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Under Water Optical Wireless Communications Technology for Short and Very Short Ranges

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Abstract—This paper has presented our interest in wireless underwater optical communications. Recent interest in ocean exploration has brought about a desire for developing wireless communication techniques in this challenging environment. Due to its high attenuation in water, a radio frequency (RF) carrier is not the optimum choice. Acoustic techniques have made tremendous progress in establishing wireless underwater links, but they are ultimately limited in bandwidth. In traditional communication systems, constructing a link budget is often relatively straight forward. In the case of underwater optical systems the variations in the optical properties of sea water lead to interesting problems when considering the feasibility and reliability of underwater optical links. The main focus of this paper is to construct an underwater link budget which includes the effects of scattering and absorption of realistic sea water. As well as we have developed the underwater optical wireless communication systems to have shorter ranges, that can provide higher bandwidth (up to several hundred Mbit/sec) communications by the assistant of exciting high brightness blue LED sources, and laser diodes suggest that high speed optical links can be viable for short range application.

Index Terms—Underwater Wireless Communication, Optical Communication, Short range, Very short range, and Performance evaluation.

1. Introduction

A resurgence is occurring in the area of underwater laser communications. While acoustic systems are currently the more mature technology, they are ultimately band-limited to sub MHz type data rates due to the frequency dependent absorption of acoustic energies in water [1]. Advances in fiber optic and free space links have shown promise for optical links to provide data rates in excess of a gigabit per second. It is not surprising then, that laser links are being considered for Naval applications involving high bandwidth communications undersea. A major challenge in implementing optical links underwater arises from the spatial dispersion of photons due to scattering. Spatial spreading of the optical beam reduces the photon density at the receiver position. A such [2], optical links are only expected to be of greatest utility in links <100 m. Nonetheless, it appears that end users may accept limited link range in exchange for the gain in information bandwidth that optical links may provide. Additionally, researchers continue to study how spatial spreading affects the time encoded portion of the transmitted optical signal. Temporal dispersion arising from multiple scattering events may result in inter-symbol interference (ISI), further limiting link range and/or capacity [3].

The challenges of underwater communication while at speed and depth are widely known in Naval communities. Despite rapid growth in radio frequency (RF) wireless technologies, undersea applications were relatively unaffected, as radio frequencies do not penetrate the sea surface and are highly absorbed by water. RF communication from land to submarines, but it is terribly inefficient due to the large ground stations required and results in dreadfully low bandwidths compared to today’s communication standards. Acoustic techniques on the other hand have enjoyed large success in providing moderate data rates undersea [4]. While sound waves generally propagate well though seawater, the acoustic channel is highly frequency dependent and can experience significant multi path delays. As such, even at short ranges, the acoustic channel is limited to sub Mbps data rates. Optics presents yet another alternative for establishing wireless underwater links. With the success of fiber optic communications, and the growing applications and success of free space optical links, optical technologies have proven their ability to provide large information bandwidths. Furthermore, seawater exhibits a “window” of decreased absorption in the blue/green region of the visible spectrum where a number of off-the-shelf laser sources are available. Using lasers for undersea communications is not a new idea, with much of the initial interest in this area arising in the 1970’s and 1980’s [5]. The majority of the work during this time examined the feasibility of communicating with submarines from aircraft or satellites. This application presented a number of critical challenges since it required the laser signal to propagate long distances through the atmosphere, through the air/water interface, and finally through the challenging underwater environment. This required high power, high repetition rate blue/green sources that were not available at the time. While new technologies for the required laser sources stand poised to revisit this application of “through the surface” communication, a wealth of new applications have arisen for horizontal links between platforms underwater [6]. With the advent of autonomous data collection nodes, giant leaps in unmanned vehicle technology, and increased need for submarine stealth, short range (<100 m) high speed

(>1Mbps) horizontal links are an attractive feature to many of these new applications.

In the present study, the importance of underwater wireless optical communication has been grown for applications of underwater observation and sea monitoring systems. We have investigated the underwater optical wireless communication links for both short transmission ranges and high speed wireless communication transmission systems, taken into account the link power budget estimation for different water media types over wide range of the affecting parameters.

2. Basic Structure of Underwater Link Model

The main motivation of this item was to research the possibility of using semiconductor light sources as a mean to communicate underwater. However, scattering and the variable optical qualities of sea water need to be considered. These varying properties change with time and location which in turn could affect the amount of light lost. This could also cause a shift in the appropriate operating wavelength of the communication link. The primary optical properties of the medium are summarized in the diagram below. These parameters will be used to construct a power link budget for a theoretical underwater optical link [7].

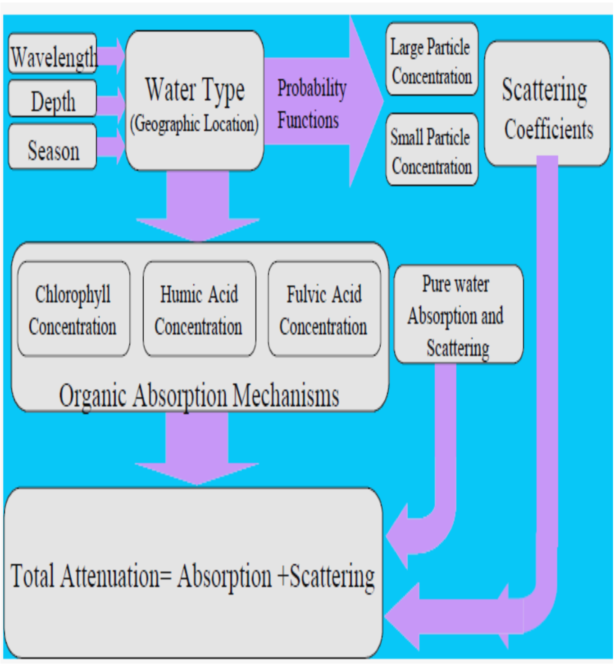

Fig. 1. Schematic view of total attenuation in sea water.

Furthermore, the optical properties of the water will affect the performance of the hardware used. Similar to fiber based communication systems, the wavelength of the transmitter source must match the transmission spectrum of sea water to achieve optimum performance [8].

