Performance of Alamouti Space Time Codes in an Optical Uplink Channel

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***Abstract*—The optical uplink, ground station to satellite, is more susceptible to signal fading compared to the downlink channel due to beam wandering experienced at the transmitter in the ground station. Alamouti space time codes have been used to partially mitigate this handicap. With the use of these codes, a bit error rate(BER) of 1×10^{-8} can be achieved for a link margin of 6dB. A transmitter beam radius of 47cm and a receiver diameter of 1m are noted to be suitable for the uplink optical system with transmitter at an altitude of 2.5km from the ground and the satellite at a zenith angle of 0^0. The performance of the Alamouti codes is simulated in MATLAB 2006b and analyzed for one, two and four receivers and the use of 2×2 is proposed in this work, since the deployment of four receivers at the satellite does not seem practical. It is demonstrated that a 2×2 Alamouti space time code achieves a total gain of 6dB when convolutional coding and QPSK modulation are used whereas a gain of about 5dB is achieved by using 8PSK or 16QAM. Link Budget analysis of the uplink scenario suggests that the proposed method reduces the required transmitter power from 24.883kW to 6.2207kW.**

***Index Terms*—Alamouti space time codes, optical uplink, link budget analysis**

I. Introduction

Free space optical communication from optical ground station to satellite has been an interesting challenge compared to the downlink due to the atmospheric effects. As the transmitting beam enters the atmosphere, the turbulence starts affecting the beam in the form of turbulent eddies. Even the smallest turbulent eddy at the ground station is sufficient enough to fade the optical beam completely along the beam width. This causes the optical axis of the beam to randomly change from its initial position, a phenomenon called Beam Wander. It is more pronounced in uplink channel since it suffers from significant turbulence from the initial stage of communication. Whereas the signal propagating through downlink channel is affected by turbulence only during the last stage of its propagation, which effects only a small area of cross section of the optical beam. Hence, a transmitter communicating with a satellite requires to send more transmitter power, about $6.28 \times 10^8 W/sr$ [1] when On Off Keying(OOK) is used.

Channel modeling of the optical uplink channel has been done in [8]. The work in this paper by L.C.Andrews et.al. suggests the use of a scintillation index which considers the effect of turbulence in the uplink channel. Though the scintillation index is calculated differently for uplink and downlink, the effect of beam wander is not considered in this work. [12] and [3] have proposed the use of exponential distribution with an inclusion of beam wander effect. Though the turbulence and beam wander are expressed in a simple closed form expression, the dependence of the expression on the radial parameter r makes it more complicated. Researchers in [1] and [6] have proposed the use of a joint probability density function which expresses the turbulence in log normal distribution and the beam wander in beta distribution. Though the expression is not in its closed form, its dependence on simple variables like the mean intensity, scintillation index and β apart from the random variable irradiance makes it simpler to model the channel. Thus, without ignoring the beam wander effect and compromising the complexity of the distribution, a simple expression for the optical uplink channel has been chosen.

Jiachen Ding et.al. in [19] have proposed the optical signal beam modulated by MSK for an operating wavelength of 800nm. This work considers wavelength of 1.55μm which is less affected by attenuation in the atmosphere than 800nm. We propose the use of Alamouti space time codes along with 16QAM modulation scheme. Convolutional coding is used to reduce errors induced by the channel. The results help in designing the transmitter at the ground station depending on the transmitter power. Section-II describes the channel model of an optical uplink channel under weak turbulence and beam wander effects. The concept of space time codes proposed by Alamouti and modified Alamouti code for On-Off Keying modulation are discussed briefly in Section-III. In Section-IV, we have discussed various parameters of the link and the improvement that can be brought about by the use of Alamouti STC. The paper is concluded in Section-V.

II. Channel modeling

In the case of uplink, the turbulent eddies are larger than the size of the beam at the transmitter resulting in complete fading of the signal and also forcing the beam to wander about its mean position. The received power (irradiance) at the end of uplink is usually modeled using a log-normal distribution for weak turbulence regime and a gamma-gamma distribution in the strong turbulence regime. The optical compatibility tests conducted by the Japanese Aerospace Exploration Agency in

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2005, revealed that a bit error rate of 2.5×10^{-5} is achieved in case of uplink channel, whereas a bit error rate in case of downlink channel is found to be 5.6×10^{-10}, for nearly equal transmitter power. This difference in BER is due to additional effect of beam wander in case of optical uplink channel. Hence, this work considers a joint probability distribution function modeling turbulence as well as beam wander effects.

