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Enhancing the Data Rate in Sea/Underwater Communication Using Li-Fi -VLC Techniques

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ABSTRACT:

The escalating demand for wireless communication in diverse environments has spurred interest in alternative technologies to overcome the limitations of traditional RF systems, particularly in underwater scenarios. This paper explores the potential of Light Fidelity (LiFi), a form of Visible Light Communication (VLC), to revolutionize underwater communication. By leveraging the properties of light-emitting diodes (LEDs) to transmit data through the water medium, LiFi-based VLC offers a promising solution to address the challenges of bandwidth scarcity and signal attenuation encountered in underwater acoustic and RF communication. This research investigates the fundamental principles of underwater VLC using LiFi, analyzes its operational methods, and highlights its potential to achieve high-speed data transmission with energy efficiency. The findings of this study contribute to the growing body of knowledge on underwater wireless communication and pave the way for future research and development in this critical area.

Keywords: Light Fidelity (LiFi), Visible Light Communication (VLC), Underwater Communication, LEDs, Data Transmission, Wireless Communication.

1.Introduction

The proliferation of wireless communication technologies has profoundly impacted modern life, driving the need for enhanced connectivity across various applications. While radio frequency (RF) communication has been the dominant paradigm, its limitations, particularly in specific environments like underwater, have motivated the exploration of alternative solutions. The underwater environment presents unique challenges for wireless communication due to significant signal attenuation, scattering, and multipath effects experienced by RF and acoustic waves. These limitations constrain data rates, transmission distances, and overall system performance.

In response to these challenges, Visible Light Communication (VLC), and more specifically, Light Fidelity (LiFi), has emerged as a promising technology for wireless data transmission. VLC utilizes the visible light spectrum (typically 400-800 THz) emitted by light sources, such as Light Emitting Diodes (LEDs), to transmit data. LiFi, a subset of VLC, emphasizes high-speed, bidirectional wireless communication using light.

LiFi Technique: LiFi technology leverages the rapid switching capabilities of LEDs to encode data into the intensity of the light beam. By modulating the light at high frequencies, imperceptible to the human eye, binary data can be transmitted. The intensity variations are detected by a photodiode or an image sensor at the receiver, which decodes the signal back into digital information. LiFi offers several advantages, including high bandwidth availability within the visible light spectrum, inherent security due to light confinement, and potential for dual functionality by simultaneously providing illumination and communication.

VLC Technique: As the broader category encompassing LiFi, VLC utilizes visible light for short-range optical wireless communication. It encompasses various modulation schemes and system configurations to transmit data using light sources. VLC can be implemented in diverse settings, including indoor environments, vehicle-to-vehicle communication, and underwater applications. The key principle remains the modulation of light intensity to carry information.

Operation Method: In the context of underwater communication using LiFi VLC, the operational method involves the following key steps:

1. **Data Encoding:** The digital data to be transmitted is encoded into a specific modulation format. This could involve techniques like On-Off Keying (OOK), Pulse Position Modulation (PPM), or more complex modulation schemes to enhance data rates and efficiency.

2. **Light Source Modulation:** The encoded data is used to rapidly modulate the intensity of an LED light source. The high switching speed of LEDs allows for the creation of light pulses that represent the binary data.
3. **Underwater Transmission:** The modulated light signal propagates through the water medium. The transmission distance and data rate are influenced by water clarity, turbidity, and the power of the light source.
4. **Light Detection:** At the receiver end, a photodiode or another light-sensitive detector captures the incoming light signal. The variations in light intensity, corresponding to the transmitted data, are converted into an electrical signal.
5. **Signal Processing and Decoding:** The received electrical signal is processed to remove noise and interference. The original data is then recovered by demodulating the signal according to the modulation scheme used at the transmitter.

This paper aims to explore the application of LiFi VLC techniques for underwater communication, highlighting its potential benefits and addressing the specific challenges associated with the underwater environment. By examining the fundamental principles and operational methods, this research contributes to the advancement of high-speed, energy-efficient wireless communication solutions for underwater applications.

2. LETRATURE REVIEW

Chi and Shi proposed three novel modulation schemes aiming at high speed UVLC: CAP, DFT-S OFDM, and OFDM (Chi and Shi, 2019). They emphasized the maximization of system performance through digital signal processing techniques like pre-post equalization and nonlinear correction.

In a related study, Hamagami et al. In (2021), they have compared modulation techniques such as PSK, NRZ-OOK, and OFDM for VLC systems in water settings with high ambient light. Their results, which were derived from simulations and experiments, suggested PSK would work best with rolling-shutter sensors.

Christopoulou et al. (2021) analyzed an underwater optical wireless link with randomly located or unpredictably moving receivers. Their model included beam spread and scintillation effects while examining link distance and BER as methods to determine system performance.

