Terrestrial Free Space LDPC Coded MIMO Optical Link

Harinder Sandhu, D. Chadha

***Abstract* – In the present paper we study a terrestrial, line-of-sight free space optical (FSO) communication link using non-repetitive MIMO scheme with On OFF Keying (OOK) signal over turbulent propagation medium described by Gamma-Gamma PDF channel. Due to its underlying low complexity, VBLAST-ZF (Vertical Bell Labs Layered Space Time Zero Forcing) detection mechanism is exploited at the receiver side to increase overall spectral efficiency and channel capacity. The variable rate Low Density Parity Check (LDPC) codes are employed to enhance the performance of the link.**

Index Terms: **FSO, LDPC, MIMO, VBLAST.**

I. INTRODUCTION

FSO is one of the future technologies of wireless networks as it meets most of the quality parameters at low implementation cost. The future emerging wireless networks over high-speed FSO based links for last-mile provisioning applications have a bright prospect [1]. The atmospheric optical systems are strongly influenced by the atmospheric molecular absorption, aerosol scattering, and turbulence. The system capacity can be increased in rich scattering environment by using Multi Input Multi Output (MIMO) scheme [2]. MIMO systems exhibit various significant gains, which can be distinguished as diversity gain, multiplexing gain, and array gain. An optical MIMO system employs an array of lasers and of the photodetectors on the transmitter and receiver side, respectively. The elements of the detector array comprise PIN/APD detectors as desired by the system design. Total power level of the input data stream can be distributed over all the elements in a repetitive or non-repetitive fashion. The non-repetitive MIMO is spectrally more efficient as compared to repetitive case but on the expense of system reliability.

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D. Chadha is with Department of Electrical Engineering, Indian Institute of Technology, New Delhi-110016, India.(phone: 91-11-26591075, fax: 91-11-26591075, dchadha@ee.iitd.ac.in)
Harinder Sandhu is with Department of Electrical Engineering, Indian Institute of Technology, New Delhi-110016,

Using error-correcting codes can increase the performance of the optical wireless links. In this work strong LDPC codes [3] are employed to enhance BER performance and reduce the link outage. The LDPC codes if designed properly can give performance up to the Shannon's limit.

This work proposes a power efficient optical link design, based on a non-repetition MIMO system to mitigate the effects of fading and turbulence, thereby increasing the channel capacity through spatial multiplexing. Variable rate LDPC codes are used to enhance the performance of the system.

The remainder of the paper is organized as follows. In section II, we review the channel model used in this work. Gamma-Gamma PDF channel model is used based on the Kolmogrov theory. Section III deals with the basic link used in this work, the modulation scheme and the VBLAST detection algorithm. Section IV describes the LDPC codes and in Section V the performance of the OOK modulate signal with and without LDPC codes is compared and section VI gives the conclusion of the work carried out.

II. CHANNEL MODEL

The medium of propagation or the channel dictates the performance of a communication link in the wireless domain. Therefore, to design a high-performance communication link for the FSO, it is of great importance to characterize the channel from the perspective of information theory. Optical communication depends most significantly on channel variations due to turbulence. In this regard, various channels models based on statistical concepts have been developed [4] utilizing the measured link performance in various conditions of turbulence, like Log Normal and Exponential which closely approximate the results of weak and strong turbulence conditions. However, Gamma-Gamma PDF closely models' experimental results over low to high turbulence strengths and is most suitable for studying link performance parameters for slow fading conditions. The propagation through this channel model is based on Kolmogrov theory of turbulence [5, 6] in which kinetic energy from larger to smaller eddy is transferred without loss. Refractive index varies rapidly across eddies causing phase and amplitude variations to the wavefront. The strength of turbulence is given by the Rytov variance, $\sigma_R^2 = 1.23 C_n^2 k^{7/6} L^{11/6}$ which represents the scintillation index of an unbounded plane wave, where $k = 2\pi/\lambda$ is the wave number, is wavelength, L is the propagation distance and C_n^2 is the refractive index structure parameter.

