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Analytical approach of an FSO Link with alamouti- type STBC considering weak atmospheric turbulence

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Abstract

An analytical approach is proposed to evaluate the bit error rate (BER) performance of a direct detection on-off keying (OOK) free space optical link over log-normal atmospheric turbulence-induced fading channels based on modified Alamouti code presented by Simon and Vilnrotter and maximal ratio combining (MRC) at the receiver. Simulations show that due to coding and diversity at the receiver, a significant improvement in the BER performance is obtained at a given BER. For diversity order of 2 in both transmitter and in receiver, the amount of BER improvement is 6.6dB at BER 10^{-5}. Further increment of the receiver diversity from 2 to 4 gives additional 3dB improvement at the same BER. A drastic improvement of the BER performance is also possible for increasing number of receiver diversity which may increase hardware complexity. Simulation results are demonstrated to confirm the analytical results.

Introduction

Free space optical (FSO) communication is a very promising and cost effecting technology for the future optical communication networks (Andrews *et al.,* 2001; Arnon, 2003; Vincent, 2006). A major impairment in FSO links is the atmospheric turbulence-induced fading which causes fluctuations in both the intensity and phase of the received light signal which results in impairments of the link performance (Antonio, 2007; Jindal and Lozano, 2010; Bhuiyan *et al.*, 2010; Tarokh *et al.*, 1999; Huang *et al.*, 1993; Zhu and Kahn, 2002). For free space optical transmission systems, most frequently used system is Intensity Modulated Direct Detection (IM/DD) system. In such system, the intensity of an optical source is modulated to transmit signals. For FSO systems, although the power efficiency is inferior to pulse position modulation (PPM), OOK encoding is more commonly used due to its efficient bandwidth usage and robustness to timing errors. Therefore, in this research work, for FSO systems we prefer intensity modulation/direct detection (IM/DD) with an OOK technique.

For the Microwave wireless communication it is found that Alamouti coding can significantly mitigate the signal fading by increasing the diversity gain (Alamouti 1998; Navidpour *et al.*, 2007; Stephen *et al.*, 2005) where complex valued vectors were essential for adding the diversity. Simon *et al.* have proposed a modified version of Alamouti code for FSO intensity modulated direct detection (FSO IM/DD) links. In Alamouti code and other orthogonal STBCs the signal polarity (phase) could be detected at the receiver (Simon and Vilnrotter, 2005). This is not possible with unipolar modulations such as OOK (on-off keying) and PPM (pulse position modulation) commonly used in FSO IM/DD links.

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Simon *et al*. have overcome this problem by modifying Alamouti code in a clever manner to avoid the necessity of transmitting the negative of a modulated signal, thereby allowing the use of unipolar modulation techniques. This coding scheme is in fact more adaptable for implementation in the free space optical channel due to diversity adding capability on real valued data (Antonio, 2007; Simon and Vilnrotter, 2005). A turbulent atmospheric channel causes the intensity of an optical beam travelling through it to fluctuate randomly due to random changes in refractive index along the beam's path. Moreover in the FSO communication system, increasing the length of the transmission path is also very much challenging due to the impact of strong atmospheric turbulence. The different types of noise encountered during optical detection were discussed with the view to understanding the limit imposed on the system performance by each of them. The review work revealed that the transmitted photons obey the Poisson distribution and this can be adequately approximated as the tractable Gaussian distribution for large photoelectron counts as is the case in terrestrial FSO systems.

