© 2015 IJSRSET | Volume 1 | Issue 1 | Print ISSN : 2395-1990 | Online ISSN : 2394-4099
Themed Section: Engineering and Technology

Performance Analysis of Space Time Block Codes for Free-Space Optical Channels

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ABSTRACT

Free Space Optic (FSO) Communication systems are ideal for setting up high speed short distance (a few kilometres) communication links. They have been in existence for more than two decades but have not gained widespread acceptance and popularity. This is primarily because they suffer from a serious handicap. Changing environmental conditions (atmospheric turbulence and fog) can drastically affect their throughput and reliability. Atmospheric turbulence can affect the FSO link in a manner similar to the impairments introduced by multi-path propagation (signal fading) in a wireless channel. It is well known that the random variation of signal strength due to fading in a communication channel can result in severe bit-error-rate (BER) performance degradation and an increase in the outage probability. This is a major challenge in all wireless communication systems and FSO Communication is not an exception. A number of receiver combining schemes and Space Time Block Codes (STBCs) have been designed to improve the performance of wireless communication systems over fading channels. In this paper, we have conducted numerical studies to determine the performance of the most widely used STBC (namely Alamouti code) over FSO channels perturbed by atmospheric turbulence. We have also employed a STBC derived from a non-binary cyclic code in this application. It is seen that the use of these codes can increase the transmission range for a given link margin and/ or result in substantial improvement in reliability of information transfer for a fixed link margin. These inferences have been arrived at after conducting large scale numerical simulations to determine channel fading losses and bit error rates for different channel conditions.

Keywords: Free Space Optic (FSO) , Space Time Block Codes (STBCs), Alamouti code

I. INTRODUCTION

FSO communication is a technology that has now been in existence for about two decades. FSO systems have the potential to provide high data-rate communication with the advantages of quick deployment times, high security and no frequency regulations. These features have resulted in FSO becoming a unique technology within the domain of wireless communication. FSO systems have the potential to be applied in a wide range of applications, from short-range wireless communication links providing network access to portable computers, to last-mile links bridging gaps between end users and existing fiber optic communications backbones, and even laser communications in outer-space links. Free space optics relies on line of sight optical communication. Typically, two specialized telescopes face each other, each having a transmitting and receiving unit, allowing bi-directional communication. On one end, a modulated optical signal is generated similar to that within a traditional fiber optic system. The optical signal is amplified through an optical amplifier, and routed to the transmitting optics in the telescope, where it is then beamed through the atmosphere. On the receiving side, the light beam is collected through the receiving telescope, optionally amplified, and then detected (converted to an electrical signal). Communication is performed identically in the other direction, and transmitters and receivers can share the same telescope.

TERRESTRIAL FSO:

For a typical FSO terrestrial link, the operating distance can range from a few hundred meters up to four kilometers. FSO links require line of sight and thus an unobstructed point-to-point straight path. In most applications, the beam path is at high elevation from the ground level and thus, the invisible laser beam is not easily accessible. As such, FSO is inherently more “secure” than other transmission methods. FSO technology typically uses two laser photo-detector transceivers to establish line of sight duplex point to point link without a guiding medium (fiber). Typically FSO links carry information at rates ranging from 10 Mbps to 2.5 Gbps, with the data rate being expected to increase to 10 Gbps. The transmitter is usually a laser diode or Vertical-Cavity Surface-Emitting Laser (VCSEL) device (optical transmit power -8dBm). The receiver typically comprises of a Si Photo diode (PD) or Avalanche Photo Detector (APD). The selection of appropriate wavelength in FSO technology is an important issue. The most common wavelengths used for optical communication range from 0.85 μm to 1.55μm. Many FSO installations utilize 0.78μm, 0.85 μm and lately 1.55 μm beams.

