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Design and Experimental Validation of Short Range Underwater Li-Fi Communication System

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Abstract: Underwater communication is a a big challenge. The Radio waves do not travel proper in underwater because water conducts electricity and absorbs them faster . Acoustic modems can work over longer distances, but they are quite expensive, bulky, and slow since sound travels slowly underwater .In this paper , a simple and low-cost underwater optical communication system is designed that avoids the above mentioned issues by visible light for transmission of short text messages. This setup has two parts: a transmitter and a receiver, both built and programmed with the Arduino IDE. The receiver compares the signal to a threshold to decode the binary data back into text. The Serial Monitors at the transmitter and receiver represents the process of data transmission in real time Increasing the feedback resistor from 220 kΩ to 1 MΩ significantly improved range from few centimeters to meters and reliability. Adding double convex lenses on both ends focus and collects the light better, boosting signal quality even more. Overall, this work shows that underwater optical communication can be built inexpensively with easy-to-find parts, making it a practical option for things like underwater sensor networks, diver communication etc…
Keywords: Underwater Li-Fi, Visible Light Communication, On-Off Keying, Short-Range Communication.

I. INTRODUCTION

Most of the technologies which everyone rely on are WiFi, Bluetooth, and cellular networks which don't work underwater. This is due to basic physics behind water which conducts electricity, which absorbs the radio waves immediately once they enter the water. Because of this, radio frequency (RF) signals can barely travel only a few centimeters underwater before they disappear completely.

For many years, the standard solution for this problem was been acoustic communication, which uses the sound waves instead of radio waves. Acoustic communication has been widely used in diving and underwater vehicle applications for decades because sound travels more distances in water than radio signals do. However, acoustic modems come with significant limitations. They require specialized transducers which is expensive and bulky, which makes the equipment less portable. Additionally, sound travels relatively slowly underwater, leading delays in communication that can affect real-time applications.

This is where underwater optical communication, known as LiFi, becomes an alternative. Instead of relying on sound or radio waves, LiFi uses visible light to transmit data through water. Since water is more transparent to visible light, than the radio waves, optical signals, enabling higher data rates over short distances. LEDs and photodiodes are also cheaper, smaller, and more energy-efficient than acoustic transducers, making LiFi attractive for compact, low-cost underwater systems.

However, underwater optical communication faces its own challenges, including water turbidity, light scattering, ambient noise, and the difficulty of achieving reliable signal detection using low-cost, off-the-shelf components rather than specialized transceivers.

This paper presents the design and implementation of a compact, low-cost underwater optical communication system using commercially available components

II. LITERATURE SURVEY

There has been a significant amount of researchs on underwater optical wireless communication, driven by its ability to achieve higher bandwidth and reduced latency compared to traditional acoustic systems, as well as the promise of lower costs [4]. While these advantages make optical methods very appealing, but acoustic communication remains the dominant technology used by commercial, scientific, and military divers. This is because acoustic systems can cover much greater distances underwater and come with decades of proven reliability and robustness in real-world applications [3]. Radio frequency (RF) communication, on the other hand, is largely impractical underwater due to severe signal attenuation caused by water's conductivity, restricting its effective range to just a few centimeters [1].

Many low-cost, open-source underwater optical modem papers use a similar approach to ours, employing an LED transmitter and photodiode receiver combined with On-Off Keying (OOK) for data transmission. Research from these papers highlights several important factors: switching from red LEDs to blue or green LEDs can significantly reduce optical attenuation underwater, improving signal reach and clarity. Furthermore, careful tuning of the receiver's gain is crucial for reliable signal detection. These findings directly shaped our design choices for both the transmitter and the amplifier circuits.

More advanced research has explored ways to improve underwater optical communication reliability. For example, deploying multiple photodiodes helps reduce the need for precise alignment between the transmitter and receiver, and incorporating forward error correction strengthens the system's robustness against noise and data loss [8]. Some diver-worn systems go further by integrating visible light communication with voice and image transmission capabilities. However, these systems require dedicated digital signal processing (DSP) hardware and highly sensitive photomultiplier receivers, making them significantly more complex and costly than the simple analog front-end used in our papers [7].

