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Optical GEO Feeder Link Design

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Abstract: Telecommunication satellites must follow the advances of terrestrial network capacities and increase their total throughputs in order to remain competitive. This paper shows how the terrestrial fibre technology at 1550-nm wavelength can be extended to support an optical feeder link between ground and a GEO satellite. With 100 Gb/s in a single direction, an optical uplink would outperform the near-term Ka-band systems. Mitigation techniques against clouds and turbulence are described. The impact of satellite transparency on the optical transmission system is discussed. To increase the profitability of the optical solution, cost and link availability associated with various ground station networks should be carefully assessed.

Keywords: GEO feeder link, free-space optical communications, satellite communications.

1. Introduction

Telecommunication satellites, typically in geosynchronous orbits (GEO), must follow the advances of terrestrial network capacities in order to remain competitive. To meet the future bandwidth requirements of the triple-play service (high-speed internet, television and telephone), satellite providers must deploy new telecommunication technologies. Currently, the largest data rates that can be reliably applied to a feeder link between the ground and a GEO satellite are provided over the Ka-band with a total throughput of about 70 Gb/s [1]. This paper considers optical communications as a technology candidate for future high-capacity feeder links and, in that sense, is primarily intended for telecommunication engineers and satellite operators. Shifting the data carriers from radio to optical frequencies has several advantages. Optical systems have more available spectral bandwidth, have no frequency regulation constraints (due to the high antenna directivities), are smaller and consume less power.

Figure 1 depicts the bent-pipe scenario where the bidirectional feeder link between the satellite and the gateway(s) consists of optical beams. The user links which feature lower data rates and economical user ground terminals are kept in the radio-frequency (RF) domain. For the optical feeder link, we target a performance of 100 Gb/s or more for a single gateway in a single direction. The main idea is to adapt and extend the standard fibre technologies to space communications. Data are multiplexed over several wavelengths around 1550 nm. The modulation of each optical carrier could be the well established differential phase shift keying (DPSK). DPSK does not require a coherent detection and offers a sensitivity benefit of 2.6 dB compared to On-Off Keying [2].

The paper goes through various design aspects of the optical feeder link and is organized as follows. Section 2 and Section 3 present the high-capacity techniques and the high-reliability techniques that suit the scenario. Section 4 discusses the case of a transparent satellite. Aspects of cost reductions are considered in Section 5. We conclude with Section 6.

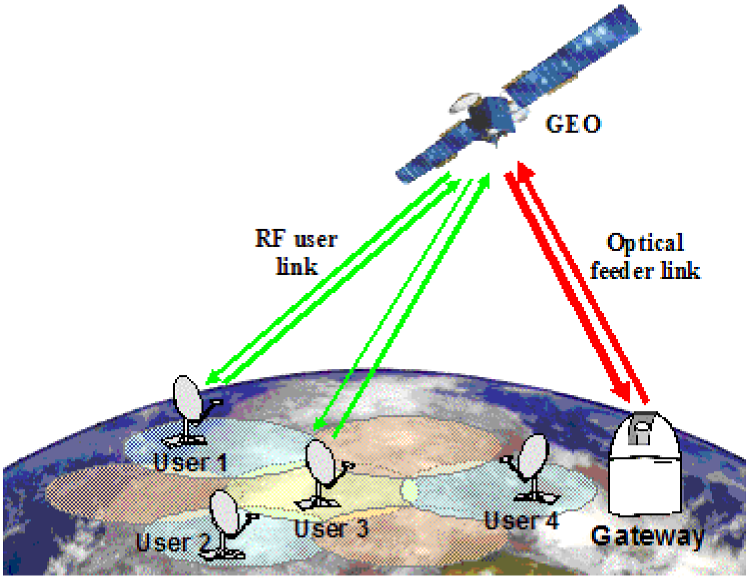

Figure 1Bent-pipe scenario with an optical feeder link.

2. High-Capacity Techniques

2.1. Wavelength selection

Figure 2-1 shows the clear-sky transmission window around the 1550-nm wavelength (193 THz). There exists a similar window around 1064 nm (282 THz). Both windows are more than 10 THz wide. For these two windows, high-data-rate (> 1 Gb/s) technologies have been developed for space communications [3][4]. Space qualification of components for 1064 nm is more advanced than for 1550 nm, on the other hand many 1550-nm components are available off the shelf as a result of terrestrial-fibre developments. Key technologies at 1550 nm like wavelength division multiplexing (WDM) suggest a higher potential for data rate growth.

