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Characteristics of Optical Channel for Underwater Optical Wireless Communication System

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Abstract: *To understand an underwater optical communication, it is necessary to describe the optical path of the light underwater and the refractive index of water. In the present work the receiver signal power underwater has been calculated using free space optical wireless communication formula. This procedure has been used to calculate the link margin, data rate as a function of the distance link. Types of water have been taken in the consideration. Our results show that the signal to noise ratio most parameter in communication systems in the distance link, particularly for the refractive index $n \leq 1.4$. The data rate, signal to noise ratio decreases as the refractive index of water and distance link increases.*
Keywords: *Refractive index of water, optical path, underwater communication, data rate, signal to noise ratio.*

I. Introduction

Wireless optical communications underwater is enjoying a renewed interest from researchers due to the wide advances in laser sources and receivers, digital communications, and signal processing. Underwater free space optics (uFSO) fulfills several niche applications for wireless communications in ocean waters. While RF communications have become ubiquitous in our everyday lives above water, the RF portion of the electromagnetic spectrum exhibits high attenuation in seawater. Acoustics on the other hand have long enjoyed success for detection and communication underwater, given their ability to propagate long distances underwater (>km). However, for high speed data transfer (>Mbps), acoustics are at a disadvantage, as it is well known that acoustic energy exhibits increasing attenuation with increasing frequency. Supported by enormous growth in the telecommunications industry over the past few decades, optical techniques are garnering serious consideration for underwater communications due to higher data rates they may provide. Additionally, as we will learn, the blue/green portion of the visible spectrum exhibits minimal absorption in seawater. Still, scattering of light by organic and inorganic particulates in ocean water can cause significant spatial and temporal dispersion, which may have a measurable impact on link range and available bandwidth [1, 2]. The attenuation of light by water is caused by two independent mechanisms, scattering and absorption, which affect the amplitude, phase and arrival angle of the light beam. Scattering is a random process that changes the directions of individual photons without altering their properties, while absorption is a thermodynamically irreversible process that transforms the energy of photon into thermal energy. This is the major absorption mechanism in the sea and varies considerably with wavelength [3].

II. Underwater Optical Wireless Communication Channel

Light pulses propagating in aquatic medium suffer from attenuation and broadening in the spatial, spatial, angular, temporal, and polarization domains. The attenuation and broadening are wavelength dependent and result from absorption and multi scattering of light by water molecules and by marine hydrosols (mineral and organic matter) [4]. The extinction coefficient $c(\lambda)$ of the aquatic medium is governed by the absorption and scattering coefficients $\alpha(\lambda)$ and $\beta(\lambda)$, respectively, and we have[5]

$$c(\lambda) = \alpha(\lambda) + \beta(\lambda) \quad (1)$$

The scattering due to pure seawater is somewhat limited in magnitude. Fig. 1 shows that the scatter is limited in nature for wavelengths above 400nm, and is much smaller than the absorption coefficient for the same wavelengths [6]

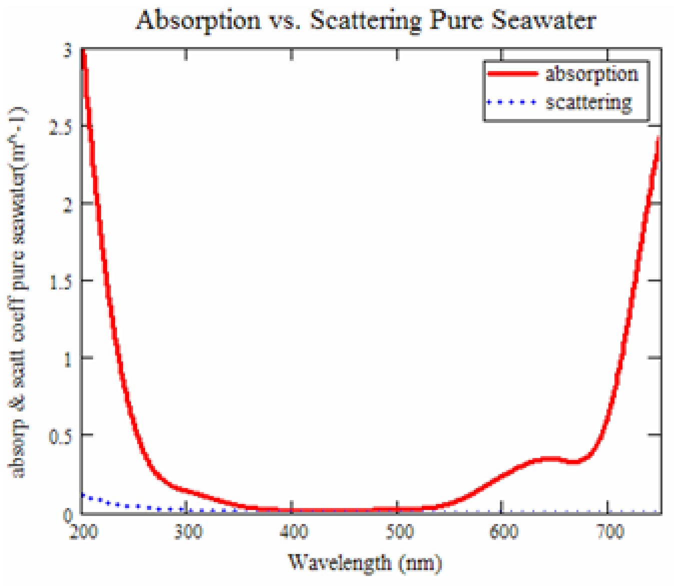


Fig. 1 Scattering coefficient compared to absorption coefficient of pure seawater vs. wavelength

