A High-Throughput Satellite System for Serving whole Europe with Fast Internet Service, Employing Optical Feeder Links

Dr. Dirk Giggenbach, Prof. Dr. Erich Lutz, Dr. Juraj Poliak, Dr. Ramon Mata-Calvo, Christian Fuchs,
German Aerospace Center, Institute of Communications and Navigation, Oberpfaffenhofen, Germany,
dirk.giggenbach@dlr.de

Abstract

Geostationary communication satellites can effectively cover gaps in internet-connectivity of European households that cannot be reached by terrestrial technology. However, these satellite systems need a major technological advancement in terms of data throughput. Therefore we propose a bidirectional communication satellite system with user links in the Ka-band and feeder-links that provide Terabits per second transmission rates. To keep the number of gateway stations at a reasonable number, higher RF frequencies (Q/V-band) or even optical feeder links are required. This new transmission technology requires a conceptual change in ground network layout, at the same time increasing satellite throughput capabilities by around two orders of magnitude.

1 Introduction

The aim of the European Union to establish fast internet access to all European households by 2020 ("Digital Agenda") faces the challenge of regions that can hardly be reached by terrestrial technology. However, these gaps on the map can be effectively covered by communication satellites. Nevertheless, these need a major technological advancement in terms of data throughput, compared to today's systems that can only serve a limited number of users with a moderate throughput.

The solution shall be a geostationary bidirectional communication satellite system with user links in the Ka-band. Implementing a variable transmission format, such as DVB-S2 or DVB-S2x, residential users can be served with up to 50 Mbps, using either fixed antennas comparable to TV-dishes, or smaller antennas that allow a few Mbps [1] [2].

For example, a satellite using a large number of spot-beams and providing data throughput in the order of a Terabit/s can serve a million customers with 40 Mbps at a user activity of 25 mErl. The required aggregated throughput at the feeder-link (from Ground-Hub to the satellite(s)) will also reach the Terabits per second range. This requires a new transmission concept in order to keep the number of gateway stations at a reasonable number, resorting to higher RF frequencies (Q/V-band) or going to the optical domain.

The application of Free-Space Optical Communication Links (FSO) to space-ground data transmission scenarios has in recent years evolved from an experimental phase towards pre-operational testing. Several Sat-OGS (Optical Ground Station) link tests are ongoing or have recently been performed (SOTA, OPALS, LLCD, OSIRIS, ArtemEx [3]), or are planned in future (Alphasat-LCT by DLR, LLCD by NASA). Also the European Data Relay System (EDRS) is using laser links for inter-satellite (LEO to GEO) data transmission which will provide valuable experience for Sat-OGS links as well. Ongoing research projects in general investigate Very High Throughput Satellite Systems (VHTS), such as BATS (EU-FP7) [4], and a series of ESA-Projects [5] while others focus specifically on the Optical Feeder Link between OGS and GEO-Satellite, like RIVOLI (ESA), and THRUST (Terabit Throughput Satellite Technology, DLR). The latter investigates the stability of free-space DWDM-transmission with Terabit per second data rates and space-diversity techniques to stabilize the uplink signal quality under atmospheric scintillations. Furthermore, diverse optical satellite-GND link scenarios are currently being standardized in the Optical Communications Working Group (SLS-OPT) of the Consultative Committee for Space Data Systems (CCSDS).

This paper will provide an overview of implementation, performance, and quality of service for both user and feeder link in a VHTS system employing optical feeder links, see figure 1. The basic challenges and solutions for achieving a Terabit/s GEO satellite system will be addressed. In particular, on the user link side, the massive frequency reuse by the spot-beams, and on the gateway link side, the concept of the optical feeder links will be discussed [6][7][8].

