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Performance of underwater wireless optical link under weak turbulence and pointing errors using heterodyne QAM technique.

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Abstract. Underwater optical wireless communications (UOWC) have gained attention due to the advantages they offer that can greatly alter the performance of a link. But such systems are affected by absorption and non predictable factors that may decrease the availability and the reliability of the system. In this work, the bit error rate (BER) of an underwater optical link with heterodyne detection modulated with M-QAM technique in presence of turbulence and pointing errors will be investigated. This investigation will lead to a closed form mathematical expression for the BER as a function of link parameters, that is very important in order to deploy an effective link. Various numerical results will also be presented for the reliability of the system.

Keywords: Underwater Optical Communications, BER, Gamma distribution, Turbulence, Pointing Errors.

1 Introduction

Optical wireless communications have attracted research and commercial interest due to the plenty advantages they offer that fulfill the requirements of modern networks [1]-[3]. Such advantages are the high bit rate they can achieve in low operational and installation cost. Such systems are point to point links that use a laser beam in order to transmit a signal between a receiver and a transmitter. So, the use of narrow beamwidth laser for transmitting information creates a license free communication link. Such systems were mostly used for terrestrial and satellite communications (FSO/sat-FSO) [1],[2],[4], but during the last few years, optical wireless communications have also been applied for underwater communications in order to solve the problem of low bit rate in relative short distances[5]-[11]. On the other hand, the laser beam that propagates along the water is affected by various factors that decrease the performance of the system. The main factor that decreases the possibilities of UOWC systems is the strong power absorption of the laser beam. Another important and non predictable factor that affects underwater OWC systems is the presence of turbulence

that creates power fluctuations at the receiver due to the local variations of the refractive index, a phenomenon called scintillation [5], [8]- [15]. In order to investigate how the link is affected by turbulence, various statistical distributions are used depending on the turbulence strength [13],[16]. In this work, that weak turbulence is assumed, gamma statistical distribution is suitable to model the channel [17]. Another factor that deteriorates the performance of an underwater OWC system is the misalignment between the transmitter and the receiver due to vibrations that come from various sources mostly from internal mechanisms of the vessel. The statistical distribution of Beckman's model is used in order to model the fluctuations of pointing errors [18]- [21]. The modulation technique that will be used in this OWC system, is the quadrature amplitude modulation (QAM), that is an extensively used modulation scheme in modern communication systems [22]-[25]. The demodulation of QAM system will be deployed using heterodyne detection, a technique that presents many advantages as high sensitivity and better frequency selectivity in case of wavelength division multiplexing [8]. In order to investigate how turbulence and pointing errors affect the performance of the system described, a closed form mathematical expression for the bit error rate (BER), will be extracted. BER is an important metric for the reliability of a communication system [16], [23]. In section II, the underwater channel will be analyzed and in section III the BER of the system will be calculated. Finally in section IV the corresponding numerical results will be presented.

2 Underwater Channel Modeling

main unpredictable factor that affects UOWC communications is the oceanic turbulence that is the chaotic change of pressure and flow velocity of the water. This phenomenon is responsible for variation of several characteristics of water through which the laser beam of an UOWC system propagates, creating lack of homogeneity of the refraction index. So the power that the receiver intercepts presents fluctuations, a phenomenon called scintillation. Such fluctuations may lead to deterioration of the performance of the system depending on its impact. A parameter that measures the strength of this effect is turbulence structure constant, C_n^2 , that can be calculated using the following equation [5],[8]:

$$C_n^2 = 16\pi^2 k^{-7/6} L^{-11/6} \operatorname{Re} \left\{ \int_0^L ds \int_0^\infty \omega d\omega [E(s, \omega, L) \times \right. \quad (1)$$

$$\left. \times E(s, -\omega, L) + |E(s, \omega, L)|^2 \right] \Phi_n(\omega) \Big\}$$

where ω is the magnitude of the spatial frequency, $E(\alpha_1, \alpha_2, \alpha_3) = ik \cdot \exp(-0.5 \cdot i \cdot s \cdot (L-s) \omega^2 / kL)$, k is the wave number, L is the distance between the transmitter and the receiver and $\Phi_n(\omega)$ is given as [5],[8]:

