Wavelength Dependence of a Fiber-Bundle Based FSO Link

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Abstract—A transmitter and receiver design based on the use of fiber optic bundles have been proposed and studied both experimentally in the laboratory and theoretically through simulation, and have shown promise for providing enhanced functionality in mitigating the effects of turbulence and weather on the pointing, acquisition and tracking problem. In this paper, the operation of an FSO link constructed from these designs is analyzed under similar environmental conditions but transmitting at two different wavelengths. A transmitter with a linear fiber array transmitted over a brick surface at either 1310 nm or 1550 nm wavelength to a receiver constructed using a hexagonal array of 19 fibers located 15 feet away. Data at 100 kb/s was transmitted across the link and the collected signal was recorded for off-line statistical analysis, including achieved bit-error rate. The investigation finds that, when eliminating effects due to artifacts in source operation, dependence of link operation on wavelength is minimal, even though the optical alignment was optimized for only 1550 nm.

Keywords—fiber bundle; wavelength dependence; weather; terrain; optical wireless; BER

I. INTRODUCTION

Several approaches have been proposed to bring the bandwidth and security advantages of FSO to the mobile environment for a variety of different distances and operational requirements. For longer distances and outdoor environments, the presence of atmospheric turbulence and weather can produce signal fade or loss for traditional FSO designs. Solutions that increase the transmitter power, the collecting area of the receiver, or the number of spatially diverse transmitter-receiver pairs [1–9] have limited utility in the mobile scenario by practical limits on the size, weight, and power consumption (SWaP) of the mobile transceivers that are imposed by the moving platform’s capabilities. While several design solutions have been proposed to address these issues, there remains room for new FSO system designs to further improve upon the performance of mobile FSO.

One promising approach for complementing other methods of turbulence mitigation is the use of wavelength diversity [10], [11]. Turbulence in the atmosphere is characterized by the inner and outer scale of the turbulent eddies that occur primarily due to heating. The strength of diffraction and refraction of the optical beam from these eddies is strongly dependent on the relative scale of the eddy size and the optical wavelength. In general, the diffraction and refraction effects decrease as the wavelength increases, and the resulting quality of the signal collected by the receiver increases [4]. Another potential benefit of wavelength diversity is the difference in absorption by water and other airborne substances at different wavelengths. Therefore a wavelength may be chosen to reduce weather effects or turbulence effect, or in the ideal case reduce both effects.

A system capable of operating with equal effectiveness at multiple transmitting wavelengths must be able to minimize the effect of the wavelength dependence of the optical components used in both the transmitter and the receiver. Such optics include lenses for shaping the transmitter beam and collecting optical power at the receiver, as well as the optics used to couple the collected light to the output optical fiber or photodiode. Given the typically tight operating requirements of these systems, even small changes in the properties of the optical systems can very negatively impact the performance of the link in terms of optical power throughput and bit-error rate, even under otherwise good atmospheric conditions. In order for wavelength diversity to be effective as a method to minimize turbulence effects, the design of the transceivers must minimize the effects of the wavelength dependence of the optics.

Preliminary work related to wavelength diversity has been performed on an FSO system that uses fiber optic bundles to increase the system performance, with promising results [12–14]. The bundle-based transceivers utilize arrays of fibers, lenslet arrays, and several other optical components that are wavelength dependent in their operation [15]. The purpose of the design is to allow the link to be maintained for a wider range of misalignments between the transceivers due to either angular misalignment or a translational displacement or misalignment. Measurements of the power collected as a function of translational and angular misalignment were obtained for three different wavelengths (850 nm, 1310 nm, and 1550 nm). The link between the transmitter and receiver was shown to be maintained during a shift in the operating wavelength, even before the position of the optical components at either end of the link was optimized for operation at the new wavelength. Although promising, the work was performed in the laboratory using only continuous wave sources and therefore turbulence and other environmental effects, and their impact on actual data transmission, were not determined.

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In this paper, we experimentally investigate the operation of an FSO link constructed from fiber-bundle based transmitter and receiver designs as a function of wavelength while operating transmitting data under realistic environmental conditions. The investigation focuses on the ability of the transmitter and receiver to maintain a viable link while operating at 1550 nm or 1310 nm as atmospheric conditions, including temperature, wind speed and direction, and humidity, vary over time. Statistical analysis of the data collected by the receiver is performed to characterize the performance of the link.

