BER PERFORMANCE OF PORTABLE OPTICAL WIRELESS SYSTEM USING WAVELENGTH DIVERSITY WITH POINTING ERROR

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Abstract

Portable optical wireless (POW) system is a rapidly deployable, light – weight and battery operated application of the outdoor optical wireless communication. In this study, wavelength diversity technique is examined to analyse the system performance, considering the short term and short distance fixed-to-fixed (f2f) POW system, in case of pointing error occurrence. The average bit error rate (BER) of POW system is mathematically derived, normalized beam width and jitter effects are investigated for wavelength channels. Evaluated results compared with the single transmitter and single receiver system that transmits M times increased average power. Numerical results show that the wavelength diversity technique increase the system performance especially for the use of narrow beam width under the assumption of small and same normalized jitter. High system displacement are also analysed for wide beam divergence angle and wavelength diversity technique enhances the system performance and has an advantage over M times increased power.

Keywords: optical wireless communication, portable systems, wavelength diversity, pointing error, bit error rate.

1. Introduction

Being a valuable solution to especially to the "*last mile problem*", optical wireless (OW) using laser, or FSOC : free space optical communication, provides a line – of – sight and higher – bandwidth link as compared to radio frequency transmission (Bloom et al., 2006; Bouchet et al., 2006). OW is also a viable option to fiber optic cabling as it is easily installed and rapidly re–deployable therefore cost–effective (Willebrand & Ghuman, 2002).

However, OW communication links which use the air as the transmission channel are prone to the adverse weather conditions, e.g. atmospheric absorption, scattering (mainly Mie Scattering), temperature dependent scintillation, and pointing error due to the building sway and system displacement (Farid & Hranilovic, 2007; Ghassemlooy et al., 2012; Willebrand & Ghuman, 2002). Atmospheric absorption and scattering can be defined as path loss, considered as a fixed scaling factor. Fog and haze are the dominant atmospheric effect and limits the achievable link range to about 500 meters (Willebrand & Ghuman, 2002; Ghassemlooy et al., 2012). The effect of the scintillation due to turbulence may significantly degrade the performance of OW communication system over distances longer than 1 km (Ghassemlooy et al., 2012; Prokes 2009; Sandalidis et al., 2008).

Adverse weather condition and pointing losses reduce the received signal power at the receiver as a result decreasing the signal to noise (SNR) and increase the bit error rate (BER) of the OW link. Multiple input multiple output (MIMO) diversity schemes are an attractive alternative approach to combat fading and reducing the potential for temporary blockages due to birds, localized fog and also helps with pointing issue (Ghassemlooy et al., 2012). In time, in spatial or in wavelength diversity techniques are used in OW communication to increase the system performance due to the fact that, multiple copies of transmitted signal lessen the influence of atmospheric effects and pointing at the receiver(s) (Rachmani & Arnon, 2012; Xarcha et al., 2012; Tsiftsis et al 2009; Nistazakis & Tombras, 2012; Farid & Hranilovic, 2012).

Wavelength diversity technique usage in OW link has studied under the effect of atmospheric turbulence in (Nistazakis & Tombras, 2012; Rachmani & Arnon, 2012; Xarcha et al., 2012), the use of wavelength diversity improves the system performance even for short link range under the effect of weak to strong turbulence conditions. In this method the same modulated data is transmitted simultaneously by M transmitters which are operating at different wavelengths without a common harmonic term through the same physical channel. Each transmitter laser is aligned to the only specific receiver, therefore the wavelength diversity scheme for OW link can be seen consist of a composite transmitter transmitting along M wavelength branches to the M receivers (Nistazakis & Tombras, 2012; Rachmani & Arnon, 2012; Xarcha et al., 2012). The spacing between transmitters, also receivers, are set to relatively large to ensure that the transmitted signals with average power are statistically independent (Chiani et al., 2003; Farid & Hranilovic, 2012; Sandalidis et al., 2009) and band pass filters can be used in order to separate the signals at the receivers. As a result, the received power will show statistically independent behaviour for each channel (wavelength) and thus a classical diversity combining schemes can be used to combine signals (Rachmani & Arnon, 2012)

Portable optical wireless (POW) system is considered in this study which is rapidly deployable, light–weight and battery operated and may be used in short–term and relatively short–distance f2f applications, for example in disaster hit areas, earthquake, flooding, etc., where all the (mobile phone) base station infrastructure is likely to be out of function, in the field geophysical tests where high / low speed data transfer from the measurement station or in security operations. If the privacy/covertness is not the prime concern, the visible lasers can be preferred to shorten the period of line of sight (LOS) alignment. Link range is chosen 500 m maximum for real time emergency applications. Loss due to the turbulence of atmosphere is taken fixed and wide divergence angle lasers usage are considered to ease the line-of-sight establishment and eliminate the need for tracking system due to the power consumption. This system can be deployed not only roof-to-roof but also ground-to-ground or ground-to-roof installation. Therefore pointing error, consisting of the mechanical vibration and system displacement, is increase.

