# NEXT GENERATION HIGH THROUHGPUT SATELLITE SYSTEM BASED ON OPTICAL FEEDER LINKS

**Oriol Vidal, Bernard Roy**
Airbus Defence and Space
31 Rue des Cosmonautes, Z.I du Palays, 31402 Toulouse Cedex 4, France
{oriol.vidal, bernard.roy}@airbus.com
**Svilen Dimitrov, Ricardo Barrios, Dirk Giggenbach**
German Aerospace Center (DLR)
82234 Wessling, Germany
{svilen.dimitrov, ricardo.barrios, dirk.giggenbach}@dlr.de
**Arnaud Le Kernec**
Thales Alenia Space
26 Av. J-F Champollion, BP 33787, 31037 Toulouse Cedex 1, France
arnaud.le-kernec@thalesaleniaspace.com

## Abstract

High-data-rate ground-to-space optical links are envisioned to be an alternative and more probably a next step to radio-frequency links, after the Q/V band still under development [1] for the feeder links of next generation high throughput satellites. Indeed, optical links allow a significant increase of the available spectral resources per link. This enables a drastic reduction of the number of gateway stations required on the feeder link, making this approach highly attractive when it comes to serve a large number of small user beams (i.e. Terabit/s scenario). In this paper, a two co-located high throughput satellites solution covering EU27 is presented, implementing an innovative free-space optical feeder link to handle the large number of user beams. An affordable site diversity system based on several optical ground stations and an optical fiber network is considered to overcome cloud blockage of the feeder link. These OGS networks are optimized for reaching at least 99.9% feeder link availability while minimizing the overall cost of the system. To achieve required high throughput on the feeder link, a trade-off has been carried out between two potential transmission scheme candidates, i.e. analog and digital optical modulations. The study has shown that both options could be feasible in the 2025-2030 time frame (assuming significant technical /technological developments), and that link budget could be closed by using the relevant atmospheric perturbation mitigation methods implemented in the optical ground station or in the on-board terminal. An end-to-end performance analysis has been carried out considering 150 user beams per satellite operating in Ka band and assuming a DVB-S2 improved air interface performances, proving that both satellite jointly obtain a total aggregated throughput beyond 1Tbps. This work has been carried out in the frame of EU FP7 BATS project, aimed at integrate broadband access across the EU for 2020 and beyond.

## 1. Introduction

The increase in number of broadband subscribers, mainly driven by increasing broadband penetration rates and service take-up across the European countries, and the shift towards more bandwidth demanding applications and services during the coming years have led to an expected increase of the traffic demand for satellite broadband of 6 fold by 2020. In order to be able to serve this increasing demand, next generation High Throughput Satellites (HTS) will need to be able to offer both higher throughput and higher data rates, flexibility to adapt to traffic demand across the coverage area, and at the same time decreasing the cost per transmitted bit.

The research project BATS [2] (Broadband Access via integrated Terrestrial & Satellite systems) addresses the delivery of Broadband future services in Europe as set forth in EC Digital Agenda [3], aiming at reliably deliver >30Mbps to 100% of European households by 2020.

In that frame, next generation broadband satellite communication systems will play an important role in the fulfilment of the Digital Agenda objectives. The deployment of current terrestrial broadband technologies will not be able to satisfy the requirements in the most isolated locations, either due to a lack of coverage in areas where the potential revenue for terrestrial service providers is not attractive enough (i.e. unserved areas) or due to technological limitations which diminish the available end-user throughput in rural environments (i.e. underserved areas). Hence, the integration of satellite is a key component of the future broadband communication systems in order to accomplish the Digital Agenda targets.