At the cutting edge, systems utilizing sophisticated modulation techniques such as orthogonal frequency-division multiplexing (OFDM) and quadrature amplitude modulation (QAM) with laser transmitters have demonstrated data rates in the hundreds of megabits per second over short underwater distances [2], [5], [6], [12]. While impressive, these high-performance setups demand specialized photodetectors and dedicated processing hardware, placing them well beyond the scope of low-budget student or hobbyist papers.

Importantly, comparative studies on modulation schemes reveal that simple On-Off Keying, despite its lower data rate, generally achieves the longest communication range in clear water compared to more complex modulation methods. This makes OOK a practical choice for systems focused on range and reliability rather than raw throughput, and it was a key factor in our decision to use it for this paper [9], [10], [11].

Overall, the research landscape shows a clear trade-off between cost, complexity, and performance in underwater optical communication, and our paper demonstrates that affordable, reliable underwater light-based communication is achievable with basic components and thoughtful design.

III. PROPOSED SYSTEM

The system consists of two NodeMCU ESP8266 boards, one acting as the transmitter and the other as the receiver, both programmed through the Arduino IDE. The goal was straightforward: let two submerged nodes exchange short text messages over a light link, without needing acoustic hardware or anything RF-based. On-Off Keying was chosen for the modulation scheme — it isn't the fastest option available, but comparative studies show it holds up best in terms of range in clear water, which mattered more for this build than raw data rate [9], [10], [11].

On the transmitter side, type a message into the Serial Monitor. The firmware takes that message and converts it into binary, one character at a time. That binary stream then gets sent out as flashes of light: an IRLZ44N MOSFET switches a high-power LED on and off, with each bit represented by a fixed duration of light or darkness. This LED-driven approach is consistent with similar low-cost optical link designs described in the literature [7], [9]. To help the light actually reach the receiver instead of scattering everywhere, a double convex lens was placed in front of the LED, focusing the beam into a tighter spot aimed at the receiver.

On the receiving end, a BPW34 photodiode paired with its own convex lens to pull in more light , picks up whether light is present or absent during each bit window, similar to other low-cost photodiode receivers reported in prior work [7], [8]. The signal coming off the photodiode is extremely weak on its own, so it's fed into an LM324 op-amp wired as a transimpedance amplifier, which boosts it into something the NodeMCU's ADC can actually work with. The receiver then compares this amplified voltage against a calibrated threshold to decide, bit by bit, whether it just saw a 1 or a 0.

Both boards print their bits live to their own Serial Monitors, so that can watch the transmitted bits on one screen and the received/decoded bits on the other, side by side. Once a full message comes through, the receiver prints the decoded text. And if nothing valid comes through in the expected time window, it just displays no garbled output, no guessing. As soon as the first valid bit arrives, decoding kicks off automatically and continues character by character until the message is complete.

Power-wise, the transmitter runs off two 18650 cells through a buck converter, while the receiver runs on a single 18650 cell through a boost converter — keeping both ends fully battery-powered with no wires trailing back to shore, in keeping with the same self-contained approach used in other low-cost underwater optical setups [9].

A few things became clear through actual testing that aren't obvious just from the circuit diagram. Alignment between the LED and photodiode turned out to matter a lot more than expected — even a slight angle between them noticeably weakens the signal. Ambient light and general electrical noise can also sneak in and throw off detection . And a power supply that's even slightly unstable or under-voltage tends to show up almost immediately as garbled or missing data on the receiver side.