Despite having been around for more than two decades, FSO has not emerged so far as a credible alternative to conventional optical fiber links over short distances. This situation should be rectified because FSO technology is well suited for deployment in high speed-short distance communication links because laying of optical fiber in densely populated urban areas can be a serious problem. Random fluctuations in the propagation medium, namely free space pose the most significant obstacle to the widespread adoption of these systems. Various environmental challenges for FSO include absorption, scattering, building sway, and scintillation. In-homogeneities in the temperature and pressure of the atmosphere lead to spatial and temporal variations in optical intensity incident on a receiver (scintillation), resulting in fading. The range is particularly limited if fog/smog and clouds are present in the atmosphere. Atmospheric effects can cause performance degradation manifested by increased bit error rate (BER) and transmission delays. Physical obstructions like birds flying across the line of sight (LOS) path can cause temporary outages and transmit power can be limited due to eye-safety considerations. Despite having significant benefits, these limitations have prevented this technology from gaining widespread acceptance as a worthwhile competitor to guided optical communications. However, FSO technology can provide reliable high speed data transmission with careful link design, choice of deployment location, use of channel coding and MIMO techniques.

II. METHODS AND MATERIAL

Space–time block code:

Space–time block coding is a technique used in wireless communications to transmit multiple copies of a data stream across a number of antennas and to exploit the various received versions of the data to improve the reliability of data-transfer. Since the transmitted signal through different channel conditions, some of the received copies of the data will be better than others. Space–time coding combines all the copies of the received signal in an optimal way to extract as much information from each of them as possible.

Orthogonal space–time block code is designed such that the vectors representing any pair of columns taken from the coding matrix are orthogonal. The result of this is simple, linear, optimal decoding at the receiver.

Alamouti's code:

Alamouti invented the simplest of all the STBCs in 1998. This is a rate-1 code. It takes two time-slots to transmit two symbols. Its bit-error rate (BER) is equivalent to 2nR-branch maximal ratio combining (MRC). It is the only orthogonal STBC that achieves rate-1. That is, it is the only STBC that can achieve its full diversity gain without needing to sacrifice its data rate.

The significance of Alamouti's proposal is that it was the first demonstration of a method of encoding which enables full diversity with linear processing at the receiver. Furthermore, it was the first open-loop transmits diversity technique which had this capability.

Rayleigh distribution:

The Rayleigh probability density function is

$$f(x;\sigma) = \frac{x}{\sigma^2} e^{-x^2/2\sigma^2}, \quad x \geq 0,$$

for parameter $\sigma > 0$

Gamma–Gamma Distribution:

The gamma-gamma distribution model is a two-parameter distribution that is based on a doubly stochastic theory of scintillation that assumes that small-scale irradiance fluctuations are modulated by large-scale irradiance fluctuations of the propagating wave, both governed by independent gamma distributions. For a wide range of turbulence conditions (weak to strong) the fading gain in FSO systems can be modeled by a Gamma–Gamma distribution [3]

$$f_I(I_{mn}) = \frac{2(\alpha\beta)^{\frac{\alpha+\beta}{2}}}{\Gamma(\alpha)\Gamma(\beta)} I_{mn}^{\left(\frac{\alpha+\beta}{2}-1\right)} K_{\alpha-\beta}\left(2\sqrt{\alpha\beta I_{mn}}\right)$$

where parameters $\alpha, \beta > 0$ are linked to the scintillation index.

