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► To cite this version:

A Le Kernec, L Canuet, A Maho, M Sotom, D Matter, et al.. Optical feeder links for high throughput satellites and the H2020 VERTIGO project. COAT-2019 - workshop (Communications and Observations through Atmospheric Turbulence: characterization and mitigation), ONERA, Dec 2019, Châtillon, France. 10.34693/COAT2019-S5-001 . hal-03143529

HAL Id: hal-03143529

<https://hal.science/hal-03143529>

Submitted on 16 Feb 2021

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Optical feeder links for high throughput satellites and the H2020 VERTIGO project

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ABSTRACT

The demand from satellite operators for ever increasing capacity during these years has led to the emergence of VHTS (Very High Throughput Satellites) system solutions. Such satellites exhibit as a minimum several times the capacity of conventional satellites and possibly up to Terabit per second and beyond.

One of the main challenges associated to the implementation of these very high capacity systems is to feed the satellite in an efficient way to limit the cost of the system, in particular that of the ground segment. While RF bands are facing saturation and are submitted to strict frequency regulation, leading to a large number of ground stations, optical feeder links are considered as a promising technology to meet the future VHTS system requirements while strongly reducing the ground segment.

Nevertheless, optical feeder links are still facing some implementation uncertainties, beyond the obvious issue of nebulosity which can be alleviated through site diversity approach. While several feeder link architectures are envisaged leading to significant implementation differences, atmospheric propagation impairments and their mitigation techniques together with high power generation and management as well as efficient modulation use are of primary importance in the design and sizing of the optical feeder link. During past years several experimentations on ground or in-flight have demonstrated part of these concepts and subsystems necessary to implement such high capacity systems. Simultaneous combination of all these concepts in comprehensive demonstrations has however not been implemented yet.

This paper recalls the main drivers of satellite systems design based on optical feeder links and introduces the H2020 VERTIGO project that is specifically addressing the topic of the GEO-ground optical link and the associated technological challenges (high optical power generation, high efficiency waveforms, atmospheric impairments mitigation techniques).

Keywords: optical feeder links, telecom satellite systems, adaptive optics, high optical power generation, channel coding.

1. INTRODUCTION

The competitive telecommunication industry is more and more oriented towards mobile devices and broadband connectivity with its associated challenges the cost reduction per bit supplied to customers and higher capacity. To stay competitive and face the concurrence of the ground fiber networks but also to deliver similar telecommunication services to people in unserved or underserved regions by ground networks, satellite operators have to propose services of comparable performance and quality to ground operators offer, and therefore are requesting cost efficient solutions from satellite systems vendors.

One of the first technological responses from the Space industry, which is in turn challenged, is to develop more competitive solutions like Very High Throughput Satellite (VHTS), based on a multi-spot coverage allowing for frequency reuse and thus, increased capacity. In order to serve this increasing demand, next generation of VHTS will need to support both higher throughput, and flexibility to adapt to traffic demand evolution across the coverage area, while at the same time decreasing the cost per transmitted bit. To meet these market expectations, such high capacity systems require a continuously rarefying resource, frequency band. To solve this issue, Q/V band systems are currently deployed, and higher frequency bands are considered for the future. Nonetheless, the technologies beyond Q/V band still exhibit a low maturity and a leap to optical technologies can be a serious alternative.

2. THE CAPACITY GROWTH TREND OF SATELLITE SYSTEMS

In Europe, the KA-SAT satellite, the first High Throughput Satellite (HTS) covering Europe and delivering broadband internet services, launched in 2010 exhibits a total throughput beyond 90 Gbit/s several times the capacity of conventional satellites of previous generation. In spite of this large capacity, Eutelsat declined in 2015 new subscription because of satellite saturation. Intelsat 33e launched in August 2016 and covering Europe, Middle East, Africa and Asia Pacific is another HTS delivering broadband services to fixed and mobile network operators, aeronautical and maritime mobility service providers and government customers as well as regionalized content for media customers. Its capacity can reach 60 Gbps.

