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TOWARDS TELECOMMUNICATION PAYLOADS WITH PHOTONIC TECHNOLOGIES

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I. INTRODUCTION

In the last decade, Thales Alenia Space has put a lot of its research effort on Photonic Technologies for Space Application with the aim to offer the market satellite telecommunication systems better performance and lower costs [1] [2]. This research effort has been concentrated on several activities, some of them sponsored by ESA. Most promising applications refer to Payload Systems. In particular, photonic payload applications have been investigated through the following two ESA studies: Artes-1 "Next Generation Telecommunication Payloads based on Photonic Technologies" and Artes-5 "OWR – Optical Wideband Receiver" activities.

The cited Artes-1 contract investigated the impacts of novel photonic technologies on low/medium-scale payloads with high flexibility, operating in Ku/Ka bands and supporting cross-banding capability. Various configurations were considered, based either on full analogue repeater, or on digital-processor architectures. The introduction of photonic technologies was found to have particular impact, primary in the channelization section, the frequency-generation unit (FGU) and RF harness, and to a lesser extent in the I/O sections.

The study put in evidence how photonic technologies bring potential improvements in TLC P/L, in terms of significant reduction of the overall payload mass, saving of the P/L power consumption, and reduction of the total number of units. The novel photonic payload is lighter, less consuming and can be easily and cost effectively manufactured.

Similar work has been carried out in the Artes-5 OWR project [3]. The introduction of photonic technologies was evaluated into large-scale, high capacity payloads for civilian telecommunications missions, in particular for broadband access, multi-beam missions in Ka band. Payload architectures with high flexibility were considered and designed thoroughly. The study has highlighted that valuable mass and power savings can be obtained. As a whole, these results provide consistent trends and conclusions that confirm the substantial savings in mass, power and/or number of equipment, in all cases of high capacity and/or flexible missions.

This paper present how telecom payloads can host photonic technologies, and all the benefits derived from the use of these technologies. Two temporal frames are here considered, i.e. short and medium term. In particular, this paper describes the benefits in terms of mass saving and P/L complexity reduction. Also benefits in terms of Program and AIT saving are recounted. At the end, the capabilities of photonic technology to provide flexible, modular and reconfigurable P/L are also illustrated. A roadmap reporting the technological steps and achievements to arrive to a flight proven photonic telecommunication payload closes the paper.

II. STUDY CASE AND REFERENCE PAYLOAD

The study carried out in the frame of Artes-1 contract Next-Generation Telecommunication Payloads based on Photonic Technologies referred to an institutional mission scenario. This choice has been driven by the necessity to analyse payload architecture characterized by high level of flexibility, which characterize the channelization section of the payload. The basis of this study has been the definition of the reference payload architecture, whose definition was based on a Ka/Ku bands, full flexible with cross-banding capability payload, designed by TAS for an institutional mission. Main feature of this payload is the flexibility, mainly provided by the channelization section, implemented in analogue techniques using units like Agile Frequency Converter and Active Switch Matrix [4]. In Fig. 1 is reported reference payload architecture whilst in Tab. 1 are reported its main budgets.

The purpose of that study was to investigate how photonic technology can be exploited in order to reduce the "dimensions" (e.g. mass, number of units, design phase, test phase…costs) of a payload similar (or even better) in performance as the reference one. The considered architectures provide a TLC Payload with the physical features given in Tab. 1.

