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Optical Feeder Link Architectures for very HTS: Issues and Possibilities

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ABSTRACT

The paper deals with an analysis of very High Throughput Satellite (VHTS) systems employing optical feeder links. To do so, a fixed set of user requirements is selected that allows for different optical feeder link options to be compared and evaluated on a common basis. The main system aspects are discussed and a rough assessment of the payload resources in terms of mass, power and dissipated power required for each is provided. This exercise reveals important trade-offs and new research avenues for the optical communications community.

Keywords: Optical feeder links, Very High Throughput Satellite, Analog Transparent, Digital Transparent

1. INTRODUCTION

As the capacities of newly announced next generation very High Throughput Satellite (VHTS) systems are exceeding the Terabit/s barrier, a large amount of investment needs to be directed not only to the space segment (as was the case traditionally), but also to the ground segment in support of the feeder links. To reduce this investment, satellite operators are reviewing various options and technologies for the feeder links, among which optical feeder links [1]. Given that RF technology already caters for feeder links in support of 1 Terabit/s VHTS [2], future optical feeder links will need to offer similar performance while being commercially attractive.

In this paper, a number of optical feeder link architectures are analyzed, focusing on the impact each has on the payload design, including fully analog and digital feeder link options [3], [4]. The baseline assumption is that of a VHTS system operating in the geostationary orbit (GEO) and providing an aggregate user link system capacity of about one Terabit/s to a high number of Ka-band user beams. For each optical feeder link architecture, the paper discusses and quantifies a) the impact on the overall end-to-end system design, b) the appropriate choice of optical modulation (analog/digital non-coherent/coherent) and its spectral/power efficiency, c) how to multiplex hundreds of RF modulated carriers onto optical (D)WDM sub-carriers, d) the interfaces between optical and RF parts of the payload, e) optical uplink and downlink budgets, f) a rough order of magnitude of the payload resources consumed in terms of mass and power taking into account the capabilities of on-board digital processing technology (OBP).

The paper highlights a number of technical issues that arise when adopting a particular optical feeder link architecture, and proposes key areas of R&D that need to be considered by the optical communications community. It does not address the topic of cloud blockage and on-ground spatial diversity (dealt with in a companion paper [5]), assuming that the number of optical ground stations is sufficient to guarantee the target feeder link availability.

2. SYSTEM DIMENSIONING/USER REQUIREMENTS CONSOLIDATION

A typical VHTS system with optical feeder link is depicted in Figure 1.

Since the purpose of this analysis is focusing on the feeder link part of a VHTS, it is decided to specify the user part of the system assuming typical values and use these for comparing the various feeder alternatives. To reach a fixed set of user link requirements for a VHTS system (of the Terabit/s class), a number of past related ESA internal, ARTES and TRP contracts were consulted regarding the frequency plan, system architecture and link budget, as defined in the frame of these studies.

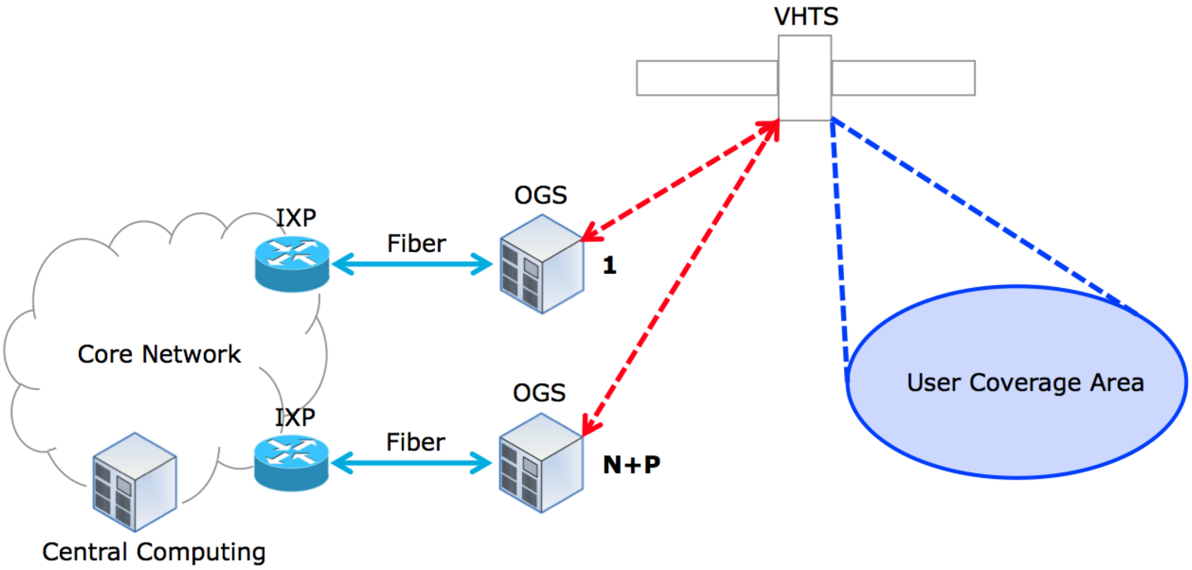


Figure 1. A typical VHTS system with optical feeder link.

After specifying this way the forward (FWD) user link requirements, an affordable (from the payload resources point of view) set of return (RTN) user link requirements was selected. Then, the various Feeder link options for this specific system were designed.

The result of employing the information coming from past activities to specify user link parameters led to the values listed in Table 1. These are the values that will be used for the design of all the different feeder link options.

Table 1. Summary of system parameters selected for the user link.

Parameter	User Downlink	User Uplink
Freq. band	Ka (20 GHz)	Ka (30 GHz)
Waveform assumed	DVB-S2	DVB-RCS2
Available bandwidth allocation	2900 MHz (non-exclusive FSS band)	600 MHz (non-exclusive FSS band)
Number of beams	230	
Bandwidth per beam	1225 MHz	300 MHz
Colouring scheme	4 colours (2 freq/2 pol.)	8 colours (4 freq/2 pol.)
Carrier bandwidth	450 MHz	12 MHz
Total aggregated system bandwidth	230 x 1.225 = 281.75 GHz	230 x 0.3 = 69 GHz

3. MAJOR PROPAGATION ELEMENTS FOR OPTICAL FEEDER LINKS

Atmospheric impairments of the optical GEO-ground channel are more critical in the uplink than in the downlink, because atmospheric turbulences are closer to the source of transmission and have a higher impact on the receiver. Once an optical link is in cloud-free line of sight (CFLOS), the main atmospheric impairments in the uplink of the Earth-space optical channel are caused by turbulence due to the refractive index structure and result in: a) Signal fading, b) Beam wander.

