Multiple Wavelength Free-Space Laser Communications

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ABSTRACT

Free-space optical communications systems in the atmosphere, based on intensity modulation and direct detection, are heavily affected by fading caused by turbulence cells of varying scale and motion. Several data sets of fading measurements under different scenarios have been recorded demonstrating this effect.

In this paper we introduce a form of free-space laser communications involving a source operating on several wavelengths. The goal is to overcome atmospheric interference on a communications link.

We have performed simulations using the DLR PILab Matlab toolbox. These indicate the extent to which the turbulence and beam properties interact. Experimental investigations are planned. Further properties are also taken into account, including the choice of appropriate laser bandwidth and wavelengths, the effect of atmospheric absorption from aerosols and molecular absorption lines, as well as effects of atmospheric structure on beam propagation.

Possible scenarios for application of this scheme will be presented as well.

Keywords: Free-space optical communications, direct detection, multiple wavelength, atmospheric turbulence

1 INTRODUCTION

1.1 Background and Theory

Of primary interest in the development of atmospheric free-space optical links, is the ability for such a system to overcome the deep fades that are caused by atmospheric turbulence. As a laser beam propagates through the atmosphere, it interacts with turbulence cells produced by atmospheric thermal gradients, distorting the beam in a number of ways. At the receiver, the intensity of the beam can vary by 10s of dB, producing a deeply fading, bursty channel when the optical data rate used is 10 – 1000 Mbit/s. Among the critical parameters in characterising the turbulence properties are the C_n^2 profile along the path, the transverse wind speed and wavelength [1].

A system that overcomes this problem would allow optical links to be used over longer distances, with higher bit rates or lower transmit powers. One proposal already attempted by several groups involves using transmitters that are spatially separated [2,3]. Such a scheme assumes that each beam is subject to different turbulence as it propagates through the atmosphere and hence can lessen or remove the effect of deep fades, when the beams are combined at the receiver. Experimental results already show some success in the use of this technique, although this success depends heavily on the turbulence properties of the transmission path and the separation of the transmitter apertures.

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1.2 Wavelength dependence of speckle

In the case of a link using more than one wavelength, there is evidence that this technique was attempted as early as the late 1960s [4]. We propose a slightly different approach, as well as use of the technique in situations not previously considered. Firstly, the two wavelengths must be sufficiently different to enable a different response of the wavefront to turbulence. Ideally, as one wavelength fades, the other should surge, producing a more uniform received power signal when the two signals are combined.

Although it has been observed many times, that scintillation is stronger in the visible than in the IR, the normalized variance, or scintillation index, does not always increase as we decrease the wavelength. It has been shown by asymptotic theory that the scintillation index for a plane wave under very strong fluctuations using the Kolmogorov-spectrum is [1]

$$\sigma_{I-plane,strong}^2 = 1 + \frac{0.86}{\left(\sigma_1^2\right)^{2/5}} \quad , \quad \sigma_1^2 \gg 1 \tag{1}$$

with $\sigma_1^2 = 1.23 \cdot C_n^2 \cdot \left(\frac{2\pi}{\lambda}\right)^{7/6} \cdot L^{11/6}$, L: propagation distance

This parameter asymptotically approaches unity for very long distances. It can not reflect the effect of locally different intensity distributions, these have to be revealed by simulation. But it can be assumed that - since speckles are inherently an interference phenomenon - the angular spacing of the closest speckles at a receiver is proportional to wavelength [5]. If the speckle size and so the speckle-pattern structure in different wavelength beams is different, and the speckle size is the dominant fade parameter at the receiver, then averaging of the beam intensity occurs as a multi-wavelength beam is detected.

1.3 Wavelength dependence of beam-path

Under certain conditions, the paths of the two wavelengths are separated in the atmosphere, and propagate along different paths (Fig. 1). In these cases we would expect that, depending on the exact nature of the path differences and physical distance between the paths, the time fluctuations in atmospheric temperature, and hence refractive index and intensity, will be different for different wavelengths. Anecdotal evidence (such as the ‘green flash’ effect) from astronomical measurements near the horizon also support this.

Maximum vertical distance between two different wavelength paths: The use of multiple wavelength beams in the atmosphere depends on the actual splitting of the beams due to atmospheric refraction. For long path lengths, the beams will pass through different parts of the atmosphere, and hence fades will be out of phase with each other at the receiver. The calculations of optical grazing paths in the upper atmosphere are complex, and only an estimate of the difference between the paths is given below.

