

In-fiber fading emulator for bidirectional optical satcom testing with asymmetric channel replay and satellite pass simulation

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ABSTRACT

Optical satellite communication links are strongly affected by channel impairments that differ by scenario. Space-to-ground and ground-to-space links experience atmospheric turbulence, which produces power fades from scintillation and beam wander. Intersatellite links are free of atmospheric effects, but remain sensitive to mechanical pointing jitter. Modeling these effects is important for the development of optical terminals, optical ground stations, detectors, and forward-error-correction schemes, yet laboratory testing is often limited to applying static attenuation or simplified fading of constant strength and bandwidth. This paper presents an under development in-fiber fading emulator for hardware-in-the-loop testing of optical communication equipment. The emulator generates synthetic optical power vectors representing space-to-ground and ground-to-space channels and applies them directly at fiber interfaces, enabling controlled testing of receivers, detector front ends, and modem/FEC implementations. The emulator supports asymmetric bidirectional operation, allowing independent forward and return channel realizations. This enables realistic testing of non-reciprocal links, such as simultaneous uplink and downlink experiments with different fading statistics, as well as terminals with unequal apertures or pointing performance. The emulator also incorporates a satellite pass simulation into the power vector generation, embedding path loss and elevation-dependent fading severity into one continuous test sequence, modeling the complete link evolution along a satellite pass.

Keywords: Optical satellite communication, fading emulator, atmospheric scintillation, power vector generation, satellite pass simulation

1. INTRODUCTION

With the growing significance of optical intersatellite links, equivalent optical space-to-ground links are subject to increased research and development effort. Multiple demonstrator projects and pilot projects are ongoing or provide already measurements and reports of successful laser-optical links. In contrast intersatellite links, a system involving optical ground stations (OGS) for interatmospheric links has to overcome additional challenges, specifically in regards to atmospheric turbulence. These atmospheric effects on the link can be primarily characterized as a fluctuation of signal power at a receiver, with signal fades and surges varying in length and depth.

Optoelectronic and optomechanical measures for counteracting the effects atmospheric turbulence on both uplink (ground-to-space) and downlink (space-to-ground) are usually employed: Wavefront sensors and deformable mirrors are an effective tool. Beyond this, the optical detector and modem hardware in both analog and digital signal processing can be adapted to these specific challenges of signal power fluctuations. To aid in the development and characterization of such hardware, in-fiber fading emulators are an essential tool. These devices allow the interconnection of two optical transceiver systems, and apply a fluctuating attenuation on the communication between them. The time-varying attenuation can be set to mimic expected fade patterns from the atmospheric link. The target fade pattern can be synthesized by simulation, or derived from actual signal power measurements of experimental optical links [1].

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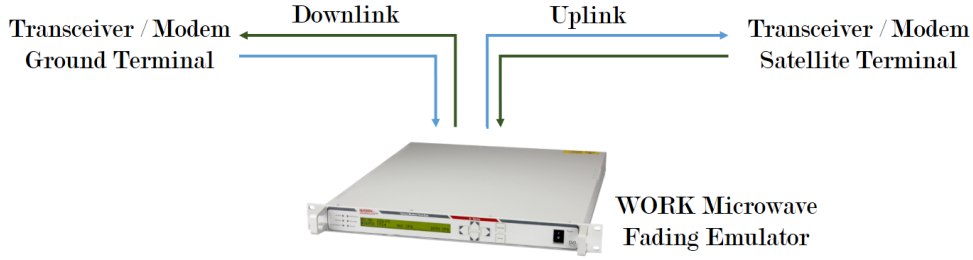


Figure 1. The fading emulator hardware fits within a 19" 1U rack housing. Single-mode optical fiber connectors (4x FC/APC) allow to interface with the uplink and downlink channels between two transceiver devices under test. An ethernet port allows monitoring and control via network connection through a graphical web-interface or SNMP commands.

Understanding of the impacts the atmospheric effects have on the optical channel is essential for a link budget analyses of a specific scenario. A common approach is to calculate the average receive power at the receiver, and separately estimate a fading buffer as additionally required margin in the link budget [2]. While the required size of this fading buffer can be estimated via several methods, it can be experimentally verified using a fading emulator. The individual behavior of specific detector and modem hardware, as well as the design of the encoding/decoding scheme (employing forward error control/correction, etc.) in combination with a specific fade pattern will generally lead to varying results for the fading buffer requirements. Hence experimental verification on the actual laser-communication hardware is valuable for any space-to-ground optical link system design.

During a satellite pass, the average receive signal power will vary with distance and elevation angle of the satellite as seen from OGS. In addition, the parameters describing the fade pattern are dynamically changing. This is specifically relevant for low earth orbit (LEO) applications. The strength of fades is usually higher when the satellite appears closer to the horizon, as the link passes through more turbulent atmosphere. In contrast, the bandwidth of the fading pattern is higher closer to zenith, when the slew rate of the satellite leads to stronger apparent crosswind through the optical link. These changing conditions can be synthesized into a power-vector with dynamically varying fluctuation strength and bandwidth, as seen in previous implementations [3]. Notably, fading power vectors are usually normalized to the average receive power. The additionally changing average receive power during a satellite pass is usually not subject to the analysis, as they are well understood.