In a free-space environment, 1550 nm has further advantages compared to 1064 nm: about 4 times less background light, less turbulence perturbation (with a Fried parameter 1.4 times larger) and a better eye safety (1550-nm lasers reach the eye-safety limit with 20 times more power than 1064-nm lasers [5]).

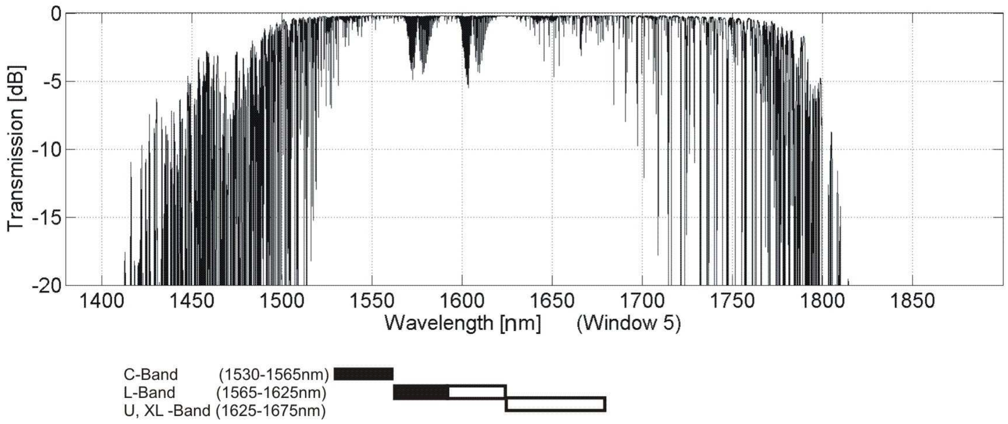

Figure 2-1: Atmospheric (clear-sky) transmission window around 1550 nm and fibre amplifier bands. The wavelength range for COTS availability of high power EDFAs is shown by the black filling of the horizontal bars.

2.2. High-power transmission techniques

It has been demonstrated that 1 Tb/s could be transmitted through the atmosphere, however over a distance of a few hundreds of meters [6]. To close the power budget of a 40'000-km link, telescope sizes cannot be arbitrarily large for cost reasons. The use of high-power transmitters and high-sensitivity receivers is thus crucial. Optical amplifiers improve the performance of both transmitter and receiver. Erbium-Doped Fibre Amplifers (EDFA) can be used as a booster (Tx side) and as a preamplifier (Rx side). Multiplexing over several wavelengths can also help save some decibels of power. Although a data rate of 100 Gb/s or more can be delivered over a single wavelength [7], such transmissions require more energy (i.e., more photons) per bit than lower data rates (e.g., 1 or 10 Gb/s). In that sense, WDM increases the power efficiency. Additionally, WDM offers an easy channel scalability and a data rate adaptation over a constant transmit power by means of EDFA.

A general assessment of optical transmission techniques shows that high communication performance is better achieved by making the optical signal propagate as a single-mode beam up to the photodetector. Fibre transmission records are usually obtained over single-mode fibres and, for free-space communications, the laser should ideally produce a Gaussian beam (given by the fundamental transverse mode) in order to maximize the Tx-gain. It results that our design relies on the emission of Gaussian beams and, at the receiver side, on the coupling of the free-space beam into a single-mode fibre.

Assuming a target data rate of 100 Gb/s for the uplink and 40 Gb/s for the downlink, a series of trade-off analyses has led to the link parameter values listed in Table 1. The apertures of the space and ground terminals are 200-mm and 1-m large, respectively. The appended link budget in Table 1 can be considered conservative as it assumes a link elevation of 30° above the horizon and does not include coding gain. The link power margin (around 6 dB) could compensate for sporadic strong clear-sky attenuations or very thin clouds.