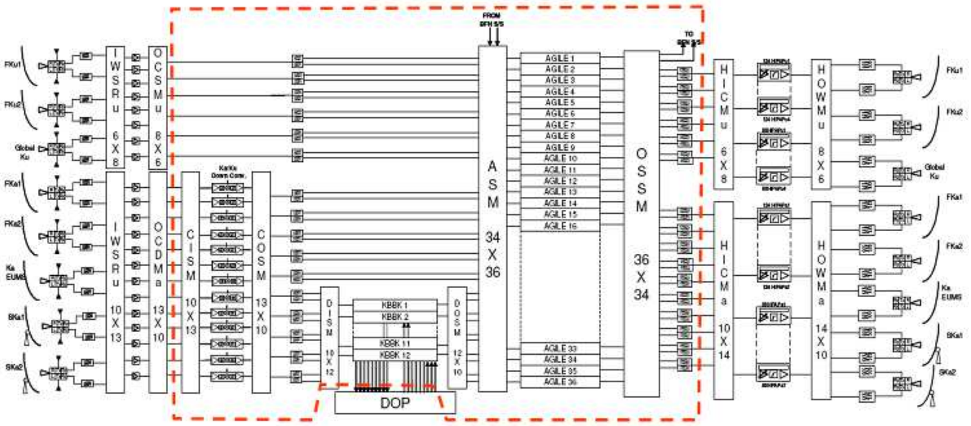


Fig. 1. Architecture of the reference analogue payload

Tab. 1. Main budgets of the reference analogue payload

Section	# of Units	Mass (kg)	Power Cons. (W)
I/P	56	24	75
Channelization	70	87	512
O/P	17	18	
HPA	42	66	3560
Total	185	195	4147

III. CHANGE: WHAT AND WHERE?

A technology migration cannot be easily achieved in complex scenario such as the case under study. One of the main encountered problem is the difficulty of space qualification (i.e. the absence of heritage) that doesn't encourage costumer and operator to invest in new technology, necessary today to provide a good answer to the market demand: more challenging payload with augmented performances, reduced costs and short delivered time. A possible solution is to act this migration step by step, starting from simpler implementation and arriving to complex solution.

A simpler, but not trivial, migration that can be implemented in short time is the replacement of the intra P/L RF communication harness (coax cables) with Fibre Optics (FO), in order to distribute analogue RF signal on FO.

This simple solution exploits some the benefits offered by photonic technology such as low cabling mass, EMI immunity, RF isolation, low propagation loss, wide bandwidth. To be put in place this solution needs of following development:

- Space qualified Fibre Optics (FO);
- Space qualified EO (Electro to Optical) converter;
- Space qualified OE (Opto to Electrical) converter;
- Space qualified FO splitter;
- Optionally, a Space qualified Optical Amplifier.

To avoid big modifications of already existing units, E/O&O/E converters could be implemented as standalone devices to be installed on the unit interface. Moreover to permit a gradual migration to photonic technology, is possible to limit coax to FO replacement just on the LO Network as shown in Fig. 2.

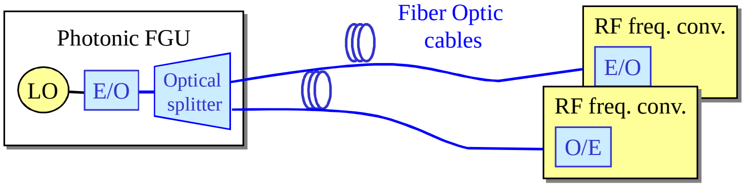


Fig. 2. Conceptual scheme of an optical LO distribution network

In Tab. 2 is reported the expected mass saving, around 38 kg, that can be reached on reference Payload by substituting in the LO network all RF cables with fiber optics, where measured data come from TAS payload used as reference, and estimated data have been evaluated considering GORE products.

Tab. 2: LO network mass comparison: Fiber Optics vs. coax cables

Item	Mass w/ Coax Cable*	Mass w/ Fiber Optics
1740 meters	44.5 kg	4.3 kg
1084 connections	4.5 kg	6.7 kg
Total LO network	49 (measured data)	11 (estimated data)

** 3mm diameter*

Next technology migration is the replacement of the frequency converter units. The optical mixing of RF signals is one of the most promising functionalities offered by photonic technologies. It permits the up/down conversion in a single step of RF signals (e.g. Ka → Ku/C or even baseband) and a new functionality such as the multi-frequency conversion. This new concept allows the simultaneous conversion of the signal to different target bands using the same equipment [1]. A conceptual scheme of single and multi-frequency up/down conversion are reported in Fig. 3.