Among all technological options for the feeder links of next generation HTS, Q/V band is now being developed to support the market need growth on the mid-term, but as capacity needs continuously increase, high-speed ground-to-space optical links have the potential to become the following step to more conventional radio-frequency solutions (e.g. Ku/Ka-band or even Q/V-band). Free space optical links have been operationally demonstrated in the SILEX [4] (LEO-GEO relay link) and LOLA [5] (airplane to GEO link, through the atmosphere) experiments at 0.8 µm wavelength at a data rate of 50 Mbps. More recently, high data rate optical links at 1.8 Gbps at 1.06 µm wavelength have been demonstrated with the LCT between two LEO satellites. Japan and NASA have experimented with optical links at 1.55 µm for deep space and near earth communication. The 1.55 µm technology has several advantages w.r.t. the 0.8 and 1.06 µm technology. First, thanks to the wavelength multiplexing technique, it can offer very high data rate [6][7][8], i.e. higher than the Terabit/s per link (free space link between two buildings demonstration with up to 1.28Tbps in [9]), and it provides better eye safety, which is critical for the uplink. The 1.55 µm technology largely developed onground can be re-used for free space links, but it needs to be qualified for space applications, in particular for the radiation levels which are critical for high power doped fiber amplifiers, while technological developments remains unavoidable to address the high optical power level requirements.

In this paper, a two co-located high throughput satellites solution being part of BATS integrated system is presented, covering EU27 plus Turkey and with a large number of user beams. A full Ka-band allocation has been assumed for the user links combined with a 4 frequency reuse pattern, thus enabling a high level of reutilization factor. A MF-TDM access combined with advanced ACM air interface based on the evolution of DVB-S2[1] has been nominally considered. DVB-RCS2 is assumed for the return link. Total system performance assessment has been carried out showing both satellites jointly obtain a total aggregated throughput beyond 1Tbps. This design has been built on recent ESA funded studies such as [10].

Concerning the feeder link, an innovative free-space optical link, based on 1.55 µm technology, has been considered as an attractive alternative to more classical RF solutions (such as Ku/Ka-band or even Q/V-band). This approach enables the use of a single active optical link per satellite thanks to a very large available bandwidth and a high telescope gain.

However, a number of challenges have to be addressed:

- **High feeder link availability:** High levels of total feeder link availability are required, going typically up to 99.9%. Site diversity schemes must be considered to avoid link blockage by the clouds and to fulfil system requirements.
- **Transmission through the atmosphere**: Atmospheric turbulence mitigation techniques are mandatory to counteract the effect of the atmospheric channel as well as high optical emission power.
- **On-ground optical network design:** Optimized location of the optical stations and operation and cost of the high data rate backbone for the on-ground optical network are cornerstones of the optical feeder link
- **Analog vs digital modulation**: A desirable option for the transmission architecture is an optical feeder link transparent with respect to the user air interface. This can be implemented using either a digital or an analog modulation of the optical carrier.

A summary of the work done on the optical feeder link design is presented herein as well as the end-to-end system performances of both satellites. For the sake of completeness, a selection of several advanced techniques studied in the frame of the BATS project, regarding innovative radio interfaces and interference mitigation strategies for forward and return links, has been assessed in order to estimate the potential gains that could be expected with respect to the baseline design.

The remainder of the paper is organized as follows. Section 2 briefly presents the user link characterization followed by section 3 where the optical feeder link requirements and configuration are described. Section 4 summarizes the trade-off carried out between analog and digital optical modulations. Section 5 presents the results of the ground segment optimization, and section 6 introduces the adaptive optics as a mean to counteract the atmospheric perturbation. Finally, section 7

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[1] Some features of DVB-Sx are considered but the official guidelines of DVB-Sx were not published yet at the time BATS study was conducting this particular design. Therefore, some assumptions were made taking into account the information currently available back then. These can be found in [11].

presents the results of the end-to-end system performance analysis and the gains obtained by introducing some advanced system techniques on the baseline design. In section 8, the conclusion and way forward are presented.

## 2. User link characterization

The proposed design is based on two GEO co-located high throughput satellites covering EU27 plus Turkey. The user beam layout is based on 302 small user beams of 0.21° of beam width, 151 for each satellite, covering the East and West side of the coverage respectively. Users beams are served by an innovative free-space optical feeder link, based on 1.55 µm technology. The design will be addressed in detail in next sections.

*Frequency plan*
User link operates in Ka-band, making use of the FSS exclusive and shared spectrum in both forward and return links. On the forward downlink, 1.45 GHz of spectrum is allocated per user spot beam, based on a regular 4-colour frequency reuse scheme. On the return uplink, on average, 525 MHz of spectrum is allocated per user spot beam, being also based on a regular 4-colour frequency reuse scheme (Figure 1).