In the standard exponential atmosphere the index of refraction decreases exponentially with the height above sea level:

$$n(h) = 1 + n'_{NN}(\lambda) \cdot e^{-h/H} \tag{2}$$

with the scaling constant H = 7400m and the differential index of refraction:

$$n'_{NN}(\lambda) = 2.879\times10^{-4} + 2.165\times10^{-18} m^2 \cdot \lambda^{-2} \tag{3}$$

Using such a model (see Fig 1.) for the index of refraction, the radius of the path curvature can be approximately calculated with [6]:

$$\rho = -\frac{dh}{dn} \tag{4}$$

Furthermore for a given length of the "Line of Sight" (LOS), the maximum vertical distance of two different wavelength paths are given by the geometrical relations with:

$$\Delta = \frac{d_{LOS}}{2}\tan\left[\frac{1}{2}\arcsin\left(\frac{d_{LOS}}{2\rho(\lambda_1)}\right)\right] - \frac{d_{LOS}}{2}\tan\left[\frac{1}{2}\arcsin\left(\frac{d_{LOS}}{2\rho(\lambda_2)}\right)\right], \text{ with } \lambda_1 < \lambda_2 \tag{5}$$

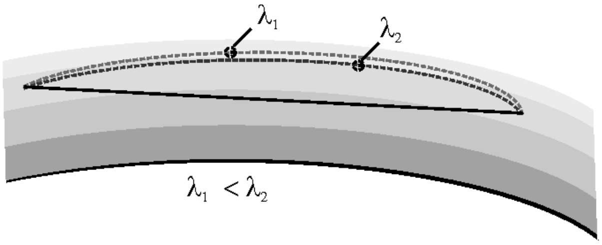


Fig. 1 Beam bending for different wavelengths

The following table displays some examples for different selected wavelength pairs, link distances and heights.

link distance: d_{LOS}	50 km	100 km
height above sea level: h	600m	
vertical path distance: Δ [cm] (808, 940nm) / (808, 1064nm) / (808, 1550nm)	3.37 / 5.47 / 9.40	13.5 / 21.9 / 37.6
height above sea level: h	10 km	
vertical path distance: Δ [cm] (808, 940nm) / (808, 1064nm) / (808, 1550nm)	0.95 / 1.53 / 2.64	3.7 / 6.14 / 10.56
height above sea level: h	15 km	
vertical path distance: Δ [cm] (808, 940nm) / (808, 1064nm) / (808, 1550nm)	0.48 / 0.78 / 1.34	1.9 / 3.12 / 5.37
height above sea level: h	20 km	
vertical path distance: Δ [cm] (808, 940nm) / (808, 1064nm) / (808, 1550nm)	0.25 / 0.40 / 0.68	0.98 / 1.59 / 2.73

Because the index of refraction varies with atmospheric pressure, the effect of beam spreading due to different wavelengths decreases with the height. To benefit from this effect very long distance links (>100km) should be used and also the wavelengths should be as far apart as possible. In simple approximation formulas for the atmospheric beam bending, the distance shows quadratic effect on the vertical beam-path separation, thus inter-HAP-links with several hundred km [9] will have sufficient offset. More sophisticated formulas and simulations regarding curvature of the Earth can produce detailed evidence [7,8].

As with the use of free space laser communications on ground-ground paths, the choice of wavelength for upper atmosphere paths depends on properties of the atmosphere. In particular, aerosol scattering plays a dominant role in the propagation of light in the stratosphere, since at these altitudes the amounts of water vapour (a strong absorbing molecule in the IR) are negligible. Aerosols are not uniformly distributed in the upper atmosphere, neither in altitude nor time, and estimates of absorption over long paths are dependent on a number of factors, volcanic activity in particular [9].

1.4 Projected Scenarios

The use of wavelength diversity has been largely ignored in the past due to the unlikely nature of it being advantageous in common link scenarios. We propose that there may exist circumstances in new scenarios where it may be of use.