The irradiance of optical field is defined as the product of two random processes, i.e., $I = I_x I_y$, where I_x arises from large scale turbulent eddies and I_y from small-scale eddies. Specifically, gamma pdf is used to model both small scale and large scale fluctuations, leading to the so-called gamma-gamma pdf, i.e.

$$f(I) = \frac{2(\alpha\beta)^{(\frac{\alpha+\beta}{2})}}{\Gamma(\alpha)\Gamma(\beta)} I^{(\frac{\alpha+\beta}{2}-1)} K_{\alpha-\beta}(2\sqrt{\alpha\beta I}) \quad (1)$$

Where, I is the signal intensity (I>0), α and β are parameters of PDF given by equations 2 and 3 below, Γ is the Gamma function and $K_{\alpha-\beta}$ is the modified Bessel function of the second kind of order .

$$\alpha = \left(\exp[\frac{0.49\sigma_R^{\ 2}}{(1+1.11\sigma_R^{\ 12/5})^{5/6}}]-1\right)^{-1} \quad (2)$$

$$\beta = \left(\exp[\frac{0.51\sigma_R^{\ 2}}{(1+0.69\sigma_R^{\ 12/5})^{5/6}}]\right)^{-1} \quad (3)$$

Besides the gamma-gamma channel model, we assume that the spatial coherence distance of the fields at the detector is large relative to the size of one detector, but the field is independent across detectors. We also assume the channel is slow fading frequency nonselective. Hence the channel is taken to be flat over many symbol or block of symbols.

III. WIRELESS FSO SYSTEM

In wireless, MIMO systems are known to provide higher capacity and throughput than SISO. Several schemes have been proposed for MIMO in the RF domain and they differ in the complexity at transmitter or the receiver or both. In an Optical MIMO system, as depicted in Fig. 1, input data is first de-multiplexed into M different sub streams and is then OOK modulated independently. Different laser transmitters are used to couple these streams to the channel, which is a gamma-gamma channel, modeled for a distance of 1 km.

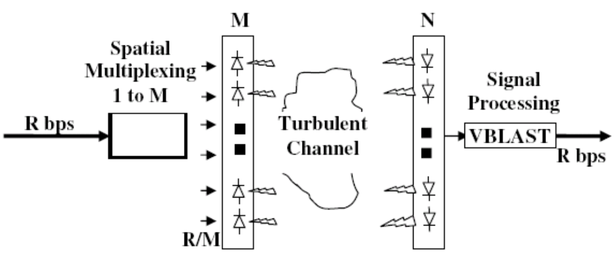

Figure 1. Basic Link Setup for FSO MIMO using VBLAST-ZF Processing at the Receiver

At the receiver the signal is converted back to electrical signal which is affected by noise. The detector array is simultaneously illuminated with each data stream signal and the space time signal processing using V-BLAST technique [7, 8] is carried out to cancel out their interference by successive cancellation. The individual streams are then demapped and multiplexed into a single stream of data. The impulse response of the atmospheric channel to the symbols propagating through it is superimposed in the form a random channel matrix, which has the dimensions of the order of the system diversity and follows the PDF as discussed above. The total power is restricted to P_o regardless of the number of transmit lasers M. The noise at the receiver comprises of the thermal noise, background noise and shot noise and assumed to be equal at the N receiver-detectors. Also, it is assumed that the thermal and background noise dominate in comparison with the shot noise, or the noise is signal independent. However, since the channel does not introduce any nonlinearity, the overall noise component can consider to be normally distributed.

In MIMO, each pair of transmitter and receiver is linked through an independently and identically distributed path. With this formulation of symbol propagation and reception, the decision at the receiver is hard or soft based on the received vector Y which is N-dimensional. The vector contains a mixture of interfering signals that have been received simultaneously. The basic vector equation that describes the channel with narrowband assumption is,

$$Y = HX + N_o \quad (4)$$

Where H is the channel matrix impulse response (Gamma-Gamma distributed) of M columns and N rows, X is M-dimensional transmitted signal vector and noise, N_o is N-dimensional Gaussian.

A. ON OFF KEYING

This is the simplest and most common form of ASK which operates as a switch, using the presence of a carrier wave to indicate a binary one and its absence to indicate a binary zero. The OOK modulation scheme is used for its easy implementation. The transmitter, operating at a bit rate R_b, emits rectangular pulses of duration $1/R_b$ and intensity 2P to generate bit 'one', and no pulse to generate bit 'zero'. The bandwidth required by OOK is approximately $R_b = 1/T$, the inverse of the pulse width. Assuming matched filtering with a maximum likelihood receiver, the bit error rate (BER) of an OOK system is:

$$BER_{ook} = Q\left(\frac{P}{\sqrt{N_0 R_b}}\right) \quad (5)$$

Where N_0 is the power spectral density of the white Gaussian noise and Q (x) is the Q-function.