Examples depicted in Figure 2-2 and Figure 2-3 show possible configurations of the flight and ground optical terminals. On the GEO satellite, the mass of the terminal is estimated to 80 kg and its total power consumption to 500 W. Compared to the depicted ground station (400-mm aperture), the size of the ground station for a feeder link would have to be approximately doubled.

Table 1: Envisaged transmission parameters for an optical feeder link and associated power budget.

	Uplink	**Downlink**	**Unit**
Total link parameters			
Total data rate	100	40	Gb/s
Number of WDM channels	40	16	
Wavelength window	1550	1550	nm
WDM channel parameters			
Data rate	2.5	2.5	Gb/s
Modulation	DPSK	DPSK	
Optical Tx-Pow (Avg.)	4 x 10 (4 beams)	0.2	W
Tx-diameter	130	200	mm
Link distance	39 000	39 000	km
Rx-diameter	200	1 000	mm
Rx-sensitivity @BER=10^{-6}	100	100	Photons/bit
Channel Link budget			
Tx-Power	46.0	23.0	dBm
Tx-Optics loss	-2.0	-1.5	dB
Tx-Gain	110.4	114.3	dBi
Free-space loss	-290.0	-290.0	dBi
Rx-Gain	111.8	125.8	dBi
Atmosp. attenuation	-1.0	-1.0	dB
Rx-Optics loss	-7.5	-5.0	dB
Pointing loss	-3.2	-3.2	dB
Scintillation loss	-2.5	-1.1	dB
Beam-spread loss	-1.6	-0.0	dB
Rx-Power:	-39.5	-38.8	dBm
Target Rx-Power	-44.9	-44.9	dBm
Link Margin	5.4	6.2	dB

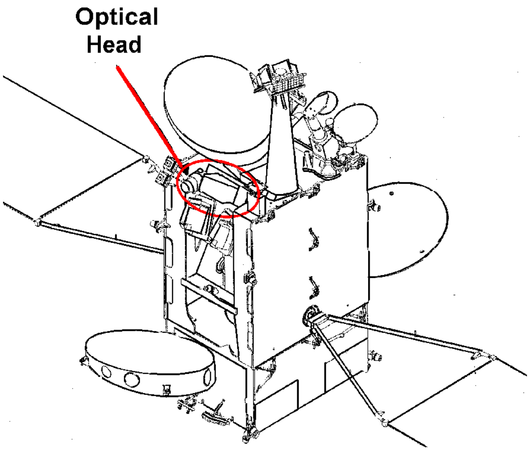

Figure 2-2: Accommodation example on a spacebus 3000 GEO satellite: The Optical Head is on the Nadir panel.

Figure 2-3:Example of optical ground station, DLR's OGS in Oberpfaffenhofen with a telescope diameter of 400 mm.

3. High-Reliability Techniques

3.1. *Ground station network*

Optical links are blocked by clouds. A network of geographically spread gateways provides spatial diversity and is the most reasonable way to increase the link availability. Figure 4 shows a network example consisting of 10 sites in South Europe. Joint cloud statistics could be calculated from observation data provided by European Cloud Climatology and acquired onboard the NOAA-Satellites [8].

The annual availability of the network, which is given by the probability that at least one station is not covered by clouds, is estimated to 99.89 %. A detailed analysis of European cloud statistics reveals that network outages (all stations are covered) occur mainly in winter so that one may think of extending the network to stations in the southern hemisphere. The cause of station unavailability may also be extreme turbulence conditions, station maintenance, presence of the Sun in the ground receiver's field of view, or safety issues (e.g. presence of aircrafts). However, cloud coverage dominates the unavailability statistics.

It is interesting to compare the ground segments of Ka-band and optical systems. The KA-SAT satellite is linked with 8 gateways (plus 2 as a backup) that perform a spatial multiplexing to augment the throughput [9]. Conversely, the network of optical gateways is fully dedicated to spatial diversity because a single gateway can handle the total satellite capacity. Gateway multiplexing is technically challenging for an optical communication payload but still conceivable [10].

