Capacity Limits of Optical Satellite Communications

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Abstract *We evaluate the impact of atmospheric absorption on the WDM capacity for ground-satellite optical links. At optimum geostationary satellite longitude over Europe, we maximise the capacity by using nonuniformly distributed channels and digital equalization; we obtain 10% capacity increase against a uniform distribution.*

Introduction

The success of coherent technologies in terrestrial networks is paving the way to a new generation of high capacity satellite-ground communications based on Wavelength-Division Multiplexing (WDM). With respect to existing 10G data optical intensity-modulated links, coherent WDM free-space optical links[1] could enable a >100x capacity leap. However, new challenges arise because of the specific nature of the propagation channel, the atmosphere, as it induces propagation effects unknown in terrestrial systems. One of these effects is gas absorption, which occurs in the lower layers of the atmosphere (troposphere, typical altitude <10 km) and may attenuate the signal power of a ground-satellite optical link by several dBs at specific wavelengths and thus limit the achievable capacity in some spectral regions.

In this work, we assess the impact of atmospheric gas absorption on a geostationary earth orbit (GEO)-ground optical link at an optimized longitude over Europe, in a scenario of C+L bands WDM transport. We first describe the absorption phenomena and evaluate the impact of the satellite elevation for ground stations (GS) over Europe. We then establish the capacity of the atmosphere with gas absorption and evaluate the advantage of using non-uniformly distributed WDM channels. Finally, we demonstrate the benefits of coherent digital signal processing on the mitigation of gas absorption.

Atmospheric gas absorption

The atmosphere is composed of gases and aerosols (solid particles or liquid droplets), which cause optical attenuation. Aerosol particles are of the same order of magnitude in size as the short infrared wavelengths and therefore mainly induce loss by scattering, which is wavelength independent [2]. On the other hand, gas particles are much smaller and therefore induce loss by absorption, but only at specific wavelengths and thus have a non-trivial impact on a WDM spectrum. We assume the use of erbium fibre amplification and hence we consider such systems are band-limited within the C and L bands windows, i.e. from 1530 nm and 1610 nm (182.1-195.9 THz). Our computations are done for a single polarisation unless specified but can be straightforwardly generalized to dual-polarization signals. The carbon dioxide CO_2 and water vapour H_2O are the most absorbent gases which affect C and L bands[2]. Carbon dioxide is strongly absorbent in L band, as shown in Fig.1 with modest location and seasonal variations. Conversely, water vapor H_2O mainly impacts the C band, as also shown in Fig. 1, and is highly dependent on the meteorological conditions (i.e. temperature and pressure) and geographical position (more concentrated in humid areas than in arid zones). In general, we expect L band to be significantly more impacted by gas absorption than C band.

Impact of satellite elevation on capacity

When establishing a satellite-ground optical link, the extent of the atmospheric layer during the propagation depends on the satellite's elevation with respect to the ground station. A geostationary satellite remains at a constant position with respect to the Earth and thus is located at the zenith of the Equator (latitude ~0°) and at an altitude of approximately 36000 km. Thus, the only degree of freedom on its position is its longitude, which must be optimized for a given set of ground stations by considering the meteorological conditions, as optical satellite communications can be interrupted by clouds/fog conditions and severely impacted by the air turbulence.

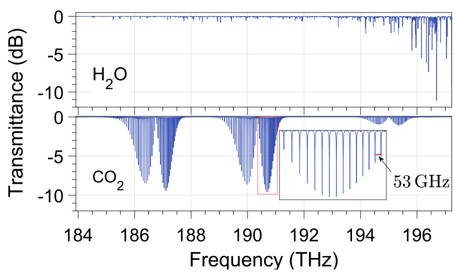

Fig. 1: H_2O and CO_2 intensity transmittance at a ground station at longitude=2.11° and latitude=47.97°.

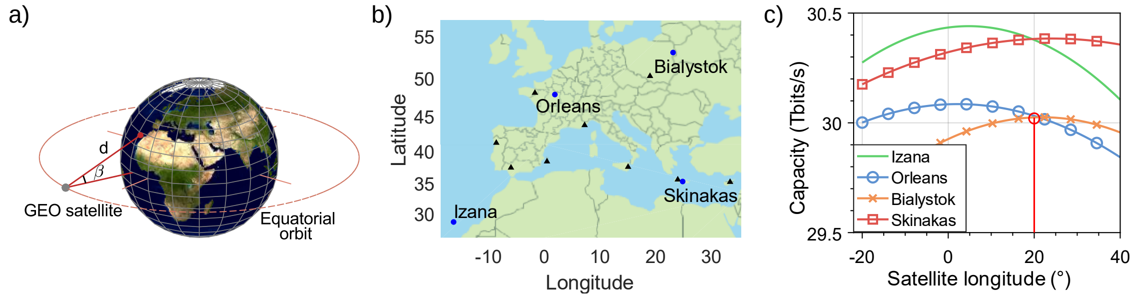

Fig. 2: a) Geostationary satellite with zenith angle β and a line-of-sight distance of d from a given ground station. b) Reference optical GS network (black triangles) and selected TAPAS locations (blue circles). c) GS network atmospheric channel capacity with molecular absorption for different ground stations.

