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Full Length Article

Underwater Data Communication Using Li-Fi Technology

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Abstract

The demand for reliable underwater communication systems has increased rapidly due to advancements in marine research, underwater robotics, environmental monitoring, and defense applications. Conventional underwater communication techniques, such as radio frequency (RF) and acoustic communication, suffer from significant limitations including high attenuation, limited bandwidth, signal distortion, and high latency. These limitations reduce the efficiency of real-time underwater data transmission and restrict the performance of underwater monitoring and exploration systems.Experimental observations indicate that Li-Fi based communication performs effectively for short-range underwater communication. The system demonstrates low latency, reduced power consumption, improved data transmission speed, and enhanced security compared to traditional methods. The results confirm that Li-Fi technology is a promising solution for future underwater communication applications including oceanographic data acquisition, underwater robotics, and remote monitoring systems.

***Keywords**: Li-Fi, Underwater Communication, Visible Light Communication, Optical Communication, Photodiode, LED Communication, Marine Monitoring*

Introduction

Underwater communication has become increasingly important in various applications such as oceanographic research, marine exploration, underwater surveillance, environmental monitoring, and naval operations. Reliable underwater communication enables data collection, vehicle control, and real-time monitoring of underwater environments. However, traditional communication techniques face significant challenges when used underwater.Radio frequency (RF) communication is widely used in terrestrial applications but performs poorly underwater because electromagnetic waves are strongly absorbed by water, especially saltwater. Acoustic communication, which is commonly used for underwater communication, provides longer communication ranges but suffers from low data rates, high latency, and interference from ambient noise and multipath propagation.This project focuses on designing and implementing an underwater Li-Fi communication system capable of transmitting digital data through water using LED-based optical communication. The proposed system includes a transmitter module, receiver module, and microcontroller-based processing unit. The system is tested in a controlled water environment to evaluate communication performance and feasibility.The developed prototype provides a low-cost and energy-efficient solution for underwater communication and establishes a foundation for further research in underwater optical communication systems.

The primary aim of this project is to design and develop an underwater data communication system using Li-Fi technology. The main objectives of the project include:

Literature Survey

Underwater communication has been an active research area due to the growing demand for ocean monitoring, underwater robotics, and marine data collection. Conventional communication technologies such as acoustic and radio frequency (RF) communication have been widely used; however, each method has significant limitations in underwater environments. Recently, optical wireless communication, particularly Light Fidelity (Li-Fi), has emerged as a promising alternative for short-range underwater communication.

RF Communication

Radio Frequency communication is widely used in terrestrial wireless systems. However, RF signals experience severe attenuation in water, particularly in saltwater environments. Akyildiz et al. (2005) reported that RF communication underwater suffers

Optical Wireless Communication (OWC)

Optical Wireless Communication uses visible, ultraviolet, or infrared light for transmitting data. According to Kaushal and Kaddoum (2016), optical communication provides several advantages for underwater environments:

Li-Fi Technology

Li-Fi technology, introduced by Professor Harald Haas in 2011, is a form of visible light communication that uses LEDs to transmit data. Initially developed for indoor wireless communication, Li-Fi has recently been explored for underwater applications.

Several studies have demonstrated the feasibility of underwater Li-Fi communication:

- Sharma et al. (2018) demonstrated short-range underwater communication using blue LEDs.
- Rani et al. (2020) developed a Li-Fi-based system for underwater sensor data transmission within short distances.
- Patil and Ingole (2019) proposed a Li-Fi-based communication model for underwater robotic systems.

These studies indicate that Li-Fi technology can provide high-speed communication for short-range underwater applications.

Motivation

Visible light, especially blue and green wavelengths, can propagate effectively through water. This creates an opportunity to develop short-range, high-speed underwater communication systems using Li-Fi technology.