In this study, wavelength diversity technique usage is examined to analyse the effect of pointing error for POW system. The average bit error rate (BER) of POW system for intensity modulation/direct-detection (IM/DD) with on-off keying (OOK) is mathematically derived as a function of instantaneous electrical SNR when pointing errors occurs under the assumption of wavelength diversity method as imitated by optimal combining (OC) at the receiver end. Evaluated results also compared with the single transmitter and single receiver system that transmits M times increased average power.

The remainder of this paper is organized as follows. Section 2 describes the system and channel model, Section 3 presents the average BER derivation for pointing error, numerical simulations and conclusion is given in Section 4 and 5 respectively.

2. System and Channel Model

POW system consists of M trans-receivers, the spacing between trans-receivers is order of centimetres, d, and each transmit laser is aligned to the corresponding receive aperture. The signal is transmitted by transmitter at M different wavelengths and propagates along a horizontal path with additive white Gaussian noise (AWGN). POW system sketch is given in Figure 1. From the receiver side, the laser sources have an appearance of single input so BER of POW system is considered under the assumption of wavelength diversity method as imitated by optimal combining (OC) (Nistazakis & Tombras, 2012; Tsiftsis et al., 2009;Xarcha et al., 2012) at the receiver end, i.e. composite transmitter and M receivers.

IM/DD with OOK modulation is considered, while the channel state information (CSI) is available at both transmitter and receiver for slow fading statistics. In this case, output signal of each of the M receivers can be expressed as in Equation (1), (Farid & Hranilovic, 2007; Nistazakis & Tombras, 2012; Tsiftsis et al 2009; Xarcha et al., 2012).

$$y_m = h_m R_m x + n \qquad m = 1, 2 \ldots M \tag{1}$$

where R_m is the detector responsivity of m^{th} receiver, x is the transmitted intensity, $x \in \{0, 2P_{tm}\}$ P_{tm} is the average transmitted power, n is the signal independent AWGN with variance, σ_n^2, h_m is the channel state of m^{th} channel. Defined in Farid & Hranilovic (2007) $h=h_l h_p h_a$ where h_l is deterministic path loss, h_p and h_a are random distributed defined as pointing errors and atmospheric turbulence, respectively.

Path loss is given in Equation (2) modelled by the exponential Beer's-Lambert law (Bouchet et al., 2006; Ghassemlooy et al., 2012; Willebrand & Ghuman, 2002)

$$h_l(R) = \exp(-\sigma R)$$
$$\sigma = \left(3.91/\mathrm{V}\right)\left(\frac{\lambda}{550nm}\right)^{-q} \tag{2}$$

In Equation (2), R is the link range, σ is the attenuation coefficient, V is the visibility (km), λ is the laser wavelength (nm) and q varies with V (Kim et al., 2001),

$$q = \begin{cases} 1.3 & \text{for } 6.0 < V < 50.0 \text{ km} \\ 0.16V+0.34 & \text{for } 1.0 < V < 6.0 \text{ km} \\ V-0.5 & \text{for } 0.5 < V < 1.0 \text{ km} \\ 0 & \text{for } V < 0.5 \text{ km} \end{cases}$$

Path loss attenuation for four wavelengths which are λ_1 = 650 nm (visible), λ_2 = 880 nm, λ_3 = 1310 nm and λ_4 = 1550 nm is given in Figure 2. Atmospheric turbulence loss is expressed as in Equation (3) (Tsukamoto et al., 2009)

$$h_a(R) = 2\sqrt{23.17 k^{7/6} C_n^2 R^{11/6}} \text{ dB} \tag{3}$$

where k=2π/λ is the wave number, C_n^2 is the refractive index structure parameter. Atmospheric turbulence loss is shown in Figure 3 for weak turbulence conditions, $C_n^2 = 5*10^{-15}$ $m^{-2/3}$.

Path loss attenuation is wavelength independent for moderate fog condition, V ≤ 0.5 km, and maximum attenuation difference is 5.5 dB / km at 1 km visibility, in Figure 2. Turbulence loss difference is 1 dB between the wavelengths of 650 nm and 1550 nm for a weak turbulence, in Figure 3.