$$\begin{aligned} \Phi_n(\omega) &= 0.388 \cdot 10^{-12} \varepsilon^{-1/3} \omega^{-11/3} \left(1 + 2.35 \omega^{2/3} \cdot \nu^{1/2} \varepsilon^{-1/6}\right) \times \\ &\times \omega^{-2} \left(\omega^2 \exp(-1.863 \cdot 10^{-2} \varphi) + \exp(-1.9 \cdot 10^{-4} \varphi) - \right. \\ &\left. - 2 \omega \exp(-9.41 \cdot 10^{-3} \varphi) \right) \end{aligned} \quad (2)$$

where ε is the rate of dissipation of kinetic energy per unit mass of the fluid, ω provides the ratio of temperature to salinity contributions to the refractive index spectrum, ν is the kinematic viscosity and $\varphi = 8.284 \omega^{4/3} \nu \varepsilon^{-1/3} + 12.978 \omega^2 \nu^{3/2} \varepsilon^{-0.5}$, [5],[8].

In order to investigate how the turbulence affects the performance of the system, various statistical models are used to model the channel depending on the turbulence strength [10]-[13]. A suitable model for weak turbulence is the gamma distribution and the pdf as a function of irradiance, I_t , is given by the following equation, [17]:

$$f_{I_t}(I_t) = I_t^{\zeta-1} \cdot \exp(-I_t \zeta) \cdot \frac{\zeta^\zeta}{\Gamma(\zeta)} \quad (3)$$

where $\Gamma(\cdot)$, signifies the Gamma function and parameter ζ can be estimated as[17]:

$$\zeta = \frac{1}{\sigma_p^2} \quad (4)$$

with σ_p^2 being the power scintillation index which is the normalized variance of the received optical power, I , and can be calculated using the following equation [13], [17], [22]:

$$\sigma_p^2 = \frac{1}{a} + \frac{1}{b} + \frac{1}{ab} \quad (5)$$

$$a = \left(\exp \left(\frac{0.49 \delta^2}{\left(1 + 0.18 d^2 + 0.56 \delta^{12/5}\right)^{7/6}} \right) - 1 \right)^{-1} \quad (6)$$

$$b = \left(\exp \left(\frac{0.51 \delta^2 \left(1 + 0.69 \delta^{12/5}\right)^{-5/6}}{\left(1 + 0.9 d^2 + 0.62 \delta^{12/5}\right)^{5/6}} \right) - 1 \right)^{-1} \quad (7)$$

where $d = \sqrt{kD^2 / (4L)}$, $k=2\pi/\lambda$ is the optical wave number, λ is the operational wavelength of the link, D is the aperture diameter of the receiver and L is the distance between the transmitter and the receiver. Parameter δ^2 , is the Rytov variance given as, [13]:

$$\delta^2 = 1.23 C_n^2 k^{7/6} L^{11/6} \quad (8)$$

Due to the narrow beamwidth of the laser beam that UOWC systems use, there must be a precision in the alignment between the receiver and the transmitter. But several phenomena like mechanical vibrations of the system or rip currents in the water may cause pointing errors that lead to power fluctuations at the receiver. In

order to investigate this pointing errors, Beckmman's model is suitable and accurate to model the channel and its pdf as a function of Irradiance, I_p , is given by the following equation [18]-[20]:

$$f_{I_p}(I_p) = \frac{g^2}{A_0^{g^2}} I_p^{g^2-1}, \quad 0 \leq I_p \leq A_0 \quad (9)$$

with g being the ratio between the equivalent beam radius at the receiver, w_{zeq} , and the pointing error displacement standard deviation, σ_s , and is given by the following equation [15]-[17]:

$$g = \frac{w_{zeq}}{2\sigma_s} \quad (10)$$

The parameter w_{zeq} can be calculated using [18]-[20]:

$$w_{zeq}^2 = \frac{w_z \sqrt{\pi} \operatorname{erf}(u)}{2u \cdot \exp(-u^2)} \quad (11)$$

where w_z is the beam waist, $u = \sqrt{\pi} r / \sqrt{2} w_z$ and $A_0 = (\operatorname{erf}(u))^2$ with w_z represents the radius of the Gaussian beam on the receiver plane.

