

Implementation and Analysis of a Laser-Based Underwater Optical Link

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Abstract

Implementation and Analysis of a Laser-Based Underwater Optical Link is a project designed to enable short-range underwater communication where traditional methods are inefficient. Acoustic systems suffer from high latency and RF signals attenuate severely in water. This system uses an optical link for communication. An electret microphone captures audio which is amplified and then digitized by an ESP32. A 555 Timer in a stable multivibrator configuration generates a carrier, enabling OOK modulation to drive a laser diode. At the receiver, a photodiode detects the signal, which is amplified, reconstructed using the ESP32 DAC, and played through a speaker.

Keywords: ESP32; Laser Diode; OOK Modulation; Photodiode; UWOC

1. Introduction

Communication in underwater environments is a critical requirement for applications such as marine research, defense operations and industrial inspections. However, conventional communication methods face significant challenges in water. Acoustic systems, while widely used, suffer from high latency and limited bandwidth whereas radio frequency signals are heavily attenuated, making them unsuitable for reliable underwater transmission. These limitations create a need for an alternative approach that can provide faster and more efficient communication over short distances. The Laser-Based Underwater Wireless Optical Communication (UWOC) project aims to address this challenge by utilizing visible light as a transmission medium. The system is designed to enable analog voice communication using a laser diode for signal propagation [1-6]. At the transmitter, an electret microphone captures voice signals, which are amplified and then digitized using an ESP32 microcontroller. A 555 Timer generates a high frequency carrier for On-Off Keying (OOK) modulation, which drives the laser diode to transmit the signal through water. At the receiver, a photodiode detects the incoming optical signal and

converts it into an electrical form. This signal is amplified, processed by the ESP32, and reconstructed into analog audio using the built-in DAC. The output is then filtered and amplified to drive a speaker, enabling real-time voice communication. This project focuses on developing a low-cost, efficient, and practical prototype for short-range underwater communication. By combining hardware-based modulation with microcontroller-based processing, the system demonstrates a feasible solution for overcoming the limitations of traditional underwater communication methods.

1.1. Underwater Environment and Water Types

Water Type Variations: The performance of underwater optical communication depends on the attenuation characteristics of the water medium. Different water types exhibit different attenuation coefficients, which directly affect signal propagation. Clear ocean water has low attenuation, coastal water shows moderate attenuation, and turbid harbor water has high attenuation, significantly limiting transmission range. These variations in attenuation for different water types at the operating wavelength are summarized in Table 1.

Table 1 Attenuation Coefficients for Jerlov Water Types at 650 nm wavelength of light.

Water Type	Jerlov Class	Attenuation Coefficient “c” (m ⁻¹)
Very Clear Ocean	Type I	0.40
Clear Ocean	Type IA	0.60
Coastal Water	Type II	1.00
Coastal Water	Type III	1.50
Turbid Harbor	Type 5C	3.00 – 6.00

- **Absorption and Scattering:** Attenuation is caused by both absorption and scattering in water. Absorption reduces the optical energy, while scattering spreads the beam and causes distortion. These effects increase with impurity levels and suspended particles in water.
- **Wavelength Dependency:** Light attenuation varies with wavelength, with blue-green light (around 450–550 nm) experiencing the least loss.
- **Propagation Distance:** The achievable communication range is inversely proportional to the attenuation coefficient. Clear water allows longer distances, while turbid water restricts communication to short ranges, typically within a few meters.
- **Alignment Sensitivity:** Due to the directional nature of laser transmission, precise alignment between transmitter and receiver is required. Misalignment results in significant signal loss, especially in high-attenuation environments.

2. Block Diagram and Signal Flow

Laser-Based Underwater Wireless Optical Communication (UWOC) system is designed to transmit analog voice signals using an optical link. The system consists of two main sections: transmitter and receiver. At the transmitter, an electret microphone captures the voice signal, which is

amplified using an LM386 audio amplifier. The amplified signal is then processed by an ESP32 microcontroller, where it is digitized and used to control the modulation process. An a stable multi-vibrator generates a high-frequency carrier (320 kHz). The ESP32 output modulates this carrier using the digitized audio, producing a modulated digital pulse stream shown in Figure 1.

