Underwater Wireless Optical Communication Channels with Directed Light and Diffused Light Transmissions in the Visible Spectrum

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Abstract - In this paper, we are doing channel modeling for underwater optical channels. Particularly, we have focused on received intensity of signal at the receiver for different water types, link distance and various parameters of transmitter and receiver. We found Monte Carlo an appropriate approach for simulation of projectile movement of emitted photons propagating in ocean water towards the receiver. We have also shown how the shadowing effect affects the received intensity in some cases. These simulated results are of great advantage to design parameters for different underwater wireless optical communication systems.

I. INTRODUCTION

Two-third of the earth’s surface is covered with water. Since ages, human have been exploring the underwater world. With the increase in global climate changes and resource depletion it has become necessary to explore the underwater system. Also it's essential for nations like India that are surrounded by oceans to develop a strong security system to protect the country from enemies. Hence it becomes important to keep improving the underwater communication networks. Underwater Wireless Sensor Networks (UWSNs) help in tracking any activity happening in the volatile underwater environment. Designing of such networks which is adapted to aqueous environment is difficult due to various factors like link capacity, propagation delays and energy consumption issues.

RF waves are highly attenuated underwater, allowing typical ranges of a few centimeters only and due to low limited bandwidth acoustic waves is also a bad option. In literature, various researches have been done on visible light communication and UWSNs. Like, SENSENet project [1] considers the implementation of UWSN in deep sea where sensor nodes communicate with each other via optical links using appropriate wavelength (380nm-550nm).

When working on UOWC, we face two major problems: absorption and scattering. Though wavelength of transmission light is selected in the blue and green spectrum, so as to minimize the transmission attenuation effect, as when photon interacts with the water molecules and other particles or matters in water, which results in absorption and scattering and severely attenuate the transmitted light signal and cause multipath fading or can create inter symbol interference

(ISI) by causing pulse stretching[12].In this paper, we considered point-to-point system as well as diffused light system and have done simulations for both cases. We have also worked on the impact of shadowing effect on received intensity in point-to-point communication system. In this work, for diffused light, the relations of the received power with the transmitter's elevation angle, the transmitter's aperture angle, the distance between the transmitter and the receiver and the field of view of the receiver are investigated. These relations are examined in pure sea, clear ocean, coastal water and turbid water. We found the Monte Carlo an appropriate approach for simulation of projectile movement of emitted photons propagating in ocean water towards the receiver.

This paper has been organized as follows. In section II, we have explained related literature work. In section III, we explained main characteristics of water channel and related algorithm work. In section IV, brief description of Monte Carlo simulator is given. In section V, we study the various numerical results as obtained by doing above mentioned simulations and in section VI we have concluded the work.

II. RELATED LITERATURE WORK

Several recent works have been done on UOWC. Most of them neglect the channel time dispersion and use a simple model for optical beam propagation. In [2], [3], the performance of a UOWC in various water types and at different ranges is studied using the simple exponential attenuation model. In [4] authors study the spatial and angular effects of scattering on a laser link based on the Radiative Transfer Equation (RTE) and also present some laboratory experiments. In [5], it is shown that channel fading due to water turbulence is negligible in most practical cases.

Studies most related to our work are [6], [7]. In [6] the author presents a laboratory experiment for a 1-Gbps rate optical transmission system over a 2m path length. They also present the channel transfer function by means of Monte Carlo simulations for longer transmission ranges for different water types. In [7], channel modeling has been shown using Monte Carlo simulation has been done for different water types over different distance ranges.