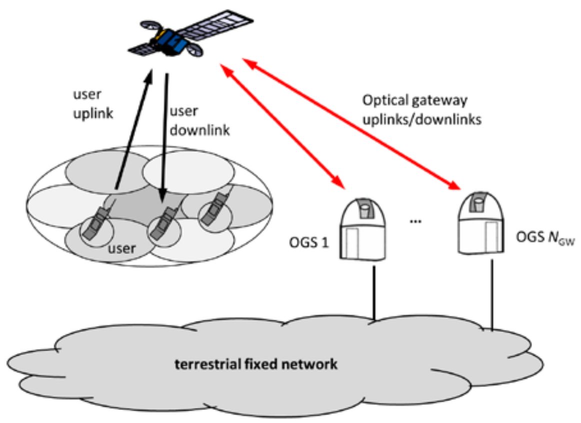

Fig.1 Very High Throughput Satellite System concept with optical feeder links

2 System Overview

On the user link side, modern high-capacity satellites use a large number of spot beams. The crucial advantage of this approach is that it allows to reuse the available frequency band many times in sufficiently separated beams. Without such a massive frequency reuse a satellite throughput approaching a Terabit/s would not be possible. Moreover, for the user downlink, the spotbeam concept concentrates the satellite transmit power for a certain user signal to a narrow spot beam, for the uplink it corresponds to a high gain of the satellite receive antenna.

On the feeder link side of the system, a considerable number of ground stations is needed to exchange the huge data traffic between the satellite and the terrestrial network. Considering RF feeder links, the ground stations are served by narrow RF spot beams, therefore, the same available RF band can be used for each feeder link. Alternatively, optical feeder links can be envisaged, providing extremely high data rates. Figure 1 shows the system concept, and figure 2 shows an example of the user link spotbeam layout over Europe, with 2 satellites and 302 beams [4].

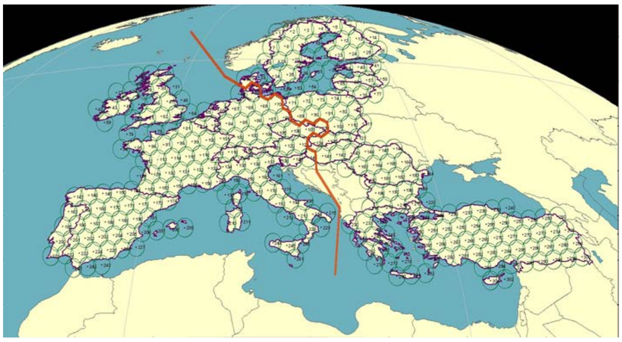

Fig.2 User-Spotbeam layout of the BATS system concept: 302 beams with 0.21° diameter each, via two GEO satellites

3 Ka-band User Links

In the spot beam concept, the coverage area is filled by narrow spot beams. The available frequency band is divided into K sub-bands which are reused in a regular pattern within the coverage area. A group of cells using the K different frequency bands is called cluster. This building block can be regularly repeated throughout the coverage area, thus achieving multiple reuse of frequencies. Figure 3 shows the user link spot beam concept [1].

Assuming fixed channel allocation with equal number of channels in all spot beams, and a cell cluster size K, the frequency reuse factor for a satellite with N_B user beams is

$$W = N_B / K \tag{1}$$

The reuse factor W tells how often a certain carrier frequency is used within the coverage area of the satellite. For a given Bandwidth B_U of the total satellite user link, the bandwidth available for a spot beam is B_U/K (equal bandwidth division assumed).

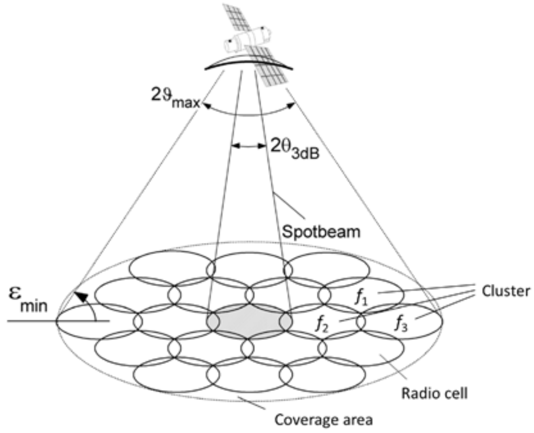

Fig. 3 Spot beam concept of the user link for a cluster size K=3

The net information throughput over a link with a given bandwidth depends on the code rate r, the order M of the modulation scheme, the roll-off factor β of the filtering, and the guard band B_G between the carriers of a generic MF-TDM multiplexing scheme. With transmission rate R_S [symb./s] the bandwidth efficiency of the transmission is

$$\eta_U = \frac{r \, \mathrm{ld} M}{1 + \beta + B_G / R_S} \quad \left[\frac{b/s}{Hz} \right] \tag{2}$$