For quantifying the severity of *fading due to turbulence* some well known parameters are:

- Refractive index structure parameter, which depends strongly on the height above sea level relative to the height of the ground station.
- Fried parameter, that is the spatial coherence of waves distorted by turbulence.
- Isoplanatic angle (IPA), that is the angular range over which the wavefront is correlated.
- Autocorrelation / Greenwood frequency, critical time constant of temporal variation of turbulence.
- Point ahead angle (PAA), angle formed by the relative velocity of the earth station and the satellite
- Scintillation index, measure of the intensity of fading due to turbulence

Beam wander is the average displacement of the beam at the receiver from boresight. In practice, the beam center can exhibit major deviations from the link optical axis after propagating through the turbulent atmosphere and it is a very serious impairment of the optical channel, as it could create interruption of the optical link. Predistorting/ precompensating this effect in the uplink has been identified as very critical for the development of optical feeder links. Therefore, there are many efforts underway in ESA to realize techniques that allow the predistortion of the beam wander in the transmitter side, reaching the level of actual demonstration by a number of research organizations. Beam wander can be compensated by tracking the angle of arrival (AoA) of a reference signal from the satellite. This method only works when the uplink and downlink optical beams propagate through the same volume of atmosphere. This, however, is only applicable when the PAA, (~18 μrad), is smaller than IPA as shown in [3]. Alternatively, in case a reference signal from the satellite cannot be used to estimate at the optical ground station (OGS) the distortion, the tracking of a different light source (e.g. of a sodium star) is being investigated.

3.1 Number of Optical Ground Stations for Cloud Free LOS

The discussion on the optical channel so far refers to CFLOS conditions. To overcome this problem, a potential optical feeder ground segment network will consist of multiple OGSs in diversity configuration in order to switch the traffic from one station to another whenever cloud blockage occurs. Hence, even though a single OGS can handle all the traffic to and from the GEO satellite from the spectrum point of view, still a high number of redundant OGS need to be available purely for achieving availability percentages in the order of 99.9%.

Several studies have addressed this problem and have calculated the required number of OGSs for achieving a very high availability, either based on pure probability analysis or based on actual cloud coverage databases. A companion paper in the ICSO 2018 [5] is presenting a relevant analysis using a comprehensive generative tool developed under ESA INFRA "Optical/RF Tool," contract [6].

4. OPTICAL FEEDER LINK DESIGN

The philosophy of designing the optical feeder link is different than for the RF feeder link. In the case of optical communications, the need of multiple ground stations is not driven by the lack of spectrum but to preserve high target availability levels against cloud blockage (see Section 3.1).

In the frame of this work, two main approaches for designing the optical feeder link are initially considered, namely the *analog transparent* and the *digital transparent*. The reason for this choice is that these two architectures preserve to the extent possible a non processing satellite payload. It is pointed out, that requiring the satellite payload to become fully regenerative on board processor (OBP) in order to accommodate the optical feeder links, would render this solution much less attractive. These two transmission architectures are also the standardized way of transmitting radio over fibre in terrestrial networks [7]. A lot of supporting material on this two architectures has been also drawn by the two ESA studies [8], [9].

4.1 Analog Transparent (see Fig.2)

In the FWD link, it consists in directly modulating the optical carrier with the RF output of a DVB-S2 modulator (or, in this respect, any type of digital modulator for the data of the user) and is based on Intensity Modulation/Direct Detection (IM/DD) optical transmission scheme. Specifically, the output of the ground DVB-S2 (or equivalent) modems directly amplitude modulates the optical carrier in analog fashion. After being received at the satellite via a non-coherent DD receiver, the optical signal is converted into an appropriate IF frequency which needs to be frequency translated (if not already) to the user Ka-band. The strong advantage of this method is that it yields the simplest payload architecture, by keeping it completely transparent and not requiring OBP. The disadvantage is that, being analog, the optical link cannot be protected from the (strong uplink) turbulence, as the DVB-S2 error correcting capabilities, designed to counter user link errors, do not suffice to address the uplink optical fading. They are tailored to the RF user downlink.

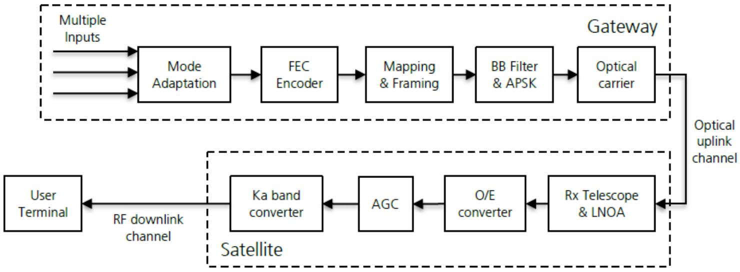


Figure 2. High level overview of the analog transparent option for the optical feeder link.

4.2 Digital Transparent (see Fig.3)

It consists in transmitting a digitized version of the RF (DVB-S2) signal intended to the end users and is based on using a digital optical modulation (typically OOK for simplicity) on the feeder link. Specifically, in the FWD direction, the output of the ground DVB-S2 modems is being digitized, which offers the chance to employ digital signal processing techniques. After being received at the satellite, the optical signal is demodulated and the samples of the signals are converted into the user Ka-band. The technique allows for FEC protection of the optical feeder link. On the other hand, there is a significant bandwidth expansion resulting from the sampling operation. Also, the satellite must be equipped with some form of digital processing to revert the digital operations carried out on ground.

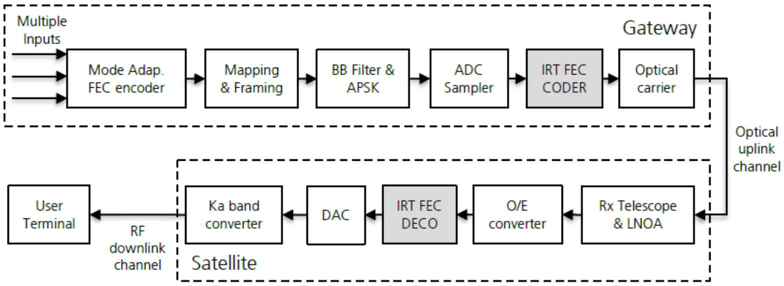


Figure 3. High level overview of the digital transparent option for the optical feeder link.

