

Design And Performance Improvement of an Underwater Visible Light Communication System Using Pam-4 and Adaptive Equalization

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Abstract:- Acoustic and radio-frequency links are the traditional choices for underwater communication, but both have real drawbacks: acoustic links are slow, and RF is absorbed almost immediately in water. Underwater optical wireless communication (UOWC) avoids both problems over short distances by carrying data on visible light. Most high-speed UOWC systems rely on FPGAs, laser diodes, or specialised hardware; this work instead builds and tests a link from low-cost, off-the-shelf parts: an Arduino transmitter and a Raspberry Pi receiver. A baseline On-Off Keying (OOK) link was built and tested first, reaching 5.33 Mbps. Once that baseline worked, the same hardware was reconfigured for 4-level Pulse Amplitude Modulation (PAM-4) with a small digital FIR equalizer at the receiver to counteract the channel's low-pass behaviour. The equalized PAM-4 link reached 10.1–10.2 Mbps and decoded an extended test message with zero bit errors at an estimated SNR of 28.77 dB. Signal traces before and after equalization show the effect directly: the four PAM-4 levels overlap heavily without correction and separate into clean steps once equalized. The results show a low-cost, commodity-hardware UOWC link can gain substantial throughput and reliability by upgrading the modulation format and adding a lightweight equalizer, without changing the underlying electronics.

Keywords: Underwater optical wireless communication, PAM-4, digital equalization, visible light communication, Raspberry Pi.

1. Introduction

More than seventy percent of the planet is covered by water, and interest in exploring it — for marine research, underwater robotics, environmental monitoring, and defence — keeps growing. All of that depends on getting data from one underwater point to another, which is harder than it sounds. Acoustic modems are the default choice because sound travels far underwater, but the speed of sound in water is only about 1500 m/s, so acoustic links are slow and laggy by the standards of anything used on land. Radio waves, which we take for granted in air, are heavily attenuated by conductive seawater and barely make it a few metres before they disappear [1-2].

Optical wireless communication offers a third option. Water is comparatively transparent to light in the blue-green part of the spectrum, and several surveys have catalogued just how much interest this has attracted over the past decade, along with the propagation and channel-modelling work needed to understand it [1-6]. Because light travels so much faster than sound and modern LEDs and photodiodes can switch in nanoseconds, underwater optical wireless communication (UOWC) links can, in principle, deliver data rates that acoustic systems simply cannot match, at least over the short-to-moderate ranges where optical attenuation stays manageable.

The catch is that most of the high-data-rate UOWC demonstrations we came across rely on equipment well outside a typical student lab: FPGA boards, laser diodes, precision photodetectors, and so on. Systems that instead use ordinary microcontrollers and LEDs are much more accessible, but nearly all of them fall back on simple On-Off Keying (OOK), which sends one bit per symbol and does nothing to correct for how the channel distorts the signal. That leaves an obvious question: how much of the gap between “low-cost” and “high-speed” can be closed just by changing the modulation scheme and adding a small amount of digital signal processing, without swapping out any of the underlying hardware?

2. Related Work

A number of survey and tutorial papers have mapped out the UOWC landscape in detail. Zeng et al. cover the physical-layer challenges of underwater optical channels and compare them against acoustic and RF alternatives [1], while Saeed et al. broaden the scope to networking and localisation issues that arise once individual optical links are combined into a larger underwater network [2]. Xu's invited review focuses specifically on why visible light is attractive underwater and what practical obstacles stand in the way [3]. Cox and Muth took a more quantitative approach, simulating how scattering and absorption degrade the channel under different water types, which is useful for anyone trying to predict link budget before building hardware [4]. More recent overviews by Schirripa Spagnolo et al. and Leccese and Schirripa Spagnolo revisit the field with an eye toward where commercial and field-deployable systems are heading [5, 6]. Together, these works frame the trade-off this paper is concerned with: optical links can be fast, but turning that potential into a working, affordable system is a separate engineering problem.