2.1 Absorption Model

The spectral absorption coefficient, α(λ), which is the change in the beam of light due to the absorption by the medium (or things in the medium) per meter of path length [7]. The total absorption is a linear combination of the absorption properties of pure seawater, chlorophyll absorption as a function of wavelength and concentration, and the two components colored dissolved organic materials (CDOM). The splitting of the yellow substance into two components allows the model to be universal for all biologically stable waters and it will permit models in the future to include the effects of fluorescence in a more consistent manner. The absorption coefficient α (λ) is given by:

$$\alpha(\lambda) = \alpha_w(\lambda) + \alpha_{cl}(\lambda) + \alpha_f(\lambda) + \alpha_h(\lambda) \qquad (2)$$

Where α_w (λ) is the absorption coefficient of water as a function of wavelength (m^{-1}), α_{cl} (λ) is the absorption chlorophyll acid coefficient as a function of wavelength, α_f (λ) is the fulvic acid absorption coefficient and α_h (λ) is the humic acid absorption coefficient both as a function of wavelength. The absorption coefficient for water types, α_w (λ), was interpolated from data from [8] with respect to water concentration of $W_c^0 = 1$ mg/m3, and water concentrations $0 \le w_c \le 15$ mg/m^3. It then became:

$$\alpha_w(\lambda) = \alpha_w^0(\lambda)\left[\frac{w_c}{w_c^0}\right]^{a_w^0} \qquad (3)$$

For pure sea water $\alpha_w^0(\lambda) = \alpha_w^0 * \lambda = 0.0405\lambda$, for clean ocean $\alpha_w^0(\lambda) = \alpha_w^0 * \lambda = 0.114\lambda$ for coastal ocean $\alpha_w^0(\lambda) = \alpha_w^0 * \lambda = 0.179\lambda$ for turbid harbor $\alpha_w^0(\lambda) = \alpha_w^0 * \lambda = 0.266\lambda$. As well as the absorption coefficient for chlorophyll, α_{cl} (λ), was interpolated from data from [9, 10] with respect to a chlorophyll concentration in $C_c^0 = 1$ mg/m^3 and chlorophyll concentrations $0 \le C_c \le 12$ mg/m^3. It then became:

$$\alpha_{cl}(\lambda) = \alpha_c^0(\lambda)\left[\frac{C_c}{C_c^0}\right]^{0.0602} \qquad (4)$$

For $\alpha_c^0(\lambda) = 0.0602\lambda$, next, the absorption coefficient of the yellow substance which is broken into two separate components: humic, α_h (λ), and fulvic, α_f (λ) acid.

$$\alpha_h(\lambda) = \alpha_h^0(\lambda) C_h \exp(-k_h \lambda) \qquad (5a)$$

$$\alpha_f(\lambda) = \alpha_f^0(\lambda) C_f \exp(-k_f \lambda) \qquad (5b)$$

Where k_h=0.01105/nm, α_h^0 =18.828 m^2/mg is the specific absorption coefficient of humic acid, the first component of CDOM and k_f= 0.0189/nm, α_f^0 = 35.959 m^2/mg is the specific absorption coefficient of fulvic acid, the second component of CDOM. Also, C_h and C_f are the concentration of humic acids and fulvic acids in mg/m3, respectively and can be [9]:

$$C_f = 1.74098\, C_c \exp\left[0.12327\left(\frac{C_c}{C_c^0}\right)\right] \tag{6a}$$

$$C_h = 0.19334\, C_c \exp\left[0.12343\left(\frac{C_c}{C_c^0}\right)\right] \tag{6b}$$