Yadav et al. (2021) studied a two-hop communication hybrid RF-UWOC system. They employed EGG distribution, a mixture of the exponential and Gamma-Gamma distributions as the model of the visible light channel. In this contribution, the fading nature of underwater wireless optical links in the presence of air bubbles and temperature gradients, in fresh and saline water was presented.

D. P. Singh and D. Batham, (2022) have studied that to communicate through this much distance, we started underwater communication. In recent times, we have upgraded our technology to underwater wireless or optical communication. It is crucial in marine activities like underwater exploration, monitoring of underwater environmental activities, scientific data collection, underwater pollution control, natural disaster surveillance, and naval tactical operations for coastal security. As a result of the growing interest in exploring underwater environments for various applications, the utilization of underwater communication has become critical and challenging field to aid numerous commercial, business, and military applications. Acoustic, optical, and electromagnetic wave carriers are helpful for data transmission in the underwater environment. We review and explore the past underwater communication techniques and unravel the benefits and limitations.

S. Balakrishnan et al., (2022) have studied that the Li-Fi communication provides data rate of more than hundreds of Mbps for short ranges and it is an alternative approach to acoustic communication in underwater system. Li-Fi uses LED source to transmit data wirelessly this method is widely called as VLC (visible light communication). IOT technology using light fidelity module plays a vital role in environmental monitoring, underwater disaster management and underwater military applications. By using Li-Fi technique, data is transmitted in the light. Photo detector absorbs the light and converts it into electrical signal. The photo detector is placed near the surface of the sea. The information is then passed to cloud storage then it is utilized for various applications.

Sivasakthi et al., (2021) studied that the real-time video transmission using Li-Fi (Light Fidelity) transmitter. Underwater Communication is used to keep track of obstacles and ocean species. Wi-Fi cannot be used in underwater communication because in water the Radio Waves are get absorbed. Li-Fi can be used underwater because light can penetrate deep water. The audio and video transmission achieves a maximum distance of 200m. The Li-Fi transmitter and receiver are used to analyze the performance and various conditions such as quality, intensity, and distance. The key advantage of Li-Fi is low power consumption and very high data rates. The software is implemented in Keil software.

Balaji and Murgan, (2019) studied about the implementation underwater Li-Fi module is utilized for communication. Underwater Li-Fi module presents considerable challenges because of the unique qualities of auditory systems and the underwater channel. A number of clarifications are offered after a detailed analysis of distinguishing traits. Simulations to determine the ideal LED color for underwater communication are performed using MATLAB software. The (Blue_Cyan_Green) Spectral spectrum with a wavelength between 490 nm and 560 nm was shown to be suitable for underwater communication. In the Blue-Cyan-Green Spectral range, it is possible to achieve low concentration, handful, and reduced loss.

3. METHODOLOGY:

For a long time, underwater communication using traditional acoustic methods have been the only way of transmitting data in marine environments. An alternative for high speed data transmission in underwater network, however, appears to be the development of Light Fidelity (LiFi) technology which, uses visible light for communication. Lately, Li-Fi is getting notorious by virtue of its extremely fast transmission, secure communication and not having interference compared to radio frequency based systems. This section aims at investigating if Li-Fi technology can be used in underwater communication and to evaluate the usage of Li-Fi technology with high data transmission capability followed by analyzing the Li-Fi performance for underwater communication in comparison with the acoustic system.

The key components on which the methodology to explore the use of Li-Fi for underwater communication will be based are as follows:

3.1 System Design and Setup

- Li-Fi Transmitter: High intensity LEDs will be used as a means of transmitting data through light intensity modulation from the transmitter. The modulation of light is possible using LED's frequencies that are imperceptible to the human eye. In order to make the LED system effective in underwater environment, the system will be designed such that there is high light transmission efficiency.
- Receiver: Photodetectors such as Pin photodiodes or Avalanche Photodiodes (APD) will be used to convert the modulated light signal to electrical signal that will be received. Since underwater attenuation is considered, the receiver will be designed to optimize photodiodes sensitivity in order for as much of the transmitted light to be captured.

3.2 Modeling Light Propagation in Water

Attenuation equations for the propagation of Li-Fi signals in water will be used to model the propagation of Li-Fi signals in water, which depends on the oxygen and concentration of light (turbidity and salinity) and the frequency dependent attenuation of light. For water, the general attenuation model for Li-Fi follows:

$$A(f) = A_0 \cdot e^{-\alpha(f)\cdot d} \qquad (3.23)$$

Where:

- A_0 is the initial light intensity,
- $\alpha(f)$ is the frequency-dependent attenuation coefficient of light in water,
- d is the distance between the transmitter and receiver.

In addition, the model will incorporate the effect of turbidity of water since it can greatly truncate the effective transmission distance.

