# OPTICAL FEEDER LINKS FOR VERY HIGH THROUGHPUT SATELLITES – SYSTEM PERSPECTIVES

Ramon Mata-Calvo
German Aerospace Center, Institute of Communications and Navigation, D-82234 Wessling
+49 8153 28 3448, ramon.matacalvo@dlr.de

Dirk Giggenbach
German Aerospace Center, Institute of Communications and Navigation, D-82234 Wessling
+49 8153 28 2821, dirk.giggenbach@dlr.de

Alessandro Le Pera
Eutelsat, 70 Rue Balard, 75015 Paris
+33 1 53 98 37 04, alepera@eutelsat.com

Juraj Poliak
German Aerospace Center, Institute of Communications and Navigation, D-82234 Wessling,
+49 8153 28 1470, juraj.poliak@dlr.de

Ricardo Barrios
German Aerospace Center, Institute of Communications and Navigation, D-82234 Wessling,
+49 8153 28 3986, ricardo.barrios@dlr.de

Svilen Dimitrov
German Aerospace Center, Institute of Communications and Navigation, D-82234 Wessling,
+49 8153 28 3058, svilen.dimitrov@dlr.de

## 1. Abstract

Since some years, an important momentum is observed in optical communication techniques development for space applications, where free-space laser links may replace classical RF-technology for the GEO feeder link in the future. In order to achieve the target of implementing a Very High Throughput Satellite (VHTS) feeder link based on Optical Communication, several developments need to be addressed, ranging from basic technology developments at 1550nm wavelength to space-qualification of complete coarse pointing assemblies of laser terminals, up to determination of “gross” capacity achievable in the uplink as well as in the downlink branch. One interesting development for the uplink branch is based on the Dense Wavelength Division Multiplexing (DWDM) technology known from terrestrial fiber communications, to aggregate the whole throughput of one GEO spacecraft through one feeder link. Typical targeted transmission values would be several Tbit/s. While the single optical link can be blocked by cloud cover over the Optical Ground Station (OGS), large-scale OGS-diversity would allow achieving the required system availability, with the option to offer multiples of the single-link-throughput during most of the time by hot redundancy. One key aspect is associated to the on-board payload architecture which shall be able to efficiently manage the optical signal and convert it back to RF for down-link to User terminals. The optimum transcoding approach is yet to be assessed, several approaches are likely possible and, for each of them, pros and cons from a satellite architecture complexity viewpoint can be evaluated. Assuming a conventional Ka-band down-link service and DVB-S2 or DVB-S2x waveform provision, the problem can be formulated into three main stages: 1) Optimal transcoding of DVB-S2 or DVB-S2x incoming symbols at the gateway into optical symbols, 2) Optical feeder link management including optimal coding and DWDM and 3) Reception in the optical domain and transcoding back to RF before the on-board high power amplifier section.

## 2. Motivation and Feasibility of Optical GEO Feeder Links

In Europe we currently see strong efforts to provide fast internet service to as many households as financially viable. Terrestrial cable and wireless techniques are being exploited to their physical maximum. Still we will also in long-term future see white spots on the connectivity map, especially in Eastern and Southern Europe. This situation applies even stronger for other densely populated areas on the globe like South America and Africa, which will see a fraction of between 1 to a few percent of the population being left without high speed internet in the long term. Satellite communications from geostationary satellites (GEOs) can provide the required connectivity since it is not obstructed by any topological issues on ground. However, currently existing communication satellite transmission technology - HTS (High Throughput Satelite System) - cannot provide the required high throughput (which will easily exceed 1 Tbit/s per satellite) to serve such large amounts of the population. New technological approaches are necessary, known as Very High Throughput Satellite System (VHTS), together with optimized data transfer protocols like DVB-Sx-RTS, plus the user-link cells on ground must be optimized for maximum frequency re-use [1][2][3][4]. For these systems, the data feeder link trunk line from the ground-hub to the GEO satellite becomes a major issue as illustrated in Figure 1: When sending the data in the radio frequency (RF) spectrum, each ground gateway is limited by its available spectrum, which is typically 3 to 5 GHz only. Thus, several ground gateways are required to deliver the agglomerated system throughput. This number reaches easily above 50 gateways already for one Tbit/s, plus additional backup stations will be required to compensate for local rain fading events. The number of ground hubs increases linearly with system throughput, as shown in Figure 1.When instead using Free-Space Optical Communications Technology (FSO), more than one Tbit/s can be send via only one Optical Ground Station (OGS) towards the GEO, this technology is called Optical GEO Feeder Link (OGEOFL).

