Optical Backhaul Links between HAPs and Satellites in the Multi-Gigabit Regime

Franz Fidler
Institute of Communications and Radio-Frequency Engineering,
Vienna University of Technology, Gusshausstrasse 25/389, 1040 Vienna
Email: ffidler@nt.tuwien.ac.at

***Abstract*—In free-space optical communication links through the atmosphere, turbulence induced effects limit system performance. We analyze link scenarios between satellites and high-altitude platforms (HAPs), where the atmospheric impact on a laser beam is less severe than directly above ground. The feasibility of optical communication links through the atmosphere between HAPs and geostationary (GEO) satellites for data rates up to 10.7 Gbit/s when using forward-error correction (FEC) is shown.**

I. Introduction

Free space laser communications - with its ability to transmit information via a collimated laser beam at high data rates using compact terminals, while avoiding interference problems and without exhausting the radio-frequency bandwidths - is a promising candidate to satisfy the ever increasing bandwidth demand associated with new communication services. While optical intersatellite links are already operable [1], laser communication from ground suffers from cloud coverage, harsh weather conditions, and atmospheric turbulence [2]. To find a remedy, current research concentrates on optical communications from or to high-altitude platforms (HAPs) - aircrafts which are situated well above the clouds at typical heights of 17 to 22 km - where the atmospheric impact on a laser beam is less severe than directly above ground [3], [4], [5], [6]. An optical link between satellite and HAP (cf. Fig. 1) could serve as a broadband backhaul communication channel if data from several sensors or radio-frequency (RF) communication terminals onboard the HAP is to be transmitted to a satellite, or if the HAP works as a data relay station, receiving information from a satellite.

While existing satellite laser communication terminals use AlGaAs semiconductor lasers with wavelengths around 830 nm [1], recent research activities focus on communication wavelengths around $\lambda = 1550$ nm. At this wavelength, highly sensitive receivers incorporating Erbium-doped fiber amplifiers (EDFAs) for optical preamplification are available.

Within the European CAPANINA project trials using a stratospheric balloon, flying at an altitude of 24 km for nine hours, were carried out [5]. The DLR (Deutsches Zentrum für Luft- und Raumfahrt) performed a 622 Mbit/s optical downlink with a bit error probability (BEP) better than 10^{-9} from the stratosphere to an optical receiver on the ground over a total link distance of 64 km. Also a 1.25 Gbit/s downlink was established within the CAPANINA trial, but no bit error measurement was performed. No experiments, but propagation simulations for the case of a horizontal laser link between two stratospheric HAPs were also already performed [7], [8]. These simulations together with communication link budget calculations show that high-data-rate laser communications between HAPs at an altitude of 20 km is feasible for link distances up to 600 km.

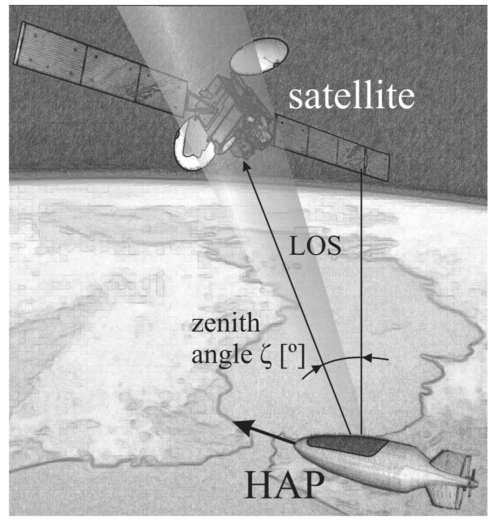

Fig. 1. Schematic of HAP-to-satellite optical communication scenario (HAP ... high-altitude platform, LOS ... line of sight).

But not only HAPs, also conventional airplanes flying at altitudes up to 10 km are considered as platforms to accommodate laser communication terminals. As part of the LOLA (*Liaison Optique Laser Aroporte*) project, the European Space Agency (ESA) established six links between an optical terminal mounted on a Dassault Mystre 20 business jet and the ARTEMIS satellite [9]. The goal of this trial was to verify the pointing ability of the terminal mounted in the jet. Also some communication data (audio and video) was transmitted.