Hardware and Software Requirements

This chapter describes the hardware and software components used to implement the underwater data transmission system based on Light Fidelity (LiFi) technology. The proposed system enables wireless communication underwater by transmitting information through modulated light signals.

In the proposed architecture, data from the source device is first processed and modulated using a microcontroller. Finally, the recovered data is displayed or delivered to the destination device.This approach offers advantages such as low electromagnetic interference, high bandwidth, and improved reliability for underwater communication compared to conventional radio-frequency-based methods.

Hardware Components

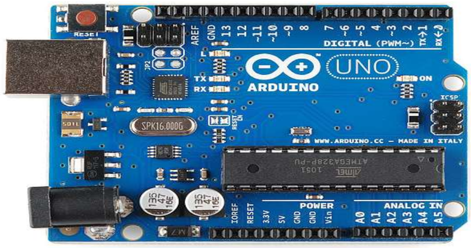

Figure 1 Arduino UNO

The Arduino Uno is an open-source microcontroller board built around the ATmega328P microcontroller operating at a clock frequency of 16 MHz. It is widely used for prototyping embedded systems due to its simplicity, flexibility, and extensive community support.The board provides 14 digital input/output pins, of which 6 pins support Pulse Width Modulation (PWM). Additionally, it includes 6 analog input pins for reading sensor values. The Arduino Uno features a USB interface for programming and serial communication, a DC barrel jack for external power supply (7–12 V), an ICSP header, and a reset button.

APR33A3 Voice Module

The APR33A3 is an 8-channel voice recording and playback module designed for audio storage and reproduction applications. The module operates within a voltage range of 3 V to 6.5 V and supports up to 340 seconds of total recording time.The APR33A3 module includes built-in flash memory, allowing non-volatile storage of recorded audio signals. It supports both push-button and microcontroller-based triggering using TTL-compatible inputs. This module is used in the proposed system to record and playback audio messages transmitted through the LiFi communication channel.

The module simplifies audio integration since it does not require additional audio processing ICs, making it suitable for low-power embedded applications.

Figure 2 LCD with I²C Interface

A 16×2 character LCD module with an I²C interface is used to display system information and received messages. The LCD is based on the HD44780 controller and includes an I²C backpack module using the PCF8574 chip.The I²C interface reduces wiring complexity by requiring only two communication lines: Serial Data (SDA) and Serial Clock (SCL). This simplifies hardware connections and reduces the number of Arduino pins required.The module operates within a voltage range of 2.5 V to 6 V and is suitable for displaying system status, transmitted messages, and debugging information.

Figure 3 Speaker

A small speaker rated between 0.5 W and 1 W is used for audio playback. The speaker is connected directly to the output of the APR33A3 voice module, which includes a built-in amplifier.

The speaker enables audible output of transmitted voice messages, making the system suitable for underwater communication scenarios involving audio instructions or alerts.

LED

Light Emitting Diodes (LEDs) are used as visual indicators within the system. LEDs are connected to Arduino digital pins and provide status information such as power indication, transmission activity, recording mode, and error alerts.Additionally, LEDs may also be used as optical transmitters in LiFi communication by modulating light intensity according to the transmitted data.

Solar Panel

Figure 4 Solar Panel

A solar panel is used as a renewable energy source for powering the underwater communication system. The system is designed to operate with low-power components such as Arduino microcontrollers and LCD modules, making solar energy a viable option.Typically, a solar panel rated between 5 V and 12 V is used along with a voltage regulator or battery storage system. This allows autonomous operation in remote underwater monitoring environments.

Regulated Power Supply (RPS) Module

Figure 5 RPS Module

The Regulated Power Supply (RPS) module is used for power management and voltage regulation. The module automatically switches between multiple power sources such as solar power and USB input.

A typical RPS module supports input voltage between 7 V and 24 V and provides regulated outputs such as 5 V and 3.3 V required for microcontrollers and peripheral devices. The RPS ensures stable and uninterrupted system operation.