4.3 Digital Regenerative (see Fig. 4)

Apart from these two basic optical feeder link architectures, for completeness the work did also add the case of a fully regenerative payload combined with an optical feeder link. Of course, this architecture implies that at least the modulation of the hundreds FWD link carriers and thousands return link carriers takes place on board the satellite. The regenerative architecture, a high level of which is depicted Fig.3, refers to the DVB-S2 digital operations (such as the coding, modulation and pulse shaping) taking place on board the satellite.

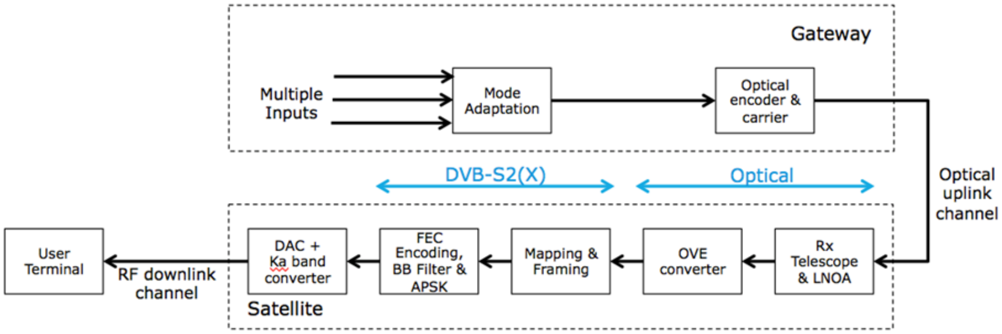


Figure 4. High level overview of the regenerative option for the optical feeder link.

5. OPTICAL FEEDER LINK BUDGETS

The optical feeder link budgets are based on the following parameters, which are typical parameters based on existing or near term technology:

- Wavelength: 1550 nm

Optical Ground Station

- Transmit diameter: optimized to minimize turbulence losses
- Receive diameter: 60 cm
- Optical power at the output of the booster amplifier: 50W
- Adaptive optics system for fiber injection on-ground

Optical Satellite Terminal

- Transmit/receive diameter: 25 cm
- Optical receiver (EDFA 1.55µm + PIN)
- Optical power at the output of the booster amplifier: 10W

Transmission scheme

- Analog transparent: Intensity Modulation/Direct Detection (IM/DD)
- Digital transparent: NRZ-OOK

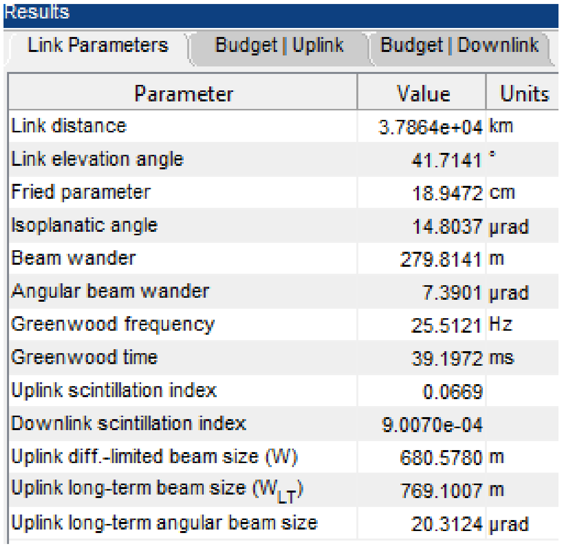
As the optical channel has a strong dependency on the OGS altitude, the exemplary location of Barcelona, Spain, at 415 m site altitude was selected for performing the link budget. Table 2 lists the geometrical and channel parameters of the link budget, many of those defined in Section 3.

Table 3 (left) presents the optical feeder uplink budget for the given parameters and location (including a 3dB cloud margin as a precaution). Table 3 (right) presents the corresponding optical feeder downlink budget. These link budgets refer to both optical schemes (analog, digital) based on the parameters given in this section. The difference is then how many of these channels need to be multiplexed together to accommodate the amount of data generated by each.

6. IMPACT ON PAYLOAD RESOURCES

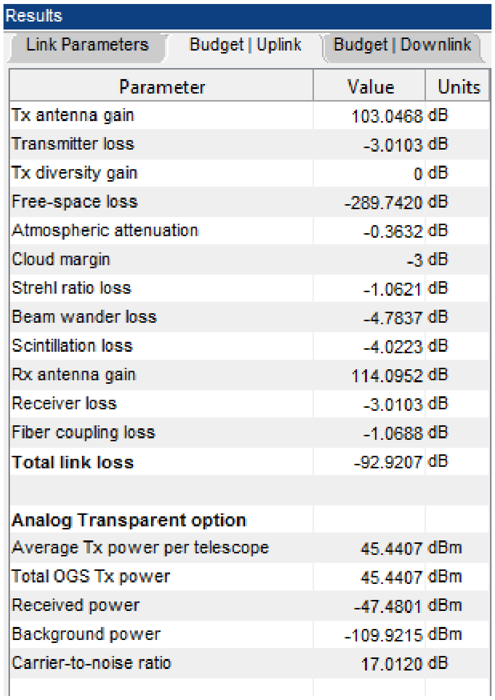
This section presents the mass/power impact on the payload stemming from the selection of each feeder link architecture. For all feeder link options, a satellite payload equipment count was attempted, and from there the feeder contribution in terms of mass, power consumed and power dissipated has been derived. The source of the values used come either from available data sheet or best guess estimates from experts in the field.

Table 2. Optical link parameters for an OGS located in Barcelona.

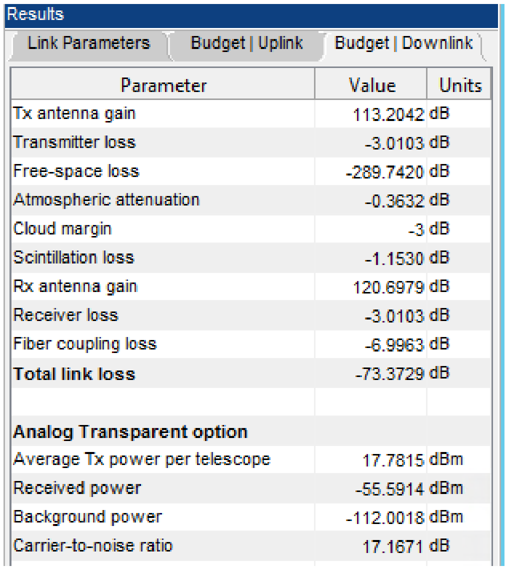


Parameter	Value	Units
Link distance	3.7864e+04	km
Link elevation angle	41.7141	°
Fried parameter	18.9472	cm
Isoplanatic angle	14.8037	µrad
Beam wander	279.8141	m
Angular beam wander	7.3901	µrad
Greenwood frequency	25.5121	Hz
Greenwood time	39.1972	ms
Uplink scintillation index	0.0669	
Downlink scintillation index	9.0070e-04	
Uplink diff.-limited beam size (W)	680.5780	m
Uplink long-term beam size (W_{LT})	769.1007	m
Uplink long-term angular beam size	20.3124	µrad