In a terrestrial FSO link, there is a limitation of peak power rather than the average power. Hence OOK modulation scheme is used in this work. It is also bandwidth efficient and can be directly implemented with any linear block-coding scheme.

B. VBLAST Detection Algorithm [7], [8]

MIMO detection can be most efficiently carried out using ML (Maximum Likelihood) decoding but demands a highly complex implementation and is therefore not cost effective as it tends to cause large delay in processing. MAP (Maximum Aposteriori Probability) using sphere decoder carries out search over a smaller domain and thus reduces the complexity of ML while providing same performance. Among the many sub-optimal schemes suggested, VBLAST with Zero Forcing (VBLAST-ZF) offers ML like performance at reduced complexity.

VBLAST works on the principle that transmitters operate co-channel and symbol synchronized using same modulation schemes for transmitting independent data sub streams. The channel information being known only at the receiver, there is no power adaptation at the transmitter side, i.e. equal power levels are radiated at each transmitter in a scaled manner so that the total power remains constant irrespective of the number of transmitters. V-BLAST is a recursive procedure in which we decode the “strongest” signal first, then subtracting this strongest signal from the received signal, proceed to decode the strongest signal of the remaining transmit signals, and so on. The optimum detection order in such a *nulling and cancellation* strategy is from the strongest to the weakest signal.

IV. LOW DENSITY PARITY CHECK CODES

Low-density parity-check (LDPC) codes proposed by Gallager in the 1960’s, and later discovered by Mackay and Neal appears as a class of codes that can yield very good performance near Shannon limit and are suited for implementations that make heavy use of parallelism. They are a class of linear block codes. These codes are constructed with the help of a parity check matrix, which is sparse, i.e., it contains only a few 1’s in comparison to the number of 0’s in the rows as well as columns. The performance of LDPC code depends on the decoding complexity, which is directly related to the density of 1s in this matrix.

In this work, we use LDPC codes [3] over MIMO antenna systems over a flat fading channel modeled as Gamma-Gamma pdf, which satisfies the shallow and deep turbulence regimes. V-BLAST detection is used, which has the limitation of error propagation [7] resulting in the poor SNR of first detected data streams. Therefore, variable rate LDPC codes are used. This can overcome the problem by assigning LDPC codes with different code rate to each transmitter. By assigning stronger LDPC codes in lower layer reduction in error propagation can be faciliated. Different parity check matrices are employed for generating these codewords.

We consider a simple detection technique, which is called the QR decomposition interference suppression combined with interference cancellation [9], [10]. The channel matrix H can be factored by the QR decomposition into an orthonormal matrix Q and an upper triangular matrix R such that H = QR. When QR decomposition interference suppression combined with interference cancellation is used over independently and identically distributed turbulence channel. The simulations have been carried out over (2,2) and (4,4) MIMO systems. The aim of implementing different parity check matrices for codewords corresponding to each layer is to avoid lower number of ones in the columns of higher rate parity check matrices, as this will render these codes unsuitable for detection by Belief Propagation algorithm. The higher rate LDPC codes have been produced by drawing submatrices from the parent irregular parity check matrix by row elimination after converting it into a lower triangular form. The codewords so generated are having the same code lengths though the code rates are different. This implies that the lower layers correspond to higher rate codes to minimize the error propagated through V-BLAST detection.

V. SIMULATION RESULTS

The simulations were performed in the Matlab environment using 1550 nm wavelength, peak power limited transmitters with OOK modulation, over low turbulence strength of 0.1. BER performance was studied for (2, 2) and (4, 4) system using variable rate LDPC code with block length 200 and 1008. A fixed link length of 1 km in terrestrial domain was used.

Fig. 2 shows the block diagram of the simulator implementation using variable rate LDPC encoders.