Here we address some key concepts and technological requirements of optical links operating in the multi-Gbit/s-regime (i.e. at data rates up to 10 Gbit/s) between HAPs and satellites. All parameters affecting the optical communication system's performance are investigated by self-developed simulation programs (cf. Fig. 2). Based on analytical models and measurements given in literature (e.g. [2][10]), mathematical channel models tailored to the envisaged path between a HAP and a satellite were developed. Other than traditional

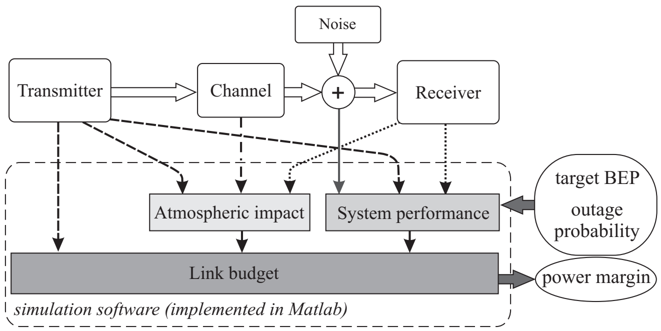

Fig. 2. Overview of software bundle developed for optical communication from/to HAPs

models for ground-to-satellite links our calculations account for the reduced amount of atmosphere at high altitudes, they include the effect of pointing errors and of beam wander in the case of strong atmospheric turbulence, and they can also be used for high HAP moving speeds. Our software allows to take into account a number of different optical modulation formats, direct-detection (DD) receiver concepts, and noise sources in order to calculate the link budget, i.e. the available power margin given a certain target BEP and system outage probability.

A. Communication system

The transmitter onboard the HAP or the satellite has the task to imprint data onto the optical carrier. The block diagram of a basic intensity modulation (IM) transmitter setup is shown in Fig. 3(a): A directly modulated laser module serves as a source with on-off-keying capability. In order to establish a sufficiently high extinction ratio or to generate return-to-zero (RZ) modulated signals, an additional external Mach-Zehnder modulator (MZM) or an electroabsorption modulator (EAM) can be used. In our scenario, the wavelength of the laser is set to $\lambda = 1550\,\text{nm}$ (193.4 THz), but in general any wavelength within the C-band (from $\lambda = 1530\,\text{nm}$ to $\lambda = 1565\,\text{nm}$) is applicable, which is the wavelength range where EDFAs are available [11]. Before the modulated data signal is fed to a transmit telescope assembly it is amplified by a booster EDFA to achieve an optical output power of up to $10\,\text{W}$.

The impossibility of in-line amplification asks for highly sensitive receivers, such as optically preamplified receivers using an EDFA. Direct detection receivers employ a photodiode as a square-law device, resulting in an electrical signal proportional to the power of the incident signal. Because of the quantum nature of light, shot noise due to the signal, amplified spontaneous emission (ASE) noise due to the EDFA, noise due to background light, and booster ASE is generated. The nonlinear relationship between the optical field and the photocurrent leads to additional beat noise terms. Thermal noise is added by the detector electronics. For our calculations all noise terms are treated as statistically independent with white Gaussian probability density functions before photodetection.

Figure 4(a) shows the calculated receiver sensitivity penalty

$$\gamma_q = 10 \log \left(\frac{n_s}{n_q} \right) \tag{1}$$

of the sensitivity n_s calculated in photons per bit (ppb) relative to the quantum limit [12] of $n_q = 41\,\text{ppb}$ at a $BEP = 10^{-9}$ for RZ intensity modulation. Both, the optical filter bandwidth and the electrical filter bandwidth have to be optimized, to find the absolute minimum in sensitivity penalty. The optical filter (with bandwidth B_o given in multiples of the data rate R) rejects ASE, background noise, and booster ASE noise, thus reducing the shot noise and the signal-independent beat noise contributions from these noise sources. However, if chosen too narrow the optical filter rejects significant portions of the input pulse energy which worsens the receiver performance [13]. Also, when optimizing the electrical filter bandwidth B_e, we have to perform a trade-off between noise and signal amplitude reduction. At the optimum bandwidths and when using an EDFA with gain $G = 39\,\text{dB}$ and noise figure $F = 3.8\,\text{dB}$ and a pin-photodiode module with sensitivity $S = 0.8\,\text{A/W}$ the receiver sensitivity is found to be only $1.6\,\text{dB}$ above the quantum limit .