This growing satellite throughput trend has been even more illustrated in US by satellites launched during last years and recent announcements: Viasat-1, launched in 2011, exhibited a capacity in excess of 140 Gbps, higher than all satellites covering North America combined at the time of its launch making it the world's highest capacity communication satellite. EchoStar 19-Jupiter 2 launched in December 2016 to provide broadband access services in North America was at that date the communication satellite exhibiting the highest capacity in the world with a capacity of 180 Gbps. Six months later, Viasat-2 was launched offering an internet services through a Ka-band multispot coverage with a throughput as high as 300 Gbps. It is currently still the world's highest capacity communication satellite but Echostar signed a contract in 2017 for the building of the 500 Gbps capacity satellite Jupiter-3/EchoStar 24 to provide broadband internet access to the Americas while Eutelsat ordered KONNECT VHTS in 2019, a satellite expected to deliver around 500 Gbps. Viasat announced its next generation satellite system (Viasat-3), a trio of geostationary high capacity Ka-band satellites exhibiting a throughput capacity of 1 Terabit each and covering Americas, Europe, Middle East and Africa and Asia-Pacific region.

To feed such VHTS with the maximum achievable data traffic and thus fully exploit the satellite system, a large number of gateways (ground stations) are necessary. As an example, based on current RF technology, 20 gateways are used for Viasat-1, 45 (smaller) gateways for Viasat-2 and hundreds of gateways expected for the trio satellite Viasat-3. Even if, specific developments are engaged to dramatically reduce the cost of gateways, the ground segment of such very high throughput satellite systems will represent a huge CAPEX.

Table 1. Illustration of satellites capacity growth during last decade and in next few years.

| Satellite | Launch year | Estimated capacity |
|-------------------------|-------------|----------------------------|
| Eutelsat | | |
| Ka-Sat | 2010 | 90 Gbps |
| KONNECT | 2019 | 75 Gbps |
| KONNECT VHTS | 2022 | 500 Gbps |
| EchoStar | | |
| Jupiter 1 | 2012 | 120 Gbps |
| EchoStar 19 – Jupiter 2 | 2016 | 180 Gbps |
| Jupiter 3 – EchoStar 24 | 2021 | 500 Gbps |
| Intelsat | | |
| Intelsat 33 | 2016 | 60 Gbps |
| ViaSat | | |
| Viasat-1 | 2011 | 140 Gbps |
| Viasat-2 | 2017 | 300 Gbps |
| Viasat-3 | 2020-2022 | 1 Tbps/sat. (3 satellites) |

Among the different technologies currently investigated to offer higher feed capacities, optical feeder links are perceived as a way to overcome the RF spectrum bottleneck and increase the achievable throughput at an affordable ground segment complexity and cost. Indeed, optical technology is expected to allow for the transmission of the whole throughput through a single (or a very limited number of) optical gateway(s). Despite the necessity of implementing site diversity to cope with cloud coverage, the total number of sites is currently evaluated to 10-12 sites in Europe.

As a result, even if the evaluation of the ground segment cost and feasibility is still today under consolidation, the use of optical links could strongly reduce the required number of gateways and so the required CAPEX for the whole satellite system deployment (space and ground segments) to meet the future throughput requirements of VHTS in the range of 1 Tbps and beyond.

Well-known assets of optical technologies for optical links are (here mostly assuming the use of the 1.5 μ m technology):

- No spectrum regulation
- Large optical bandwidth available
- Large availability of components from terrestrial telecom networks applications
- Leveraging large R&D efforts
- Possible seamless interfacing to photonic payloads [1]
- Possibly future integration with terrestrial optical networks

3. TOWARDS TERABIT/S CAPACITY

3.1 Typical high level system requirements relevant for feeder links

The communication links between the ground and the satellite are schematically shown in figure 1. Such a high capacity system relies on a (RF) multispot coverage with frequency bands reuse. In the targeted system, the high throughput capacity feeding the satellite is made possible via one or a few simultaneous laser links making an extensive use of wavelength division multiplexing to meet the capacity requirements. Generic high level system requirements are as follows:

- User downlink band: 17.3 – 20.2 GHz
- User uplink bands : 28.44 – 28.94 GHz and 29.5 – 30 GHz
- RF band/beam : FWD: 1.45 GHz / RTN: 0.5 GHz
- Physical layer: FWD: DVB-S2X / RTN: DVB-RCS2

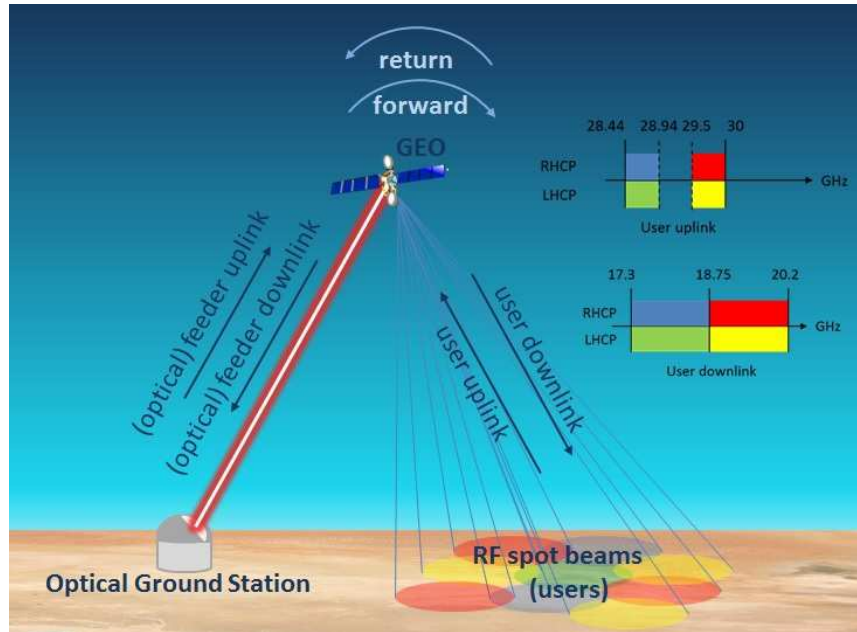


Figure 1. Illustration of the optical feeder and RF user links.

3.2 Optical feeder link family options

The main purpose of the feeder link is to convey the total up and down RF bands while ensuring the required level of service. Several “families” of optical feeder link architecture are envisaged to transmit these bands relying either on digital or analog modulations. All these options have in common to make a massive use of dense wavelength division multiplexing in optical C/L bands concurrently with high power optical amplification, while using opto-mechanical techniques (such as adaptive optics on-ground) and digital techniques (interleaving and coding) to mitigate impairments induced by atmospheric turbulence. Each family of architectural options offers a variety of implementations, the details of which are out of the scope of this paper, and only the high-level principle are reminded hereunder.

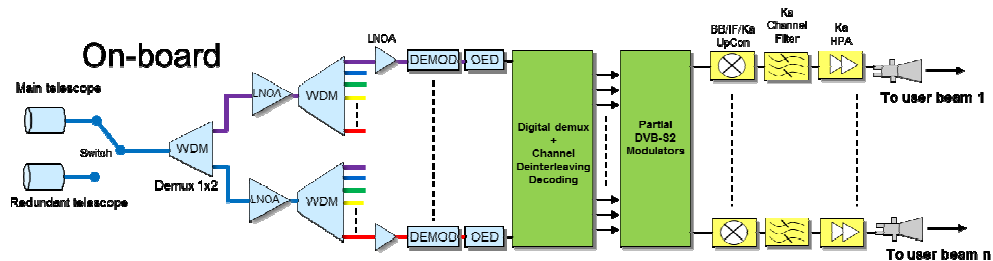
A key aspect having strong consequences on optical link requirements and implementation is the necessity or not for a transparent system. This feature derives from the system capability (or not) to transmit any waveform to the users.