In order to investigate both turbulence and pointing errors effect, a combined pdf will be extracted using the following mathematical property [19]:

$$f_I(I) = \int f_{I|I_t}(I | I_t) f_{I_t}(I_t) dI_t \quad (12)$$

where $I=I_p$.

Substituting equations (3) and (9) in (12), the combined pdf for weak turbulence strength and pointing errors will be given as [18]:

$$f_I(I) = \frac{g^2 \zeta}{A_0 \Gamma(\zeta)} G_{1,2}^{2,0} \left(\frac{\zeta I}{A_0} \middle| \begin{matrix} g^2 \\ g^2 - 1, \zeta - 1 \end{matrix} \right) \quad (13)$$

The combined pdf can be expressed as a function of the instantaneous SNR, μ , and the average SNR, ζ , using the following equation for the case of heterodyne detection systems, [8],[19]:

$$I = \frac{\mu}{\zeta} \quad (14)$$

So applying random variable transformation in equation (13) using equation (14), the combined pdf as a function of SNR will be given by the following equation:

$$f_\mu(\mu) = \frac{g^2 \zeta}{A_0 \Gamma(\zeta) \zeta} G_{1,2}^{2,0} \left(\frac{\zeta \mu}{A_0 \zeta} \middle| \begin{matrix} g^2 \\ g^2 - 1, \zeta - 1 \end{matrix} \right) \quad (15)$$

3 Bit Error Rate Calculation

A very important metric concerning the performance of a link is the bit error rate that represents the probability of receiving an error bit at the receiver. The modulation technique that is assumed to be applied in the underwater link will be M-QAM with heterodyne detection.

The BER for the received M-QAM signal is given by[22], [24]:

$$P(\mu) = \frac{2(1-M^{-1/2})}{\log_2(M)} \cdot \operatorname{erfc} \left(\sqrt{\frac{3 \cdot \mu}{4(M-1)}} \right) \quad (16)$$

Using equation (16), the average BER can be obtained by averaging over the combined distribution of equation (15) :

$$P_{av}(\xi) = \frac{2(1-M^{-1/2})g^2\zeta}{\log_2(M)A_0\Gamma(\zeta)\xi} \times \int_0^\infty \operatorname{erfc} \left(\sqrt{\frac{3 \cdot \mu}{4(M-1)}} \right) G_{1,2}^{2,0} \left(\frac{\zeta}{A_0} \frac{\mu}{\xi} \middle| \begin{matrix} g^2 \\ g^2-1, \zeta-1 \end{matrix} \right) \quad (17)$$

The above integral can be solved by expressing the $\operatorname{erfc}(\cdot)$ function using Meijer G function and after some mathematical manipulations [26] the BER of an underwater optical link in a channel with weak turbulence and pointing errors using M-QAM modulation will be given as:

$$P_{av}(\xi) = \frac{8(1-M^{-1/2})(M-1)g^2\zeta}{3\sqrt{\pi}\log_2(M)A_0\Gamma(\zeta)\xi} \times G_{3,3}^{2,2} \left(\frac{4\zeta(M-1)}{3 \cdot A_0\xi} \middle| \begin{matrix} 0, -\frac{1}{2}, g^2 \\ g^2-1, \zeta-1, -1 \end{matrix} \right) \quad (18)$$

4 Numerical Results

In this section the results of the average BER, P_{av} , will be presented for an underwater optical communication system using M-QAM modulation technique according to equation (18). We have chosen three to values for the modulation index $M=4$ and 16 and three values for the ratio of temperature to salinity contributions to the refractive index, $w=[-0.05, -1, -3]$, the rate of dissipation of kinetic energy per unit mass $\varepsilon=[10^{-1}, 10^{-2}, 10^{-4}]m^2/s^3$ and the viscosity, $\nu=[0.01, 0.002, 10^{-5}]$. All values were chosen for low values of the scintillation index m^2 [5]. The wavelength of the laser beam is assumed to be $\lambda=532nm$, the aperture diameter of the receiver $D=1cm$ and the distance $L=80m$. Concerning the pointing errors, we assume normalized spatial jitters with equal to $\sigma_x/r=0.05$ and $\sigma_y/R=0.1$.