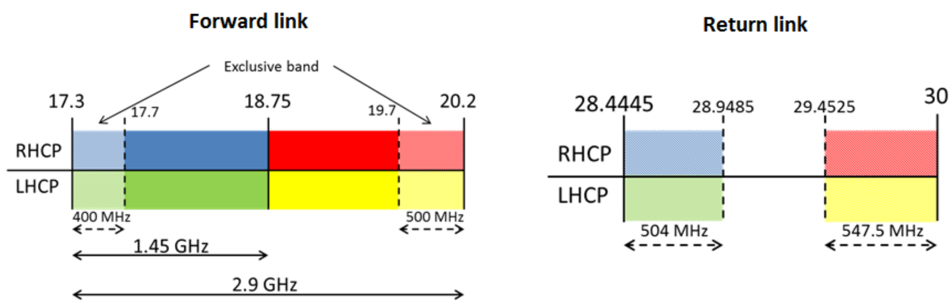



**Figure 1: BATS user beam layout (2 SATs) and optical feed link based architecture.**

*Air interface*
A MF-TDM access combined with advanced ACM air interface, based on the evolution of DVB-S2, has been nominally considered. It is assumed that from the 1450 MHz of spectrum allocated per user beam in the forward link, up to 1340 MHz would be useful bandwidth (taking into account ~10% of satellite on-board filtering). Assuming the forward link carrier would implement an equivalent 5% roll-off factor, and carrier spacing would be equal to the roll-off factor, 3 carriers of 425 Msps can be supported per forward user beam.

DVB-RCS2 is assumed for the return link. In the same manner, assuming 10% of spectrum allocated per user beam is needed for satellite on-board filtering, up to 472 MHz on average would be the useful bandwidth. A peak carrier symbol rate of 12 Msps has been selected, as it answers to the peak data rate requirement on the return link of 20 Mbps, as stated in [11]; Assuming that the RTN link carrier would implement an equivalent 5% roll-off factor, and carrier spacing would be equal to the roll-off factor, 37 carriers of 12 Msps can be supported per RTN user beam.

*Payload architecture*
A Ka-band antenna solution based on Multi Feed per Beam (MFPB) configuration has been retained for each satellite. A 5m diameter class is needed for such small beams (0.21°) formation. Thus, the antenna geometry is based on two reflectors, one single transmit reflector of 5m o and one receive reflector scaled (ratio 1.5) to generate the return link patterns.

Concerning the repeater side, a transparent RF payload has been assumed. The proposed repeater architecture assumes 110W Ka-band TWTAs shared by 2 user beams.

## 3. Optical feeder link: requirements and configuration

The innovative optical feeder link architecture proposed in the BATS project is based on the 1.55 µm wavelength terrestrial technology, using Dense Wavelength Division Multiplexing (DWDM) technique for the multiplexing of channels and high power Erbium Doped Fiber Amplifier (EDFA) booster amplifiers for the communication part. As a performance requirement, it is assumed that the feeder link, when the link is available, achieves an equivalent link budget contribution on the forward link of

17dB and on the return link of 18 dB. This figure has been taken into account as a performance target for the feeder link design.

For the acquisition of the optical link, which is a critical phase due to the very low divergence of the optical beam, it is proposed to use a beacon located on ground and an Acquisition and Tracking matrix on board. As demonstrated in the SILEX and LOLA projects, the beacon acquisition allows minimizing the duration of the handover, when the active optical link is interrupted by clouds, and the telecommunication signal is routed towards a redundant on-ground station.

The optical feeder link must be transparent with respect to the user air interface in order to allow changes during the satellite lifetime. This is possible using either digital or analog modulation of the optical carrier. Both options are assessed for the BATS mission.