In the following, the figures present a high-level functional view of such optical feeder uplink architectures which does not presume of the hardware implementation. Similar architectures, except for the regenerative option, can also be derived for the downlink but are not presented here.

Regenerative architectures

In this architecture family, baseband data are optionally encapsulated in frames generated from standard waveforms including Forward Error Coding up to mapping (e.g. based on DVB-S2 standard), undergo specific coding/interleaving for the optical channel, and are transmitted over optical feeder link through digital optical modulation (OOK, DPSK, coherent ...). Optical signals are demodulated on-board and RF signals to be transmitted to users are generated on-board using RF modulators.

This option is in principle applicable only on forward path as each RF carrier has to be demodulated on-board and is thus not compatible with a very large number of RF carriers (from users on return path).



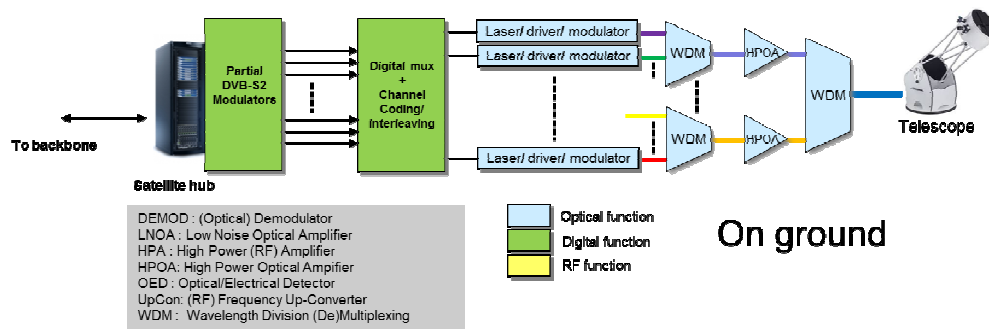


Figure 2. Regenerative optical feeder link architecture.

Digital transparent architectures

This options family uses waveforms similar to those used in the regenerative case for the optical transmission. However instead of transmitting baseband data, RF channels are digitized through ADCs before applying channel coding and interleaving. Also, on-board, the RF channels are reconstructed through DACs before being frequency converted and amplified to be transmitted to users. Comparable architectures can be described on the return path.

While this architecture type support the desired transparency regarding the RF waveform used, thus offering the possibility for an operator to modify this waveform during the satellite lifetime, this is at the expense of a large increase of the total throughput to be conveyed on the optical feeder link. Indeed, depending on system and subsystems requirements, an expanding factor relative to the RF band to be digitized shall be applied, which leads to an increase in bandwidth typically from 10 to 16. This drawback makes this option relevant only for low to medium throughput.