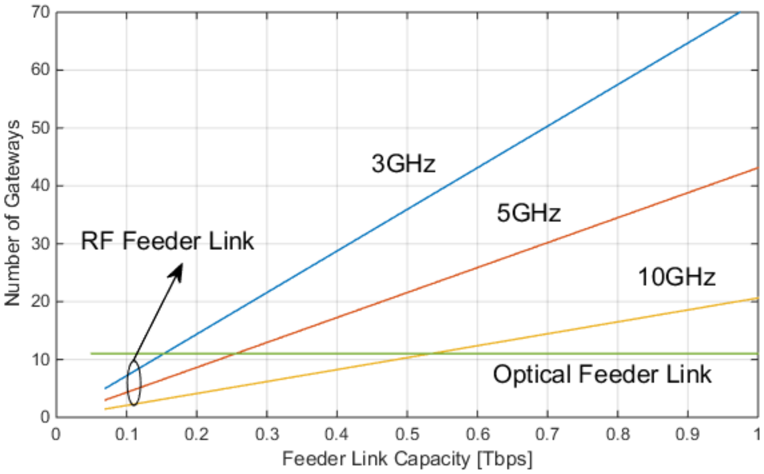


Figure 1. Advantage of Optical Feeder Link Technology versus conventional Ka-band Links, in terms of required ground hubs [5]. Number of OGEOFL-gateways is fixed to between 10 to 12, depending on correlated cloud blockage statistics.

Besides the increased throughput and availability with lower number of gateways, the OGEOFL technology provides enlarged “economy of scale” based on two considerations:

- Centralizing the up-link service has positive effects on Ground Network cost: ground station capital cost and operational cost is a non-negligible part of the overall investment an Operator has to plan for an HTS;

- Reaching very high capacity on a single Satellite permits to definitively lower the cost per Mbit, as the cost of the infrastructure (Satellite design and procurement, launch and operations) is sub-linear with respect to provided capacity;

On the first point, an additional aspect is that the Ground Network minimization is a general driver which is independent from the adopted up-link bandwidth. What is clear with Optical Communication is that the concept can be pushed to the extreme as a single up-link infrastructure could potentially feed the entire Spacecraft. This positive point has to be balanced with an increased demand for site diversity, potentially higher than Q/V band, to grant the necessary up-link service availability.

### Atmospheric impact: cloud-cover diversity and attenuation

An additional consideration which pushes in favor of non-Ka-band up-link access schemes is the fact that bandwidth is a limited resource and needs to be shared amongst all different actors in an HTS system. In a conventional Ka-band HTS composed of FWD (Gateway to User) and RTN (User to Gateway) missions, the up-link Ka-band has to be used by both Gateway and User in such a way as to permit simultaneous operations. This means that Gateway locations have to be carefully selected as it could impact bandwidth availability for the Users located in Spots close to the Gateway. A common trend is to locate the Gateways outside of the User Coverage, so as to have full frequency reuse. This has a negative impact on cost as the Gateways are sometime forced to be located in foreign territory with difficult access to Internet Backbones, so needing to perform dedicated ground fiber connections.

The Optical up-link would provide the best possible solution as it does not need to be shared. Additionally, no ITU regulations / restrictions exist at the present time which could adversely affect the System development.

One however needs to compensate link blockage through clouds by large-scale OGS-diversity. By analysis of long term cloud data it can be shown that for OGSs in the Mediterranean (or similar favorable areas between 20° and 40° latitude in the northern or southern hemisphere) optimally around 11 gateway stations can be sufficient to fulfil availability requirements for satellite telecom systems (red line in Figure 2), while this number can even be reduced when an inter-continental ground network allows exploitation of the counter-correlated seasonal weather statistics (green line in Figure 2) [5][7].