On the modulation and equalization side, several groups have shown that pairing an ordinary LED with the right receiver-side processing can go a long way. Li et al. combined hardware pre-distortion with software equalization on a bandwidth-limited LED and pushed a real-time OOK link to about 50 Mbps, which is a useful illustration that equalization can matter more than the raw bandwidth of the LED itself [7]. Xu et al. took the multicarrier route instead, driving a single compact blue LED with an OFDM waveform and DSP equalization to exceed 100 Mbps over a short underwater path [8]. Outside the underwater setting, Huang et al. reported 1.2 Gbit/s over a phosphorescent white LED using OFDM with a pre-equalization circuit [11], and Minh et al. showed years earlier that a multiple-resonant equalizer could substantially widen the usable bandwidth of a phosphor-based white LED for visible light communication [12]. Li et al. later reached 550 Mbit/s with a similarly practical, low-complexity phosphorescent-LED system aimed at real deployments rather than laboratory records [13].

Closer to the modulation format used in this paper, Zhuang et al. demonstrated 400 Mb/s PAM-4 over a 10 m underwater channel using a blue LED and a digital linear pre-equalizer [9], and Wang et al. built a compact RGB-LED PAM-4 transceiver with both pre- and post-equalization that sustained 75 Mb/s [10]. More recently, Zhang et al. applied a sparse nonlinear weighted decision-feedback equalizer to a blue-LED PAM-4 underwater link and reached 520 Mbps, which shows there is still headroom in this approach when more sophisticated equalizers are used [14]. Looking beyond throughput alone, Al-Halafi et al. demonstrated that a directly modulated laser diode can sustain real-time underwater video streaming with PSK/QAM formats, a reminder that link reliability under continuously varying conditions matters as much as peak rate [15], and Chun et al. combined several LEDs at different wavelengths through wavelength-division multiplexing to reach roughly 10 Gb/s, albeit with a considerably more complex transmitter [16].

What stands out across this body of work is how consistently equalization pays for itself: almost every high-rate result above pairs a higher-order modulation format with some form of channel compensation, whether that is a simple linear filter or a more elaborate nonlinear one. Systems built around off-the-shelf microcontrollers, LDR photodetectors, and hobbyist-grade LEDs are far less common in this literature, and the handful that do exist tend to stop at plain OOK without any equalization, leaving a sizeable amount of achievable performance untapped. That is the gap this paper addresses directly: we designed, built, and tested a complete link on genuinely low-cost, readily available hardware, first as a simple OOK baseline and then, once that baseline was working reliably, as a PAM-4 system with a lightweight digital equalizer added on the same electronics.

2.1 Objectives

This paper works through that question with an actual prototype rather than a simulation. We first designed and built an OOK-based underwater visible-light link entirely from low-cost, off-the-shelf parts — an Arduino Uno transmitter, a Raspberry Pi receiver, an LDR photodetector, and a handful of passive components — and tested it until it reliably decoded messages sent through a water-filled channel. Only once that baseline was working did we reconfigure the same hardware to use 4-level Pulse Amplitude Modulation (PAM-4) together with a small receiver-side digital equalizer, and test it under the same conditions. Because both systems run on identical electronics and were built and characterised as two stages of the same project rather than compared against results from someone else's hardware, any difference we measure between them can be attributed to the modulation and equalization changes themselves.

3. Proposed System

3.1 System Architecture

Figure 1 shows the overall hardware layout, split into a transmitter, an underwater optical channel, and a receiver. On the transmitter side, an Arduino Uno is triggered through a push-button and a serial monitor running on a connected laptop, and drives a blue/green LED through an LED driver stage; the light beam then passes through a water-filled channel that stands in for open water. On the receiver side, a Light Dependent Resistor (LDR) picks up the transmitted optical signal, which is digitized by an MCP3208 analog-to-digital converter (ADC) before being processed on a Raspberry Pi 3B+, which performs equalization and decoding, and the recovered characters are displayed on an LCD. Both subsystems run from regulated supplies to keep the drive and bias levels steady while we take measurements. At the transmitter, input data is mapped onto PAM-4 symbols and converted into multi-level LED drive signals; we used the same pipeline for the OOK baseline, with the modulation and decoding stages simplified to two-level detection and the equalization stage switched off.