II. SYSTEM UNDER INVESTIGATION

A. Experimental Design

The experimental design used in the investigation is shown in Fig. 1. The optical signal source is an electrical-to-optical converter with a fiber-coupled laser diode. Two such devices were used for this study, one operating at a wavelength of 1550 nm and a second operating at a wavelength of 1310 nm. The converter was driven by a pseudo-random bit stream generator operating at 100 kb/s with a 2^48 – 1 pattern length. The output from the converter was passed through an optical amplifier. A doped fiber optical amplifier was used for the 1550 nm source and a semiconductor optical amplifier was used for the 1310 nm source. Initially, optical power from the signal source was coupled to one of the fibers in the transmitting fiber array. The array is a commercially available fiber ribbon cable containing eight fibers in a linear arrangement, and the signal source was typically connected to one of the two fibers (fiber 4 or fiber 5) at the center of the array. In the transmitter, the linear array is aligned along the horizontal (x) axis and placed on a platform consisting of a three-dimensional translation stage and a goniometer to allow precise alignment of the fiber array with the optical telescope. The telescope consists of three lenses: an input convex lens, a concave lens for adjusting the effective illumination or a large area at the output plane can be illuminated in a more uniform manner than that achieved by increasing the divergence (multi-fiber illumination).

At the receiver, a hexagonal array of small (0.09 in diameter) lenses is used to collect the light and couple it to an array of optical fibers. Each fiber has a core of 400 μm in diameter and a numerical aperture of 0.37. The output from the fiber array is coupled through lenses to the collecting area of an amplified InGaAs photodetector (PDA10CF from ThorLabs) with 300 MHz bandwidth. The detector’s output is coupled to an oscilloscope for visual inspection of the signal and a data acquisition system that sampled and stored the signal. The receiver is mounted on a long-range translation platform to allow studies of link performance on receiver motion. An enclosure is constructed on the platform to protect the receiver from wind and to limit ambient light entering the receiver. In practice this platform was still slightly unstable with respect to wind, and this instability must be considered as a factor in the performance of the link during the analysis.

In the initial setup of each experiment, the following procedure was used. The transmitter head, mounted on an optical breadboard, was placed on the terrain feature. The head was leveled so that the optical beam propagated parallel to the surface of the terrain. The receiver components were likewise mounted on an optical breadboard, which was then secured onto the mounting plate of the long travel stage and covered by the protective enclosure. The transmitter and receiver assemblies, minus the receiver’s enclosure, are shown in Fig. 2. The receiver was placed 15 feet from the transmitter, measured from the output of the transmitter’s telescope to the receiver’s input lens array. The receiver system was also leveled, and then the overall system was aligned to ensure the transmitter and receiver optical axes were coincident and parallel.

The data acquisition system was programmed to sample the data stream from the detector and store it for further analysis. For the results presented in this work, the 100 kb/s data stream was sampled at 1 Mb/s and recorded over 90 second intervals. The interval time was limited by the internal memory of the data acquisition system. One 90 second interval was recorded every 2 minutes, with the exception of one 20 minute interval during the 1310 nm recording process, with 20 recording intervals for 1550 nm starting at 12:50 pm and 34 recording intervals for 1310 nm starting at 2:50 pm. A portable weather station was set up alongside the link to record temperature, humidity, wind speed, wind direction, and precipitation, and this data was logged along with the received data from the receiver. The raw data in these logs served as the input to the data analysis programs.

B. Data Analysis

The goal of the data analysis was to fully characterize the operation of the link as a function of the operating conditions for each of the wavelengths studied. Several parameters were calculated and studied to evaluate the performance of the link, including the BER achieved by the link, the statistics of the collected ones and zeroes, the threshold values required to minimize the BER, and the variation of these parameters with

Fig. 1. Experimental setup

Fig. 2. Constructed transmitter and receiver
respect to time and wavelength. All data extraction and analysis was performed using MATLAB. The behavior of the system could then be studied to better understand how wavelength affected the performance of the fiber-bundle based system under realistic operating conditions.

The analysis process commenced by extracting and sorting of the data contained within the output files of the data acquisition system. Each data file was imported into MATLAB and the data-containing column(s) were loaded into data vectors. The mean of the entire vector was computed as a beginning reference for sorting ones and zeros. The sorting process was synchronized with the data by finding the first recorded transition (one to zero or zero to one) and starting the sorting process from this point. Ideally, each bit of the data stream should have been sampled 10 times (10^6 samples/s divided by 10^3 bits/s) and thus each new bit located 10 samples after the beginning of the previous bit. In practice, non-idealities in the clock provided by the function generator resulted in some bits to be sampled 11 times instead of 10. The sorting process had to be periodically resynchronized to ensure that ones and zeros were identified and sorted correctly.