**Table 1 – Mission requirements [11]**

| Parameter | Value |
|---|---|
| Feeder availability | Baseline : 99.9% |
| | Option : 99.7% (if significant cost reduction) |
| Feeder link degradation | < 1.5dB |
| Elevation | 30° |
| Main NCC/NMS position | Central Europe |
| Colour scheme | 4 colours |
| FWD link BW/beam | 1.45GHz/Beam |
| RTN link BW/beam | 0.526GHz/Beam |
| Number beam/ satellite | 151 beams/ satellite |
| Number of satellites | 2 |
| Satellite co-localized | Position: 13°E<br>0.001°<Separation<0.3° |
| Payload DC power | 22kW |
| Payload Mass | 2100kg |
| User signals physical layer | DVB-Sx / DVB-RCS2 |
| Handover packet loss | 0 (target) |
| Small packet delay | 700ms |
| Jitter | 30 ms |
| IP packet loss | 0.1% |

## 4. Optical modulation: Analog option vs Digital option

The Ka-band user signals will make use of DVB-S2 (forward) and DVB-RCS (return) communication standards in BATS system. In order to avoid the implementation of the modulation/demodulation of these standards on-board the satellite (which increases the on-board hardware and limits flexibility), it is assumed that the optical feeder must transmit the user signals in a transparent way.

Two possible types of modulation are considered to implement the transparent optical feeder links: either modulating the optical carrier with a digital technique, or with an analog technique. While using partly common equipment these two options impact differently the on-board and on-ground optical hardware, the interface with the RF user payload and the operation of the laser link. Both options have been analyzed in the frame of BATS:

- **The digital option** is based on the well-known terrestrial fiber communication technique which is able to transport several Tbps on optical fiber backbones and is currently implemented worldwide. In BATS case, the RF signal to be transmitted is first digitized and samples are transmitted over the optical carrier. In reception, the RF signal is recovered by reversing the operation, i.e. digital-to-analog converting the optical signal. Even though this approach increases the required optical bandwidth due to the quantization of DVB-S2/RCS signals it benefits from well mastered error correcting code techniques (and the related hardware) against random errors [6].

- **The analog option** is based on RoF (RF over Fibre) techniques commonly used on ground to transport RF signals efficiently (for example to remotely located antenna sites or for CATV applications). In BATS case, the RF signal is directly used to modulate the optical carrier in the feeder link, avoiding the use of on-board high-speed processors and being more efficient in terms of optical bandwidth requirements. The well-known advantages of photonic technologies such as a low loss transmission medium (optical fiber up to the gateway), light weight, large bandwidth characteristics, small size and low cable cost can benefit to an implementation on-board and on-ground and provide transparency at a relatively low complexity cost (except for atmospheric propagation mitigation techniques).

In addition to specific architectures, both options will have to deal with the atmospheric channel impairments (in terms of random errors and fading), using common or different techniques. The opto-mechanical mitigation techniques are implemented on ground (adaptive optics and aperture averaging on downlink, transmitter diversity [12] and pre-distortion adaptive optics on uplink) while the error correcting coding and interleaving techniques (only applicable for the digital option) are implemented in the on-ground and on-board hardware. Figure 2 displays the setup of the optical links in forward and return directions.

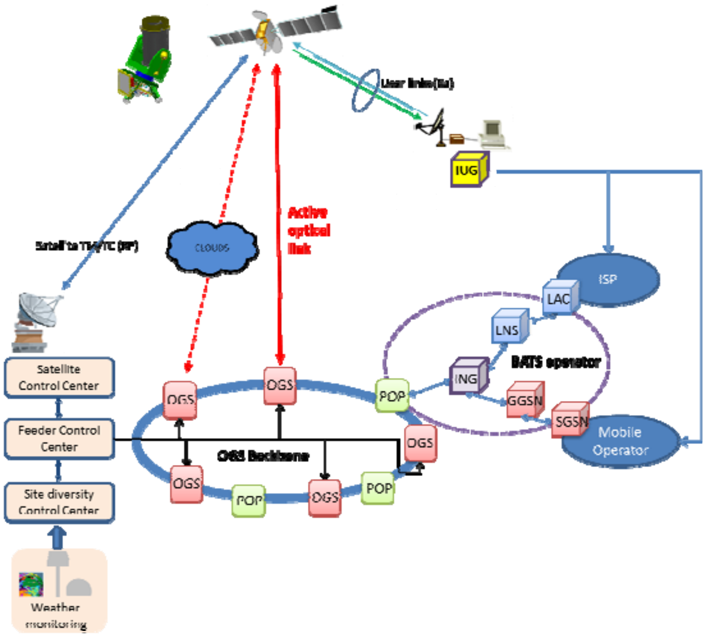



**Figure 2: BATS optical feeder link with OGS backbone**

In the performance analysis, it has appeared that, considering an overall available optical bandwidth of 60 nm (forward and return links), one optical link was not sufficient in both options to support the overall feeder optical bandwidth and throughput requirements. Therefore the concept of an OGS cluster was introduced. A cluster is composed of two to four telescopes with wavelength re-use, located in the same area but separated by a few kilometers in order to avoid interference of the beams on the satellite receive side.