Especially for short distance applications, which are maximum 0.5 km for POW system, path loss and turbulence loss are considered fixed scaling factor. So in this paper, pointing error dominant channel is considered, $h_m = h_{pm}$. Pointing error, defined in Farid & Hranilovic (2007), is approximated by Equation (4).

$$h_{pm} \approx A_{0_m} \exp\left(-\frac{r^2}{w_{zeq_m}^2}\right) \tag{4}$$

where r as the radial displacement at the receiver, A_{0m} is the fraction of the m[th] receiver's collected power at r = 0, $w_{zeq_m} = w_{z_m} \dfrac{\sqrt{\pi} erf(v_m)}{2v_m \exp(-v_m^2)}$ is the equivalent beam width. $A_{0m} = [erf(v_m)]^2$ with $v_m = \sqrt{\pi/2}\left(a_m/w_{z_m}\right)$, w_{zm} / a_m is the m[th] beam width normalized by the radius of the m[th] receiver aperture. Considering independent and identical Gaussian distributions with variance σ_s^2 for either horizontal and vertical sway or system displacement, the probability density function (pdf) of h_{pm} expressed in Equation (5),

$$f_{h_{pm}} = \frac{\gamma_m^{\,2}}{A_{0_m}^{\gamma_m^2}} h_m^{\gamma_m^2 - 1} \quad 0 \le h_m \le A_{0m} \tag{5}$$

where $\gamma_m = w_{zeq_m}/2\sigma_s$ is the ratio between the equivalent beam radius and the pointing error displacement standard deviation at the m[th] receiver.

3. The Average BER Derivation for POW system

Average BER is an important metric for communication system indicating the system performance and instantaneous electrical SNR parameter at the receiver can be used to evaluate the average BER of system in practice. The instantaneous electrical SNR of IM/DD with OOK signalling for slow fading channel is defined as $\mu_m = 2\left(\dfrac{P_{t_m} R_m h_l h_a h_m}{\sigma_n}\right)^2$ and the average electrical SNR as $\delta_m = \dfrac{2P_{t_m}^2 R_m^2 h_l^2 h_a^2 E\left[h_m\right]^2}{\sigma_n^2}$ with E[.] being the expected value of the pointing error of the m[th] wavelength, $E\left[h_{pm}\right] = A_{0m}\gamma_m^2/\gamma_m^2 + 1$ (Nistazakis & Tombras, 2012;Tsiftsis et al 2009;Xarcha et al., 2012;Sandalidis et al., 2009).

Assuming the "0" and "1" bits are transmitted with equal probability, the BER for each of M links can be shown in Equation (6) that condition on h_m (Sandalidis et al., 2008)

$$P_m\left(e/h_m\right) = p\left(e/1, h_m\right) = p\left(e/0, h_m\right) = Q\left(\frac{\sqrt{2}P_{t_m} R_m h_l h_a h_m}{\sigma_n}\right) = Q\left(\sqrt{\mu_m}\right) \tag{6}$$

where Q(.) is the Gaussian Q-function. The average BER, $P_{av,m}$, for each wavelength channel can be obtained in Equation (7) by averaging Equation (6) over the pdf of h_m,

$$P_{av,m} = \int_0^\infty f_{h_m}(h_m) P_m\left(e/h_m\right) dh_m = \int_0^\infty f_{h_m}(h_m) Q\left(\frac{\sqrt{2}P_{t_m} R_m h_l h_a h_m}{\sigma_n}\right) dh_m \tag{7}$$

Wavelength diversity technique usage is considered for POW system design. Defined in Section 2 and Figure 1, using M pair of transmitter and receiver at different wavelengths and the aperture separation is of order of centimetres, i.e. this system is equivalent to single input multiple output (SIMO) system, M receiver will be independent and identically distributed (i.i.d.) and uncorrelated (Letzepis et al., 2008; Nistazakis & Tombras, 2012; Xarcha et al., 2012). Thus γ_m, A_{0m}, path loss, average and instantaneous electrical SNR are the same for all copies of the transmitted signal. Optimum decision rule for OOK is given in Equation (8) (Tsiftsis et al., 2009)

$$P(\vec{y} \mid on, h_m) \underset{off}{\overset{on}{\gtrless}} P(\vec{y} \mid off, h_m) \tag{8}$$

where $\vec{y} = (y_1, y_2, ..., y_m)$ is the vector signal with M components arriving at the receivers, given in Equation (1). The average BER of POW system will be obtained from OC signal reception for different wavelength channels according to (Nistazakis & Tombras, 2012; Rachmani & Arnon, 2012; Xarcha et al., 2012) in Equation (9),

$$P_{e_m} = \int_{\vec{h}} f_{\vec{h}}(\vec{h}) Q\left(\frac{1}{\sqrt{M}}\sqrt{\sum_{m=1}^{M} 2\left(\frac{P_{t_m} R_m h_l h_a h_m}{\sigma_n}\right)^2}\right) d\vec{h} \qquad (9)$$

$\vec{h}$ = (h_1, h_2... h_m) is the vector of channel state for each of the M receivers for wavelength diversity scheme. Responsivity of the detectors is unique thus $R_1=R_2=...=R_M=R$.