After sorting, statistical analysis of the ones and zeros was carried out. To replicate a typical data recovery system, each bit was sampled by taking the data sample that was nearest the middle of the bit, which was sample number 5. After all of the samples were extracted, the data from all of the ones (or zeros) were combined and the mean and standard deviation of the data calculated. Probability density functions (pdf) for both ones and zeros were constructed. The BER calculation proceeded by first calculating the threshold value from the statistical data, then integrating over the areas of the pdf curves that crossed over the threshold, and then calculating the BER using

\[ BER = P(0)P(1|0) + P(1)P(0|1). \]  

(1)

Threshold values were obtained from the weighted threshold given by

\[ V_w = \frac{\bar{V}_1 \sigma_0 + \bar{V}_0 \sigma_1}{\sigma_1 + \sigma_0}, \]  

(2)

where \( \bar{V}_1 \) and \( \bar{V}_0 \) are the mean and \( \sigma \) and \( \sigma_n \) are the standard deviations of the recorded voltage for a one and a zero, respectively.

The analysis described above was carried out for a subset of each individual 90 second interval and for the combination of all intervals within a given day or experiment. The goal was to investigate the system performance as a function of wavelength and attempt to correlate changes in performance with changes in the ambient weather conditions as well as the wavelength. To this end, additional data was collected, including the minimum and maximum value of the ones and of the zeros in each interval and an estimate of the structure parameter \( C_0^2 \) based on the statistical distribution of the received data [16, (3.109)]. The composite data was plotted over time to view the temporal dependence.

III. Analysis Results

The wavelength dependence data analyzed here was collected over the course of one day, October 7, 2013, with no alterations to the setup, including the positioning of the optical components within the transmitter and receiver, other than the transmitting wavelength. All of the data was taken with the link located on a brick sidewalk located adjacent to a two-story building. Data was taken first at one wavelength and then at the other, so that a continuous time dependence was recorded at each wavelength while maintaining a segment of time where the two wavelengths were transmitting under the same atmospheric conditions.

A. Fundamental Operation

A sample of the raw data is presented along with the processed results in figures 3 through 10. Examples of the raw sampled data that was collected for each wavelength are shown in Fig. 3 and Fig. 4. In comparing the data samples, some distinct differences are noted in the waveforms, attributable to the operation of the electrical-to-optical converter, which is of importance in interpreting the results of the statistical analysis of the link. First, when the data transitions from a zero to a one, the 1550 nm source produced an initial overshoot followed by a settling period. The initial overshoot became larger as the number of zeros preceding the one was larger, and thus when the converter had been idle for a longer period of time. For the 1310 nm source, no such overshoot or dependence on the number of preceding zeros was observed. This caused a larger spread in the measured voltage of a one for 1550 nm than for 1310 nm, and this spread will add to that caused by any turbulence that may be present. Second, the transition from a one to a zero was more exponential in nature, or less sharp, for the 1550 nm source than for the 1310 nm source, with a fall time that was larger than the rise time of the zero-to-one

![Fig. 3. Sampled bit stream (1550 nm)](image)

![Fig. 4. Sampled bit stream (1310 nm)](image)
transition. This fall time did not measurably depend on the number of preceding ones, but would broaden the range of collected zero voltages as zeros occurring just after a one would register as having a higher measured voltage than for a zero occurring later in a string of two or more zeros. It is also important to note that the voltage difference between a zero and a one is smaller for 1310 nm (about 30 mV) than for 1550 nm (about 50 mV) which would favor the use of the 1550 nm source for a low BER link. These artifacts must be kept in mind when interpreting the analysis results.

Examples of the pdfs that were generated using only the center sample of each bit at each wavelength are shown in Fig. 5 and Fig. 6. Also indicated on the graphs is the threshold voltage calculated from (2). Distinct differences in the link statistics between the two wavelengths are clearly evident, as is the influence of the artifacts observed in Fig. 3 and Fig. 4. The pdfs for 1310 nm are narrower in range than for 1550 nm particularly for the ones (> 70 mV for 1550 nm versus ≈ 40 mV for 1310 nm). The pdf for ones for 1550 nm is distinctly bimodal and demonstrates a long tail toward higher values indicative of the overshoot observed in the output of the source. The zeros for 1550 nm also exhibit a tail at higher voltage readings in part due to the longer fall time of the source, and this tail more closely approaches the calculated threshold voltage than the extreme values of the zeros do in the 1310 nm data. The 1310 nm ones have a much smaller tail at the higher end and more closely approximate a normal distribution.

