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Performance Analysis of FSO under Turbulent Channel Using OSTBC

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Abstract

Free Space Optics (FSO) plays a vital role in modern wireless communications due to its advantages over fiber optics and RF techniques where a transmission of huge bandwidth and access to remote places become possible.

The specific aim of this research is to analyze the Bit-Error Rate (BER) for FSO communication system when the signal is sent the over medium of turbulence channel, where the fading channel is described by the Gamma-Gamma model. The signal quality is improved by using Optical Space-Time Block- Code (OSTBC) and then the BER will be reduced. Optical 2×2 Alamouti scheme required 14 dB bit energy to noise ratio (E_b/N_0) at 10^{-5} bit error rate (BER) which gives 3.5 dB gain as compared to no diversity scheme.

The results show that using Multiple-Input-Multiple-Output (MIMO) technique represented by Alamouti scheme gives the improved BER performance as compared with no diversity (Single-Input-Single-Output (SISO)) technique.

Keywords: FSO, OSTBC, Gamma-Gamma, MIMO

1. Introduction

FSO was initially created by US military and NASA being utilized recently in different systems to provide fast communication links. These systems offer automatic power-level control, and eliminate short-distance optical saturation. FSO is a wireless technology that transfer information through a free space medium where a modulated light beam is used as a carrier for data rather than RF signals [1]. In FSO system, different modulation schemes are used to modulate information signal at source such as ON-OFF Keying (OOK), Pulse Time Modulation Pulse Time Modulation (PTM), Polarization Shift Keying (PoSK). Each FSO system uses optical transmitter for transmit information towards destination and in receiving side high sensitive photodetector is used. But due to free space transmission, the attenuation caused by the atmosphere is major challenge faced by optical wireless communications which affect the performance of the link. The other factors which can affect the FSO are aerosols, beam scintillation, spreading and wandering signals absorption, and smoke [2].

To mitigate theses effects and improve the performance of overall system, MIMO is a suitable optical antennatechnology for wireless communications in which multiple antennas are used at transmitter as well as at receiver. The telescopes at each transmitter and receiver are combined to reduce BER and improve the data rate [3].

According to the optimization of the Alamouti Space Time Block Code (STBC) presented by Simon in [4], by using the complement signals, a special approach is considered in Space-Time-Code (STC) to match the optical requirements where the transmitted signal must be positive anyway [5-7]. To the best of the authors' knowledge, Diversity technique in FSO communications is considered widely in [8].

In this paper, On-Off Keying (OOK) is used to adapt STBC to optical signal where IM/DD is used as a modulation technique [9].

Our performance metric is the average BER where statistical characteristics for medium turbulence conditions modeled by (gamma-gamma distribution) and derived for two optical transmitting antennas and two optical receiving antennas taking in consideration the characteristics of optical signals.

In the following pages, section 2 presents the analysis of MIMO-FSO communication system. In section 3, the BER is analyzed and derived for the current system. In section 4 numerical results for 2×2, 2×1 Alamouti and No diversity schemes as well as the BER performance for selected modulation scheme (OOK) are computed where the numerical results is verified by Monte Carlo simulation.

2. Analysis of MIMO FSO Communication System

Let us now describes the block diagram in figure (1). OOK is a type of IM scheme where the bits '0' and '1' are represented by the presence and absence light. OOK is used in this work for simplicity although it is more sensitive to atmospheric effects.

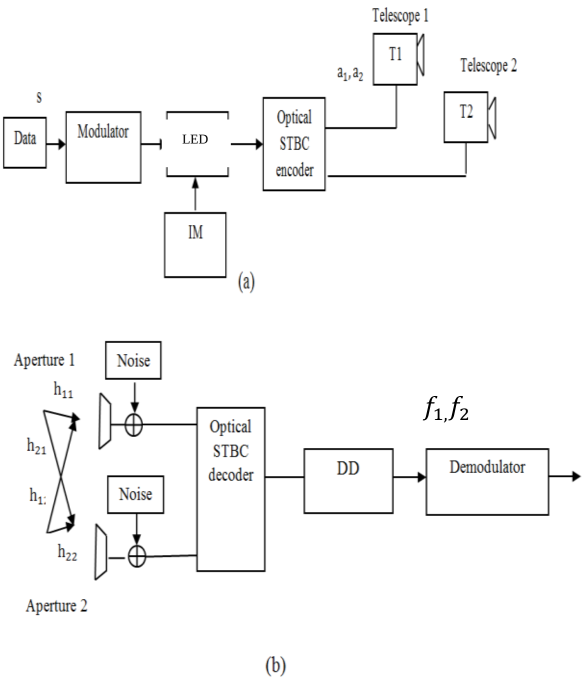

Figure 1: FSO communication system, a) transmitter with two antennas, b) receiver with two antennas. IM: Intensity Modulation and DD: Direct Detection.