In particular, the effect of aperture dimensions, (particularly receivers), selected to match the turbulence conditions on a link, will be of importance in deciding the value of lambda diversity. In ground-ground or ground-space optical links, high turbulence produces large-scale speckles, which can be largely accounted for by using multiple aperture detectors [3]. In the upper atmosphere, where turbulence is low, single small apertures can be used to provide diversity using transmitters on different wavelengths, since the speckles are much larger and aperture averaging is not required. The longer path lengths through the atmosphere for high altitude links, will enable such systems to make the most of any existing difference in the ray paths between different wavelengths. An extreme case would be a system that uses diversity on very widely spaced wavelengths, eg. a visible wavelength transmitter and a NIR one.

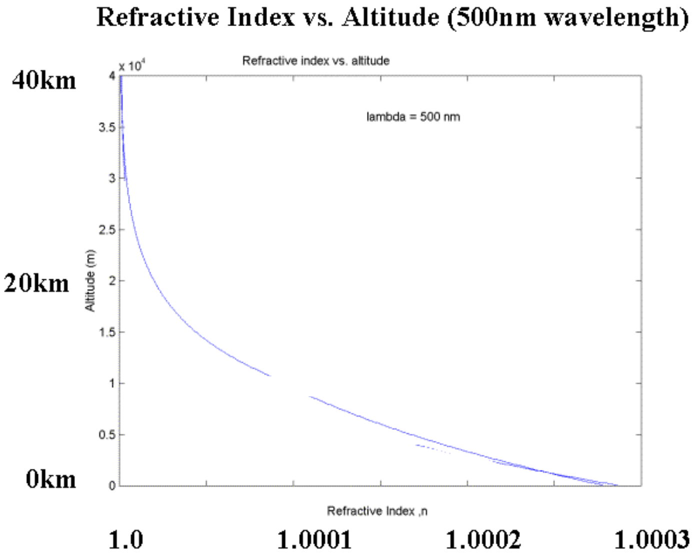


Fig. 2 Variation of refractive index with altitude

One possible scenario is the use of multi-wavelength optical communications to transmit data between High Altitude Platforms. Such platforms are projected to operate from altitudes in the stratosphere (10 – 25 km), and enable communications over medium scale areas on the Earths surface (footprint diameters up to 500 km). An analysis of the general properties of the optical links between such platforms has been presented in [9].

2. THEORY AND OPTICAL SIMULATION

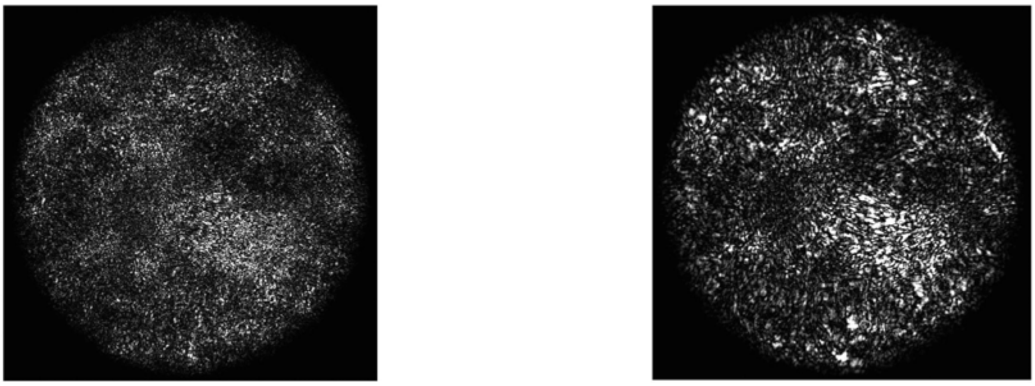
2.1 Pilab Simulation Tool

Simulation of the concept of different speckle-patterns was made, using the DLR in-house Matlab toolbox ‘PILab’. This toolbox propagates optical fields through generation of a series of phase planes. A more complete description of the workings of this toolbox, based on the Talanov transform and algebra, is given in [10].

The PILab toolbox operates by firstly constructing an optical system (as a set of phase objects), then simplifying the optical system (by combining the effect of several objects into single objects), and finally, by a series of Fourier transform procedures (with some limitations), propagating the initial beam through this optical system. The toolbox is undergoing continual improvement with possibilities for use with multi-wavelength beams, multiple beams, and time-evolving simulations.