2.2. Scattering Model

This phenomenon is called the spectral beam scattering coefficient, β(λ), which describes the loss of flux due to the redirection of photons by means of total scattering. The total scattering is a linear combination of the scattering coefficient of water, $\beta_w(\lambda)$, scattering from small particles, $\beta_s^0(\lambda)$ as a function of wavelength and concentration, and scattering from large particle, $\beta_l^0(\lambda)$ as a function of wavelength and concentration, is given by [9]:

$$\beta(\lambda) = \beta_w(\lambda) + \beta_s^0(\lambda).C_s + \beta_l^0(\lambda).C_l \tag{7}$$

The equation for $\beta_w(\lambda)$ is derived by interpolating the data published by[9] to get:

$$\beta_w(\lambda) = 0.005826\left(\frac{0.4}{\lambda}\right)^{4.322},\ m^{-1} \tag{8}$$

The spectral dependencies for scattering coefficients of small and large particulate matter are given by:

$$\beta_s^0(\lambda) = 1.151302\left(\frac{0.4}{\lambda}\right)^{1.7},\ m^2/g \tag{9a}$$

$$\beta_l^0(\lambda) = 0.3411\left(\frac{0.4}{\lambda}\right)^{0.3},\ m^2/g \tag{9b}$$

Where C_s and C_l are the total concentration of small and large particles in g/m3, respectively given by:

$$C_s = 0.01739\, C_c.\exp\left[0.11631\left(\frac{C_c}{C_l}\right)\right], g/m^3 \tag{10a}$$

$$C_l = 0.76284\, C_c.\exp\left[0.03092\left(\frac{C_c}{C_l}\right)\right], g/m^3 \tag{10b}$$

III. Communication Link Model

There are different parameters important of communications systems such as: the received signal power, link margin, and data rate. In addition, we performed a signal to noise ratio calculation.

3.1 Receiver Signal Power

We shall consider the situation of optical propagation between points underwater. Consider a laser transmitting a total power P_T at the wavelength 532nm. The signal power received at the communications detector can be expressed as [11]

$$P_{rec} = P_{trans}\frac{D^2}{\vartheta_{div}^2 L^2}.10^{-\gamma.L/10}\,\tau_{trans}\tau_{rec} \tag{11}$$

Where D is the receiver diameter, θ is the divergence angle, γ is the underwater attenuation factor (dB/m), τ_T, τ_R are the transmitter and receiver optical efficiency respectively. The optical path *d* of a ray of light in any medium is given [12]

$$d = n.L \tag{12a}$$

Where d is the optical path, n is the refractive index of water, and L represents the geometrical optical distance. So that, eq. (11) can be written as

$$P_{rec} = P_{trans} \frac{D^2}{\vartheta_{div}^2 \left(\frac{d}{n}\right)^2} .10^{-\left(\frac{\gamma.d}{10.n}\right)} \tau_{trans} \tau_{rec} \tag{12b}$$

3.2 Link Margin

Another important parameter in the optical communications link analysis is "Link Margin", which is the ratio of available received power to the receiver power required to achieve a specified BER at a given data rate. Note that the "required" power at the receiver P_{REQ} (watts) to achieve a given data rate, R (bits/sec), we can define the link margin LM as [12]:

$$LM = [P_T \lambda / (N_b Rhc] * [D^2 / (\theta^2 L^2)] 10^{-\gamma L/10} \tau_{trans} \tau_{rec} \tag{13}$$

Where R is a data rate, h is a plank constant and c is the light velocity.