In above block diagram, consider a binary Intensity Modulation (IM) where x_0 represents symbol '0' and x_1 represents symbol '1'.

Consider the information symbols ($s_l \in \{0,1\}$) with symbol interval T_S. The data passed through IM block in figure (1) and sent to space-time block are from the set {0,I}, where I represents the intensity of the optical source at emitter for symbol 1.

$$\mathrm{s_0(t)} = 0, \qquad 0 \le \mathrm{t} \le T_s \qquad \ldots\ldots (1)$$
$$\mathrm{s_1(t)} = \mathrm{I}, \qquad 0 \le \mathrm{t} \le T_s \qquad \ldots\ldots (2)$$

The transmitted signal at the output of the emitter is:

$$\mathrm{u(t)} = 2P_T(t)\sum_{\mathrm{l}=0}^{\infty} \mathrm{s_l} \qquad \ldots\ldots (3)$$

Where P_T is the radiated power transmitted by the LED. Then, the received signal is

$$\mathrm{r(t)} = h\mathrm{Ru(t)} + \mathrm{z(t)} \qquad \ldots\ldots (4)$$

In equation (4) h represents the channel gain, R is the responsivity of the photodetector and $z(t)$ is the AWGN with zero mean and PSD equal to $Z = 2qI_B$ where Z represents the noise power, q and I_B are the electron charge and the photocurrent generated by background light respectively.

The received signal is demodulated by the replica of the local sequence, and then integrated over T_s. Finally data are estimated by computing the sign of the decision variable at the output of correlator,

$$\mathrm{Ds_l} = \mathrm{sign}\ (\mathrm{s_l} + \mathrm{w_l}) \qquad \ldots\ldots (5)$$

where the $sign(.)$ is the sign operator and $\mathrm{w_l}$ is a noise components after correlator. Let,

$$s_i(t) = -s_j(t) + I, \qquad i \ne j,\ \ i,j \in \{0,1\} \ \ldots(6)$$

$\overline{f_i}$ is the complement of signal f_i that represents the complement binary state of the signal f_i (i.e., if $f_i = s_0$ then $\overline{f_i} = s_1$ and if $f = s_1$ then $\overline{f_i} = s_0$).

Stratify the above criteria to equation (6) leads to the following relationship,

$$\bar{f}(t) = -f(t) + I, \qquad f(t) \in \{s_0, s_1\} \ \ \ldots..(7)$$

We can note that $f(t) = 0, I$ the relationship in equation (7) ensure that $f(t)$ is non-negative. The primary property of a space-time code $F(f_1, \ldots\ldots\ldots, f_a) = F(x)$ with $f = (f_1, \ldots\ldots\ldots f_a)^T$ is

$$F^T(f)F(f) = I_A\|f\|^2 \qquad \ldots\ldots (8)$$

Where,$(*)^T$ denotes transpose operation, I_A is the $F \times F$ unit matrix, F is the number of transmitter antennas and $\|f\|^2 = (f_1^2 + f_2^2 + \cdots + f_a^2)$.

However, a coding scheme satisfying (8) cannot be implemented in IM/DD system because transmitted IM signal must be non-negative at all times.

The coding scheme in the above equations shows that the transmitter outputs must be negated to match the orthogonality.

To solve the above problem, we use the matrix in equation (9)

$$(|F|(f,\bar{f}))_{i,j} = \begin{cases} (F(f))_{i,j} & if\ (F(f_1 = 1, \ldots\ldots\ldots f_a = 1))_{i,j} \ge 0 \\ -(F(f))_{i,j} & otherwise \end{cases} \qquad \ldots\ldots (9)$$