For the estimation of the multiple integral of Equation (9), Q-function approximation is used (Chiani et al., 2003) i.e. $Q(x) \approx \frac{1}{12} e^{\left(-x^2/2\right)} + \frac{1}{4} e^{\left(-2x^2/3\right)}$, and the transformation in a product of single integral as in (Alouini & Simon, 2000) hence Equation (9) can transformed to Equation (10)

$$P_{e_m} \approx \frac{1}{12}\prod_{m=1}^{M}\int_{h_m} \exp\left(-\frac{1}{M}\sum_{m=1}^{M}\left(\frac{P_{t_m} R h_l h_a h_m}{\sigma_n}\right)^2\right) f_{h_m}(h_m)\, dh_m + \frac{1}{4}\prod_{m=1}^{M}\int_{h_m} \exp\left(-\frac{4}{3M}\sum_{m=1}^{M}\left(\frac{P_{t_m} R h_l h_a h_m}{\sigma_n}\right)^2\right) f_{h_m}(h_m)\, dh_m \qquad (10)$$

replacing $f_{h_m}(h_m)$, given in Equation (5), the following integral will be obtained in Equation (11)

$$P_{e_m} \approx \frac{1}{12}\prod_{m=1}^{M}\int_0^{A_{0_m}} \exp\left(-\frac{1}{M}\left(\frac{P_{t_m} R h_l h_a h_m}{\sigma_n}\right)^2\right) \frac{\gamma_m{}^2}{A_{0_m}{}^{\gamma_m{}^2}} h_m{}^{\gamma^2-1} dh_m + \frac{1}{4}\prod_{m=1}^{M}\int_0^{A_{0_m}} \exp\left(-\frac{4}{3M}\left(\frac{P_{t_m} R h_l h_a h_m}{\sigma_n}\right)^2\right) \frac{\gamma_m{}^2}{A_{0_m}{}^{\gamma_m{}^2}} h_m{}^{\gamma^2-1} dh_m \qquad (11)$$

Closed-form solution of Equation (11), which is the average BER of POW system with wavelength diversity in case of pointing error, is mathematically derived in Equation (12), with the help of (Wolfram function site, 2013, (01.03.21.0099.01)).

$$P_{e_m} \approx \frac{1}{12}\left\{\frac{\gamma^2}{2A_0{}^{\gamma^2}}\left(\frac{1}{M}\left(\frac{P_{t_m} R h_l h_a}{\sigma_n}\right)^2\right)^{-0.5\gamma^2}\left[\Gamma\left(0.5\gamma^2\right) - \Gamma\left(0.5\gamma^2, \frac{1}{M}\left(\frac{P_{t_m} R h_l h_a}{\sigma_n}\right)^2 A_0{}^2\right)\right]\right\}^M$$
$$+\frac{1}{4}\left\{\frac{\gamma^2}{2A_0{}^{\gamma^2}}\left(\frac{4}{3M}\left(\frac{P_{t_m} R h_l h_a}{\sigma_n}\right)^2\right)^{-0.5\gamma^2}\left[\Gamma\left(0.5\gamma^2\right) - \Gamma\left(0.5\gamma^2, \frac{4}{3M}\left(\frac{P_{t_m} R h_l h_a}{\sigma_n}\right)^2 A_0{}^2\right)\right]\right\}^M \qquad (12)$$

where Γ(.) and Γ(.,.) being the gamma and incomplete gamma functions, respectively. Equation (12) also expressed as the function of the average electrical SNR in (13), inserting $\frac{2P_{t_m}^2 h_l^2 h_a^2 R^2}{\sigma_n^2} = \frac{\delta_m}{E\left[h_m\right]^2}$.

$$P_{e_m} \approx \frac{1}{12}\left\{\frac{\gamma^2}{2}\left(\frac{\delta_m}{2M}\left(\frac{\gamma^2+1}{\gamma^2}\right)^2\right)^{-0.5\gamma^2}\left[\Gamma\left(0.5\gamma^2\right) - \Gamma\left(0.5\gamma^2, \frac{\delta_m}{2M}\left(\frac{\gamma^2+1}{\gamma^2}\right)^2\right)\right]\right\}^M$$
$$+\frac{1}{4}\left\{\frac{\gamma^2}{2}\left(\frac{2\delta_m}{3M}\left(\frac{\gamma^2+1}{\gamma^2}\right)^2\right)^{-0.5\gamma^2}\left[\Gamma\left(0.5\gamma^2\right) - \Gamma\left(0.5\gamma^2, \frac{2\delta_m}{3M}\left(\frac{\gamma^2+1}{\gamma^2}\right)^2\right)\right]\right\}^M \qquad (13)$$

The average BER can be estimated using (13) when the pointing error dominant and the OC method at the receiver for a single point-to-point, M=1, or wavelength diversity of M channels. In case of M = 1, SISO system, the obtained results from (13) are same as (7).