3.3 Data Rate

Given a laser transmitter power P_{trans}, with transmitter divergence of *θ,* receiver diameter D, transmit and receive optical efficiency τ_{trans}, τ_{rec} the achievable data rate R can be obtained from [13]

$$R = \frac{P_T .\tau_{trans} .\tau_{rec} .10^{-\gamma.L/10} D^2}{\pi(\theta/2)^2 L^2 E_p N_b} \tag{14}$$

Where E_p=hc/λ, is the photon energy at wavelength λ and N_b is the receiver sensitivity (photon/bits) or (dBm)

3.4 Signal to Noise Ratio (SNR)

The electrical power of the received optical signal is proportional to the mean squared avalanche photodiode APD current, which can be written as [14]

$$\left\langle i_{APD}^2 \right\rangle = (R_0 P_{rec} M)^2 \tag{15}$$

and

$$R_0 = \frac{\eta q \lambda}{h c} \tag{16}$$

where R_0 denotes the primary sensitivity of the APD, P_{rec} is the received power, *M* is the APD gain, η is the quantum efficiency, *q* is the electron charge, *h* is Planck's constant, *c* is the speed of light. The noise contributions

(i.e., the mean-square values of the APD current) are shot noise:

$$\sigma_{sig-noise}^2 = 2q(R_0 P_{rec}) M^{x+2} B \tag{17}$$

Surface leakage current noise:

$$\sigma_{surface}^2 = 2qI_L B \tag{18}$$

multiplied dark current noise:

$$\sigma_{dark,m}^2 = 2q(I_D) M^{x+2} B \tag{19}$$

And Johnson noise:

$$\sigma^2_{johnson} = \frac{4kT\,B\,F_T}{R_{eq}} \tag{20}$$

where I_D is the bulk dark current, I_L is the surface leakage current, $F(M) \approx M^x\,(0 \le x \le 1)$ is the excess noise factor, *k* is the Boltzmann constant, *B* is the equivalent noise bandwidth, R_{eq} is the equivalent circuit resistance, F_T is the noise figure of the electric circuit, and *T* is the system temperature. The SNR for the optical communication system is thus given by

$$SNR_{APD} = \frac{(R_0\,P_{rec}\,M)^2}{2q(R_0\,P_{rec} + I_D)\,M^{x+2}\,B + 2q\,I_L\,B + 4kT\,B\,F_T\,/\,R_{eq}} \tag{21}$$

IV. Simulation results

Simulation by Matlab carried out to show the effect of refractive index of water in underwater optical wireless communication system (UOWCS). The performance of (UOWC) system can be evaluated by the receiver signal power, link margin, data rate and signal to noise ratio. We have investigated the high quality and the best performance of underwater optical wireless communication link systems for different types of water. The investigating based on the modeling equations analysis and the assumed set of the operating parameters are shown in Table 1.

Table 1. Proposed operating parameters for underwater optical communications link

Parameters		Values
Transmitter optical power		50mw
Transmitter divergence angle		1.5mrad
Transmitter efficiency		0.5
Receiver efficiency		0.5
Optical path		$0 \le d\ (m) \le 100$
Receiver diameter		1cm
Receiver sensitivity		-20dBm
Chlorophyll concentration c_c and water concentration w_c	Pure sea water	Cc=0.03mg/m^3, w_c=0.035 mg/m^3
	Clean ocean water	Cc=0.4mg/m^3, w_c=0.55 mg/m^3
	Coastal ocean water	Cc=3mg/m^3, w_c=4 mg/m^3
	Turbid harbor water	Cc=12mg/m^3, w_c=15 mg/m^3
Bulk dark current, ID		0.05 nA
The APD gain		100
The excess noise factor, x		0.5
Electrical band, B		25MHz
Surface leakage current, I_L		0.001A
System temperature, T		290K
Noise figure, F_T		3dB
Equivalent resistance, R_{eq}		50kΩ

So the receiver signal power (dBm) due to the refractive index of water types can be evaluated. The receiver signal power is achieved in pure sea water, clean ocean water, coastal ocean water and turbid harbor for wavelength (532) nm at optical path underwater reach to100 m as shown in Fig. 2. The pure and clean water has very close behavior and it's different about the ocean and turbid. When the refractive index of water is increasing the receiver signal power decreases, on the other hand, when the refractive index of water decreasing the received signal power can be reached to long distances.