Figure 4(b) presents the sensitivity penalty as a function of the background noise power spectral density. In the case of blue sky (i.e. the satellite-to-HAP downlink) or Earth as background source (i.e. the HAP-to-satellite uplink), no significant degradation of receiver performance is found when compared to the case where there is no background light at all. Even when directly looking into the Sun, only a deterioration of $1.4\,\text{dB}$ compared to the optimum case has to be expected. It is known that DD receivers suffer from background radiation but like in heterodyning, single-mode coupled receivers are less vulnerable to background light than e.g. APD-based receivers because only one spatial mode is detected. The fiber provides an excellent spatial filter function [4].

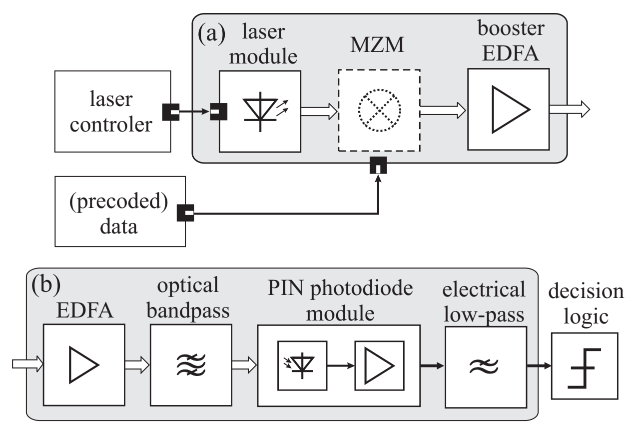

Fig. 3. Block diagram of (a) transmitter and (b) optically preamplified DD receiver.

B. Atmospheric influence on optical beam

The Earth's atmosphere extends approximately $700\,\text{km}$ above the surface and consists of several distinct layers [2]. Pronounced density is found within the lowest $20\,\text{km}$, still influencing satellite-to-HAP links. When a laser beam propagates through a turbulent medium like the atmosphere, one observes absorption, scattering, additional beam spreading and beam wander, scintillation, and phasefront distortions. These phenomena result in loss of power and (the latter three) in

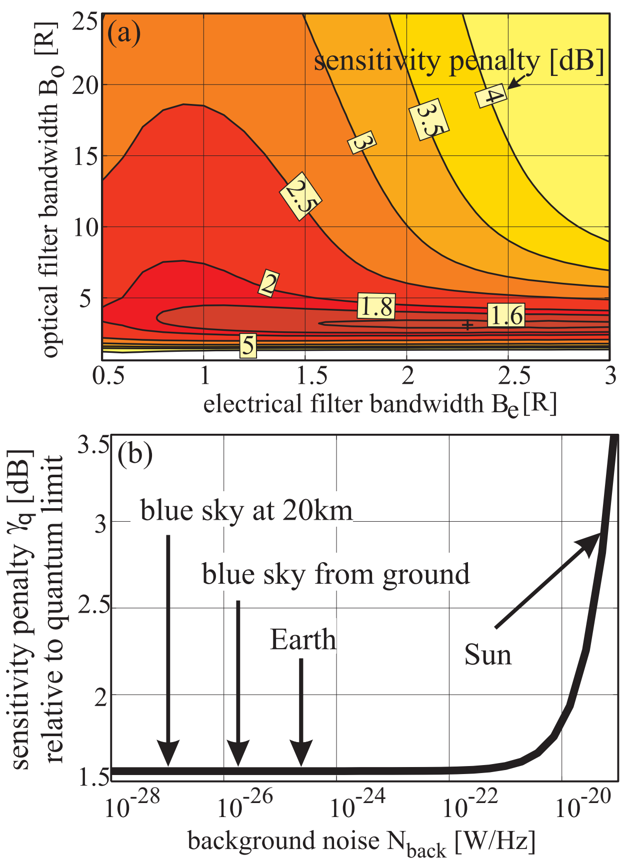

Fig. 4. Receiver sensitivity penalty γ_q of an optically preamplified receiver at a $BEP = 10^{-9}$ as a function of (a) optical filter bandwidth B_o and electrical filter bandwidth B_e given in multiples of the data rate R, and (b) background noise power spectral density N_{back}

intensity fluctuations at the receiver (i.e. fading) and - in the worst case - may lead to a link failure.

While some measured data and mathematical models are available in literature [2], [10] for ground-to-satellite links, such information is scarce or even non-existent for optical links from or to HAPs. The following sections discuss each degrading effect and present methods for the quantitative estimation of losses and power fluctuations.