Materials and methods

System model

The overall system model for FSO system is depicted in Fig. 1. The Alamouti-type STBC coded OOK data is transmitted by the laser sources and received by photo detector using direct detection method. At the receiver end, the incoming optical radiation is passed through an optical band pass filter (OBPF) before being converted into an electrical signal by the photo detector. The OBPF is used to limit the amount of background radiation noise detected by the photo detector. The received signals (photo detectors current) are then passed through the pre-amplifier (PA). The outputs of the pre-amplifiers are then put into the combiner. Various methods such as maximal ratio combiner (MRC), selection combiner (SC), equal gain combiner (EGC) etc have been proposed for

combining independently faded signal components and the trade off among these methods is the receiver complexity versus transmission performance improvement. In FSO system, all the signals are the light intensity, they must be real signals. For OOK modulation, the signals can be described as:

$$s_1 = 0 \quad ; \qquad 0 < t \le T_b \quad \text{light off}$$

$$s_2 = A \quad ; \qquad 0 < t \le T_b \quad \text{light on}$$

where 'A' is a positive constant related to the intensity of the light source and T_b is the bit duration. We can express one of these signal waveforms in terms of the other by

$$s_i = -s_j + A \quad ; \quad j \ne i \tag{1}$$

The new formation of the transmit symbols become as:

$$\{s_1, s_2\} \rightarrow \begin{bmatrix} x_1 & \bar{x}_2 \\ x_2 & x_1 \end{bmatrix}$$

For the FSO system we define the complement of a signal x_i as x_i where x_i and x_i are used for "light on" and "light off" respectively. For example, if, x_i then

$$\bar{x}_i = s_2 = -s_1 + A = -x_i + A$$

Otherwise, if $x_i = s_2$, then $x_i = s_1 = -s_2 + A = -x_i + A$

Channel model

In homogeneities caused by turbulence can be viewed as discrete cells, or eddies of different temperature, acting like refractive prisms of different sizes and indices of refraction. The interaction between the laser beam and the turbulent medium results in random phase and amplitude variations (scintillation) of the information-bearing optical beam which ultimately results in performance degradation of FSO links.

Atmospheric turbulence results in random fluctuation of the atmospheric refractive index, n along the path of the optical field/radiation traversing the atmosphere. This refractive index fluctuation is the direct end product of random

variations in atmospheric temperature from point to point (Pratt, 1969). These random temperature changes are a function of the atmospheric pressure, altitude and wind speed.

The atmospheric turbulence impairs the performance of an FSO link by causing the received optical signal to vary randomly thus giving rise to signal fading. The fading strength depends on the link length, the wavelength of the optical radiation and the refractive index structure parameter of the C^2 channel.

The log-normal distribution is generally used to model the fading associated with the weak atmospheric turbulence regime. This model is mathematically tractable and it is characterized by the Ryotov variance σ^2. The turbulence induced fading is termed weak when $\sigma^2 < 1.2$ and this defines the limit of validity of the log-normal model. Beyond the weak turbulence regime, other models such as the gamma-gamma and the negative exponential will have to be considered. The Ryotov variance σ^2 can be calculated as

$$\sigma_X^2 = 1.23 C_n^2 (\sqrt[6]{k^7 L^{11}}) \qquad (2)$$

where L is the propagation distance and k is the wave number.

The amplitude of the random path gain, $H = e^x$, where X is normal with mean μ_X and variance σ^2. Thus, the logarithm of the field amplitude scale factor is normally distributed. The optical intensity $I = H^2$ is also log normally distributed in this case (Stephen *et al.,* 2005, 2005a). The pdf for H is

$$f_H(a) = \frac{1}{(2\pi\sigma_X^2)^{0.5}a} \exp\left(-\frac{(\log_e a - \mu_x)^2}{2\sigma_X^2}\right), \quad a > 1 \quad (3)$$

So that the mean path intensity is unity, i.e., $E[H^2]=1$. For the *log-normal* distribution, the scintillation index, defined as

$$S.I. = \frac{E[H^4]}{E^2[H^2]} - 1 \qquad (4)$$

This index can be related to the parameter σ^2 by S.I. = $e^{4\sigma2}$-1. Typical values appearing in the literature for S.I. are in the range 0.4–1.0.

