Toward a Testbed for the Internet of Underwater Things: Challenges and Considerations

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Abstract

The Internet of Underwater Things (IoUT) is an emerging approach composed of a network of underwater devices, such as sensors, vehicles, and communication nodes, that collaboratively collect, transmit, and analyze data for applications such as ocean monitoring, underwater exploration, and defense. The vision of IoUT includes significant challenges for communication due to signal attenuation, multipath interference, and limited bandwidth. This paper presents the design, implementation, and evaluation of a basic underwater acoustic communication system. One of the purposes of this paper was to explore how components coming from the Internet of Things (IoT) ecosystem can be integrated into the IoUT paradigm. Therefore, we compare a microcontroller with a signal generator for the signal generation process to evaluate performance trade-offs. Performance was assessed across configurations in a pool environment. Key findings include reliable communication at 300 bps up to 6 meters (BER $<$ 10% with Hamming encoding) and reliable performance up to 1000 bps at 1 meter (BER $\approx$ 1%) using a microcontroller instead of a signal generator. This paper demonstrates the first steps to build a testbed to evaluate IoUT solutions that will offer practical insights into the challenges and performance factors of simple underwater acoustic communication.

CCS Concepts

• **Networks** → **Network experimentation**; **Network measurement**; **Network performance analysis**; • **Computer systems organization** → **Embedded and cyber-physical systems**.

Keywords

Underwater Acoustic Communication, Internet of Underwater Things

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1 Introduction

The vision of the Internet of Underwater Things (IoUT) aims to extend the ecosystem of the Internet of Things (IoT) to aquatic environments [4, 15]. This requires reliable communication infrastructure in challenging underwater channels. Unlike terrestrial IoT, which primarily uses electromagnetic or optical waves [14], underwater communication relies predominantly on acoustic waves due to their better propagation characteristics over long distances [18]. However, acoustic channels present unique difficulties: limited bandwidth (often kHz range), high latency (approximately 1500 m/s speed of sound), significant multipath propagation, Doppler shifts, and energy constraints on submerged devices [10, 11].

This paper highlights these challenges by designing and implementing a basic underwater acoustic communication system [17]. The primary goal is to establish reliable data transmission underwater using accessible hardware and fundamental signal processing techniques and explore how components coming for the IoT ecosystem, such as a low-power microcontroller, can be integrated into the IoUT. A secondary goal is to investigate and understand the practical challenges of this environment through experimental evaluation.

The implemented system employs Amplitude Shift Keying (ASK) modulation for its simplicity and non-coherent envelope detection on the receiver side, avoiding complex phase synchronization. We incorporate preamble-based synchronization using Barker codes [9] for reliable message detection and explore error-correcting encoding schemes to improve data integrity.

The performance of the system is extensively evaluated in a controlled pool environment illustrated in Figure 1, focusing on factors such as transmission distance, carrier frequency, signal amplitude, bitrate, payload characteristics and the impact of error correction.

This paper presents a functional IoUT system and provides valuable insights into the practical performance and limitations of ASK-based underwater acoustic communication, under realistic (though controlled) channel conditions. In addition, it lays the foundation for the building of a testbed to enable large-scale evaluation of IoT solutions in both hardware and software.

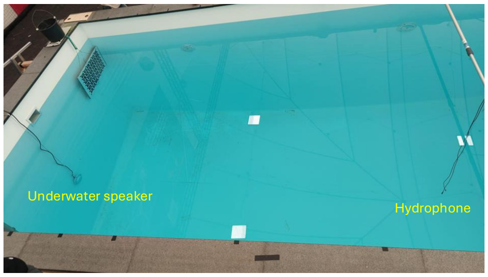


Figure 1: The pool used for the evaluation.

2 System Design

The implemented underwater acoustic communication system is based on off-the-shelf electronics. Namely we used a signal generator [12] or an ESP32 microcontroller [1] with an amplifier [7] to generate the signal, an underwater speaker [6] to transmit the signal through acoustic waves and a hydrophone [3] as receiver. The signal is received at the sound card of a laptop and then post-processing techniques take place. Figure 2 presents the overview of the system.