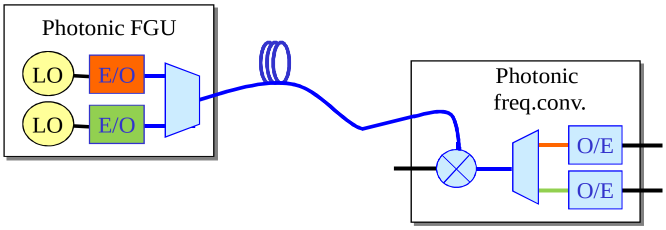


Fig. 3. Conceptual scheme of a Photonic Frequency Converter (for multi-frequency conversion)

Additional feature of the novel photonic converter design is the "*Transparency*" (independence from Input and Output frequencies) which permits an high level of unit reuse and re-configurability. **Erreur ! Source du renvoi introuvable.** reports preliminary budgets for a single channel converter.
In Tab. 3 is reported the results of a simulation in which a TAS 20 channel standard Ka down-converter subsystem has been compared with an equivalent one developed using photonic technology. From the comparison, a significant saving in mass and power consumptions is, once again, highlighted.

Tab. 3. Mass and power budgets for a single channel converter

Item	µWave	Photonic
# RF signal conversion	20	20
DC Power Consumption	80 W	11 W
Mass	12 kg	5.2 kg

From these first migrations, arises the necessity to develop a Photonic Frequency Generation Unit (FGU). At least three different approaches to the photonic LO can be considered. A first approach consists in generating photonic LO lines from a conventional RF/microwave FGU line, through direct-modulation of a semiconductor laser. This approach was studied and demonstrated within the ESA Artes5 MPLOD Microwave Photonic Local Oscillator Distribution project. A second approach consists in generating photonic LO lines from a conventional RF/microwave FGU line, through EO modulation of a CW laser. This enables to generate LO's easily up to 30 GHz and above, with nearly 100% modulation, therefore well suited for photonic RF frequency conversion. This is under study and development within the ESA Artes5 OWR project under TAS responsibility. A third approach consists in generating photonic LO lines directly in the optical domain, e.g. through Opto-Electronic Oscillators (based on fiber loops, micro-ring resonators …). This approach to be investigated in other ESA activities, will be considered in the new ESA contract "Roadmap for the introduction of Photonic technologies based payloads"; further activity related to FGU miniaturization is also under TAS evaluation.

A further function to be implemented in photonic is the signal routing. Also in this case this function can take benefit from photonics features like transparency (RF frequency independence), RF isolation (from path to path, and from input to output) and suppression of EMI/EMC issues, as well as mass and volume savings and scalability to large port counts.

Among the different options, free-space 3D micro-optical switches are considered as best solutions for photonic payload applications, as they provide superior optical performance and scalability to very large port counts, the underlying technology permitting to obtain low insertion loss combined with high crosstalk isolation. The miniature package withstands rugged environments and is well suited for direct mounting on printed circuit boards. Within Artes 5 project "Large Optical MEMS switch for broadband applications", SERCALO (CH) has manufactured a breadboard of a medium/high port count (50x50) optical cross connect for satellite based telecom applications [5]. The expected mass (and envelope) saving is disruptive also with respect to conventional low mass MEM switch. Also the cross-connection capability can improve in a significant way the in-flight routing and re-configurability of the P/L.

Summarizing, the above described functionalities, signal Distribution, signal frequency conversion and signal routing, together with their related processing techniques and equipment, have been identified as the best candidates for implementation of first-generation analogue photonic payloads. Tab. 4 summarizes the current perception on how photonic signal distribution and processing techniques could take place on board a generic telecom payload, and how the payload functionalities would be split between microwave and photonic technologies. Along with it, Fig. 4 below gives a long-term vision of an analogue telecom payload architecture, and illustrates how photonic signal distribution and processing could be used, and how these functionalities could interface to each other, and where E/O and O/E conversions might be needed.