Ber analysis

The transmitted optical signal by the lasers-

for laser-1, $\quad S_1(t) = \sqrt{2P_s\varepsilon} \qquad for \quad 0 \angle t \angle \dfrac{T_b}{2}$

$$= -\sqrt{2P_s\varepsilon} + A \quad for \quad \dfrac{T_b}{2} \angle t \angle T_b$$

for laser-1, $\quad S_2(t) = \sqrt{2P_s\varepsilon} \qquad for \quad 0 \angle t \angle \dfrac{T_b}{2}$

$$= \sqrt{2P_s\varepsilon} \qquad for \quad \dfrac{T_b}{2} \angle t \angle T_b$$

where T_b is the bit duration.

At the receiver end, the received photo current for ith photodetector is –

$$i_i(t) = R_d |s_i(t)|^2 \times |h_i|^2 + n(t) = 2R_d P_s\varepsilon|h_i|^2 + n(t) = 2R_d I|h_i|^2 + n(t) \ (5)$$

The total photodetector's current is given by

$$i(t) = \begin{bmatrix} |h_{11}|^2 & |h_{21}|^2 \\ |h_{12}|^2 & |h_{22}|^2 \end{bmatrix} \times 2R_d I + n(t) \qquad (6)$$

$$i_{ji}(t) = |h_{ji}|^2 \times 2R_d I + n(t) \qquad (7)$$

$$i(t) = \sum_{j=1}^{L}\sum_{i=1}^{M} i_{ji}$$

where,

R_d = photodetector responsivity

P_s = symbol power (power at the bias level of the semiconductor)

ε = modulation index
I = maximum optical intensity

$n(t)$ = AWGN (Additive White Gaussian Noise)

= Thermal Noise+ Background radiation shot Noise

The additive white Gaussian noise *n(t)* consists of both the thermal noise and the background radiation shot noise.

The shot noise is,

$$\sigma_{shot}^2 = 2qB.i_{sho} \qquad (8)$$

And the background noise is

$$\sigma_{bg}^2 = 2qB_{el.}i_{bg} \qquad (9)$$

where ,

B_{el} =Post detection electrical filter bandwidth.

i_{bg} =Background current=$R_d I_{bg}$;

Considering I_{bg} = background radiation irradiance. Now, equation (9) can be written as-

$$\sigma_{bg}^2 = 2qB_{el.} R_d I_{Bg}$$

Here the thermal noise,

$$\sigma^2_{th} = 4kTB_{el}/R_L \qquad (10)$$

where,

k = Boltzman constant = $1.38*10^{-23}$

R_L = Receiver circuit load resistance

T = Temperature

Now, considering the background noise and thermal noise power from equations (9) and (10), total noise power is-

$$\sigma^2 = \sigma^2_{bg} + \sigma^2_{th}$$

$$= 2qB_{el.}R_dI_{Bg} + 4kTB_{el}/R_L$$

$$= 2B_{el.}(qR_dI_{Bg} + 2kT/R_L) \qquad (11)$$

In presence of turbulence the total bit energy to noise spectral density ratio is expressed as

$$\bar{\gamma} = \bar{h}_{ji}^2 E_b / N_0$$

$$= \bar{h}_{ji}^2 2R_dP_s\varepsilon T_b / N_0$$

$$= \bar{h}_{ji}^2 2R_dP_s\varepsilon / (N_0 \frac{1}{T_b})$$

$$= \bar{h}_{ji}^2 2R_dP_s\varepsilon / \sigma^2 \qquad (12)$$

In OOK, E_b represent the energy of the detected pulse in the 'on' state.

Assuming transmission matrices based on real orthogonal designs for full rate and a full diversity space time block code, the adoption of an array based on *M* laser sources, all pointed towards a distant array of *N* photodetectors, implies a diversity of order *NM*, so that the conditional BER is given by (Huang *et al.,* 1993),

$$P_b\left(E\big|\{h_{ji}\}_{\substack{1 \le i \le M \\ 1 \le j \le N}}\right) = Q\left(\sqrt{\frac{E_b}{2N_0}\sum_{j=1}^{N}\sum_{i=1}^{M}h_{ji}^2}\right) \qquad (13)$$

where *Q(x)* is the Gaussian-*Q* function with argument *x*.