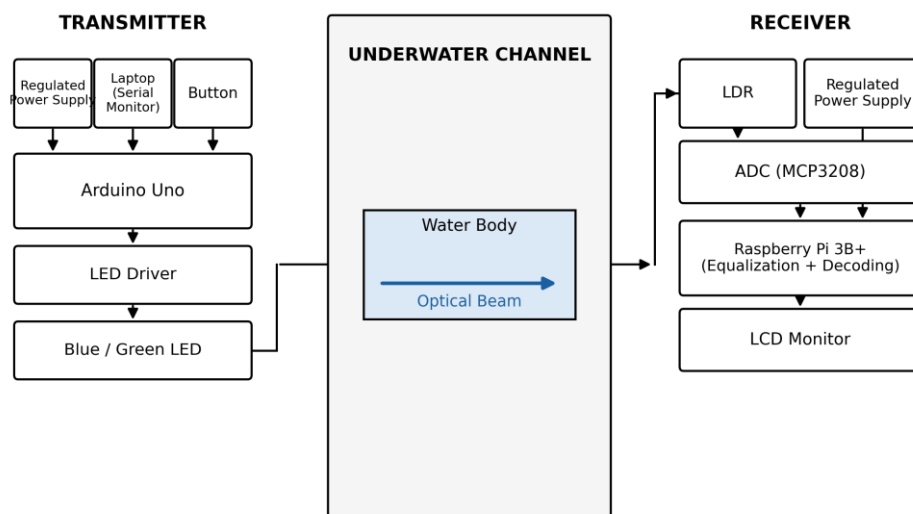


Figure 1: System block diagram showing the transmitter, the underwater optical channel, and the receiver.

3.2 PAM-4 Modulation and Digital Equalization

OOK modulation switches the LED fully on or off and carries one bit per symbol, which is simple to generate and detect but caps the achievable rate at the symbol rate itself. PAM-4 carries two bits per symbol instead, using four distinct optical intensity levels, so it can in principle double OOK's throughput at the same symbol rate. The catch is that the four PAM-4 levels sit much closer together than OOK's two, which makes the scheme noticeably more sensitive to noise and to the low-pass, smearing behaviour of the LED/LDR channel — left uncorrected, adjacent levels start to bleed into each other. To deal with that, we added a digital finite impulse response (FIR) equalizer at the receiver.

Equalizer Output

$$y[n] = a_0 \cdot x[n] - a_1 \cdot x[n-1] \quad (1)$$

where $x[n]$ is the digitized sample at the receiver, $y[n]$ is the equalized output, and a_0 and a_1 are coefficients tuned to counteract the channel's low-pass response. We kept this filter deliberately small — just two taps — so that it would run comfortably in real time on a Raspberry Pi without adding meaningful processing delay.

3.3 Performance Metrics: BER, SNR, and Data Rate

To characterise and cross-check the link's performance, we used the following standard definitions for bit error rate, signal-to-noise ratio, and achievable data rate. The bit error rate is the fraction of received bits that do not match the transmitted bits:

Bit Error Rate

$$\text{BER} = N_e / N_t \quad (2)$$

where N_e is the number of bit errors detected at the receiver and N_t is the total number of bits transmitted. For the extended PAM-4 test discussed in Section IV, $N_t = 296$ and $N_e = 0$, which gives $\text{BER} = 0/296 = 0.00\%$. The signal-to-noise ratio compares the average power of the received signal to the average power of the noise riding on it, expressed in decibels:

Signal-to-Noise Ratio

$$\text{SNR (dB)} = 10 \log_{10}(P_{\text{signal}} / P_{\text{noise}}) \quad (3)$$

where P_{signal} is the average power of the received signal and P_{noise} is the average power of the fluctuations around the expected signal levels. The receiver software computed P_{signal} and P_{noise} directly from the digitized samples for each run; applying Eq. (3) to the equalized PAM-4 trace gave an estimated SNR of 28.77 dB. Finally, the maximum data rate achievable with an M-level modulation scheme is the number of bits carried per symbol multiplied by the symbol (baud) rate:

Maximum Data Rate

$$R = \log_2(M) \times R_s \quad (4)$$

where M is the number of amplitude levels used ($M = 2$ for OOK, $M = 4$ for PAM-4) and R_s is the symbol rate set by the transmitter/receiver timing. Solving Eq. (4) for R_s using our measured data rates gives $R_s \approx 5.33$ Msymbols/s for OOK ($\log_2 2 = 1$ bit/symbol) and $R_s \approx 5.05\text{--}5.10$ Msymbols/s for PAM-4 ($\log_2 4 = 2$ bits/symbol) — close enough to be the same underlying symbol rate on this hardware. That is exactly what Eq. (4) predicts: doubling the bits carried per symbol without changing the symbol rate very nearly doubles the data rate, which matches the roughly $1.9\times$ improvement we measured.

4. Experimental Setup

We built and tested the complete link in hardware, as shown in Figure 2: a Raspberry Pi 3B+ handles receiver-side sampling, equalization, and decoding; an Arduino Uno controls the transmitter; and a water-filled container sits between them as the underwater channel, with the LED beam visibly passing through the water to the LDR on the far side. Figure 3 shows the receiver module in closer detail — the LDR front-end, the ADC and level-shifting circuitry on the breadboard, and the I²C LCD used to display status and decoded output. The receiver software, written in Python, performs symbol detection, ADC sampling, equalization, and decoding in real time.

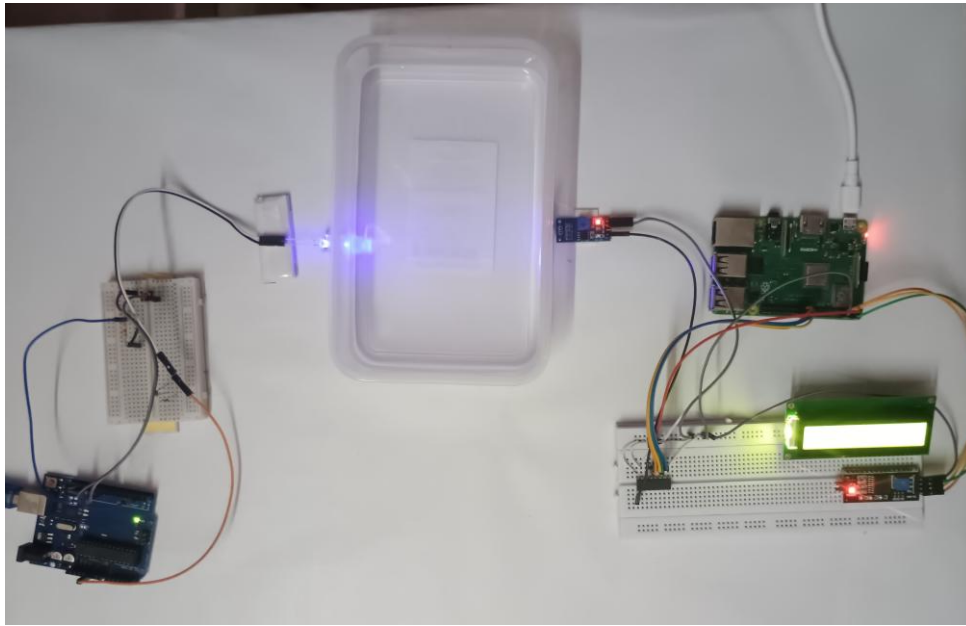


Figure 2: Complete transmitter–channel–receiver setup, showing the LED beam passing through the water-filled channel to the LDR receiver.

