An Alternative Experimental Method for Determination of Light Beam Attenuation Coefficient in Underwater Wireless Optical Communication

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Abstract — In wireless optical communication systems, the transmission of optical signals via the channel (air or water) is affected by absorption and scattering. These reduce the signal strength (attenuation) and transmission distance of the signals. In pure water, the blue-green region of the visible light gives low attenuation. Some models have been developed to characterize the underwater optical channel such as Beer Lambert’s law, Radiative Transfer equation and Monte Carlo model. In underwater optical communication, optical power meters are an invaluable tool in the determination of attenuation coefficients. However, optical power meters for underwater optical communication are very expensive. There is a need to be able to determine the attenuation in the underwater optical communication channel at a low cost, especially in the absence of underwater optical power meters. In this paper, we present an alternative low-cost experimental method of obtaining the approximate attenuation coefficient of the visible light beam in underwater optical wireless communication without the use of optical power meters. A wireless visible light communication system was set up experimentally for underwater measurements involving an oscilloscope as the only measuring device. The system uses sub-carrier frequency modulation; a white light-emitting diode array for the transmitter, and a solar panel at the receiver front end. A theoretical transmission model was developed from the experimental setup based on the line of sight method in an unbounded medium, Beer Lambert’s law, and the received sub-carrier signals; in order to provide an alternative method of determining approximately the attenuation coefficient of the underwater medium. Experiments were performed in air, clear water and in saline water. The attenuation in the air was used as a reference upon which attenuation in the clear water and the saline water was based. The saline water has a salt concentration of 6.7 g/100 mL by weight and a total dissolved solid of 86.2 ppt. The trend of the measured received sub-carrier signals showed deviation from the developed theoretical model, and the model was therefore adjusted to conform to the experimental results. From the adjusted model, the attenuation coefficient of 0.0007379 cm⁻¹ and 0.02447 cm⁻¹ were obtained for clear water and the saline water respectively. The method is simple, straightforward, easy to set up in a laboratory, low cost and can be applied to visible light of any wavelength.

Keywords — absorption; attenuation coefficient; optical power meters; scattering; transmission model; underwater wireless optical communication.

I. INTRODUCTION

Wireless optical communication has gained significant interest globally due to its usefulness in the military, industry, and scientific community [1]. Optical communication aids in predicting natural disasters, disaster prevention, pollution monitoring and frequent data collection such as water temperature, specific conductivity, pH, and turbidity [2]. Wireless optical communication has proved to be a useful system at low cost, low power consumption and high data rates for indoor, outdoor, and underwater high-speed communications [3]. However, these advantages are hampered by absorption and scattering caused by the transmission channel (air, water, or matter) and result in attenuation of received power and reduced communication range to a few meters [2].

Absorption is the interaction of photons of light with molecules of water and matter resulting in the loss of optical signals and received power [4]. The energy lost is converted into forms such as heat, chemicals, etc. [5]. Duntley [6] discovered that within the blue-green wavelengths (450–550 nm), there is low attenuation of light by pure water, and the attenuation increases towards the red end of the visible light spectrum. Absorption of pure water is affected by salinity and temperature changes resulting in an increase/decrease in absorption at different wavelengths [7]. As the salinity of the water increases, absorption increases significantly in the blue region than in the red region [8].

Scattering involves the deflection of light from its path after interacting with particles in water [4]. The intensity of the received signal is reduced. Scattering results in spatial dispersion, when the light from the source spreads out in space; and temporal dispersion due to the photons arriving at the receiver at various times [9].

The underwater optical communication (UWOC) channel is modelled via its optical properties. The inherent optical property of water, which is absorption and scattering, are dependent on the medium. The apparent property of water such as irradiance, radiancy and reflectance are dependent on both the medium and the geometrical structure of the light field [10].