Thus, for a given Bandwidth B_U of the total satellite user link, the capacity of a spot beam is

$$C_{beam} = \frac{B_U}{K} \cdot \eta_U \tag{3}$$

and the capacity of the total satellite user link becomes

$$C_{sat} = N_B \cdot C_{beam} = W \cdot B_U \cdot \eta_U \tag{4}$$

Eq. (4) shows that for a given bandwidth, the system capacity is proportional to the frequency reuse factor W:

$$\text{System Capacity} \sim W \sim N_B / K \tag{5}$$

The system capacity is large when using a large number of narrow spot beams (small cells) and a small cluster size K. Resolving Eq. (4) to B_U gives the bandwidth of the satellite user link that is required for achieving a user link capacity of C_{sat}:

$$B_U = \frac{C_{sat}}{W \cdot \eta_U} \tag{6}$$

Typical cluster sizes are K = 1 (each beam uses the same frequency band), 3, 4, and 7. The smaller the cluster, the higher is the frequency reuse, the spot-beam antenna sidelobes will however cause co-channel interference (CCI) between beams using the same frequency [1]. Highest frequency reuse can be achieved if the total frequency

band is reused in each spot-beam (cluster size K = 1), however resulting in very strong CCI.
The bandwidth efficiency of the multi-beam user link can be substantially increased by using quasi-orthogonal polarizations, either simultaneously within each beam, or alternatively in neighboring beams. This however causes cross-polarization interference.
For the user link, multi-frequency TDMA is typically used, thus, the bandwidth available for a beam is divided into m channels, each one containing a TDMA carrier. In this scenario, adjacent-channel interference is caused by slight overlap of neighboring signal spectra and spectral re-growth in the non-linear satellite transponder.

4 Optical Feeder Links

The RF-bandwidth allocations for feeder links are much too narrow for transporting Terabits/s. A solution is the usage of several RF-gateway stations in parallel, thus scaling down the traffic requirement of the single feeder links. For this, a multitude of feeder link antennas (e.g. multi-feed reflector antennas) must be installed at the satellite.
The bandwidth required for a single feeder link is determined by the number of parallel RF-gateways, N_{GW}, and the bandwidth efficiency η_F of the feeder link:

$$B_F = \frac{C_{sat}}{2N_{GW} \cdot \eta_F} \qquad (7)$$

Eq. (7) assumes that each feeder link has the same capacity and uses two polarizations in parallel.
The bandwidth required for a single feeder link much depends on the question if the satellite is transparent or regenerative. A regenerative satellite would have the advantage that an extremely bandwidth-efficient transmission scheme could be used. But even in this case a very large number of RF-gateway stations is required for transporting the Tb/s traffic. If, instead, optical feeder links are used, the total system throughput is transmitted from only one OGS. OGS-diversity however is required to compensate link blockage by clouds, see figure 4.

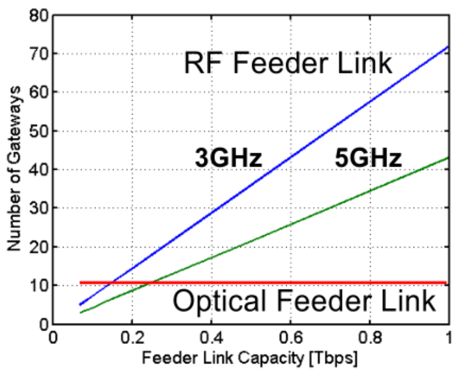

Fig. 4 Number of required ground stations for conventional RF Feeder links, and for optical feeder links at secured availability (OGS-diversity required for cloud cover mitigation). Break even between both technologies is around 300Gbps total throughput capacity.

4.1 Satellite Transceiver Options for Optical Feeder Links

If the satellite would have a regenerative payload, the optical feeder link could be terminated on board the satellite with regard to modulation and coding. A suitable modulation scheme could be chosen for the optical transmission, and a powerful error correction scheme could be applied to counteract the bit errors resulting from the turbulence fading of the optical free space link [8]. A regenerative payload for a Terabit/s throughput seems not to be feasible for the next several years, however. Moreover, the satellite payload would be confined to a certain user link signal standard and not be flexible to adapt to an upcoming standard.
Employing a transparent payload with an optical feeder link, the concept is similar to "radio over fiber". However, the behavior of the free space optical link is drastically different from a fiber. In this scenario, for the optical link the same modulation and coding scheme must be used as for the RF user link. This means that e.g. a 16-level modulation scheme must be used for the optical free space link, prone to deep turbulence fading (see figure 6). This would require a huge fade margin corresponding to a very large optical transmit power, possibly in combination with transmitter diversity and automatic gain control.
Another possibility is to transport on the optical link the samples of the high-order modulated user link signal in a convenient digital representation and modulation and applying a suitable powerful error correction scheme. Then, only fast D/A and A/D converters would be needed on board the satellite as an interface between the user and feeder links. The sampling rate of the on board converters would have to adapt to future developments of the symbol transmission rate of the user link.