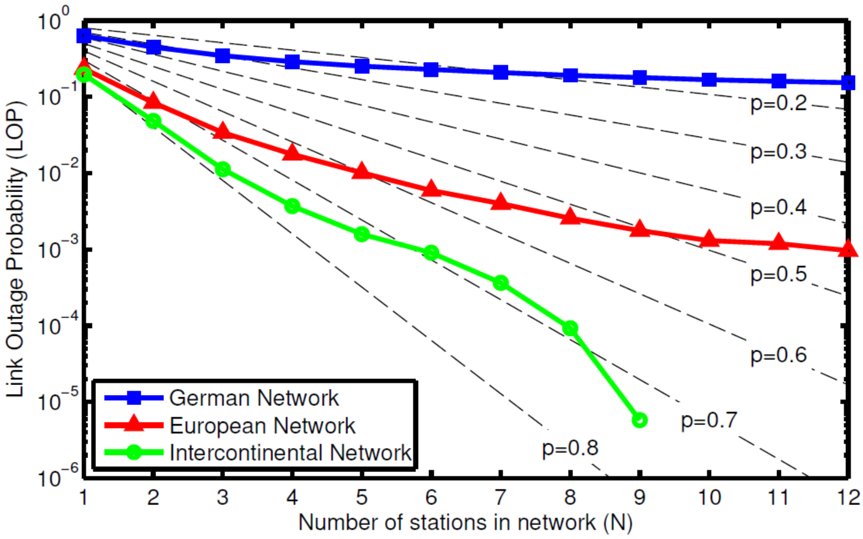


Figure 2. Simulative assessment of OGS-network availability, calculated from long-term cloud cover data, assuming optimized decorrelated ground station locations [8]

Transmission technology for OGEOFLs will be employing components from terrestrial fiber communications in the DWDM-grid (Dense Wavelength Division Multiplexing), namely laser sources, optical fiber amplifiers, and multiplexers and demultiplexers. The clear-sky attenuation of the atmosphere features a minimum exactly around the DWDM spectral region from 1530nm up to 1680nm (Figure 3).

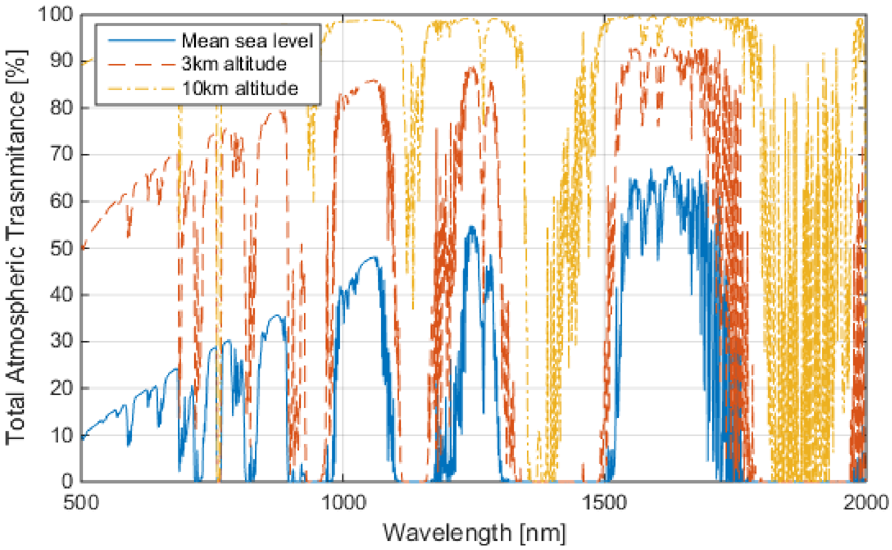


Figure 3. Available optical spectrum for atmospheric FSO, based on atmospheric transmission windows. The window from 1530nm to 1680nm coincides with terrestrial fiber transmission components technology.

### Atmospheric Turbulence Fading

A major challenge however to be solved for OGEOFL is the clear-sky turbulence of the free atmosphere, caused by index-of-refraction turbulence cells (IRT) [9]. These cells cause intensity-fluctuations and wave-front distortions of the propagated laser signal. While the IRT effect in the downlink from the GEO to the OGS can be compensated by means of aperture averaging and adaptive optics wave-front correction, the uplink beams suffers from stochastic direction deviations called beam-wander, which are hard to compensate with standard techniques. This beam wander-effect thus can cause a major degradation of the overall link budget [10].