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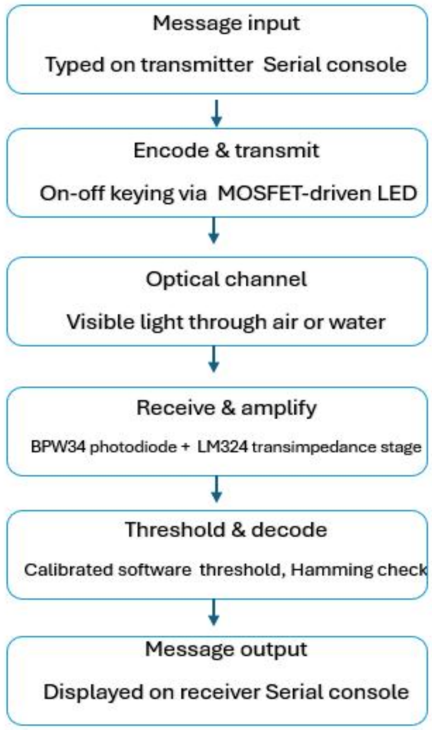

Fig.1. Process workflow of the proposed underwater optical communication system.

This Fig.1 illustrates the end-to-end workflow of the proposed underwater optical communication system. A message typed on the transmitter's Serial console is encoded and sent as light pulses using On-Off Keying via a MOSFET-driven LED. These pulses travel through the optical channel and are picked up by a BPW34 photodiode, then amplified by the LM324 transimpedance stage. The receiver applies a calibrated software threshold with Hamming-distance error checking to decode the signal, finally displaying the reconstructed message on its own Serial console

Fig2. Shows the workflow of the Transmitter

The transmitter subsystem converts an input text message into a binary frame consisting of a synchronization byte followed by a length byte and the message payload, ensuring reliable byte-level synchronization at the receiver. This binary stream modulates a MOSFET-driven LED using On-Off Keying (OOK), where logic '1' and '0' correspond to LED-ON and LED-OFF states respectively. The optical output is subsequently focused using a convex lens to narrow the beam divergence, thereby improving the effective transmission range through the underwater or open-air optical channel.

Fig3. Shows the workflow of the Receiver

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The receiver subsystem detects incoming light pulses through a lens-focused BPW34 photodiode, converting the optical signal into a proportional photocurrent. This photocurrent is converted into a usable voltage using an LM324 op-amp configured as a transimpedance amplifier, which is then compared against a calibrated software threshold and validated using Hamming-based error checking to correctly decode each bit. The recovered binary stream is finally reconstructed into the original text message and output via the serial console.

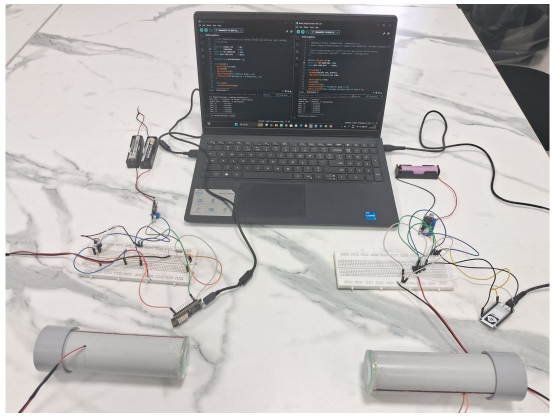

Fig. 4. Complete hardware setup of the transmitter and receiver nodes with live Serial Monitor output.

The setup shows both nodes fully assembled: the transmitter circuit (left breadboard, with the IRLZ44N MOSFET driver) and receiver circuit (right breadboard, with BPW34 photodiode and LM324 amplifier), each independently battery-powered and connected to a NodeMCU. Both are wired to the same laptop, whose dual Serial Monitor windows show live outgoing and incoming data during testing. The LED and photodiode are housed inside sealed, transparent-windowed PVC pipes so they can be submerged underwater while staying aligned along the same optical path.

IV. METHODOLOGY

A. Photoconductive Principle of the Receiver

The receiver's ability to detect incoming light pulses relies on the photoconductive behaviour of the BPW34 PIN photodiode. When reverse-biased, the photodiode generates a photocurrent, Iph, approximately proportional to the incident optical power

$$I_{ph} = R \cdot P_{opt} \qquad (1)$$

where R is the photodiode's responsivity. Since Iph typically falls in the microampere range, it is far too small to be read directly by the microcontroller and must first be converted into a usable voltage — the role of the transimpedance stage described next. Reverse-bias operation was chosen for its faster response time, which matters since the system must resolve individual pulses on the order of hundreds of milliseconds, consistent with low-cost photodiode receiver designs reported elsewhere [7], [8].