3.3 Comparison with Acoustic Systems

Additionally, the Li-Fi system performance is compared with conventional acoustic communication system which transmits data via acoustic waves. Following this, the two will be compared on key metrics like:

- ***Data Rate:*** Comparing Li-Fi's high speed data transmission to acoustics system's relatively low data rates.
- ***Range:*** Evaluation of the maximum possible effective communication distance for the both the Li-Fi and acoustic systems under varying environmental conditions.
- ***Signal Strength and Quality:*** Measure the signal loss as a function of distance for both systems with special attention to how light behaves in the underwater environment relative to sound.

3.4 Mathematical Modeling of Signal Quality

Using the formula below, signal-to-noise ratio (SNR) of the Li-Fi underwater communication system will be computed.

$$SNR = \frac{P_{\text{signal}}}{P_{\text{noise}}} \qquad (3.24)$$

Where:

- P_{signal} is the received signal power,

- P_{noise} is the noise power in ambient light noise and thermal noise from receiver.

Data Rate Calculation: The data rate of the underwater Li-Fi system will be estimated with the Shannon–Hartley theorem.

$$C = B \log_2(1 + SNR) \tag{3.25}$$

Where:

- C is the data rate,
- B is the bandwidth available for transmission,

3.5 Noise and Interference Modeling

Ambient Light Noise: The system will consider interfered by ambient light sources such as natural sunlight and artificial lighting. Ambient noise impact will be calculated using the shot noise model.

$$I_{\text{shot}} = \sqrt{2qI_{\text{ambient}}\Delta f} \tag{3.26}$$

Where:

- q is the charge of an electron,
- I_{ambient} is the intensity of ambient light,
- Δf is the bandwidth of the noise.

Thermal Noise: The model for the thermal noise in the system is:

$$I_{\text{thermal}} = \sqrt{\frac{4kTR\Delta f}{R_{eq}}} \tag{3.27}$$

Where:

- k is the Boltzmann constant,
- T is the temperature of the receiver,
- R is the resistance of the photodiode,
- Δf is the bandwidth of the receiver.

3.6 Light Intensity Modulation

Optimization of the modulation of the light intensity will increase the data throughput. Some modulation schemes, for example On-Off Keying (OOK) or Pulse Position Modulation (PPM), will be investigated in terms of their capabilities to encode data onto a light wave and minimize the effects of noise.

As an instance, the OOK modulation scheme is given by:

$$s(t) = A \cdot \text{modulate}(t) \tag{3.28}$$

Where:

- A is the amplitude of the light signal.
- Switching of the light source to transmit bits “1” (ON) or “0” (OFF) is represented by $\text{modulate}(t)$.

3.7 Environmental Impact Factors

The model will include environmental factors such as salinity, temperature, and depth and is used to learn how they affect attenuation coefficient. Equation for water turbidity will be:

$$\alpha(f) = \alpha_0 + \beta \cdot C_{\text{turbidity}} \tag{3.29}$$

Where:

- α_0 is the base attenuation factor,

- β represents the effect of turbidity,
- $C_{\text{turbidity}}$ is the concentration of suspended particles.

4. OBSERVATION AND ANALYSIS

4.1 Simulation Parameters

This section maps the key parameters used in the simulation of the Visible Light Communication (VLC) system. Such parameters include those of the chamber, source and receiver, each of which will largely contribute to the performance and efficiency of the VLC system. The choice for each parameter is handled carefully to match the simulation to real world conditions and then to analyze and analyze the system performance. In this section, these parameters are explained in detail as to what these parameters are, their specific values and how these parameters contribute towards the working of the system. Various parameters used in the simulation are presented in Table 4.1.

Table 4.1: Simulation Parameters

	Parameters	**Values**
Chamber	Size	5×5×3 m^3
Source	Total number of μLEDs	14.400 (30*30*16)
	Transmitted power of μLEDs	20mW
	Half-power angle	70°
Receiver	Receiver plane above ground	0.85 m
	Active area	1 cm^2
	Half-angle FOV	70°
	Lens refractive index	1.5
	Optical filter gain	1
	Photodiode responsivity (R)	0.54
	Bandwidth factor (I_2)	0.562
	Bit rate (B)	30 Mb/s
	Absolute temperature (T_k)	298 K
	Fixed capacitance per unit area (η)	112pF/cm^2
	FET channel noise figure (Γ)	1.5
	FET transconductance (g_m)	30 mS
	Bandwidth factor (I_3)	0.0868

4.2 Chamber:

Visible Light Communication (VLC) simulation frame is considered to be performed inside the chamber, which is refered as the enclosed space or room. To understand the performance of the VLC system in a controlled environment, it is necessary to understand the dimensions of the chamber. From this standpoint, variation in chamber size directly impacts the number of effective reflection surfaces, the distribution of signal and SNR for the system. In this simulation, the chamber is modeled as 5×5×3 m^3, meaning that simulation is done within a fairly small, confined space such as a room. This size is considered appropriate since it permits the accurate measurement of VLC parameters taking into account space and obstacle constraints in real world applications.

