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Fundamental Analysis for Underwater Wireless Visible Light Communication

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Abstract —*The 71% surface of Earth is covered with water in one form or another, but till date this area is less elaborated as compared to free space wireless communication in deep space and in air. The underwater communication is always been subject to improvement and advancements as the medium is subject to changes that is directly proportional to the natural habitats and Eco system. Due to advance in technology in past decades the underwater communication has received the prime importance and dedications, the result of which the Acoustical communication which is communication technology using the sound as media has reached to the peak position, but it is not the supreme technology though the RF and majority of Electromagnetic spectrum absorbs by water. On the other hand the visible light communication has opened the door for the fast, mobile, flexible and application dependent short range communication. The present thesis describes the overall effect of underwater time varied parameters on the beam of light transmitted from transmitter to receiver there by enabling the readers and researchers to summarizes the practical communication underwater using free space visible light. Further the recent advance in modulating scheme like CSK and variable OOK with dimming control, have influence this entitled thesis to implement the mathematical model for the inhibiting such technique at a specific frequency of interest that is subject to least attenuation while propagating underwater, thereby providing long range , speed and flicker free and Inter symbol interference free communication. The thesis is summarized and concluded by the simulating various channel parameters and hardware effect on the overall power received*

Keywords- *UWOC (Underwater Optical Communication), Phytoplankton, OOK (On-Off Keying), BER vs. SNR analysis. Acoustic Communication.*

I. INTRODUCTION

The marine environment is, or is fast becoming, the critical frontier of exploration for transport, oxygen and food production, hydrocarbon exploitation, aquaculture, biofuel production, mineral exploitation, climate, and global water circulation. The future of mankind is, therefore, dependent on careful monitoring, control, and sustainable exploitation of marine environments. As of today, however, our ocean basins are less well mapped, explored, and understood than not only our Moon, but even Mars. This extraordinary gap in the knowledge of our life-support system called Earth is because the body of the ocean is significantly more hostile to man than the air or land surface, lacking the essential oxygen to breathe and posing the challenges of crushing pressures in a corrosive fluid. With the maturing of intelligent autonomous underwater robotics, we are now on the boat of capability to accomplish our work at sea by means of unmanned collaborative networks. But to form a functional network, and to enable collaboration, requires communication.

At-sea experimentation is expensive and difficult. Even when possible, there is normally only a limited time in which to perform the experiments, perhaps only one physical environment and a limited number of configurations that can be tested. There is often little or no control over what the natural environment provides. There may be no opportunity for repeating tests. If one wishes to explore how a particular coding scheme or protocol performs in comparison to another, it may not even be possible to test both under the same conditions, since the environment may change too rapidly to enable sequential testing and the channel may prohibit parallel testing. Bad weather or a broken system component can cancel an entire test. There are, therefore, many reasons why it is attractive to simulate, emulate, or replay to learn about the performance of our nascent technologies. In addition, we are now also beginning to see at-sea test beds contributing to this mix of methods [3]

II. UNDERWATER CHANNEL CHARACTERISTICS

The aquatic environment has posed many challenges for feasible and successful undersea communications due to the dynamic and complex ocean conditions being generally very difficult to predict. In this sense, there are many issues affecting communication depending on the applied technology, such as large propagation losses and scattering issues [1]
The underwater environment is a uniquely difficult one for communications. Water movements are never-ceasing, and conditions are always changing drastically depending on location, time of day and weather. Hence, the performance of any undersea communication can be unpredictable. [3]

The physical signals that are used to carry digital information through an underwater channel are sound, radio and optical waves. While acoustic communications undergo large propagation losses, extended and variable propagation delays, strong multi-path signals, and limited bandwidth capacity and channel stability, underwater non-acoustic signaling methods also experience large propagation losses and scattering issues. As an electromagnetic (EM) wave does not propagate well underwater over long distances, sound is mainly used as the communication medium. Thus, this section will describe the underwater acoustic channel and examine technical differences between underwater acoustics and terrestrial wireless communication.

The development of practical underwater networks is a difficult task that requires a broad range of skills. Not only must the physical layer provide reliable links in all environmental conditions, but there are a host of protocols that are required to support the network discovery and maintenance as well as interoperability, message formation, and system security. As electromagnetic waves do not propagate well underwater, acoustics plays a key role in underwater communication. Due to significant differences in the characteristics of electromagnetic and acoustic channels, the design of feasible underwater networks needs to take into account a wide variety of different constraints. The long delays, frequency-dependence and extreme limitations in achievable bandwidth and link range of acoustics should be of primary concern at an early design stage in addition to power and throughput efficiency, and system reliability. These factors make underwater networking a challenging and rewarding endeavor.