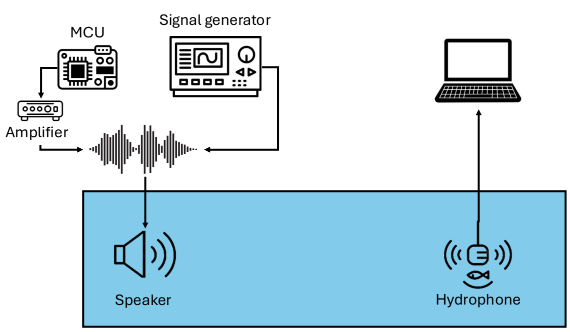


Figure 2: System overview, both the MCU and the signal generator are used in our setup to compare their performance.

The main functions of the transmission side is to convert a random string of characters to bits, append a preamble, and apply error-correction encoding. Then a modulated waveform is generated using ASK modulation, where binary '1' is represented by a carrier wave burst and binary '0' by a low-amplitude (ideally zero) signal. The main idea here is to investigate the performance of two different components generating the signal. The first one was a **Agilent 33250A Signal Generator:** which provides arbitrary waveform generation with high resolution and precise timing utilizing a 12-bit Digital to Analog Converter (DAC), modulating a precomputed waveform onto a carrier. The second component was a component that is more fitting to the IoT ecosystem due to its low-cost and its low-power consumption. Namely **ESP32 Microcontroller:** has an 8-bit DAC and generates waveforms by switching between precomputed symbol waveforms for '1' (carrier burst) and '0' (low value). However it requires external amplification and voltage division to drive the underwater speaker effectively, introducing potential discontinuities between symbols. Both setups use an UW30 underwater speaker [6] as a transducer. A Barker-13 sequence is used as the preamble due to its strong autocorrelation properties aiding synchronization [9]. Hamming encoding is implemented to correct single-bit errors in the payload. The receiver is an AS-1 hydrophone [3] connected to an external sound card [16] for analog-to-digital conversion (sampled at 96 kHz). The digital signal undergoes a DSP pipeline: **1. Filtering:** Band-pass filtering is optionally applied to the raw signal to mitigate noise outside the carrier frequency band. **2. Envelope Detection:** Non-coherent demodulation is performed by computing the magnitude of the analytic signal's frequency spectrum. This removes the carrier frequency, leaving the envelope which carries the data information. **3. Normalization and Thresholding:** The envelope is low-pass filtered to remove high-frequency noise normalized to the range [0, 1], and then binarized using a fixed threshold. Symbol values (0 or 1) are determined by averaging samples within each symbol period. **4. Preamble Detection:** Cross-correlation with the known Barker-13 preamble is computed to locate transmission starts. Peaks in the correlation output indicate potential preamble locations. **5. ECC Decoding:** If Hamming encoding was used by the transmitter, the corresponding decoding is applied to correct bit errors in the detected payload.

The non-coherent envelope detection simplifies receiver hardware but makes the system more susceptible to noise and amplitude variations compared to coherent methods [13].

3 Methodology and Evaluation

The system's performance was evaluated through a series of tests conducted in a pool environment (6.5 m x 3.5 m x 3 m). The speaker and the hydrophone were placed at a depth of 2 m. The tests explored the impact of physical parameters (distance, carrier frequency, amplitude) and DSP parameters (payload characteristics, bitrate, ECC). The key performance indicators were the bit error rate (BER) and the invalid transmission rate (ITR), defined as the inability to successfully detect the preamble. The following highlights summarize our key findings.

Distance and Carrier Frequency: Performance varied significantly with distance and carrier frequency, suggesting the presence of multipath interference in the pool. High signal power did not always correlate with low BER. For instance, when we used 11 kHz as carrier frequency we observed high power but also high BER as it is depicted in Figure 3. In a different experiment, when carrier frequency was 13 kHz we measured lower signal power but less BER. This highlights the need for careful frequency selection based on the environment.

Varying Amplitude: Another expected yet quantified observation is the impact of the signal amplitude on the detection of the preamble. We observed that when the amplitude was below 2 V (peak-to-peak), 80% of the received transmissions could not be decoded. When the amplitude was above 2 V, the amount of received transmissions that could not be decoded was below 16%, indicating a threshold for reliable detection. BER was less sensitive to amplitude variations above this threshold. *Payload Characteristics* The system performance was highly sensitive to payload composition. Payloads with a Payload Preamble Correlation (PPC) value of 9 led to a significant increase in the bit error rate (BER), reaching