In this work, we aim to extend the possible use-cases for a fading emulator by overlaying a dynamic fading power vector with the average receive power vector, or more precisely a non-fluctuating attenuation term, which only changes gradually during a satellite pass. We developed a power vector generator, which starts from a basic orbital motion simulation of the satellite to generate geometric data for expected satellite passes. For any selected satellite pass, the generated power vector dynamically describes the change of average receive power at the detector, as well as the fluctuating fading pattern expected from atmospheric turbulence and beam pointing jitter. Two distinct power-vectors are generated, to represent the uplink and downlink optical channels separately, as they experience vastly different fading behavior. However, both share the same time basis to allow exact alignment and simultaneous replay on suitable hardware. For replaying these power vectors on real optical in-fiber channels between optical transceivers, the fading emulator hardware is currently under development by WORK Microwave.

2. OPTICAL CHANNEL MODEL

The basis for generating the desired power vectors is a suitable mathematical model describing the underlying physical behavior of the optical beam traveling through the atmosphere. Hence, the power vector will be entirely synthetic, created from the model input parameters. Available publications describe similar approaches [4].

The first step consists of calculating satellite passes. The target results are realistic relationships between link distance, satellite elevation angles and angular slew speeds as seen from the OGS, dynamically changing as function of time. For proof-of-concept implementation, orbital motion is approximated as purely circular unperturbed orbits with a given orbital altitude and inclination, while the OGS is giving coordinates and height above sea level on a rotating earth (table 1). Final implementation will also accept input of complete orbital elements in common formats (TLE, etc.). From the described orbit and OGS position, a list of resulting satellite passes is generated, varying naturally in duration and maximum elevation (see fig. 2).

Table 1. Model assumptions describing the satellite optical terminal and ground station.

Parameter	Satellite terminal	Ground terminal	Note
RX Aperture diameter	80 mm	600 mm	
TX beam diameter	20 mm	40 mm	$1/e^2$ diameter
TX beam divergence	98.6 μ rad	49.3 μ rad	$1/e^2$ full angle
TX signal power	4.0 W	10.0 W	
TX optical Wavelength	1553.3 nm	1536.6 nm	
Mechanical pointing jitter	5 μ rad	5 μ rad	Linear RMS, 10 Hz bandwidth
Orbit	LEO, 550 km	-	Inclination 50°
Location	-	Sea level	Latitude 40°

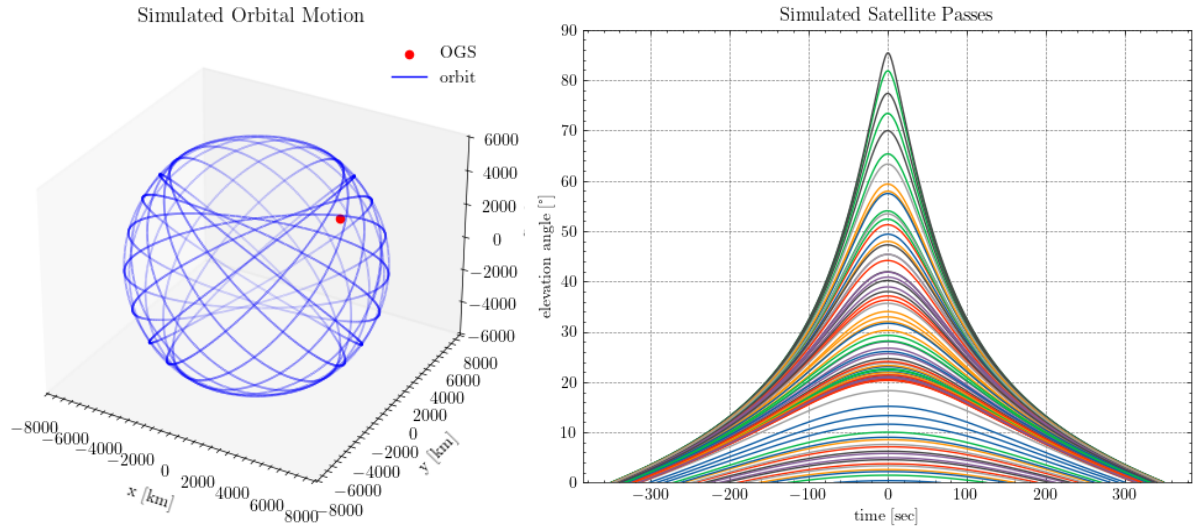


Figure 2. Left: Simulated satellite path as seen from the static reference frame of the OGS. The satellite in circular orbit with altitude of 550 km and 50° inclination passes several times over the OGS at 40° latitude within a period of 24 hours. Right: All resulting 78 satellites passes in a period of 10 days, plotted by satellite elevation as seen from the OGS, centered around maximum elevation. A majority (44 out of 78) of resulting LEO satellite passes don't rise to elevations above 30°. Hence, investigating link quality at lower elevations is of particular interest for LEO-to-ground applications.

One specific pass is selected here for illustrative purposes (see fig. 3). From the selected satellite pass, the link distance, elevation angles and slew speeds as functions of time are used as geometric inputs for the channel characterization. The selected pass covers almost the complete range of elevations. This type of overhead pass was chosen for illustrative purposes, not because it is particularly common.