Transmitter inputs Medium inputs Receiver inputs

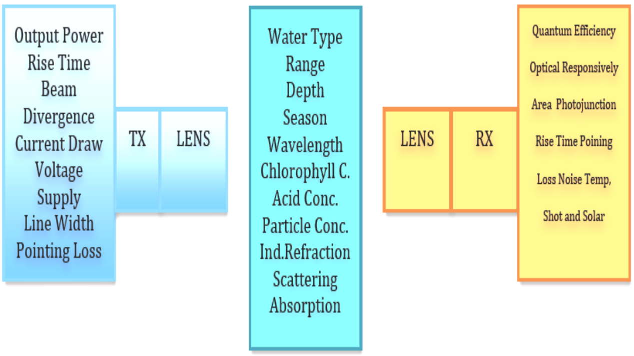

Fig. 2. General block diagram containing all the variable consideration in the link budget.

In addition to the optical parameters in Fig. 1, the receiver and transmitter inputs are now considered as shown in Fig. 2, when building a comprehensive model of the optical performance of the link [9].

3. Mathematical Model Analysis

In the design of optical fiber systems, one computes a link budget to determine if information can be successfully transmitted over the desired distance [3]. Typically one considers an optical power budget and a bandwidth budget. The power budget is to determine that there is sufficient signal to noise for a specific bit error rate. The bandwidth budget determines the rate at which bits can be distinguished from adjacent bits in the bit stream and is a function of the rise and fall times of the light source and receiver, which are typically fast, and the dispersion of the optical pulse introduced by the fiber which depends on the information channel. Typically the dispersion of the information channel is the limiting factor of the bandwidth budget [7]. Assuming a specific wavelength of operation, and a goal of a specific bit error rate (BER) to construct the power budget for a simple point to point link, one should consider: a) The transmitter output power, b) Coupling efficiency of the source and receiver to the fiber, c) Attenuation or loss of optical energy due to scattering, or absorption in (dB/km), d) Losses due to fiber splices, and e) Receiver sensitivity typically expressed in dB (or sometimes bit-rate/mW), f) System margin, typically about 6 dB to account for system component ageing. If the transmitter power minus the sum of the losses is greater than the sum of the receiver sensitivity plus the system margin for a given wavelength and bit error rate, the link should be successful [8].

3.1. Wireless power link budget

The basic formula for a typical optical link is an exponential decaying as function of the path length L_m as the following expression [9]:

$$P_R = P_T\, e^{-\alpha(\lambda) L_m} \qquad (1)$$

Where P_R is the received power after traveling the path length L_m through the lossy medium, P_T is the initial transmitted power, and α is the total attenuation coefficient of the medium. Along with the beam size there is the problem of collecting enough light to retrieve the signal. The larger the beam is at the receiver the lower the photon density that is collected through the receiving aperture. Since line of sight is so critical, the system would need to make use of a beam divergence or diffused beam approach, which involves a large field of view that toleration substantial line of sight interference without significant impact on overall signal quality. Taking this into account Eq. 1 becomes [10, 11]:

$$P_R = P_T \frac{D_r}{\left(D_t + \left(\theta_{div} + L_m\right)\right)^2} e^{-\alpha(\lambda) L_m} \quad , \qquad (2)$$

Where D_r is the diameter of the receiver aperture, D_t is the diameter of the transmitter lens, θ_{div} is the transmitter divergence of the beam in radians, and θ_{div} is the transmitter divergence of the beam in degree can be given by:

$$\theta_{div} = \frac{720\lambda}{\pi^2 D_t} \quad , \text{ degree} \qquad (3)$$

3. 2. Underwater optical link budget model

3. 2.1. Absorption model

The absorption as the spectral absorption coefficient, a(λ), which is the change in the beam of light due to the absorption by the medium per meter of path length [10]. 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 permits models in the future to include the effects of fluorescence in a more consistent manner. The absorption coefficient a(λ) is given by:

$$a(\lambda)=a_w(\lambda)+a_{cl}(\lambda)+a_f(\lambda)+a_h(\lambda) \ , \qquad (4)$$

Where $a_w(\lambda)$ is the absorption coefficient of water as a function of wavelength (m^{-1}), $a_{cl}(\lambda)$ is the absorption chlorophyll acid coefficient as a function of wavelength, $a_f(\lambda)$ is the fulvic acid absorption coefficient and $a_h(\lambda)$ is the humic acid absorption coefficient both as a function of wavelength. The absorption coefficient for sea water type, $a_w(\lambda)$, was interpolated from data from [11] with respect to water concentration of $w_c^0 = 1$ mg/m³, and water concentrations $0 \le w_c \le 15$ mg/m³ . It then became:

$$a_w(\lambda) = a_w^0(\lambda)\left[\frac{w_c}{w_c^0}\right]^{a_w^0} , \qquad (5)$$

For sea water $a_w^0(\lambda) = a_w^0\,\lambda = 0.0405\lambda$. As well as the absorption coefficient for chlorophyll, $a_{cl}(\lambda)$, was interpolated from data from [12, 13] with respect to a chlorophyll concentration of $C_c^0 = 1$ mg/m³ and chlorophyll concentrations $0 \le C_c \le 12$ mg/m³. It then became:

$$a_{cl}(\lambda) = a_c^0(\lambda)\left[\frac{C_c}{C_c^0}\right]^{0.0602} , \qquad (6)$$

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

$$a_h(\lambda) = a_h^0\, C_h \exp(-k_h\,\lambda) , \qquad (7)$$

$$a_f(\lambda) = a_f^0\, C_f \exp\left(-k_f\,\lambda\right) , \qquad (8)$$

Where k_h= 0.01105/nm, a_h^0=18.828 m²/mg is the specific absorption coefficient of humic acid, the first component of CDOM and k_f= 0.0189/nm, a_f^0 = 35.959 m²/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 expressed as follows [12]:

$$C_f = 1.74098 C_c \exp\left[0.12327\left(\frac{C_c}{C_c^0}\right)\right] , \qquad (9)$$

$$C_h = 0.19334 C_c \exp\left[0.12343\left(\frac{C_c}{C_c^0}\right)\right] , \qquad (10)$$