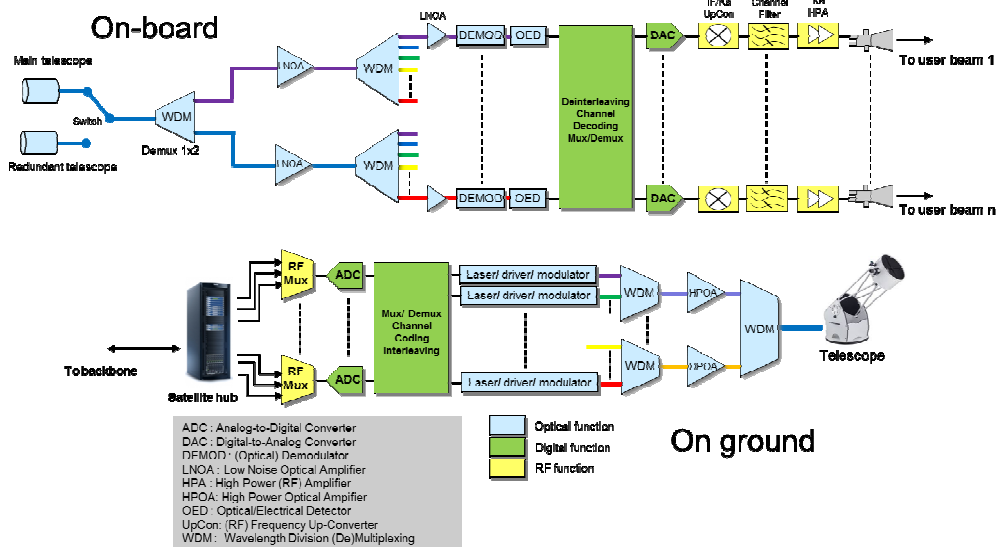


Figure 3. Digital transparent optical feeder link architecture.

Analog transparent architectures

The last options family is, in its basic form, comparable to a classical RF bent-pipe satellite repeater as all operations take place in the analog domain. The RF spectra to be transmitted (from DVB standard for example) modulate directly (without any incursion in digital domain) the optical carriers. On board the RF signals are recovered directly through photo-detection and easily handled by the RF payload. If no additional operations are applied up- and downstream the

optical link, this option may suffer strong turbulence-induced impairments not compensated by coding/interleaving. As a result, to be viable, particularly on the uplink which induces the strongest perturbations, the analog options shall be made more robust through digital assistance by relevant processing up- and downstream the optical link.

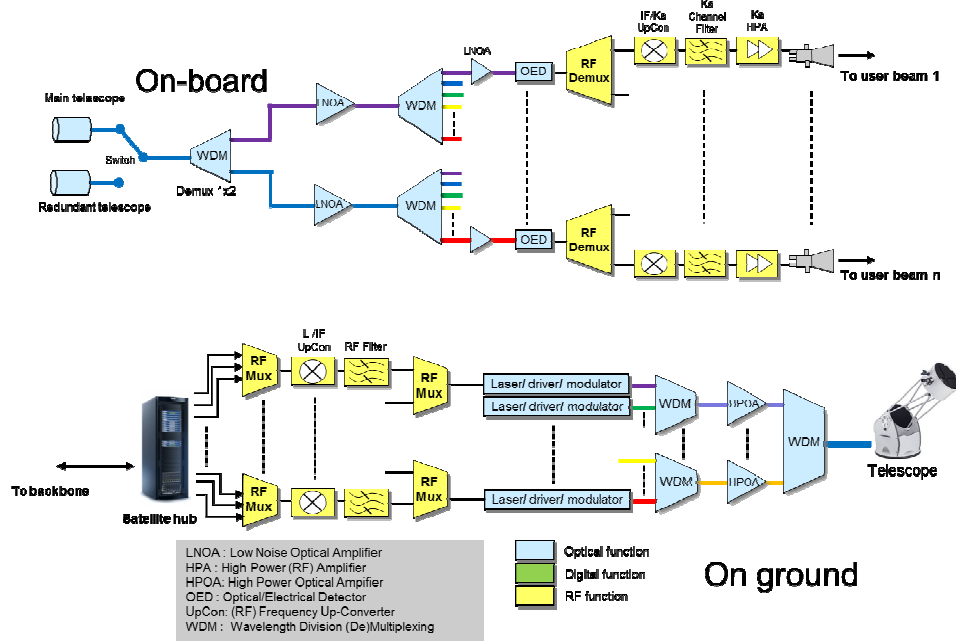


Figure 4. Analog transparent optical feeder link architecture.

3.3 A promising but challenging technology

Optical feeder links are considered as a promising technology to cope with the continuous growth in capacity demand and surpass classical RF technology limitations. However the inherent assets of optical technology shall not conceal the still remaining challenges to be overcome to make it relevant for operational missions. To date, some experimentations in flight (a comprehensive list is provided in [2]) or on ground [3][4], have provided precious results on several topics to be mastered for a successful implementation of optical feeder links. However, even if these demonstrations implemented relevant parts of an optical feeder link, all required aspects were not addressed simultaneously.