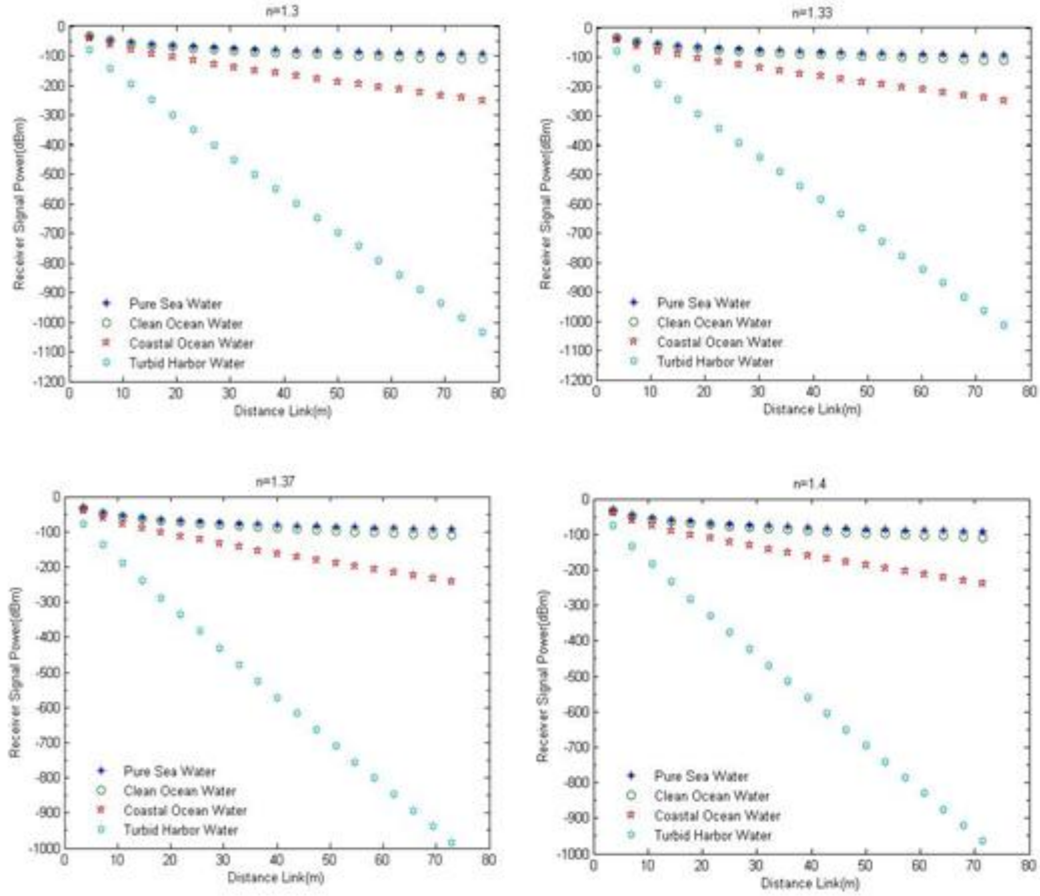
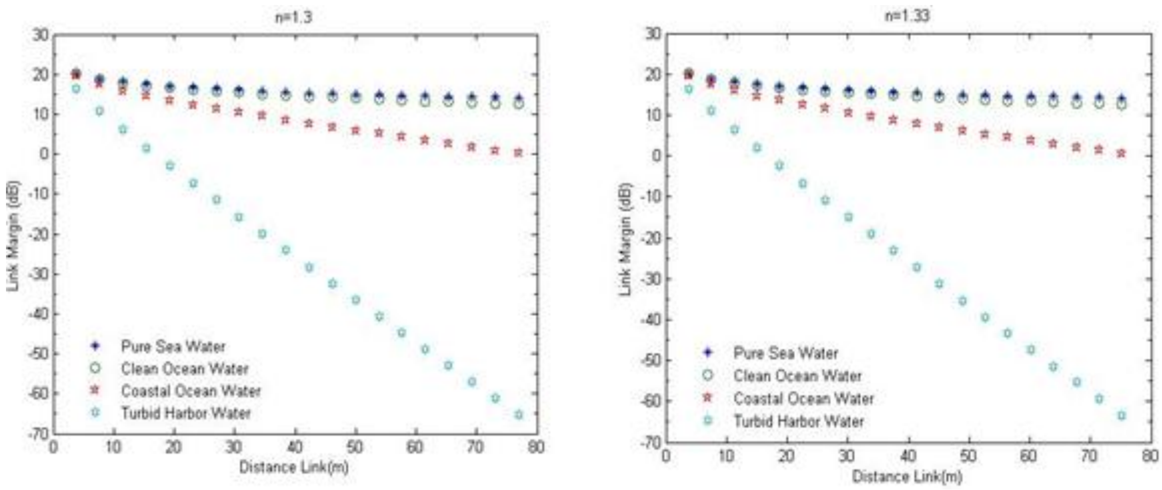