## 3. Technology for Optical Feeder Links with DWDM

One of the key advantages of the optical communications technology, compared to RF, is the relatively high available bandwidth. Mainly due to technology limitations, this immense bandwidth, which reaches several tens of THz, cannot be addressed as whole. First, it is divided into bands of several THz based on material properties and atmospheric transmission windows. This DWDM division of optical spectra is defined by ITU [11] and includes, for instance, widely-used C-band, sometimes referred to as “erbium window”. The C-band is more than 4THz broad and it is sub-divided into individual channels. The channel width defines the channel spacing (200GHz down to 25GHz). Ultimately, the channel spacing combination in a specific application is up to user’s definition, which makes DWDM technology very versatile for optical communications application.

Unlike Radio-over-Fiber (RoF), where individual data channels are modulated on a radio-frequency (RF) carrier and then on top of an optical carrier, in DWDM system one directly modulates the input RF signal on the optical carrier, which is centered in the optical DWDM channel. In order to effectively use the whole available spectrum, the channel spacing needs to be carefully chosen with respect to the bandwidth of the transmitted RF signal. Here, spectral efficiency comes into role, defined in the digital communications as the data-rate of the transmitted signal divided by the physical bandwidth it occupies, expressed in units of bits/s/Hz. Maximum achievable spectral efficiency of 1bit/s/Hz in case of intensity modulated signals with direct detection (IM/DD) can be increased by means of using higher-order modulation techniques or spectral shaping.

### DWDM Channels for Uplink and Downlink

An exemplary DWDM communications system for the GEO Feeder-link is shown in Figure 4, consisting of two units: transmitter (Tx) and receiver (Rx) at both the OGS and the satellite terminal (payload). Here, the optical carriers are generated either by a tunable laser or using fixed DFB lasers with wavelength centered at one of the DWDM channels. The optical carrier is then modulated by the transmitting RF signal. The modulation can be either direct, where the drive current of a photodiode is directly modulated with the data signal, or using a field modulator, e.g. Mach-Zehnder modulator (MZM). The latter solution adds more complexity to the system due to the need of biasing and larger modulating voltage, but allows for higher bandwidth, typically up to 40GHz. The individual optical data channels are then multiplexed into a single fiber (typically single-mode – SMF), amplified and sent through the telescope. The satellite telescopes (in both UL and DL direction) are steerable in order to point towards different OGS locations and allow for site-diversity.

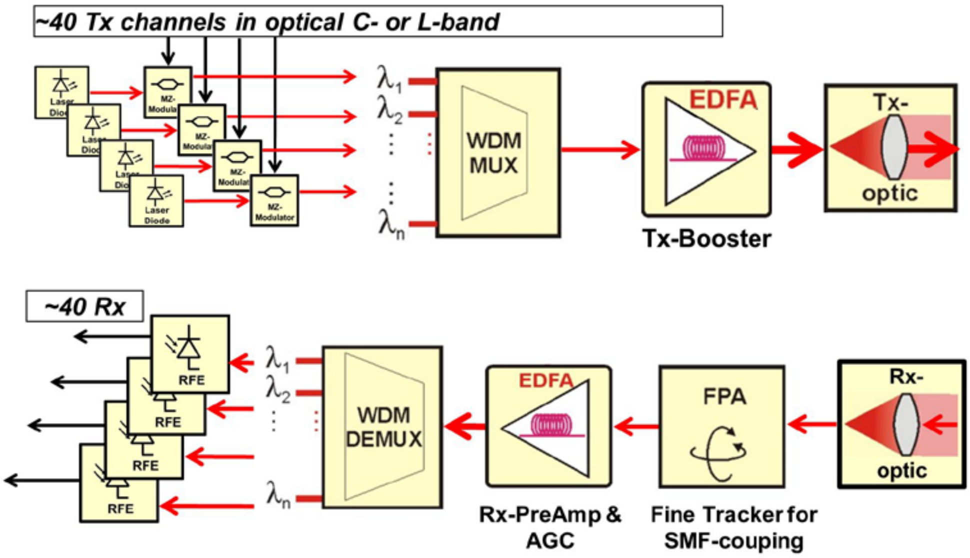


Figure 4. An exemplary DWDM communications consisting of several data streams separated at individual DWDM channels with central wavelengths $\lambda_i$, WDM multiplexer (MUX), erbium-doped fiber amplifier (EDFA), , preamplifier EDFA with automatic gain control (AGC) and receiver front-ends (RFEs).