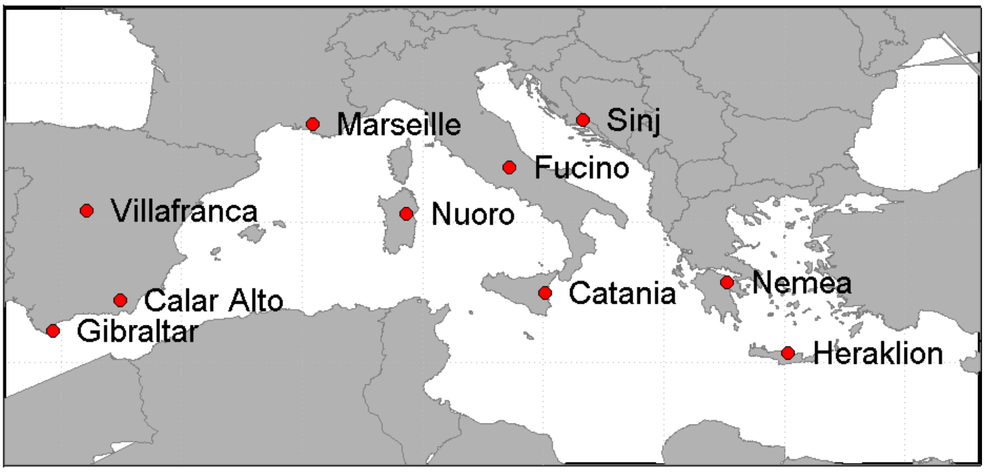

Figure 4: Network of ground stations in South Europe. The estimated annual availability is 99.89 %

An important design aspect is the achievement of seamless handovers between gateways. In order to avoid data loss during a gateway switch, simultaneous links with the two involved gateways should be maintained till the data streams are synchronized. Two bidirectional links imply two transceivers on the GEO, which can take the form of two identical terminals or a single telescope with enhanced focal-plane capabilities for multiplexing two gateways. It also implies that a gateway unavailability should be predicted early enough (e.g. 10 minutes before interruption) by means of cloud coverage monitoring.

3.2. *Turbulence mitigation*

Random atmospheric turbulence leads to wavefront distortions and scintillation. Figure 5 shows a Gaussian beam spot without and with turbulence. For the uplink, the beam diameter is of the order of 100 m and the turbulence-induced spatial dissemination of the beam energy leads to deep fades at the satellite receiver. For the downlink, the beam diameter of the focal spot is of the order of 10 µm and the turbulence-induced spatial dissemination of the beam energy, in a similar way to the uplink, leads to deep fades when this focused beam is coupled into a single-mode fibre. Techniques of turbulence mitigation can be implemented on the ground terminal for both up- and downlinks:

- On the uplink, multiple transmitters are deployed with a separation distance significantly larger than the atmospheric transversal coherence length (i.e. Fried parameter). A typical separation distance is 0.5 m. The multiple beams carry the same information but undergo different distortions through different turbulent volumes. In this multiple-input single-output (MISO) configuration, the spatially diverse beams are averaged at the receiver and the signal fade probability is reduced [11]. The deployment of several laser sources additionally increases the average Tx-power. The multiple transmitters must be mutually incoherent to prevent inter-beam interferences at the satellite receiver. This mutual incoherence requires additional optical spectrum bandwidth.
- On the downlink, adaptive optics corrects the distorted wavefront so that the received optical beam can then be focused into a single-mode fibre with a good coupling efficiency [12]. Furthermore, the large Rx-aperture provides spatial averaging of scintillation [13].

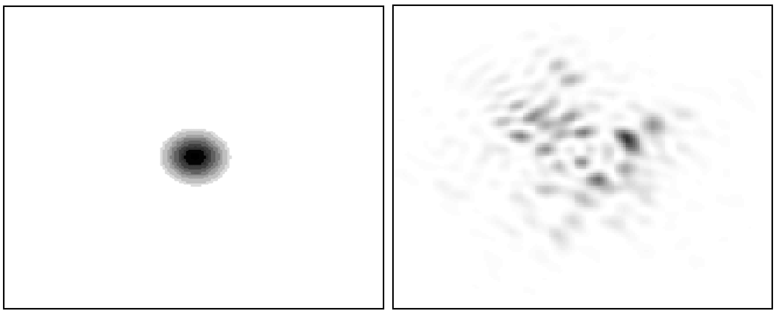

Figure 5: Received optical beam spots. Left: unperturbed Gaussian beam or beam corrected by adaptive optics. Right: beam perturbed by propagation through atmospheric turbulence. The spatial spot scale differs whether this is the uplink beam (several tens of meters large) or in the focal plane of the downlink receiver (several microns)