4. Simulations

POW systems are light weighted, small volume and battery operated systems and are good for short term, short distance f2f applications. Especially in emergency applications, speech signal transfer is considered. The average BER values lower than 10^{-3} is sufficient for speech transmission (Kondoz, 1995).

Average BER is calculated using Equation (13) as a function of the average electrical SNR, δ_m , and γ, related to the normalized beam width and normalized jitter of the POW system for wavelength channels.

POW system size is considered 30 cm x 30 cm that each of the receivers have a circular aperture of radius 5 cm, the spacing between trans-receivers is d=20 cm and the link distance is 300 m. Four wavelengths are selected, λ_1 = 650 nm (visible), λ_2 = 880 nm, λ_3 = 1310 nm and λ_4 = 1550 nm. Visible light is chosen to ease the LOS establishment. Also, w_{zm}, γ_m, A_{0m}, and δ_m are assumed the same for all copies of the transmitted signal.

The average BER variations depend on the beam divergence, varies between 1 to 3 mrad, for M channel wavelength diversity is evaluated and normalized jitter is taken 2 in Figure 4. Use of wavelength diversity technique decrease the average BER of the POW system for the narrow beam width, $w_z/a < 6$, especially compared with the when no wavelength diversity (M=1) is applied. Expanding beam widths give close average BER values for SNR ≤ 10 dB, SNR values higher than 10 dB decrease the average BER of POW system when the wavelength channels are augmented.

Increasing beam divergence also shortens LOS establishment time. Beam divergence is chosen 2 mrad which corresponding 30 cm beam waist at the receiver plane to examine the wide beam divergence effect. The average BER of wavelength diversity and four times increased transmitted power of SISO, M=1 & $P_{t1} = 4P_t$, system are compared under the assumption of σ_s / a = 2, Figure 5. The average BER lower than 10^{-3} is fulfilled the average SNR values greater than 20 dB, 13 dB, 11 dB and 10 dB and 15 dB for M = 1, 2, 3, 4 and M=1 & $P_{t1} = 4P_t$ respectively, depicted in Figure 5. Also the results show that four channel wavelength diversity technique gives lower average BER compared with the SISO system with $4P_t$ for the SNR values greater than 10 dB.

Normalized jitter effect related to the system displacement is another important parameter with respect to the localization difficulties of POW system. Average BER changes are given in Figure 6 for the use of wide beam divergence and normalized jitter varies between the 1 and 6. The average SNR value is chosen as 10 dB and 15 dB respectively, from the results obtained in Figure 5.

Deviation of trans-receivers alignment decrease the system performance but the use of wavelength diversity technique result in approximately 10^{-2} average BER improvement between the M=1 and M=4 for the normalized jitter variations. In Figure 6, depend on the BER threshold of speech transmission, SISO system with $4P_t$ requires the normalized jitter lower than 2 which is also equivalent to the use of two wavelength channels for SNR = 15 dB. Four channel decrease the effect of displacement compared with the M=1 & $4P_t$ system. In this case wavelength diversity technique has an advantage over SISO with $4P_t$ respect to the increased normalized jitter values.

5. Conclusion

In this work, portable laser optical wireless system is considered for short distance real time emergency applications. The use of wavelength diversity technique is analysed in case of pointing error and mathematical expression is derived for the average BER of POW system. Four wavelength channels are chosen and one of them is assumed to be visible to ease the line-of-sight establishment.

The obtained results have shown that wavelength diversity technique depend on the optimal combining method decrease the average BER, especially compared with when no wavelength diversity is applied for the use of narrow beam width. Expanding beam width gives the close average BER values and enhances the system performance under the assumption of the same normalized jitter values. Wavelength channels are compared with the SISO system with the M times increased power. At the low electrical SNR levels SISO system with MP_t has an advantage over wavelength diversity technique but wavelength diversity performs better at the high electrical SNRs'.

Normalized jitter effect of pointing error is also investigated. Normalized jitter variations, depend on the displacement, decrease the system performance but the use of wavelength diversity technique results in approximately 10^{-2} average BER improvement between no wavelength diversity and 4 wavelength channels. M channel wavelength diversity has an advantage over SISO system with MP_t in case of high displacement and building sway state.