B. Transimpedance Amplification and Lensing

The weak photocurrent is converted into a voltage by the LM324, configured as a transimpedance amplifier, with the output governed by the feedback resistor, Rf:

$$V_{out} = -\, I_{ph} \cdot R_f \qquad (2)$$

Because the photodiode sits at the amplifier's inverting input, brighter light produces a lower Vout — a relationship confirmed experimentally and accounted for in the thresholding logic. Increasing Rf raises sensitivity at the cost of bandwidth, an acceptable trade-off given the system's slow bit timing. Rf was set to 220 kΩ during initial bench testing and raised to 1 MΩ for final testing, meaningfully improving range and reliability. Double convex lenses were also added at both ends — one focusing the transmitter LED's output into a narrower beam, the other concentrating incoming light onto the photodiode — increasing the effective Popt reaching the receiver and working alongside the resistor change to extend usable range [7], [9].

C. Software-Based Adaptive Threshold Calibration

Rather than a hardware comparator, the amplified signal is read by the NodeMCU's ADC and thresholded in firmware. Each cycle averages n = 8 samples to reduce noise:

$$\bar{V} = (1/n)\, \Sigma\, V_i \qquad (3)$$

A bit is registered as present when

D = 1 if ∇ > T, else D = 0 (4).

This threshold is recalibrated before every session as the midpoint of dark and illuminated readings:

T = (Vdark + Vlight) / 2 (5)

This keeps the receiver simple and low-cost but does not automatically compensate for ambient light changes mid-session — a limitation discussed further below [9].

D. Bit Sampling

Each bit occupies a fixed duration, Tbit, sampled at its midpoint to avoid switching transitions:

tk = k·Tbit + Tbit/2 (6)

with Tbit = 200 ms, giving an effective raw bit rate:

Rb = 1 / Tbit (7)

This conservative duration keeps the system tolerant of the amplifier's reduced bandwidth (from the 1 MΩ resistor) and the added settling time introduced by the lenses and the underwater optical path.

E. Error Detection Using Hamming Distance

Each received sync byte, R, is checked against the fixed byte, S (0xAA), using Hamming distance:

E = popcount(R ⊕ S) (8)

A transmission is accepted only if:

Accept if E ≤ Eth = 5 (9)

allowing minor bit-level noise — inherent in any real-world optical link — to be tolerated without discarding an otherwise valid message, in the same spirit as forward error correction strategies used in related underwater optical systems [8].

V. RESULTS

The system was tested step-by-step, beginning in air over short distances and then underwater, with the transmitter and receiver properly aligned facing each other. With the feedback resistor (Rf) set at 220 kΩ, the link worked reliably only at very short ranges and required near-perfect alignment; even slight tilts or offsets caused missed bits or total signal loss, which the receiver accurately displayed as "no signal received." By increasing Rf to 1 MΩ and adding double convex lenses to both the transmitter and receiver, signal detection improved . The receiver was able to detect valid signals at longer distances and could tolerate minor misalignment better, although correct orientation remained important for consistent communication. Lowering the supply voltage at either node weakened the signal, leading to a higher rate of dropped or incorrect bits. Throughout testing, binary sequences shown on both Serial Monitors matched perfectly whenever alignment, power, and lens conditions were sufficient, and the receiver consistently reproduced the original transmitted message accurately under those conditions