III. OPTICAL PROPERTIES OF THE WATER

Optical properties of water are divided into two mutually exclusive groups: inherent and apparent. Inherent properties describe optical parameters which depend only on the medium, more specifically the composition and particulate substances present. Apparent properties depend on both the medium and the geometric structure of illumination, thus is a directional property. In- herent and apparent properties are explored in sections below [3]. Inherent Optical Property(IOP) includes Absorption, Scattering and Refractive Index subject to temperature, salinity and wavelength and Apparent optical Property (AOP) includes Radiance, Irradiance and Down welling light

When a beam of light is sent through a medium there are two reasons that a reduced number of photons reaches the receiver. The first possibility is that the photon changes direction, this phenomenon is known as *Scattering.* Alternatively, the photon could have its energy converted into another form, such as heat or chemical, which removes it from the light path completely; this process is known as *Absorption*. Scattering and Absorption are combined to give the overall beam attenuation

3.1. Attenuation models

This section will going to elaborate about the mathematical model used in this proposed thesis for channel attenuation which is broadly classify in two categories : Absorption and scattering. The absorption model is based on chlorophyll concentration, phytoplankton, salts and two components of a yellow substance: fulvic and humic acids. The splitting of the yellow substance on two components is practically justified for two reasons. First, it makes this model universal for all biologically stable waters. Second, it permits models in the future to include effects of fluorescence by CDOM (Color Dependant Organic Matters) in a more consistent manner. The absorption coefficient ***a* (λ)** of seawater which is wavelength dependent is taken as follow: [3][6]

$$a(\lambda)_{Total}(m^{-1}) = a(\lambda)_{Phytoplankton} + a(\lambda)_{CDOM} + a(\lambda)_{Pure\ Water}$$

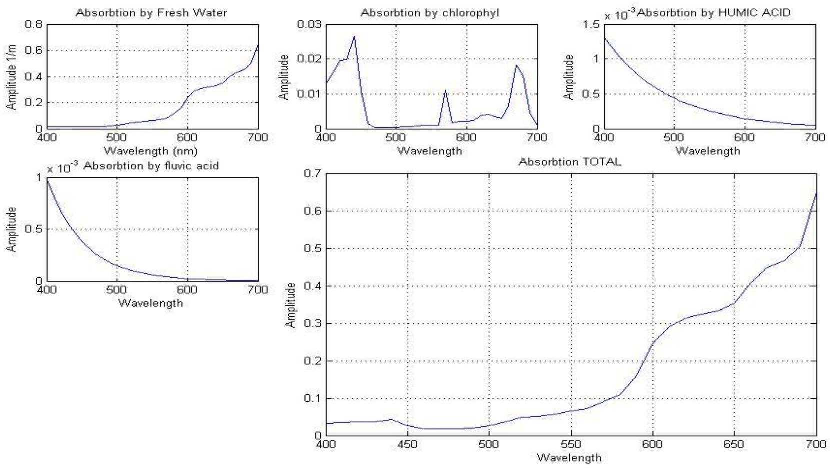

Figure 1. Absorption spectra by various components at individual wavelengths in m^{-1}

The scattering model is adopted from the research of Kopelevich. The Kopelevich scattering model is a result of extensive optical measurements taken in the Atlantic, Pacific, and Indian oceans and surrounding seas by researchers at the Shirshov Institute of Oceanology. This model couples an angular scattering coefficient of seawater with concentrations of two fractions of marine hydrosol. The first fraction consists of large organic particles with a refractive index equal to 1.03 and density 1 g/cm^3. The second fraction consists of small terrigenic particles with a refractive index equal to 1.15 and density 2 g/cm^3. Further the model do mentions the concentration of small and large particles based on the water type starting from pure ocean water to turbid harbor water. The scattering Coefficient **b (λ)** of seawater which is wavelength dependent is taken as :

$$b(\lambda)_{Total}(m^{-1}) = b(\lambda)_{Water} + (b(\lambda)_{small\ particles})C_s + (b(\lambda)_{Large\ particles})C_l$$