Table 3. Optical Feeder link budget. Left (uplink) Right (downlink)



Parameter	Value	Units
Tx antenna gain	103.0468	dB
Transmitter loss	-3.0103	dB
Tx diversity gain	0	dB
Free-space loss	-289.7420	dB
Atmospheric attenuation	-0.3632	dB
Cloud margin	-3	dB
Strehl ratio loss	-1.0621	dB
Beam wander loss	-4.7837	dB
Scintillation loss	-4.0223	dB
Rx antenna gain	114.0952	dB
Receiver loss	-3.0103	dB
Fiber coupling loss	-1.0688	dB
Total link loss	-92.9207	dB
Analog Transparent option		
Average Tx power per telescope	45.4407	dBm
Total OGS Tx power	45.4407	dBm
Received power	-47.4801	dBm
Background power	-109.9215	dBm
Carrier-to-noise ratio	17.0120	dB



Parameter	Value	Units
Tx antenna gain	113.2042	dB
Transmitter loss	-3.0103	dB
Free-space loss	-289.7420	dB
Atmospheric attenuation	-0.3632	dB
Cloud margin	-3	dB
Scintillation loss	-1.1530	dB
Rx antenna gain	120.6979	dB
Receiver loss	-3.0103	dB
Fiber coupling loss	-6.9963	dB
Total link loss	-73.3729	dB
Analog Transparent option		
Average Tx power per telescope	17.7815	dBm
Received power	-55.5914	dBm
Background power	-112.0018	dBm
Carrier-to-noise ratio	17.1671	dB

6.1 Optical Analog Transparent

The WDM grid and IF frequency trade-off

An important element in the payload sizing is the selection of WDM grid that will be used to map the RF carriers onto optical wavelengths[1]. Starting from the available optical bands around 1550 nm, there is the optical C band (1569 – 1530 nm) and the L band (1611 nm – 1570 nm). These are split into a number of wavelengths depending on the size of the

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[1] In the following, and to avoid confusion, the term RF or DVB-S2 carriers will be referring to the electrical domain, whereas the elementary optical channels in WDM will be referred to as wavelengths.

available WDM grid (spacing between wavelengths). The grid options recommended by the ITU-T G.694.1 are: 0.8 nm (100 GHz), 0.4 nm (50 GHz), 0.2 nm (25 GHz) and 0.1 nm (12.5 GHz) spacing amid wavelengths. Avoiding the two narrowest choices (0.2 nm and 0.1 nm), the two remaining options offer:

- 0.8 nm offers 100 wavelengths in total in C and L band
- 0.4 nm offers 200 wavelengths in total in C and L band

Therefore, one choice that the system designer needs to make is how to select the WDM grid size, which is a trade-off between number of WDM wavelengths, background noise, width of the passband, and stability requirements on the temperature controlled laser source. Another element of the problem is that, according to ITU, the passband of each wavelength should be limited to a percentage of the grid distance to ensure sufficient isolation between wavelengths. For the purpose of this study, a 25% of effective pass band was selected.

Another important element for making the mapping of RF carriers onto optical wavelengths as efficiently as possible is the choice of which IF frequency the RF (DVB-based) carriers will be up-converted to before they enter the optical domain. This is important because for IM/DD systems, which are based on a non-coherent detector employing Amplitude Modulation Double Side Band with carrier (AM – DSB+C), the IF before optical modulation will be the frequency of the RF carrier after photodetection. Two typical options for the IF are the C-band (4 GHz) and the Ka-band (20 GHz). This choice has a significant implication on the payload, as for example if the Ka-band is used there is no need to realize any frequency converter stages on board the satellite, which is a major mass/power benefit. Furthermore, it defines the number of optical wavelengths required to carry the total system traffic, which, in turn, translates into equipment in the form of optical modulator and detectors in space.

In this work, 1.5 GHz is selected for a single RF multiplex; therefore three DVB-S2 carriers of ~500 MHz can be transferred by each optical wavelength in the FWD link. Since there are 575 DVB-S2 total carriers in the system, 575/3=192 optical wavelengths will be required, which approaches the total available number of channels (200).

AM-DSB+C is wasteful of bandwidth as it transmits both sidebands. As is well known from continuous wave modulation, the solution of only transmitting one of the two sidebands (SSB) is much more spectrally and power efficient. However, for optical feeder links, this implies a more complex coherent demodulator.

The need for biasing

Apart from being wasteful of bandwidth, analog AM-DSB+C is also wasteful of power. For the optical transmitter to operate in the linear region, the laser diode needs to be driven (biased) with the appropriate input current. If this bias is too low, clipping of the modulated signal $m(t)$ takes place, if it is too high, the composite signal enters the saturation (non-linear region) [10]. In this course, the choice of β, the modulation index, represents the most critical parameter for evaluating the power that is wasted by the transmission scheme. To quantify a realistic value for the modulation index β in order to assess how much of dc power is wasted on biasing, the dynamics of the underlying RF signal $m(t)$ in the sense of the peak-to-average-power ratio (PAPR) were taken into account. Taking the basic linearity condition for AM, it can be claimed that

$$\beta|m(t)| \le 1 => \beta \le \frac{1}{|m(t)|_{max}} = \frac{1}{\sqrt{PAPR}},$$

For n independent carriers, the condition becomes $\beta \le \frac{1}{\sqrt{n \cdot PAPR}}$

It is deemed more relevant to investigate the sizing of the modulation index β for the RTN link of the optical analog transparent scenario. The reason is that it is the RTN feeder link where the High Power Optical Amplifier (HPOA) is placed on board the satellite, making any waste of power more critical. In the scenario of interest (HPOA sizing for the RTN link), there are hundreds of ‘small’ 12 MHz DVB-RCS2 carriers, which are typically transmitted employing QPSK/8PSK. In other words, the signal practically looks like noise. For example, even transmitting three carriers leads to a PAPR=4.8 dB. Hence, any DC consumption will be roughly tripled, that is the no. of HPOAs at a given output power also needs to be tripled. Extending further this line of thinking, a PAPR for a multicarrier of signals is between 10 dB and 12 dB. For PAPR=10 dB, the number of HPOA is increased by a factor of 10. As will become clear once the power consumption for this scenario is assessed, the need to bias the laser transmitter in the case of analog modulation makes this scheme prohibitive in the RTN link. To overcome the need for biasing, a detector other than an envelope detector is required, for example a coherent detector paired with a SSB version of amplitude modulation.