This equation ensures that the emitted symbols are always positive for an IM/DD system. The estimated signal at receiver is

$$\tilde{f} = F^T(h)J_P \times (J_P F(h)x + z) \qquad \ldots\ldots (10)$$

Using the relation $\mathrm{J_P \times J_P = I_P}$, we obtain:

$$\tilde{f} = \|\mathrm{h}\|^2\mathrm{x} + \mathrm{F^T(h)J_P m} \qquad (11)$$

Where P represents the transmission time slots, $\mathrm{J_P}$ is $\mathrm{P \times P}$ matrix with $\mathrm{J} = \mathrm{diag}(1, -1, -1, -1, \ldots, -1)$, $\bar{x} = (\overline{x_1} \ldots\ldots\ldots\ldots. \overline{x_a})^T$, $m = (m \ldots\ldots\ldots.. m_P)^T$ are Gaussian noise, which may include contribution from thermal and/or shot noise and $h = (h_1 \ldots\ldots\ldots. h_a)^T$ is the quasi-static channel response for transmitters $i = 1,2, \ldots\ldots\ldots a$ respectively [10,11].

Then, the optical Alamouti matrix becomes

$$X(x,\bar{x}) = \begin{pmatrix} f_1 & f_2 \\ \overline{f_2} & f_1 \end{pmatrix} \qquad \ldots\ldots (12)$$

This matrix is considered in optical communication to overcome the negative values already considered in the matrix of traditional STBC where the power must be non-negative.

For 2×1 optical Alamouti, the estimated signal at receiver

$$\begin{pmatrix} \tilde{f}_1 \\ \tilde{f}_2 \end{pmatrix} = (h_1^2 + h_2^2)\begin{pmatrix} f_1 \\ f_2 \end{pmatrix} + \begin{pmatrix} h_1 z_1 + h_2 z_2 \\ h_2 z_1 - h_1 z_2 \end{pmatrix} \quad \ldots\ldots (13)$$

Where $h = (h_1, h_2)^T$ is the channel gain for two lasers (antennas).

For 2 transmit antennas and 2 receive antennas and according to equation (12), the estimated signal at receiver

$$\begin{pmatrix} \tilde{f}_1 \\ \tilde{f}_2 \end{pmatrix} = (h_{11}^2 + h_{21}^2 + h_{12}^2 + h_{22}^2)\begin{pmatrix} f_1 \\ f_2 \end{pmatrix}\begin{pmatrix} h_{11} z_1 + h_{21} z_2 \\ h_{22} z_1 - h_{12} z_2 \end{pmatrix} \quad \ldots\ldots (14)$$

Table 1: The design of the emitted signal of 2×2 Alamouti.

Time	$f_1(t)$from $Telescope\ 1$	$f_2(t)$from $Telescope\ 2$
$1st\ time\ slot$	$f_1 u_i(\mathrm{t})$	$f_2 u_i(\mathrm{t})$
$2nd\ time\ slot$	$\bar{f}_2 u_{i+time\ slot}(\mathrm{t})$	$f_1 u_{i+time\ slot}(\mathrm{t})$

Table 2: The design of received signal on $aperture$ 1

Time	Received signal on $aperture$ 1
$1st\ time\ slot$	$2P_T R[h_{11}u_i(\mathrm{t})f_1 + h_{21}u_i(\mathrm{t})f_2] + Z_{11}$
$2nd\ time\ slot$	$2P_T R[h_{11}u_{i+time\ slot}(\mathrm{t})\bar{f}_2 + h_{21}u_{i+time\ slot}(\mathrm{t})f_1] + Z_{21}$

Table 3: The design of received signal on $aperture$ 2

Time	Received signal on $aperture$ 2
$1st\ time\ slot$	$2P_T R[h_{12}u_i(\mathrm{t})f_1 + h_{22}u_i(\mathrm{t})f_2] + Z_{12}$
$2nd\ time\ slot$	$2P_T R[h_{12}u_{i+ime\ slot}(\mathrm{t})\bar{f}_2 + h_{22}u_{i+ime\ slot}(\mathrm{t})f_1] + Z_{22}$

Table 4: The baseband of the received signals on the $aperture$ 1

Time	The baseband of the received signals on the $aperture$ 1
$1st\ time\ slot$	$V_{11} = 2P_T^2 R\ \ (h_{11}f_1 + h_{21}f_2) + Z_{11}$
$2nd\ time\ slot$	$V_{21} = 2P_T^2 R\ \ (h_{11}\bar{f}_2 + h_{21}f_1) + Z_{21}$

Where $Z_{11}$and Z_{21} are the components of the noise.