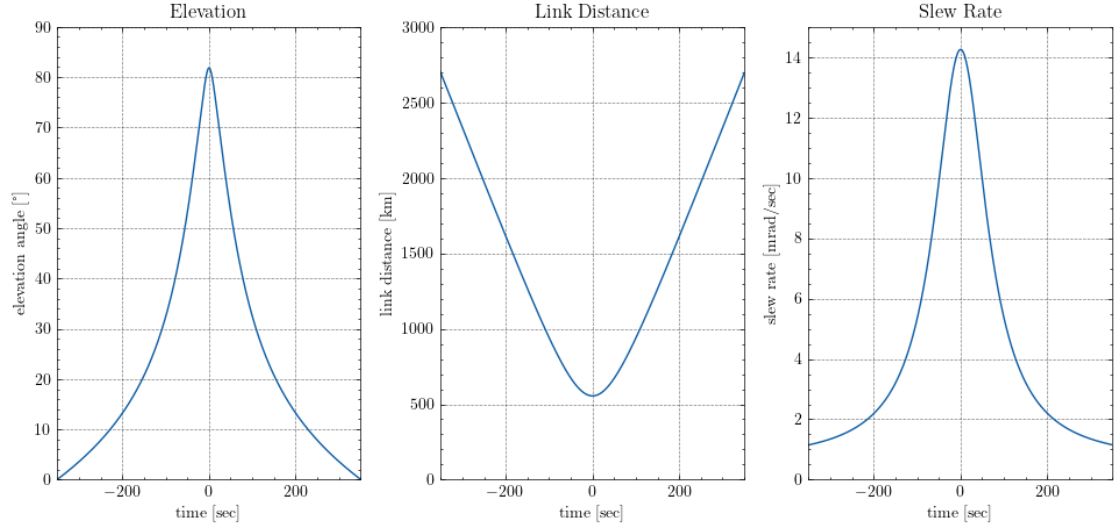


Figure 3. The particular individual satellite pass selected for this analysis from the pool of generated options. Left: The elevation angle of the satellite, meaning the apparent angle of the satellite above the horizon from the OGS perspective. Middle: The true distance between the satellite and OGS. Right: The angular slew rate of the satellite from the OGS perspective. The high slew rate at the center of the overhead pass then leads to fast apparent crosswinds through the optical path.

To evaluate the atmospheric impact on the optical channel, a set of characteristic height profiles need to be assumed (fig. 4). The variation in the turbulence structure parameter as function of height is of primary concern. Following the example of other link budget evaluations [5], the Hufnagel-Valley HV 5/11 model is used. Other atmospheric turbulence profiles can be easily swapped in, depending on the target scenario.

For modeling the optical channel any given moment in time along the satellite pass, the atmospheric characteristics need to be described as function along the link path. A straightforward mapping function allows to convert any atmospheric function of height onto the path position instead. We ensure to avoid the common secant approximation, to enable channel models for lower elevations (fig. 5). Additionally, at this evaluation step the apparent slew rate of the satellite is considered to calculate the pseudo-crosswind as function along the link path (adding also the real atmospheric crosswinds).

Once the geometry and atmospheric parameters along the path are completely defined, calculating the resulting channel fading parameters requires evaluating a series of integrals along the link path. The calculations are done as described in literature [7], following the example of other link budget calculations [5] [2]. This creates a list of resulting parameters, for the evaluated moment in time along the satellite pass (table 2). By evaluating these integrals for a series of time values along the satellite pass, a continuous change in the parameters becomes apparent (fig. 6).

The geometric losses (free space losses) are modeled by including the receiver aperture and the transmitter beam diameter as parameters (table 1). They are also crucial in the calculation for the beam wander and the aperture averaged scintillation index.

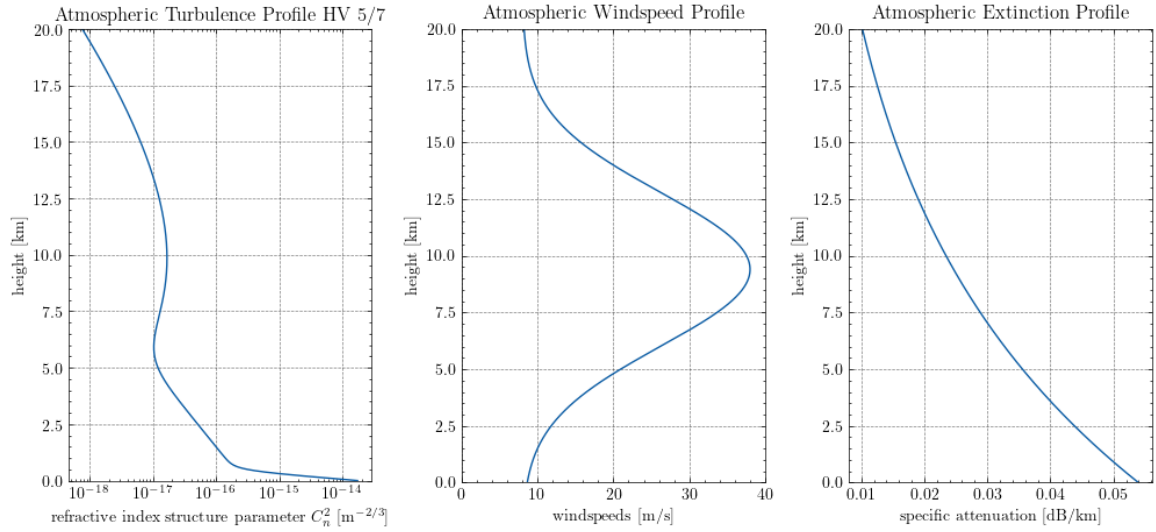


Figure 4. The atmospheric model used for this analysis. Left: The turbulence structure as function of height follows the 5/7 Hufnagel-Valley-model. Middle: The crosswind is model using the Bufton wind model with a ground speed of 8 m/s, tropopause height of 9.4 km and layer width of 4.8 km. This diagram does not include the apparent crosswind effects from the satellite slow speed. Right: The extinction by the atmosphere caused by absorption and scattering, modeled after [6], assuming an excellent ground visibility of 60 km and a signal wavelength of 1550 nm. These three models can be easily adjusted to describe different atmospheric conditions, or completely replaced by alternative models.