There are different amplifier technologies for different optical bands. In C-band, erbium-doped fiber amplifier (EDFA) is used, allowing for high optical amplifications (several Watts in multi-channel operation). The EDFA amplifier gain curve has a strong peak, which can be tuned, allowing for high-power single-channel applications. For DWDM system applications, the EDFA gain curve has to be flattened using a gain-flattening filter, which gives rise to smaller, but very flat (+/-0.5dB) gain curve over the whole C-band. After precise beam-steering by fine pointing mechanics, the signal is sent out through the transmit telescope.

In order to increase the receiver sensitivity after the reception of a relatively weak optical signal, preamplifier EDFA is used. The output of the preamp EDFA is observed and in a feedback loop, its gain is controlled to stabilize it and effectively to mitigate the atmospheric fading. Selection of this component is critical due to very low OSNR (optical signal-to-noise ratio) of the signal at its input.

After improving the OSNR of the signal, demultiplexing the signals will again divide the individual DWDM channels, which are then detected by individual receiver front-ends (RFE). The signal received by individual RFEs reconstitutes the different data streams devoted to different user beams. After converting them into the data flux of individual RF channels in Ka-band, it is sent to the users.

The above-described exemplary setup would be similar for both uplink and downlink of the optical GEO feeder link. This link would be strongly affected by IRT, the effect of which needs to be compensated for. However, due to different nature of the effects in the atmosphere in respective direction, the compensation techniques are also different.

In the GEO downlink, the receiver energetically benefits from aperture averaging effect, but at the same time, it reduces its fiber-coupling efficiency due to strong phase front distortions at the receiver aperture. These phase distortions can be compensated using adaptive optics (AO) techniques, which can significantly improve the fiber-coupling efficiency. AO system consists of four main elements, namely a wave-front sensor, wave-front processor and a conjugation element. The phase conjugation operation is normally executed in two stages, i.e. first a fast steering mirror is employed to compensate tilt, and a deformable mirror (DM) is employed to compensate higher order phase distortions.

In the GEO uplink, the satellite receiver is modelled by a point receiver. The optimal IRT-compensation technique is diversity, namely transmitter-diversity. This technique benefits from the existence of a so-called isoplanatic angle, which defines the angular cone of the atmosphere as seen from an aperture, where the atmospheric behavior is similar. If two transmitters are separated by approx. 1m, the IRT effects from each of the transmitters will not be correlated anymore, which will effectively mitigate the fades at the receiver by channel diversity. This can be also referred to as small-scale (transmitter) diversity, in order to differentiate it from the large-scale (site) diversity, as required for cloud-coverage mitigation. Another IRT-mitigation technique in the uplink channel is using pre-distortion adaptive optics (PAO). The aim of this approach is to sense the phase distortion introduced by the atmosphere, which can be accomplished using the satellite downlink signal, a dedicated downlink beacon, or a reference generated by the OGS — i.e. a laser guide star. Provided this signal reference is available within the isoplanatic patch of OGEOFL scenarios, PAO can be applied.

## Transmission Format Options

After the optical receiver onboard the satellite, digital processing may be required before converting the information flux to the Ka-band user link. A trade-off between link robustness and satellite complexity can be established between three feeder-link transmission technologies:

- Analog Transparent DWDM channels with physical fading mitigation and AGC
- Digital Transparent with Coding for the Optical Channel
- Complete Digital Regenerative DVB-S2-RCS

In the analog transparent transmission scheme, the signal processing architecture is the same as the one presented in numerous publications on the transmission of wireless RF services over FSO ([12]-[17]). Here, the RF signal from the DVB-S2X chain at the GW is directly modulated onto the optical carrier. The transmission is carried out in an intensity modulation direct detection (IM/DD) fashion. On-board the GEO, the signal is collected by a telescope, optically pre-amplified by means of a low noise optical amplifier (LNOA), and finally converted by a square law opto-electrical detector to recover the original DVB-S2X RF signal. In this scheme, each stream per user beam can be allocated to a DWDM channel. In addition, the intermediate frequency (IF) for the uplink RF signal can conveniently be selected in order to minimize the impact on the satellite's RF payload. In the downlink, a similar approach is followed for the electrical-to-optical conversion of the DVB-RCS2 signal.

Another possibility to implement an optical feeder link keeping the transparency requirement is by transmitting a digitized version of the DVB-S2X RF signal generated at the GW [18][19][20][21]. Each baseband complex-valued data stream, i.e. signal on a carrier, is sampled individually by means of an analog-to-digital converter (ADC), using e.g. 12 bits per complex-valued sample to achieve a sufficient signal-to-distortion ratio (SDR). On-board the satellite, a digital-to-analog converter is required to reconstruct the baseband complex-valued signal to be up-converted to Ka-band for transmission over the user link in a transparent fashion. Current technology for high-speed ADCs/DACs can offer conversions in the GigaSample/s domain [22], which is considered sufficient.