3. 2.2. Scattering model

This phenomenon as called the spectral beam scattering coefficient, b(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, $b_w(\lambda)$, scattering from small particles, $b_s^0(\lambda)$ as a function of wavelength and concentration, and scattering form large particle, $b_l^0(\lambda)$ as a function of wavelength and concentration. From Ref. [12] b(λ) is given by:

$$b(\lambda) = b_w(\lambda) + b_s^0(\lambda) C_s + b_l^0(\lambda) C_1 , \qquad (11)$$

The equation for $b_w(\lambda)$ is derived by interpolating the data published by Ref. [13] to get:

$$b_w(\lambda) = 0.005826\left(\frac{0.4}{\lambda}\right)^{4.322} , \ m^{-1} \qquad (12)$$

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

$$b_s^0 = 1.151302\left(\frac{0.4}{\lambda}\right)^{1.7} , \ m^2/g \qquad (13)$$

$$b_l^0 = 0.3411\left(\frac{0.4}{\lambda}\right)^{0.3} , \ m^2/g \qquad (14)$$

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

$$C_s = 0.01739 C_c \exp\left[0.11631\left(\frac{C_c}{C_c^0}\right)\right], \text{g/m}^3 \qquad (15)$$

$$C_l = 0.76284 C_c \exp\left[0.03092\left(\frac{C_c}{C_c^0}\right)\right], \text{g/m}^3 \qquad (16)$$

The total spectral attenuation coefficient, $\alpha(\lambda)$ is defined as the sum of the spectral absorption coefficient and spectral scattering coefficient [14]:

$$\alpha(\lambda)=a(\lambda)+b(\lambda) \quad , \qquad (17)$$

Then the total attenuation can be expressed in dB/m as the following expression:

$$\alpha(\lambda)_{dB/m} = 10\log a(\lambda) + 10\log b(\lambda) \,, \qquad (18)$$

3. 2.3. Optical wireless communication link model

To consider the design of underwater optical communications systems for propagation of light in water, the light noise, and the basic light in water attenuation parameters as analyzed above. The main parameters in underwater communications are shown in the evaluation criterion for optical communication, Signal-to-noise (SNR), noise equivalent power (NEP) and bit rate (BR). The SNR is defined as the ratio of a signal power to the noise power corrupting the signal [15]:

$$SNR = \left[\left(\frac{P_T}{\tan\theta}\right)_{TX}\left(\frac{\exp(-3\alpha(\lambda)L_m)}{4L_m^2}\right)_{medium}\left(\frac{D_r^2\cos\varphi}{NEP}\right)_{RX}\right]^2 \qquad (19)$$

This equation assumes the beam pattern of the transmitter is a constant for angles up to the 3-dB (halfway) point and zero beyond that angle. Where P_T is the transmitter power in mWatt, θ half angle transmitter beamwidth in degree, $\alpha(\lambda)$ is the signal attenuation as a function of wavelength, L_m is the transmission distance in km, D_r is the receiver a aperture diameter in meter, φ is the angle between the optical axis of the receiver and the line of sight between transmitter and receiver, noise equivalent power (NEP) is defined as the incident optical power at a particular wavelength or with a specified spectral content required to produce a photodetector current equal to the root mean square noise current and can be expressed as [16-18]:

$$NEP = \frac{2hc}{\eta\lambda} \,, \qquad \text{Watt} \qquad (20)$$

Where h is the Planck's constant ($6.02\text{x}10^{-34}$ J.sec), c is the velocity of light ($3\text{x}10^{8}$ m/sec), η is the quantum efficiency, and λ is the operation optical signal wavelength. The basic components of optical wireless communication system links are shown in Fig. 3, to Illustrate of signal to noise ratio equation concept.

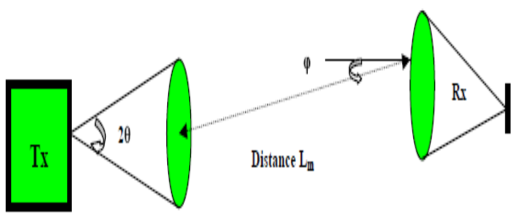

Fig. 3. Block diagram of optical wireless communication model.

By using MATLAB curve fitting program, the fitting the relationship between the optical received power and bit error rate (BER) can be expressed as [21]:

$$BER = 0.4969\text{x}10^{-9} - 0.1077P_R + 0.001P_R^2 \,, \qquad (21)$$

The multi limitations bit rate based on absorption and scattering losses are calculated based on the same spirit of the model of Ref. [22], the signal bandwidth can be simplified using classical model as:

$$BW_{sig.} = \frac{BR}{\sqrt{8\log\frac{B_u}{BR}\exp\left(-\left(\alpha(\lambda)L_m + \alpha_m\right)\right)}} \qquad (22)$$

Where B_u is the maximum available transmission bit rate without any limitations, and α_m is the system marginal loss=6 dB.

4. Simulation Results and Performance Evaluation

We have investigated transmission performance of the short and very short ranges optical wireless communication link systems with using classical transmission technique to upgrade transmission bit rates, transmitted signal bandwidth, signal to noise ratio and decrease BER.

Table 1: Proposed operating parameters for short range wireless optical communication links.