In literature, some models have been developed to analyze the optical characteristics of the underwater optical communication channel such as Beer Lambert’s law, Radiative Transfer equation and Monte Carlo model. Li et al. [11] experimentally designed a 25 Gb/s underwater optical communication system over a 5m highly turbid harbor water link. The attenuation coefficient of harbor water is reduced at 680 nm compared to 450 and 520 nm.
Majlesein et al. [12] proposed an underwater optical communication system model for the effects of noises (shot noise, thermal noise and background noise), turbulence, scattering and absorption in clear, coastal and harbor water. The scattering was modelled via Monte Carlo simulation and the optical link deteriorates at increased range. Miramirkhani and Uysal [13] carried out the channel modeling of the underwater optical communication system by investigating the effects of shadowing and blockage caused by human and man-made objects. A blocked line-of-sight results in path loss though scattered signals can still get to the receiver. Smaller transmitter viewing angles and larger aperture sizes can reduce the losses.

Li et al. [14] determined the effects of environmental factors such as temperature, turbulence, and salinity which cause attenuation in underwater optical communication systems. A temperature of 25 °C has a good performance. The data rate and the transmission distance are reduced in the presence of salt. Cai et al. [15] proposed a multi-parameter model to integrate the effects of absorption, scattering and turbulence in underwater optical communication systems using Beer Lambert’s law and Monte Carlo. An increase in transmission distance worsens the attenuation and significantly increases the fluctuation of light signals.

There are some commercially available meters that measure optical beam attenuation coefficient using propagation paths that are less than one meter. For a medium with high attenuation, attenuation distance will be very short, and such a measurement can be carried out on a laboratory bench. For some media with very low attenuation such as pure water, the attenuation distance may run to several meters which makes it impossible to use such a method on a laboratory bench, and also technically difficult in a long water tank or large body of water in the open.

Estes [16], [17] developed an attenuation meter and method that is capable of providing accurate measurements of optical attenuation coefficient in water with low attenuation. The meter produces a collimated laser beam which propagates through the water and filtered back-scattered light arrives at a camera of the meter. A light image is formed at the focal plane of the camera which is recorded and analysed by a microcomputer to provide optical beam attenuation coefficients. Lin et al. [18] proposed an estimation method for optical attenuation coefficient in water through the imaging of the backscattered light with a pulsed laser range-gated imaging (PLRGI) system. The imaging model is based on light propagation theory, and the attenuation coefficient is calculated by non-linear estimation method.

Optical power meters are used to measure the power of an optical signal, and thus can be used to determine the power loss while passing through an optical medium [19]. It is made up of a calibrated sensor, measuring amplifier and display. Optical power meters used for free space and underwater wireless visible light communication systems are somewhat different from those used in fibre-optic networks as they are used to measure the average optical power in a continuous optical beam. They are usually very costly and are more expensive than those for fibre optic systems. Most have sensors external to the main measuring/display unit. The sensor can be pyroelectric, photodiode or thermal depending on the level or range of power to measure. The sensors are also wavelength-dependent, and the display unit shows the measured optical power and set wavelength. Some have sensors for narrow collimated beams such as laser, while some have sensors with integrating spheres for diverging beams such as from light-emitting diodes (LEDs). They run into thousands of dollars, and some require an extensive calibration process. Some optical power meters are hand-held or stand-alone benches.

There is a need to be able to determine, at least to an approximate value, the attenuation coefficient of an optical beam in an underwater optical communication channel at a low cost to the researcher, and/or in the absence of underwater optical power meters. In this paper, a simple and straightforward method is presented. The method involves laboratory experiments and the use of models developed from the experimental results. The rest of the paper is organized as follows: Section II discuss briefly water types and some ways of determining attenuation coefficient from Beer Lambert’s law. Section III presents the materials and methods involved while Section IV presents the experimental results and discusses the results. Section V concludes the paper.