The optimized configuration for both options is finally:

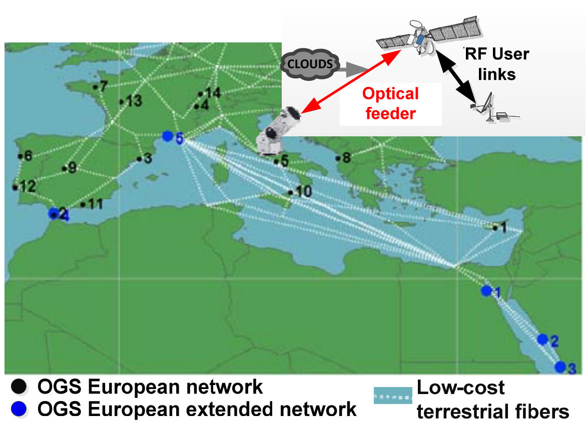
- **Analog option**: cluster of 3 OGSs using 135 nm in total (forward + return), adaptive optics, large receive telescope aperture and 4 transmitter diversity (on-ground)
- **Digital coded option**: cluster of 2 OGS using 90 nm in total (forward + return), adaptive optics, large receive telescope aperture, 1 transmitter only and erasure correcting code.

The feeder link is required to transfer a total of 520 Gbps user data in the forward and return links in a transparent manner. A main outcome from this study is that in both digital and analog options, the bandwidth of the optical feeder is expanded w.r.t. the user bandwidth. In the digital option, this is due to the digitalization of the user RF signal, while in the analog option this is due to the transmit diversity technique in the uplink (the optical bandwidth needed to support the 400 Gbps user data in forward is multiplied by the number of transmitters).

In conclusion, it can be said that both analog and digital options are envisioned feasible in the 2025-2030 timeframe, but the digital option is more mature w.r.t. implementation of mitigation techniques for the atmosphere impairments.

## 5. Ground segment optimization

The backbone of the BATS satellite operator has been optimized to limit its cost while reaching the required optical feeder link availability of 99.9% over the year. For this purpose, an algorithm selects optimized locations within a pool of more than 300 ingress and egress points of existing low cost high data rate optical fibers. The maximal distance for the segment between the optical ground station and these ingress points has been set to 50km to limit its cost. Then, another algorithm has been applied to minimize the overall cost of the BATS backbone (including OGS network and fiber connection to Intelligent Network Gateway (ING) that is specific to BATS project). Figure 3 depicts two optimized networks. The European network is restricted to EU-27 ingress points, while the European extended network (including sites in the North Africa and the Middle East) benefits from submarine cable with capacity compatible with the Terabits/s. The availability performances of these two networks have been computed by simulation on a two year cloud mask data bank. For the simulation, attention was paid to take realistic assumptions on their concept of operations.




| | Extended Network | European Network |
|---|---|---|
| Number OGS | 5 | 14 |
| Availability | >99.9% | >99.9% |
| Number of handovers | 202 | 481 |
| Backbone cost | ~150 M$ | ~300M$ |
| #OGS 90% utilization | 2 | 9 |

**Figure 3: Optical ground station networks and average availability performances and cost estimates per year.**

The ground segment optimization has proven that clouds obstruction is definitely not a losing battle. Two OGS networks reaching 99.9% link availability have been designed. The interest of North African location has been highlighted, as it divides by three the number of OGSs in the network, by two the number of handover per year and by two the annual cost of BATS backbone. For further details on the ground segment optimization methods described in this section please refer to [13].