1) Absorption and scattering: When transmitting an optical signal from the ground on a vertical path through the atmosphere, some 1 to 2 dB of atmospheric loss have to be expected for clear skies, at zenith, and at a wavelength of $\lambda = 1550$ nm due to *absorption* and *scattering* [10]. At 20 km height this value reduces to 0.2 dB [8]. The variation of the atmospheric attenuation with zenith angle ζ, which is the angle between zenith and the LOS between transmit and receive telescope (cf. Fig. 1), can be approximated as [14]

$$a_{atm}(\zeta) = a_{atm}(0) \sec(\zeta), \tag{2}$$

which reduces the atmospheric loss to 0.2 to 0.8 dB for typical satellite-HAP links. Unfortunately, even light clouds would interrupt the link, causing attenuation of several tens of dB [5]. However, because the platforms are situated well above the clouds [8], free-space optical communication links are an ideal option for HAP-to-satellite transmission.

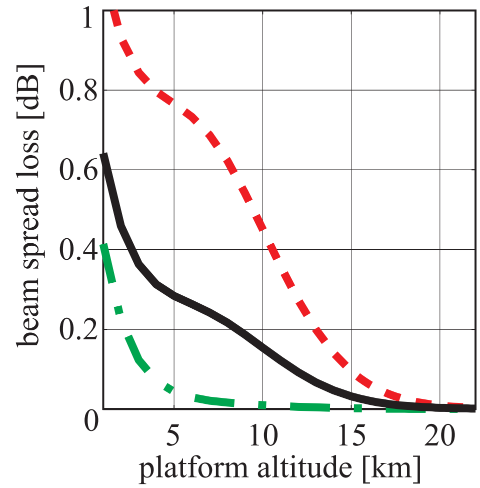

Fig. 5. Beam spread loss vs. platform altitude for a HAP-to-GEO uplink (dashed-dotted line ... $v_{wind} = 0$ m/s, $C_n^2(0) = 10^{-17}\,\text{m}^{-2/3}$, solid line ... $v_{wind} = 3$ m/s, $C_n^2(0) = 1.7 \cdot 10^{-14}\,\text{m}^{-2/3}$, dashed line ... $v_{wind} = 20$ m/s, $C_n^2(0) = 10^{-13}\,\text{m}^{-2/3}$).

2) Beam spread and beam wander: Because of random deflections during propagation through turbulent atmosphere, the beam profile moves off the LOS between transmitter and receiver. The instantaneous center of the beam, i.e. the point of maximum intensity, is randomly displaced in the receiver plane, which is commonly called *beam wander* [2]. It is caused mainly by large-scale turbulence near the transmitter and therefore can typically be neglected for downlink scenarios. Atmospheric turbulence also causes *beam spread* beyond the diffraction limited divergence θ_{DL}, leading to an effective divergence angle, θ_{eff}, which causes a degradation of the mean received optical power by a factor $(\theta_{eff}/\theta_{DL})^2$. For the calculation of this, additional, beam spread loss, the diffraction limited beam radius of a Gaussian beam truncated by the transmit telescope [15] is compared to the effective beam radius of the same beam but in the presence of turbulence [2]. For downlink paths only high-altitude turbulence - which is weak and relatively far away from the transmitting source - has an influence on beam broadening. It is found that in the downlink - where turbulent eddies are small compared to the beam diameter - the effective spot size is essentially the same as the diffractive spot size. Hence, beam spread loss is negligible. In the uplink, where the size of turbulent eddies situated just in front of the transmitter is large relative to the beam diameter, the maximum beam spread loss is also only 0.03 dB. Figure 5 illustrates the variation in beam spread loss with increasing platform altitude in the case of a HAP-to-GEO uplink and in different turbulence conditions. The structure parameter C_n^2 is a measure of turbulence strength [2], whereas v_{wind} is the wind speed on ground.

3) Scintillation: A quantitative measure for the temporal effect of atmospheric turbulence is the *scintillation index*, σ_I^2, i.e. the variance of intensity fluctuations normalized to the square of the mean intensity,

$$\sigma_I^2 = \frac{\langle I^2 \rangle}{\langle I \rangle^2} - 1, \tag{3}$$

where $\langle I \rangle$ is the temporal mean intensity of the optical wave at the receiver [2]. The scintillation index is generally used to characterize the strength of turbulence for an optical link. Our simulations showed that contrary to satellite-ground links the scintillation parameter σ_I^2 is typically smaller than 0.025 for HAP-to-satellite scenarios.