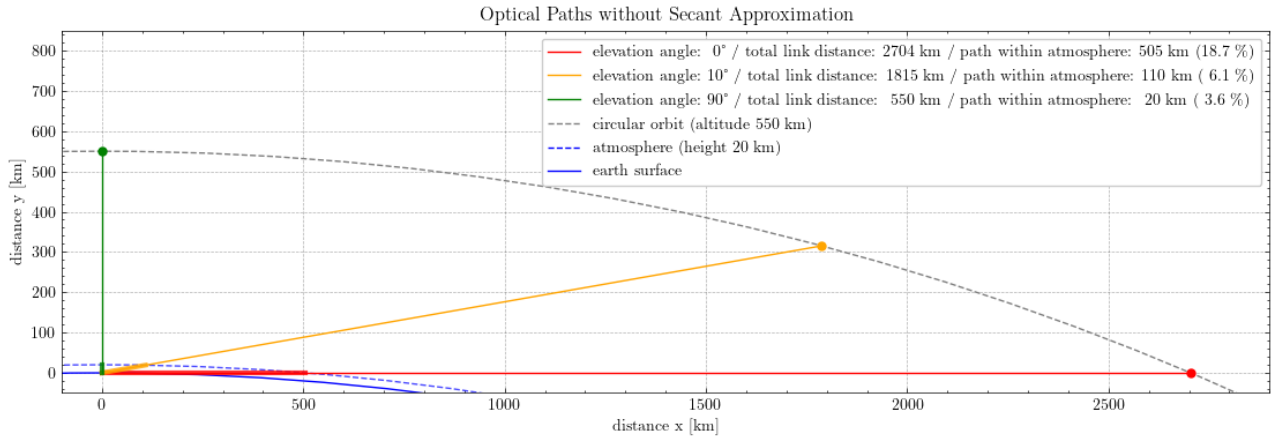


Figure 5. A common simplification used in calculating link budgets and fading strength is the assumption of a flat earth via the secant approximation. Parameters are only evaluated for the vertical path through the atmosphere, and then scaled according to the secant of the elevation angle. This approximation breaks down for lower elevations, not only overestimating the link distance, but also subsequently underestimating the portion of the path subjected to atmospheric effects. When evaluating integrals to determine characteristic parameters for these atmospheric effects (like Rytov variance or scintillation bandwidth), correct weighing of different effects dependent on the position along the path needs to be applied. The secant approximation leads to distorted geometry and improper weighing. For the implemented fading simulation, the path is correctly scaled at any elevation. The atmospheric profiles described as functions of height (fig. 4) are properly mapped to the corresponding positions along the link path. The flexible implementation allows the varying paths of multiple further scenarios to be included in this emulator: Air-to-ground, air-to-space, intersatellite, etc.

Table 2. Optical channel parameters for a single specific moment along the satellite pass. Note: Instead of single value parameters shown in this table, a continuous function is generated for each (example fig. 6). This describes the complete evolution of the optical path throughout the whole satellite pass.

Channel parameter	Value	Note
Moment in time	-100 sec	meaning 100 sec before satellite pass peak
Elevation	32.1 °	Above horizon
Link distance	947 km	
Slew rate	5.27 mrad/sec	
Fried parameter	13.1 cm	for 1550 nm
Downlink		
Free space loss	-43.8 dB	purely geometric considerations
Atmospheric extinction	-1.2 dB	Scattering and absorption
Power scintillation index	0.15	Aperture averaged
Scintillation bandwidth	89 Hz	path-weighted pseudo-crosswind: 108 m/s
Uplink		
Free space loss	-55.3 dB	purely geometric considerations
Atmospheric extinction	-1.2 dB	Scattering and absorption
Beam widening loss	-0.7 dB	Short term, Strehl ratio 0.86
Power scintillation index	1.17	in saturation
Scintillation bandwidth	25 Hz	path-weighted pseudo-crosswind: 30.3 m/s
Beam wander	7.5 μ rad	Linear RMS
Beam wander bandwidth	240 Hz	