FWD Sizing

Assuming the elementary RF multiplex of 1.5 GHz, the number of optical wavelengths required to carry 575 DVB-S2 carriers with C-band as IF is rounded to 200. Figure 5 presents the high level block diagram of the FWD link for this scenario, by splitting the blocks into on ground processing and on board processing. The 200 optical wavelengths correspond to this number of external optical modulators (Mach Zehnder) on ground and optical detectors on space. It is noted that no kind of digital processing takes place on board the satellite, which is the strong point of this scenario.

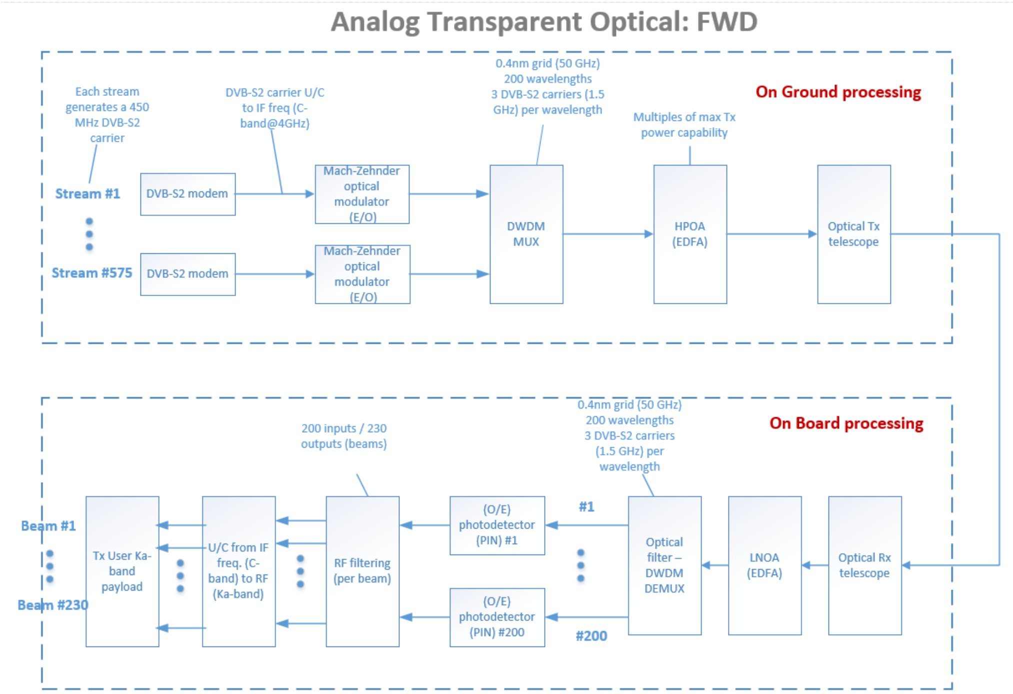

Figure 5. Analog Transparent Optical: FWD Block Diagram.

RTN Sizing

In the RTN link, the number of required optical wavelengths is much less than in the FWD link, due to the traffic asymmetry. In the RTN, there are 300 MHz per beam (25 DVB-RCS2 carriers), 230 beams, 69 GHz of RTN link spectrum, therefore 5750 DVB-RCS2 carriers in total. Assuming again the 0.4nm grid and BW_{RF}=1.5 GHz (that corresponds to 11 GHz of AM DSB bandwidth), there are 69 GHz/1.5 GHz = 46 RTN optical wavelengths required. It is assumed that the RTN will be using the opposite polarization than the FWD. The high level block diagram of the RTN direction of the analog transparent optical feeder link is presented in Figure 6.

Despite the lower number of wavelengths, the RTN link defines the power consumption on board the satellite due to the presence of the HPOAs. A link budget exercise has been carried out to assess the total on board HPOA power consumption needed for achieving a required C/N better than 17 dB (see Section 5) for each DVB-RCS2 carrier in the RTN link in Table 4. The calculations behind this table assume 25 cm on board telescope, HPOA wall plug efficiency 20% and optimal fiber coupling loss. Moreover, this calculation does not include the impact of the biasing.

Mass/Power Impact

The complete payload impact of the analog transparent optical scenario in terms of mass, power consumed and power dissipated for the combined FWD and RTN feeder link is listed in[2] Table 5 including the impact of biasing for PAPR=4.8 dB.

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[2] It is assumed that the max output optical power from the on board HPOA is 10 W (50 W DC) and that the OGS telescope size is 60 cm (first row of Table 4).

