MULTI-BEAM FREE-SPACE OPTICAL LINK USING SPACE-TIME CODING

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Abstract

We demonstrate the performance advantage of multi-beam terrestrial free-space optical communication links over single-beam links in the presence of strong optical turbulence. We adapt a space-time block code proposed for RF wireless systems to be used with intensity-modulated optical signals, and find that significant signal-to-noise ratio gains are obtained by using a four-beam link over a single-beam link with the same total electrical power.

1 Introduction

The atmospheric free-space optical (FSO) channel is a natural medium for outdoor wireless communications and offers a higher capacity than that of the radio-frequency (RF) channel. That is, more users and larger bandwidth applications can be supported. The availability of optical components for fiber-optic communications make FSO links a cost-effective solution for voice and data communications [1]. Because the FSO channel exploits line-of-sight links, it does not cause interference on other links and does not require the allocation of a specific segment of the already congested electromagnetic spectrum. Also, FSO communication systems can be deployed in hours. These features make FSO systems an excellent option in places and situations where other communication links are not viable.

The performance of an FSO communication system can be severely affected by atmospheric turbulence. This turbulence is caused by variations in the refractive index of the air as the latter experiences temperature gradients due to solar heating and wind [2]. This produces intensity variations, or scintillation, at the receiver of the communication link, which translates into a lower channel capacity and higher bit-error rate (BER) [3]. It has been found that turbulence reduces the spatial correlation of the optical wave front [4]. As a consequence, optical beams that propagate in neighboring paths –in a multiple-input multiple-output (MIMO) configuration– experience different channel gains. If the spatial separation of the beams' paths is larger than the spatial correlation length, then the channel gains become uncorrelated. This spatial diversity can be exploited to improve the signal-to-noise ratio (SNR) at the receiver. In practice, the correlation distance varies from about 20 cm in weak turbulence to about 1.5 cm in strong turbulence. This allows the use of parallel beams at close distance to achieve diversity.

The optical atmospheric channel also shows temporal correlation. Although the temporal statistics of the FSO channel are no yet well-understood, the correlation time seems to be of the order of a millisecond [5]. At Gigabit per second rates, the channel gain varies very slowly, and can be assumed as constant for many thousands of consecutive bits. Space-time (ST) codes can take advantage of the spatial-temporal diversity of MIMO FSO systems to reduce the bit-error rate (BER) of the communication system for a given transmitted signal energy.

We adapt a ST block code, initially proposed for MIMO RF channels, to use it on intensity-modulated On-Off Keying (OOK) optical links. In particular, we evaluate a square, rate one, size four ST block code, in an optical link with four transmitting optical beams and one receiver, and we compare its BER performance with that of a single-transmitter single-receiver system with the same overall electrical signal power. This evaluation is done by means of a numerical optical beam propagation simulator, and as such, all turbulence effects, like scintillation, beam spreading and beam wandering, are included. By using the 4x1 scheme with the ST block code we obtain large electrical SNR gains. We present in this paper four cases, on which we vary the turbulence strength and/or the receiver aperture. These examples consider moderate and strong turbulence conditions and show gains from 9dB to 15dB. Further SNR gains are expected when this ST code is used in combination with error-correction codes.