Operating parameter	Value and unit
Signal transmitted power, P_T	P_T=100 mWatt
Operating signal wavelength, λ	$0.85 \le \lambda$, µm ≤ 1.6
Half angle transmitter beamwidth, θ	$20 \le \theta$, degree ≤ 80
Quantum efficiency, η	η=0.9
System marginal loss, α_m	4 dB
Transmitter lens diameter, D_t	$0.05 \le D_t$, m ≤ 0.3
Receiver aperture diameter, D_r	$0.1 \le D_r$, m ≤ 0.6
Maximum bit rate without any limitations, B_u (Short range)	0.1 Mbit/sec
Maximum bit rate without any limitations, B_u (very short range)	2 Mbit/sec
Bit rate , BR (for short range)	BR=0.01 Mbit/sec
Bit rate , BR (for very short range)	BR=1 Mbit/sec
Transmission distance, L_m (Short range)	100 m $\le L_m$, m ≤ 1000
Transmission distance, L_m (very short range)	10 m $\le L_m$, m ≤ 100
Receiver angle, φ	φ =60 degree
Pure sea water	C_c=0.03 mg/m^3, w_c=0.035 mg/m^3

Based on the modeling equations analysis and the assumed set of the operating parameters as shown in Table 1. The following facts are assured as shown in the series of Figs. (4-18):

i) Figs. (4, 5) have assured that received power decreases with increasing transmission distance and operating optical signal wavelength for both short and very short ranges.
ii) Figs. (6-9) have demonstrated that signal to noise ratio increases, while bit error rate decreases with increasing of both operating optical signal wavelength and receiver aperture diameter for both short and very short ranges under considerations.
iii) As shown in figs. (10, 11) have proved that transmitted signal bandwidth decreases with increasing of both system transmission distance and operating optical signal wavelength for both short and very short ranges under study.
iv) Fig. 12 has indicated that transmitter beam divergence increases with increasing operating optical signal wavelength, and with decreasing transmitter lens diameter. This is lead to the limitation of the received signal power at the receiver side.
v) As shown in figs. (13, 14) have proved that received signal power increases with decreasing of both operating optical signal wavelength and transmitter lens diameter for both short and very short ranges under study.
vi) Figs. (15-18) have assured that signal to noise ratio increases, and bit error rate decreases with increasing operating optical signal wavelength and decreasing of half angle transmitter beamwidth for both short and very short ranges under considerations.

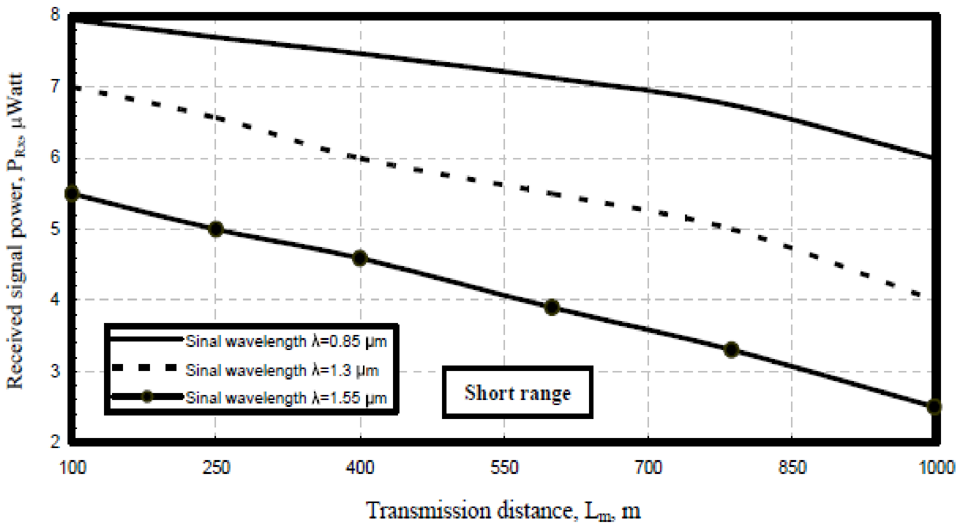

Fig. 4. Received signal power in relation to transmission distance and operating optical signal wavelength at the assumed set of the operating parameters.

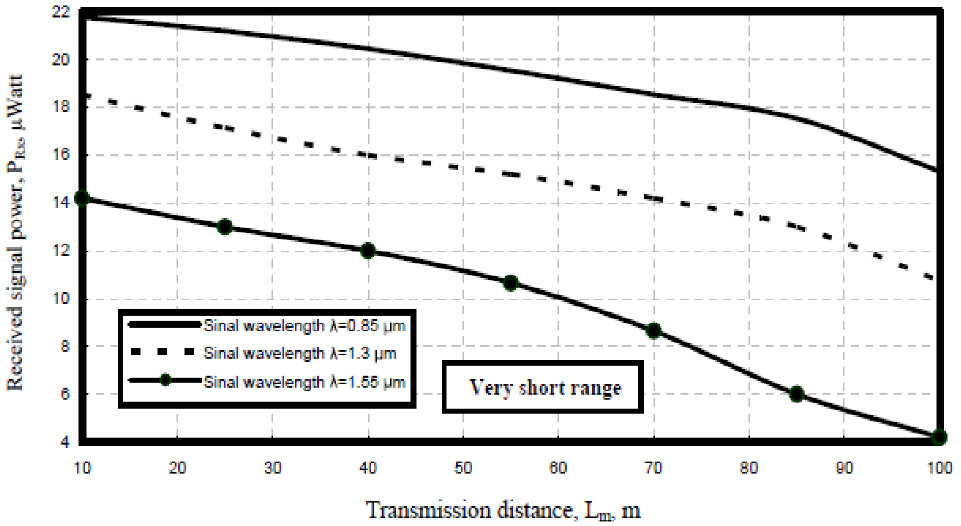

Fig. 5. Received signal power in relation to transmission distance and operating optical signal wavelength at the assumed set of the operating parameters.