4) Phasefront distortions: When a laser beam propagates through the atmosphere its phasefront gets perturbed, which reduces the coupling efficiency into a single-mode fiber [4]. In the downlink the turbulent eddies are relatively small when compared to the beam diameter, leading to noticeable phasefront distortions within the receiving aperture. However, in a satellite-to-HAP scenario this coupling loss into a standard single-mode fiber is smaller than 1.2 dB whereas for links to a ground station a coupling loss of more than 7 dB has to be expected [4]. In the uplink the turbulent eddies are right in front of the transmitter and comparatively large relative to the optical beam, causing the phasefront disturbance to be negligible within the small receiving aperture at the satellite [2].

II. SATELLITE-TO-HAP COMMUNICATION

A. Scenario

Optical satellite-to-HAP connections allow establishing broadband backhaul links, which are required to globally receive from and distribute data to HAPs. The satellite is located at a height h_{SAT} above ground, which may range from 400 km for a low Earth orbiting satellite (LEO) to 35786 km for a geostationary satellite (GEO). The HAP altitude h_{HAP} gives the height above ground for the high-altitude platform. The telescope diameter D denotes the transmit telescope diameter in the uplink case and the receive telescope diameter in the downlink. Typical optical antenna diameters - below 30 cm - in general lead to a reduced flight terminal mass and small momentum disturbances when compared to RF communication systems. System parameter values used for the calculations in the following sections (assuming the HAP to be positioned in Central Europe) are given in Table I.

Parameter	Symbol	Default value
HAP altitude	h_{HAP}	20 km
Satellite altitude	h_{SAT}	35786 km
Telescope diameters	D_{HAP}, D_{SAT}	0.135 m
Zenith angle	ζ	50
Communication wavelength	λ	1550 nm

TABLE I
DEFAULT PARAMETERS FOR HAP-TO-GEO COMMUNICATION SCENARIO.

B. Performance

For the calculation of the receiver sensitivity the optical filter bandwidths are either optimized or, at data rates lower than 10 Gbit/s, determined by the available filter technology. Electrical filter bandwidths are always optimized with respect to maximum receiver sensitivity. Table II gives an overview of possible receiver sensitivities when using RZ intensity modulation. The quantitative indicator for the quality of the modulation is the extinction ratio which for RZ signaling we define as the ratio of the peak optical power during a logical "one" to the average optical power during a logical "zero".

Parameter	Symbol	Scenario (a)	Scenario (b)
Data rate	R	10 Gbit/s	1 Gbit/s
Extinction ratio	ζ_{ex}	15 dB	20 dB
Optical filter bandwidth	B_o	31 GHz	19 GHz
Electrical filter bandwidth	B_e	23 GHz	0.9 GHz
Receiver sensitivity		-40.5 dBm	-50.3 dBm

TABLE II
OPTICALLY PREAMPLIFIED RECEIVER SENSITIVITIES AT $BEP = 10^{-9}$ FOR 2 DIFFERENT SET-UPS IN A GEO-TO-HAP LINK: EXTERNAL MODULATION AT (A) 10 GBIT/S AND (B) 1 GBIT/S.

When calculating the link budget the impact of atmospheric turbulence, background noise originating from Earth and its atmosphere, antenna gains (assuming a Schiefspiegler, i.e. the beam is only truncated but not obscured), as well as all losses within the transmitter and receiver assembly are taken into account. The system's power margin is the difference between available signal power and the minimum signal power needed to achieve a given performance level, i.e. a certain BEP. At a data rate of $R = 1$ Gbit/s and a transmit power of 40 dBm a positive link margin as large as 9.7 dB at $BEP = 10^{-9}$ is achieved. At larger data rates (e.g. at $R = 10$ Gbit/s) additional measures, such as forward-error correction (FEC), have to be applied to allow for a positive link margin.

1) System outage probability: Due to atmospheric turbulence, surges and fades of the received optical power are to be expected with a certain probability in a satellite-to-HAP link, leading to a certain dynamic range with which the system has to cope. Slow fading (compared to the bit duration) also occurs in fiber-based wavelength division multiplexing systems, due to polarization mode dispersion [11] or due to coherent crosstalk between adjacent channels [16]. Like in the atmospheric channel, measurement and calculation techniques based on an average BEP are insufficient because the occurrence of error-bursts will most likely be averaged out [16]. System performance is therefore characterized by an *outage probability*, which is the probability that the communication link can not be closed [17], [18]. The outage probability p_{BEP} describes the probability by which the BEP is larger than a certain target value BEP_t (achieved at an optical power P_t) after the optical receive power P was multiplied by a factor a_{ch}. This factor a_{ch} can be interpreted as a "short term" power loss that has to be compensated for, so that the BEP is larger than BEP_t only with a probability p_{BEP}. Mathematically, this may be expressed as

