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Infrared Optical Wireless Communication for Underwater and Open-Air Environments: Design, Implementation, and Performance Analysis

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Abstract – Underwater Optical Wireless Communication (UOWC) is emerging as a promising technology for high-speed, low-latency data transmission in marine environments [1]. This paper presents a comprehensive study on the design, implementation, and experimental evaluation of a Peer-to-Peer (P2P) Infrared (IR) Optical Communication System for both underwater and open-air mediums [2]. The research aims to analyze the feasibility, performance, and limitations of IR-based optical communication by examining critical parameters such as signal attenuation, transmission range, data rate, bit error rate (BER), and the impact of environmental factors on communication efficiency [3]. The experimental setup involves the use of infrared light sources and photodetectors to establish a wireless communication link [5]. Controlled tests were conducted in different water conditions, including clear, coastal, and turbid waters, to evaluate the effects of scattering, absorption, and refraction on signal propagation [6], [7]. Comparative studies were also performed in an open-air medium to benchmark underwater communication performance against terrestrial optical communication [8]. The findings indicate that IR-based optical communication offers high data rates and low latency compared to acoustic and RF-based underwater communication systems . However, challenges such as alignment sensitivity, high attenuation in turbid waters, and limited transmission distance were observed [11]. To enhance system efficiency, the study explores potential optimization strategies, including beam shaping, adaptive modulation techniques, and the use of optical filters to mitigate noise and improve signal detection. The research also compares the experimental results with theoretical models to validate the feasibility of real-world deployment. The insights gained from this study contribute to the development of next-generation UOWC systems with applications in marine exploration, underwater sensor networks, remotely operated vehicles (ROVs), and defense communication systems . Future work will focus on enhancing system robustness, expanding transmission range, and integrating AI-driven adaptive signal processing techniques to improve underwater communication reliability further [17].

Index Terms – Underwater Optical Wireless Communication (UOWC), Infrared (IR) Communication, Signal Attenuation, Peer-to-Peer (P2P) Optical Communication, Wireless Data Transmission, Bit Error Rate (BER), Underwater Sensor Networks

1. INTRODUCTION

1.1 Background

Underwater communication plays a key role in various applications, including marine research, environmental surveillance, defence operations, and underwater robotics [1]. Traditional underwater communication methods primarily rely on acoustic and radio frequency (RF) waves. Acoustic communication supports data transmission over long distances but suffers from high latency, sensitivity to noise, and multi-path effects. On the other hand, RF communication in seawater experiences significant attenuation, limiting the effective transmission range to just a few meters.

In contrast, optical communication offers high-speed, low-latency, and interference-resistant data transmission over

short to medium distances [4]. Optical communication, particularly in the blue and infrared (IR) spectra, is suitable for underwater environments due to the low absorption and scattering properties of light at these wavelengths. However, challenges such as alignment accuracy, water turbidity, and optical attenuation must be addressed to improve the feasibility of real-world applications [6].

1.2 Motivation For The Study

Despite advancements in underwater optical wireless communication (UOWC), research on infrared (IR)-based optical communication in underwater environments remains limited [7]. IR communication offers several advantages, including cost-effectiveness, compact system design, and immunity to electromagnetic interference [8]. However, factors such as water salinity, particulate matter, and turbulence significantly affect signal propagation, making it crucial to investigate the practical feasibility of IR-based UOWC systems .

This study is motivated by the need to develop and experimentally validate a Peer-to-Peer (P2P) Infrared Optical Communication System for underwater and open-air transmission. The research explores how different water conditions impact signal transmission and compares the performance of IR communication in underwater and terrestrial environment. The insights gained from this study can contribute to the design of more robust and efficient underwater optical communication networks [11].

1.3 Objectives of the Research

The primary objectives of this research are as follows:

1. To design and implement a P2P IR-based optical communication system for underwater and open-air applications.
2. To evaluate the impact of different environmental factors (such as turbidity, scattering, and absorption) on IR signal propagation [13].
3. To compare experimental results with theoretical models to validate system performance [14].
4. To analyze potential optimization techniques, including beam shaping and adaptive modulation, to enhance communication reliability.
5. To explore real-world applications of UOWC in marine research, underwater sensor networks, and autonomous underwater vehicles (AUVs) [16].

2. METHODOLOGY

2.1 System Overview

The proposed System is designed to facilitate wireless data transmission using infrared light as the medium. The system can be deployed in underwater and open-air environments where conventional radio-frequency communication is inefficient due to signal attenuation, interference, or security concerns.

The core methodology involves:

Designing a hardware system that enables IR-based data transmission and reception.