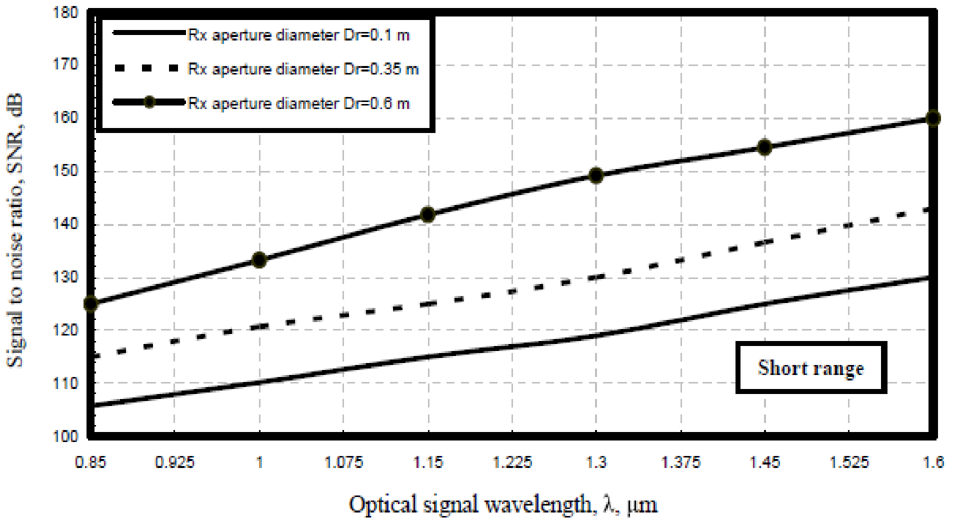

Fig. 6. Signal to noise ratio in relation to operating optical signal wavelength and receiver aperture diameter at the assumed set of the operating parameters.

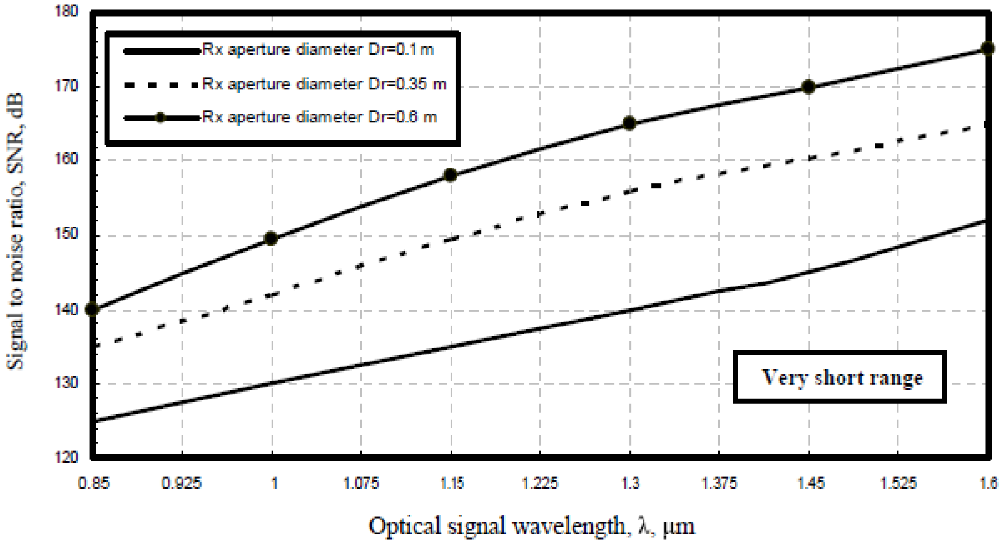

Fig. 7. Signal to noise ratio in relation to operating optical signal wavelength and receiver aperture diameter at the assumed set of the operating parameters.

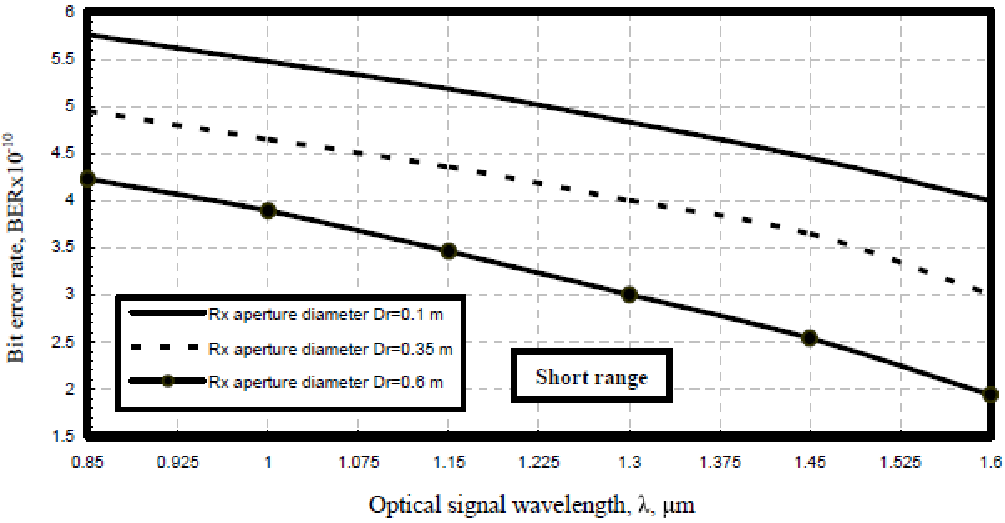

Fig. 8. Bit error rate in relation to operating optical signal wavelength and receiver aperture diameter at the assumed set of the operating parameters.

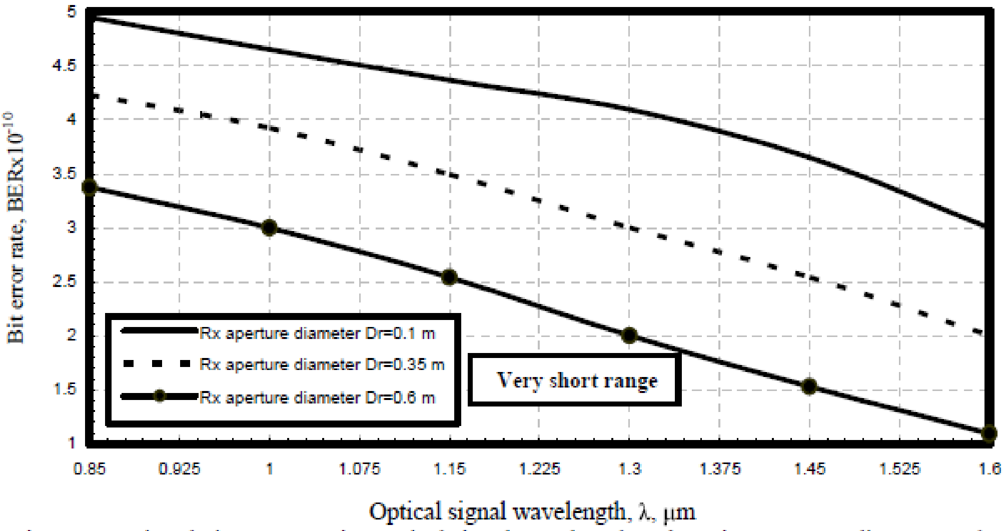

Fig. 9. Bit error rate in relation to operating optical signal wavelength and receiver aperture diameter at the assumed set of the operating parameters.