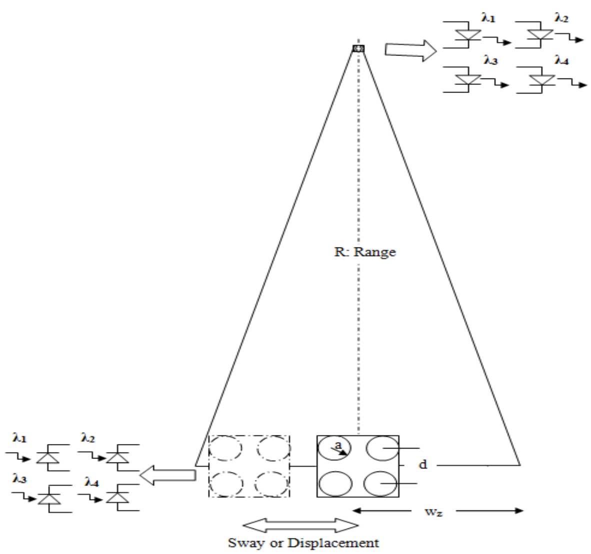

Figure 1. Basic sketch of POW system.

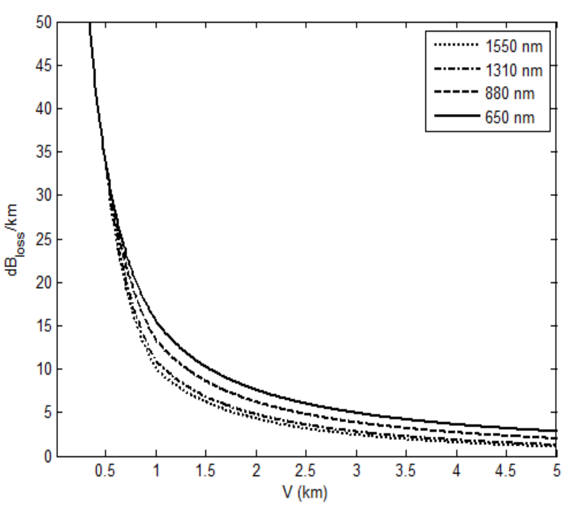

Figure 2. Path loss attenuation versus visibility for different wavelengths.

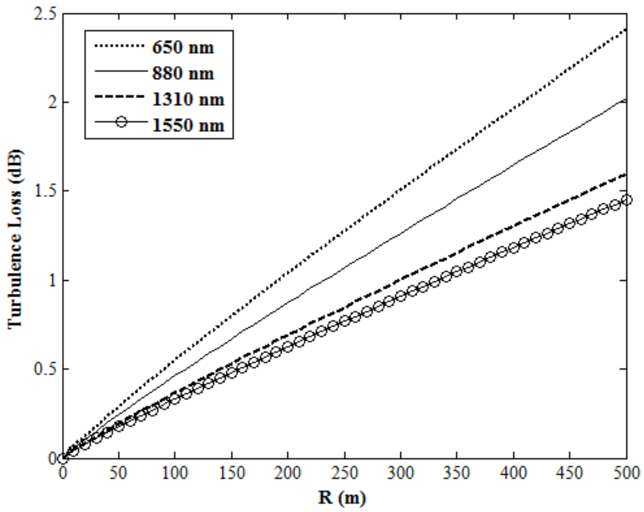

Figure 3. Turbulence loss against the link range for different wavelengths.