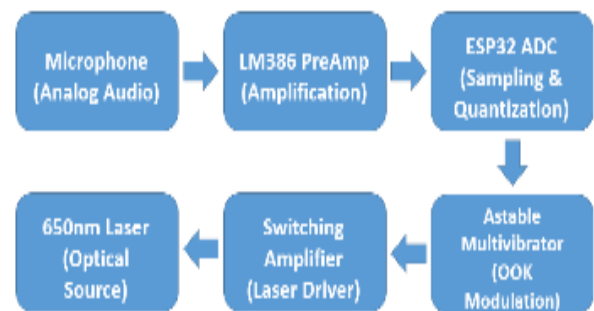


Figure 1 Block Diagram of the Transmitter

This modulated signal drives a laser diode through a transistor switching stage, generating a focused optical beam for underwater transmission [7-10]. Proper alignment between transmitter and receiver is maintained to ensure efficient signal propagation shown in Figure 2.

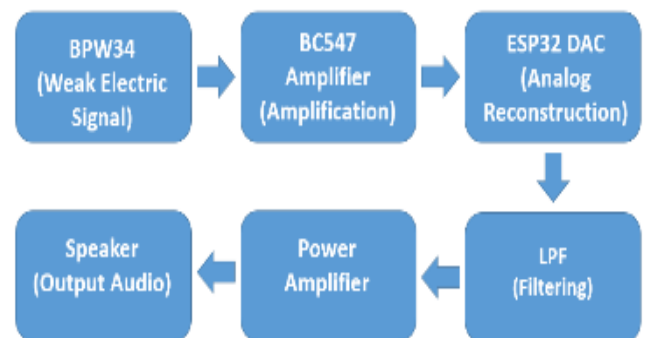


Figure 2 Block Diagram of the Receiver

At the receiver, a BPW34 photodiode detects the incoming optical signal and converts it into a weak electrical signal. A preamplifier boosts this signal, which is then fed to the ESP32. The ESP32reconstructs the analog waveform using its built-in DAC. The output is filtered and amplified to drive a speaker.

3. Circuit Implementation

3.1. Transmitter

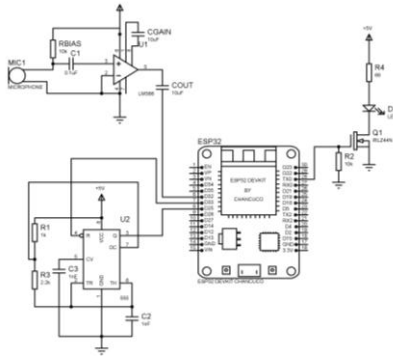


Figure 3 Transmitter Circuit

3.1.1. Microphone Pre-Amplifier

The input voice signal is captured using an electret microphone and amplified using an LM386 audio amplifier shown in Figure 3.

Component Values:

- Microphone bias resistor (Rbias): 6.8 kΩ
- Input coupling capacitor (Cin): 0.1 μF
- Gain capacitor (between Pin 1 & 8): 10 μF
- Output coupling capacitor (Cout): 10 μF
- Supply voltage: 5V

Notes:

- Provides amplification from ~10 mV to ~1–2 V
- This is sampled by the ESP32 at 8kHz

3.1.2. 555 Timer OOK Modulator

A 555 Timer in astable multivibrator mode generates a 320 kHz carrier, modulated using ESP32.

Component Values:

- R1 = 1 kΩ
- R2 = 2.2 kΩ
- C1 = 1 nF
- Control pin capacitor (Pin 5): 10 nF
- Supply voltage: 5V

Connections:

- Pin 4 (RESET) → ESP32 digital output
- Pin 3 → Laser driver stage

3.1.3. Laser Diode Driver

The modulated output drives a 650 nm laser diode. Component Values shown in Figure 4.

- Current limiting resistor (RL): 68 Ω

- Laser diode: 650 nm, ~10 mW
- Supply: 5V

Notes:

- RL Prevents thermal runaway

3.2. Receiver

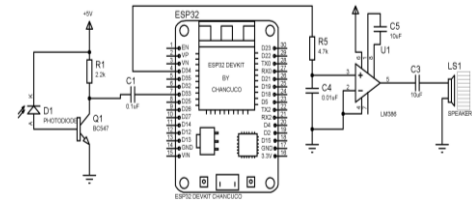


Figure 4 Receiver Circuit

3.2.1. Pre-Amplifier (BC547)

A transistor amplifier boosts weak photocurrent signals.