Fig. 2 Receiver signal power (dBm) as a function of distance link (m)

The link margin for receiver sensitivity-20dBm is achieved for data rate 0.1 Gb/s operating under typical water conditions for optical path about100 m as shown in Fig. 3. The link margin for water can be reached to long distance when the refractive index of water decreases, also the pure and clean water have the same behavior.

The data rate 0.1Gb/s is achieved for refractive index and total attenuation underwater. The data rate of 0.1 Gb/s is obtained at 532 nm for the optical path underwater reaches to100 as shown in Fig. 4. The data rate 0.1 Gb/s can be achieved easily for the other types of waters (pure sea, clean ocean, coastal ocean). Also note that when the refractive index of water decreasing the data rate can be sent to long distances



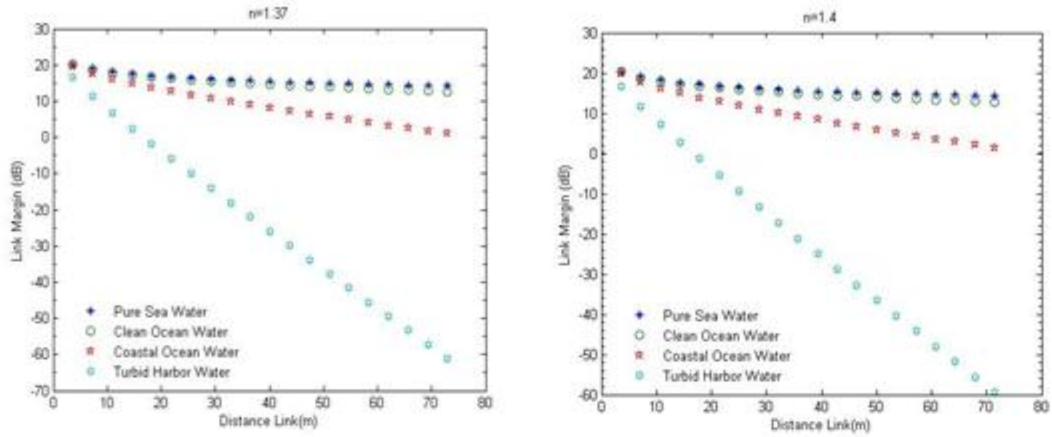


Fig. 3 link margin (dB) as a function of distance link (m)

The signal to noise ratio (S/N) is achieved depends on an avalanche photodiode receiver power as shown in fig. (5); the signal to noise ratio increases with decreasing of refractive index of water for different water types under study. It is achieved that pure sea, clean ocean water has close values and the same behavior, as well as the first two types has a higher signal to noise ratio compared to other water types under the same operating conditions. As well as the signal to noise ratio (S/N) decreasing with increasing distance link.