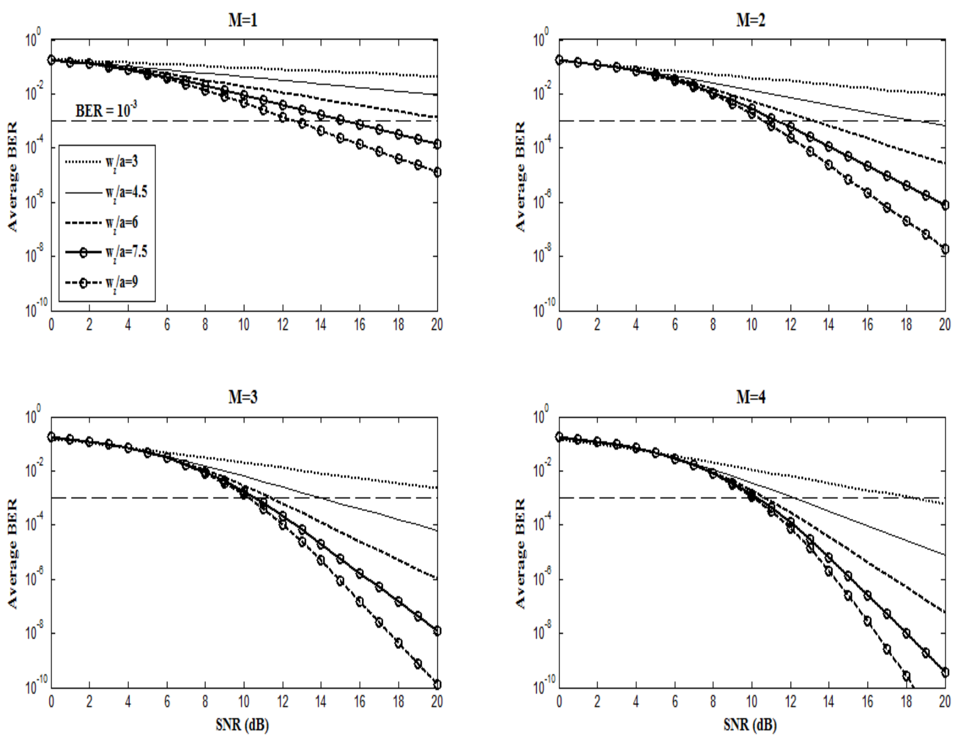

Figure 4. The normalized beam width effect of the average BER for different wavelength channels.

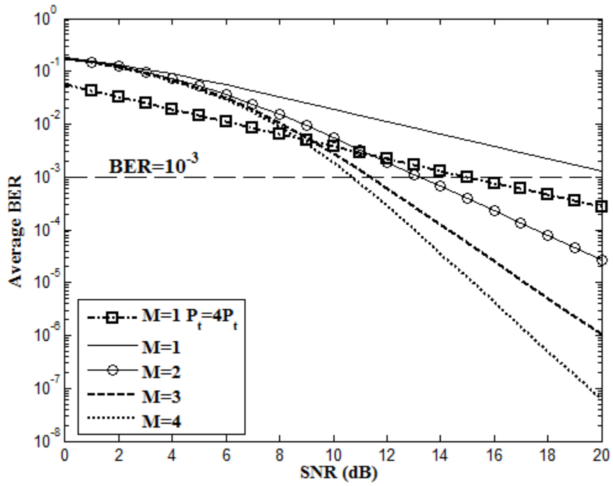

Figure 5. Variations of average BER vs. the average SNR for wavelength diversity and SISO system with $4P_t$ for w_z / a = 6.

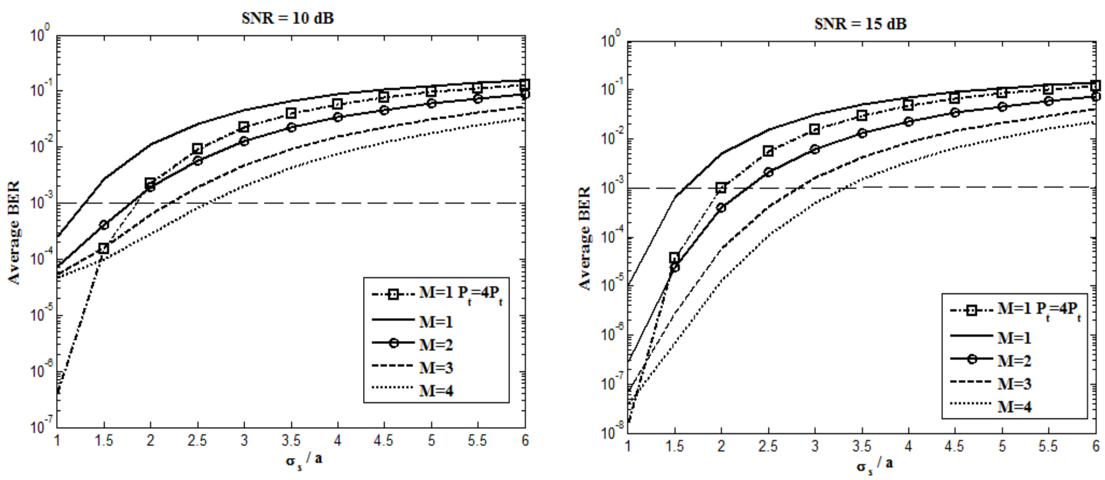

Figure 6. Average BER variations vs. normalized jitter for δ_m=10 dB and δ_m=15 dB,

References

Alouini, M.S. & Simon M.K. (2000). An MGF-based performance analysis of generalized selection combining over Rayleigh fading channels. *IEEE Transactions on Communications*, 48(3) , 401-415. doi: 10.1109/26.837044

Bloom S., Korevaar E., Schuster J., Willebrand H. (2006) Understanding the performance of free – space optics. *Journal of Optical Networking*, 2 (6), 178 – 200.