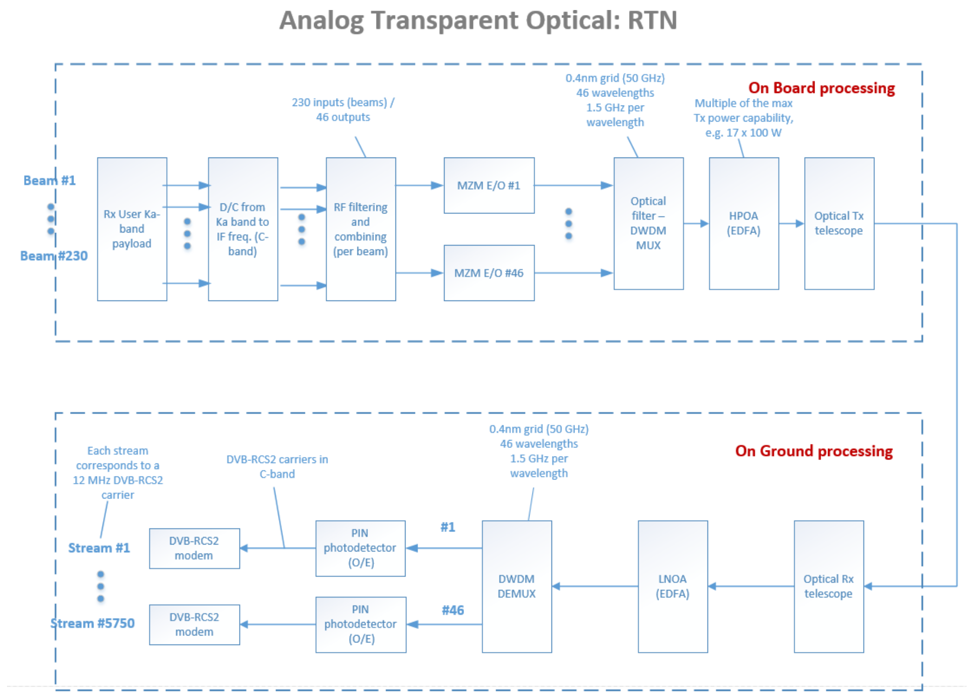
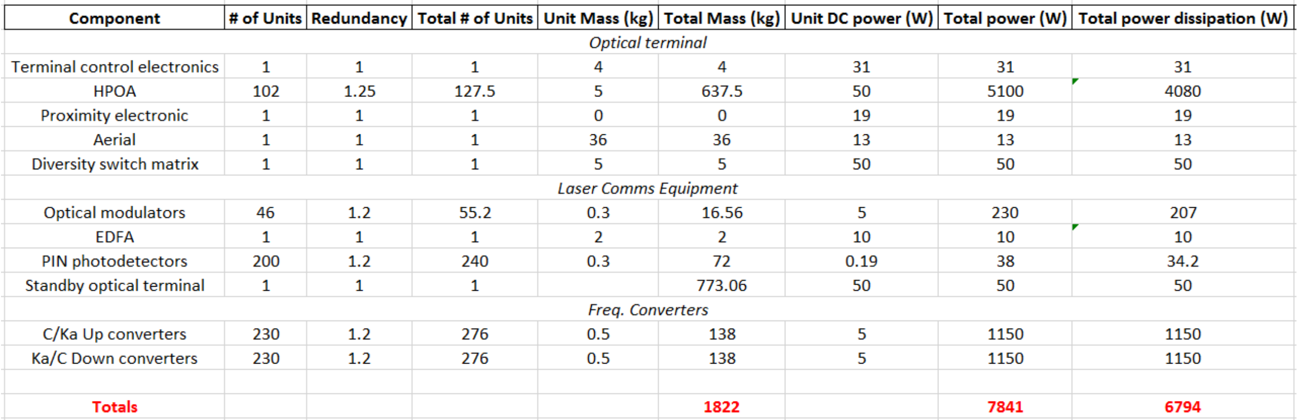


Figure 6. Analog Transparent Optical: RTN Block Diagram.

Table 4. Calculation of total on board HPOA power consumption (analog optical, without biasing).

OGS telescope size	Req. power per carrier for C/N>17 dB	Total on board HPOA power consumption
0.6 m	60 mW	1.72 kW
1 m	53 mW	1.52 kW

Table 5. Mass/power impact of analog transparent optical scenario (PAPR=4.8 dB for biasing).



Component	# of Units	Redundancy	Total # of Units	Unit Mass (kg)	Total Mass (kg)	Unit DC power (W)	Total power (W)	Total power dissipation (W)
				Optical terminal				
Terminal control electronics	1	1	1	4	4	31	31	31
HPOA	102	1.25	127.5	5	637.5	50	5100	4080
Proximity electronic	1	1	1	0	0	19	19	19
Aerial	1	1	1	36	36	13	13	13
Diversity switch matrix	1	1	1	5	5	50	50	50
				Laser Comms Equipment				
Optical modulators	46	1.2	55.2	0.3	16.56	5	230	207
EDFA	1	1	1	2	2	10	10	10
PIN photodetectors	200	1.2	240	0.3	72	0.19	38	34.2
Standby optical terminal	1	1	1		773.06	50	50	50
				Freq. Converters				
C/Ka Up converters	230	1.2	276	0.5	138	5	1150	1150
Ka/C Down converters	230	1.2	276	0.5	138	5	1150	1150
Totals					1822		7841	6794

6.2 Optical Digital Transparent

FWD Sizing

Concerning the FWD sizing of the digital transparent optical scenario, each beam offers two or three carriers of 450 MHz each. On average, 2.5x450MHz=>2.5x375 Msym/s (roll off 0.2 assumed). For a (complex) sampling factor 2x1.1:

(2.5x375 Msym/s)x (2.2 samples /symbol)=2062 MSamples/s per beam. This very tight sampling factor is achieved via steep digital filter. For accommodating 2062 MSam/s, one high speed ADC can be envisaged. Hence, the number of required ADCs turns out to be equal to the number of spot beams (230). For the ADC, we need a resolution of at least 9 effective bits/complex sample: 18.6 Gbps per beam. Adding FEC coding, e.g. RS (255, 239) = 18.6 x 255/239 = 19.8 ~20 Gbit/s for each 3-carrier beam. Scaling this to the total number of 230 beams yields 4.5 Tbit/s to support the whole FWD link of around 9 times. Since a digital optical modulation is used in this scenario, 20 Gbps are then OOK-NRZ modulated, requiring 20 GHz of optical bandwidth. To accommodate 20 GHz in the WDM passband, the 0.8 nm grid (passband of 25 GHz) is required. The total number of optical wavelengths is 230, which in principle exceeds the number of available wavelengths in optical C and L bands, meaning that either more optical bands are required or a better spectral efficiency (e.g. using quadrature modulation instead of binary). On board the satellite, the digital processing of the optical waveform is reversed (including de-interleaving, demodulation and decoding of the optical signal), and then a bank of space qualified DACs returns the digitized signal in the RF domain (DVB-S2 carriers). Space qualified DACs exceeding 2GSam/s are already commercially available (e.g. EV12DS130A from E2V and DAC5670 from Texas Instruments).

A high level block diagram of the digital transparent optical FWD link is depicted in Figure 7. If the IF used on ground after the DVB-S2 modem bank and before digitization is different than the Ka-band, the figure will require the addition of frequency converters in order to bring the RF signals to user downlink frequency band.

RTN Sizing

In the RTN, there are 5750 DVB-RCS2 carriers in total summing up to a 69 GHz spectrum, or equivalently, 57.5 Gsym/s (roll off 0.2) equal to 126.5 Gsam/s. In the RTN direction, space qualified on board ADCs are needed, a candidate being EV10AS180A ADC from E2V, with 10 effective bits per sample, offering a maximal sample rate of 1.5 Gsam/s. This means that the in total 85 ADCs are required:

(126.5 Gsam/s) x (10 bits/sample) = 1.23 Tbits/s

Adding FEC coding, e.g. RS (255, 239) =255/239 x 1.23~1.3 Tbits/s of total traffic, expanding the bandwidth roughly 8 to 9 times. This total traffic of 1300 Gbits/s => 1300 GHz (OOK NRZ) => 1300/20 = 65 wavelengths required in the 0.8 nm grid.