Table 5: The baseband of the received signals on the $aperture$ 2

Time	The baseband of the received signals on the $aperture$ 2
$1st\ time\ slot$	$V_{12} = 2P_T^2 R\ \ (h_{12}f_1 + h_{22}f_2) + Z_{12}$
$2nd\ time\ slot$	$V_{22} = 2P_T^2 R\ \ (h_{12}\bar{f}_2 + h_{22}f_1) + Z_{22}$

where $Z_{12} = Z_{11}$ and $Z_{22} = Z_{21}$.

The channel model is written as,

$$\mathrm{V} = 2P_T^2 R\mathrm{HF} + \mathrm{Z} \quad \ldots\ldots (15)$$

Then, the received signal for 2×2 Alamouti

$$\begin{pmatrix} V_{11} \\ V_{12} \\ V_{21}^* \\ V_{22}^* \end{pmatrix} = 2P_T^2 R \begin{pmatrix} h_{11} & h_{21} \\ h_{12} & h_{22} \\ h_{21}^* & \tilde{h}_{11}^* \\ \hat{h}_{22} & \tilde{h}_{12}^* \end{pmatrix}\begin{pmatrix} f_1 \\ f_2 \end{pmatrix} + \begin{pmatrix} Z_{11} \\ Z_{12} \\ Z_{21}^* \\ Z_{22}^* \end{pmatrix} \quad \ldots\ \ldots\ (16)$$

The emitted bits are reconstructed by multiplying the received signal V by the conjugate transpose of the matrix H:

$$\begin{pmatrix} \mathrm{D}_{s1} \\ \mathrm{D}_{s2} \end{pmatrix} = \mathrm{H}^*\mathrm{V} \quad \ldots\ldots (17)$$

The estimated bits can be computed from the sign of the decision variables,

$$D_{s1} = 2P_T^2 R\ \ f_1(h_{11}^2 + h_{21}^2 + h_{12}^2 + h_{22}^2) + (h_{11} + h_{12} + h_{21}^* + h_{22}^*)Z \quad \ldots\ldots (18)$$

$$D_{s2} = 2P_T^2 R f_2(h_{11}^2 + h_{21}^2 + h_{12}^2 + h_{22}^2) + \left(h_{21} + h_{22} + \tilde{h}_{11}^* + \tilde{h}_{12}^*\right)Z \quad \ldots\ldots (19)$$

Then, the emitted bits are

$$\acute{f}_1 = sign\ D_{s1};\ \acute{f}_2 = sign\ D_{s2} \quad \ldots\ldots (20)$$

In the turbulence channel model, the radiated power is multiplied by the irradiance of channel as a noise model which is substituted mathematically by two random variables independent on each other that is, p(I)=p(Ix)p(Iy) , Ix represents the large scale and Iy represents the small scale. This leads to the so-called gamma-gamma model, whose PDF is given by,

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

Where:

$\alpha > 0\ and\ \ \beta > 0.\ So,\ the$ scintillation index $\triangleq \frac{1}{\alpha} + \frac{1}{\beta} + \frac{1}{\alpha\beta}$ and $\Gamma(.)$ is the gamma function.

Where:

$$\alpha = [exp\left(\frac{0.49x^2}{(1+0.18d^2+0.56x^{12/5})^{7/6}}\right) - 1]^{-1}$$

$$\beta = [\exp\left(\frac{0.51x^2(1+0.69x^{12/5})^{-5/6}}{(1+0.9d^2+0.62d^2x^{12/5})^{5/6}}\right) - 1]^{-1}$$

Where:

x^2=0.5$* C_n^2 * K^{\frac{7}{6}*} * L^{11/6}$,$d = (\frac{KD^2}{4L})^{1/2}$, and $k = \frac{2\pi}{\lambda}$ is the wave number and $\lambda, D, C_n^2, and\ L$ are the wavelength , diameter of the receiver collecting lens aperture, refraction index structure parameter and L is the distance between emitter and receiver respectively . The parameters used in this work are [8],

λ= 1550 nm where the loss is minimum. D= 0.02 m. C= 10^{-15} for medium turbulence. L= 1 Km.

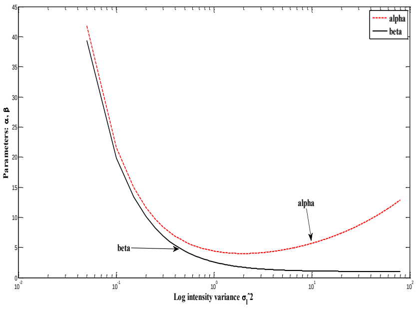

Figure 2: Values of $\alpha \, and \, \beta$ from weak turbulence to strong turbulence.

