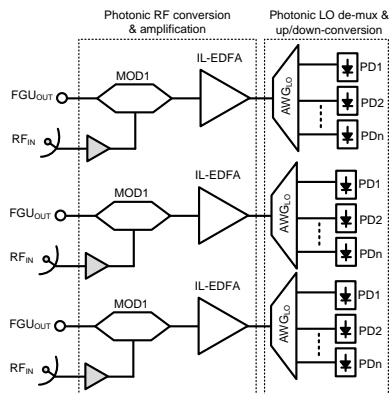


Fig. 6. Simplified Block Diagram of PRC Equipment

According to the PRC equipment requirements the critical parameters for selecting the candidate EO-MZM technologies are:

- **Modulator linearity:** RF photonic applications typically require high linearity and operation of the modulator in the linear regime to avoid distortion (e.g. signal clipping, additional signal harmonics) of the RF signals. The critical parameter that defines modulator linearity is the Spurious Free Dynamic Range (SFDR).
- **Driving voltage:** Lower driving voltages imply the use of low power consumption modulator drivers and reduced electrical power consumption.
- **Module packaging:** Module hermeticity is required to avoid contamination effects. The use of material sensitive to out-gassing during the packaging process has been identified as a critical failure mode [4]. Additional requirement is the capability to integrate/co-package EO-MZMs in arrays to reduce component size and fabrication cost given the high volume context of the photonic payload application.

Space qualification of commercially available, EO-MZMs has been carried out through dedicated procurement/qualification ESA and NASA programs. The strict requirement set by these programs was that modulators must comply with Telcordia standards in order to be considered a reliable candidate for further assessment. Data on the space qualification of EO-MZMs are available in the public domain [5]. The general remark is that Telcordia qualified Lithium Niobate (LiNbO₃) and semiconductor (Indium Phosphide (InP), Gallium Arsenide (GaAs)) MZMs are able to withstand most environmental tests while keeping a good performance.

High Speed Photo-detectors:

Detection of microwave frequencies sets challenges on bandwidth/saturation limitation, thermal dissipation and linearity. Additional requirements on the detector are: the wide temperature operation and high responsivity for efficient O/E conversion.

The material choice for detectors is Indium Phosphide (InP) due to their maturity, high performance and radiation hardness. Mature components supplied to the terrestrial communications industry are available featuring 3-dB roll-off frequencies of >40 GHz and responsivity of >0.7 A/W. Linear photo detectors optimized for analogue applications are also available featuring 3-dB roll off frequency of >20 GHz and state-of-the-art responsivity of 0.95 A/W. Finally, InP detectors for RF Photonic applications are under development in United States within Department of Defence (DoD) and Defence Advanced Research Projects Agency (DARPA) funded programs.

Photonic RF Filtering:

RF channel filtering in the optical domain is considered as a promising option in order to fully exploit the advantages of photonics in payloads. Wide bandwidth, tunability, size/mass reduction and elimination of optoelectronic interfaces are the advantages over microwave filtering. The basic requirement from the application perspective is the combination of narrow bandwidth (30-50 MHz) which translates into a high Q factor and small size.

The Photonic RF filtering technologies can be divided into two main categories:

- Fiber-based filters which include discrete time delays (DTD), Bragg gratings, and Brillouin filters (BF)
- Photonic integrated filters which include resonator cavities in silicon or InP material.

DTD and BF filters are bulk, they require a number of fiber based components and their payload deployment would be impractical due to size, optical loss and power consumption. Bragg gratings are compact devices but they are limited in terms of optical bandwidth and temperature dependence.

Photonic integrated filters are the only option that combines small footprint and narrow bandwidth down to 10 MHz. The technology is becoming mature with the involvement of industrial organizations which use qualified fabrication processes. Photonic integrated filters in InP and Silicon are being pursued in DoD and DARPA funded projects in the US. For example, micro-cavity RF filters in InP have been recently developed by Freedom Photonics [6], whereas thermally-efficient reconfigurable narrowband RF-photonic filters in silicon have been demonstrated by US-based Kotura [7]. The latter is now considered as a promising candidate for RF photonic applications since it overcomes the disadvantages of micro-cavity filters and combines: small size, integration using industrial CMOS-compatible methods, narrow bandwidth (<50 MHz) and low power consumption (120 mW per filter cell).

In Europe, RF photonic filters integrated in foundry-level CMOS industrial processes are being attempted in FP7-SPACE BEACON project. The approach relies on miniaturized silicon photonic MZMs realized by 2x2 MMI couplers which are proven robust devices with respect to fabrication tolerances for their excellent repeatability and stable performance under temperature fluctuations [8].