## 6. Pre-distortion adaptive optics

Optical wave propagation through the turbulent atmosphere produces self-interference of the traveling wave, which translates into phase distortions that are responsible for the stochastic degradation of the transmitted energy. In the downlink, the adaptive optics implement a-posteriori compensation of the phase distortion. In the uplink, the idea of the pre-distortion adaptive optics is to compensate a-priori the phase distortion using the phase distortion measured on the downlink signal. A simplified block-diagram of pre-distortion adaptive optics is displayed Figure 4.

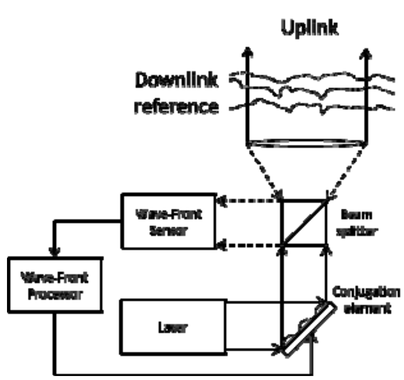



**Figure 4: Pre-distortion adaptive optics simplified system block diagram**

The performance of the pre-adaptive optics depends on three angles: the uplink beam divergence, the point-ahead angle (PAA), which is typically 18 µrad 18 µrad for a GEO satellite due to the relative velocity of the satellite versus the optical ground station (OGS), and the isoplanatic angle (IPA) produced by the atmospheric index-of-refraction turbulence. For elevation angles between 20 and 50º, the PAA is larger than the IPA. Nevertheless, in such scenarios a complete decorrelation of the down and uplink path does not happen and pointing by tracking is still beneficial in an optical GEO feeder link [12].

Applying pre-distortion adaptive optics (PAO) correction to an optical wave front in the uplink, aberrated by atmospheric turbulence, is accomplished by applying phase conjugation corresponding to a finite number of Zernike modes of the sensed distorted wave front. A preliminary analysis shows that the implementation of PAO might beneficial for optical GEO feeder links, improving link performance respect to scintillation index (SI), as well as beam wander and beam spreading loss induced by the atmospheric turbulent channel. It is concluded that most of the compensation in terms of the Strehl ratio can be achieved correcting the first 10 Zernike modes. Furthermore, in terms of scintillation effects, about 100 Zernike modes are required to obtain at least a one order of magnitude improvement in SI for all tested scenarios. Additionally, transmitter beam divergence is optimized in terms of OGS altitude, elevation angle to the GEO satellite and number of Zernike modes corrected. The study has shown that is possible to reduce the adverse atmospheric effects by means of pre-distortion adaptive optics, which allows the reduction of the scintillation index, improving the performance of the digital transmission schemes (and potentially of analog scheme as well).

## 7. End-to-end System performances

Based on the assumptions summarized in the previous sections, the forward and return links total throughput of the baseline design has been assessed in clear sky conditions. In the forward link, 3 carriers of 425Msps per beam are considered, assuming a roll-off factor of 5% and spacing between carriers equivalent to the roll-off. Considering a 4-colour frequency reuse (FR) scheme, a total forward link capacity of 800Gbps is achieved jointly by the two satellites, assuming 17dB forward uplink budget. This leads to an average spectral efficiency of 2.08 bits/symbol, an average carrier data rate of 882 Mbps and around 2.6 Gbps of supported capacity per beam. The total link budget figures plotted over the service area are illustrated in Figure 5.

In the return link, 37 carriers of 12Msps per beam are considered. Assuming a 4-colour frequency reuse scheme, a total return link capacity of 249Gbps is achieved jointly by the two satellites, assuming 18dB return downlink budget. This leads to an average spectral efficiency of 1.85 bits/symbol, an average carrier data rate of 22 Mbps and around 823 Mbps of supported capacity per beam. In both links, the availability achieved is greater than 99.7% over the coverage, being fully compliant with BATS system requirements.