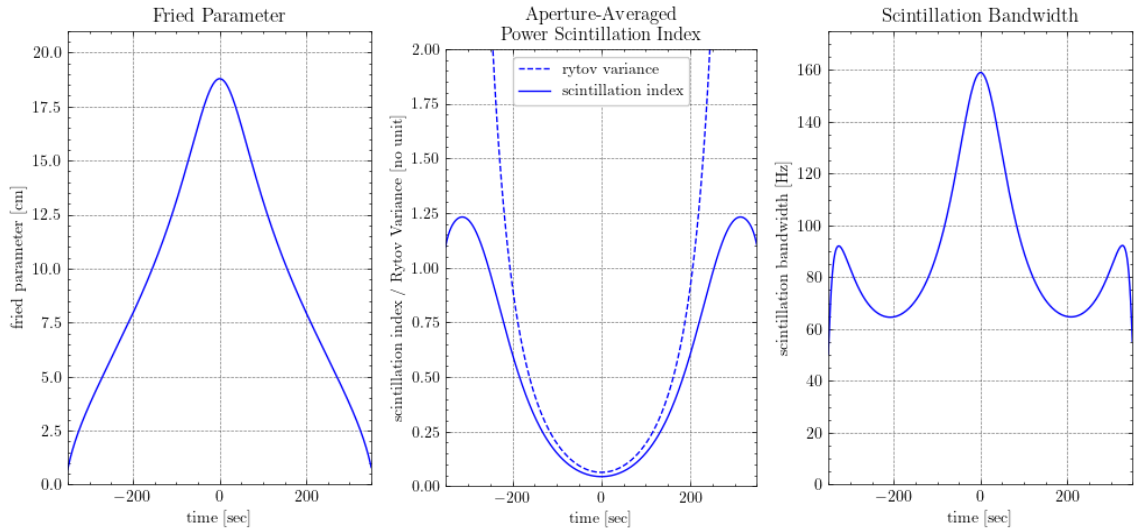


Figure 6. Atmospheric parameters for the downlink channel calculated for every moment along the satellite pass. A common indicator for the strength of turbulence along a path is the Fried parameter, which reduces to very small values at the start end and of the pass, confirming high turbulence at these points. The power scintillation index is the lognormal variance of the receive power values. Due to different impacts of large- and small-scale turbulent effects, the scintillation index saturates around a value of 1.0 to 1.2. The bandwidth of scintillations is primarily determined by the pseudo-crosswind of the optical path through the atmosphere. At the center of the pass, the angular slew speed of the satellite across the sky reaches a maximum, leading to the highest pseudo-crosswinds.

3. POWER VECTOR GENERATION

Given the channel parameters at any given point in time (example: table 2), a fluctuating power vector can be synthetically created. The power vector is a time series of power values at high sampling rate, that describe the instantaneous momentary signal power level, mapping the exact fades and surges of the signal as small timescales. The process of creating this power vector is described in detail by previous publications [4]. First, random normal-distributed variables are generated with a desired sampling frequency. These are then low-pass filtered with the target bandwidth as filter threshold. Finally, the resulting vector is re-normalized and then scaled to match the required target variance. For modeling atmospheric scintillations, this is further adapted to create a lognormal distribution for the intensity variations. For beam-wander and pointing jitter, two independent random vectors are generated for x- and y-axis miss-pointing, and then compared to the beam gauss profile to derive intensity fluctuations. These vectors can be combined for the final fading pattern (see fig. 7)

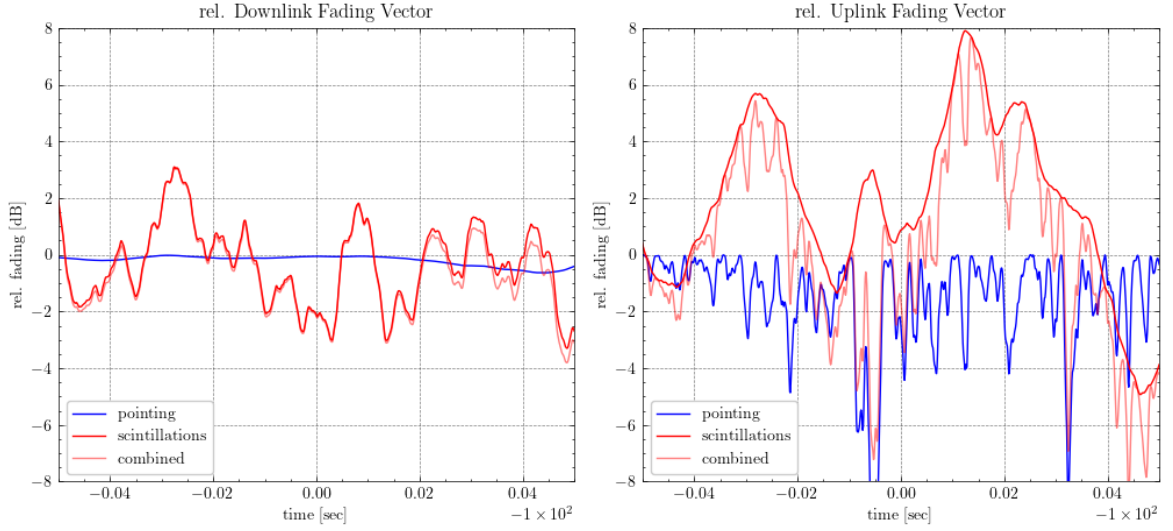


Figure 7. Short section of the fading behavior from the channel parameters around the specific moment characterized in table 2. The values are generated at a sampling rate of 10 kHz, as a continuous series for the complete satellite pass. Within the continuous series, the bandwidth and strength of the fluctuations gradually change depending on the dynamic behavior of the optical channel during the satellite pass (example fig. 6)

This approach is required to be extended, to allow a dynamic change of bandwidth and variance over the length of the vector, as implemented by other groups [3]. As the changes in bandwidth and variance are very gradual, this can be done numerically stable without introducing non-physical artifacts in the final power vector. When generating a power vector for intersatellite links, only the link path geometry and mechanical pointing jitter needs to be considered. However, a dynamically changing strength and bandwidth in pointing jitter can also be modeled, based on satellite orientation and characteristics of the optical terminal mechanics. The dynamically changing fading vector can simply be combined with the static losses at any point along the satellite pass. This results in a complete signal power vector, usable to evaluate the entire pass seamlessly, for example by comparing it to the expected receiver sensitivity (see fig. 8).