3. BER Performance Analysis

The decision variables of both D_{s1} and D_{s2} are the same, so the statistical properties are also the same. Then we can compute the mean and variance of the random variables for one of them.

The elements of noise components are zero mean and independent. So equation (18) can be minimized to

$$E\left[D_{s1}^{(l)}\right] = 2P_T^2 R \;\; f_1^{(l)}(h_{11}^2 + h_{21}^2 + h_{12}^2 + h_{22}^2) \quad \ldots\ldots (21)$$

The variance $var[.]$ of the D_{s1} can be computed as

$$v\left[D_{s1}^{(l)}\right] = E[(D_{s1})^2] - E[D_{s1}]^2 = E[f_1 \;\; P_T^2(h_{11}^2 + h_{21}^2 + h_{12}^2 + h_{22}^2)\}^2] - [f_1 \;\; P_T^2(h_{11}^2 + h_{21}^2 + h_{12}^2 + h_{22}^2)]^2 + E[\{(h_{11} + h_{12} + h_{21}^* + h_{22}^*)Z\}^2 \quad \ldots(22)$$

Since the samples of gaussian noise are independent and uncorrelated, the variance of D_{s1} for a given lth bit is

$$\sigma_{D_{s1}}^2 = var[h_{11}Z_{11}] + var[h_{12}Z_{12}] + var[h_{21}^* Z_{21}^*] + var[h_{22}^* Z_{22}^*] \quad \ldots\ldots (23)$$

Then,

$\sigma_1^2 = var[h_{11}Z_{11}] = var[h_{11} \sum_{k=1}^{W} z_l^k \;]$,

Where W is an integer and $\sum \;\; z_l^k$ is a sumation of a large number of the noise components. Then,

$$\sigma_1^2 = h_{11}\frac{Z}{2} \quad \ldots\ldots (24)$$

by analogy, the variances σ_2^2, σ_3^2 and σ_4^2 are given as follows:

$$\sigma_2^2 = h_{12}\frac{Z}{2}, \sigma_3^2 = h_{21}\frac{Z}{2}, \sigma_4^2 = h_{22}\frac{Z}{2}, \quad \ldots\ldots (25)$$

Then, the total variance can be computed as,

$$v\left[D_{s1}^{(l)}\right] = (h_{11}^2 + h_{21}^2 + h_{12}^2 + h_{22}^2)\frac{Z}{2} \quad \ldots.(26)$$

$$P_e(P_T^2) = \frac{1}{2} erfc[\frac{E\left[D_{s1}^{(l)}\right]}{\sqrt{2v[D_{s1}^{(l)}]}}] \quad \ldots\ldots (27)$$

As a result, this error probability for 2×2 Alamouti is given by

$$P_e(P_T^2) = \frac{1}{2} erfc\sqrt{[\frac{2P_T^2 R\left(h_{11}^2 + h_{21}^2 + h_{12}^2 + h_{22}^2\right)}{Z}]} \quad \ldots(28)$$

Where h_{ij} in equation (28) is not constant and represents the channel gain of Gamma-Gamma fading channel. So if h_{ij} is constant and equal to 1, it represents AWGN assumption.

4. Results and Discussions

One interesting computing the BER of OOK-NRZ, where the radiated power P_T is equal to 10 mW and photodetector responsivity is equal to 1. It is observed in figure (3) that the blue graph represent BER curve for simulated OOK-NRZ which is a large extent align with the red curve which represent theoretical BER.

The graph in figure (4) shows a BER performance comparison of different schemes (SISO (No Diversity) and Alamouti (2×1 and 2×2)) schemes for FSO communication system under medium turbulent channel (C= 10^{-15}) represented by Gamma-Gamma fading channel.

Figure (4) reveals that a 2×2 Alamouti scheme gives the superior BER performance when compared with 2×1 scheme and No Diversity communication schemes. 2×2 Alamouti scheme gives 1.5 dB gain as compared to 2×1 and 3.5 dB gain at 10^{-5} BER as compared to No diversity schemes under the same conditions.

These results reveals that the BER performance of optical Alamouti communication systems (2×1 and 2×2) is the best as compared to the performance offered by no diversity. Hence, a combined system gives acceptable BER under Gamma-Gamma fading.