Arduino IDE

The Arduino Integrated Development Environment (IDE) is used for programming and uploading code to Arduino microcontroller boards such as Arduino Uno and Arduino Nano. The Arduino IDE is a free and open-source software platform designed for embedded system development.

Programs written in the Arduino IDE are known as sketches and are developed using a simplified version of C/C++ programming language. The IDE provides built-in libraries and supports additional libraries for interfacing with sensors, displays, and communication modules.

Block Diagram

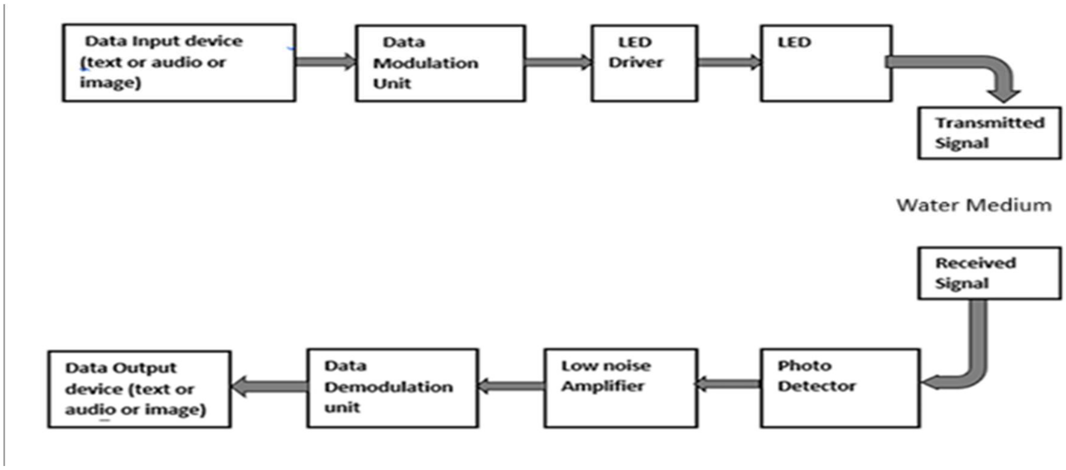

Figure 6 Block Diagram

Illustrates the block diagram of the underwater communication system using Li-Fi technology. The system is divided into transmitter and receiver sections connected through an underwater optical communication channel. The transmitter section begins with a data input device that acts as the source of information to be transmitted. The input data may consist of text, audio, images, or sensor information. The amplified signal is then fed into the data demodulation unit, where the original digital information is extracted by reversing the modulation process. Signal filtering and error correction techniques may also be applied to enhance reliability. Finally, the recovered information is delivered to the data output device such as a display or speaker, which presents the transmitted information in its original form.

Working Methodology

The working methodology of underwater Li-Fi communication involves a sequence of processes including data generation, modulation, optical transmission, reception, demodulation, and data reconstruction. Initially, digital data representing the information to be transmitted is generated. This information may include images, control signals, sensor data, or audio signals. The generated data is encoded and prepared using suitable modulation techniques for optical transmission.The encoded data is then used to modulate a high-speed light source such as LEDs or laser diodes. Modulation schemes such as On-Off Keying (OOK) and Pulse Width Modulation (PWM) are commonly used to represent binary data. These modulation techniques allow the light intensity to change rapidly, thereby embedding the information within the optical signal. The blue-green wavelength range, typically between 450 nm and 550 nm, is selected for transmission because it experiences lower attenuation in underwater environments. This wavelength selection improves transmission range and communication efficiency.Furthermore, underwater Li-Fi systems are designed to adapt to dynamic environmental conditions. Techniques such as beam focusing and collimation are used to maintain signal strength over longer distances. Adaptive modulation methods are also implemented to ensure stable communication even when environmental conditions change. This adaptability enhances the reliability and performance of underwater Li-Fi communication systems, making them suitable for next-generation underwater communication applications.