WORKING PRINCIPLE

Description of 2 X 1 Alamouti scheme:

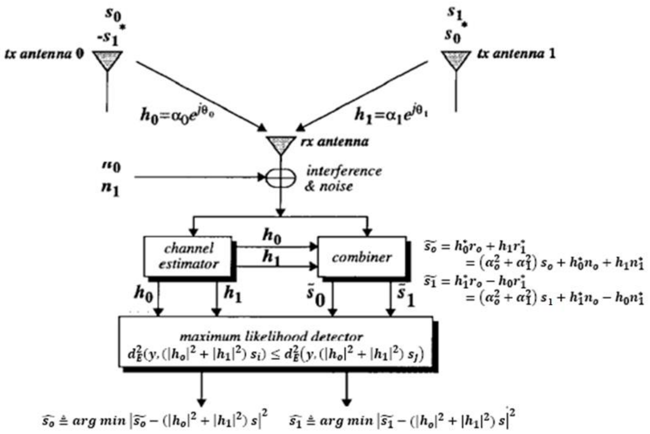

Figure 1: Alamouti Two-Branch Transmit Diversity with One Receiver

1) The Encoding and Transmission Sequence: At a given symbol period, the signal transmitted from antenna-0 is denoted by s_0 and from antenna-1 by s_1. During the next symbol period signal ($-s_1^*$) is transmitted from antenna-0, and signal s_0^* is transmitted from antenna-1, where * is the complex conjugate operation.

$$r_o = r(t) = s_o h_o + s_1 h_1 + n_o$$
$$r_1 = r(t+T) = s_o^* h_1 - s_1^* h_0 + n_1$$

where r_o and r_1 are the received signals at time t and t+T and $n_o$and n_1 are complex random variables representing receiver noise and interference.

2) The Combining Scheme: The combiner computes the following two combined signals that are sent to the maximum likelihood detector:

$$\tilde{s_o} = h_0^* r_o + h_1 r_1^* = (\alpha_0^2 + \alpha_1^2) s_o + h_0^* n_o + h_1 n_1^*$$

$$\tilde{s_1} = h_1^* r_o - h_o r_1^* = (\alpha_0^2 + \alpha_1^2) s_o + h_1^* n_o - h_o n_1^*$$

3) The Maximum Likelihood Decision Rule: The outputs of the combiner $\tilde{s_o}$ and $\tilde{s_1}$ are processed by a Maximum Likelihood Decoder (MLD) to determine the most likely transmitted symbols $\hat{s_o}$ and $\hat{s_1}$. This operation is expressed mathematically as,

$$\hat{s_o} \triangleq \underset{s\,\epsilon S}{argmin} |\tilde{s_o} - (|h_o|^2 + |h_1|^2)s|^2$$

$$\hat{s_1} \triangleq \underset{s\,\epsilon S}{argmin} |\tilde{s_1} - (|h_o|^2 + |h_1|^2)s|^2$$

The reconstructed symbol stream at the receiver is now compared with the transmitted symbol stream to determine the BER under various turbulence conditions and signal to noise ratios.

Description of 2X2 Alamouti scheme:

In applications where it is feasible to employ multiple receivers, we can improve the error performance of the FSO system further, by using two antennas at the receiver end also. Therefore we have considered Alamouti 2X2 scheme next. Employing more than two antennas at the transmitter/receiver end increases the decoding complexity significantly. Hence we have studied STBCs derived from non-binary cyclic codes next, instead of Alamouti schemes of higher order, to improve the error performance further.