These synthetic fading vectors can be played in real-time on the fading emulator hardware: The fading emulator will adjust the optical attenuation through an optical fiber link at rapid speeds, mapping the digitally created power fluctuations as actual signal attenuations. By installing the fading emulator between a transmitter and receiver and adding a simple additional constant attenuation term for proper offsetting, the optical signal strength between both devices will fluctuate. This bridges the application from a purely theoretical calculation to actual performance measurements of communication hardware. Note the limitations of this approach: While

the emulated signal power fluctuations are the primary disruption on cross-atmospheric optical links, other impairments like Doppler shift and signal delay is not modeled. As long as these limitations are considered, the tool can be used for various optical modulation schemes: Simple direct-detection on-off-keying or more advanced coherent modulation.

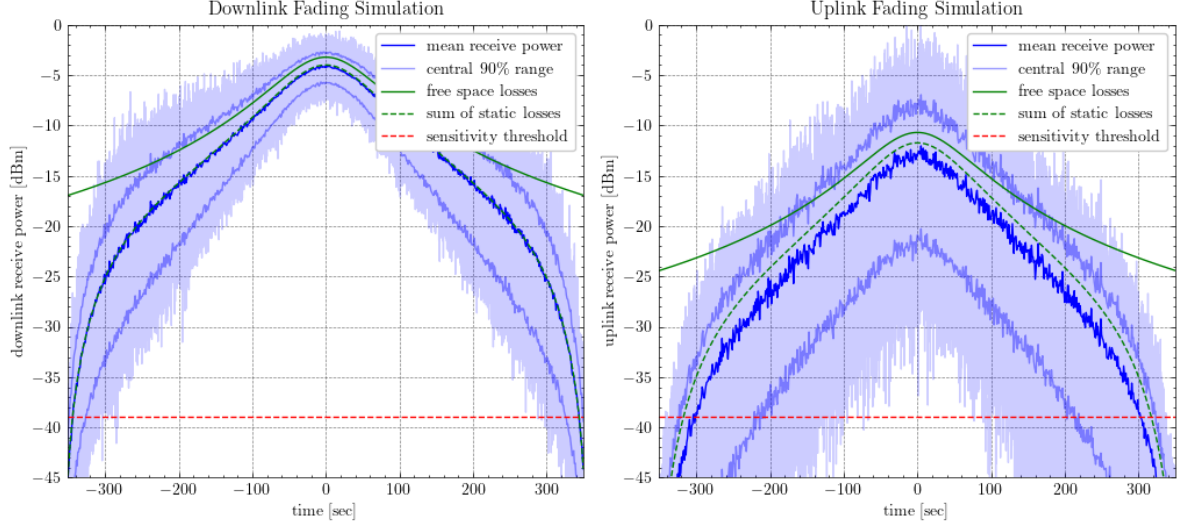


Figure 8. The uplink and downlink received power vector resulting from the previously described satellite pass in fig. 3. These vectors include the static losses from atmospheric extinction, beam widening and geometric considerations of beam divergence, link distance and receiver aperture, which vary during the satellite pass. Additionally, overlaid is the fluctuating variations from mechanical pointing jitter, atmospheric beam wander and atmospheric scintillations. These also change in severity and fluctuation bandwidth during the satellite pass (see fig. 6). For the downlink direction, the fluctuations are dominated by atmospheric scintillation while turbulence induced beam wander is not present. For the uplink direction, the dominating source of fluctuations is the uncompensated turbulence induced beam wander. Scintillations cause surges and fades according to a mathematical lognormal distribution, that occasional lead to strong surges much higher than the average signal power. Fluctuating losses from beam wander and pointing jitter can only cause fades, not contribute to surges above the average. Comparing both link directions matches the expectation, that the uplink channel is impacted significantly stronger by atmospheric turbulence than the downlink channel.

Replaying the generated power vector on suitable fading emulator hardware connecting two optical transceivers would be the ideal measurements to evaluate this approach. As the required hardware prototype is not yet available for this test, an evaluation based on a simplified detector and modem model is made. From a detector sensitivity curve that relates the receive power to a resulting Bit-Error-Rate (BER), the power vector can be converted into a BER curve for the entire satellite pass. In addition, a characteristic lock-time can be assumed, requiring the modem a specific duration to recover from a deep fade. This analysis does not take into account forward error correction (FEC) or other mechanism on the encoding/decoding layer to reduce errors. The resulting expected data transmission performance can be seen in figure 9. A measurement on commercial optical communication hardware via the physical fading emulator will be repeated as soon as possible.