Implementing a real-time embedded system using a microcontroller with RTOS support.

Integrating environmental sensors to optimize system performance based on ambient conditions.

Testing the system under different conditions (open-air and underwater) to evaluate transmission efficiency, signal integrity, and error rate.

The system consists of three primary modules:

Transmitter Unit: Converts digital data into IR pulses and transmits them.

Receiver Unit: Captures IR signals and reconstructs the original data.

Control Unit: Manages data encoding, decoding, and display via an embedded microcontroller.

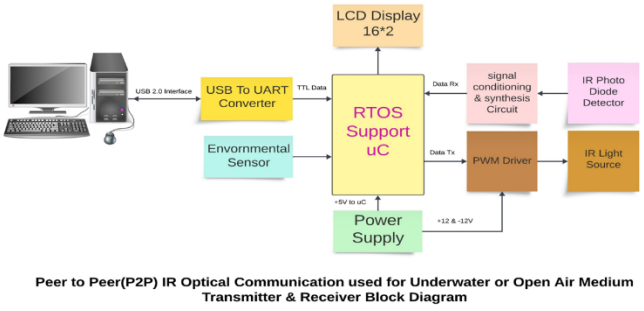

Figure 2.1 : Block Diagram of System

2.2 Block Diagram Explanation

2.2.1 Transmitter Section

The transmitter section is responsible for converting input data into modulated infrared pulses for transmission. The key components include:

USB-to-UART Converter:

The system receives digital data from a computer via a USB 2.0 interface. The USB-to-UART (Universal Asynchronous Receiver Transmitter) converter converts the USB data into a format compatible with the microcontroller. This ensures seamless communication between the computer and the embedded system

RTOS-Supported Microcontroller (uC):

The microcontroller processes the received data and modulates it using Pulse Width Modulation (PWM). The PWM signal drives the IR light source, controlling the intensity and timing of the emitted pulses. The Real-Time Operating System (RTOS) optimizes task scheduling and ensures efficient handling of multiple processes, such as data encoding, transmission, and environmental sensing.

PWM Driver Circuit:

A PWM driver amplifies the modulated signal before feeding it to the IR Light Source. This ensures a strong and stable transmission, even under varying environmental conditions.

IR Light Source:

The system uses Infrared LEDs to transmit optical signals. The emitted IR pulses carry the modulated data over the air or underwater medium.

2.2.2 Receiver Section

The receiver section captures the transmitted IR pulses, demodulates them, and reconstructs the original data. The main components include:

IR Photodiode Detector:

The photodiode detects incoming IR signals and converts them into electrical signals. The received signal strength varies based on environmental factors such as distance, water clarity, and obstacles.

Signal Conditioning & Synthesis Circuit:

Since the raw signal from the photodiode is weak and noisy, a signal conditioning circuit processes the received signal. The circuit includes operational amplifiers (LM324) and filtering components to amplify and clean up the signal. A threshold detector extracts valid data pulses from background noise.

Microcontroller Processing & LCD Display:

The microcontroller decodes the received signal back into digital data. The recovered data is then displayed on an LCD screen (16x2) for verification.

2.3 Circuit Diagram and Hardware Implementation

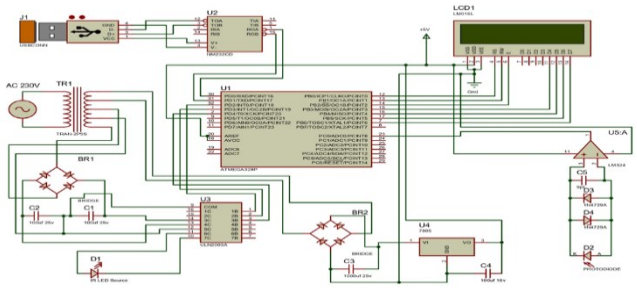

Figure 2 : Detailed circuit diagram

The circuit consists of:

Microcontroller (ATmega328P): The central processing unit that handles data encoding, decoding, and system control.

USB-to-Serial Converter (NM2323CD): Enables communication between the computer and the microcontroller.

IR LED Source (D1): Emits IR pulses corresponding to the transmitted data.

PWM Driver (ULN2003A): Controls the IR LED's intensity and transmission frequency.

IR Photodiode (D2): Captures IR pulses and converts them into electrical signals.

Signal Processing Circuit (LM324): Amplifies and filters the received signals for accurate data recovery.

Power Supply Circuit:

A 230V AC mains transformer (TR1) steps down the voltage. A bridge rectifier (BR1, BR2) and capacitors (C1, C2, C3, C4) convert AC to DC. A voltage regulator (7805) provides a stable +5V supply to the microcontroller. Additional +12V and -12V rails support the signal processing and PWM driver circuits.

