20 Mb/s Experimental Demonstration Using Modulated 460 nm Blue LED for Underwater Wireless Optical Communications (UOWC)

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Abstract. This paper has demonstrated an experimental low power consumption underwater wireless optical communication (UWOC) system with 460-nm LZ1-00DB00 Blue LED and avalanche photodetector. With the LZ1-00DB00 Blue LED operating at a driving current of 1200 mA with an optical power of 5280 mW, UWOC link offering a data rate up to 20 Mb/s over a transmission range of 5 meters under an underwater channel link. The measured bit-error rate (BER) is $3 \times 10^{-3}$ which pass well the forward error correction (FEC) threshold.

1. Introduction
The technology of Visible Light Communication (VLC) has become a popular research topic in nowadays due to its optical characteristics which is able to provide data transmission between channel with high-speed, high security with low-cost Light Emitting Diodes (LED) and photodiodes [1]. The characteristic of VLC was by using visible light region (400THz – 790 THz) in electromagnetic spectrum as transmission medium, a short-mid range optical communication is able to transmit and receive data. There are several VLC applications has proposed and become research topic nowadays which one of the it was underwater wireless optical communication (UWOC) due to the increase demand of underwater activities such as oceanography research, undersea oil seismic monitoring, pollution monitoring control, offshore oil exploration and military application. The terms of wireless are important for underwater because cables will face many challenges like physical damage, maintenance issues and fragility that cause by ocean environment corrosions. The present underwater wireless technology use acoustic wave has the limitation on low bandwidth, low data rate, high latency and time varying multipath propagation. Although acoustic communication can support a long distances of transmission range (up to km) but data rate only supports from ten Kbps up to hundred Kbps depends on transmission range. Hence acoustic unsupportable for application that require a communication link with data rates at least few to tens of Mbps, for example sensors, real-time applications and various underwater vehicles, underwater technology, radio frequency (RF) is suitable to support a high data rate in short distance but it has been found a fatal drawback which the attenuation of RF waves will heavily attenuated by ocean environment with the increase in frequency. The latest wireless technology use optical or visible light as transmission channel can support high data rate over moderate transmission range but optical light will be affected by optical underwater propagation phenomena such as temperature fluctuations, absorption, scattering, dispersion and beam steering in ocean [2].
UOWC had the advantage of fast transmission speed of light in water, hence it immune to link latency with higher communication security over the acoustic and RF methods. For UOWC, there is a relatively low attenuation optical window of blue-green wavelengths as show as Figure 1. In contrast to the above impairments, seawater shows a decreased absorption in the blue/green region of the visible spectrum [3] which blue-green wavelengths are capable of proving high bandwidth communication.

![Absorption & Scattering of visible light in Pure Seawater](image)

**Figure 1.** Absorption & Scattering of visible light in Pure Seawater [3]

2. Mathematical Preliminaries of VLC UWOC Approach

A VLC system can be applied to application for both indoor and outdoor and the concept was same where LED served as transmitter while Photodetector have served as receiver; In this case, we have assumed the LED are in LOS with receivers through Free Space Optic (FSO).

2.1. Channel Modelling for VLC

To calculate the path loss or channel gain in LED Lambertian radiation pattern, The DC gain, $H(0)$ in a LOS channel can be derived as [4]:

$$H(0) = \begin{cases} \frac{A.\cos^m(\Phi).T_s(\psi).g(\psi).\cos(\psi)}{2\pi d^2}, & 0 \leq \psi \leq \psi_c \\ 0, & \psi > \psi_c \end{cases}$$

(1)

Where $A$ is define as detector area in $m^2$, $\Phi$ represent angle of irradiance with respect to the transmitter perpendicular axis, $\psi$ as the angle of incidence with respect to the receiver axis, $T_s(\psi)$ as gain of optical filter. $g(\psi)$ represent concentrator gain of PD and the equation can be express as [5]:

$$g(\psi) = \begin{cases} \frac{n^2}{\sin^2\psi_c}, & 0 \leq \psi \leq \psi_c \\ 0, & else \end{cases}$$

(2)
In formula (2), n defined as refraction index and ψ_c defined as maximum angle of FOV. Lambertian emission m equation is given as [6]:

\[ m = \frac{-\ln(2)}{\ln(\cos(\phi_{1/2}))} \]  

(3)

2.2. Channel Modelling for UOWC approach

In underwater environment, the challenge faced by optical signals in underwater was absorption and scattering which will degrade the communication range due to optical beam scattering by all the particles existing inside the sea. To comprehension the underwater optical signal in absorption and scattering respectively, the mathematically formula of absorption and scattering coefficients can be derived by introduce a simple geometrical model in Fig 2 [7].

![Figure 2. Geometry of inherent optical properties [7]](image)

Assume an elemental volume of water ΔV with thickness ΔD is illuminated with a light beam with incident power \( P_I \) having a wavelength \( \lambda \). then a small fraction of the incident light \( P_A \) is absorbed by the water and others portion of light is scattered denoted by \( P_S \). The remaining light power, \( P_R \) will propagate as desired. Therefore, according to law of conservation of energy, it can be derived as [7], [8], [9]:

\[ P_I = P_A + P_S + P_R \]  

(4)

The linear combination of absorption and scattering coefficient can be described as \( c (\lambda) \) which is expressed as [10]:

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

(5)

The absorption coefficient \( a (\lambda) \) can be further represented as summation of four absorption factors [11]:

\[ a(\lambda) = a_w(\lambda) + a_{CDOM}(\lambda) + a_{phy}(\lambda) + a_{det}(\lambda) \]  

(6)
Where $a_w(\lambda)$ represent absorption due to pure seawater, $a_{CDOM}(\lambda)$ represent absorption due to CDOM, $a_{phy}(\lambda)$ represent absorption due to phytoplankton and $a_{det}(\lambda)$ represents the absorption due to detritus.