The transmission of the digitized signal can be performed either with IM/DD or coherently, as the uplink optical source is transmitting bits. IM/DD supports transmitter diversity, allowing for an increased transmitted power and reduced IRT-fading due to scintillation at the receiver plane on the satellite. In coherent modulation, all the necessary power in the uplink must be transmitted through a single telescope, as weakly correlated multiple sources in a transmitter diversity scheme would randomly interfere with each other destroying the phase-conveyed information. In addition, further robustness against burst errors in the turbulent channel can be achieved by protecting the digital samples using forward error correction (FEC) coding, specifically designed to compensate IRT adverse effects [20].

In digital regenerative (DR) transmission scheme, the original baseband bit stream is directly transmitted through the optical carrier. Therefore, modulation and physical layer framing are executed on-board the satellite. Digital regenerative transmission can be performed as soft or fully regenerative transmission.

In the DR soft option, the baseband (BB) data bit frames with the DVB-S2X FEC coding, which can be additionally protected against fading by an IRT-FEC, are transmitted over the optical carrier through the atmospheric turbulent channel and received by the optical payload onboard the satellite.

Once data is recovered in the electrical domain, the IRT-FEC is decoded to correct for errors introduced by the atmospheric fading channel, the BB frames can be processed on-board by the remainder of the DVB chain with the corresponding amplitude and phase modulation, and the baseband filter — i.e. pulse shaping.

The fully DT regenerative option is similar in concept to the soft regenerative as the BB frames are also transmitted over the optical carrier, but the DVB-S2X FEC coding and modulation blocks are included in the satellite RF chain. Similarly, an additional IRT-FEC code can be applied to the BB frames, to be transmitted from the GW to the satellite through the optical uplink channel, in order to protect the data against the IRT-induced fading.

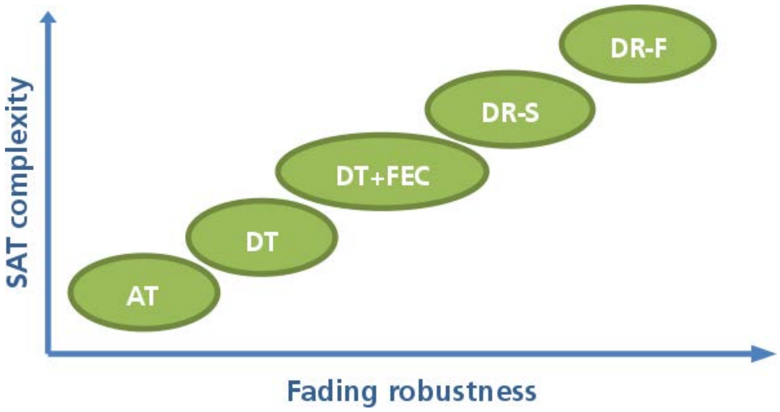


Figure 5. Trade-off between optical GEO Feederlink transmission technologies

Figure 5 presents the trade-off between the different alternatives to implement an optical GEO feeder link for HTS in terms of satellite complexity and their robustness against atmospheric induced fading events. In the lower left of the plot the AT and DT are located, as they represent the options with least impact on satellite transparency. Complexity of the DT option is somewhat higher, due to the need of high-speed digital-analog converters to recover the original RF signal. The middle of the chart holds the DT plus FEC option, which can still provide a certain level of satellite transparency while providing extra robustness against IRT-fading imposed by the optical uplink channel, at the expense of increased satellite complexity to perform the necessary onboard processing to decode the IRT-FEC protected data. Finally, in the upper right zone of the chart alternatives with improved error correction capabilities are grouped (Soft and Full Digital-Regenerative), which come at the expense of increasing satellite complexity and complete loss of flexibility.

### Technical Challenges

The evaluation and implementation of the optimal transmission format to efficiently modulate the optical carrier is still an open issue. The main driver is the evaluation of trade-offs related to the complexity and cost of the payload section. Depending on the selection of the transmission format, the satellite payload is significantly impacted. In the following, the main considerations of the different modulation options are discussed.