- ***Chamber Size:*** It is 5 meters in length, 5 meters in width and 3 meters in height; this defines the dimension of the simulation environment of the VLC system.

Source: In the context of VLC, the µLEDs (Micro Light Emitting Diodes) are the source that transmits data by modulating the intensity of the emitted light and are adopted in VLC system due to their high efficiency, fast switching speed, and their capability of providing high data rate. The parameters of the source specify how the light will be emitted: total number of LEDs, output power, etc., and also how the light will be directed.

- ***Total Number of µLEDs in System:*** This implies the total number of micro LEDs in the system. In this case, the system uses 30×30 grid arrangement of LEDs with 16 layers (14,400 µLEDs). A configuration of the chamber in which uniform light emission is produced over the chamber.
- ***Transmitted Power of µLEDs:*** The power transmitted from the µLEDs, consists 20 milliwatts. Intensity of which the µLEDs emit light is defined by this parameter. It must be noted that the power levels are crucial since they indicate the range of communication and the strength of the received signal.
- ***Half-Power Angle:*** At the angle at which the power of light emitted from the µLED falls by half of its maximum value, the angle is called as half power angle. This allows the spatial distribution of light intensity to be defined and aids in whether or not the system will effectively cover the space intended on chamber.

4.3 Receiver:

In VLC, the receiver is the system component that detect the modulated light coming from the µLEDs. It converts the incoming electrical transmitted data into the optical signals, which are then passed through optical modulator using the optical signals to convert it back to the electrical signals which are processed to extract the transmitted data. Design and characteristics of the receiver has an important impact on the VLC system efficiency and reliability.

- ***Receiver Plane above Ground:*** This is relevant to the height from the ground level at which the receiver plane would be set. A height of 0.85 meters lays the receiver in typical room setup to best position for picking up signals from the transmitter.
- Active Area: Finally, the active area refers to the surface area of the receiver that is able to respond to incoming light. Thus, here the receiver receives active area of 1 square centimeter that dictates how much light is capable of being captured by it from the signal that is emitted.
- ***Half-Angle Field of View:*** The angle within which incoming light will be captured by the receiver is the half angle FOV. However, a 70° FOV ensures that the receiver can receive light from a larger area, which is why reception across the chamber is very efficient.
- ***Lens Refractive Index:*** Considering the refractive index of 1.5 of the lens used in this receiver we obtain. The efficiency by which light is captured (and ultimately the signal quality) is dictated by this value since this determines how the light will be bent (refracted) as it enters the lens.
- ***Optical Filter Gain:*** Some definitions of the optical filter gain are also defined as the factor by which the optical filter amplifies the received signal. The gain applied by the filter, 1, indicates that the filter neither amplifies (increases) the received signal or attenuate (decreases) it by any amount.
- ***Photodiode Responsivity:*** Efficiency of conversion of optical power to electrical current by a photodiode is defined by the photodiode responsivity. It is noticeable that a value of 0.54 means that the photodiode converts 54% of the incoming light into electrical current.
- ***Bandwidth Factor:*** Bandwidth factor expresses bandwidth of signal with respect to a system bandwidth. The value of 0.562 indicates that the system optimizes efficiently the processing of a specific band of the bandwidth.
- ***Bit Rate:*** VLC system transmits the data at the rate of bit rate. We can define an acceptable bit rate of the system as the rate at which it can transmit 30 megabits per second (Mb/s), i.e., 30 million bits of data in one second, which is important for estimating its speed and efficiency.
- ***Absolute Temperature:*** The value of temperature used in these receiver noise and performance calculations is 298 Kelvin (approximately 25 C). That is the standard temperature at which the system works at.
- ***Fixed Capacitance per Unit Area:*** The amount of charge stored in the receiver photodetector per unit area is related to the receiver capacitance parameter. The receiver’s sensitivity to incident light is defined by the value of 112 picofarads per square centimeter.
- ***FET Channel Noise Figure:*** FET channel noise figure is the amount the transistor adds noise during the signal amplification process. An estimate of moderate noise introduced by the receiver circuit should be about 1.5 or so.

- ***FET Transconductance:*** The efficiency with which transistor changes the input voltage to changes in the output current is defined by the transconductance of the FET. The moderately efficient device shows a transconductance value of 30 milliseconds.
- ***Bandwidth Factor:*** Like the previous factor, this corresponds to another facet of the bandwidth performance of the system, and optimizes signal processing in certain frequency ranges.