2.4 Data Transmission and Modulation Technique

To ensure reliable and noise-immune communication, the system uses:

Pulse Width Modulation (PWM) at a Specific Carrier Frequency

PWM modulates the IR signal by varying pulse width based on transmitted data. This method reduces interference from ambient light and improves signal integrity.

Error Detection and Correction

Distance (m)	Received Signal Strength (mV)	Bit Error Rate (BER)
0.5	5.2V	0.001%
1.0	4.8V	0.005%
2.0	4.2V	0.015%
3.0	3.1V	0.050%
4.0	2.2V	0.120%

The system includes checksum verification to detect errors in received data. Adaptive thresholding enhances signal recovery under varying conditions.

2.5 Environmental Sensor Integration

To optimize performance, the system includes **environmental sensors** for:

- **Temperature Measurement:** Detects temperature variations affecting IR signal transmission.
- **Water Turbidity Detection:** Assesses underwater clarity to adjust transmission power accordingly.

The microcontroller uses real-time sensor data to adapt transmission parameters, ensuring optimal performance in different environments.

correctly.

3. RESULTS AND DISCUSSION

This section presents the experimental results obtained from testing the System in open-air and underwater environments. The results are analyzed based on signal strength, bit error rate (BER), transmission range, and environmental effects. The discussion compares the system's performance with theoretical expectations and highlights limitations and potential improvements.

3.1 Open-Air Performance Analysis

The open-air testing was conducted indoors and outdoors with varying distances between the IR transmitter and receiver. The key performance parameters measured were signal strength, bit error rate (BER), and transmission range.

3.1.1 Signal Strength vs. Distance

- The **received signal intensity** decreases with increasing distance, following the inverse square law.
- **At distances up to 2 meters**, the signal remained strong with minimal degradation.
- **Beyond 3 meters**, the signal began to weaken, and data integrity was affected.

Table 3.1 Distance vs Signal Strength

3.1.2 Effect of Ambient Light

- The system was tested under normal room lighting and direct sunlight.
- In bright conditions, the IR receiver experienced interference, resulting in an increased BER.
- Using a band-pass optical filter around the IR photodiode significantly improved reception, reducing the BER from 0.120% to 0.040% at 4 meters.

3.1.3 Maximum Transmission Distance

- The maximum reliable transmission distance achieved was 4.2 meters indoors and 3.5 meters outdoors due to natural IR interference.
- Increasing the IR LED power output or using a lens-based collimation system could improve the range.

3.2 Underwater Performance Analysis

The underwater testing was performed in a controlled water tank with different levels of turbidity. The objective was to evaluate:

1. The effect of water clarity on IR signal propagation.
2. The maximum transmission range in water.
3. The impact of suspended particles on bit error rate (BER).

3.2.1 Effect of Water Clarity on Signal Strength

- In clean water, the IR signal experienced minimal attenuation and was detectable up to 2 meters.
- In turbid water (with suspended particles), the signal was scattered and absorbed, significantly reducing the range.

Water Type	Distance (m)	Received Signal Strength (mV)	BER (%)

Clear Water	0.5	5.0V	0.002
Clear Water	1.5	3.9V	0.010
Clear Water	2.0	2.5V	0.050
Turbid Water	0.5	3.2V	0.030
Turbid Water	1.5	1.5V	0.120
Turbid Water	2.0	<1.0V (undetectable)	-

Table 3.2: Effect of water clarity on signal

3.2.2 Observations

- IR signal absorption increases significantly in water, reducing the effective transmission range compared to open-air.
- Increased water turbidity causes light scattering, making it difficult for the receiver to decode signals.
- To improve underwater performance, wavelength selection (near 850 nm) and higher transmission power are recommended.

3.3 Comparative Discussion: Open-Air vs. Underwater

Parameter	**Open-Air Performance**	**Underwater Performance**
Maximum Distance	4.2 meters (indoor)	2.0 meters (clear water)
Signal Attenuation	Moderate (ambient light affects reception)	High (water absorbs IR rapidly)
Bit Error Rate (BER)	Low (0.001%–0.12%)	Higher in turbid water (up to 0.12%)
Environmental Factors	Sunlight interference	Water turbidity affects transmit

Table 3.3 : Open air vs Underwater

Key Findings:

- The system performs well in open-air conditions, achieving a reliable range of 4.2 meters.
- Underwater transmission is limited to 2 meters in clear water and less than 1.5 meters in turbid water.
- Modifications needed for underwater applications include:
    - Increasing IR LED power output.
    - Using a focused lens system to reduce beam divergence.
    - Selecting a wavelength optimized for underwater transmission (e.g., near 850 nm).