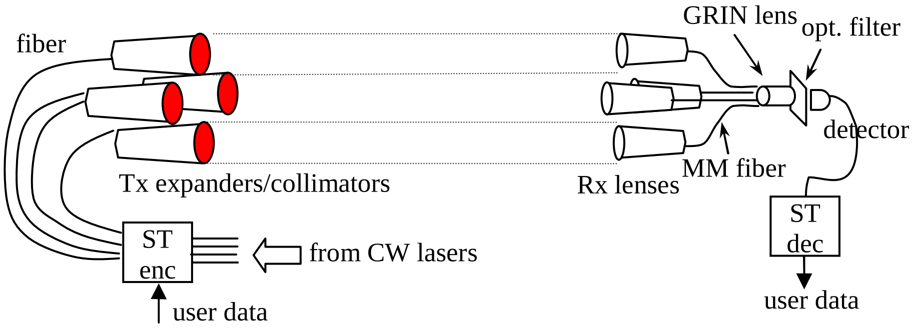

Figure 1. Diagram of the multi-beam FSO communication link using space-

2 System description

A diagram of the multiple-beam FSO system under evaluation is shown in figure 1. The transmitter consists of four laser sources. The incoming data stream is encoded using the ST block code and the encoded bits modulate the sources. The optical beams are expanded and collimated to limit the beams' broadening caused by diffraction. The modulated beams are projected toward the receiver. At the receiver, four lenses aligned to the incoming beams collect the light. Each beam is focused onto a multi-mode fiber. The four fibers can be bundled together and placed next to a pitch-1/4 graded-index (GRIN) lens with the other end of the lens onto a filter to remove unwanted background light and an optical detector. The detector delivers an electrical signal proportional to the incoherent sum of the four incoming optical signals. The receiver electronics introduce noise, making the detection of the binary data subject to errors. The data is then decoded to obtain the information data stream. If error-correction codes are used, they must be used as outer codes, that is, the input electrical data stream is encoded with the error-correction code before the ST code and later decoded at the receiver after ST decoding. In this study we model the noise as additive white Gaussian (AWG).

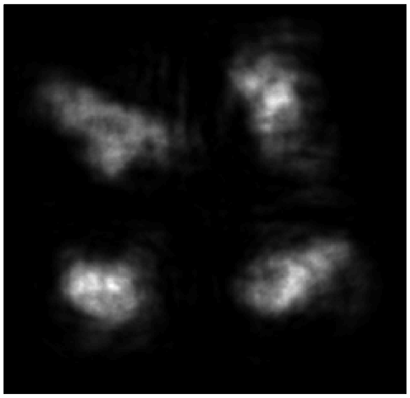

Figure 2. Intensity pattern of 4 parallel beams after 1km in moderate turbulence.

Beam propagation is performed using a numerical simulator based on the split-step Fourier method. Turbulence is produced by generating phase screens with random index variations that follow the modified von Karman model [6]. We use the propagated instance of the channels for 10,000 bits and then we generate a new instance independent of the previous. Figure 2 shows an instance of the intensity distribution of four beams after 1000 meters in moderate turbulence conditions.

3 Space-time block code description

A ST block code is defined by an n_T x p transmission matrix, where n_T is the number of transmit antennas, or beams in the system described above, and p is the number of time periods required to transmit all coded symbols. In a binary system, k bits are encoded into n_T parallel binary sequences of length p, according to the transmission matrix **X**. The rate of the code is given by $R = k/p$ [7]. We evaluate a modified rate 1, size four, full-diversity code given by [8]

$$\mathbf{X} = \begin{bmatrix} x_1 & -x_2 & -x_3 & -x_4 \\ x_2 & x_1 & x_4 & -x_3 \\ x_3 & -x_4 & x_1 & x_2 \\ x_4 & x_3 & -x_2 & x_1 \end{bmatrix} \tag{1}$$

Because we consider OOK-modulated signals, we replace the negative signs in **X** with binary complement, that is, $\bar{x}_i = -x_i + A$, where A is the intensity of the OOK signal, following the adaptation for the Alamouti code proposed in [9]. The first column of the transmission matrix corresponds to the four bits transmitted during the first time interval. The following columns correspond to the second, third, and fourth group of transmitted bits, respectively. The received intensity at time interval p for the case of one receiver is given by

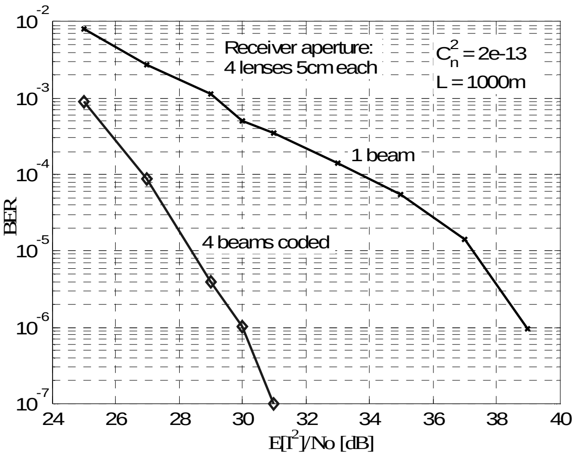

Figure 3. BER vs. SNR for $C_n^2 = 2\times10^{-13}$ and L= 1km.