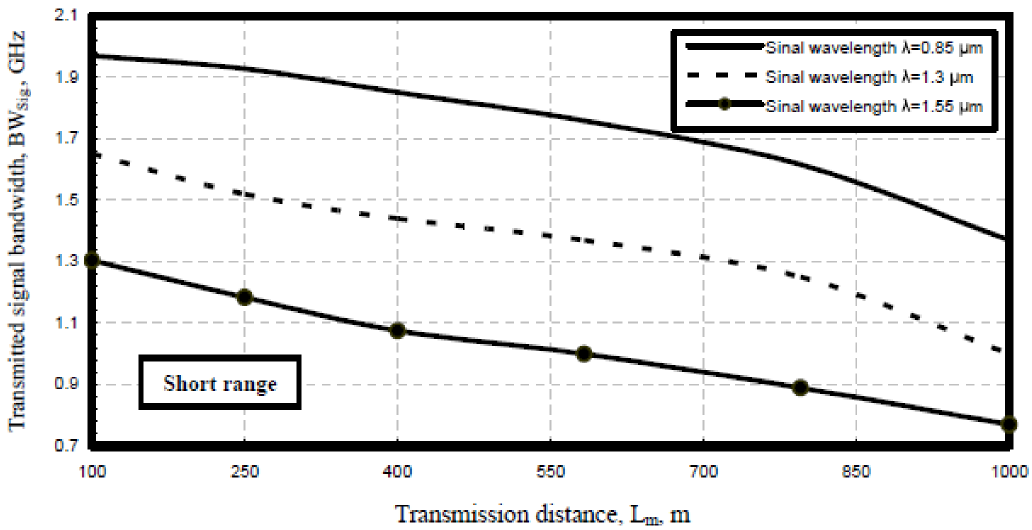

Fig. 10. Transmitted signal bandwidth in relation to transmission distance and operating optical signal wavelength at the assumed set of the operating parameters.

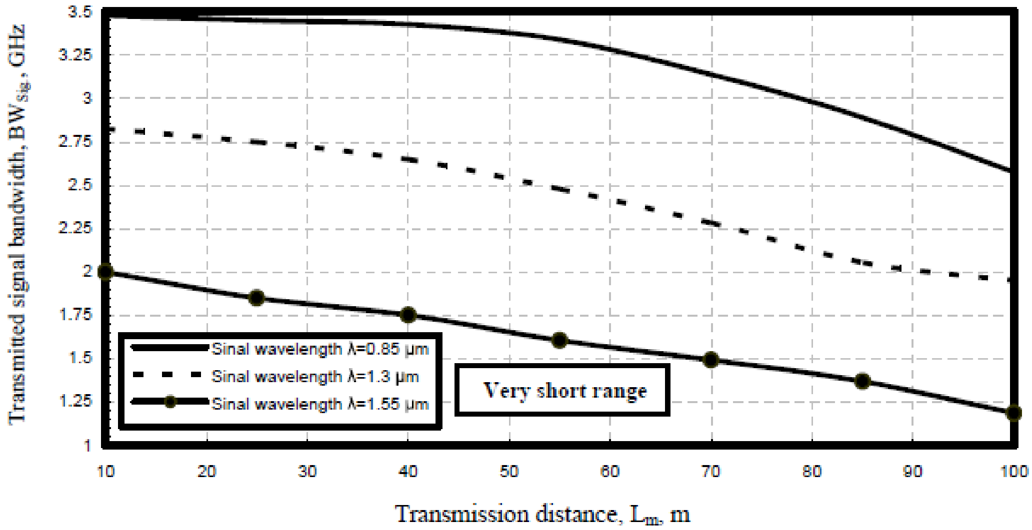

Fig. 11. Transmitted signal bandwidth in relation to transmission distance and operating optical signal wavelength at the assumed set of the operating parameters.

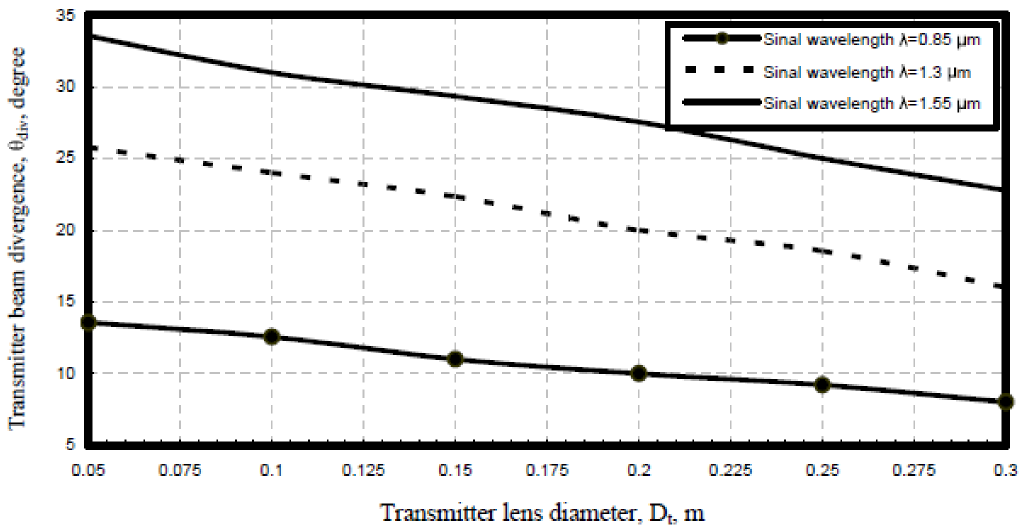

Fig. 12. Transmitter beam divergence in relation to transmitter lens diameter and operating optical signal wavelength at the assumed set of the operating parameters.