From equation (13), using the alternating form of Q(x), is obtained as

$$P_b\left(E\big|h_{ji}\right) = \frac{1}{\pi}\int_0^{\frac{\pi}{2}}\prod_{j=1}^{N}\prod_{i=1}^{M}\exp\left(-\frac{\bar{\gamma}h_{ji}^2}{2\times 2\sin^2\theta}\right)d\theta \qquad (14)$$

The conditional BER averaged over the pdf of the channel irradiance thus yielding

$$P_b(E) = \underbrace{\int_0^\infty\int_0^\infty \cdots \quad \cdots \quad \cdots \int_0^\infty}_{MN-fold}\frac{1}{\pi}\int_0^{\frac{\pi}{2}}\prod_{j=1}^{N}\prod_{i=1}^{M}\left[\exp\left(-\frac{\bar{\gamma}h_{ji}^2}{2\times 2\sin^2\theta}\right)\right] \qquad (15)$$

where

$$p(h_{ji}) = \frac{1}{(2\pi\sigma_X^2)^{0.5}h_{ji}}\exp\left(-\frac{(\log_e h_{ji} - \mu_x)^2}{2\sigma_X^2}\right), \quad a > 1$$

where the mean . $\quad \mu_x = -\dfrac{\sigma_x^2}{2} \quad$ By changing the order of

integration in equation (15) and one gets subsequently grouping the terms of index ij,

$$P_b(E) = \frac{1}{\pi}\int_0^{\frac{\pi}{2}}[D(\theta,\bar{\gamma})]^{NM}d\theta \qquad (16)$$

where

$$D(\theta,\bar{\gamma}) = \int_0^\infty\exp\left(-\frac{\bar{\gamma}h^2}{2\times 2\sin^2\theta}\right)\times\frac{1}{\sqrt{2\pi\sigma_x^2}\,h}\exp\left(-\frac{(\log_e h + \frac{\sigma_x^2}{2})^2}{2\sigma_x^2}\right)dh$$

A closed-form solution of equation (16) does not exist and could result in truncating the upper limit using the numerical integration. By using an alternative representation of the Q-function together with the Gauss-Hermite quadrature integration (Popoola *et al.,* 2008), these problems can be circumvented. These are expressed as

$$Q(x) = \frac{1}{\pi}\int_0^{\frac{\pi}{2}}\exp(-\frac{x^2}{2\sin^2\theta})d\theta$$

$$\int_{-\infty}^{\infty}f(x)\exp(-x^2)dx \cong \sum_{i=1}^{m}w_i f(x_i) \qquad (17)$$

where and represent the zeros and weight factors of the *m*th order Hermite polynomial respectively (Popoola *et al.,* 2008; Ghassemlooy *et al.,* 2009). The degree of accuracy of equation (17) is determined by the value of m.

Let us consider, $\quad x = \dfrac{(\log_e h + \dfrac{\sigma_x^2}{2})}{\sqrt{2\sigma_x^2}} \qquad (18)$

Thus, $\quad h = \exp(\sqrt{2\sigma_x^2}x - \dfrac{\sigma_x^2}{2}) \quad$ and

$$dh = \sqrt{2\sigma_x^2}\exp(\sqrt{2\sigma_x^2}x - \frac{\sigma_x^2}{2})dx \qquad (19)$$

Using equations (17), (18) and (19) in equation (16) the resultant BER is obtained as,

$$P_b(E) = \frac{1}{\pi} \int_0^{\frac{\pi}{2}} \left[\frac{1}{\sqrt{\pi}} \sum_{i=1}^{m} w_i \exp\left(-\frac{\bar{\gamma} \exp(2\sqrt{2\sigma_x^2} x_i - \sigma_x^2)}{2 \times 2 \sin^2 \theta} \right) \right]^{MN} d\theta \quad (20)$$

Fig.1. System model of an FSO link with STBC

Fig. 2. Analytical and Simulated BER performance of an FSO link over log-normal turbulence model with Alamouti type STBC with different receiver diversity.