Photonic technologies could support LO distribution, RF frequency-conversion with single or multiple LO's, as well as RF signal distribution and routing. Such first-generation photonic analogue payloads are expected to be made available in the medium term.

Tab. 4. Technology migration in a TLC P/L – x: baseline option; v: second generation

Functionality	**Microwave**	**Photonic**
RX-Beam Forming	X	V
Low-Noise Amplification	X	
LO Generation		X
LO Distribution		X
Frequency Conversion		X
RF Distribution		X
Switching		X
Channel Filtering	X	V
Demuxing / muxing	X	
Hi-speed interconnects		X
Sampling and ADC	X	V
Hi Power Amplification	X	
TX Beam Forming	X	

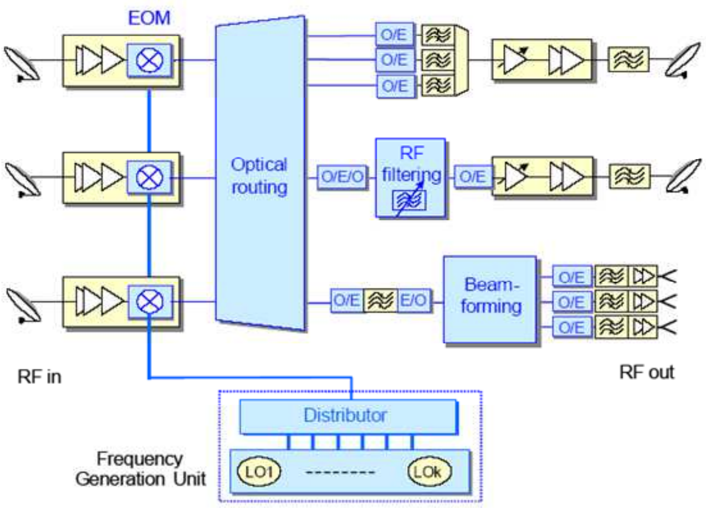


Fig. 4. Conceptual block diagram of photonic analog telecom payloads in the long-term perspective

In the longer term, photonics could contribute to high-frequency LO generation and antenna beam-forming as well to more advanced, functionalities such as fast sampling for ADC (analogue-to-digital conversion) or RF filtering/demultiplexing. On the other hand, such second-generation, photonic analogue payloads are not expected to be available in a timeframe of less than seven years from now.

IV. NEW PAYLOAD SOLUTIONS

Considering the evolutions discussed in previous chapter, new payload architectures of 1st generation, providing the same functionalities as the reference one, can be designed using photonic technologies available in the short term. The channelization section (red circled area) is mainly affected by the technology migration, but also the I/P section can have benefits. Several possible solutions were analyzed, one of the most promising is reported in Fig. 4. showing the repeater layout and the photonic elements (in blue).

The architecture makes use of two optical switching stages, respectively at the input and output of the canalization section. The RF signals outgoing from the LNA’s are input to electro-optical mixers, also fed by optical LO’s delivered from the centralized photonic Frequency Generation Unit (FGU). Each electro-optical mixer is fed by two LO’s, on for each of the two frequency channels, and achieves frequency-conversion for these two channels independently. These channels are routed separately through the input optical switch matrix, either to a bank of converters for entering the digital processor, or to a bank of band-pass filters for being routed transparently. The signals going out from the converters and from the RF filter bank are mixed in electro-optical mixers with LO’s for up-conversion to Ku/ka band. The output optical switch matrix supports flexible connection of these signals either to Ku or Ka output sections. Two 32x34 optical switch matrices are required in order to route all signals, which fits well within the capabilities of micro-optical switching technologies.

This 1st generation photonic P/L is characterized by the relevant figures (w/o considering RF harness replacement) given in Tab. 5.