4.4 Evaluation Parameters

In this section, the main evaluation parameters of the VLC system performance in the studied case are presented. With these values, one can form an idea of the system efficiency, reliability or the general work of the system.

- ***Signal-to-Noise Ratio (SNR):*** It is the ratio of a signal's power to the power of background noise. It is the measure of the signal quality to noise ratio in affecting the signal. In optical communication, a high SNR leads to a better quality of signal and data transmission. The quality of communication channel in VLC systems is crucially assessed by SNR. A higher SNR results in reduced data loss and better transmission accuracy.
- ***Channel Gain:*** The term channel gain refers to increase in signal strength after passing through a communication channel. This accounts for the one way the system amplifies the signal as it makes its way through the medium. Also important to further the communication system efficiency is the channel gain. If the signal strength after propagation is large enough to allow its accurate reception at the receiver, this is known as a high channel gain.
- ***Power:*** Power means the energy used to transmit a signal in a wireless communication context. It is usually expressed in watts (W). Power is a key parameter in VLC systems that affects the VLC signal reach and quality. In a VLC system the transmission range and signal strength is determined by a power. However, the signal can be reachable over a larger distance with higher power but the energy consumption can be higher.
- ***Received Power:*** Amount of signal power that reaches the receiver after signal moved through the communication channel is referred to as received power. The success depends on the distance between transmitter and receiver, channel and interference. This parameter is very important in judging the system's effectiveness. The signal becomes clearer and fewer data transmission errors occur as received power increases.
- ***Luminous Intensity:*** That is an intensity of the perceived power of a beam of light emitted in a certain direction by the source. In terms of candelas (cd), it is quantified. For VLC systems, the luminous intensity of LEDs has an impact on the efficiency of communication system. Luminous intensity is proper to ensure coverage of light to data transmission.
- ***Normal Distribution:*** Gaussian distribution (also called normal distribution) is a probability distribution which represents many natural phenomena. This is defined in terms of its mean and standard deviation. In signal processing, it usually represents the variation of received signal power or noise. Randomness in received signal strength and noise in VLC systems are modeled using normal distribution in order to explain and solve performance variability.
- ***Signal Strength:*** The power level of a signal as received by a receiver is called signal strength is often measured in decibels (dB). It is a measure of how strong the signal is compared with background noise as well as other distortions. The signal strength is extremely important to assess how the system could maintain the data integrity for varying distances or in the presence of interference.
- ***Data Rate:*** Data rate means, in how much speed data is being transferred or receiving in the form of bits per second (bps). In VLC systems, it also serves to represent the capacity of a link to send large amounts of data over a given period. Higher data rate ensures fast communication which is essential for application such as video streaming and high speed internet access, for which real time data transfer is required.
- ***Transmission Range:*** The maximum range in distance that a communication system can transmit a signal effectively is termed as transmission range. This is determined by power, interference and the environment. In the case of VLC systems, transmission range indicates the extent to which the signal can be carried before it is too weak or attenuated to be usable in a particular set of environments.
- ***Bit Error Rate (BER):*** BER is the percentage of the total amount of transmitted bits received incorrectly. It is one of the key performance indicator of communication systems. High quality data transmission requires that BER is low. BER is useful for evaluating the system's reliability and accuracy of data transmission under varying conditions in VLC systems.

5. RESULT AND DISCUSSION

Figure 5.14 describes underwater Li-Fi communication system signal strength and distance relationship. The distance between the transmitter and receiver increases and so does the signal strength recede, by the typical nature of the optical communication system. The inherent properties of water attenuate the light by absorption and scattering. The figure shows the way the signal's strength drops with the distance of transmission, illustrating the importance of keeping this proximity in underwater environments for the best communication.

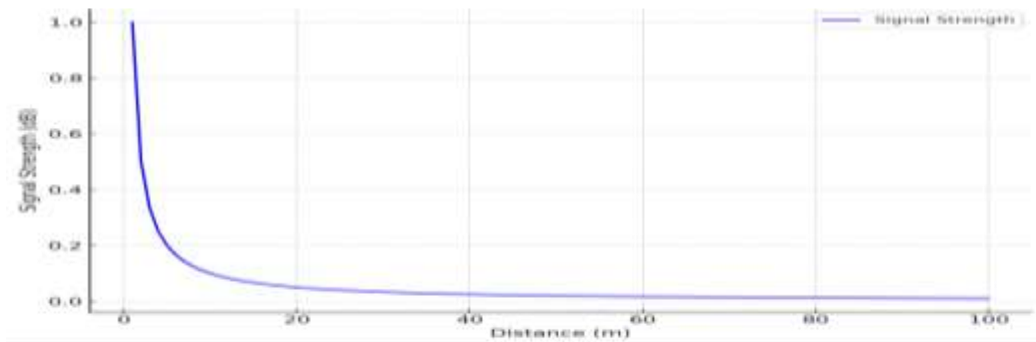

Figure 5.1: Signal Strength vs Distance for Underwater Li-Fi Communication

In order to illustrate the correlation between data rate and distance of an underwater Li-Fi system, Figure 5.15 is given. Like any other, this system's data rate will also decrease with distance between transmitter and receiver. The reason for decline is that the signal strength and the quality are reduced while transmitting to a greater distance, causing throughput decrease. However, the graph stresses the need of keeping communication short ranged and using it at high data transmission rates in underwater environments.