III. EFFECT OF WATER ON OPTICAL BEAM

Absorption is an energy transfer process in which photons lose their energy and convert it into other forms such as heat and chemical (photosynthesis). Scattering results from the interaction of light with the molecules and atoms of the transmission medium [8]. Both these processes depend on wavelength λ [9],[10]. Spectral absorption coefficient a(λ)is IOP to model water absorption. On the other hand, spectral volume scattering function (VSF) β(ψ,λ) is defined as the fraction of the incident power scattered out of the beam through an angle ψ within a solid angle ΔΩ centered on ψ. VSF is the IOP used to model scattering in water. From [7], Integrating VSF over all directions, give the scattering coefficient b(λ):

$$b(\lambda)=2\Pi \int_0^{\Pi} \beta(\psi,\lambda)\sin(\psi)d\psi$$

(2)

Extinction coefficient c is defined as :

$$c(\lambda)=a(\lambda)+b(\lambda)$$

a, b, and c are in unit of m^{-1}.

A. WATER PARTICLES

In addition to water molecules, there are other infinitesimally small particles in water that affect the absorption and scattering [11]. We can use chlorophyll concentration C(in mg.m^{-3}) to compute a and b[9].

Water type	C(mg/ m^3)	a(m^{-1})	b(m^{-1})	c(m^{-1})
Pure sea	0.005	0.005	0.003	0.056
Clear ocean	0.31	0.069	0.08	0.15
Coastal	0.83	0.83	0.216	0.305
Harbor	5.9	0.295	1.875	2.17

Table 1 a, b and c parameters associated with these four water types[4].

B. WATER TYPES

There are four major water types described in literature differentiated on the ground of water quality[4],[6].

1.Pure sea water: Absorption is the biggest challenge for pure sea water. Low b and forward angle scattering make the beam propagate approximately in a straight line.

2.Clear ocean water: High concentration of dissolved particles in clear ocean water mainly affect scattering.

3.Coastal ocean water: They have a high concentration of phytoplanktons and other components that affect absorption and scattering.

4.Turbid harbor and estuary water: They have high concentration of dissolved and in-suspension matters.

IV. MONTE CARLO SIMULATIONS

Monte Carlo has its own advantage over RTE hence in recent years it has been extensively used to study the channel modeling and characterization. Several parameters such as aperture size, field of view, distance between receiver and transmitter are taken into account. We have used Monte Carlo simulator in order to evaluate the channel capacity of UOWC system for below mentioned cases.

Line-of-sight (LOS)

(a)With different link distances for four water condition.

(b)With different link distances including shadowing/blocking effect.

Non-line-of-sight (NLOS)

(a)Shallow sea (20meter depth): we study received intensity for various parameters like transmitter's elevation angle, transmitter's divergence angle, distance between transmitter and receiver.

(b)Deep sea (220meter depth): same parameters are studied for deep depth as for shallow depth.

This simulator relies on probabilistic rules of photon propagation in water. Initially, each photon is launched in the medium with a unity weight. The initial position of the photon is calculated using three uniform distributions knowing the beam width, maximum initial divergence angle and angle of elevation. Then, the considered emitted photon travels a distance Δd before facing scattering phenomenon with a particle in the medium, what we consider as step size. To generate Δd randomly, we consider a RV ϒ, with uniform distribution U[0,1], and use Δd=log(ϒ)/c [13].After scattering, the photon loses a fraction of its weight. If we denote initial weight by weight_ph and after interaction weight by weight_new, then we have [11]:

$$\text{weight\_new} = \text{weight\_ph}\ (1-a/c) \quad (3)$$

So, photon is scattered from its initial position. To obtain random scattering angle θ, we generate a RV ϒ with U[0,Π], and calculate θ from ϒ according to Henyey-Greenstein function [11]:

$$\Upsilon=\frac{1-g^2}{2(1+g^2-2g\cos\theta)^{3/2}}$$

(4)

Ψ is considered as the azimuthal angle of the scattering direction according to U[0,2Π]. For studying the shadowing /blocking effect we have introduced a RV 'p' in the range [0,1].