Fig. 3. BER performance curve for FSO link over log-normal turbulent condition with varying turbulence variance considering M=2, L=1 and MRC at the receiver.

Fig. 4. BER performance curve for FSO log-normal with different detector diversity with different variance using MRC at the receiver.

Results and discussion

Following the aforementioned analytical approach, the BER performance of an IM/DD optical FS link with Alamouti-type STBC over log nor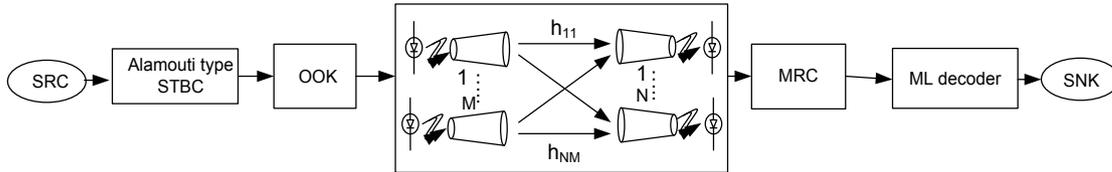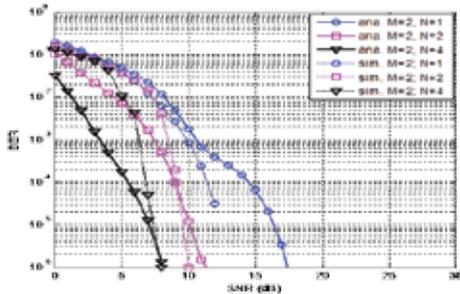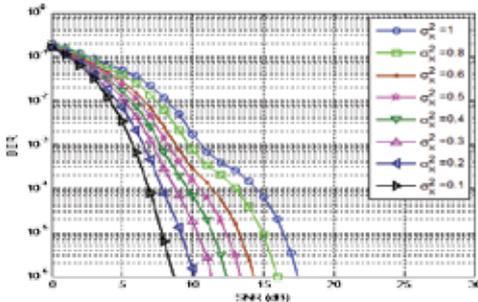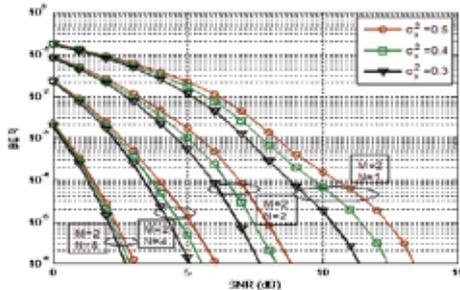mal turbulence channel is evaluated numerically. Results are evaluated in terms of BER as a function of average SNR with Alamouti-type STBC considering weak turbulence model. Figure 2 shows both analytical and simulated results. The amount of BER improvement for (2×2) and (2×4) STBC is of the order 6.6dB and 9.6dB respectively w.r.t (2×1) at BER 10^{-5}. In figure 3 it is clearly shown that with the increasing turbulence variance the BER performance falls significantly. Figure 4 shows the comparison of the BER performances due to increment of number of detectors along with the variation of the turbulence variance. At turbulence variance 0.3, the BER improvement is 4.5dB, 7dB and 9.5dB for photodetector 2, 4 and 8 respectively at BER 10^{-6}. The more the number of detectors the better the link performance is.

Conclusion

The error rate performance for modified Alamouti-type STBC in FSO communication systems with direct detection operating over log normal turbulence channels is analyzed in this paper. The proposed analytical approach almost matches with the simulation results. We have simulated the performance of an optical link using Alamouti type space–time block coding at weak atmospheric turbulent condition considering different receiver diversity and also compare the BER curves. In this paper, it is clearly found that Alamouti-type STBC code can significantly improve the BER performance of FSO system with OOK technique considering weak atmospheric turbulent condition.

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