The high level block diagram of the digital transparent optical RTN is the reverse of what shown in Figure 6.

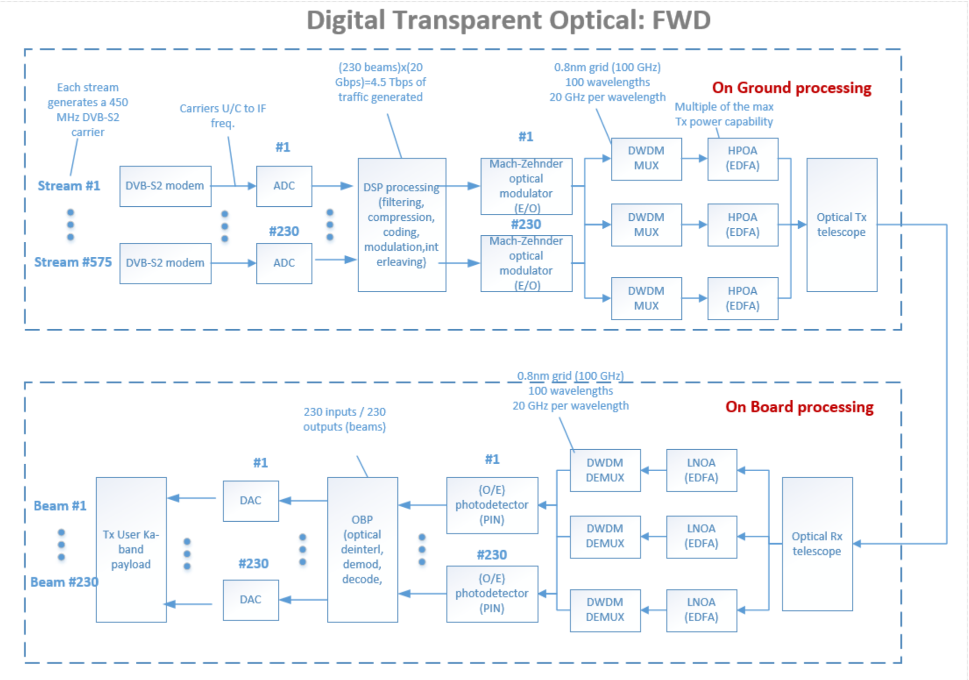


Figure 7. Digital Transparent Optical: FWD Block Diagram.

Despite the lower number of wavelengths, the RTN link defines the power consumption on board the satellite due to the presence of the HPOAs. A similar link budget exercise as for the analog case has been carried out to assess the total on board HPOA power consumption. However, due to the digital nature of the optical transmission scheme used, the target criterion for each DVB-RCS2 carries was the BER@1e-9. The calculations are shown in Table 6. The calculations behind this table assume RS block coding, 25 cm on board telescope, 10 W HPOA with wall plug efficiency 20% and optimal fiber coupling loss. It is worth highlighting that the biasing is irrelevant to the digital transparent optical feeder link scenario.

Table 6. Calculation of total on board HPOA power consumption (digital optical).

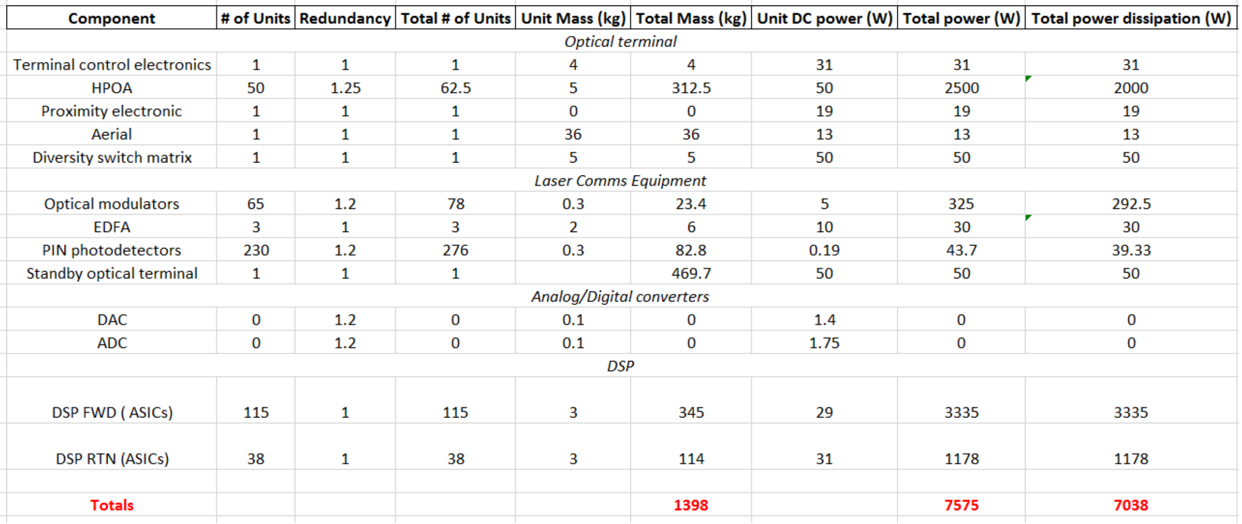
OGS telescope size	**Req. power for BER@1e-9 (RS coding)**	**Total on board HPOA power consumption**
0.6 m	90 mW	2.58 kW
1 m	77 mW	2.2 kW

Mass/Power Impact

In terms of mass/power impact, there is an additional unit that needs to be added in the digital transparent scenario compared to the analog one, that is the OBP unit. For this, we extrapolated the results of the GSP ONUBLA activity [9] to the present system. The extrapolation led to 115 ASICs in the FWD / 38 ASICs in the RTN.

The complete payload impact of the digital transparent optical scenario in terms of mass, power consumed and power dissipated (for 10 W HPOA and 60 cm OGS, first line in Table 6) for the combined FWD and RTN feeder link is listed in Table 7 in the case ASIC for the OBP. In case, an FPGA is used there is about a 1.8kW additional power consumed/dissipated.

Table 7. Mass/power impact of digital transparent optical scenario (assuming OBP is using ASIC technology).