In the analog option, the requirements imposed by the link budget in the optical GEO uplink channel with IRT force the use of high optical power amplifiers at the GW transmitter, thus making the analog signal prone to degradation due optical nonlinearities in the amplifier. This might have some impact on the RF signal quality, and ultimately on the signal-to-noise ratio (SNR) at the satellite uplink receiver. The design and implementation of suitable transmitter diversity techniques is the key to counteract the IRT channel. However, due to the restriction of non-overlapping transmitter spectra to avoid laser carrier interference, a higher number of transmitters require a respective expansion of the required optical bandwidth.

In the digital transparent option, high-speed ADCs and DACs need first to be qualified for space operation. The bandwidth here is also expanded according to the sampling factor. However, this expansion becomes less significant when higher order modulation is used on the underlying sampled RF signal, as a complex-valued symbol already carries several bits, increasing the electrical-to-optical-bit ratio. In addition, the implementation of IRT-FEC results in processing requirements of about 20 Gbit/s that have been demonstrated elsewhere [23]. Nevertheless, hardware expansion and parallelization of the processing is mandatory to cope with the overall capacity of a Tbit/s throughput GEO satellite [20]. On the other hand, considering the long fades inherent to the optical turbulent channel, on-board memory in the order a few GByte is required for the interleaver size.

In the digital regenerative option, this improved performance against fading comes with the price of notably increased satellite design complexity and transparency is no longer possible. Additionally, the satellite flexibility to adapt to new changes in the DVB format, which might appear in future revisions of the standard, is lost once the satellite has been launched.

A deeper evaluation of complexity and efficiency together with Industry is required to further develop the optical feeder-link. But in our opinion, currently, the digital transparent option is considered most mature for its application.

A part from the feeder-link transmission scheme other technologies need to be further developed. For example in PAO, the DM represents one of the major challenges for successful implementation, as it will be a single element that needs to withstand the aggregated optical Tx-power in a future OGEOFL. Most likely the uplink channel will consist of some hundreds of wavelengths, each operating in the range of a few tens of Watts of average power. Currently, promising research is being conducted in the field of high-power DMs that could potentially handle up to 6.2kW [24].

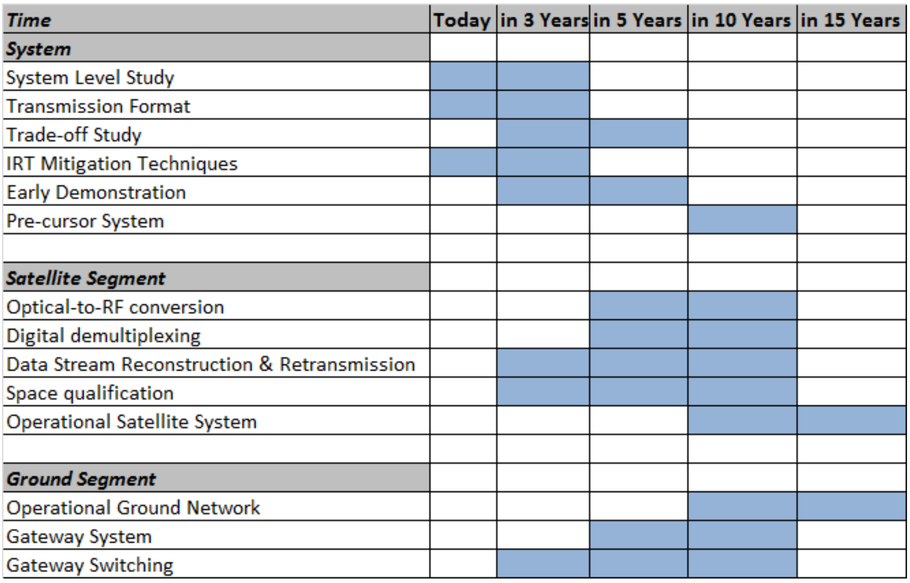
The switching between gateways also has to be taken into consideration. This issue is especially challenging for the optical feeder link since all the throughput is redirected to a single gateway. The use of more than one gateway for the uplink should be also taken into consideration. Currently analyses for Q/V band have been already performed, calculating the outage probability, the switching probability, and the spectral efficiency from several given switching configurations [25].

## 4. Summary and Development Roadmap

DWDM technologies can provide more than 1 Tbit/s for the optical feeder-link in satellite communications, minimizing the number of gateways in the ground network. With around 11 gateways one can cope with the cloud coverage and provide the required availability. Additionally optical frequencies can overcome the bandwidth limitation of a conventional Ka-band HTS.