$$p_{BEP} = P(BEP > BEP_t) \quad (4a)$$

$$p_{BEP} = P(a_{ch} P \leq P_t) \quad (4b)$$

$$p_{BEP} = P\left(\frac{P}{P_t} \leq \frac{1}{a_{ch}}\right). \quad (4c)$$

The power loss factor a_{ch} can then be calculated via the cumulative distribution function (CDF) of $\xi = P/P_t$, given as

$$p_{BEP} = F_\xi\left(\frac{1}{a_{ch}}\right) = \int_{-\infty}^{1/a_{ch}} p(I) dI, \quad (5)$$

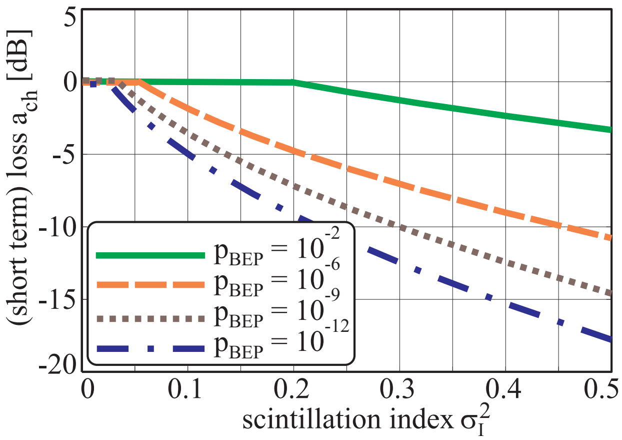

Fig. 6. Loss a_{ch} based on "short term" BEP vs. scintillation index σ_I^2 (as a function of the outage probability p_{BEP}), assumptions: $R = 10.7$ Gbit/s, external modulation, optically preamplified receiver; calculation of fade statistics using lognormal PDF.

where $p(I)$ is the probability distribution function (pdf) of the intensity fluctuations (e.g. a lognormal distribution for weak turbulence or a gamma-gamma distribution for strong turbulence, [2]).

2) Forward-error correction: In terrestrial fiber-based systems, FEC coding is one possibility to improve the quality of the communication, regardless of the physical origin of transmission degradations. For terrestrial systems the ITU has standardized a 7% coding overhead [19], leading to an effective data rate of $R = 10.7$ Gbit/s. A 16-way interleaved Reed-Solomon RS(255,239) code that can correct error bursts of up to 1024 bits is recommended by ITU-T standard G.975. At $R = 10.7$ Gbit/s the 1024 correctable bits correspond to a duration of 95.7 ns, which is still very short when compared to the milliseconds to microseconds time scale of power fluctuations caused by the atmosphere [2]. Events, during which more than 1024 consecutive bits are disturbed lead to a fading induced outage. Figure 6 illustrates the loss a_{ch} based on the "short term" BEP when using the RS(255,239) code with increasing strength of turbulence (i.e. with increasing scintillation index) for various probability values p_{BEP}. At $\sigma_I^2 = 0$ no additional power is required to close the link at 10.7 Gbit/s when using FEC. At increased turbulence the link can only be closed with a certain probability. Some 5 dB of additional optical power have to be available for example at $\sigma_I^2 = 0.1$ to close a link with an outage probability of $p_{BEP} = 10^{-12}$. If these additional 5 dB are not available, the link fails. Figure 6 illustrates that when using FEC in a HAP-from/to-satellite communication scenario with scintillation indices typically smaller than 0.025, error free optical communication (i.e. at $BEP = 10^{-9}$) is possible at the data rate of $R = 10.7$ Gbit/s with an outage probability better than 10^{-12}.

III. Conclusion

We have analyzed the effect of atmospheric turbulence on a free-space optical communication system for link scenarios including satellites and high-altitude platforms. Using single-mode coupled optically preamplified receivers allows for efficient suppression of background noise and highly sensitive detection. We could show the feasibility of an optical communication link through the atmosphere between a HAP and a geostationary satellite at the wavelength of 1550 nm for data rates up to 10.7 Gbit/s when using RZ intensity modulation in combination with FEC.

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