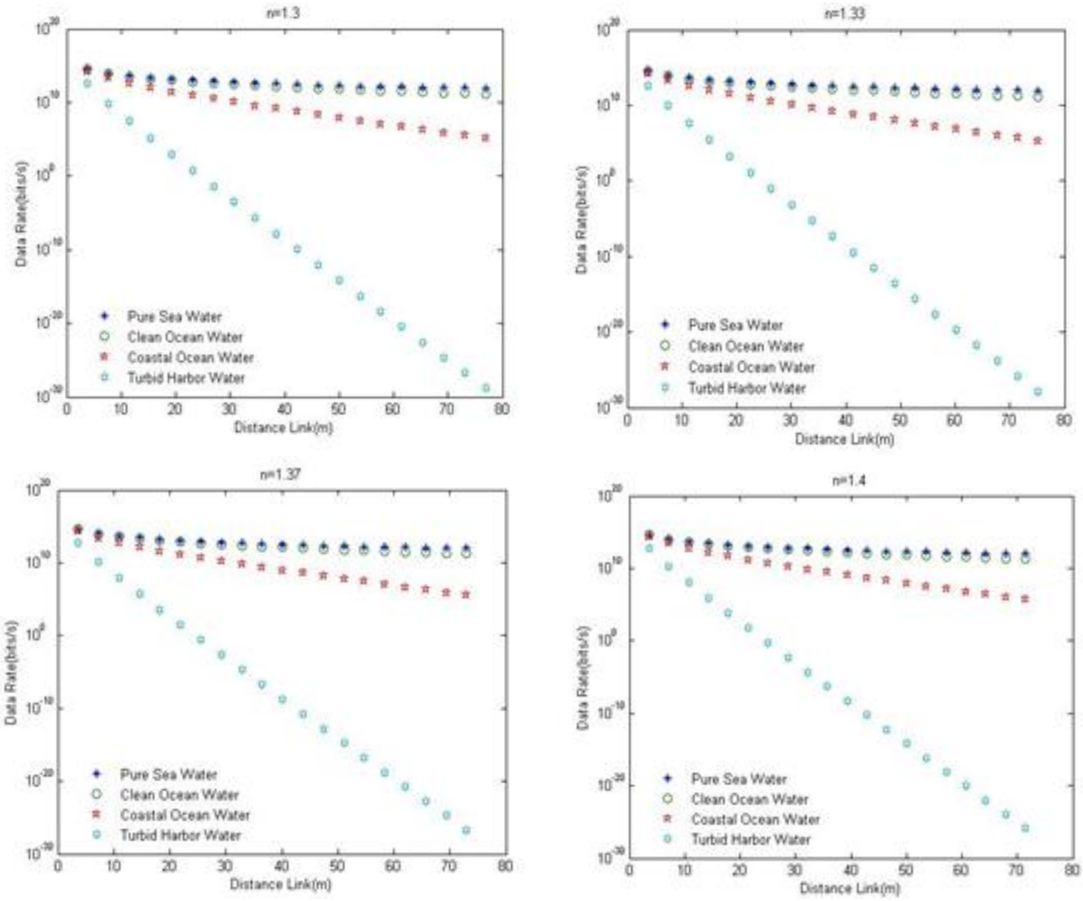


Fig. 4 data rate (bits/s) as a function of distance link (m)