A. Turbulence

The effect of weak turbulence on the received intensity is considered using a normalized random variable I_u with log-normal distribution given by,

$$f_{I_u}(i_u)=\frac{1}{\sqrt{2\pi\sigma^2}i_u}exp\left(\frac{-(ln(i_u)-\mu)^2}{2\sigma^2}\right) \quad (1)$$

where, σ^2 is the scintillation index of the transmitting beam and μ is the mean intensity. The mean value of the irradiance μ is given by

$$\mu=\langle I(0,L)\rangle=\frac{W_0^2}{W_{LT}^2} \quad (2)$$

where $W_{LT}=W^2\left(1+(\frac{2\sqrt{2}W_0}{r_0})^{5/3}\right)$ [2].

The Gaussian wave model takes the radial variations into consideration in the optical beam, unlike the spherical wave model which only accounts to the uniform variations [3]. Hence, the scintillation index of the optical beam is calculated using a Gaussian wave model instead of the more common spherical wave model used in slant path modeling. The scintillation index of an uplink consists of two components, on-axis $\sigma_I^2(L)$ and radial $\sigma_I^2(\mathbf{r},L)$ scintillation indices. However, due to beam flattening [2], the radial part of the scintillation index will be negligible for a smaller radial distance r particularly when $r<\sigma_{pe}$(pointing error variance) i.e., when the point received is within the beam flattened area [3]. Therefore, the total scintillation index , equal to the longitudinal or on-axis scintillation index is given by [8],

$$\sigma_I^2(L)=34.29\left(\frac{\Lambda L}{kr_0^2}\right)^{5/6}\left(\frac{\sigma_{pe}}{W}\right)^2+exp(\sigma_{lnX}^2+\sigma_{lnY}^2)-1 \quad (3)$$

$$\sigma_{lnX}^2=\frac{(0.49\sigma_{Bu}^2)}{\left(1+(1+\Theta)\sigma_{Bu}^{12/5}\right)^{7/6}} \quad (4)$$

$$\sigma_{lnY}^2=\frac{(0.51\sigma_{Bu}^2)}{\left(1+0.69\sigma_{Bu}^{12/5}\right)^{5/6}} \quad (5)$$

with σ_{Bu}^2 being the longitudinal scintillation index without considering the beam wander [3] given by,

$$\sigma_{Bu}^2=8.7\mu_u k^{7/6}(H-h_0)^{5/6}sec^{11/6}?(\zeta) \quad (6)$$

$$\mu_u=Re\left[\int_{h_0}^{H}C_n^2(h)\xi^{5/6}\Lambda\xi+j(1-\Theta\bar{\xi})^{5/6}-\Lambda^{5/6}\xi^{5/3}dh\right] \quad (7)$$

$$\xi=1-\frac{h-h_0}{H-h_0} \quad (8)$$

the atmospheric coherence width or the Fried's parameter [4],

$$r_0=\left[0.423k^2sec(\zeta)\int_{h_0}^{H}C_n^2(h)dh\right]^{-3/5},H>>20km \quad (9)$$

the pointing error variance for a collimated beam [5],

$$\sigma_{pe}^2=\langle r_c^2\rangle\left[1-\left(\frac{\pi^2W_0^2/r_0^2}{1+\pi^2W_0^2/r_0^2}\right)^{1/6}\right] \quad (10)$$

with the beam wander variance which causes the deviation from the original transmitting beam given by,

$$\langle r_c^2\rangle\approx0.54L^2\left(\frac{\lambda^2}{2W_0^2}\right)^2\left(\frac{2W_0}{r_0}\right)^{5/3} \quad (11)$$

where h_0 is the height of the transmitter, W_0 is the transmitter beam radius, L is the link distance, H is the altitude at which the satellite is located from the ground, ξ is the zenith angle, λ is the operating wavelength of the optical system and k is the optical wave number. The parameters Λ and Θ are called the curvature parameter and the Fresnel ratio at the receiver respectively, which depend on similar parameters at the transmitter, represented by Ω_0 and Ω respectively. The parameter $W=W_0\sqrt{(\Omega_0^2+\Omega^2)}$ is the beam width at the receiver. The effect of refractive index fluctuations due to atmosphere represented by C_n^2 depends on height,h, for a slant path. The most common Hufnagel-Valley model is used to represent the refractive structure parameter.