Fig. 7 shows the maximum, minimum and mean values of the ones and zeros for each of the measurement intervals for each wavelength. Also shown is the mean value of all of the samples within the interval and the threshold voltage $V_{th}$ from (2). The differences in signal range and distribution for the two wavelengths observed in the pdfs are clearly visible in the maximum, minimum and mean values, particularly of the ones, as a function of time. The difference in distributions is also observed in the placement of the threshold value. For 1550 nm, the threshold value is coincident or just slightly lower than the maximum recorded value for a zero throughout the entire recording period, while the threshold value for the 1310 nm data is larger than the maximum zero value for almost every segment of the recording period. This is likely a result of the large standard deviation of the ones in the 1550 nm experiment, which would force the threshold to move lower based on (2). There were no significant changes observed in the mean signal strength for 1310 nm, while the mean signal strength decreased over time for the 1550 nm transmission. This decline in the 1550 nm signal strength with time is recurring and has been observed in prior experimental recordings.

The calculated BER for each wavelength and the corresponding calculation of $C_n^2$ for each wavelength are shown in Fig. 8 and Fig. 9 for 1310 nm and 1550 nm, respectively. An initial observation of the results suggests that there exists a significant difference, in terms of propagation through a turbulent atmosphere, between the two wavelengths. The 1310 nm data exhibits a very small value of both BER and $C_n^2$, most notably at the beginning of the recording session when the atmospheric conditions were most similar to that occurring during the 1550 nm recording session. Except for one spike in the 6th recording interval, which corresponded to a spike in the value of $C_n^2$ to 1.1·10^{-16}, the BER was essentially zero for the entire 1310 nm recording session.

By contrast, the value of $C_n^2$ effectively seen by the 1550 nm transmission appears to be three times higher at the same period of the day (toward the end of the 1550 nm recording session) resulting in a predicted BER that is quite large – between 1·10^{-4} and 4·10^{-4} – for almost the entire recording session. However, the sudden drop in the value of $C_n^2$ from the end of the 1550 nm session to the beginning of the 1310 nm session...
session, when no corresponding change in the prevailing atmospheric conditions was observed, is incongruous with the expected $\lambda^{-7/6}$ dependence of $C_{n2}$ on wavelength. This suggests that the artifacts of the 1550 nm source are more responsible for the increase in BER than the atmospheric turbulence.

A further investigation of the 1550 nm data for the entire recording session provides strong support for the hypothesis that the artifacts are the main source of error. Plots of the raw sampled data stream reveal that no overshoot and minimal exponential decay was present in the 1550 nm source at the beginning of the recording session. This is observed in Fig. 7(a) as a much lower peak value of the one bits and in Fig. 9(a) as a near-zero BER. As the recording progressed, the artifacts became more pronounced until the artifacts dominated the response of the system in Fig. 3. An example pdf from the 10th recording interval, where the overshoot was present only after long series of zeros and the fall time decay was still small, is shown in Fig. 10. The pdf for the ones has two distinct peaks, one for the overshoots and one for all of the other one bits. As an exercise, the peak for the overshoots was eliminated from the pdf, and only the peak for the non-overshoot ones was used for analysis. In doing so, the estimated value of $C_{n2}$ dropped from $2.8 \cdot 10^{-16}$ to $4.4 \cdot 10^{-17}$ and the BER decreased from $2.82 \cdot 10^{-4}$ to $9.59 \cdot 10^{-5}$. The threshold voltage increased from 0.010 V to 0.017 V. The change in BER was less pronounced than the change in $C_{n2}$ because of the maximum values of the zeros, where a few still exceeded the threshold, even with the increased value of the threshold. Based on this additional evaluation, it is concluded that the source artifacts contributed the most to the lower performance of the link at 1550 nm, and that the performance of the link due to only atmospheric turbulence did not change in a significant manner with a change in the wavelength.

A surprising aspect of the result is that, since the initial setup of the link was performed using the 1550 nm source, the performance of the link should have been optimized at this wavelength as part of the initial setup process. When the differences in operation of the two sources are accounted for, it appears that the link operation is similar for both wavelengths without the need to adjust the optical alignment of the

![Fig. 8. (a) BER, (b) $C_{n2}$ for 1310 nm](image)

![Fig. 9. (a) BER, (b) $C_{n2}$ for 1550 nm](image)

![Fig. 10. (a) Original and (b) modified pdf for 1550 nm, 10th recording interval](image)
components in either the transmitter or receiver when the wavelength is changed. This is a significant strength of the transceiver design.

IV. Conclusions
Experimental investigations were carried out for an FSO link using fiber-bundle based receiving and transmitting elements as a function of wavelength. After accounting for the artifacts present in the operation of the 1550 nm source, it was determined that the frequency of operating wavelength did not produce a significant change in the operating parameters of the link. This lack of change occurred even though the receiver and transmitter were optimized for only one of the wavelengths used. This operational consistency with wavelength is an important quality for a system to effectively use wavelength diversity as a solution to the turbulence problem. Additional investigations are ongoing that examine the behavior of the system to misalignment and the use of multiple transmitting fibers to affect beam shaping for improving tracking functions in mobile scenarios.

REFERENCES