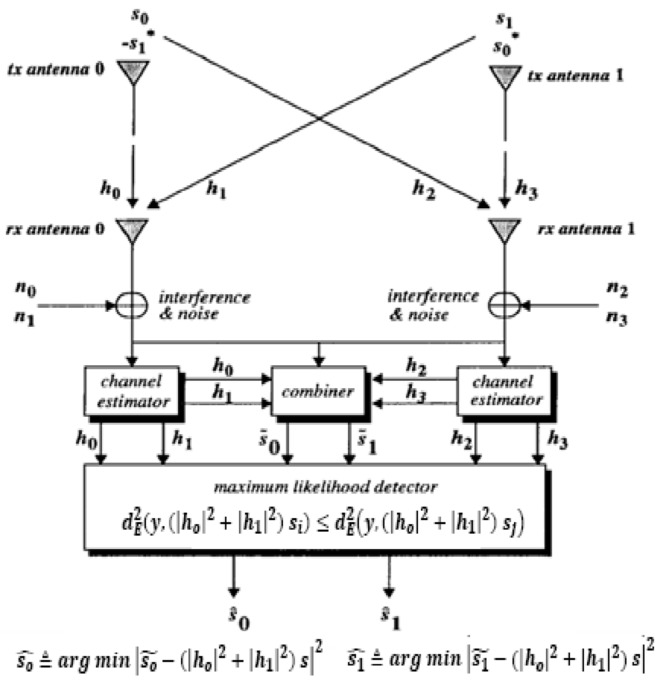

Figure 2: Alamouti Two-Branch Transmit Diversity with Two Receivers

1) The Encoding and Transmission Sequence: At a given symbol period, the signal transmitted from antenna-0 is denoted by s_0 and from antenna-1 by s_1. During the next symbol period signal ($-s_1^*$) is transmitted from antenna-0, and signal s_0^* is transmitted from antenna-1, where * is the complex conjugate operation.

$$r_o = s_o h_o + s_1 h_1 + n_o$$
$$r_1 = s_o^* h_1 - s_1^* h_0 + n_1$$

$r_2 = s_o h_2 + s_1 h_3 + n_2$
$r_3 = s_o^* h_3 - s_1^* h_2 + n_3$

Where r_o and r_1 are the received signals at receiver-0 at time t and t+T, r_2 and r_3 are the received signals at receiver-1 at time t and t+T and n_o, n_1, n_2, n_3 are complex random variables representing receiver thermal noise and interference.

2) The Combining Scheme: The combiner computes the following two combined signals that are sent to the maximum likelihood detector:

$$\tilde{s_o} = h_0^* r_o + h_1 r_1^* + h_2^* r_2 + h_3 r_3^* = (\alpha_o^2 + \alpha_1^2 + \alpha_2^2 + \alpha_3^2) s_o + h_0^* n_o + h_1 n_1^* + h_2^* n_2 + h_2 n_2^*$$

$$\tilde{s_1} = h_1^* r_o - h_0 r_1^* + h_3^* r_2 - h_2 = (\alpha_o^2 + \alpha_1^2 + \alpha_2^2 + \alpha_3^2) s_o + h_1^* n_o - h_0 n_1^* + h_3^* n_2 - h_2 n_3^*$$

3) The Maximum Likelihood Decision Rule: The decision criteria of the maximum likelihood decoder is expressed mathematically as,

$$\hat{s_o} \triangleq \underset{s \in S}{argmin} |\tilde{s_o} - (|h_o|^2 + |h_1|^2 + |h_2|^2 + |h_3|^2) s|^2 \hat{s_1} \triangleq \underset{s \in S}{argmin} |\tilde{s_1} - (|h_o|^2 + |h_1|^2 + |h_2|^2 + |h_3|^2) s|^2$$

Modified Alamouti code:

When the modulation scheme being used in FSO is unipolar like OOK or PPM, the complement of a signal x_i defined by $\bar{x}_i$, is the signal waveform obtained by reversing the roles of "on" and "off." For example if $x_i = s_i$, then $\bar{x}_i = -x_i + A = -s_i + A$ where A is the amplitude of the transmitted signal corresponding to the "on" state. Also, since we deal with real signals, complex conjugate concept is absent.

III. RESULTS AND DISCUSSION

Comparison of the Alamouti Scheme and STBCs derived from non-binary cyclic code

We have compared the error correcting performance of the Alamouti Scheme and the STBC derived from non-binary cyclic code in 2X1 and 2X2 configurations, under typical and strong turbulence channel conditions, in the figures 6 and 7 respectively.