Scintillation index is calculated assuming a point receiver at the satellite. When a receiver of finite diameter is used at the satellite, it receives a number of patches of the optical signal which will be integrated over the area of the receiver diameter. This effect of receiving several speckles of the optical beam improves the received signal power and is called the Aperture averaging effect. It is estimated by the Aperture averaging factor A for a given receiver diameter D given by,

$$A=\frac{16}{\pi}\int_0^1 xexp\left[-\frac{D^2x^2}{r_0^2}(2+\frac{r_0^2}{W_0^2\Omega^2}+\frac{r_0^2\phi^2}{W^2})\right](arccosx-x\sqrt{1-x^2})dx. \quad (12)$$

where

$$\phi=\frac{\Omega W_0^2}{r_0^2}+\frac{\Omega_0}{\Omega} \quad (13)$$

B. Beam Wander

Toyoshima et.al. [1] have proposed that the received intensity due to random jitter can be modeled by a random variable I_g, which is a special case of Beta random variable [6] [7] given by,

$$f_{I_g}(i_g)=\beta i_g^{(\beta-1)},\beta>0 \quad (14)$$

where the value β is given by [8],

$$\beta=\sqrt{(1+\frac{exp(\sigma_{lnX}^2+\sigma_{lnY}^2)}{(34.29(\Lambda L/kr_0^2)^{5/6}(\sigma_{pe}/W)^2)})-1} \quad (15)$$

The probability distribution function $f_{I_t}(i_t)$ considering the effects of both the turbulence and the beam wander is specified by

$$f_{I_t}(i_t) = Q\left(\frac{(ln(I_t) + \sigma_I^2(\beta + 1/2))}{\sqrt{2}\sigma_I}\right) \times \beta exp\left[\frac{\sigma_I^2}{2}\beta(\beta+1)\right] {I_t}^{\beta-1} \quad (16)$$

where the parameters, σ_I^2 denotes the scintillation index and β is a random variable that describes the effect of beam wandering. The optical signal received is modeled using this joint probability distribution function in this work.

III. Alamouti space time codes

The Alamouti space time code sends symbols in two consecutive symbol periods where the channel is assumed to be static. The receiver uses both these symbols from the two transmitters to decode the transmitted symbols. For a 2×1 ASTC(Alamouti Space time code), the symbols sent at two consecutive intervals from the two transmitters are given by the matrix [9],

$$\begin{pmatrix} s_0 & s_1 \\ -s_1^* & s_0^* \end{pmatrix}$$

The first row indicates the symbols sent through first and second transmitters during the first symbol period and the second row indicates the symbols from the transmitters during the second symbol period. The receiver is assumed to know the perfect channel state coefficients which provides them to a combiner. The combiner decouples the signals from the two transmitters by calculating the estimates of the two symbols $\widetilde{s_0}$ and $\widetilde{s_1}$ at the receiver. Finally, the maximum likelihood decoder computes the most likely symbol for a given estimate and the symbol set.

For a Rayleigh fading and additive white Gaussian noise channel, the Alamouti space time coding has achieved 30 dB improvement compared to no diversity case and 11 dB improvement compared to maximal ratio receiver combining (MRRC) at a bit error rate of 10^{-5} with one receiver [9]. This advantage of Alamouti scheme is exploited to improve the bit error rate at the receiver of an optical uplink channel. In [10], Simon et.al. investigated the modification of Alamouti code for OOK technique commonly used in optical channels. The modified Alamouti code is given by,

$$\begin{pmatrix} s_0 & s_1 \\ \overline{s_1} & s_0 \end{pmatrix}$$

where $\overline{s_1}$ is the complement of s_1. Thus, only two symbols 0 and 1 are transmitted from the transmitter. The receiver works in a similar way except for a different symbol set.