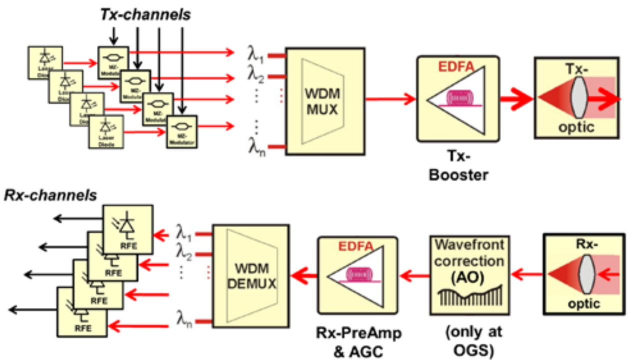

Fig. 5 Transmission scheme for an optical Tbps feeder link using DWDM technology

Wavelengths in most of the optical C- and L-Band (from 1530nm to 1610nm) are transmitted well through the cloud-free atmosphere, providing 10THz of spectrum. However several aspects of the atmospheric transmission need to be considered.

4.2 Transmission Channel

Together with the static loss due to the beam diffraction, losses by the atmospheric channel have to be taken into account.

The atmospheric transmission channel is mainly characterized through two types of disturbances: attenuation and atmospheric turbulence. Absorption and scattering are the main contributions to the atmospheric channel attenuation and are mainly significant only at low elevation angles, assuming clear-sky conditions.

Turbulence causes dynamic variations of the optical transmission performance. Mixing of warm and cool air creates air turbulence characterized by small fluctuations of the refractive index. Atmospheric turbulence is a random spatio-temporal field, assumed statistically homogeneous and isotropic, and characterized by the structure parameter C_n^2. This parameter changes with altitude, being larger at ground level where the atmosphere is denser, and decreasing at higher altitudes. The dependency of the C_n^2 with the altitude is determined by several variables like weather conditions, location, or time-of-day, but usually some standard functions can be assumed to simulate a certain scenario, like the well-known Hufnagel-Valley profile [9].

Whereas large-scale refractive index fluctuations produce a tilt of the wave, the small-scale refractive index variations produce wave-front distortions, leading to intensity fluctuations at the receiver site, due to destructive self-interferences. The turbulence impact on the communications performance depends on the scenario and it is different for an uplink than for a downlink.

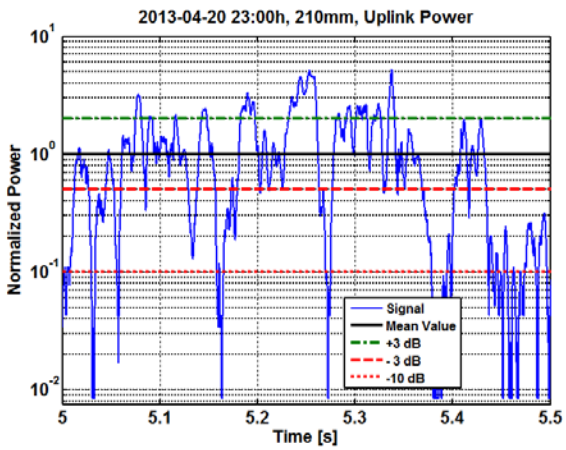

Fig. 6 Example of a measured optical received-power in the uplink channel from the ESA-Ground Station on Tenerife to the GEO Satellite Artemis [3]. Strong fading outages occur because of atmospheric beam-wander in this example with very small beam divergence.

4.2.1 Optical Uplink

The receiver on the satellite site can be considered a point-receiver from the turbulence point-of-view. This means that the receiver area is much smaller than the size of the both intensity and phase distortion speckles. Since the receiver aperture is much smaller than the phase coherence diameter, the receiver will be not affected by the phase distortions and single-mode fiber coupling will be possible. However, it will strongly suffer from intensity fluctuations, also called scintillation, because the aperture will be illuminated by only one intensity speckle, which irradiance will depend on the degree of self-interference. These intensity fluctuations are characterized by the scintillation index, defined as the normalized variance of the received intensity [9].