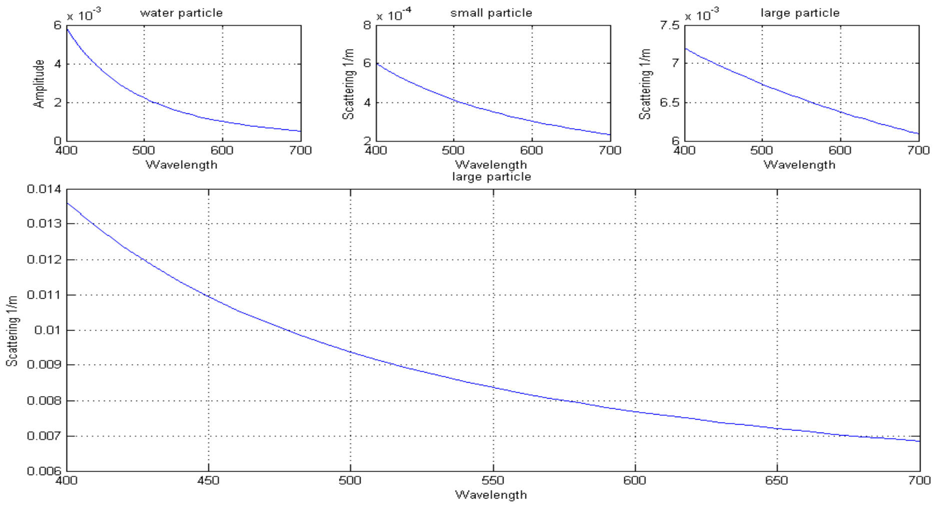

Figure 2. Scattering spectra by various components at individual wavelengths in m^{-1}

Based on the above data the total attenuation at any geographical location and based on the water characteristics is given Total Attenuation = $C(\lambda)_{Total}(m^{-1}) = a(\lambda)_{Total}(m^{-1}) + b(\lambda)_{Total}(m^{-1})$

IV. LINK BUDGET

The Aim of the link budget is to provide a reliable estimate of requirement and performance analysis for wireless underwater VLC. In this section, we start with the transmitter with a given transmit power and move towards the receiver. We then use user specific and application specific receiver performance parameters.[5]

4.1. Transmitter to Receiver

A point-to-point link from Transmitter to Receiver is affected by following components 1) Channel Loss 2) Geometrical Loss 3) Refractive index 4) Received Power

4.1.1 Channel Loss

For a theoretical approximation, Beer's Law provides a simple calculation for path loss. Beer's law is mathematically defined below in terms of Power analogy and attenuation faced by the beam

$$P_{RX}(\lambda,d) = P_{TX}(e^{-c(\lambda).d})$$

Where λ is wavelength of the transmitter source in nm, d is the distance between the transmitter and the receiver in meter. $C(\lambda)$ is the total attenuation coefficient in m^{-1}. $P_{rx}(\lambda,d)$ is the wavelength and distance dependent power at the face of receiver in watts unit and P_{tx} is the transmitted power with in watts

4.1.2 Geometrical Loss

Geometric loss is calculated as the ratio of receiver area to transmitter beam spot area at the receiver whose mathematical representation is as follow:

$$T_G = (A_{TX}/A_{RX}) = [\square(d \cdot \tan(\theta_{div}/2))^2] / [(\square/4)(D_{RX})^2]$$, where all the terms have their usual meanings

4.1.3 Refractive index

Literature survey has generally accepted that the refractive index of the water remains same irrespective of the location and climate but it is not true the refractive index of water do changes based on the dissolved salts known as Slinity, Temperature and Wavelength used of communication which in turns results in noticeable change in power received and thus signal to noise ratio. The mathematical formula for such relationship is shown below[5]

$$n(S, T, \lambda) = n_0 + (n_1 + n_2T + n_3T^2)S + n_4T^2 + (n_5 + n_6S + n_7T)/\lambda + (n_8/\lambda^2) + (n_9/\lambda^3)$$

where,
S is the salinity in parts per thousand (ppt) , ***T*** is the temperature in degrees Celsius; $\boldsymbol{\lambda}$ is the wavelength in nanometers.
The coefficients have the following values:
$n_0 = 1.31405$, $n_1 = 1.779 \times 10^{-4}$, $n_2 = -1.05 \times 10^{-6}$, $n_3 = 1.6\times10^{-8}$, $n_4 = -2.02\times10^{-6}$,
$n_5 = 15.868$, $n_6 = 0.01155$, $n_7 = -0.00423$, $n_8 = -438$, $n_9 = 1.1455 \times 10^{6}$.