In particular, a series of propagation algorithms have been developed for simulating propagation of beams through turbulent phase screens. Distances between the phase screens are based on given turbulence parameters (such as C_n^2 and wavelength), with constant or piece-wise C_n^2 profiles along the propagation path. In addition it has proved necessary, given the finite extent of the viewing screen, as well as beam spreading along the path, to include regular scaling and damping factors into the simulation code. These are required to avoid aliasing artefacts from the simulation code entering the propagating field.

Simulations were produced using PILab, for a path over a length of 100 km. The two sets of simulations were similar in all respects except for wavelength (the randomly generated phase screens are also identical). The turbulence conditions were characterized by a refractive-index structure constant $C_n^2 = 1\times10^{-15}$. Both beams had an exit divergence of approximately 50 μrad, which produces a beam several meters in diameter at a receiver 100 km away. Fig. 3 shows the produced intensity patterns by the simulation for both wavelengths, while Fig. 4 shows their central vertical cross-sections. It can be observed that the spatial intensity distribution for the two wavelengths is different after propagating through the same volume.



$\lambda = 810$ nm $\qquad$ $\lambda = 1550$ nm

Fig. 3 Simulated intensity matrices of two beams with different wavelengths propagating 100 km through the same turbulent volume (no beam-path dependency simulated, only wavelength-dependency of speckle)

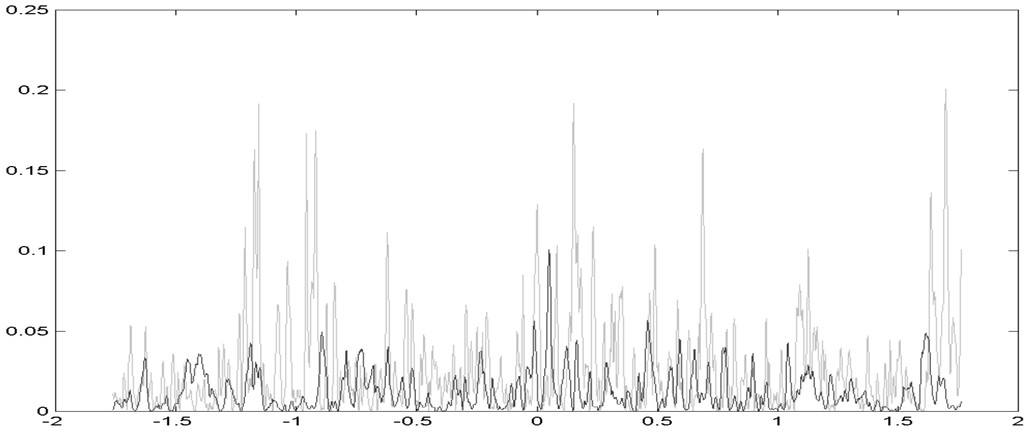


Fig. 4 Simulated vertical cross-section of 810nm (gray) and 1550nm (black) beams at 100 km from transmitter (low turbulence path)

The following table displays the scintillation indices calculated from the two simulated intensity patterns:

	810 nm ONLY	1550 nm ONLY	810 + 1550nm
scintillation index	1.43	1.63	0.90

From Fig. 5 it can be seen that the sum of the two beams reduces the probability of deep fades.

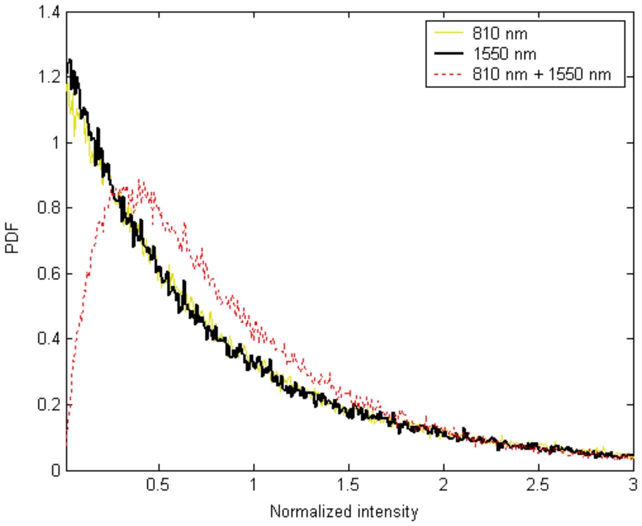


Fig. 5: PDFs of the normalized beam intensity for λ = 810 nm and λ = 1550 nm, and PDF of their sum

3. DIVERSITY RECEPTION

3.1 Receiver Characteristics

A number of different receivers are possible for wavelength diverse systems. Important factors to consider include the wavelength response of optical detectors, intrinsic detector noise (especially if different detectors are used for different wavelengths), focal lengths, optical losses and coating design, and fiber coupling (if it is used).