II. BEER LAMBERT’S LAW, ATTENUATION COEFFICIENT AND WATER TYPES

The most widely used theoretical basis to model the effects of attenuation is the Beer-Lambert’s law [15]. In UWOCS, the received power through the water medium can be obtained via the law as expressed in (1) [1].

\[ P_r(x, \lambda) = P_t e^{-c(\lambda)x} \]  

(1)

where \( P_o \) is the initial optical power from transmitter, \( P_r(x, \lambda) \) is the transmitted optical power at distance \( x \) which gets to the receiver, and \( \lambda \) is the wavelength. The attenuation coefficient \( c(\lambda) \), which is wavelength dependent, comprises of absorption coefficient, \( a(\lambda) \) and scattering coefficient \( b(\lambda) \), as expressed in (2).

\[ c(\lambda) = a(\lambda) + b(\lambda) \]  

(2)

The attenuation coefficient can be derived from the measured received optical power [1].

If the initial optical power \( P_o \), and the received optical power \( P_r(x_o, \lambda) \) at a particular distance \( x_o \) and wavelength \( \lambda \) are known, then the attenuation coefficient \( c(\lambda) \), can be determined from (1) as expressed in (3):

\[ c(\lambda) = \frac{\ln \left( \frac{P_o}{P_r(x_o, \lambda)} \right)}{x_o} \]  

(3)

If initial optical power \( P_o \) is not known, but if possible to measure the optical power at the receiver \( P_r(x, \lambda) \), the attenuation coefficient can still be determined from series of...
measurements by measuring the optical power at the receiver at varying distances from the transmitter, keeping $P_o$ constant, and maintaining the conditions of the medium to be constant and uniform. In this case, using (1), $c(\lambda)$ can be determined from a plot of logarithm of $P_r$ ($x, \lambda$) against distance $x$, resulting in a straight line graph with a negative slope as expressed in (4).

$$\ln P_r (x, \lambda) = \ln P_o - c(\lambda)x \quad (4)$$

The value of the slope gives the attenuation coefficient. In the two cases described above, optical power meters become an invaluable tool for easy measurements especially the optical power at the receiver.

In an underwater medium, another method to determine the attenuation coefficient involving optical power meters is also by taking power measurements looking for a distance $x_d$ referred to as attenuation distance or attenuation length, where the ratio of $P_r$ to $P_o$ is 0.368, and in this case, the $c(\lambda)$ will be equal to the reciprocal of $x_d$. There are some commercial meters that work on this principle.

Four common water types in underwater optical communication are briefly discussed. Pure sea water is mainly limited by absorption as the low scattering coefficient frees the beam from divergence.

Clear ocean water consists of salts like sodium chloride, potassium chloride, magnesium chloride etc., and other minerals and organic matter that cause absorption and scattering.

Coastal ocean water has more dissolved particles (water molecules, suspended particles, dissolved salts, mineral and organic matter), and hence, the turbidity, absorption and scattering are increased.

Turbid harbor has the highest concentration of particles (dissolved and in-suspension) hence the light propagation is highly limited by absorption, scattering and turbidity. Table I shows the attenuation coefficient of these types of water. The attenuation coefficient varies with different types of water and optical wavelengths [10].

<table>
<thead>
<tr>
<th>Water Type</th>
<th>$a$ (m$^{-1}$)</th>
<th>$b$ (m$^{-1}$)</th>
<th>$c$ (m$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pure Sea</td>
<td>0.053</td>
<td>0.003</td>
<td>0.056</td>
</tr>
<tr>
<td>Clear Ocean</td>
<td>0.069</td>
<td>0.08</td>
<td>0.15</td>
</tr>
<tr>
<td>Coastal Ocean</td>
<td>0.088</td>
<td>0.216</td>
<td>0.305</td>
</tr>
<tr>
<td>Turbid Harbour</td>
<td>0.295</td>
<td>1.875</td>
<td>2.17</td>
</tr>
</tbody>
</table>

III. M MATERIALS AND METHODS

A. The Visible Light Communication in Air and Water

An experimental underwater wireless visible light communication (VLC) system was set up as shown in Fig. 1 using sub-carrier frequency modulation, a white LED array at the transmitter back end and solar panel at the receiver front end. The transmitter circuit consists of the signal generator, a preamplifier, a sub-carrier frequency modulator, a LED driver and the white LED array. The receiver circuit is made up of a mini solar panel, a high gain preamplifier, FM demodulator, and an oscilloscope. The oscilloscope (GDS-2104 from GW-INSTEK) was used to measure the amplified received sub-carrier signals from the high gain preamplifier. The tank is a transparent rectangular plastic container.