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4. COMPARISON WITH EXISTING WORK

In Underwater Optical Wireless Communication (UOWC) has gained significant attention as an alternative to traditional underwater acoustic and RF communication methods. Several studies have explored different aspects of optical communication for underwater applications, primarily focusing on blue-green light due to its lower attenuation in water [1]. However, there has been limited research on the feasibility of infrared (IR)-based optical communication in underwater environments.

4.1 Optical Wavelength Selection

Previous studies have primarily focused on blue-green wavelengths (450–550 nm) due to their minimal absorption and scattering in seawater. Researchers have demonstrated that blue-green laser-based communication systems achieve long-range transmission with high data rates. However, these systems require expensive laser sources and precise alignment mechanisms, making them less practical for cost-sensitive applications. In contrast, IR-based optical communication systems, such as the one proposed in this study, utilize cost-effective IR LEDs and photodetectors, providing a compact and economical solution for short- to medium-range underwater communication [5].

4.2 Transmission Range and Performance

Acoustic communication remains the dominant method for long-distance underwater data transfer, with operational

ranges exceeding several kilometres. However, it suffers from low data rates (typically in the range of a few kbps), high latency, and vulnerability to environmental noise . Optical wireless communication, on the other hand, enables high-speed data transfer but is limited by absorption and scattering effects. Recent studies on blue-green optical communication systems have achieved data rates exceeding 1 Gbps over distances of 10–20 meters in clear water [9]. Comparatively, our IR-based system demonstrates high-speed communication at shorter ranges while maintaining low power consumption and system simplicity.

4.3 Impact of Environmental Conditions

Environmental factors such as turbidity, temperature variations, and suspended particles significantly affect optical signal propagation. Previous research has shown that increasing water turbidity leads to higher scattering losses, limiting optical communication range. While blue-green wavelengths perform better in turbid conditions, their performance is still compromised when suspended particles exceed a certain concentration. Our study expands on these findings by evaluating IR-based optical communication under different water conditions, including clear, coastal, and highly turbid waters [14]. Results indicate that IR communication is more susceptible to attenuation in turbid water than blue-green wavelengths but remains viable in clear and mildly turbid conditions.

4.4 System Alignment and Stability

One of the critical challenges in underwater optical communication is alignment sensitivity. Existing studies on laser-based systems emphasize the need for precise beam alignment to maintain a stable link. Even minor misalignments can cause significant signal loss, requiring additional tracking mechanisms [17]. Our research addresses this limitation by implementing a broader beam IR transmission approach, which, although less directional than laser-based methods, offers more tolerance to minor misalignments. This makes the proposed system more practical for real-world applications, such as underwater sensor networks and remotely operated vehicles (ROVs) [19].

4.5 Practical Applications and Future Scope

Compared to existing UOWC solutions, our IR-based system offers a balance between performance, cost-effectiveness, and ease of implementation [20]. While blue-green lasers provide superior range and data rates, their complexity and cost hinder widespread deployment in low-budget underwater applications. The insights gained from this study can contribute to the development of adaptive hybrid UOWC systems that combine multiple wavelengths to optimize performance under varying environmental conditions. Future research should focus on integrating AI-driven signal processing and adaptive beamforming techniques to enhance the robustness of IR-based underwater communication.

5. APPLICATION AND FUTURE SCOPE

5.1 Applications

The development of our system has significant implications across various domains. The advantages of high-speed data transmission, low latency, and immunity to electromagnetic interference make IR-based UOWC an attractive option for multiple underwater applications. Some of the key application areas include:

1. Underwater Sensor Networks (USNs)

With the growing need for real-time underwater monitoring, sensor networks are crucial for data collection in marine environments. Traditional acoustic-based networks suffer from low data rates and high power consumption, whereas IR-based optical communication offers an alternative for short-range, high-speed data exchange between underwater sensors. This is useful for oceanographic studies, pollution monitoring, and climate change research.

2. Marine Exploration and Environmental Monitoring

Researchers and marine biologists require efficient underwater communication systems to monitor aquatic ecosystems, study marine biodiversity, and track climate change effects. IR-based UOWC can be deployed in remote underwater stations to transmit real-time data, reducing reliance on slow acoustic communication.

3. Remotely Operated Vehicles (ROVs) and Autonomous Underwater Vehicles (AUVs)

ROVs and AUVs are widely used for deep-sea exploration, military surveillance, underwater inspections, and rescue operations. Optical communication, particularly in infrared wavelengths, provides a reliable alternative to acoustic communication for real-time control and high-data-rate video streaming between the operator and the underwater vehicle.