The simplest receiver would contain a single detector with equally good responses at all wavelengths used, so the diversity-sum would be directly detected. More sophisticated setups detect each wavelength with a separate receiver (chromatic beam splitting is required in the Rx-terminal) and process them differently according to well-known diversity-receiver algorithms. The combination of the electrical signal from the different detectors depends on a good knowledge of the noise of the systems and correct equalization of the channels is desirable.

3.2 Implementation of Coding with Wavelength Diversity

If little or no statistical dependence can be achieved between the n channels (corresponding to the $\lambda_1 \ldots \lambda_n$ wavelengths), one can transmit n symbols of a channel code sequence in parallel, and guarantee an equalized distribution of erroneous bits in each code sequence. In each atmospheric optical channel, one has to deal with a very long fade duration. Simulations for typical stratospheric scenarios have shown that the fade duration is between 1 and 50 msec, mainly depending on the wind speed surrounding the platform. For the investigated high data rates the fade duration (in terms of bits) is very long and error bursts in the signal can be split only by using extremely long interleavers [11]. Transmitting code sequences over n uncorrelated channels allows one channel to be in a bad state for long time, while the other channels are at that time in a good state. For instance, as shown in Figure 6, a block code can be used and symbols of one word can be transmitted at the same time over n independent channels. If only a few channels are in a bad state, then the code can correct all errors. The required redundancy is very low, if the channels are widely independent and a deep fade only occurs on one of the channels at a time. This block code FEC scheme uses only short block lengths (between 4 and 15 bits per block) and additionally can be implemented with soft decision. Block codes with soft decision are even more effective than convolutional codes and can already be implemented in hardware for high data rates.

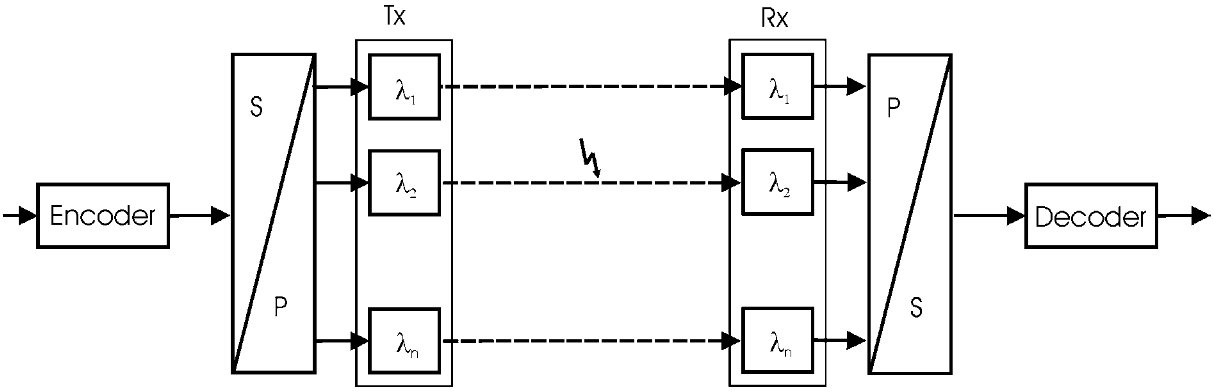


Figure 6: Combining block coding and wavelength diversity

4. CONCLUSIONS AND FUTURE WORK

The technique discussed here is still being investigated. Preparations are currently underway to test the concept over the test path described, with ground-ground path lengths up to 31km.

Ultimately, the use of the technique over long path lengths (100 km and greater) in the upper atmosphere may be useful. Stable High Altitude Platforms (HAPs) are still undergoing development, however a typical initial test could involve a downlink between a HAP and an optical ground station. The aim of such an experiment would be to measure the turbulence and absorption properties, and hence propagation characteristics, in situ. The greatest uncertainty in such a scenario at the moment is the stability of the platform. There may also be skin turbulence effects, depending on the local winds speeds and altitude of the platform.

Theoretical simulations, using more complete models of atmospheric refraction over long path lengths and low elevation angles, are also underway.

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