The scattering coefficient for underwater optical propagation can be represented as a summation of different factors given by [12]:

$$b(\lambda) = b_w(\lambda) + b_{phy}(\lambda) + b_{det}(\lambda)$$  (7)

Where $b_w(\lambda)$ is scattering due to pure seawater; $b_{phy}(\lambda)$ denotes the scattering due to phytoplankton and $b_{det}(\lambda)$ represents the scattering due to detritus [8], [12].

Typical values of $a(\lambda)$, $b(\lambda)$, and $c(\lambda)$ associated with different water types can be sum up in Table 1.

| Water Type             | $a(\lambda)$ ($m^{-1}$) | $b(\lambda)$ ($m^{-1}$) | $c(\lambda)$ ($m^{-1}$) |
|------------------------|--------------------------|--------------------------|--------------------------|
| Pure Seawater          | 0.053                    | 0.003                    | 0.056                    |
| Clear Ocean Water      | 0.114                    | 0.037                    | 0.151                    |
| Costal Ocean Water     | 0.179                    | 0.219                    | 0.398                    |
| Turbid harbour water   | 0.295                    | 1.875                    | 2.17                     |

3. Experimental Results and Discussion

The experimental demonstration of visible light for underwater application as shown in Figure 3. In this UWOC, Pseudo Random Bit Sequence (PRBS) used to generate random bit as transmitter data while blue LED with 460 nm wavelength to carry out the data signals. To create an underwater wireless optical environment, both transmitter (Blue LED) and receiver (Photodetector) will be located inside the water tank. The measurement will be conducted based on Line of Sight (LoS) approach from transmitter to receiver under the water tank via utilize Digital Communication Analyzer (DCA) Eye Viewer.

Figure 3. Experimental setup for 5-meter underwater wireless optical communication link with blue LED.
Figure 4 shows the BER performance in different data rate of 20 Mbps, 30 Mbps and 50 Mbps as a function of the received optical power at 5-meter water tank. Increasing water channel length, will therefore increase the signal attenuation in the underwater link due to scattering and absorption. Hence, BER and received optical power is an important parameter to evaluate the designed underwater wireless communication system by knowing the minimum required received optical power for the LED to achieve a certain data rate at a certain transmission distance. From Figure 4, it shows the higher the data rate needs to support in the system, the higher the optical power of $-3 \text{ dBm}$ is required to achieve a BER of $1.0 \times 10^{-9}$.

![Figure 4](image)

**Figure 4.** Measured BER vs. received optical power at 20 Mbps, 30 Mbps and 50 Mbps for underwater.

Figure 5 shows variation of plot between BER versus data rate for underwater link. It is shown that at BER $3.0 \times 10^{-3}$ can achieved the FEC limit. By introducing equalizers at the receiver, the transmission in underwater optical wireless link can be improved due to equalizers can reduce the inter-symbol interference (ISI). In Figure 5, large eyes open are observed for 5-meter at 20 Mbps as compared to 50 Mbps. Based on this wireless optical communication link experimental result, we can conclude that the highest data rate achieved for this underwater system exceeding 5 meters by using 460nm blue LED.
Figure 5. Measured BER vs data rate for underwater transmission at 20Mbps in 5-meter.

Figure 6 show the light output power – current – voltage (LIV) characteristics of the light emitting diode (LED) for this underwater system setup. The LIV curve was important clues for the performance of the LED, which it can decide the system either good or bad. The LED shows when threshold current of 0.0128 mA, corresponding to a voltage of 0.64 V and output optical power corresponding to 0.00819 mW.

Figure 6. Light output LIV characteristics for the LED performance in designed underwater system

Figure 7 show that the small signal frequency response of the system is measured which it takes into account of the transmitter, the LED and the receiver, the avalanche photodiode (APD). At −3 dB bandwidth, a 10MHz frequency is measured.
4. Conclusion

As conclusion, we have demonstrated a underwater wireless optical communication (UWOC) system by using 460nm blue LED diode with a data rate of 20 Mbps based on a simple NRZ-OOK modulation scheme and achieve a transmission distance over a 5-meter in underwater channel. To minimize the attenuation to achieve better transmitters for UWOC system, the blue-green wavelengths has relatively low attenuation optical window as suggested; hence LZ1-00DB00 blue LED emitting in the blue color regime are selected into this UOWC system. The measured results have observed an open eye diagrams and FEC compliant BER for a data rate of 50 Mbps were successfully achieved for a 5-meter underwater transmission distance. The experimental study of UWOC system has shown a promising platform technique for high-speed visible light communication (VLC) for underwater application.

References

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Figure 7. Measured small frequency response of underwater system. When -3 dB bandwidth, frequency response was 10MHz
Acknowledgments

The author would like to acknowledge the support from the International Collaboration Fund (ICF) under a grant number of IF0718M1024 from the Ministry of Energy, Science, Technology, Environment & Climate Change (MESTECC)