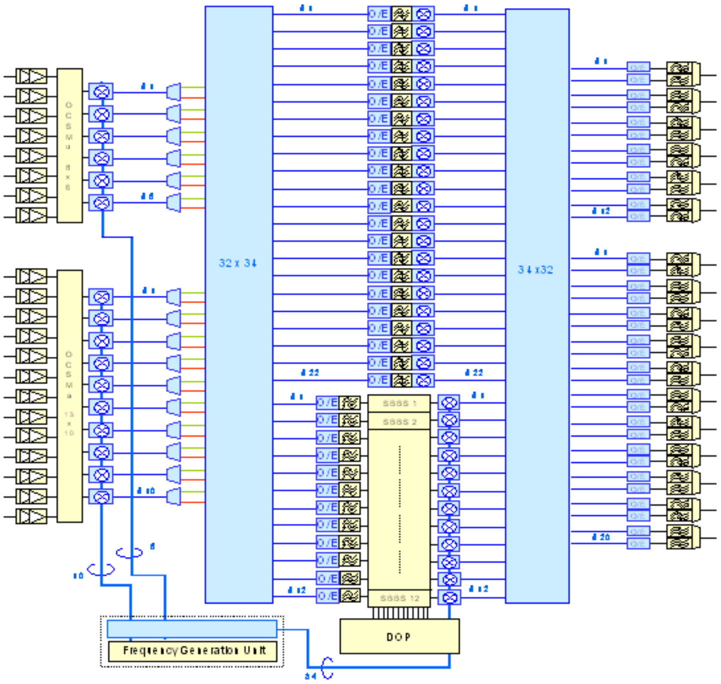


Fig. 4. Architecture of a 1st generation photonic analog payload

Tab. 5. Main budgets of the 1st-generation photonic analog payload

Section	# of Units	Mass (kg)	Power Cons. (W)
I/P	49	18	28
Channelization	34	30	13
O/P	17	11	16
HPA	42	66	3560
Total	142	125	3747

These data were first compared with the ones reported in Tab. 1. Tab. 6 below gives the results in terms of number of units, mass and power consumption. In particular, savings in number of units and total mass are considerable. On the other hand, power consumption reduction is limited as expected since any modification not linked to the output power amplification will always have marginal on consumption.

The mass and power consumption of the photonic FGU required to such a repeater were then estimated by considering the characteristics of a microwave FGU and those of the additional photonic interfaces. Thus, a total mass of 47.8 kg and power consumption of 338.8 W were obtained. The comparison between conventional and photonic P/L including both the FGU and the RF harness is given in Tab. 7. It shows that the delta is still significant, especially for savings in mass and number of units.

Fig. 6 shows in more detail on which sections of the reference P/L, the introduction of photonic technology has a significant impact on the mass budget, i.e. the canalization section, the FGU and RF harness, and the I/O sections, and where substitution is particularly effective in terms of mass saving.

Tab. 6. Preliminary comparison at repeater level

Item	# of units	Mass (kg)	Power Cons. (W)
Conventional P/L	185	195.9	4147.4
Photonic PL/	142	125.2	3747.4
Saving (C-P)	-43	-70.7	-400
Saving (%)	-23%	-36%	-9.5%

Tab. 7. Comparison at overall payload level

Item	# of units	Mass (kg)	Power Cons. (W)
Conventional P/L	186	251.9	4199.4
Photonic P/L	143	184	4086,2
Saving (C-P)	-43	-67.9	-113.2
Saving (%)	-23%	-27%	-3%

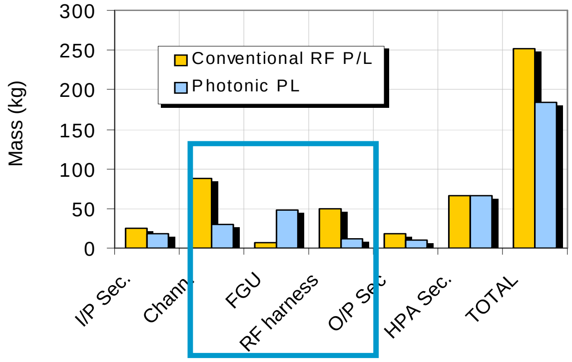


Fig. 6. Mass comparison for each section of the reference P/L architecture

V. WHICH BENEFITS AND HOW TO INCREASE THEM

According to the results of the study, migration to photonic technology provides significant saving in mass and number of units. The figures above are expected to be further improved optimizing the payload architecture design. Other benefits, strictly related to the technology itself (like EMI immunity, transparency, low propagation-induced loss, wide bandwidth), provide additional valuable features whose impact can be evaluated case by case. All these benefits together concur to obtain a full flexible, reconfigurable payload with reduced mass and even costs.