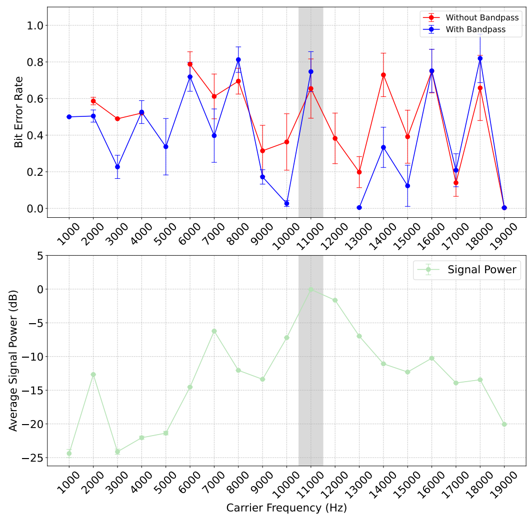
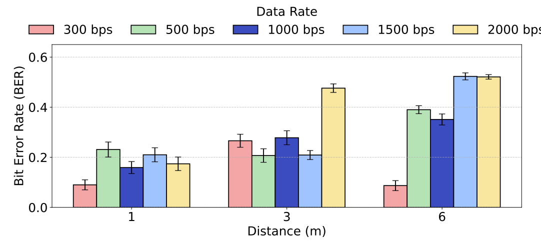
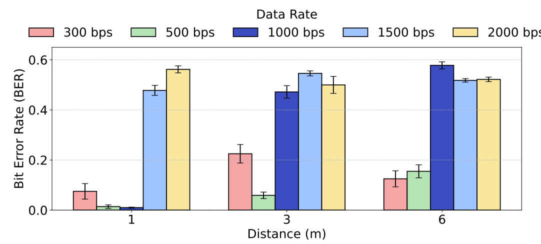


Figure 3: Signal power and BER at 2 meters, 200 bps, with 11 kHz carrier frequency highlighted for high power and BER.



(a) BER for signals generated with ESP32.



(b) BER for signals generated with the Signal Generator.

Figure 4: Overall caption for both figures

50%, due to incorrect preamble detections occurring within the payload. Messages with alternating '1's and '0's resulted in lower BER and less transmissions that could not be decoded than random payloads of similar length. Most likely this was observed because alternating patterns create a more predictable, narrowband signal structure. *BER Comparison* We performed another experimental scenario in which we investigated the BER of both ESP32 and the signal generator for different distances and bitrate values. Figure 4 presents the results that show that performance is dependent on both distance and data rate, with higher data rates leading to higher BER as expected. When comparing the two signal sources, the signal generator provides slightly better performance at very low data rates (300, 500 bps) over short distances (1m). However, its performance deteriorates for moderate data rates (1000 bps) beyond 1m and is severely limited for higher data rates (1500, 2000 bps) across all distances tested. The ESP32, while not achieving the lowest BER at 1m for all low rates, demonstrates significantly better distance robustness, particularly for the 300 bps rate. Surprisingly, the ESP32 substantially outperforms the Agilent generator at moderate (1000 bps beyond 1m) and especially at high data rates (1500, 2000 bps) across all distances.

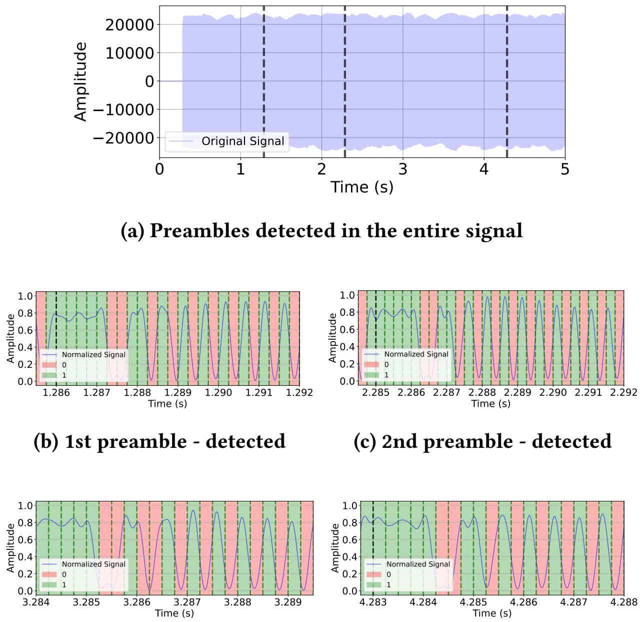
These findings suggest that for applications requiring moderate to high data rates in this acoustic communication setup, the ESP32 is a more suitable and effective signal source than the Agilent 33250A signal generator, despite the latter being a professional laboratory instrument. The ESP32's performance at higher data rates should be investigated further as it demonstrated a promising performance and it has the specifications (i.e., low-cost, low-power) that IoT ecosystem is built upon.