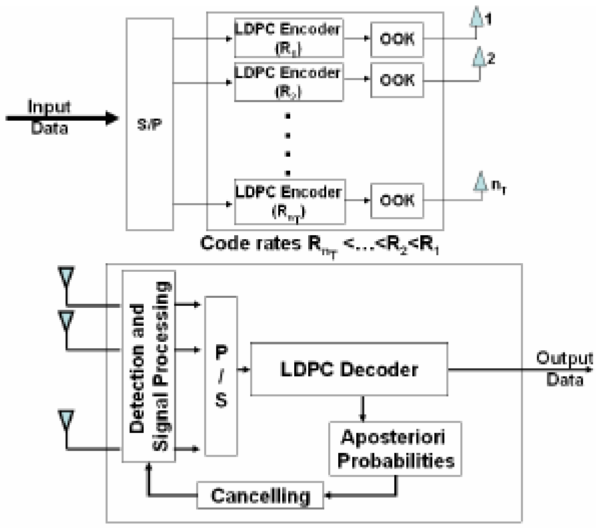

Fig.2 Block diagram of variable rate LDPC coded systems

Fig 3 shows improvement in performance of a variable rate LDPC coded system with 2 degrees of freedom in MIMO over the uncoded case. The code rates employed are 0.665 and 0.58 for transmit antennas 1 and 2, respectively. At a BER value of 10^{-4} an improvement of 4 dB and 9 dB could be obtained over the uncoded channel for the code lengths of 200 and 1008, respectively. Similar simulation results are shown in Fig.4 for a (4, 4) variable rate system. For system having degree of freedom 4, code rates are 0.75, 0,665, 0.58 and 0.5 for transmit antenna 1, 2, 3 and 4, respectively.

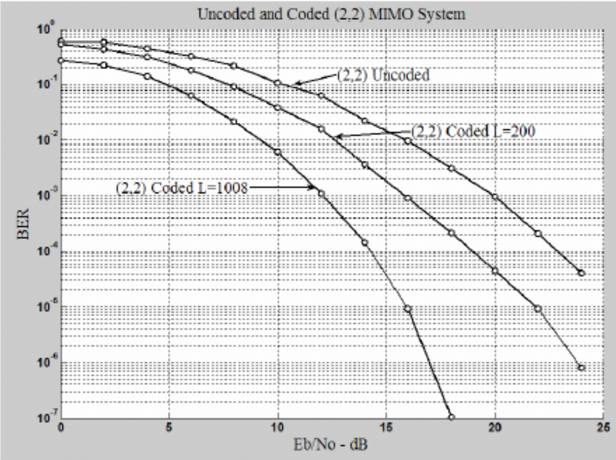

Fig 3 BER vs SNR for (2,2) System

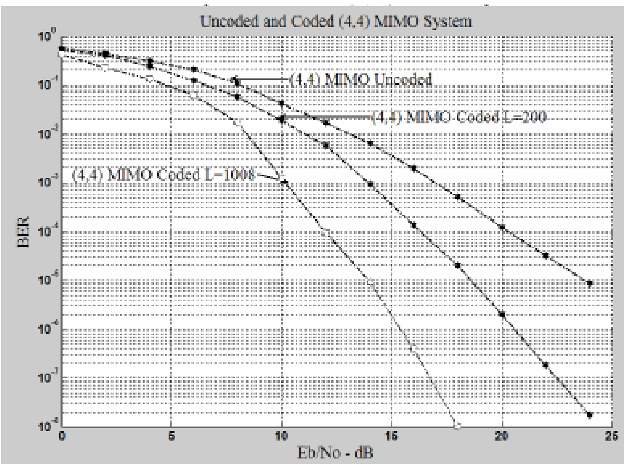

Fig. 4 BER vs SNR for (4,4) MIMO system.

VI. CONCLUSION

The performance of non-repetitive MIMO optical link with channel characterized by gamma-gamma PDF has been carried out. In order to increase the robustness of the system error correcting LDPC codes have been added. The layered space time architecture based VBLAST-ZF detection is chosen in this work to overcome the complexity of ML detection. As VBLAST-ZF has a limitation in the form of error propagation to the subsequent layers, variable rate LDPC codes are used to overcome this. Simulation results show significant improvement in the performance of the system over the uncoded case. A higher order of degree of MIMO system gives further more performance improvement in terms of BER as compared to the uncoded case of same order with VBLAST system. This is attributed to the additional variability in the rates of LDPC codes that is included in the coded case.

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