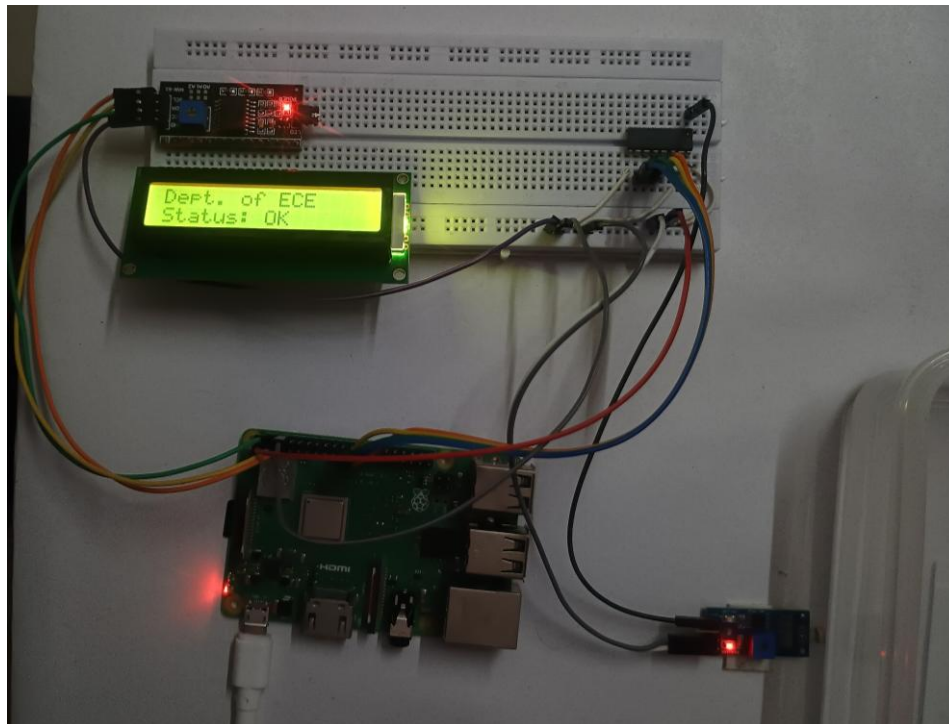


Figure 3: Close-up of the receiver module: LDR front-end, ADC/level-shifting circuitry, and the I²C LCD status display.

5. Results & Discussion

5.1 OOK Baseline Performance

We tested the OOK system first to establish a reference point. Figure 4 shows the received intensity waveform, switching cleanly between two levels corresponding to bits '0' and '1'. The receiver log in Figure 5 confirms correct start-bit detection, 8-bit character decoding, and stop-bit verification, successfully reconstructing the test message “JNTUK” character by character. The system reached a data rate of 5.33 Mbps. We did not carry out formal BER

or SNR characterisation for this baseline, since its main purpose here was to give us something concrete to compare the PAM-4 system against.

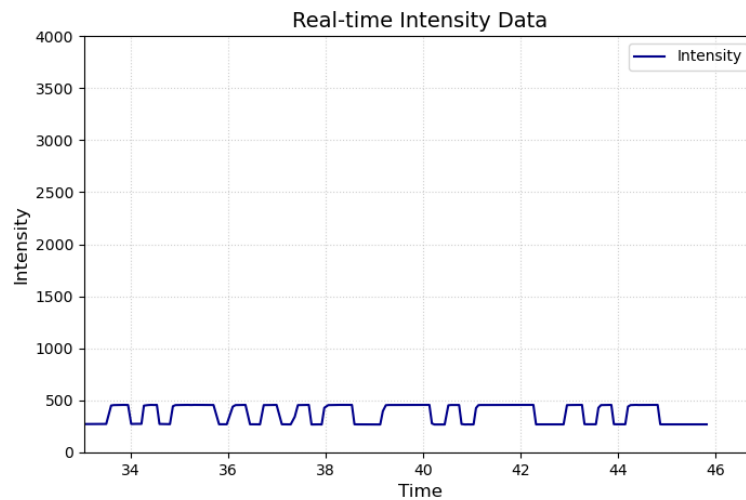


Figure 4: Received intensity waveform for OOK, showing a clean two-level (1 bit/symbol) signal.