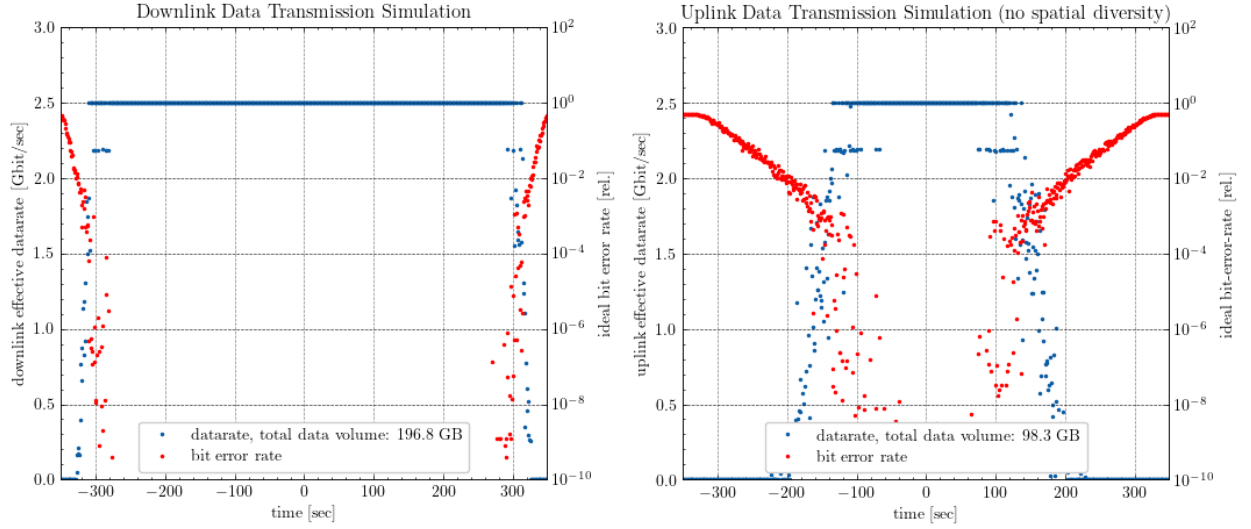


Figure 9. The generated receive power vectors (fig. 8) are used to estimate gross data throughput. The receiver is modeled via a characteristic gradual sensitivity curve, that results in a bit-error-rate (BER) of $1e-3$ at -39 dBm signal power, and BER of $1e-8$ at -35 dBm signal power. The BER in this model is assuming ideal detector and modem behavior, with no dead-time due to loss-of-signal-lock. To give a better estimate for data throughput, a loss-of-signal-lock was simulated for the receiver: if signal power drops below the sensitivity threshold, data transmission becomes impossible, only after a minimum re-lock time of 125 ms above the sensitivity threshold, data transmission is resumed. In combination, the BER and loss-of-signal simulation results in the shown datarate, reaching the nominal rate of 2.5 Gbps only under ideal conditions.

4. USE CASE EXAMPLES

Numerous use cases can be considered by bundling the described functionality into a widely available tool. Primarily, optical modems and transceivers can be easily tested in a laboratory. Additionally, the tool can be used for ground station or satellite constellations operators, supporting routine operational decisions: Real time atmospheric and orbital data can be used as model inputs to rapidly produce a profile of expected data transmission performance, immediately before a scheduled satellite pass. The operational decision for a selected optical symbolrate can be based on the expected performance curve and requirements (figure. 10).

A further use case can be found in developing ground station architecture to evaluate the impact of design decisions quickly. Spatial diversity is a common approach to reduce the turbulence effects for the optical uplink [8]. The effect on the uplink channel can be quickly modeled due to the flexibility of the implementation (see fig. 11).