Another atmospheric effect that has to be taken into account is the beam-wander: the direction of propagation will be diverged by turbulence cells larger than the beam diameter and this will cause a beam wandering at the satellite site. The beam wandering will produce strong fading of the received signal.

To minimize the uplink beam wandering effect, the downlink signal is tracked and the measured angle-of-arrival fluctuations are applied to the uplink beam pointing, as a sort of pre-correction. However the beam pointing cannot completely correct the beam wander because the uplink and downlink paths through the atmosphere are not the same due to the point-ahead angle (PAA), which for a geostationary orbit is 18.5 µrad. Since both paths are not the same, the efficiency of the beam-wander correction depends on coherence between paths. This coherence is represented by the so-called isoplanatic angle and decreases with the turbulence strength; i.e. the misspointing due to residual beam-wander will be large at low elevation angles, low altitudes or high C_n^2 [10].

Fig. 6 shows the measured received power sampled at 8 kHz by the optical terminal onboard the Artemis satellite with four thresholds: the mean value, the surge level at 3 dB, the fading level at -3 dB and at -10 dB. The signal fluctuations are caused by scintillation and misspointing. This uplink transmitted beam had a divergence of 4.7µrad FWHM. The power fluctuations due to scintillation are typically lognormal distributed, for weak turbulence conditions. On top of them, the misspointing due to the beam wandering produces short deep fades of more than 20 dB below the mean received power level [3].

4.2.2 Optical Downlink

The receiver telescope at the optical ground station telescope is usually much bigger than the phase or intensity distortions. By collecting several intensity speckles, the received power fluctuations is smaller than for a point-receiver through the so-called aperture averaging [9]. However, a receiver aperture larger than the phase distortions coherence diameter will produce intensity speckles at the focus plane impairing an efficient single-mode fiber coupling [11]. In the same way the heterodyne efficiency decreases in coherent reception schemes.

To avoid single-mode fiber coupling losses or low heterodyne efficiency, adaptive optics systems are used to estimate the incoming wave-front and correct the phase distortions produced by atmospheric turbulence. Alternatively a receiver-front-end with a large-enough sensor area is used directly at the focus plane of the telescope, to avoid the use of adaptive optics systems. In this case the communication link is limited to non-coherent schemes with data-rates below 10Gbps and standard DWDM components developed for single-mode-fiber communications cannot be used.

4.3 Cloud Cover Mitigation and Availability

Optical Ground-to-Space links suffer from limited availability due to cloud blockage. This requires the use of an optical ground station network in order to achieve spatial diversity. The goal is to reach availability figures in the order of 99.99 %, equal to a link outage probability (LOP) of 10^{-4}. This is compatible or exceeds typical operator requirements when a low-rate RF backup is available to bridge rare and short outages. Switching from blocked to available OGSs has to be performed by the optical link terminals, see figure 7.

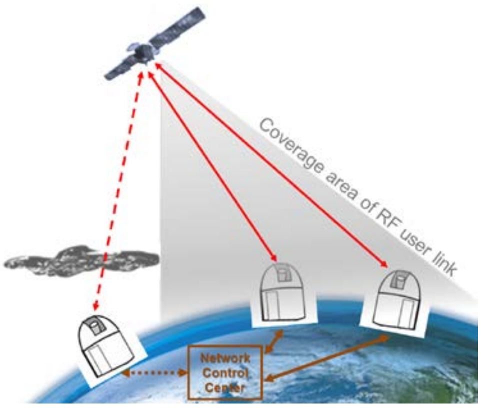

Fig. 7 Optical Feeder Link Network with redundant OGSs for cloud cover mitigation

Figure 8 shows the LOP for different single site availabilities p plotted vs. the number of stations N in an optical ground station network, neglecting the effect of weather correlation between the OGS sites. It is visible that about eight stations are required to reach a LOP of 10^{-4} with OGS-sites that offer an availability of p=0.7 each.