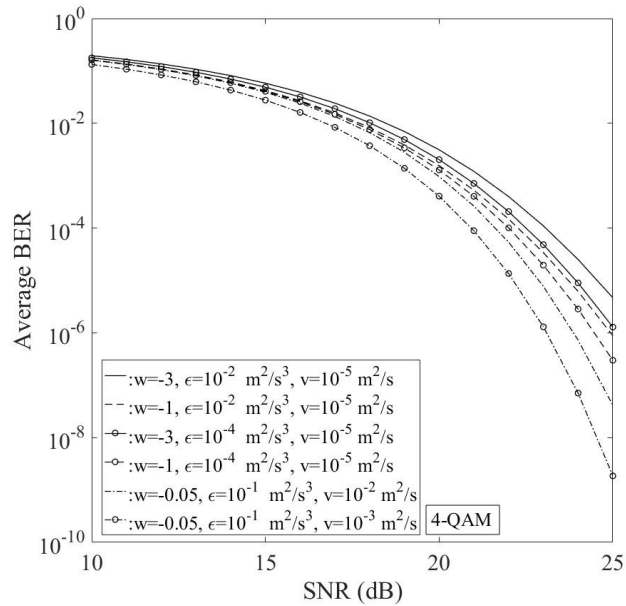


Fig. 1. Average BER of UOWC for 4-QAM

In Fig. 1, the BER of the underwater OWC system for 4-QAM is presented as a function of links parameters. It is clear that as parameters w , ϵ and ν are not stable, the BER of the system may change even for 2 orders of magnitude. More precisely, as the absolute value w increases, the performance of the system decreases, as the BER becomes higher. Furthermore, the reliability of the system increases when parameter ϵ , decreases. Viscosity also affects the BER of the systems as the systems performs better for lower values of ν .

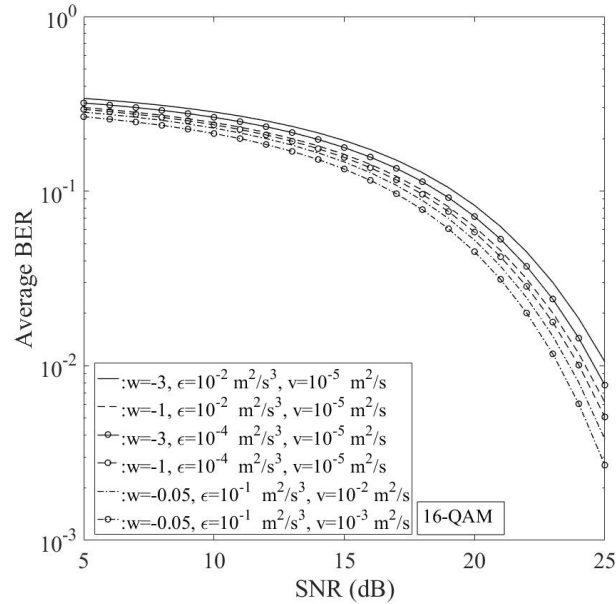


Fig. 2. Average BER of UOWC for 4-QAM

In fig. 2, the corresponding results of BER are presented in case of 16-QAM. It is clear that the system's performance deteriorates as the BER increases and as in figure 1, the system's BER strongly depends on link's and channel's parameters.

5 Conclusions

In this work we derived a closed form mathematical expression for the BER of an underwater optical link modulated with M-QAM with heterodyne detection that is affected by weak turbulence and pointing errors. According to the results presented, UOWC systems are strongly depended on oceanic turbulence and pointing errors, so the choice of link parameters must be careful in order to deploy a communication system with high performance.

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