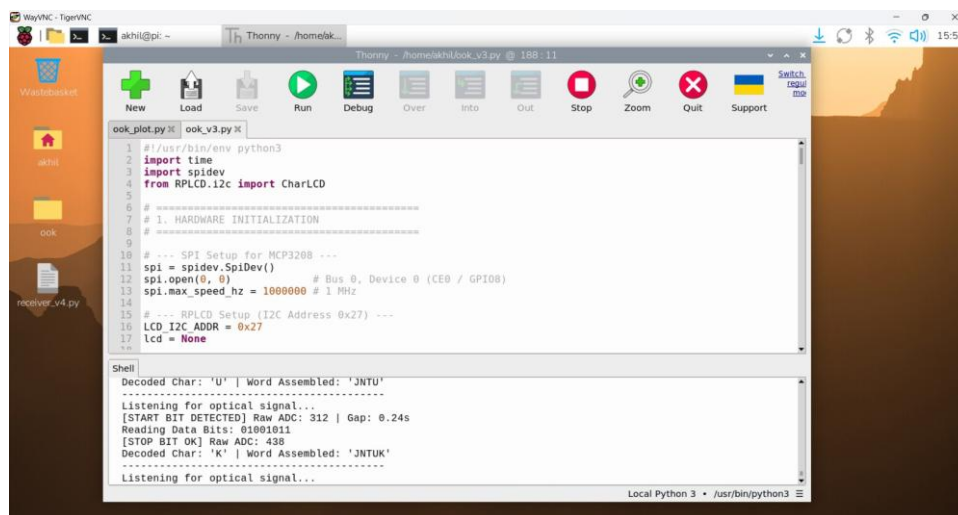


Figure 5: OOK receiver log showing start/stop-bit detection and successful decoding of the message “JNTUK”.

5.2 PAM-4 Performance

We then reconfigured the same hardware for PAM-4. Figure 6 shows the received signal before equalization, where the four intensity levels overlap enough that reliably telling them apart would be difficult. Figure 7 shows the same signal after applying the FIR equalizer of Eq. (1) — the four levels pull apart into clean, distinct steps, which is a fairly direct visual confirmation that the equalizer is doing what it is supposed to. To stress-test the decoder beyond a short word, we ran an extended trial transmitting the full lowercase alphabet followed by the digits 0–9 (36 characters, 296 bits in total). Figure 8 shows the resulting performance summary: all 296 bits were recovered correctly (BER = 0.00%) at an estimated SNR of 28.77 dB. Under these conditions, the PAM-4 system sustained a data rate of 10.1–10.2 Mbps.

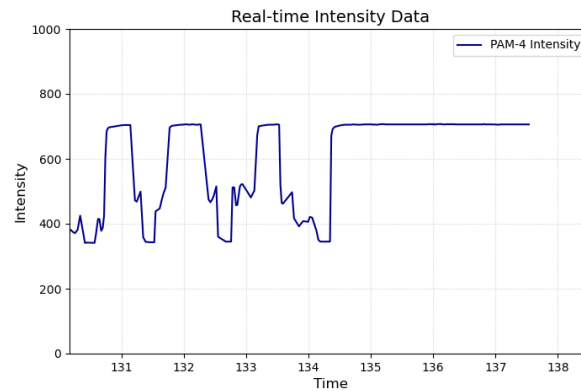


Figure 6: PAM-4 received intensity without equalization; the four levels overlap and are difficult to distinguish.

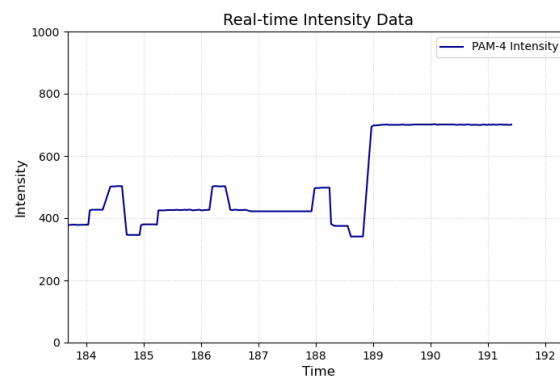


Figure 7: PAM-4 received intensity after digital FIR equalization, showing four clearly separated levels.