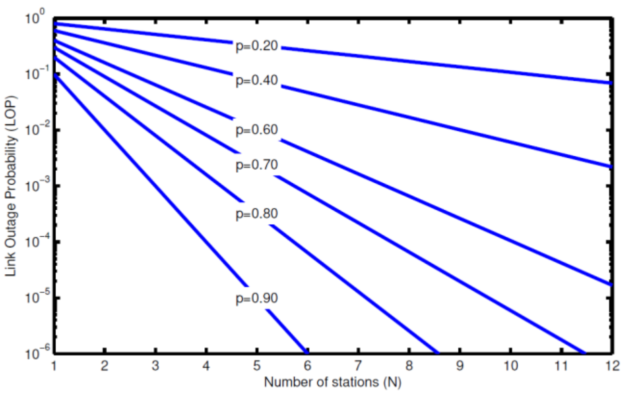

Fig. 8 Theoretical Link Outage Probability (LOP) of an OGS-network plotted vs. the Number of Stations (N) for equal single site availabilities p, not regarding availability correlation between OGSs; taken from [12]

A good OGS network will thus be composed of sites with good single-site availability, and with a low weather-correlation between those sites. For the purpose of finding a suitable network topology, real-world cloud data has to be used for estimating realistic availability figures and to optimize potential OGS networks. Figure 9 shows the results of a study based on such cloud data for different network topologies. The potential locations for OGS sites were chosen according to available infrastructure (e.g. at astronomical observation sites) and are typically close to fiber access networks. The Distance between the sites is typically larger than 300km, ensuring low weather correlation among them.

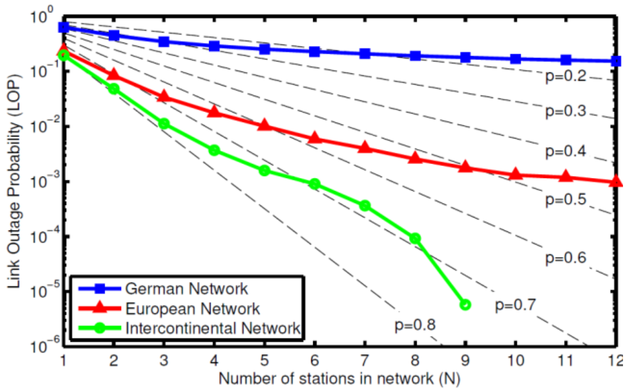

Fig. 9 Link Outage Probability (LOP) for optimized German, European, and Intercontinental OGS networks, based on analysis of 5 years cloud data; taken from [12]

It is obvious that the relatively high cloud probability in Germany (typical 60%), in combination with the high correlation between sites, limits the achievable LOP to a value in the order of 10^{-1}.

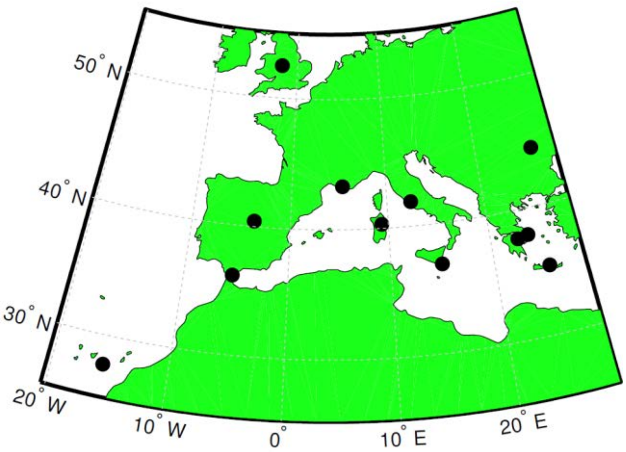

Fig. 10 Optimal ground station locations for a network in Europe: Maspalomas, Marseille, Noto, Athens, Heraklion, Madrid, Rome, Birmingham, Bucarest, Gibraltar, Nuro, Nemea; taken from [12]

The situation improves strongly by extending the network to European locations, with LOP-figures as low as 10^{-3} for larger networks. The 12 European stations (red curve in figure 9), that have been found to be optimal, are visible in figure 10. However, the achievable LOP is still dominated by the generally worse weather during winter time. Thus, a further extension of the network with intercontinental sites balances seasons and becomes again remarkably better. For the observation period of 5 years, an intercontinental network with additional stations in the southern hemisphere could be found to be completely outage free for N>9.