The experimental system was set up under three conditions: in free air, and in clear and saline water. The LED array and the solar panel were aligned such that the solar panel was in direct line of sight (LOS) of the LED array. The distance between the transmitter (LED array) and the receiver (solar panel) was varied.

For the clear water experiment, the tank was filled with clear water with pH value of about 6.66 (measured with a Poit digital pH meter). The temperature of the water was measured by Zacro aquarium digital thermometer.

For the saline water experiment, table salts (sodium chloride) were weighed with SF-400 digital weighing scale and dissolved in clear water to have a salt concentration of 6.7 g/100 mL, pH of 6.76, and total dissolved solid (TDS) of 86.2 ppt measured by a TDS meter.

Theoretical transmission model from the experimental setup was developed based on transmission in a free unbounded medium, Beer Lambert’s law, and the expected received subcarrier signal amplitudes. The model was then modified to conform to the results of the experiments in order to be able to determine the attenuation coefficient of the clear water and the saline water. The setup for air was used as reference upon which the results of the clear water and the saline water were based.

B. Initial Modeling of the Underwater Optical Communication Medium

As mentioned in the last sub-section, the theoretical transmission model used is based on the LOS method in a free unbounded medium, Beer Lambert’s law, and the expected received subcarrier signal amplitudes. LOS is a well-known topology in use for many years.

![Fig. 1. Schematic of experimental setup in air and water.](image-url)
The diagrammatic illustration of the light beam from transmitter to receiver in an unbounded underwater medium is shown in Fig. 2.

Let the transmitter $T_x$ be situated at location A, and the receiver $R_x$ be situated at location B. Let the distance between the transmitter and the receiver be $d$. Let the unbounded intervening medium be uniform with attenuation coefficient, $\alpha$. Let the optical power $P_t$ from the transmitter be represented as $P_{tA}$, and the optical power at location B be $P_{tB}$.

Optical power density at B (assuming the beam is uniform within its cross section),

$$ P_{dB} = \frac{P_{tB}}{\pi r^2} $$

(5)

where $r$ is the radius of the beam cross section at location B (assuming a uniform circular beam and $r \ll d$).

$r$ is related to $d$ and the beam divergence angle, $\theta$ as:

$$ r = d \tan \theta $$

(6)

Substituting for $r$ in (5):

$$ P_{dB} = \frac{P_{tB}}{\pi d^2 \tan^2 \theta} $$

(7)

Let the received (captured) optical power by the solar panel be $P_r$. This received power is affected by the optical power density at point B, the surface area of the solar panel $A_{sp}$, and the slop angle $\Phi$, which is the angle between the normal to the solar panel surface and the transmitter – receiver trajectory.

$$ P_r = P_{dB} A_{sp} \cos \Phi $$

(8)

Substituting for $P_{dB}$ from (7), (8) becomes:

$$ P_r = \frac{A_{sp} \cos \Phi}{\pi \tan^2 \theta} \left( \frac{P_{tB}}{d^2} \right) $$

(9)

In this case, $P_{dB} \neq P_{tA}$ because of attenuation within the medium. Introducing Beer Lambert’s law:

$$ P_{dB} = P_{tA} e^{-\alpha d} $$

(10)

Substituting for $P_{dB}$ in (9), and since $P_r = P_{tA}$, therefore, the received power by the solar panel:

$$ P_r = \frac{A_{sp} \cos \Phi}{\pi \tan^2 \theta} \left( e^{-\alpha d} \right) $$

(11)

$$ P_r = K P_e \left( e^{-\alpha d} \right) $$

(12)

where

$$ K = \frac{A_{sp} \cos \Phi}{\pi \tan^2 \theta} $$

(13)

In all the experiments, $P_r$ is maintained constant, and $\Phi$ is maintained at 0°. $K$ is constant and is not medium-dependent. Only $d$ is variable.