Photonic Frequency Generation Unit (FGU):

The frequency generation unit (FGU) equipment comprises the generation, amplification and distribution of photonic local oscillator signals to facilitate the Photonic RF conversion process. Fig. 7 below illustrates a block diagram schematic of the FGU equipment. Below we focus on local oscillators (C1...n), high power OFAs (HP-EDFA) and fiber splitters. EO-MZMs (MOD1...n) have been discussed in PRC equipment section and AWG is discussed in the optical switching equipment section (common technologies for different equipment).

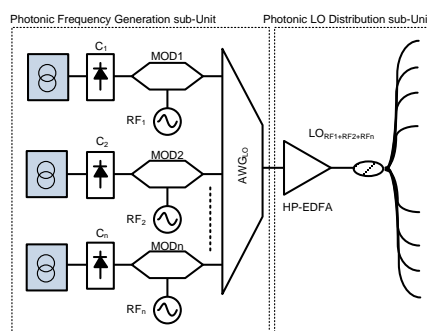


Fig. 7. Simplified Schematic Diagram of FGU Equipment

The FGU units and the basic equipment-level requirements are:

Local oscillator (LO) laser: The FGU equipment deploys laser arrays to provide the optical signals used for RF frequency conversion using the optical domain. In the FGU equipment, lasers will be system integrated together with their current drivers and temperature control electronics. Basic FGU equipment requirements are:

- Low noise: low laser phase noise which translates into narrow line-widths and low RIN
- Wavelength accuracy and stability: in case of WDM operation deployment,
- Wide operating temperature range
- Space compatible packaging for reliable operation in the space harsh environment.

Optical fiber amplifier (OFA): The OFA is required to boost the output of the local oscillators (LOs). In the FGU equipment OFAs will be system integrated as modules comprising passive and active components (pump laser) together with their electronic drivers. Optical powers in excess of >1W are required to enable a high splitting ratio. Given the reported sensitivity of doped fibers under gamma radiation (radiation induced absorption-RIA) the basic FGU equipment requirement from OFAs is radiation hardness. During a 2014 research, iXFiber has developed a radiation hardened Er fiber with Cerium co-dopant and HACC protection coating, with excellent performances (degradation less than 10% after 300 krad [9]). In addition, OFAs have to be developed with polarization maintaining (PM) components and PM active fibers since the cascaded MZMs operate optimally with a specific state of polarization. For low electrical power FGU equipment, OFAs should deploy cooler-less components with a wide operating temperature range.

Fiber optic splitter: These are passive components used to split and route the LO output to the EO MZMs. The components must be fabricated and packaged with high-rel compatible processes.

Optical Switching and Routing:

On-board optical switches are required in order to achieve switching and routing of photonic signals within the satellite. A simplified block diagram of photonic switching and routing equipment is presented in Fig. 8. Optical switching has been the focus of terrestrial research and development during the last decades in order to provide the necessary dynamicity and reconfiguration required by operators. More recently, new architectures for reconfigurable Add/Drop multiplexers have been proposed that blend Wavelength Selective Switching (WSS) and Optical Matrix Switching (OXC) technologies [10].

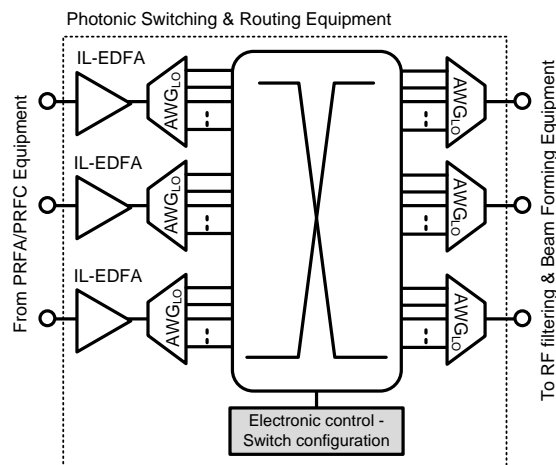


Fig. 8. Simplified block Diagram of Photonic Switching and Routing Equipment

Wavelength Division Multiplexing (WDM):

The optical switching and routing equipment is responsible for directing incoming optical signals containing RF data to suitable output ports that would subsequently be directed to the output part of the photonic repeater.

The dimensioning of the wavelength selective switching and optical matrix switching parts of the equipment heavily depends on the payload architecture under consideration. As multiple LO signals would be required in order to develop scalable payload architectures, coarse wavelength selective switches would not be applicable due to the broad pass-band characteristics. The key characteristics relevant to this unit are:

- Channel spacing
- Operational temperature
- Shock/vibration resistance
- Radiation hardness

Amongst the narrow-band Dense Wavelength Division Multiplexing (DWDM) components, planar lightwave circuit-based and bulk optics-based components are the most promising candidates.