4. THE H2020 VERTIGO PROJECT

VERTIGO (Very High Throughput Satellite Ground Optical Link) is a 3-year H2020 project funded by the European commission [6] which focuses on the feasibility of the optical link itself regardless of site diversity aspect to meet overall system availability requirement, and aims at demonstrating the technologies required for the implementation of very high capacity optical feeder links.

The ambition of VERTIGO is to establish the required breakthrough by developing and demonstrating the on-board and ground concepts and technologies enabling for a drastic increase of the link throughput towards and beyond 1 Tbps. As shown in figure 5 below, it is all about setting the technology solutions to bring the performance level beyond existing experimentations of free-space optical links for space applications tested in-flight or on-ground.

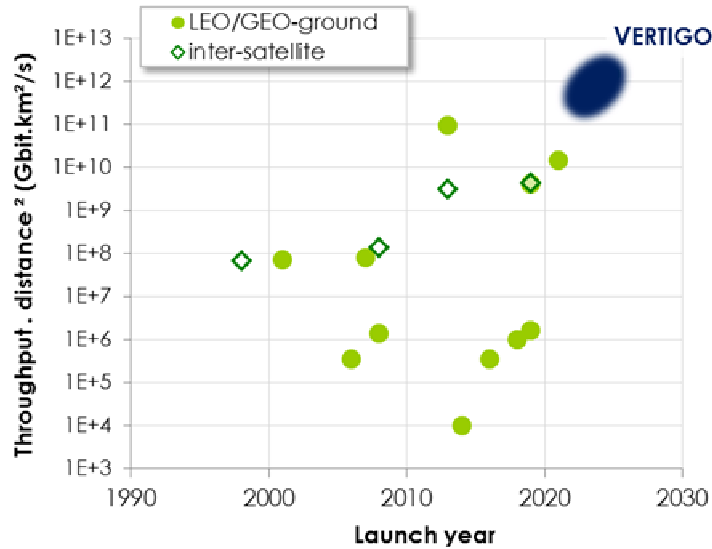


Figure 5. Comparison of past and planned FSO links in function of the product of the throughput by the squared distance.

Started during summer 2019, VERTIGO will implement two ground demonstrations, indoor (laboratory environment) and outdoor (several kilometers optical transmission through the atmosphere), to address the following 3 primary objectives:

- Throughput increase: while current space optical comms use 1bit/symb modulation formats, VERTIGO will prove advanced schemes with higher power and/or spectral efficiency (e.g. DPSK [5], DQPSK, coherent ...), including RF-over-Fiber approach,
- High optical power generation: to close the demanding link budgets, VERTIGO will develop on-board and ground means to raise the transmitted optical power, not only based on amplifier power increase, but also on incoherent/coherent power combining,
- Mitigation of atmospheric propagation impairments, to make full use of throughput and power increases. Opto-mechanical techniques using adaptive optics and aperture diversity, and digital processing (error correction coding/interleaving) will be developed to enhance the robustness of future optical feeder links.

Thus, VERTIGO is based on three pillars each addressing a key issue for high throughput optical links: intrinsic communication chain capability to transmit and receive very high bitrates, high and very high-power generation and atmospheric perturbations. These aspects are closely linked since the solution(s) to one of them is(are) necessary but not sufficient to allow for high throughput transmissions. VERTIGO approach is to address each key issue with at least one solution and to combine them in an unprecedented manner. The figure 6 hereafter provides a quick view of this approach.

To reach these objectives, VERTIGO will lean on a highly skilled consortium composed of CREONIC, ETH Zürich, Fraunhofer HHI, G&H, Leo Space Photonics R&D, ONERA, Thales Research & Technology, Thales Alenia Space in France and Switzerland.