4.2. At the Receiver

4.2.1. Received Power

As refractive index do changes based on the geographical conditions it is to be used in the calculation for the raw power received. The expression for the received power is then derived as follow; it is to be clear that the power is at the face of receiver depending in the structure and orientation of hardware this power will then to be converted in to signal based on responsivity, gain and diameter of the receiver

$$P_{RX}(\lambda,d) = [P_{TX}(e^{-c(\lambda).d\ .\ n(S,\ T,\ \lambda)})]^* \ T_G$$

The received optical power is further corrupted by a variety of noise sources. The power calculations for signal and noise power are given below and used to obtain a Signal-to-noise ratio (SNR).

4.2.3. Signal Power

We assume baseband direct detection for the following calculations. As is typical for such a receiver, we assume the optical detector with a load R_L and gain G. The power collected by the receiver can be converted to a photo detector current equal to

$$I_{SIG} = \text{Responsivity} * P_{RX}(\lambda,d)$$
$$P_{SIG} = [(\text{Gain} * I_{SIG})^2] * R_L$$

V. SIGNAL NOISE UNDERWATER

There are many sources of noise that disturb the optical communication system under water. Here, we discuss each noise and give the expression for its variance . The variance of noise translates into the noise power spectrum which we can use in the bit transmission simulation. The modeled noise consists of following terms [5]

5.1. Background noise

The background noise consists of the blackbody radiation and the ambient light under water whose primary source is the refracted sunlight from the surface of the water. The background noise power can be written as
$P_{BG} = P_{BG\ solar} + P_{BG\ blackbody}$
The variance of the background noise is
$\sigma^2_{BG} = 2qRP_{BG}B$
where, R is the responsivity, λ is the wavelength, $h = 6.6261\times10^{-34}$ Js is the Planck's constant, the electron charge $q = 1.6 \times 10^{-19}$ coulombs, B is the electronic bandwidth.

5.2. Dark current noise

Dark current noise is the noise presence at the detector (photo diode).
The variance of the dark current noise is $\sigma^2_{DC} = 2qI_{DC}B$. where $I_{DC} = 1.226 \times 10^{-9}$ Ampere.

5.3. Thermal noise (Johnson noise)

The variance of the thermal noise is $\sigma^2_{TH} = 4kTeFBR_L$
where we assume that the equivalent temperature Te is 290 K, F = 4 is the noise figure of the system, and $R_L = 100\Omega$ is the load resistance.

5.4. Current shot noise

Shot noise exists when the received signal is present.
The variance of current shot noise is $\sigma^2_{ss} = 2qRP_sB$ where P_s is the signal power. R is responsivity.

The total noise variance is the combination of all the noise sources. Therefore, the variance in current noise in the detector *without any optical signal* is given by
$\sigma^2_0 = \sigma^2_{TH} + \sigma^2_{DC} + \sigma^2_{BG}$

Because of the shot noise presence, the variance in current noise in the detector for *receiving* an optical signal is given by
$\sigma^2_1 = \sigma^2_{TH} + \sigma^2_{DC} + \sigma^2_{BG} + \sigma^2_{ss}$

Signal to Noise Ratio is defined as ration of Signal power and individual noise power for “0” and “1”. Mathematically

$$SNR_{(1)} = I^2_{SIG} / N_{TOTAL\ NOISE}$$
$$= [(R.G.P_{RX})] / [(\sigma^2_{TH} + \sigma^2_{DC} + \sigma^2_{BG} + \sigma^2_{ss})]$$

$$SNR_{(0)} = I^2_{SIG} / N_{TOTAL\ NOISE}$$
$$= [(R.G.P_{RX})] / [(\sigma^2_{TH} + \sigma^2_{DC} + \sigma^2_{BG})]$$
$$= 0 \text{ (ideally)}$$

VI. PROPOSED SYSTEM

Figure 3. Proposed receiver architecture

The receivers available in the market are generally having Field of View (FOV) = 60°, 90°, or maximally 120°, the proposed research provides a design using which the total 180 degree of FOV can be constructed which is the ideal case using single receiver. The proposed system can also diverted the 7 multichannel receivers as shown in the figure aside there by enabling the 7 different data logging process. This simple change in the design leads to noticeable change in the BER vs. SNR Analysis which is shown below.