Hamming Encoding: Hamming Encoding significantly improved BER and ITR, particularly at longer distances and higher data rates. This was another observation that was expected. At 300 bps and 6 meters, Hamming encoding reduced the signal generator's BER from 11.2% to 5.4%. At 2000 bps and 1 meter, Hamming reduced the Signal Generator's BER from 30.8% to 7.0%. Bit flips from $1 \rightarrow 0$ were consistently $2\% - 6\%$ more frequent than $0 \rightarrow 1$ flips. Note that we did not manage to implement Hamming encoding for the ESP32 case within the time-frame of this project.

Limitations: A limitation that was noticed is that for messages longer than 1000 bits, cumulative timing errors between transmitter and receiver clocks caused symbol misalignment, leading to bit insertions and deletions. The reason for this issue comes from clock mismatches and the receiver's fixed decision window without continuous symbol tracking. To verify that this drift comes from digital timing mismatch rather than acoustic propagation, a closed loop is constructed directly from the transmitter's output into the sound card input.

Figure 5 shows successive detections of the Barker-13 preamble during a 4000-bit transmission at 4,000 bps with a 10 kHz carrier frequency. While the first, second and fourth preamble (Figures 5b, 5c and 5e) align closely, during the third (Figure 5d) the misalignment becomes significant enough to prevent preamble detection. This confirms that timing error accumulates and reverts over the course of the payload.

Two factors drive this drift. First, clocks between transmitter and receiver can differ by up to several tens of parts per million (ppm), resulting in small timing offsets that accumulate over the duration of the transmission. A small frequency offset gradually shifts symbol boundaries by one or more samples, causing random bit flips when decoding over seconds. Second, the receiver currently uses a fixed timing window, set only at the start of each session, with no mechanism for dynamic symbol tracking. Hence, symbol alignment relies solely on initial synchronization and remains vulnerable to drift. For short packets or lower data rates, total timing error remains below half a symbol period, so this issue can be avoided. Shorter payloads introduce less overhead before



(a) Preambles detected in the entire signal

(b) 1st preamble - detected **(c) 2nd preamble - detected**

(d) 3rd preamble - not detected **(e) 4th preamble - detected**

Figure 5: 4 preambles detected in a transmitted signal. The 3rd preamble is not correct detected due to bit drifting.

transmission. In the testing setup, the signal is transmitted and recorded in a fast succession, increasing the likelihood that the timing windows aligns for these shorter transmissions. To eliminate bit drift, a timing-recovery stage prior to thresholding should be implemented but due to time constraints it was postponed to future work.

The system demonstrates the feasibility of basic underwater acoustic communication using low-cost components from the IoT ecosystem. The exploratory approach yielded valuable insights into the practical challenges. The sensitivity to environmental factors (distance, carrier frequency) highlights the need for adaptability in real-world deployments, possibly addressed by feedback protocols using techniques like OFDM [5] to select optimal frequencies. The simplicity of ASK while less challenging to implement, it is vulnerable to amplitude distortions and noise, leading to asymmetric bit flips (more 1→0 errors) [2]. Exploring alternative modulations like BPSK could offer higher robustness, though it introduces the complexity of coherent detection and phase synchronization [8].

4 Conclusion and Future Work

We successfully designed, implemented, and evaluated a basic underwater acoustic communication system using ASK, DSP, and ECC. The system achieved bitrates up to 2000 bps at short range and reliable communication (BER < 10%) up to 6 meters at lower bitrates with Hamming encoding. Performance is sensitive to physical parameters, payload characteristics, and timing synchronization. Furthermore, we plan to use less powerful underwater speakers in order to be operated solely by a microcontroller, without an additional amplifier to decrease the power consumption even further. Key limitations, including bit drifting and a preamble detection flaw, were identified through systematic testing. Despite these limitations, the paper demonstrates a functional system and provides empirical insights into the practical challenges of underwater acoustic communication, laying the groundwork for future improvements towards more robust and practical IoUT applications.

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