Traditional and important problem presented in figure (5) where the power requirements for any communication scheme increases when we need more bandwidth. It is clear that the OOK perform better than PPM modulation schemes in this context for proposed system where it is required less power to provide more bandwidth.

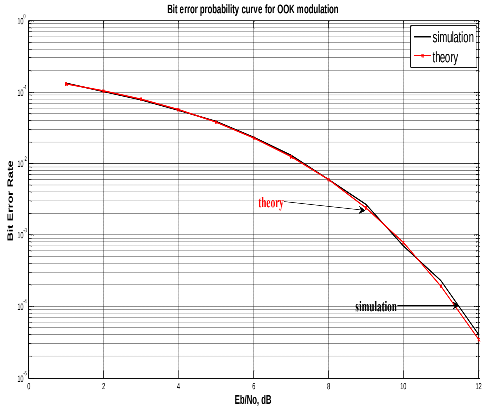

Figure 3: BER vs. Eb/N0 of OOK-NRZ for FSO communication system

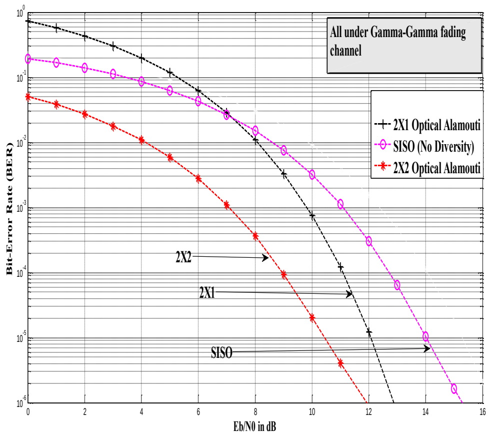

Figure 4: BER performances for different communication schemes using2 × 2, 2 × 1 Alamouti and No diversity under Gamma-Gamma fading channel

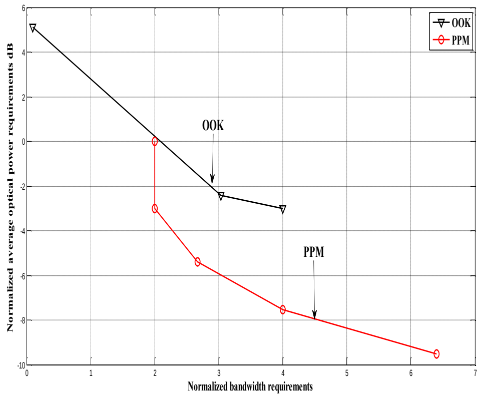

Figure 5: power requirement Vs. bandwidth

5. Conclusions

In this work, we designed an FSO communication system combined with Alamouti scheme using OOK modulation format to mitigate the BER due to the atmospheric turbulence. We have been concluded that 2×2 Alamouti gives a good BER performance as compared to 2×1 Alamouti and both gives the best BER performance as compared to no diversity communication system under Gamma-Gamma fading channel. Mathematical analysis for the FSO MIMO communication system has been derived and achieved using Matlab.

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تحليل اداء منظومة الاتصالات الضوئية اللاسلكية تحت تأثير المعوقات الجوية بأستخدام تقنية الهوائيات المتعددة

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الخلاصة

ان الهدف من هذه المخطوطةهو لتصميم منظومة للاتصالات الضوئية اللاسلكية التي تقع تحت تأثير معوقات كثيرة مثل تشتت الاشارة وامتصاصها والتأثيرات الجوية و التعامل معها من خلال معاملات رياضية خاصة مثل كاما كاما وغيرها باستخدام نوع التضمين المناسب للاتصالات الضوئية اللاسلكية.OOK. ولتقليل هذه التأثيرات تم اقتراح استخدام تقنية الهوائيات المتعددة وخاصة طريقة (OSTBC) لقد تم تحليل (BER) للمنظومة المقترحة ووجد بانه مع زيادة عدد الهوائيات لعدد محدود ممكن ان نحصل من خلاله على اشارة محسنة عند مقارنتها مع التقنيات الاخرى مثل (SISO) . استخدام التقنية الضوئية للـ Alamouti2× 2 يحتاج SNR dB 14 عند 10^{-5} BER مما يؤدى الى تحسين اداء المظومة بمقدار dB3.5 بالمقارنة مع المنظومة التقليدية.