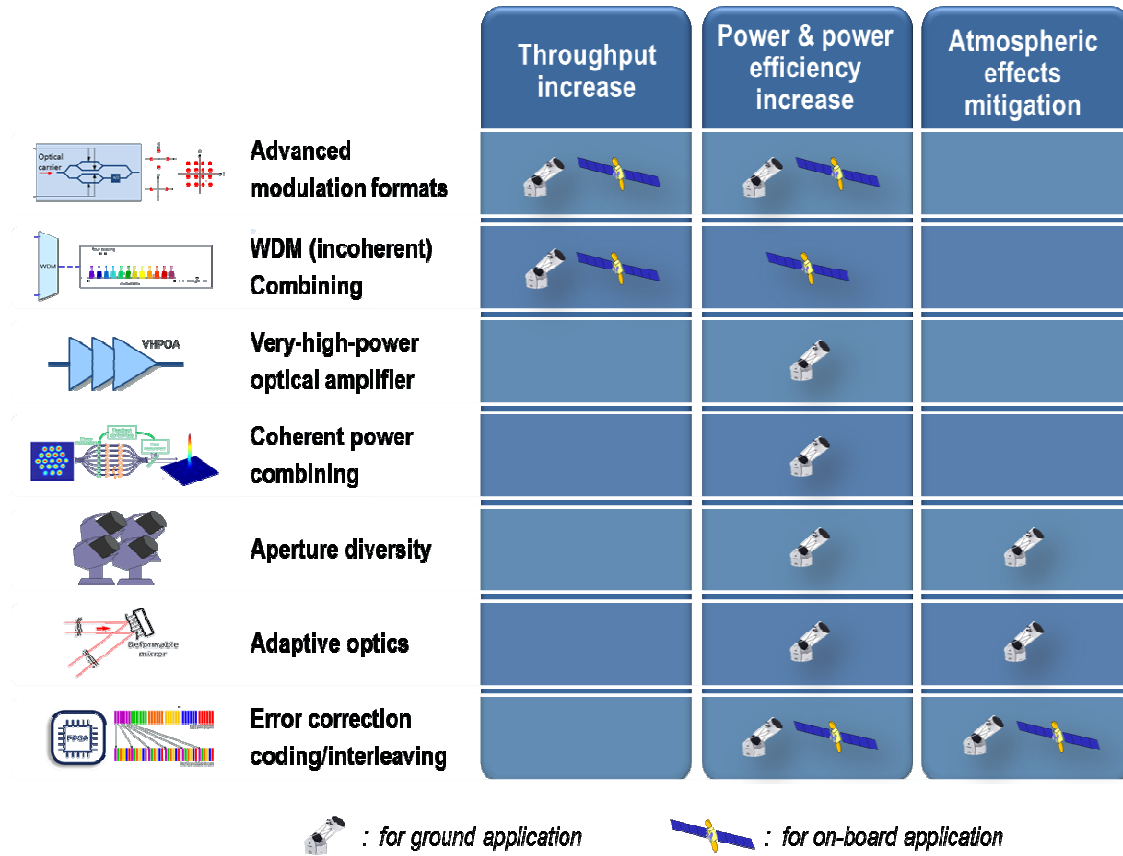


Figure 6. How VERTIGO technologies serve VERTIGO objectives.

5. CONCLUSION

The capacity bottleneck induced by the scarcity of spectral resource as well as the high ground segment costs of very high throughput satellite systems (VHTS) foster the emergence of new solutions in particular to feed satellites. Free-space optical communication link technology is considered as a serious candidate to overcome the problems of spectral resource and costs of the ground segment. However, technical challenges still remain to make this approach a viable solution. The H2020 project VERTIGO ambitions to implement and demonstrate the relevant technologies for optical feeder links in a representative environment and pave the way towards very high throughput satellite systems, thereby contributing to maintain EU technology at the leading edge and to strengthen industry competitiveness.

6. ACKNOWLEDGMENT

The VERTIGO project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 822030.

The authors thank all their VERTIGO project partners for their kind and fruitful cooperation.

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