In Fig. 2, let $V_s$ be the sub-carrier voltage produced by the solar panel, let $\eta_R$ be the optical efficiency of the solar panel, let $C_1$ be the conversion factor or responsivity of the solar panel (i.e., volt/watt), and let $G_A$ be the voltage gain of the amplifier (i.e., the high gain preamplifier in the receiver).

The sub-carrier output voltage from the voltage amplifier, $V_{OA} = P_r \eta_R C_1 G_A$

(14)

Substituting for $P_r$ from (12), then (14) becomes:
The optical signals’ strength reduces with distance in all the media. The received visible light signal is inversely proportional to the transmission distance. When salt was introduced into the clear water, the conductivity, and the permittivity changes, then the behavior of the medium to visible light changes, and further attenuation is experienced due to absorption of the light in the medium. The visible light signals suffered highest attenuation in the salt water, and the least attenuation in the free air. In clear water, the strength of the visible light signals with distance is almost the same as in free air except at increased long distances.

B. Modified Model Derived from the Experimental Results

Using some experimental and assumed parameters for simulation for air in the model in (18) as shown in Table II, the expected sub-carrier output voltage amplitudes are shown in Fig. 4, which is plotted against the measured received sub-carrier amplitudes for the air experiment.

![Graph showing subcarrier amplitude comparison](image)

**Fig. 4. Sub-carrier output voltage amplitudes from the initial model compared with the measured received sub-carrier amplitudes for the air experiment.**

Comparing (18) for free air transmission with the graph in Fig. 3 and 4 for free air, it can be observed that the received sub-carrier output voltage from the receiver high gain preamplifier from the experiment does not vary as the inverse square of the transmitter-receiver distance i.e., the exponent of the inverse variation with distance in (18) seems to be less than 2. At a distance of 15 cm from the LED array transmitter, the measured subcarrier signal amplitude and that from the simulation are the same. At this distance, the solar panel receiver is so close to the transmitter such that almost all the light beam reaching the solar panel surface has a direct optical path from the transmitter. At increasing distances further, the values from experiments and simulations deviated remarkably. The reason for this is not
farfetched. Equation (18) is for LOS in a free unbounded medium, but in the experimental setup, the medium is bounded by the transparent rectangular plastic tank. There might be some reflections from the side walls of the water tank reaching the solar panel surface. Reception from the sidewalls will not allow the overall reception to quickly decrease with distance. Therefore, for the experiments conducted, (18) has to be modified to conform to experimental results.

Still following (16), let the model of the received sub-carrier amplitude, \( V_{OA} \) with distance \( d \) be represented as:

\[
V_{OA} = Qd^n e^{-\alpha d} \quad (20)
\]

where \( Q \) caters for the beam divergence, effective apertures, solar panel power-voltage conversion factor (responsivity), amplifier gain, and the transmitter power. It corresponds to M in (16). Multiplying with \( d^n \) shows how \( V_{OA} \) may vary with \( d \), and \( n \) is the exponent of the variation.

Assuming for free air, \( \alpha = 0 \), then the equation for free air becomes:

\[
V_{OA} = Qd^n \quad \text{(similar to (18))} \quad (21)
\]

Taking the logarithm of both sides,

\[
\ln V_{OA} = \ln Q + n \ln d \quad (22)
\]

\( Q \) and \( n \) are determined from a plot of the graph of \( \log_e V_{OA} \) against \( \log_e d \) where \( n \) is the slope and \( \log_e Q \) is the intercept on the vertical axis.