For NLOS we also had to consider the case when the photon is propagated across a boundary into a region with a different refractive index like the water – air surface and the bottom of the sea due to which internal reflection occurs. In this case, if $Z_{photon} > Z_{max}$, where Z_{max} denotes the height of the surface when calculated from the sea bottom. Then using a random number ξ, U[0,1], we decide whether the photon is reflected or transmitted. The probability for the same is determined by the Fresnel reflection coefficient $R(\theta_i)$:

$$R(\theta_i)=\frac{1}{2}\left[\frac{\sin(\theta i-\theta t)^2}{\sin(\theta i+\theta t)^2}+\frac{\tan(\theta i-\theta t)^2}{\tan(\theta i+\theta t)^2}\right]$$

(5)

where θ_i is the angle of incidence on the boundary and θ_t is the angle of transmission and is given by the Snell's law:

$$n_i \quad \sin\theta_i \quad = \quad n_t \quad \sin\theta_t$$

(6)

After deciding if the photon is internally reflected or it exit the water and gets lost, we need to update the position and direction of photon.

Similarly , when photon reaches the sea bed , parameters change as above , the only difference is we replace Z_{max} with Z_{min}, where $Z_{min}=0$.

The whole process is repeated until one of the two events happens:

(i)The photon weight is too small and negligible. Then the photon is considered to be totally absorbed. This limit is set to 10^{-4}.

(ii)The photon reaches the receiver. If it is in the aperture, it is considered as effectively received.

Otherwise, it is completely lost in the water environment or in the air.

Given a number of emitted photons, the accumulated weight of the photons collected at the receiver gives the received signal intensity. So, this simulator gives the proportion lost, absorbed and received photons weights as well as Cartesian coordinates of the point of impact at the receiver plane. It also gives information about total distance travelled by the photon until it reaches the receiver, which is easily predicted by the propagation delay from the transmitter to receiver.

V. NUMERICAL RESULTS

We provide here simulation results to study the characteristics of underwater optical channel. We consider, λ=532nm, Henyey-Greenstein parameter g, the average cosine g is calculated for clean ocean, coastal and turbid harbor water which is equal to 0.8708, 0.9470 and 0.9199 respectively. So, we take the average value of g=0.924 proposed in [10] for all water types. In our simulations, we have generated 10^6 photons for each experiment.

A. Received intensity as a function of distance for LOS

In fig.1 we have shown the simulation results for LOS, we consider receiver's FOV of 180^0. That is because in deep sea we can effectively neglect background radiations and hence, there would be no need to limit the FOV. We have shown in Fig.1 curves of the total received intensity as a function of distance L for the four water types specified in Table I. Let us assume a tolerable loss of −100 dB beyond which the signal is not detectable at the receiver (in practice, this depends on the transmitted power and the receiver sensitivity). We notice that, the transmission range is limited to 20m and 50m for clear ocean and pure sea waters, respectively, for instance.