4.4 DWDM Transmission Format

Technically useable bandwidth of a standard single-mode fibre (SMF) is around 50 THz (1280 nm – 1625 nm). This whole useable spectrum of the standard single-mode optical fibre is divided into several frequency bands (O, E, S, C, L, U) depending on the application (e.g. GPON, CATV) and practical implementation constraints (e.g. fibre amplifier bandwidth). Each of the frequency bands is further subdivided into a set of equally or flexible spaced channels [13]. The band of the lowest attenuation, which at the same time offers erbium-doped fibre amplifier (EDFA) implementation, is the C-band centred at the frequency f_0 = 193.1 THz, see figure. 11 [14]. The individual channels are spaced according to a so-called ITU (spectral) grid. This grid can have channel separation of 200 GHz, 100 GHz or 50 GHz, but spectral grids with 25 GHz or even 12.5 GHz separation are not uncommon [15].
The choice of the spectral grid in a specific implementation depends mainly on the bandwidth of the transmitted signal, linewidth and frequency stability of the carrier laser source and bandwidth of the demodulator. Mostly the latter being the main constraint when tighter spacing is to be taken into consideration.
In satellite optical communications, each channel from the UL spectral grid may directly correspond to one DL spot beam of the Ka-band user link. With 25 GHz spectral grid that corresponds to 192 channels in C-band only. One may implement other fibre amplifiers to address L or S-band as well.
On the other hand, using tighter spectral grids one loses the possibility to freely increase the data-rate and to adopt some of the fading mitigation techniques explained later. Moreover, the channel bandwidth equals to the channel spacing only theoretically. One needs to introduce gaps at the edges of the channels in order to prevent inter-channel interference. In practice, the channel bandwidth is limited to maximum 75% of the channel spacing. All this poses severe practical constraints and limits to the system data-rate and requires a trade-off between the systems availability and through-put.

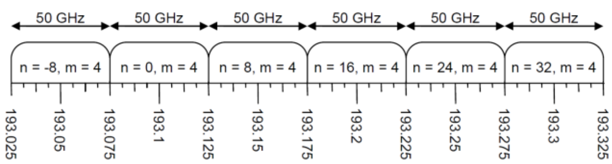

Fig. 11 DWDM spectrum, x axis is frequency in THz, *n* refers to the relative position of the centre of the channel from *f*=193.1THz, multiplied by 6.25GHz and *m* to the channel spacing in multiples of 12.5GHz [14].

4.5 Fading Mitigation – Transmitter Diversity

As was discussed in section 4.2, the limiting factor of the optical satellite signal transmission is the atmospheric turbulence, which causes strong signal fading. In order to minimize this fading, transmitter aperture diversity techniques can be implemented. The transmitter diversity technique uses transmission of the signal from *N* spatially separated transmitters into a single receiver. As figure 12 demonstrates, the implementation of the transmitter diversity technique reduces the fading by scintillation and misspointing dramatically, and gives rise to a more stable signal after reception at the GEO satellite.

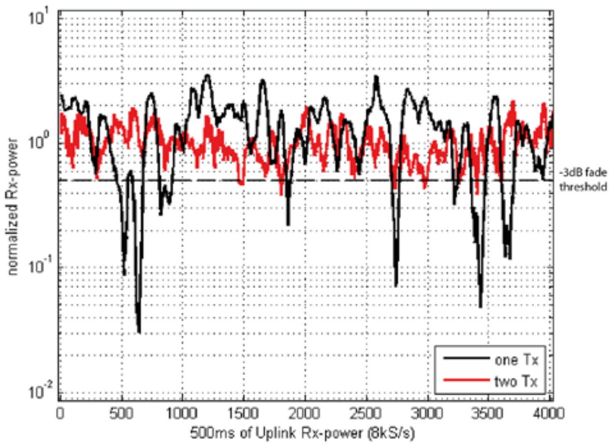

Fig. 12 Measured mean-normalized received optical power in GEO uplink for the single transmitter link (black line) and the two transmitter diversity (red line) case. Dotted line represents the -3dB fade threshold.

In order to prevent cross-interference between individual transmitters, implementation of a division technique is essential. There are various techniques, which can be used for the purpose, e.g. wavelength-division or polarization-division. While the first being spectrally inefficient due to the requirement of *N*-times the bandwidth of the original signal, the polarization division allows to use much tighter spectral grids by combining two orthogonal polarization states for the transmission of the optical signal. This results in the reception of a signal with much smaller scintillation index and lower fading probability, hence lower BER.