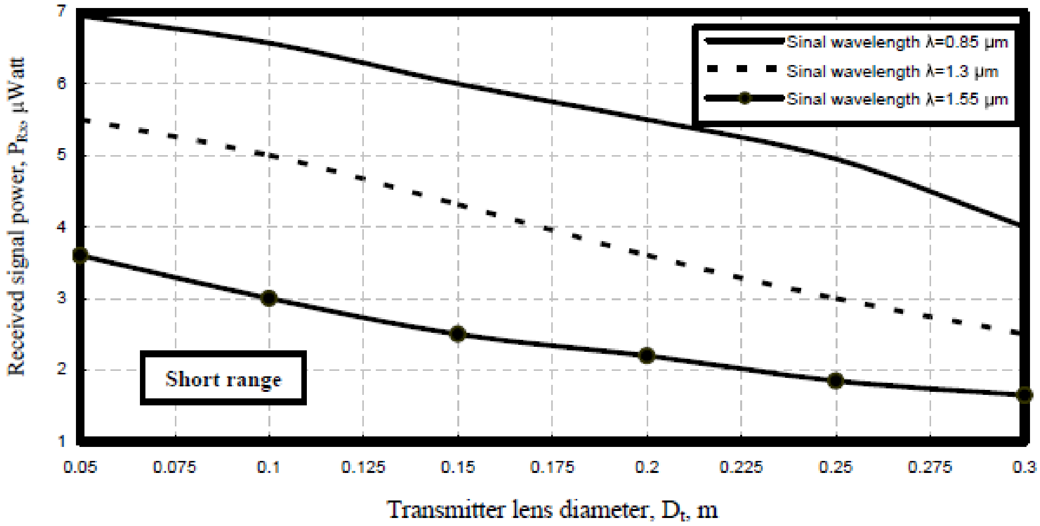

Fig. 13. Received signal power in relation to transmitter lens diameter and operating optical signal wavelength at the assumed set of the operating parameters.

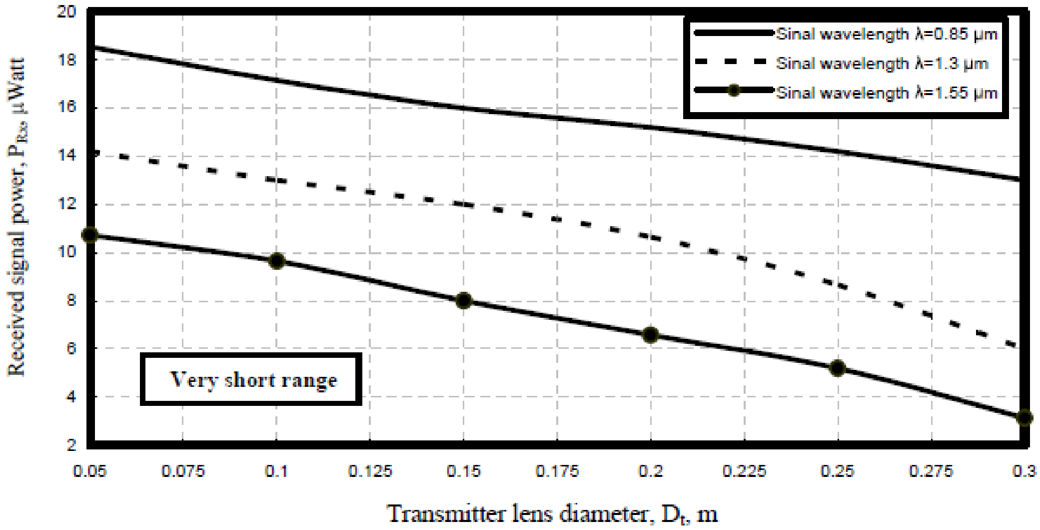

Fig. 14. Received signal power in relation to transmitter lens diameter and operating optical signal wavelength at the assumed set of the operating parameters.

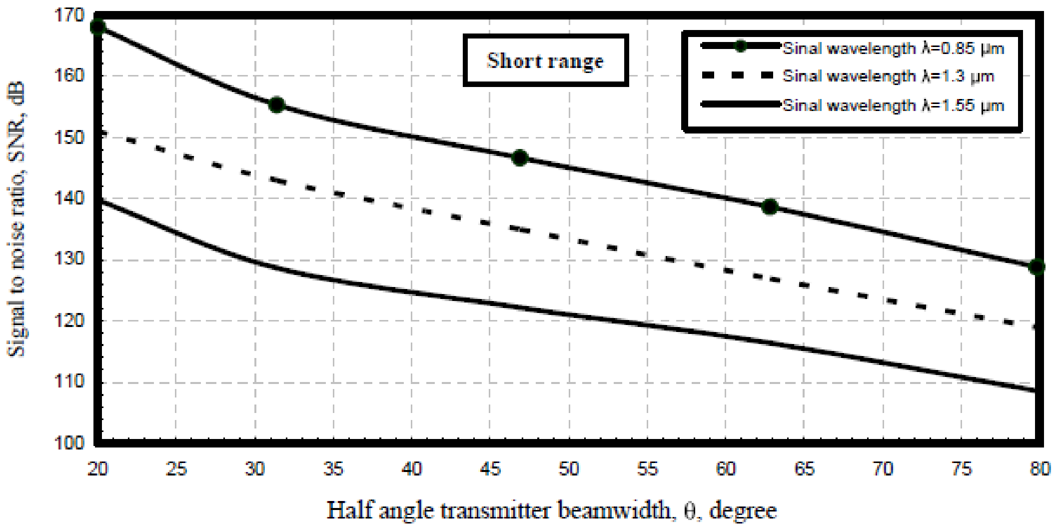

Fig. 15. Signal to noise ratio in relation to Half angle transmitter beamwidth and operating optical signal wavelength at the assumed set of the operating parameters.