Component	# of Units	Redundancy	Total # of Units	Unit Mass (kg)	Total Mass (kg)	Unit DC power (W)	Total power (W)	Total power dissipation (W)
				Optical terminal				
Terminal control electronics	1	1	1	4	4	31	31	31
HPOA	50	1.25	62.5	5	312.5	50	2500	2000
Proximity electronic	1	1	1	0	0	19	19	19
Aerial	1	1	1	36	36	13	13	13
Diversity switch matrix	1	1	1	5	5	50	50	50
				Laser Comms Equipment				
Optical modulators	65	1.2	78	0.3	23.4	5	325	292.5
EDFA	3	1	3	2	6	10	30	30
PIN photodetectors	230	1.2	276	0.3	82.8	0.19	43.7	39.33
Standby optical terminal	1	1	1		469.7	50	50	50
				Analog/Digital converters				
DAC	0	1.2	0	0.1	0	1.4	0	0
ADC	0	1.2	0	0.1	0	1.75	0	0
				DSP				
DSP FWD (ASICs)	115	1	115	3	345	29	3335	3335
DSP RTN (ASICs)	38	1	38	3	114	31	1178	1178
Totals					**1398**		**7575**	**7038**

6.3 Optical Regenerative

The analysis of the optical regenerative feeder link was restricted to the FWD direction. Although satellite operators are currently reluctant to consider a full regenerative payload for a VHTS, the idea is that future advanced processing units (ASICs, FPGAs) may make this solution more appealing, especially since a regenerative payload avoids the need for biasing of the analog transparent and also the bandwidth expansion of the digital transparent. It does condition though the choice of waveform, although DVB-S2(x) in the FWD seems to be the established solution industry-wide.

FWD Sizing

On ground, differently than the previous scenarios, user data are directly optical encoded (code rate 0.8) and optical digitally modulated (OOK). The total system bandwidth of 260 GHz fits into just 11 optical wavelengths of 0.8 nm WDM passband. This number is multiplied by 1.25 due to optical coding overhead resulting in 14 WDM wavelengths. There is a secondary trade-off whether DVB-S2X encoding and modulation needs to be performed on ground or on board. The former option reduces on board processing at the cost of slightly expanding the bandwidth through the feeder.

On board, a full DVB-S2x processing takes place after the O/E conversion, that is encoding & modulating, DAC and frequency converting to Ka-band. A DAC of 3 GSam/s (EV12DS130A) can carry (3000MSam/s)/(2.2 Sam/symbol)/(450Msymbols/s) = 3 DVB-S2X carriers. This yields a total number of DACs 575/3=192.

Mass/Power Impact

To estimate the payload mass/power impact of the regenerative optical solution, there are two operations that need to be considered in term of processing:

1) The optical demodulation and decoding of the optical feeder link
2) The DVB-S2x encoding and modulation of the 575 RF carriers x 450 MHz (FWD)

Point 1) was dealt with similarly to the digital transparent case taking into account that the regenerative FWD case corresponds to much less (260 GHz x 1.25 = 325 GHz) processed bandwidth for the whole satellite. Between them there is a factor of 14. Hence, assuming an ASIC technology is used for the OBP, we can assume the impact from the digital transparent of the previous section divided by 14. The largest impact for the full regenerative OBP comes from point 2), which is not part of the payload operations of the digital transparent scenario. Performing an estimate of on board power consumption realizing 575 carriers of ~500 MHz assuming future ASIC technology, Table 8 presents a list of payload mass and power resources required for the FWD link only of a regenerative optical feeder link employing ASIC technology.

Table 8. Mass/power impact of regenerative optical scenario (ASIC). FWD only.

Component	# of Units	Redundancy	Total # of Units	Unit Mass (kg)	Total Mass (kg)	Unit DC power (W)	Total power (W)	Total power dissipation (W)
Optical terminal								
Terminal control electronics	1	1	1	4	4	31	31	31
Proximity electronic	1	1	1	0	0	19	19	19
Aerial	1	1	1	36	36	13	13	13
Diversity switch matrix	1	1	1	5	5	50	50	50
Laser Comms Equipment								
EDFA	1	1	1	2	2	10	10	10
PIN photodetectors	14	1.2	16.8	0.3	5.04	0.19	2.66	2.394
Standby optical terminal	1	1	1		52.04	50	50	50
Analog/Digital converters								
DAC	192	1.2	230.4	0.1	23.04	1.4	268.8	268.8
ADC	0	1.2	0	0.1	0	1.75	0	0
DSP								
DSP FWD (ASICs) optical decode	8.2	1.0	8.2	3.0	24.6	29.0	238.2	238.2
DSP FWD (ASICs) DVB-S2 mod	58	1	58	3	174	22.5	1305	1305
Freq. Converters								
L/Ka Up converters	230	1.2	276	0.5	138	5	1150	1150
Totals					**464**		**3138**	**3137**

7. CONCLUSIONS AND LESSONS LEARNED

Concluding the analysis on optical feeder link architectures, it is worth commenting the fact that optical feeder links for VHTS systems are required to carry a huge amount of RF signals over an optical carrier, which leads *per se* to a non-optimum setup for optical communications. It is the result of the fact that UTs in these systems receive the data using conventional RF technology. Moreover, there are additional limitations that burden the optical feeder link technology coming from the stringent requirement of satellite payloads to remain, to the extent possible, non-processing.

Some conclusions of the analysis are as follows:

- The feasibility of any type of (uplink) optical feeder link (whether analogue or digital), critically depends on the feasibility of pre-compensating the beam wandering effect at the transmitter side (OGS). For this reason, ESA is funding a number of R&D and demo activities in this area.
- To keep the payload impact realistic, Ka-band IF and 0.8 nm WDM grid are suggested –if feasible- for both analog/digital radio over fiber (to avoid freq. converters/high number of optical detectors/modulators).
- Analog Transparent Optical option is heavily penalized by the need for biasing.

- Digital Transparent Optical option is heavily penalized due to bandwidth expansion coming from digitization. Solution might be interesting for smaller systems (~100-150 beams) but does not scale to very large HTS of Terabit/s class.
- Regenerative Optical (and RF) might be an interesting solution in the mid-term when technology becomes available. This approach however constraints the choice of the air interface.
- The analysis suggests departing from standard Radio over Fiber options for the optical feeder link due to poor spectral and power efficiency. New optical waveform options need to be considered, e.g. analog coherent with SSB and carrier suppression (avoids beta factor, bandwidth expansion) or digital transparent using digital modulations of higher spectral efficiencies (link budget allowing).

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