The satellite elevation for a given GS is the complement of β (see Fig.2a) and is given by:

$$\alpha = 90 - sin^{-1}\left[\left(\frac{r}{d}\right) sin\,(\gamma)\right] \qquad (1)$$

with γ the zenith angle and, d the line-of-sight distance, evaluated using the equations:

$$cos(\gamma) = cos(\phi_{GS})\, cos\,(\theta_{sat} - \theta_{GS}) \qquad (2)$$

$$d = r\left[1 + \left(\frac{R}{r}\right)^2 - 2\left(\frac{R}{r}\right) cos\,(\gamma)\right]^{1/2} \qquad (3)$$

With R the Earth radius (average 6371 km), r the satellite distance to the Earth's centre, θ_{sat} the satellite longitude, θ_{GS} the GS longitude, ϕ_{GS} the GS latitude.

In order to guarantee 99.9% reliability for a given link despite changing weather conditions, it is necessary to diversify the locations of GS. We consider the GS topology proposed in [3] and we reproduce it in Fig. 1b. We simulate the atmospheric transmittance using the web-service TAPAS [4] for 4 representative stations at Orleans (France), Bialystok (Poland), Izana (Spain) and Skinakas (Greece).

When transmitting optical signals across the atmosphere, the molecular absorption reduces the signal power at certain wavelengths. The total capacity of a frequency bounded $[f_{min,}f_{max}]$ system can be calculated using:

$$C(f) = \int_{f_{min}}^{f_{max}} log_2\left(1 + \frac{S(f)}{N_0 B}\right) df \quad (bps) \qquad (4)$$

Where $S(f)$ is the product of the signal average power per bit and of the atmospheric transmittance, $N_0/2$ is the band-limited noise power (considered as constant over the entire bandwidth) and B its differential bandwidth.

Applying Eq. (4) to the spectrum of Fig.1 we compute the atmospheric channel capacity across C and L bands for the 4 ground stations as a function of the satellite longitude, while assuming a Signal to Noise Ratio (SNR) of 9 dB (in the absence of absorption), and report results in Fig.2c. Data can be rerouted to any other GS if a link fails; hence, the GEO system capacity is set by the link to the GS with the smallest capacity.

We can see that the worst cases are Orléans and Bialystok, for which the satellite elevation is the lowest. In order to maximize the GEO system capacity, the satellite longitude must be set to 20°, which results in elevation angles of 28° for the Bialystok GS and 32° for Orléans GS and yields a satellite capacity of 30 Tbps. In what follows, we consider absorption data from Bialystok to calculate the capacity loss with respect to the capacity limit due to absorption.

WDM channel allocation

The information will likely be sent over wavelength division multiplexed (WDM) channels occupying spectral slots distributed across the full spectral window. To make network planning simpler, we assume that all channels carry the same information rate. Molecular absorption degrades the performance of channels [5] with a performance penalty unless the power booster can deliver additional power to compensate for it. As a first design rule, we discard all slots overlapping an absorption line with depth larger than a given threshold. We investigate two scenarios: (1) the WDM channels are packed with equal spacing (uniform grid), not aligned along an arbitrary ITU reference, but optimized to the absorption lines, or (2) the WDM channels are spaced with variable spacings (nonuniform grid) while avoiding the absorption lines. To account for channel multi/demultiplexing, we define the information spectral density (ISD), as the ratio of channel occupied bandwidth with and without guard bands on each side. Fig. 3a reports the unavailable L band channels in red for both uniform (first row) and nonuniform (second row) distributions, using spectral slots of width 33 Gbaud, a threshold of 3 dB and 100% ISD (i.e. no gap between channels). Over the total C+L bands, we manage to accommodate 212 nonuniformly spaced slots, which gives a capacity loss of 27% with respect to the atmosphere capacity with absorption, using 9 dB as reference SNR. Under the same conditions, nonuniform distribution gets 244 slots with 16.1% of capacity loss. The difference is of 10.9% i.e. ~3.28 Tbit/s.