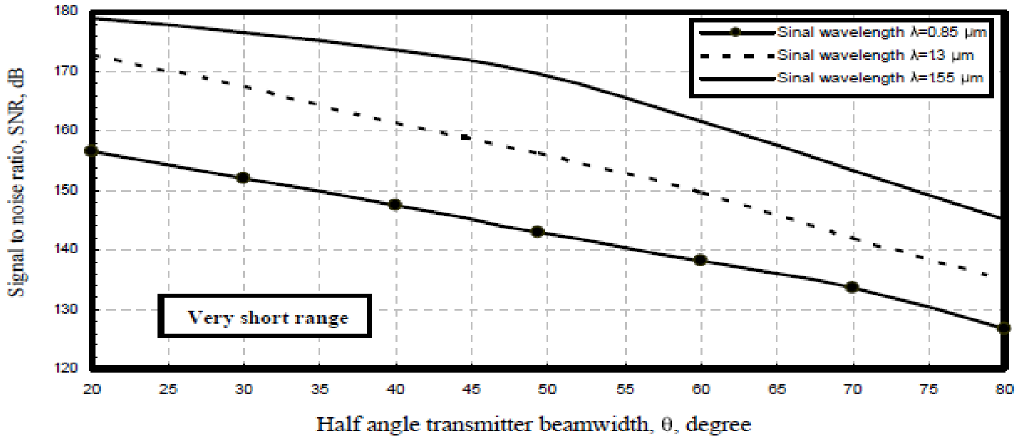

Fig. 16. Signal to noise ratio in relation to Half angle transmitter beamwidth and operating optical signal wavelength at the assumed set of the operating parameters.

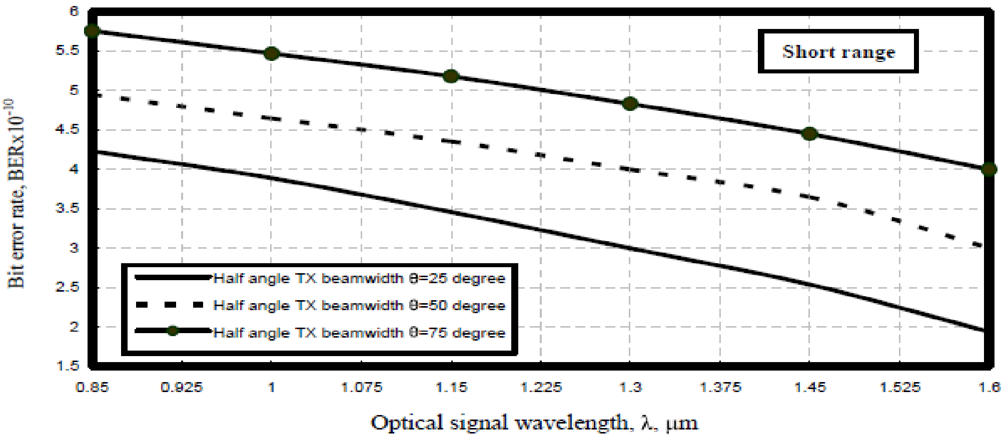

Fig. 17. Bit error rate in relation to operating optical signal wavelength and half angle transmitter beamwidth at the assumed set of the operating parameters.

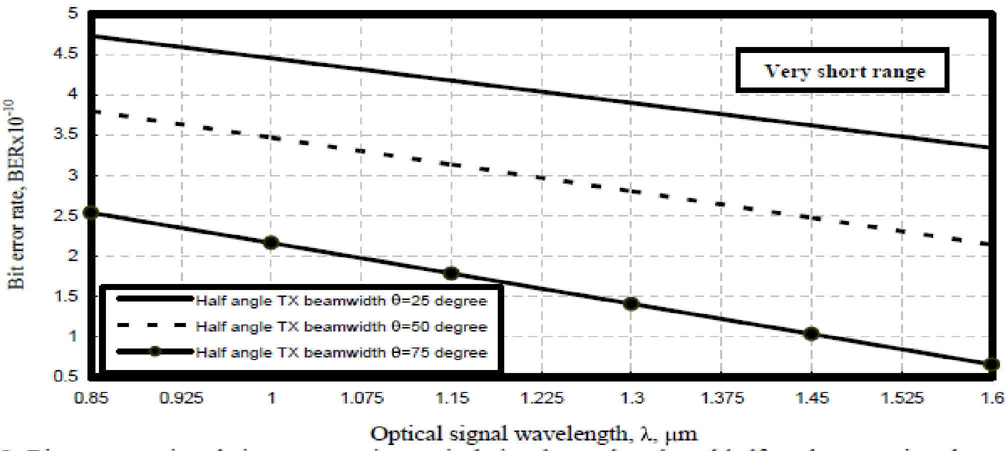

Fig. 18. Bit error rate in relation to operating optical signal wavelength and half angle transmitter beamwidth at the assumed set of the operating parameters.

5. Conclusions

Optical wireless systems based on free space optics technology. Free space optical communications is a line of sight (LOS) technology that transmits a modulated beam of visible or infrared light through the atmosphere or as in our study concerning on wireless system underwater for broadband communications. It represents one of the most promising approaches for addressing the emerging broadband access market. It offers many features, principal among them being low start up and operational costs, rapid deployment and high fiber link bandwidth. Wireless optical communications under water primarily deployed where performance, security, rapid deployment, and cost-savings are critical issues. It is observed that the increased operating optical signal wavelength, resulting in the increased SNR and the decreased BER, transmitted signal bandwidth, and received signal power for both short and very short ranges under considerations. As well as it is theoretically found that the increased both receiver aperture diameter and operating optical signal wavelength, and the decreased half angle transmitter beam width, lead to the increased SNR and the decreased BER for both short and very short ranges under study. Moreover we have observed that the increased both operating optical signal wavelength and transmission, resulting in the decreased transmitted signal bandwidth for both wireless ranges under the same operating parameters. Finally it is indicated that very short wireless range has presented higher P_R, SNR, and $BW_{Sig.}$, and lower BER compared to short wireless range.

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