Several transmission schemes have been studied and the next steps towards further development of the optical feeder-link need to be performed. The digital transparent option appears to be the most mature option, requiring additional developments for the digital processing in space-environment applications. Other aspects like gateway switching or transmitter diversity and PAO, to mitigate the effects of the atmospheric turbulence in the uplink, need to be further investigated to provide an operational robust system. Despite all these technical and scientific challenges, which need to be addressed, the optical feeder-link remains the most promising technology for the long-term future of commercial satellite communications.

The economics associated to a generic HTS System are such that, today, a Gigabit/s of goodput (final throughput to end user) is sold for less than 3 M€, with new architectural design for bigger systems aiming to further drive down the cost. This cost has to remain competitive compared to ground infrastructure. Fiber provision operating costs are effectively negligible but it suffers from a high initial investment. On the other side, Satellite Internet provision permits to mitigate the Digital Divide associated to situations where it is not profitable to provide fiber connections. To make Internet by Satellite competitive, the operational costs impact can be mitigated by increasing the system capacity, while maintaining similar capital cost and operational cost. A VHTS based on optical feeder-link can provide a large increase of the system capacity with respect to current HTS. From the commercial point-of-view, one first assessment would be to reach the breakeven point where current HTS capacity on conventional Ka-band Satellites, like Ka-Sat, Viasat1 or Hughes, is obtained with optical feeder links (one active uplink gateway with additional sites for diversity) at the same price (ground network, satellite procurement and launch, operation of the network and satellite) as HTS. Any additional development addressing an improvement on the uplink capacity rate by a single uplink station would result in a more competitive cost of the delivered bit to the end user.



| ***Time*** | **Today** | **in 3 Years** | **in 5 Years** | **in 10 Years** | **in 15 Years** |
|---|---|---|---|---|---|
| ***System*** | | | | | |
| System Level Study | ■ | ■ | | | |
| Transmission Format | ■ | ■ | | | |
| Trade-off Study | | ■ | ■ | | |
| IRT Mitigation Techniques | ■ | ■ | | | |
| Early Demonstration | | ■ | ■ | | |
| Pre-cursor System | | | | ■ | |
| | | | | | |
| ***Satellite Segment*** | | | | | |
| Optical-to-RF conversion | | | ■ | ■ | |
| Digital demultiplexing | | | ■ | ■ | |
| Data Stream Reconstruction & Retransmission | | ■ | ■ | ■ | |
| Space qualification | | ■ | ■ | ■ | |
| Operational Satellite System | | | | ■ | ■ |
| | | | | | |
| ***Ground Segment*** | | | | | |
| Operational Ground Network | | | | ■ | ■ |
| Gateway System | | | ■ | ■ | |
| Gateway Switching | | ■ | ■ | ■ | |

Table 1. Roadmap for the development of optical GEO feeder-link system

The development roadmap of a VHTS based on single Optical Uplink Station (apart the additional ones for diversity) has to be driven by the overall efficiency (cost, complexity, development time) in reaching the intended capacity. To exploit the promising performance of such technology and avoid development impairments, a reasonable technological approach would be to start hardware development in parallel to the System Level Study devoted to assess the system configuration in terms of ground network, optical access scheme, and satellite.

In the roadmap depicted in Table 1 an operational system is envisioned in 15 years, one precursor system in 10 years and one early demonstration in 5 years. Currently DLR is working in an early demonstration of DWDM transmission through the atmosphere, to demonstrate the feasibility of such techniques in GEO-like turbulent conditions [26].

The system level study may continue the current work and come up with a selected transmission format and answer the management of Tbit-throughput onboard the satellite. A trade-off study between the HTS and VHTS based on optical feeder-links should be performed to ensure the economic viability of the selected system design.

In the satellite system the main identified challenges are the chain from optical-to-RF conversion to the user data retransmission and the space qualification of the system components, like DWDM technology. These satellite units should be developed in the next 10 years to enable a precursor system. The early stage demonstration can target to demonstrate the performance of most critical elements, before the system is completely developed. In the ground segment, the gateway-switching together with the gateway development should allow the functionality of a single gateway in the precursor system. After a successful precursor system, the operational system can be deployed, completing the gateway network and launching an operational satellite terminal.

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