One of the focal goals in a technology migration is the reduction of the overall cost. In the previous sections the benefits that can be obtained implementing photonic technology on TLC P/L, have been identified. They are:

- Mass Saving
- Volume savings (equipment miniaturization)
- Number of units saving
- Equipment functionality scalability
- EMI immunity

- Wide bandwidth available
- Equipment Transparency (I/P&O/P RF frequency independent)
- Low propagation-induced loss

How these benefits can contribute to reduce the costs of a TLC P/L manufacturing? The quantitative analysis of this cost saving figure is part of the scope of the new ESA contract related to ITT 7725 "Roadmap for the introduction of Photonic Technologies based Payloads". A qualitative analysis is hereafter reported.

The first cost saving factor is the EMI Immunity. Thanks to this property, it could be possible to drastically reduce all the activities (analytical and testing) required to verify and certify the P/L EMC compatibility. These saving includes also easier and faster units procurement with the reduction of EMC related activities at satellite level. This reduction of activities contribute to reduce also the on-ground delivery time. Therefore this EMI feature may be directly translated in hour-per-man reduction at Unit Supplier, Payload and Satellite Engineering and AIT levels.

Low propagation-induced loss permits to avoid a lot of problems related to the unit routing over the spacecraft panels and to reduce the analytical effort at engineering level. This matter can be directly translated in hour-per-man reduction at Unit Supplier, Payload and Satellite Engineering.

Number of units saving together with units Volume saving, make easier unit routing over the spacecraft panels, make easier and faster unit installation and test on spacecraft panels and reduce the overall P/L complexity by reducing the number of suppliers to be managed. This feature may be directly translated in hour-per-man reduction along all the P/L design and test phases.

Mass savings can be spent in different ways. In case the P/L mass saving is such to permit a platform class reduction, this saving may be directly translated in a less expensive launch. If the mass saving cannot reduce the platform class, it can be spent to increase satellite lifetime (bigger tank, more fuel). Mass savings and Volume reduction, allow to embark on the same platform class a P/L with increased and augmented performances. In this case the saved mass and volume will be used to embark additional equipment, providing additional capability and delta performances. In any case the mass/volume saving may generate both costs savings and extra incomings.

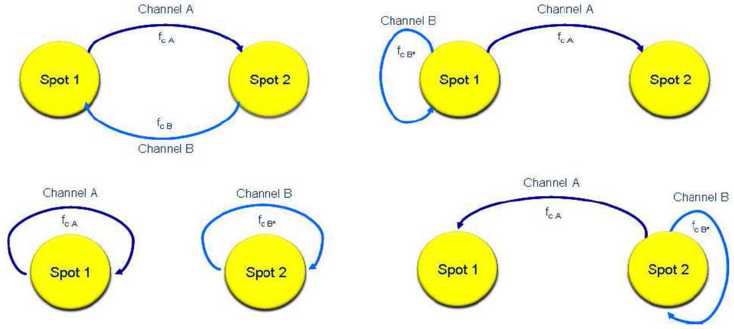
All the other benefits, Equipment Transparency, Wide bandwidth available, Equipment functionality scalability, contribute to the flexibility paradigms: P/L design and manufacturing without the full knowledge of the mission scenario and on flight P/L re-configurability.