TABLE I
OPERATING CONDITIONS

PARAMETER	VALUE
Wavelength	$1.55\mu m$
Height of the Transmitter	$2.5km$
Altitude of the satellite	$38.5 \times 10^3 km$
Link distance	$40,000km$
Transmitter beam radius	$47cm$
Receiver diameter	$1m$
Zenith angle	0^0
Curvature parameter(Ω_0)	1
Data rate	$3Gbps$

IV. Results and discussion

The operating parameters for the optical system simulated in this work are as mentioned in Table I. Two more important parameters to be chosen for this optical communication are the transmitter beam radius and the receiver diameter. The receiver diameter chosen decides the aperture averaging factor and hence the amount of signal averaged along the area of the receiver. Hence, the variation of aperture averaging factor with respect to receiver diameter, according to Equation(12) is studied as shown in Figure 1. As the Aperture averaging factor decreases, the effective scintillation index reduces. The aperture averaging factor reduces as the receiver diameter increases, significantly between $99cm$ and $100cm$ as shown in the figure. The aperture averaging factor at $0.99m$ is 0.002806 and at $1m$ is 7.221×10^{-5}, reduced by 10^3 times. A further reduction by the same factor occurs for a receiver with a diameter of $1.43m$. This needs an extra space of $43cm(40\%$ more) for the same advantage of 10^3 decrease in the parameter. Hence, a compromise between the aperture averaging and the space required on the satellite suggests the use of a receiver with $1m$ diameter.

Also, the required transmitter beam radius depends on the scintillation index and its components. These components like the pointing error variance, longitudinal scintillation index with and without considering beam wander, vary differently with respect to the transmitter beam radius [3] as shown in Figure 2. The pointing error variance and the component σ_{Bu}^2 decrease whereas the longitudinal scintillation index increases with an increase in the transmitter beam radius. A wider transmitter beam decreases the effective beam width,W_{LT} at the receiver as shown in the Figure 2. For example, $W_{LT} = 1.7km$ for $W_0 = 3cm$ whereas $1.088km$ for $13cm$ and $884.3m$ for $43cm$ of transmitter beam radii. However, increasing the transmitter beam radius to decrease the beam width at the receiver may not be possible as the scintillation index increases simultaneously. An optimum transmitter radius of $47cm$ is selected depending on the values of σ_{Bu}^2,σ_{IL}^2 and σ_{pe}^2.

The performance of Alamouti space time codes, is studied in an optical uplink channel with weak turbulence and beam wandering. The propagating optical signal is assumed to be affected by an additive white Gaussian noise in addition to the channel fading. Firstly, the behavior of this channel is studied

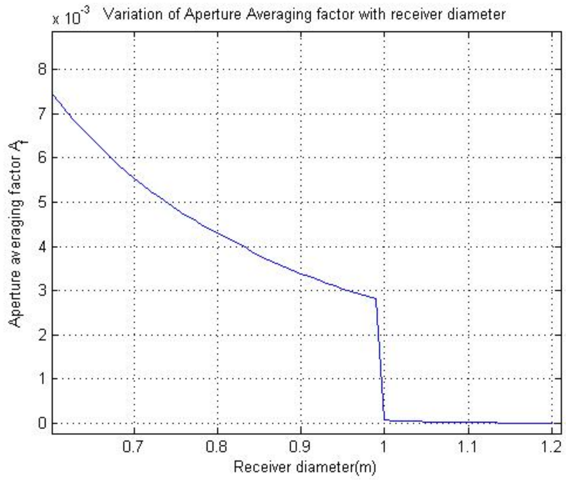

Fig. 1. Aperture Averaging Factor for different receiver diameter values

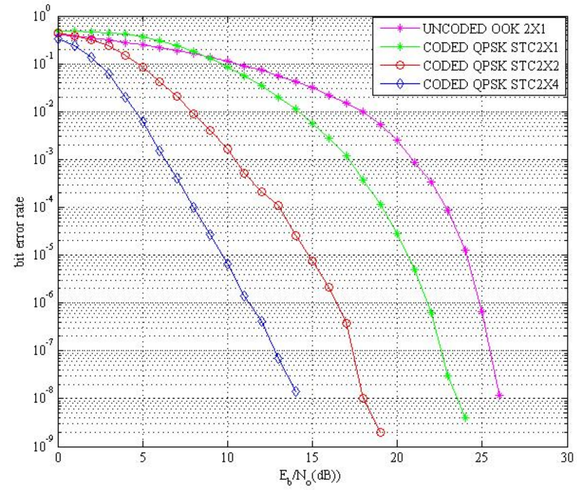

Fig. 3. BER of an optical uplink signal with one transmitter and one receiver(uncoded OOK)