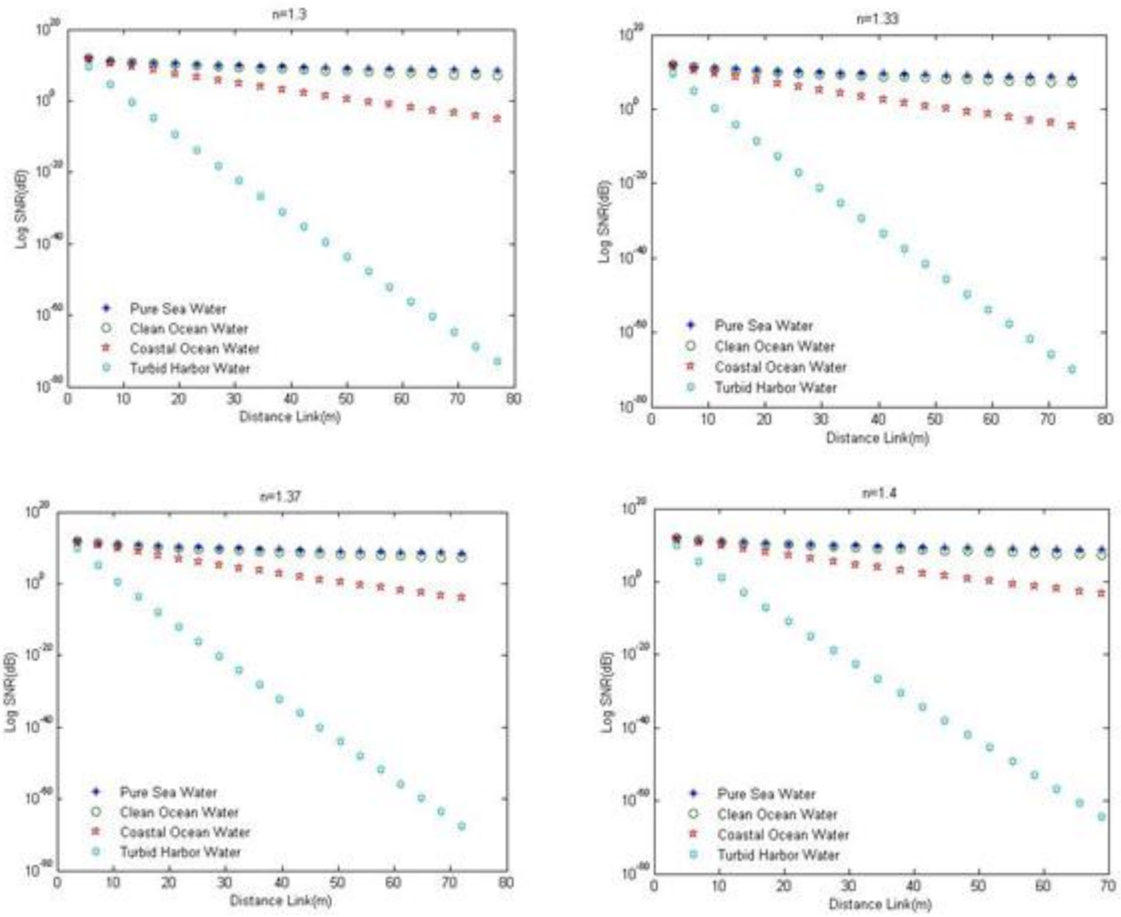


Fig. 5- signal to noise ratio (dB) as a function of distance link (m)

V. Conclusion

An underwater wireless optical communications system studying based on free space optical wireless communications link and by employing the refractive index of water. We are studying the effects of total attenuation and refractive index on underwater optical communication links. The present work focuses on the optical path of the light underwater and calculates some parameters such as: the received signal power, link margin, data rate and signal to noise ratio. The study was carried to the wavelengths 532 nm for four water types pure, clean, coastal and turbid harbor water. It is theoretically found that the increases the refractive index of water the received signal power, link margin, and data rate is decreasing under the same conditions. As well as the signal to noise ratio SNR increases with decreasing the refractive index of water and the optical link. Therefore, it is concluded that the pure and clean water has presented the highest received signal power, link margin, data rate and signal to noise ratio compared to other water types under the same operating conditions.

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