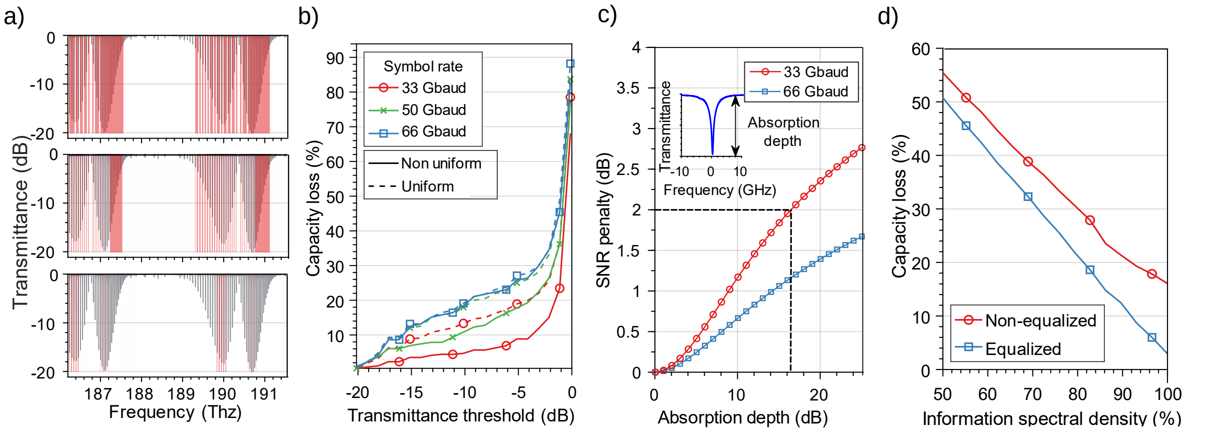

Fig. 3: a) Unavailable spectral windows (in red) for uniform (first row), nonuniform (second row) and nonuniform after equalizer (third row) slot distribution. b) Impact of the threshold on the capacity. c) SNR penalty as a function of absorption depth when the absorption is at the center of the spectrum d) Capacity loss as a function of ISD for equalized and non-equalized signals.

In Fig.3b, we plot the capacity loss as a function of the threshold for 3 slot sizes, at 100% ISD and for uniformly and non-uniformly spaced channels. When varying baud rate from 33 to 66 Gbaud, the capacity loss is found to vary significantly. This can be explained by the periodic distribution of the absorption lines (see Fig.1) as a result of the rotational energy levels distribution in the CO_2 molecule. In the present case, the period is ~53 GHz. Careful allocation of channels between absorption lines is therefore precluded at 66 Gbaud but eased at 33 GBaud.

We now study the system capacity as a function of the power threshold (Fig.3b). When the acceptable absorption depth grows from 0 dB to 5 dB, the capacity loss drops (from 90% to 20%) but nearly saturates beyond 5 dB. If we set a threshold equal to the deepest absorption peak (~20 dB), the capacity of the WDM multiplex would match the total achievable capacity, but increasing the launched power, which is of several Watts, by about 20 dB is very expensive or often impossible. Next, we show how coherent systems can circumvent this issue.

Digital signal processing in coherent systems

We simulate a dual-polarisation QPSK modulated signal with a spectral roll-off factor of 0.2. Without absorption, the signal to noise ratio (SNR) is set to 9 dB. We consider a variable absorption depth from 0 to 25 dB with the typical absorption spectrum in the inset of Fig.3c which has a full-width at half maximum of ~2 GHz. We consider that the signal overlaps with the absorption line in its centre (worst-case). In Fig.3c, we show the SNR penalty as a function of the absorption depth for two symbol rates 33 Gbaud and 66 Gbaud. We observe higher penalty for lower symbol rates as the relative absorbed energy is higher for lower symbol rates. To compensate for a penalty of x dB and nullify the impact of the corresponding impairment, the booster should deliver x dB more power.

This is only possible if the booster has enough power margins. However, with digital equalization, the required margins are found much lower. For example, an absorption line with 16 dB depth causes a penalty of no more than 2 dB and 1.2 dB, at 33 Gbaud and 66 Gbaud resp. Whereas with intensity-modulation like today's 10G, a safe system design would require following Fig. 3b approach, forbidding channels overlapping with absorption lines of depth in excess of a few dBs, coherent system with equalization could easily survive many such lines. In the Fig. 3a bottom, we showcase this advantage by reporting the unavailable channels with more than 2dB penalty after equalization

In Fig.3d, we compare the capacity limits over C and L band with/without the digital equalizer of Fig.3c at 33Gbaud, both with optimized nonuniform channels. Without equalization, a max 2dB absorption depth threshold is assumed. Fig.3d is not provided with the ambition to derive capacity limits with the ultimate form of equalization but to give a first assessment with today's digital processing. In contrast to the other figures where 100% ISD is assumed, we parametrize here the capacity limits with a variable ISD, accounting for a spectral gap between neighbouring channels for safe multi-/demultiplexing of WDM channels. The reference capacity here is the ultimate capacity with absorption (eq 4). At an idealized 100% ISD, we can notice that equalization recovers most of the reference capacity (only 2.9% loss). Overall, digital equalization provides a capacity gain of 13% with respect to non-equalized reception

Conclusion

We evaluated the total capacity for any ground to satellite link and, also studied the impact of molecular absorption. We demonstrated a gain of more 10% by using non-uniform channel spacing in a WDM system. Finally, we showed that digital coherent technologies can bring further capacity gain against absorption owing to equalization.

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