VI. PHOTONIC P/L IN-ORBIT DEMONSTRATOR: CLOSER TO THE FUTURE

According to the considerations above, the future for the TLC P/L should be towards the intensive use of photonic technology. How to reach the future? The main difficulty is strictly related to the space qualification of the photonic equipment and components. A typical qualification campaign is too much expensive to be sustained by unit suppliers only. Additionally the market cannot wait too long for. Therefore the point to be solved is: Equipment space qualification shall be reached as soon as possible. The state of art of all photonic equipment shall be therefore evaluated carefully. The FO and related ancillaries are space qualified by different suppliers (e.g. GORE). Majority of the other equipment are in TRL5 or lower.

In order to speed up the introduction of this new technology in the commercial field, TAS and its partners have proposed an In-Orbit Demonstrator, called 2PIOD (Photonic Payload In-Orbit Demonstrator) and illustrated in Fig. 7, with the following goals:

- Achieve in short time the “Flight Heritage”;
- The “Flight-proof” will better address the qualification campaign so shortening in time it;
- Opportunity to team together system integrators, unit manufacturers, satellite operators and potential customers in an early stage R&D innovative program. Such integration will allow to optimize the system design at all levels;
- Several photonic technologies would be validated for space application in one shot.



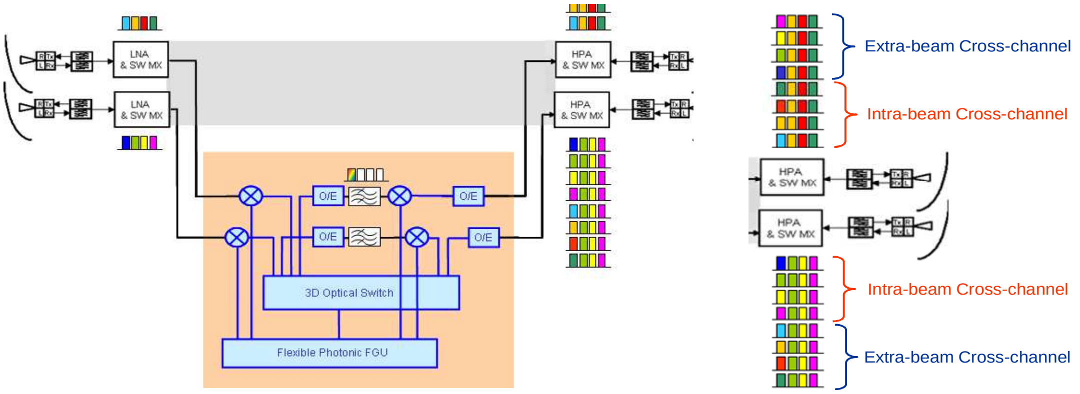


Fig. 7. Photonic Payload In-Orbit Demonstration (2PIOD): 2-spot mission scenario (top), payload architecture (bottom left), and cross banding/channel capability (bottom-right)

The preferred 2PIOD is the option in which the demonstrator will be an auxiliary part of an operating commercial or institutional payload, e.g. one or more redundant I/F chains of the P/L, as shown in Fig. 7. The strength point is that the test of the technology will be done in a real commercial environment without risks to degrade the mission, thanks to the chains that can be switched on/off by appropriate switches.

VII. CONCLUSIONS

This paper has presented how innovative telecom payloads can be designed making use of photonic technologies, that in a number of cases can advantageously replace conventional RF units. Their capabilities to provide flexible and modular architectures have been illustrated by designing 1st-generation photonic architectures of a reference P/L, and the benefits have been highlighted in terms of mass saving and P/L complexity reduction. Additional benefits in terms of Program and AIT effort saving are also anticipated.

The work carried out in the OWR project [3] concluded to substantial mass and power savings in large-scale, high-capacity payloads for broadband multi-beam missions, thus confirming the attractive perspectives for high capacity and/or flexible payloads and missions.

Nevertheless, photonic technologies are still at TRL lower than 6. In this respect, the “2PIOD” approach has been proposed, consisting in substituting one or more IF chains using photonic technology in an up-to-date telecom payload, in order to facilitate the full space qualification and adoption of the technology, and to involve all space actors, i.e. unit manufacturers, satellite integrators and operators, in this process.

ACKNOWLEDGEMENTS

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