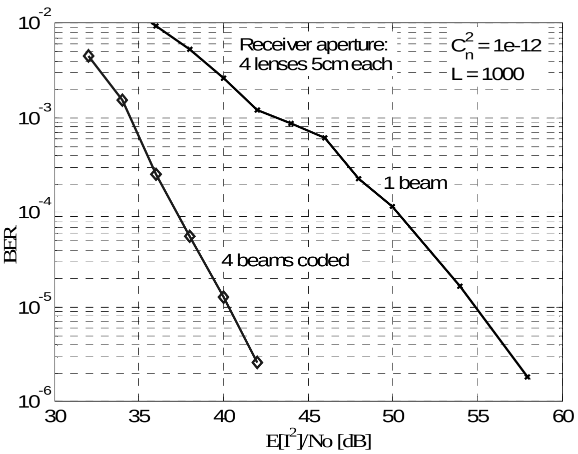

Figure 4. BER vs. SNR for $C_n^2 = 1\times10^{-12}$ and L= 1km.

$$r_p = \sum_{i=1}^{n_T} h_i X_{i,p} + n_p \tag{2}$$

where h_i is the intensity coefficient of channel i, $X_{i,p}$ is the (i,p) element of **X**, and n_p is white Gaussian noise added by the detector at interval p. The channel coefficients must be known to the receiver and are assumed to remain constant for the duration of the transmission of the entire matrix **X**. This is a sound assumption in FSO links, because of the slow fading of scintillation, which permit the transmission of pilot signals to determine the mentioned coefficients.

Unlike the original code, which assumes real signals, in optical direct detection systems we use non-negative signals, and the receiver is not balanced. Therefore, the latter must be modified to be able to use the maximum likelihood decoding scheme with linear processing proposed for RF systems [8]. In our case, the decision statistic for symbol x_k is given by the expression

$$\tilde{x}_k = \sum_{i=1}^{n_T} \delta_i(k)\, r_i\, h_{e_i(k)} + b_k \tag{3}$$

where $\delta_i(k)$ represents the sign of symbol x_k at column i of **X**, $e_i(k)$ is the position of symbol x_k in column i, and b_k is the bias added to balance the decision statistic, given by

$$b_k = -\sum_{i\neq 1}^{n_T} \delta_i(k)\, h_{e_i(k)}\, C_i \tag{4}$$

where C_i are constants that derive from the bias added by the complemented signals involved in computing r_i. In particular, $C_2 = A(h_1+h_3)$, $C_3 = A(h_1+h_4)$, and $C_4 = A(h_1+h_2)$. These modifications allow the use a linear maximum likelihood decoding strategy. With the decision statistic given by Equation (3), we decide in favor of the symbol s that minimizes the expression [8]

$$m_k = \left|\tilde{x}_k - s\right|^2 + \left(\sum_{i=1}^{n_T} \left|h_i\right|^2 - 1\right)\left|s\right|^2 . \tag{5}$$

4 Performance evaluation

We present the BER performance of the ST coded 4x1 system and we compare it with that of a 1x1 system. The transmit powers are chosen so that the electrical SNR of the two systems is equal in the absence of turbulence. We define SNR = $E[I^2]/N_0$, where E[] is the expectation operator, I is the transmitted intensity, and N_0 is the electrical noise power. The turbulence strength is characterized by C_n^2, which ranges from about 1×10^{-17} for very weak turbulence to 1×10^{-12} $m^{-2/3}$ or more for strong turbulence. Other parameters that characterize the physical conditions of the turbulence are the outer scale L_0 and the inner scale l_0 [6].