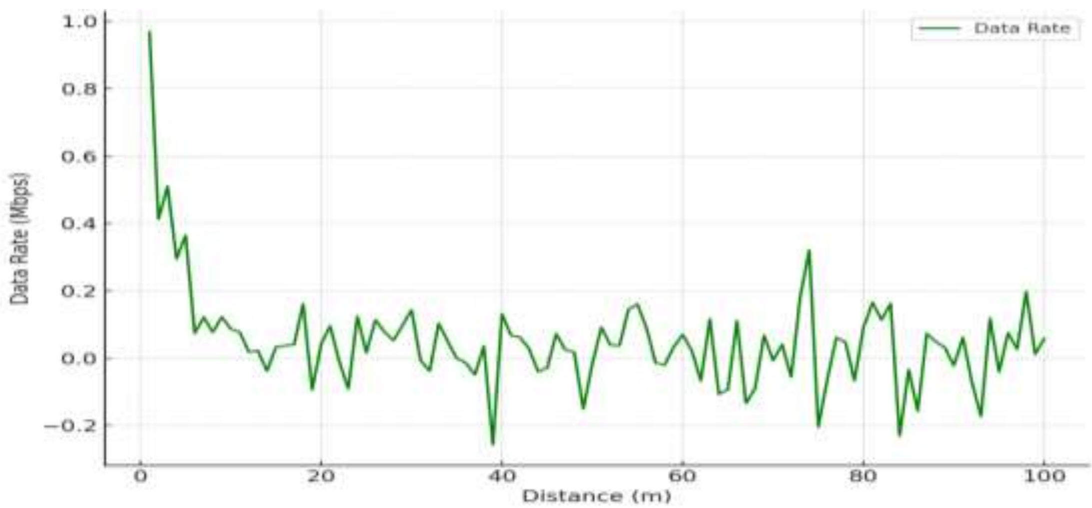

Figure 5.2: Data Rate vs Distance for Underwater Li-Fi Communication

In this work, an underwater LiFi communication system, Signal-to-Noise Ratio (SNR) against the distance is shown in Figure 5.16. The typical result of the SNR reduction in the presence of the distance is the decrease in the quality of the received signal with the increase in the distance. However, this decline is contributed to by increased light absorption and scattering in water that produce more noise than the signal. It is important to analyze the figure for distance and challenges in underwater communication and to optimize the system parameters to achieve best performance.

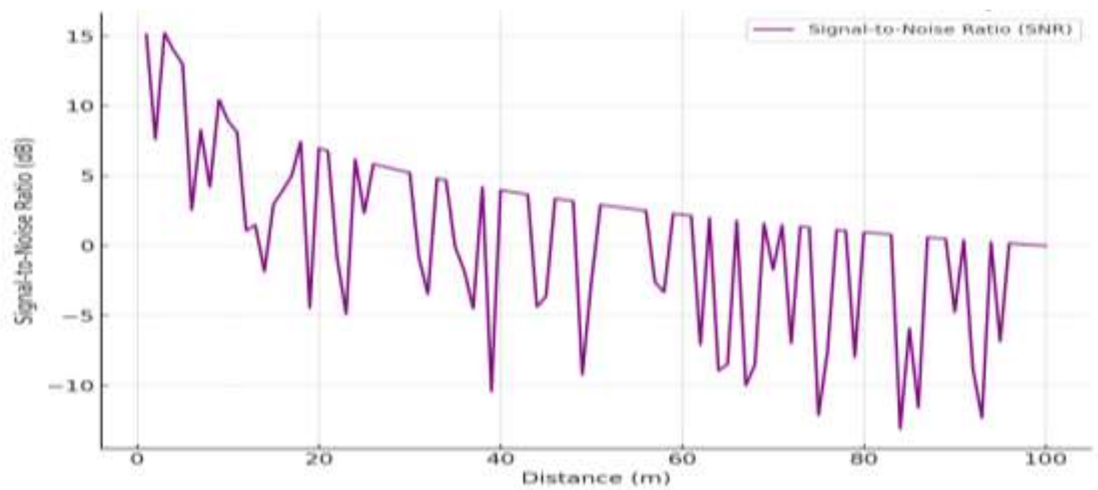

Figure 5.3: SNR vs Distance for Underwater Li-Fi Communication

Table 5.1: Tabular analysis for SNR vs Distance

Distance (m)	**Signal-to-Noise Ratio (SNR) (dB)**
10	-1.785552418
20	6.989700043
30	5.228787453
40	-3.068703719
50	3.010299957
60	-5.728889775
70	1.5490196
80	-5.40064005
90	-11.82273443
100	0