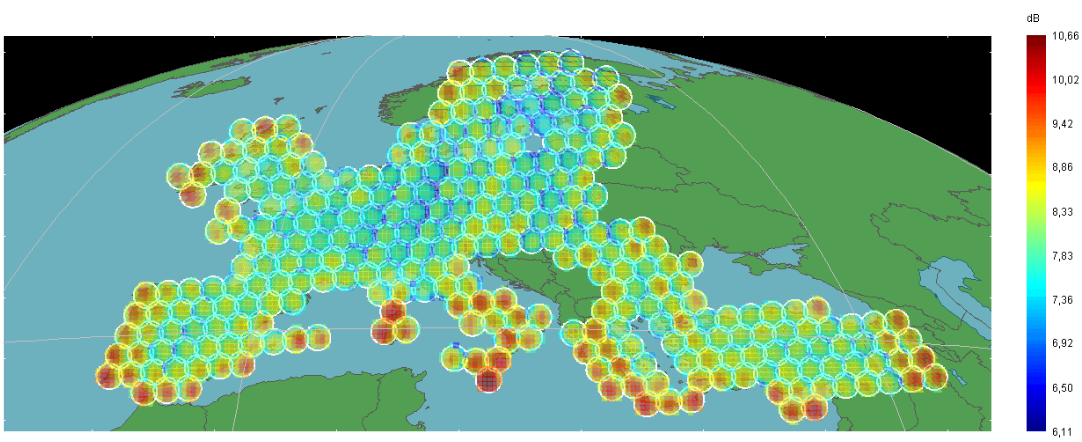



**Figure 5: BATS optical baseline design: Total link budget figures in Clear Sky conditions.**

A selection of several advanced techniques studied in the frame of BATS project, regarding innovative radio interfaces and interference mitigation strategies for both links, has been assessed in order to estimate the potential gains that could be expected with respect to the baseline design. The impact of pre-distortion and equalization strategies under tighter roll-off to mitigate the effects of the linear and non-linear behavior of the satellite channel is one of them. In the same manner, interference mitigation techniques such as precoding for the forward link (L-MMSE and THP-MMSE precoders) and Multi-

User detection (Multi-branch Successive Interference Cancellation – MB-SIC) techniques along with interference cancellation (MMSE-CPIC) and interference coordination strategies for the return link have proven to be attractive solutions to further improve the overall system capacity. Gains up to 12% w.r.t. baseline design are potentially reachable, further improving the already attractive performances obtained by the baseline design. A summary of the results obtained are described in Table 2. For further details on the techniques mentioned please refer to the references provided in the table.

**Table 2 – Delta gain in total throughput w.r.t baseline BATS optical feeder link satellite mission.**

| Techniques | System performance gains | |
|---|---|---|
| | FWD | RTN |
| *Baseline design (2 satellites)* | *800 Gbps* | *249 Gbps* |
| Pre-distortion /Equalization with tighter roll-off [14] | +11,2% | - |
| Precoding (THP-MMSE) [15],[16],[14] | +12,7% | - |
| MUD (MB-SIC) [15],[16],[14] | - | +5,2% |
| Interference Cancellation (MMSE-CPIC) [16],[14] | - | +10% |
| Interference Coordination [17] | - | +8% |

## 8. Conclusions

In order to meet the European Digital Agenda target to reliably deliver 30Mbps to 100% of households by 2020, we have presented the system architecture, sizing and performance assessment of a High Throughput Satellite system targeted to users in the remote and rural areas of EU27 and Turkey. This is based on two co-located GEO satellites handling 151 user beams each, covering West and East sides of the coverage. In order to maximize the overall throughput, the entire FSS civil Ka-band (exclusive + shared bands) has been allocated to the user links. Given the significant aggregated bandwidth that is required, an innovative free space optical link is considered for the feeder links. A trade-off has been carried out between two potential transmission scheme candidates, i.e. analog and digital optical modulations. The study has shown that both options may be feasible in the 2025-2030 time frame (with challenging issues to be addressed at component; equipment and system levels), and that it is possible to close the link budget by using the relevant atmospheric perturbation mitigation methods implemented in the optical ground station or in the on-board terminal, such as terminal diversity or pre-distortion adaptive optics. Link budgets in clear sky conditions resulted on total satellite capacities of 800 Gbps on the forward link and 249 Gbps on the return link. In addition, an affordable site diversity system based on several optical ground stations and an optical fiber network has been presented to overcome cloud obstruction of the feeder link, reaching 99.9% feeder link availability while minimizing the overall cost of the system.

## 9. Acknowledgements

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