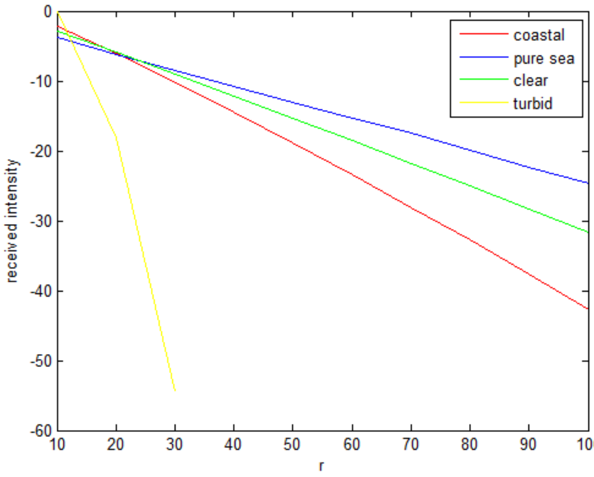


Fig.1 intensity vs. distance between receiver and transmitter

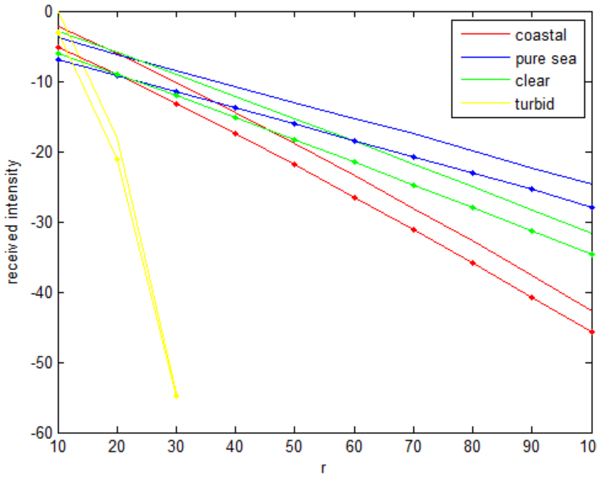


Fig.2 Comparison of intensity received under shadowing effect with intensity received under no shadowing effect along the distance between receiver and transmitter.

When working in turbid harbor waters, the high signal dispersion and attenuation limit the communication range to less than a few meters.

In fig.2 we compare the received intensity as a function of distance with and without shadowing/blocking effect. Here we notice that due to shadowing effect the received intensity decreases considerably throughout the range. Dotted line is for with shadowing and solid shows intensity received under no shadowing effect.

B. Received intensity vs. transmitter's elevation angle for d = 20 m and depth = 220 m

In this section, we study the impact the transmitter's elevation angle on the received intensity. Fig.3 and fig.4 depict the diagrams of intensity vs. the elevation angle for the deep sea and fig.5 depicts the same for shallow sea. In fig.3 and fig.5 divergence angle of transmitter is fixed at 60^0 and in fig.4 intensity for different elevation angles is compared for transmitter's divergence angle 60^0 (solid line) and 45^0 (dotted line). For all three simulations distance between transmitter and receiver is 20m, elevation angle of receiver is 45^0 and FOV of receiver is 180^0.

From fig.3 we notice that, after the 45^0, as the elevation angle is increased, the intensity seems almost constant for coastal, clear and turbid. In reality, it is reduced with a slow rate. This is due to the fact that the beam direction is not in line of sight with the receiver. The lower the elevation angle is, the more it approximates the line of sight configuration. Due to large depth there are not many reflections at the water-air interface. Therefore, the non-line-of-sight regime imposed the intensity decrease with slow rate for the large elevation angles.

From fig.4 we see that, in case of pure water , intensity is higher till 60^0 of elevation angle when divergence angle is 60^0 . After 60^0 of elevation angle intensity received is higher for divergence angle 45^0. In other three cases difference is minor.

From fig.5 we can say that, the impact of depth is more noticeable when we examine the cases of pure water. In this case, when the elevation and the divergence angle of transmitter are both 60^0, then the received power is much greater at 20 m depth compared to the one at 220 m depth. This is also due the geometry of the link. For pure water, there is mild scattering and more reflections at water-boundaries. Hence we see that intensity is continuously decreasing. More components of the optical beam will be reflected at the water-air boundary even more than two times and will be then guided to the receiver.

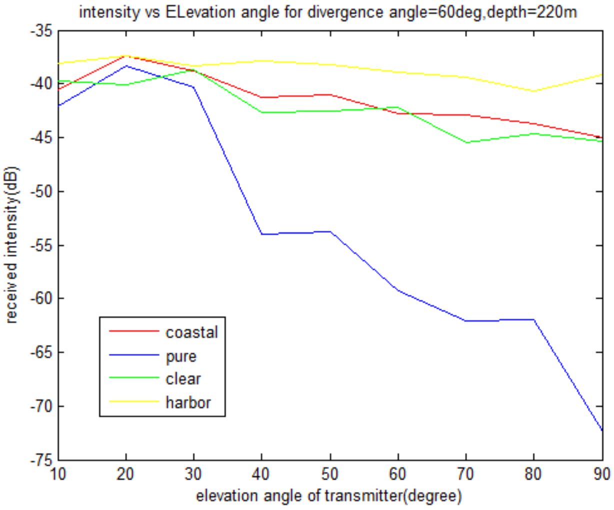


Fig.3 Received intensity for different elevation angles for fixed transmitter’s divergence angle 60^0(deep sea)