From analysis of results of experiments for free air, and obtaining a straight line of best fit, the following values were obtained for \( n \) and \( Q \):

\[
n = -0.428, \quad Q = 2992.91
\]

The equation of the model (20) now becomes:

\[
V_{OA} = 2992.91 \left( e^{-0.428d} \right) \quad (23)
\]

Equation (20) can be re-written as:

\[
\frac{V_{OA}}{Qd^n} = e^{-\alpha d} \quad (24)
\]

Taking logarithm of both sides:

\[
\ln \left( \frac{V_{OA}}{Qd^n} \right) = -\alpha d \quad (25)
\]

Equation (25) shows that a graph of \( \log_e \left( \frac{V_{OA}}{Qd^n} \right) \) against \( d \) is expected to be a straight line with negative slope of \( \alpha \) and zero intercept on the vertical axis. The modified model was used to obtain the attenuation coefficient for the clear and the salt water.

Using the values obtained for \( n \) and \( Q \) in the analysis for the clear water and the saline water experimental results in (25) yield a straight line graph, and by obtaining the line of best fit yields:

- Attenuation coefficient for the clear water: \( \alpha_{cw} = 0.0007379 \text{ cm}^{-1} \)
- Attenuation coefficient for the saline water: \( \alpha_{sw} = 0.02447 \text{ cm}^{-1} \)

The resulting plots of the sub-carrier amplitude from the modified model for the free air, the clear water and the saline water are shown in Fig. 5. The plots show similar characteristics with the experimental results in Fig. 3.

This method is simple, straight forward, easy to setup in the laboratory and is of low cost. Considering (13) and (17), none of the actual values of each of the parameters defining \( K \) and \( M \) need to be known or worried about, though it is advisable to let the beam divergence angle, \( \theta \) be very small; and maintain the slope angle, \( \Phi \) at 0° for more accurate results. Also, the gain of the receiver preamplifier must not be too high to ensure that output signals from the preamplifier are not saturated throughout the measurements. It is to be noted that for this method, we assumed that the optical power at the receiver is fully described by Beer Lambert’s law; that the attenuation coefficient of light beam in free air is zero; that the water is static; that the nature of the water medium is uniform from the transmitter to the receiver; and that the temperature of the water medium remains fairly constant throughout measurements. However, our method cannot be used for turbulent waters or moving water bodies.

The method can be used at any wavelength within the visible spectrum of light provided the LED is of the desired wavelength. This restriction is because of the optical spectrum of the solar panel used as receiver. In further work, we intend to work with infra red (IR) and ultra violet (UV) LEDs, with corresponding or suitable solar panels or appropriate photodiode receivers.

Fig. 5. Plots of the sub-carrier amplitude from the modified model for free air, clear water, and salt water experiments.
V. CONCLUSION

A wireless visible light communication system using a white LED array as the transmitter and a solar panel as receiver was setup and used to experimentally derive an alternative method of determining the attenuation coefficient of light beam in underwater medium in the absence of costly (non-fiber optic) optical power meters. Experimental investigation was done in free air and underwater. Clear water and saline water were used as the underwater medium. Results showed that as the distance between the transmitter and receiver is increased; the received optical signal at the receiver becomes reduced in strength both for free air and underwater. A theoretical transmission model based on the LOS method in an unbounded medium, Beer Lambert’s law, and the expected received signal amplitudes was developed which was modified to conform to experimental results. The attenuation for free air was used as reference. Higher attenuation value was obtained for the saline water than the clear water.

This alternative method can be used to approximately derive the attenuation coefficient of optical beam in underwater optical communication systems. The method is simple, straightforward, easy to setup in the laboratory, of low cost, and can also be applied to visible light of any wavelength.

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CONFLICT OF INTEREST

The authors declare that they do not have any conflict of interest.

REFERENCES


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