Results

This section presents a detailed evaluation of the Arduino-based underwater Li-Fi communication system employing Pulse Width Modulation (PWM). The performance of the system was assessed under different operating and environmental conditions, focusing on signal integrity, transmission distance, data reliability, and noise susceptibility.

PWM Signal Analysis

The PWM signal generated by the Arduino transmitter was analyzed using an oscilloscope to verify proper modulation. The transmitted data was encoded through variations in duty cycle, representing binary values of 1 and 0. The captured waveforms clearly demonstrated distinct duty cycle variations corresponding to digital data, confirming proper signal generation and modulation at the transmitter.

The high-brightness LED successfully converted the PWM electrical signal into optical pulses. These light pulses were transmitted through the water medium without noticeable distortion at short distances, confirming effective optical modulation.

Signal Reception and Demodulation

At the receiver end, a photodiode coupled with an Arduino microcontroller detected the incoming optical signals. The photodiode converted light pulses into electrical signals, which were then processed by the receiver circuit. Voltage variations measured at the receiver closely matched the transmitted PWM waveform.The Arduino receiver successfully decoded the incoming signal and reconstructed the transmitted binary data. This confirmed that the optical signal maintained sufficient integrity during underwater transmission, particularly at shorter distances.

Noise Impact and Environmental Effects

The system was tested under different ambient lighting conditions to evaluate noise susceptibility. Experimental observations indicated that strong ambient light sources introduced noise into the receiver circuit. This interference resulted in reduced signal clarity and increased bit error rates.

To mitigate these issues, shielding techniques and optical filters were considered. The implementation of these improvements can enhance system performance in real-world underwater environments.

Hardware Demonstration

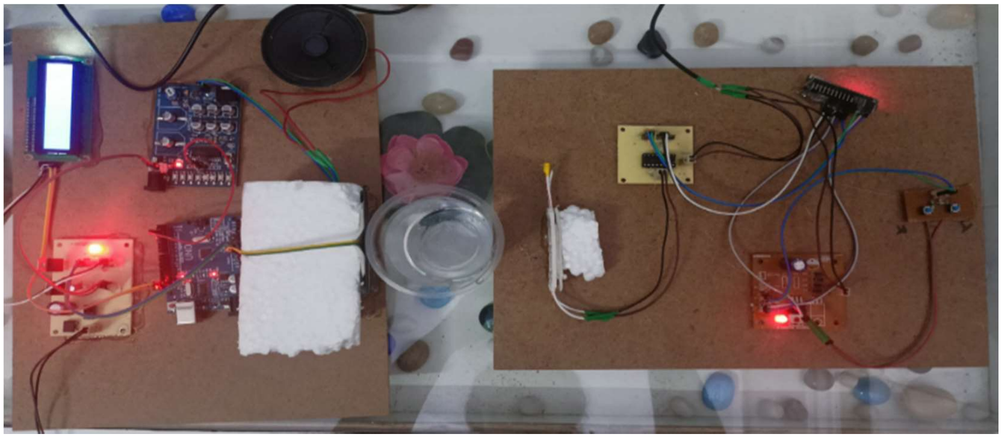

Figure 7 Hardware Setup

illustrates the prototype setup of the underwater Li-Fi communication system. The transmitter section consists of an Arduino-controlled high-intensity LED, while the receiver section includes a photodiode with signal conditioning circuitry. The glass container filled with water acts as the underwater communication medium.In this setup, the LED is in an OFF state, indicating that no data transmission is currently taking place. This configuration demonstrates the hardware components used to implement underwater optical communication.