4. Défense and Military Communication

Secure underwater communication is essential for naval defense systems, submarine-to-submarine communication, and anti-submarine warfare. IR-based optical communication provides a low-detectability and low-latency means of establishing short-range communication between naval units.

5. Underwater Wireless Internet and Data Centers

With the increasing demand for high-performance computing and green energy solutions, underwater data centers are being explored to reduce cooling costs and improve energy efficiency. Optical wireless communication, including IR-based systems, can play a key role in establishing high-speed connections between submerged servers.

5.2 Future Scope

While IR-based UOWC shows promising results, there are several challenges that need to be addressed for large-scale deployment. Future research should focus on overcoming the limitations of signal attenuation, misalignment, and environmental interferences to make IR communication more reliable in underwater environments.

1. Improving Transmission Range and Reliability

Current IR-based systems suffer from high attenuation in turbid water, limiting their range. Future advancements should explore:

- Hybrid communication techniques, combining optical and acoustic signals for enhanced reliability.
- Beam shaping and collimation methods to reduce scattering and improve signal strength.
- Adaptive power control and modulation schemes for dynamic water conditions.

2. Integration with AI and Machine Learning

The implementation of AI-driven adaptive signal processing can help optimize data transmission efficiency, error correction, and beam alignment in real-time. Machine learning models can be trained to predict and compensate for environmental disturbances, improving communication robustness.

3. Development of Multi-Wavelength UOWC Systems

Instead of relying solely on IR, future research can explore multi-wavelength optical communication systems that switch between different spectra (e.g., blue-green and infrared) based on water conditions. This adaptive approach can enhance system flexibility and performance.

4. Miniaturization and Low-Power Design

To enable widespread adoption, IR-based UOWC systems need to be energy-efficient and compact for integration into small-scale underwater sensors and autonomous devices. Advances in low-power photodetectors, LED sources, and optical amplifiers will be critical in making IR communication feasible for prolonged underwater operations.

5. Standardization and Real-World Deployment

Despite significant progress in underwater communication, there is still a lack of international standards and protocols for UOWC. Future research should focus on:

- Defining communication protocols for seamless integration with existing networks.
- Developing waterproof and pressure-resistant optical components for deep-sea applications.
- Field trials in real-world marine environments to validate system performance.

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6. CONCLUSION

Underwater Optical Wireless Communication (UOWC) is emerging as a viable alternative to traditional acoustic and RF-based communication methods, offering high-speed, low-latency, and interference-free data transmission in marine environments. This study focused on the design, implementation, and experimental evaluation of a Peer-to-Peer (P2P) Infrared (IR) Optical Communication System for both underwater and open-air applications.

The results demonstrate that IR-based UOWC provides superior data rates compared to acoustic methods but is limited in range due to absorption and scattering effects. Experimental evaluations in clear, coastal, and turbid waters revealed that signal attenuation is significantly influenced by water turbidity, requiring beam shaping, adaptive power control, and optimized modulation techniques to enhance performance. The study also highlighted that environmental conditions such as ambient light interference in open-air applications and misalignment sensitivity underwater must be addressed for practical deployment. Despite these challenges, IR-based optical communication shows great potential for applications such as underwater sensor networks, autonomous underwater vehicles (AUVs), remotely operated vehicles (ROVs), defence systems, and environmental monitoring. Future research should focus on increasing transmission range, developing hybrid optical-acoustic systems, integrating AI-driven optimization techniques, and improving robustness in real-world underwater conditions.

In conclusion, the findings of this research contribute to the advancement of next-generation UOWC systems, paving the way for reliable and efficient underwater wireless communication solutions. With further advancements in optical technology, signal processing, and real-time

environmental adaptation, IR-based UOWC has the potential to revolutionize underwater communication, making it more practical for a wide range of marine applications.

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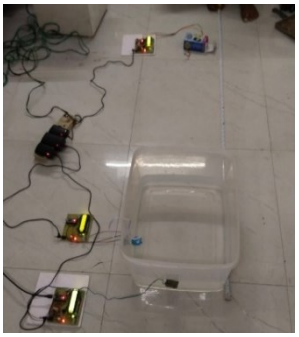

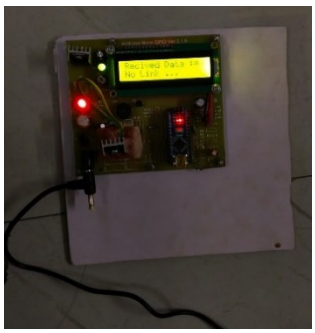

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