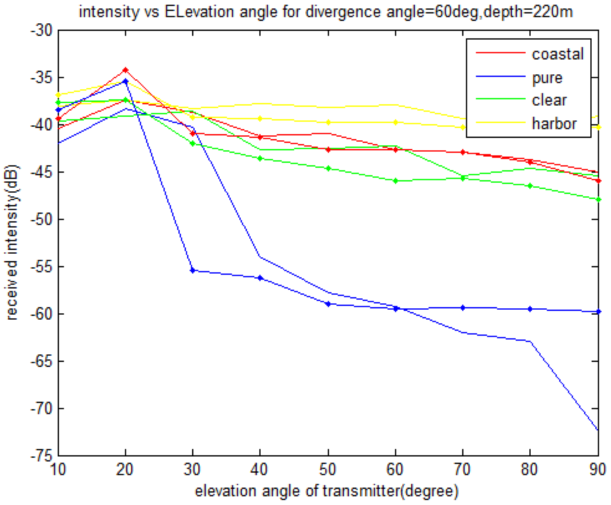


Fig.4 Comparision for received intensity for different elevation angles for transmitter’s divergence angle 60^0 and 45^0

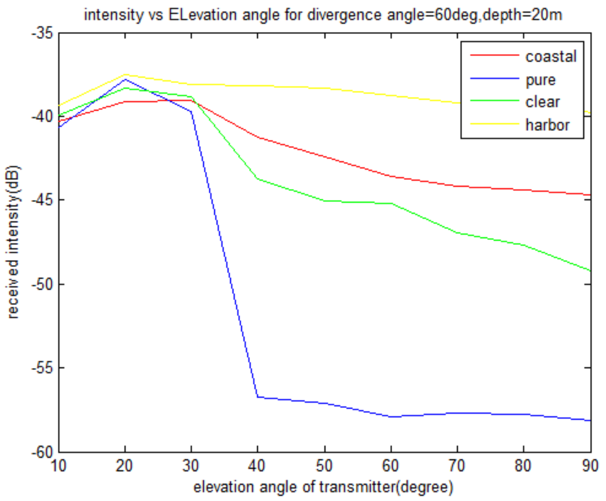
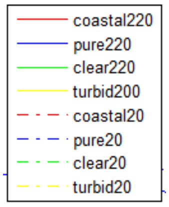


Fig.5 Received intensity for different elevation angles for fixed transmitter's divergence angle 60^0(shallow sea)

C. Effect of the transmitter's aperture angle

In fig.6 we present the simulation result of intensity versus the transmitter's aperture angle. Particularly, for the pure sea environment, the effect of aperture angle is quite noticeable, as large number of reflections in the water – air surface takes place for this case. For pure sea, the larger number of reflections at both ends (water-air, water-bottom interfaces) at 20 m depth led to lower intensity level for divergence angle up to 50^0. The larger divergence angle of 60^0 changes the configuration geometry of the link and favors the shallow waters case. However, as the water becomes more turbid, the dept's impact is reduced.