Inter-Equipment Fiber-Optic Connectivity:

Active and passive fiber optic cables are required in photonic payloads to transfer optical signals between modules and equipment boxes reliably and efficiently. Active cables are deployable in photonic digital payloads to support new generation on-board digital processors, whereas passive optical cables are deployed in every part of the photonic payload. The basic requirements identified for fiber optic cables are:

- Low power consumption (active cables),
- Light weight and small size,
- Resistance to vibration and shock,
- Radiation resistance (especially for ASICs in active cables),
- Wide operating temperature operation
- Ruggedized hermetic packaging (especially for active cables).

V. SUMMARY COMPARISON OF CONVENTIONAL VS PHOTONIC PAYLOADS:

Summary of the main budget parameters for the payload using conventional and photonic technologies for Terabit Satellite is outline in Table 2. It should be noticed that when using photonic solutions the payload main performance (EIPR, G/T) are not changed compared to conventional RF architectures.

Table 2. Summary Comparison of Photonic vs. Conventional Payload

Parameter	Unit	Conventional Payload	Photonic Payload	% Change	Photonic Payload Comments
Mass	kg	2078	1553	-25.3%	25.3% less mass
Power	kW	25.1	22.9	-8.7%	8.7% less power consumption
Thermal dissipation	kW	14.8	12.5	-15.5%	15.5% less thermal power diss.

Table 3 provides a summary comparison of mass budget in Kg per equipment type for the conventional vs. photonic repeater.

Table 3. Summary Comparison of Photonic vs. Conventional Repeater by Equipment Type

Equipment Type	Conventional Payload (kg)	Photonic Payload (kg)	% Change
Filters	485	415	-14.4%
LNAs	77	79	+2.6%
MPMs	487	487	0%
Converters	147	70	-52.4%
Waveguide & Coax Cables	611	353	-42.2%
Switches & Misc.	271	149	-45.2%
TOTAL	2078	1553	-25.3%

VI. CONCLUSION:

The present paper has demonstrated that replacement of conventional RF payload equipment with their photonic counterparts and using fiber optic cables in place of coaxial cables and waveguides can enable dramatic reduction of mass for the terabit/s satellite.

Several challenges associated to using photonic technologies for this type of system have been reviewed. Majority of photonic technologies and techniques investigated are not still mature enough to be used in space environment and require further development and space qualification to reach their final implementation stage.

The authors would like to express their gratitude to ESA for their continued support and for funding the Terabit/s satellite study (contract N°4000103563/11/NL/AD), and to the consortium members for their support to the study and expert contributions.

REFERENCES

- [1] G. Verelst, O. Vidal, E. Albery, D. Galinier, N. Metzger, P. Inigo (Astrium SAS); S. Stirland, G. Huggins (Astrium Ltd), "Innovative System Architecture to reach the Terabit/s Satellite", 19th Ka and Broadband Communications, Navigation and Earth Observation Conference, October 2013.
- [2] P. Inigo, O. Vidal, B. Roy, E. Albery, N. Metzger, D. Galinier (Astrium SAS); J. Anzalchi, G. Huggins, S. Stirland (Astrium Ltd), "Review of the Terabit/s Satellite, the Next Generation of HTS Systems", 7th Advanced Satellite Multimedia Systems Conference (ASMS) and 13th Signal Processing for Space Communications Workshop (SPSC) (ASMS/SPSC 2014), September 2014.
- [3] Argyrios Kyrgiazos, Barry Evans, Paul Thompson (CCSR/University of Surrey), Nicolas Jeannin (DEMR/ONERA), Gateway Diversity scheme for a Future Broadband Satellite System, 18th Ka and Broadband Communications, Navigation and Earth Observation Conference, 2012.
- [4] M. Ott, Reliability of Optical Fibre Modulators for Space Flight Environments, on-line: misspiggy.gsfc.nasa.gov/tva/meldoc/modulatorreliability.pdf
- [5] A. Le Kernec, et al, Space Evaluation of Optical Modulators for Microwave Photonic On-board Applications, ICSO 2010 Rhodes, Greece International Conference on Space Optics 4 - 8 October 2010
- [6] E. J. Norberg, Journal of Lightwave Technology, IEEE, Vol.29, no. 11, pp. 1611-1619, June 2011
- [7] N. N. Feng, "Thermally-efficient reconfigurable narrowband RF-photonic filter", Vol. 18, No. 24 / Optics Express, 22 November 2010
- [8] L. Zimmermann, "C-band Optical 90deg Hybrids Based on Silicon-on-Insulator 4x4 waveguide Couplers", IEEE Photonics Technology Letters, Vol. 21, Issue 3, pp. 143-145, February 2009
- [9] Thomas et al, "Radiation-resistant erbium-doped-nanoparticles optical fiber for space applications", Opt. Express, vol. 20, pp. 2435, 2012
- [10] Richard A Jense, "Optical Switch Architectures for Emerging Colourless/Directionless/Contentionless ROADMs Networks", OFC 2011, 6-10 March 2011