Component Values:

- Transistor: BC547
- Collector resistor (RC): 2.2 kΩ
- Supply: 5V

Notes:

- The BPW34 is operated in reverse bias mode giving a responsivity of 0.4 A/W for 650nm light.

3.2.2. DAC Output Filter (Reconstruction Filter)

A low-pass filter smooths the DAC output.

Component Values:

- Resistor (R): 4.7 kΩ
- Capacitor (C): 0.01 μF
- Cutoff frequency: ~4 kHz

3.2.3. Power Amplifier

The signal is amplified using an LM386 audio amplifier.

Component Values:

- Gain capacitor (between Pin 1 & 8): 10 μF
- Output coupling capacitor (Cout): 10 μF
- Supply voltage: 5V

4. Results and Discussion

4.1. Results

The system was tested in shallow water under natural to evaluate the performance. The transmitter and receiver were aligned, and the link distance was gradually increased shown in Figure 5.



Figure 5 The Transmitter (Left) And Receiver (Right) Modules



Figure 6 Testing of the modules.

The system demonstrated stable communication up to approximately 4 meters. Within this range, the link was stable. Beyond 4 meters, signal degradation became significant shown in Figure 6. The received signal showed increased noise, eventually leading to complete loss overcommunication. In addition to hardware testing, the system performance was analyzed using MATLAB by simulating Bit Error Rate (BER) versus Signal-to-Noise Ratio (SNR) for different water types shown in Figure 7.

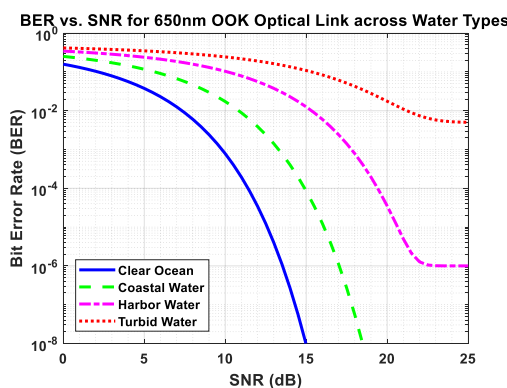


Figure 7 BER vs SNR for different water types.

The above figure illustrates the relationship between bit error rate (BER) and signal-to-noise ratio (SNR) for a 650 nm one-off keying (OOK) optical communication link operating under different water conditions. It is observed that BER decreases with increasing SNR for all cases; however, the rate of improvement strongly depends on the optical properties of the medium. Clear ocean water exhibits the best performance due to minimal absorption and scattering, achieving very low BER at relatively low SNR values. In contrast, coastal and harbor waters show progressively degraded performance, requiring higher SNR to attain acceptable error rates because of increased turbidity and particle-induced attenuation. Turbid water demonstrates the poorest performance, where BER remains significantly high even at elevated SNR levels, indicating severe signal degradation and the presence of an error floor. These results highlight that underwater optical communication performance is highly sensitive to environmental conditions, and system design must account for water type to ensure reliable data transmission[11-15].

4.2. Discussion

The results show that the system is effective for short-range communication and demonstrate that laser-based optical links can overcome the limitations of acoustic and RF methods in such environments. Performance degradation beyond the 4m range is primarily due to attenuation and scattering in water, along with ambient sunlight introducing noise at the receiver. These factors reduce the effective Signal-to-Noise Ratio (SNR), leading to distortion and eventual link failure. The MATLAB BER vs SNR analysis supports the experimental results, showing that higher attenuation water types require greater SNR to maintain reliable communication. Overall, the system performs as expected and highlights the importance of channel conditions in UWOC systems.

Conclusion

The results obtained from both hardware testing and simulation confirm the challenges associated with underwater optical communication, particularly attenuation, scattering, and ambient light interference. The system performance observed during experiments aligns with these limitations, as stable communication was achieved up to

approximately 4 meters. The MATLAB BER vs SNR analysis further supports these findings by showing that higher attenuation in different water types leads to increased error rates unless sufficient signal strength is maintained. These observations show that underwater conditions significantly affect signal propagation and reliability. The project shows that while UWOC offers advantages over acoustic and RF methods, its performance is highly dependent on environmental conditions.

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