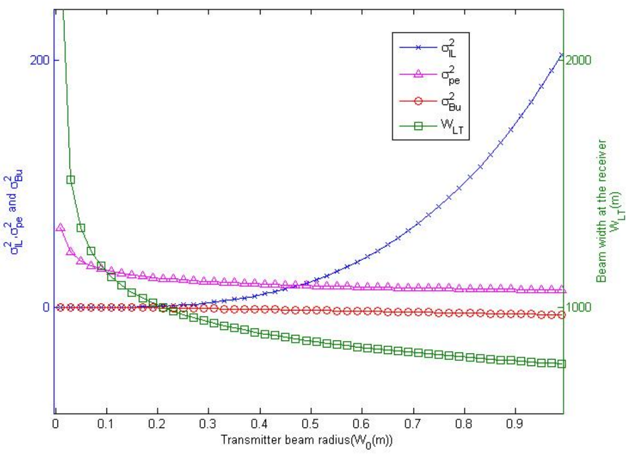

Fig. 2. Optimum transmitter beam radius

by sending an uncoded OOK modulated signal and plotting the bit error rates as shown in Figure 3. An E_b/N_o value of 26dB is required for a bit error rate of 10^{-8} when a 2×1 Alamouti code is used.

Due to it's dependence on intensity, the OOK scheme is more prone to noise compared to any other phase dependent schemes since phase information is less effected by noise. Hence, the performance of other modulation schemes such as QPSK, 8PSK and 16QAM are also investigated. Lithium Niobate Mach Zehnder modulators [13] can be used at the transmitter to realize these modulation schemes in optical domain. Further, an error control code improves the bit error performance of the signal. Hence, a convolutional code of rate $1/3$, is chosen, which has shown better performance compared to those of rates $2/3, 1/2$ to achieve same bit error rates at lesser signal to noise ratios compared to uncoded signal. G(D) of the convolutional code is given by

$$\begin{pmatrix} 1+D+D^2 \\ 1+D^2 \\ D+D^2 \end{pmatrix}$$

Figure 3 shows the bit error performances of the normal uplink channel and the Alamouti coded scheme with the convolutional coding and QPSK modulation. For a convolutionally coded and QPSK modulated signal, it is observed that a normal uplink(without coding and diversity) required about 26dB to achieve a bit error rate of 10^{-8} whereas an Alamouti space time code required only about 23dB. Thus, the Alamouti space time codes show an advantage of 4dB compared to a normal uplink.

These bit error rates can be obtained at even lower SNR values by increasing the number of transmitters or the number of receivers. However, since the effect of optical turbulence is more pronounced at the transmitter, it is proposed to increase the number of receivers. When two and four receivers with spacing of more than the atmospheric coherence width(r_0) are used to receive the signal, the bit error rate plots show significant improvement compared to those of a single receiver, as shown in Figure 3. Figure 3 shows that a bit error rate of 1×10^{-8} is obtained at an E_b/N_o value of 18dB for two receivers and at around 14dB for four receivers. The performance of the optical uplink channel with Almouti space time codes is analyzed for two other modulation schemes. Since 8-PSK performs better than 8-QAM and 16-QAM performs better than 16-PSK in communication systems, the performance of 8-PSK and 16-QAM are also studied. The performance of various modulation schemes on a coded input data with Alamouti space time codes of two transmitters and two receivers is as shown in Figure 4.