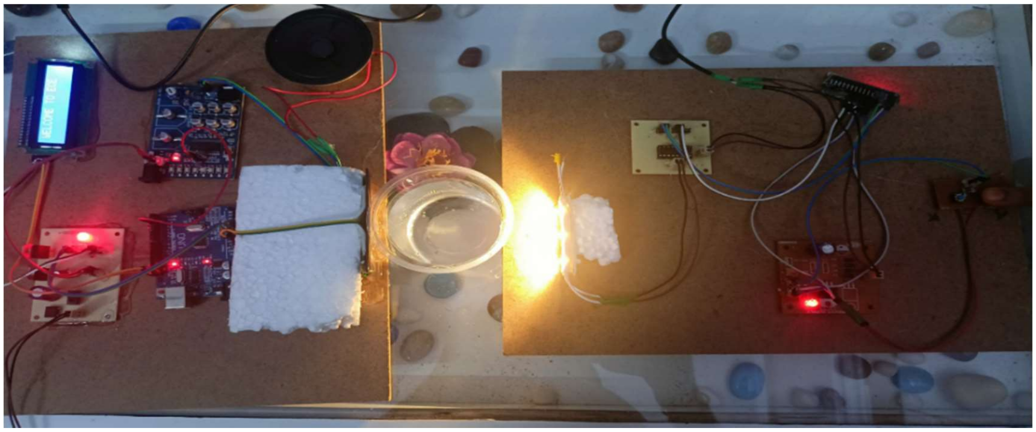

Figure 8 Data transmitting through LED

presents the active transmission state of the underwater Li-Fi system. The high-intensity LED is illuminated, indicating ongoing data transmission. The LCD display shows the message "WELCOME TO ECE," confirming successful digital data transmission. Additionally, an audio input signal is simultaneously transmitted and reproduced through a speaker, demonstrating multi-input capability. The water container acts as the underwater communication channel, while the photodiode at the receiver detects the incoming optical signals. The illuminated receiver LED confirms signal detection and system operation. This experimental setup validates real-time underwater data communication using visible light.

Discussion

The developed underwater Li-Fi communication system demonstrates the feasibility of optical wireless communication using PWM modulation and Arduino-based hardware. The system successfully transmitted binary data across short distances in clear water conditions.

Conclusion

This project successfully implemented and analyzed an underwater Li-Fi communication system using Pulse Width Modulation (PWM) with Arduino-based hardware. The experimental results demonstrated reliable short-range underwater communication using visible light. Performance evaluation based on PWM signal fidelity, bit error rate, and signal attenuation confirmed the feasibility of optical wireless communication underwater. The system achieved reliable communication within short distances and performed best in clear water environments.

Although signal degradation occurred at longer distances due to scattering and absorption, the system proved to be a simple, low-cost, and energy-efficient solution for underwater communication. This work demonstrates the potential of Li-Fi technology for underwater sensor monitoring, diver communication, and short-range robotic communication.

The proposed system provides a foundation for future research aimed at improving transmission speed, communication range, and noise resilience.

Future Scope

Future enhancements to the system can focus on improving speed, reliability, and scalability of underwater communication. Advanced modulation techniques such as On-Off Keying (OOK), Frequency Shift Keying (FSK), and Quadrature Amplitude Modulation (QAM) can be implemented to increase data transmission speed. Reliability in noisy underwater environments can be improved by incorporating error detection and correction methods like CRC, Hamming codes, and forward error correction. The integration of optical lenses can extend communication range, while band-pass filters can minimize ambient light interference. Future systems may also support bi-directional communication using half-duplex or full-duplex modes for two-way data transmission. Additionally, multiple underwater nodes can be connected to form wireless sensor networks for environmental monitoring and marine research. The use of blue-green lasers can further enhance transmission range due to their better underwater propagation characteristics. Energy optimization through low-power hardware and efficient algorithms can extend battery life. Machine learning techniques can also be employed for adaptive signal detection and noise reduction. Moreover, compact and modular hardware designs can simplify deployment and improve scalability. Finally, the system can be integrated with autonomous platforms such as Autonomous Underwater Vehicles (AUVs) and Remotely Operated Vehicles (ROVs) for advanced underwater applications.

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