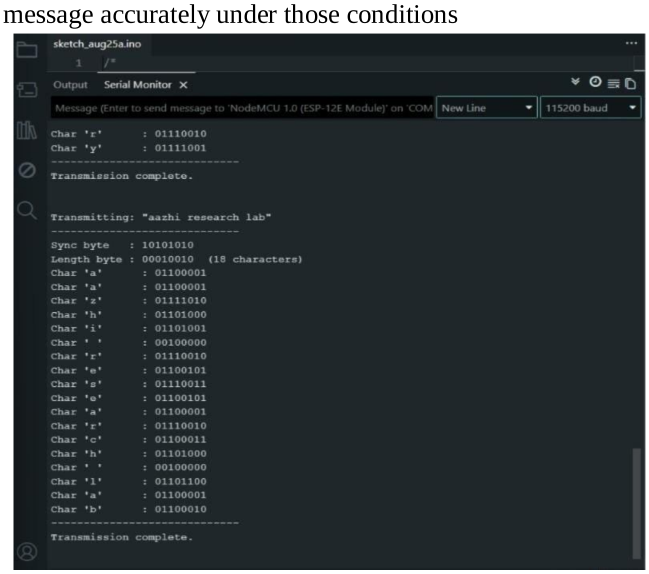

Fig.5 Transmitter Serial Monitor output.

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This Shows the transmitter encoding and sending the message "aazhi research lab" as a sync byte, a length byte, and the binary representation of each character. Every character's ASCII value is displayed in binary alongside its printed form before being sent as light pulses. The log confirms successful transmission with a clear "Transmission complete" status.

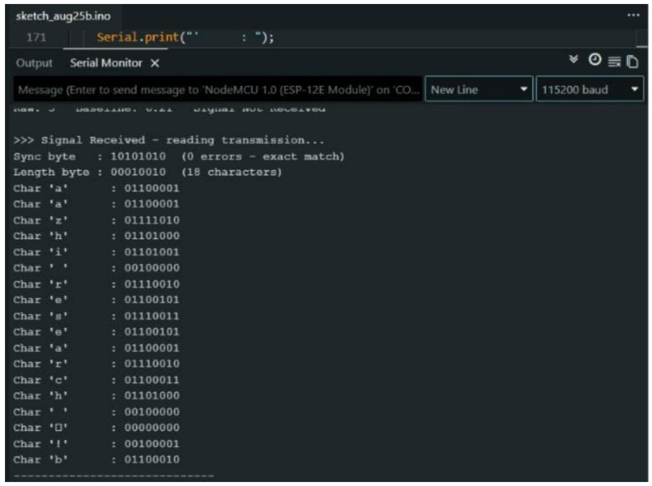

Fig. 6 — Receiver Serial Monitor output.

This Shows the receiver detecting a valid signal, reading the sync byte with zero bit errors (exact match) and the correct 18-character length byte. Each received character's binary sequence matches the transmitted values exactly, and the message is fully reconstructed character by character. This confirms error-free decoding under the tested alignment and power conditions.

VI. CONCLUSION

Radio waves die almost instantly underwater, and sound takes its place but drags speed and complexity along with it. This paper takes a different route entirely: light. By pairing a high-power LED and IRLZ44N MOSFET transmitter with a BPW34 photodiode and LM324 transimpedance-amplifier receiver, the system sends typed text messages as binary data straight through air and water, encoding every character in a pattern of on-off light pulses and decoding it back, bit by bit, on the other side, with both the sent and received binary sequences visible in real time on the two Serial Monitors.

Getting there meant real troubleshooting, not just wiring parts together. Reliable reception depended heavily on precise alignment and orientation between transmitter and receiver, and on adequate, stable power to both nodes — weak supply or poor alignment reliably showed up as noise, dropped bits, or an explicit "no signal received" report from the receiver. Increasing the receiver's feedback resistor from 220 kΩ to 1 MΩ, along with adding double convex lenses at both the transmitter and receiver ends to better focus and collect the light, meaningfully improved sensitivity and range, illustrating how much simple component and optical tuning can matter in a minimal analog front end. Under well-aligned, adequately powered conditions, the system consistently achieved accurate, error-free text transmission, as confirmed during testing.

What emerged is a working, self-contained optical link — no acoustic transducers, no WiFi, no external infrastructure, just a transmitter and receiver talking to each other through water using light alone. It proves the core idea cleanly: visible light can reliably carry real data underwater when the circuit is designed carefully and every failure mode is chased down. Future work may extend this system through automatic ambient-light calibration, a hardware comparator stage, forward error correction, and higher-throughput modulation schemes, to bring it closer to real-world diver communication and underwater sensor network deployments.

VII. ACKNOWLEDGMENT

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