16 QAM modulation scheme is implemented considering the average symbol energy as 1. As can be inferred in Figure 4,

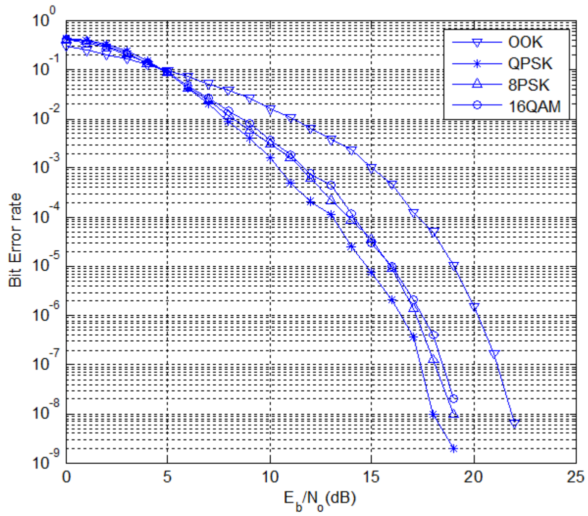

Fig. 4. BER performance of different modulation schemes with Alamouti STC 2×2

OOK requires more SNR compared to any other modulation scheme as expected. Interestingly, all the modulation schemes require nearly equal SNR values which differ only in 1dB, for a given number of receivers. The performances of different modulation schemes are plotted for the same number of receivers ,say two receivers, to observe this result. As can be inferred from Figure 4, OOK requires 22dB whereas other schemes require a maximum of about 4dB lesser SNR. QPSK requires about $18dB$, while 8PSK and 16 QAM require a little above $19dB$. The spectral efficiencies offered by 8PSK and 16 QAM are $3b/s/Hz$ and $4b/s/Hz$. 16QAM provides better spectral efficiency compared to QPSK and 8PSK while requiring an SNR value of 1dB greater than QPSK and only less than 1dB than 8 PSK. Though QPSK requires less SNR compared to 16 QAM, considering the spectral efficiency advantage, it is proposed to use 16QAM to modulate the optical signal.

A link budget analysis of the optical uplink channel is presented in the table for an OOK modulation scheme in Table II. From Table II,it can be concluded that the communication between a transmitter and a receiver of the uplink considered requires a transmitter power of about $24.883kW$. Implementing ASTC reduces this transmitter power due to the diversity gain. Since two transmitters are used to transmit the symbols, the resulting power of transmission is equal to the sum of the power transmitted on each antenna [20]. This provides a gain of $3dB$ which reduces the required transmitter power by half to $12.4415kW$. Using two receivers is proposed to achieve required bit error rate at a lesser SNR. Since two different receivers receive the same signal, the resultant signal strength increases by a further $3dB$. Thus, using two receivers reduces the required transmitter power by half of the actual value, that is $6.22075kW$.

TABLE II
LINK BUDGET ANALYSIS

PARAMETER	LINEAR VALUE	VALUE IN dB
Transmitter gain	1.45×10^{13}	131.619
Transmitter optical loss	0.1	-010.000
Space loss	9.5×10^{-13}	-290.218
Receiver Antenna Gain	1.47×10^{12}	121.699
Receiver optical loss	0.1	-010.000
SYSTEM LOSSES		**-056.899**
Turbulence margin(atmosphere)		-011.300
Geometric loss(D=1m)	1.84×10^{-4}	-037.375
TOTAL LINK LOSS		**-105.57**
Link margin		-006.000
DESIGN LOSS		**-111.574**
Required receiver power at 3Gbps	$0.173\mu W$	-067.616
Required transmitter power	$24.883kW$	-067.616 $+111.574$ 043.959

V. CONCLUSION

The behavior of an uplink optical channel in the presence of weak turbulence and beam wander is simulated considering the transmitter at a height of $2.5km$ and the satellite at a zenith angle of 0^0 at a distance of $40,000km$. The optimum values for the transmitter beam width and the receiver diameter are proposed for the particular scenario simulated. Alamouti space time codes are proposed to mitigate the beam wander effect and turbulence effect. Convolutional coding and modulation techniques such as 8 PSK and 16 QAM are used to achieve required bit error rates at lesser SNR values. Link budget analysis for the optical uplink channel is presented which results in a decrease of $6dB$ in the required transmitter power. This brings down the required transmitter power of $24.883kW$ to about $6.2207kW$ if the proposed method is used.

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