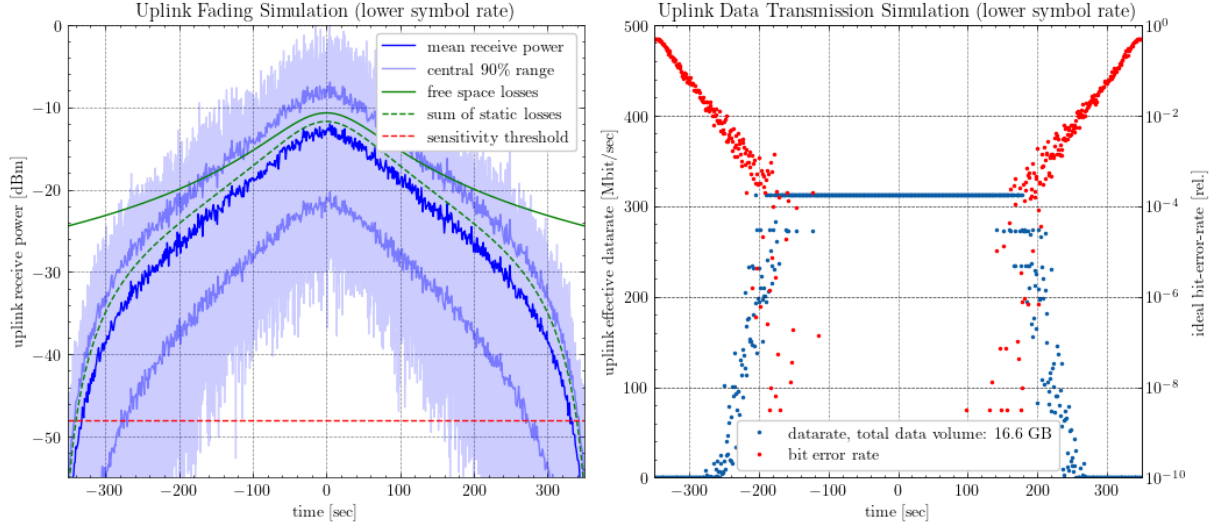


Figure 10. Alternative uplink results from adapting the scenario with lower uplink symbolrate: To mitigate the effects of atmospheric turbulence on the optical uplink, a slower symbolrate can be used. Assumed is a 9 dB improvement in receiver sensitivity, if 313 Mbps instead of 2.5 Gbps are used. The total transmitted data volume is significantly smaller compared to the original scenario (fig. 9), but the duration window of useable uplink transmission was widened noticeably. For applications that rely on simultaneous bi-directional channels, an asymmetric symbolrate for up- and downlink direction might be beneficial, to maximize transmission window overlap. The optimal symbolrate to balance throughput, and availability can be found experimentally using the here described fading emulator.

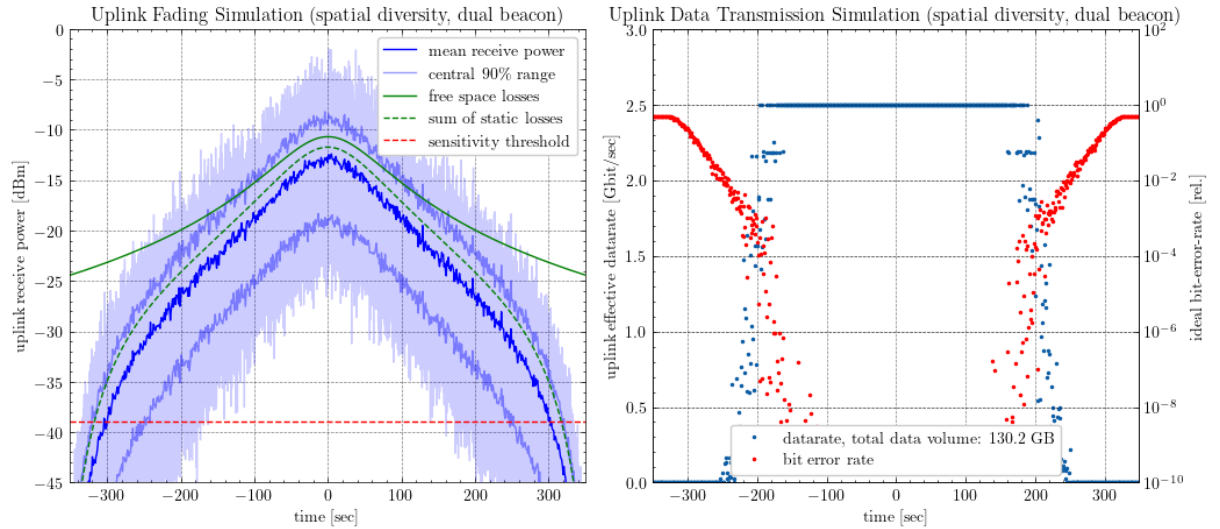


Figure 11. Alternative uplink results from adapting the scenario with dual beacon architecture. To mitigate the effects of atmospheric turbulence on the optical uplink, a spatial diversity scheme can be employed. Assumed is an equal split of the optical uplink signal power between two separated transmission apertures. The atmospheric scintillation and beam wander effects are assumed to be uncorrelated between both transmission paths, smoothing out fluctuations in the total receive signal power at the satellite receiver. Compared to the single beacon model (fig. 8 and fig. 9) the total transmitted data volume was increased by 32% without increasing the total signal power.

5. HARDWARE OUTLOOK

Generating these power vectors has only limited use, if they can't be replayed as varying attenuation between two real optical transceiver systems. We are currently developing this fading emulator device to be available to interested users. Unfortunately, results from replaying power vectors on a prototype version of this hardware is not yet available as of writing of this paper. The main hardware requirement lies in sufficient dynamic attenuation range of the device. Commercially available variable optical attenuators (VOAs) are not generally suitable to both cover the dynamic range and bandwidth of the fluctuating fading and the wide ranges of average receive power simultaneously. The linearity of the attenuation is also a concern, ensuring that a specific high frequency fading pattern is not distorted, when adjusting the slow average receive power over its entire range. Additionally, the uplink and downlink channel cannot be covered by the same VOA, as they differ completely in average receive power and fading pattern. The device under development consists of a network of custom VOAs, arranged both in-series and in-parallel configuration, and the corresponding arbitrary function generation and control hardware to orchestrate these VOA simultaneously. Two input and two output connectors for optical single-mode fiber are used as interfaces for the uplink and downlink channel directions (fig. 1) Sufficient computing hardware allows the real-time generation of power vectors based on model parameters supplied by the user, or selected from default parameters. In addition, uploading and replaying fading vectors from external sources is supported. For basic laboratory use, the complete satellite pass simulation with dynamically adjusting fading pattern is not always required. The user interface allows for basic operation, setting a specific scintillation index, bandwidth and average power. The graphical user interface is available via a network connection. In addition, all monitoring and control commands can be send via Simple Network Management Protocol (SNMP), to integrate the device with other automated systems. Hardware variants are available, to cover various optical wavelength ranges, or optionally support polarization maintaining fiber (PM-Fiber).

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