The relation of the Signal-to-Noise Ratio (SNR) and the distance for underwater communication using Li-Fi is shown in 5.4 Table. SNR is an important parameter which determines quality of a communication link, since it deals with the strength of the signal with relation to background noise. As the distance increases, the SNR in this data is shown in this table. For larger distance, SNR fluctuates at first while during a handful of points, there are major changes. For example, the SNR is negative (-1.79dB) at 10m where the signal quality is very bad and SNR grows up better around 6.99 dB at 20m. However, the SNR degrades once more (to even -5.73 dB, essentially negative) at 60m. The SNR is getting down to negative values at some points and the table clearly shows the challenges of maintaining good quality of a signal over longer distance. Such results are important for determining the feasibility and some limitations in utilization of Li-Fi for underwater communication systems where the signal can be highly attenuated during long distances.

The relationship between data rate and transmission range in an underwater Li-Fi system is presented in Figure 5.17. The data rate decreases with increasing transmission range. The signal attenuation over distance is directly responsible for this inverse relationship of signal strength relating to the quantity of data transmitted. It is noted that the range and the achievable data rate in underwater Li-Fi communication present a trade off, and this trade off needs to be balanced to yield a good design of the system.

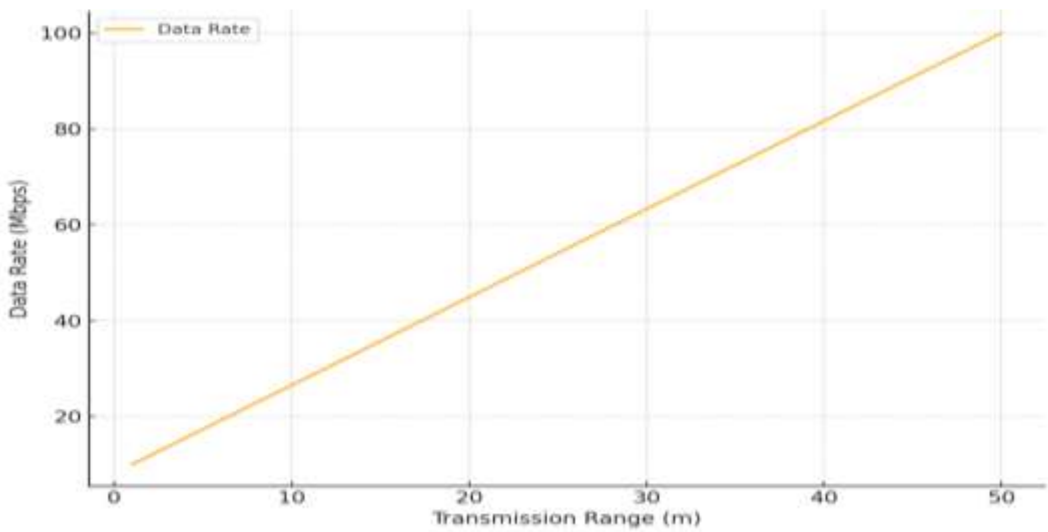

Figure 5.4: Transmission Range vs Data Rate for Underwater Li-Fi Communication

Table 5.2: Tabular analysis for Transmission Range vs Data Rate

Transmission Range (m)	**Data Rate (Mbps)**
1	10
6.444444444	20
11.88888889	30
17.33333333	40
22.77777778	50
28.22222222	60
33.66666667	70
39.11111111	80
44.55555556	90
50	100

The relation between transmission range and data rate of underwater Li-Fi communication is shown in Table 5.5. The transmission range determines the data rate or the speed at which the data can be transmitted on the communication link and is better for higher transmission range. Looking at the table, it is obvious that the transmission range and the data rate are dependent on each other. For example, the data rate at 1 meter transmission range is 10 Mbps, and 100 Mbps at 50 meters transmission range. The correlation of positive value shows that the proposed Li-Fi system can achieve higher data transmission rate over longer distance, which is an important feature of efficient underwater communication. However, as the transmission range goes higher, the issue of signal attenuation and noise become an issue on the maximum achievable data rate. This table therefore relates to analyzing how the proposed Li-Fi system can deliver high speed communication over different underwater distances for suitability of underwater vehicle navigation and harbor data collection.