Bouchet O., Sizun H., Boisrobert C., Fornel F., Favennec P.N. (2006) Free – Space Optics: Propagation and Communication. ISTE Ltd: London.

Chiani M., Dardari D., Simon M.K. (2003). New exponential bounds and approximations for the computation of error probability in fading channels. *IEEE Transactions on Wireless Communications*, 2(4), 840-845. doi:10.1109/TWC.2003.814350

Chiani M., Dardari D., Simon M.K. (2003). New exponential bounds and approximations for the computation of error probability in fading channels. *IEEE Transactions on Wireless Communications*, 2(4), 840-845. doi:10.1109/TWC.2003.814350

Farid, A.A. & Hranilovic S. (2007). Outage Capacity Optimization for Free-Space Optical Links With Pointing Errors. *Journal of Lightwave Technology,* 25 (7), 1702-1710. doi: 10.1109/JLT.2007.899174

Ghassemlooy Z., Popoola W., Rajbhandari S. (2012). Optical Wireless Communications: System and Channel Modelling with Matlab. CRC Press; New York.

Hranilovic S. & Farid A.A. (2012) Diversity Gain and Outage Probability for MIMO Free-Space Optical Links with Misalignment. *Communications, IEEE Transactions on*, 60(2), 479 – 487. doi: 10.1109/TCOMM.2011.121611.110181

Kim, I.I., MCArthur, B., Korevaar, E.J. (2001). Comparison of laser beam propagation at 785 nm and 1550 nm in fog and haze for optical wireless communications. *Proc. SPIE,* 4214, 26 – 37.

Kondoz A.M. (1995). Digital Speech. John Wiley & Sons: New York, 304.

Letzepis N., Holland I., Cowley W. (2008).The Gaussian free space optical MIMO channel with Q-ary pulse position modulation. *IEEE Transactions on Wireless Communications*, 7(5)*,* 1744-1753. doi: 10.1109/TWC.2008.061002

Nistazakis H.E.& Tombras G.S. (2012). On the use of wavelength and time diversity in optical wireless communication systems over gamma–gamma turbulence channels. *Optics & Laser Technology*, 44, 2088–2094. doi: 10.1016/j.optlastec.2012.03.021

Prokes A. (2009) Modelling of atmospheric turbulence effect on terrestrial fso link. *Radioengineering* 18(1), 42-47.

Rachmani R. & Arnon S. (2012). Server backplane with optical wavelength diversity links. *Journal of Lightwave Technology,* 30(9), 1359 – 1365. doi: 10.1109/JLT.2012.2189755

Sandalidis H.G, Tsiftsis T.A., Karagiannidis G.K. (2009) Optical wireless communications with heterodyne detection over turbulence channels with pointing errors. *Journal of lightwave technology*, 27(20), 4440-4445. doi: 10.1109/JLT.2009.2024169

Sandalidis H.G., Tsiftsis T.A., Karagiannidis G.K. (2009). Optical wireless communications with heterodyne detection over turbulence channels with pointing errors. *Journal of lightwave technology*, 27(20), 4440-4445. doi: 10.1109/JLT.2009.2024169

Sandalidis HG, Tsiftsis TA, Karagiannidis GK, Uysal M. (2008) BER Performance of FSO Links over Strong Atmospheric Turbulence Channels with Pointing Errors. *IEEE Communications Letters*. 12(1), 44-46. doi: 10.1109/LCOMM.2008.071408

The Wolfram function site (2013). [Online] Available: http://functions.wolfram.com.

Tsiftsis T.A., Sandalidis H.G., Karagiannidis G.K., Uysal M. (2009). Optical wireless links with spatial diversity over strong atmospheric turbulence channels. *IEEE Transactions on Wireless Communications*, 8(2)*,* 951-957. doi: 10.1109/TWC.2009.071318

Tsukamoto, K., Hashimoto, A., Aburakawa, Y., Matsumoto, M., (2009). The case for free space. *Microwave Magazine, IEEE*, 10 (5), 84-92, doi: 10.1109/MMM.2009.933086

Willebrand H. & Ghuman B.S. (2002) *Free – Space Optics: Enabling Optical Connectivity in Today's Networks.* SAMs Publishing: Indianapolis, 2002.

Xarcha V., Stassinakis A.N., Nistazakis H.E., Latsas M.P., Hanias M.P., Tombras G.S., Tsigopolus A. (2012). Wavelength diversity for Free Space Optical Systems: Performance evaluation over log normal turbulence channels. *MIKON 2012*, 678 – 683.