4. Transparent satellite

Data transmissions in high-capacity fibre networks are based on digital modulations. If such a transmission scheme (e.g. DPSK) is to be applied to an optical GEO feeder link, the satellite will have to convert this optical modulation to the RF modulations (e.g., DVB-S2 schemes) of the user link, and vice versa. Therefore, to fully profit from the technological advances of terrestrial fibre communications, the satellite should accommodate a regenerative payload. However, when satellite transparency is a requirement, the payload must accept and forward any kind of user signals. In practice the satellite is usually transparent to the modulation and the data rate of user signals within a given bandwidth. This means user data cannot be decoded onboard. The requirement of satellite transparency directly impacts the optical feeder link design as the RF user signals must be treated as analogue signals. Two main solutions can be identified:

1. Transparency is obtained by implementing an analogue optical link. Such a system is designated as a “Radio over FSO” technology [14][15][16]. Because analogue receivers cannot apply any channel decoding, atmospheric perturbations must be mitigated at the physical layer.

2. A digital optical link may still provide some transparency if the RF analogue signals are densely sampled and quantized to produce bits that are optically transmitted. Transparency is achieved through a waste of optical resources (power and bandwidth) compared to an optical analogue link. Before digitizing the RF signal, it is advisable to identify the different channels of the RF signal (FDM and I-Q components) and to digitize them separately. This allows optical multiplexing and can save significant optical power or bandwidth.

If only limited transparency is required (e.g. if the range of modulations are well-defined in advance), one may favour the digital optical solution. However, as the need for more transparency increases, there will be a threshold on the satellite complexity above which an analogue optical link will be more attractive.

5. Cost considerations

Today, compared to the Ka-band technology, one can expect the optical GEO terminal to be associated with higher costs. On the other hand, the optical version of the ground terminal, with an aperture diameter of 1 m or less, may turn out to be cheaper. Compared to links involving non-stationary satellites, the two terminals of a GEO feeder link have simplified tracking systems as the beam axis is quasi-static. In any case, a well-balanced design between space segment and ground segment is required to minimize the total system costs. A payload aperture size around 200 mm keeps the terminal compact and provides enough Tx- and Rx-antenna gain. To minimize the payload complexity the following tasks are assigned to the ground segment:

- Activation of high-power optical beacons for link acquisition
- Weather monitoring and cloud prediction
- Management of gateway handovers

However, the ground segment cannot afford an overload. Larger ground telescopes (> 1 m) at imaging-like quality for WDM fibre-coupling ground receivers are significantly more costly and also more sensitive to turbulence. Furthermore, the extra effort associated with the installation of an enhanced terminal must be repeated for each gateway of the network.

Because the ground site location is driven by weather statistics, new sites with the appropriate infrastructure and connection to the terrestrial network would have to be built. A new site can be more profitable if it accommodates several gateways that communicate with different satellites. Another costly aspect of the ground segment is the terrestrial networking of the different sites: a reliable high-capacity terrestrial connection between distant gateways is crucial for seamless handovers. To interconnect the gateways, a ring or line topology is simpler than a star topology.

Clearly, there is a direct relation between the ground segment cost and the targeted link availability. If many stations are required and if the costs for these stations are too high, an option is the implementation of an optics-RF hybrid system where lower data rates could be provided under the unavailability of the optical link.

6. Conclusion

We have shown how the terrestrial fibre technology at the wavelength 1550 nm can be extended to support an optical feeder link between ground and a GEO satellite. An optical uplink of 100 Gb/s would outperform the near-term Ka-band systems. A link upgrade from 100 Gb/s to 1 Tb/s is conceivable but faces additional technical challenges due to power and spectrum limitations of current components (in particular WDM components and optical amplifiers). Link reliability is achieved with specific mitigation techniques against clouds and turbulence. Regarding the profitability of the optical solution, careful estimations of cost and link availability associated with various ground station networks shall be performed.

Acknowledgments

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