5 Summary and Outlook

Several projects are currently investigating the possibility to fill the gaps in private and industrial internet access in Europe by a VHTS system, achieving more than 1Tbps throughput.
On the user link side, massive frequency reuse among a large number of spotbeams is the means to achieve the very high data rate within the limited available bandwidth, e.g. in Ka band. The resulting interference between spotbeams must be taken into account by a suitable choice of the frequency reuse scheme (cluster size, dual polariza-

tions). Moreover, interference cancellation in the return link and scheduling in the forward link can mitigate the interference effects.

On the feeder link side, gateway-GEO feeder links must dramatically increase their capacity by using dozens of RF-feeder links in parallel, or rather by resorting to optical transmission. For VHTS systems, optical GEO Feeder links seem to be the ideal solution, however requiring a change in ground network topology, to allow cloud-blockage diversity instead of diversity for frequency reuse as in conventional RF feeder links. Moreover, optical feeder links are robust against jamming and spoofing.

The atmospheric index of refraction turbulence has an impact on the performance of the feeder-link in terms of signal fading, due to two main effects: scintillation and misspointing (residual beam-wander). In the downlink, the optical ground station will require an adaptive optics system to be able to couple into a single-mode fiber and use the standard DWDM fiber components.

In near future we will see several developments and practical demonstrations of high-speed optical GND-Sat communication links, targeting at implementations of Terabit/s satellite systems by around 2020.

6 Literature

[1] E. Lutz “Achieving a terabit/s GEO satellite system. 19th Ka and Broadband Communications”, Navigation and Earth Observation Conference: Florence, Italy, Oct. 14-17, 2013; 509-516

[2] E. Lutz, M. Werner, A. Jahn, "Satellite systems for personal and broadband communications", Springer, 2000. (available from: http://books.google.co.uk/)

[3] R. Mata-Calvo, P. Becker, D. Giggenbach, F. Moll, M. Schwarzer, M. Hinz, Z. Sodnik, “Transmitter diversity verification on ARTEMIS geostationary satellite“, SPIE Photonics West, Feb. 2014

[4] Broadband Access via Integrated Terrestrial and Satellite Systems (BATS), “ICT-2011.1.1 BATS D4.1: Satellite Network Mission Requirements” European Project, Tech. Rep., 2013

[5] ESA Artes projects UTMBeam, Terasat, at http://artes.esa.int/projects/

[6] D. Giggenbach, "Tutorial: Optical Free Space Links for Satellite-Ground Communications", 7th Advanced Satellite Multimedia Systems Conference, Livorno, Sept. 2014

[7] S. Dimitrov, B. Matuz, G. Liva, R. Barrios, R. Mata-Calvo, D. Giggenbach, “Digital Modulation and Coding for Satellite Optical Feeder Links”, 7th Advanced Satellite Multimedia Systems Conference (ASMS), Livorno, Italy, Sept. 2014

[8] W. Cowley, D. Giggenbach, R. Mata Calvo, “Optical Transmission Schemes for GEO Feeder Links”, IEEE ICC 2014 - Selected Areas in Communications Symposium, Sydney, June 2014

[9] L. Andrews, R. Phillips, “Laser Beam Propagation through Random Media”, SPIE Press, 2005

[10] G.C. Valley, “Isoplanatic degradation of tilt correction and short-term imaging systems”, Appl. Opt., OSA, 1980, 19, 574-577

[11] H. Wu, H. Yan, X. Li, “Modal correction for fiber-coupling efficiency in free-space optical communication systems through atmospheric turbulence”, Optik - International Journal for Light and Electron Optics, 2010, 121, 1789 – 1793

[12] C. Fuchs, F. Moll, “Ground Station Network Optimization for Space-to-Ground Optical Communication Links“, accepted for publication in: IEEE JSAC Special Issue on Optical Wireless Communications, 2015

[13] A. Klekamp, U. Gebhard, "Benefits for mixed-line-rate (MLR) and elastic networks using flexible frequency grids", 38th European Conference and Exhibition on Optical Communications (ECOC), 2012

[14] Recommendation ITU-T G.694.1 (2012), Spectral grids for WDM applications: DWDM frequency grid

[15] M-F. Huang, D. Qian, S. Zhang, T. Inoue, Y. Inada, T. Wang, "Over 4,200km WDM transmission of 80-Gb/s PDM-OFDM-16QAM signals with 12.5-GHz channel spacing employing EDFA only amplification," Optical Fiber Communication Conference and Exposition (OFC/NFOEC), 2012