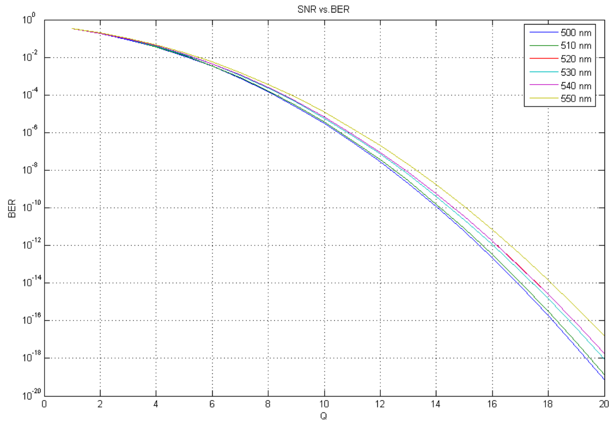

Figure 4. BER vs. SNR graph for FOV = 180°

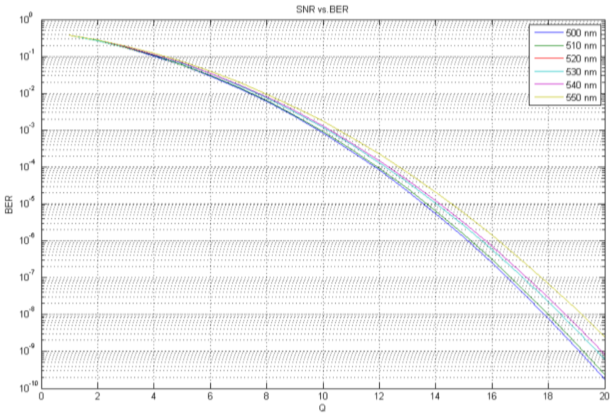

Figure 5. BER vs. SNR graph for FOV = 60°

The BER vs, SNR analysis for 180° is better than 60° for the predefined set of parameters because the ocean channel we have chosen is real time and not the theoretical, hence the analysis will be correct and valid, but the values of the results proposed by this research may slightly varies for theoretical channels readily available in MATLAB for simulation purpose. Following are list of parameters that are taken for the analysis the UWOC is affected by the below mentioned parameters as far as the scope of this Thesis is concerned because the ocean is subject to dynamic change that are valid for a specific interval of time because the ecology doesn’t remain same for long time the scenarios which affects their values are also discussed below

Sr. No	Parameter	Conditions affecting the parameters	Parameters value chosen for research
1	Absorption	Based on the biological species found at a place of research	Based on the biological species found at a place of research and mentioned above also
2	Scattering		
3	Temperature	Locations and ecology at the sea shore and underwater	37 °C
4	Salinity	Dissolved salts	35 ppt
5	Refractive index	Temperature Salinity and Wavelength	1.32 to 1.35
6	Presence of Solar radiation in day time	Based on the angular position of TX / RX	$\sigma^2_{BG} = 2qRP_{BG}B$
7	Organic Matters	Based on location	Mentioned in the absorption and scattering
8	Type of ocean	Harbour, Coastal, Sea shore etc.	Pure Sea Water
9	Physical dimension of transmitter and receiver	Limits because of mobile and ease of carry while diving underwater	Tx with 5 ° divergence angle Rx with 180° FOV
10	Receiver Noises and Gain	Depends on the material used for construction	Gain = 150 (APD diode) Gain = 1 (PIN diode)
11	Power requirement	Based on the distance location and time for which research to be carried out	1 Watt
12	Separation between Tx. and Rx	Widely suffers from above parameters and moving hurdles	20 mtr
13	Frequency band	Perfect choice is necessary in order to diminish the noise	500 nm to 550 nm
14	Responsivity of Receiver	Should be moderate because high responsivity results in to fake results also	70 or ($n q \lambda / hc$)

Table 1. List of Parameters

VI. CONCLUSION AND FUTURE SCOPE

Though the ocean atmosphere is subject to change the proposed system have shown the remarkable change in the results as compared to the conventional systems and have also provided the best feasible bandwidth for the analysis at more reliable level based on real data which are wavelength specific attenuation. In order to invite ignited minds for research the future scope is must and for this research the physical layer that is Light can be partly shared by the Acoustic communication there by providing a hybrid system so that at one time one of the two technology remains supreme for best out comes. Underwater is home for many species which are sensitive to light or sound or both hence this future system will provide much more reliable out comes so that the research can be carried out with least damage to the Earth ecosystem.

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