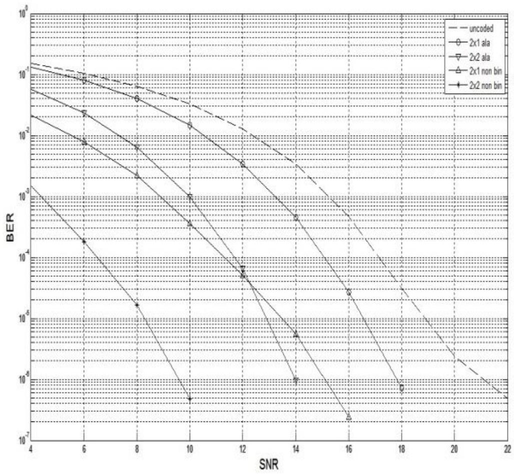

Figure 3: Comparison of Alamouti scheme and STBCs derived from cyclic codes under typical turbulence channel conditions

We observe that the STBCs derived from cyclic codes achieve a given BER at lower SNRs than the corresponding Alamouti codes. Hence we can use these coding schemes to improve the error performance of an FSO system at a fixed transmit power or to reduce the transmit power required to achieve a given BER requirement.

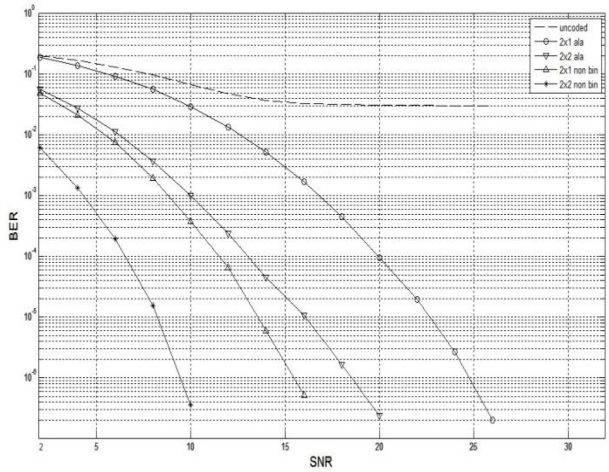

Figure 4: Comparison of Alamouti scheme and STBCs derived from cyclic codes under strong turbulence channel conditions.

This graph indicates that communication with acceptably low bit error rate (BER $\leq 10^{-5}$) is not possible through a channel of strong turbulence without the use of error control codes. The Alamouti scheme and STBCs derived from non-binary cyclic codes enable us to achieve the required low BER. We observe that BER=10^{-6} can be obtained at a SNR of 9dB if 2X2 STBC derived from cyclic code is employed, and at a SNR of 15dB if 2X1 STBC derived from cyclic code is employed, at a SNR of 18dB if 2X2 Alamouti scheme is used and at a SNR of 25dB if 2X1 Alamouti scheme is employed.

Table 1: Coding gain of STBCs derived from cyclic code over Alamouti code

BER	Gain (dB) for 2x2 STBC over 2x2 Alamouti	Gain (dB) for 2x2 STBC over 2x2 Alamouti
10^{-5}	8 dB	9 dB
10^{-6}	9 dB	9.5 dB

It is apparent from this plot that an FSO system employing the STBCs derived from cyclic codes provides substantial coding gain over the corresponding Alamouti scheme. This would translate into reduced transmit power requirement. Given that a coding gain of 8 dB implies a reduction in transmit power requirement by a factor of 0.158, it is apparent that the use of suitable Space Time Codes can make terrestrial FSO links practically deployable over a wide range of distances and applications. The use of suitable channel codes can ensure that FSO links can be used to communicate at high speeds over adverse environmental conditions while simultaneously complying with eye safety regulations.

IV. Conclusion

In conclusion, we feel that FSO technology aided by suitable channel coding techniques can be used to realize reliable high speed communication short distance links across distances less than four kilometres under good as well as adverse weather conditions with the level of data integrity being as good as is required by the application. This development can help in widespread deployment of this attractive technology with its benefits of enabling high data-rate communication with the advantages of quick deployment time, high security and no spectral licensing requirements.

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