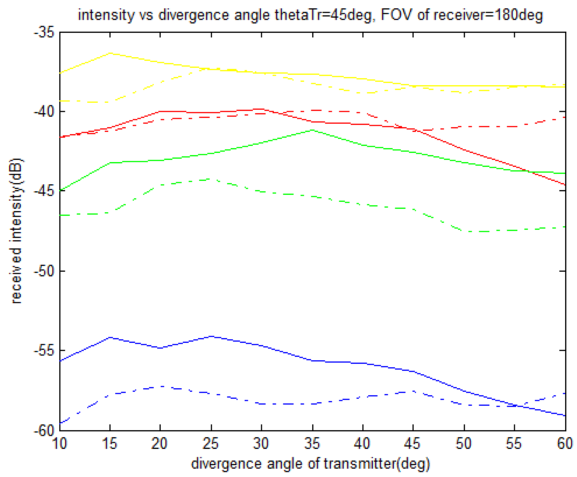


Fig.6 intensity vs. divergence angle for 220m and 20m

D. Effect of the transmitter's and the receiver's distance

Fig.7 and fig.8 represent the impact of the distance between the two communicating nodes for all environments and for both depths. The distance varies from 10 m to 100 m, with step 10m. In general, the higher the distance between the transmitter and the receiver, the lower the intensity gets. Concerning all environments, the maximum of the intensity is reached when the examined distance is 10 m. Another notable comment is that the intensity for distance 100 m in turbid water is slightly higher than the one for distance 10 m in pure water. For example, for shallow waters (Figure 8) the intensity is -53.8493 dB for 100 m distance in turbid waters and -55.9241 dB for 10 m distance in pure waters. Finally, even though the results seem to be slightly better for deep waters compared to shallow waters, the differences in the intensity values are very small and in some cases almost negligible between the two depths. Therefore, the water depth has a minimum impact on the relation between the received intensity and the distance.

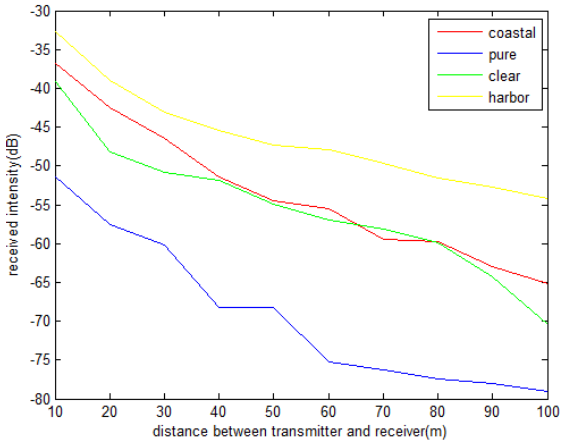


Fig.7 intensity vs.. distance between transmitter and receiver for deep sea

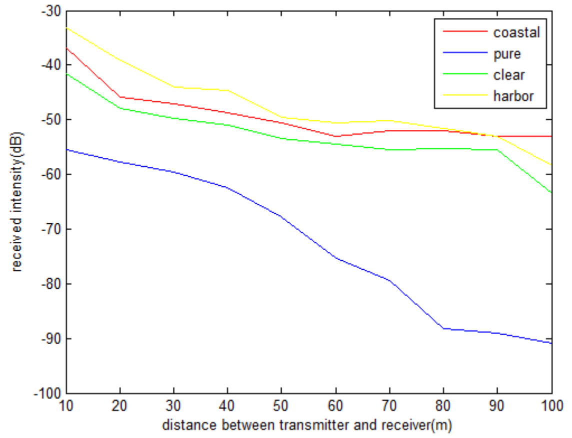


Fig.8 intensity vs. distance between transmitter and receiver for shallow sea

VI. CONCLUSION

In this research paper, we presented a realistic model for underwater wireless optical communication. We used the Monte Carlo simulator for channel modeling, considering different parameters like, water type and various characteristics of transmitter and receiver, for deep and shallow ocean. It was observed that as the transmitting range was increased, the received power was reduced. Comparing the two water environments, it was noticed that in turbid water the intensity was stronger and the time dispersion was tighter, making the turbid environment even more suitable for the specific link configurations. Therefore, we can conclude that a configuration which functions well in a coastal environment, it will operate equally well, if not better, in turbid water.

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