We show results for four cases. In all of them, the beam separation is 10 cm and the $1/e^2$ beam width is 4 cm. The collecting lenses of the simulated receiver have focal lengths 15 cm. The multi-mode fibers are assumed to have 50 µm core diameters, and the detector is 30 µm wide. Turbulence outerscale L_0 = 3 m and innerscale l_0 = 3 mm. For each BER evaluation, we generate many thousands of channel instances, and for each of these, we determine the channel coefficients and simulate the transmission of 10,000 bits. The received signals are corrupted by additive white Gaussian noise from the detector. In the first and second cases, the collecting apertures are 5 cm in diameter and the link distance is 1000m. The turbulence strength is C_n^2 = 2×10^{-13} $m^{-2/3}$ and $C_n^2 = 1\times10^{-12}$ $m^{-2/3}$, respectively. The BER versus electrical SNR for the first case is plotted in figure 3. The SNR gain obtained by using the 4x1 system over the 1x1 system is 9dB at BER=10^{-6}. The coding gain obtained in the second case, as shown in figure 4, is about 15dB at BER = 4×10^{-6}.

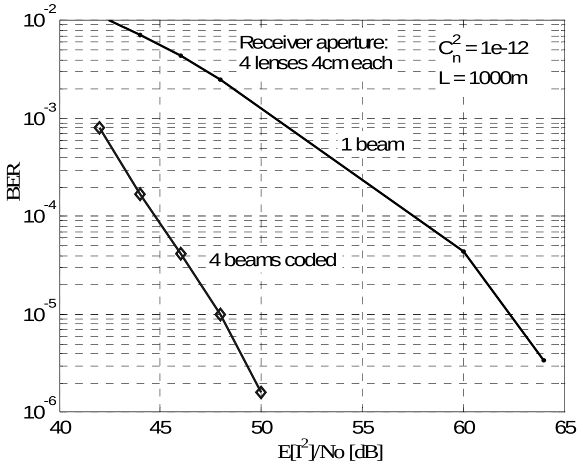

Figure 5. BER vs. SNR for C_n^2 = 1x10^{-12} and *L*= 1km. Receiver aperture is 4cm.

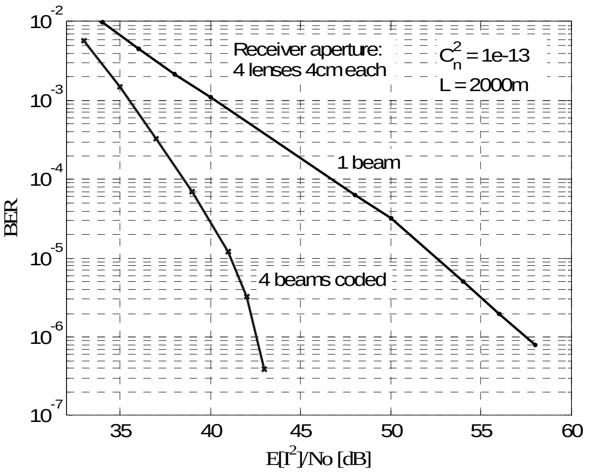

Figure 6. BER vs. SNR for C_n^2 = 1x10^{-13} and *L*= 2km. Receiver aperture is 4cm.

The third and forth cases were simulated using receiver apertures of 4 cm. The simulation conditions of the third case are like those of the second one, so they only differ in the receiver aperture. We observe a gain of 14 dB in SNR at BER = 10^{-5}, but the BER curves have shifted about 7 dB, due to the reduced collecting area. In the fourth case we have considered a turbulence strength of C_n^2 = 1x10^{-13} and a link distance of 2 km. Again, we observe a gain of about 15 dB at BER = 10^{-6}. We have performed other simulation to test see how sensitive this SNR gain is to beam separation, but we have not observed significant changes in performance if the beam separation is made larger in the strong turbulence regime. Gains from this or any other ST block codes are expected to be smaller under conditions of weaker turbulence and/or shorter link distance. However, by concatenating error-correction codes as outer codes to this ST block code we foresee additional coding gains that will make FSO a reliable alternative in wireless communication links.

5 Conclusions

By means of numerical simulations we evaluate the BER performance of a multi-beam free-space optical communication link. We observe that channel diversity is achieved with just a few centimeters of beam separation. We modify the decoding scheme of a space-time block code proposed for RF communications and apply it to the multi-beam FSO link. We obtain significant improvement in BER performance compared to a single-beam FSO link with the same signal power conditions.

6 Acknowledgements

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7 References

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