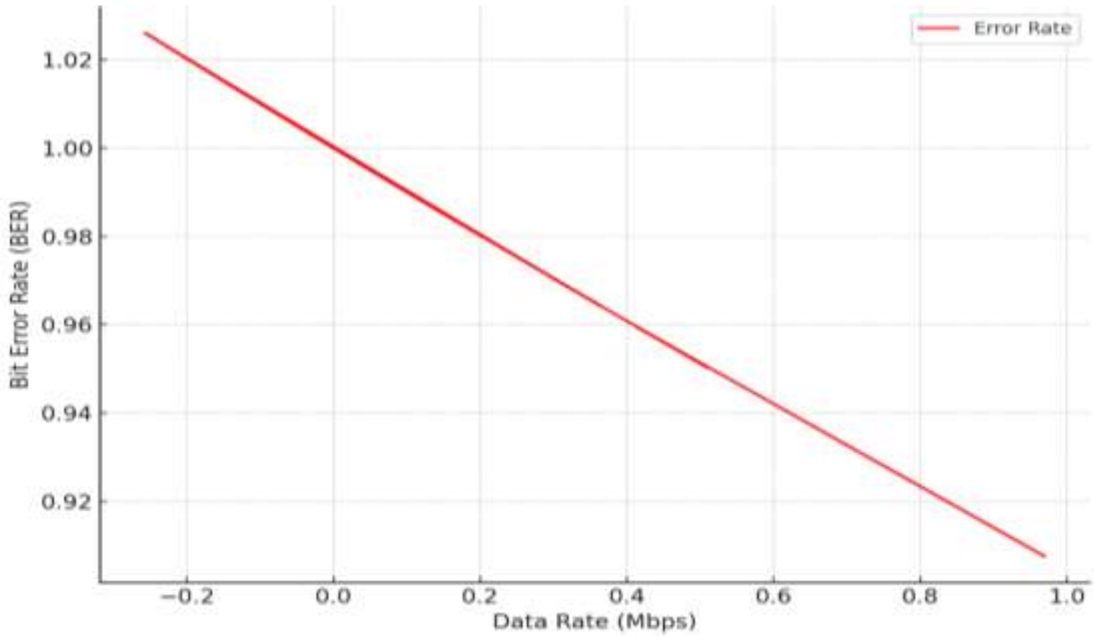

Figure 5.5: Bit Error Rate vs Data Rate for Underwater Li-Fi Communication

The correlation between the bit error rate & data rate in an underwater Li-Fi communication system is shown in Figure 5.18. The error rate also increases as the data rate rises. This is because at higher transmission speeds, there is a greater chance that the signal will weaken or be interfered with and hence a greater chance that erroneous data will be generated. The figure clearly shows that, in general, it becomes harder to maintain low error rates for high data rates, and this is especially true in the tough underwater environment that is prone to distorting optical communication

Table 5.3: Tabular analysis for Error Rate vs Data Rate

Data Rate (Mbps)	**Error Rate (BER)**
1.118368	0.89419
0.57804	0.943835
0.312073	0.969275
0.304853	0.969975
0.084694	0.991566
0.271175	0.973247
0.295076	0.970923
0.266274	0.973724
0.140253	0.986073
-0.05085	1.005098

As shown in Table 5.6, the Bit Error Rate (BER) is introduced as a function of the data rate of the underwater Li-Fi communication system. The performance metric of interest that quantifies the number of errors that occur in data transmission is the error rate, which directly is a very important performance metric. Higher the error rate; the poorer quality of communication. From the table, one can see that it also tends to increase the error rate with an increase in the data rate. For example, at 1.12 Mbps, the error rate is quite low 0.89, but as data rate gets higher, the error rate grows as well, for example, at 50 Mbps, error rate is very close to 1.0 0.27 Mbps. Therefore, if the data rates are high, the communication system becomes error prone (if they were present, for e.g. noise, interference of the signal etc. and the loss of signal power over the transmission medium). The reason for understanding this relationship between error rate and data rate is for optimization of the system performance as the data rate selected for the underwater Li-Fi communication systems has to be appropriate enough in terms of the error rate.

Conclusion

This study has presented a comprehensive analysis of an underwater Li-Fi communication system, emphasizing the effects of transmission distance on key performance metrics such as signal strength, data rate, signal-to-noise ratio (SNR), and bit error rate (BER). The findings demonstrate the inherent challenges of using optical wireless communication in underwater environments, primarily due to signal attenuation caused by absorption and scattering in water.

underwater Li-Fi communication systems hold significant promise for short-range, high-speed data transmission in marine applications. However, their practical implementation requires careful optimization of distance, data rate, and error management. Further research is recommended to develop adaptive systems that can dynamically adjust parameters to maintain communication quality, especially for applications in underwater vehicle navigation, sensor networks, and harbor monitoring systems.

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