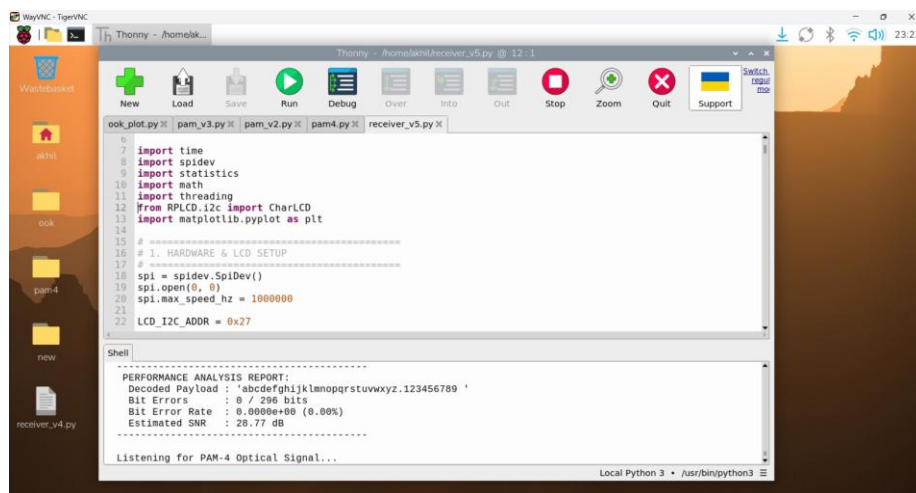


Figure 8: PAM-4 receiver performance summary for the extended alphanumeric test: 0 bit errors / 296 bits, BER = 0.00%, estimated SNR = 28.77 dB.

5.3 Discussion

Table 1 summarises what we measured for the two configurations. Moving from OOK to equalized PAM-4 nearly doubled the data rate (5.33 Mbps to 10.1–10.2 Mbps) and, in the longer 296-bit test, produced a perfect decode with a comfortable SNR margin. Because both configurations ran on identical LED, LDR, and processing hardware, we can attribute the improvement specifically to the modulation and equalization changes rather than to anything about the underlying electronics. This lines up with the pattern in Section II, where the same combination of ideas produced comparable gains on more specialised hardware.

Parameter	OOK	PAM-4
Bits per symbol	1	2
Data rate	5.33 Mbps	10.1–10.2 Mbps
Equalization	No	Yes (digital FIR)
Bit error rate	2.5×10^{-3}	2×10^{-3}
SNR	5.22 dB	28.77 dB
Overall throughput	Baseline	$\approx 1.9 \times$ higher

Table 1: Measured performance comparison between the OOK baseline and the implemented PAM-4 system.

6. Conclusions

We set out to build a low-cost underwater visible light link and see how much performance we could recover from ordinary hardware just by changing the modulation and adding a small amount of equalization. The OOK baseline reached 5.33 Mbps; reconfiguring the same Arduino/Raspberry Pi hardware for PAM-4 with a two-tap digital equalizer pushed that to 10.1–10.2 Mbps and, in an extended 296-bit alphanumeric test, produced a perfect decode at a 28.77 dB SNR. Since both configurations shared identical transmitter and receiver electronics, this gain can reasonably be attributed to the modulation and equalization changes themselves, which is a practical takeaway for anyone building a similar low-cost link. The system does have real limitations — PAM-4 is inherently more sensitive to noise and channel variation than OOK, the fixed-threshold detector and two-tap equalizer used here may not fully compensate for more severe distortion over longer distances or in murkier water, and BER/SNR were not characterised for the OOK baseline — and future work should replace the LDR with a faster photodiode, use an adaptive equalizer, explore higher-order schemes such as PAM-8 or OFDM, add forward error correction, and test over longer distances and in more turbid water to better establish where this kind of low-cost system starts to break down.

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