



PERFORMANCE IMPROVEMENT OF AN UNDERWATER SENSOR NETWORK USING MULTIPATH-AWARE ACOUSTIC COMMUNICATION AND EQUALIZATION

Girish Kumar Tiwari*1, Anil Chouhan*2,

M.E. (Digital Communication), Department of Electronics & Communication Engineering, Ujjain Engineering College,
Ujjain, Madhya Pradesh, India

ABSTRACT

This paper presents the second phase of an underwater sensor network study for environmental monitoring. The earlier phase evaluated packet forwarding and energy use in a simplified acoustic link. The present work moves to the next communication problem: multipath propagation. In water, the transmitted acoustic signal can arrive at the receiver through a direct path and through delayed reflected paths. These delayed components produce inter-symbol interference and can increase the bit error rate even when the routing path is suitable. To study this effect without making the project unnecessarily complex, a three-path acoustic channel is introduced and a short trained linear equalizer is applied at the receiver. Binary phase-shift keying is used and the channel is evaluated from 0 to 20 dB SNR. The comparison is made between the same multipath link before and after equalization using Bit Error Rate (BER) and Packet Delivery Ratio (PDR). In the reproducible numerical simulation, BER at 10 dB decreases from about 0.0480 without equalization to about 0.0048 with equalization. At 12 dB, the estimated PDR of a 256-bit packet improves from almost zero to about 85.8%. At 14 dB, the equalized link provides approximately 99.4% packet delivery. The results show that a simple receiver equalizer can reduce the effect of multipath and ISI and can provide the communication-layer improvement required after the routing-focused first phase. In the common executed results, packet delivery is also counted directly over non-overlapping 256-bit held-out blocks; the table reports that direct error-free packet fraction, not a full routed-network PDR.

Keywords: Underwater Sensor Network, Acoustic Communication, Environmental Monitoring, Multipath, Inter-Symbol Interference, Equalization, BER, PDR.

I. INTRODUCTION

Underwater sensor networks provide a practical way to observe water environments at locations where continuous manual measurement is difficult. Sensor nodes can collect temperature, pressure and water-quality information and forward these measurements to a surface station. For moderate and long underwater links, acoustic communication is commonly studied because electromagnetic radio signals are strongly attenuated in water.

The first phase of this project established the environmental-monitoring network and compared Basic Depth-Based Routing with an energy- and reliability-based forwarding method. That phase intentionally used a simplified acoustic link so that the effect of routing could be observed clearly. It also identified a limitation: improving the route cannot by itself remove distortion produced by the underwater propagation channel.

Multipath is one of the important physical-layer problems in underwater acoustic communication. A transmitted waveform may reach the receiver through the direct path and also after reflection from the water surface, bottom or nearby boundaries. The copies do not arrive at exactly the same time. When a delayed copy of one symbol overlaps the next symbol, inter-symbol interference (ISI) is produced. The receiver can therefore make bit errors even when the average received signal power is acceptable.

Equalization is used at the receiver to reduce this type of distortion. Advanced underwater receivers may use decision-feedback processing, iterative detection, message passing or learning-based channel estimation. For the present M.E. phase, however, a simpler equalizer is more suitable because its operation and result can be explained directly. The objective is not to reproduce a highly complex receiver from the literature, but to demonstrate the communication improvement obtained when multipath distortion is compensated.

Accordingly, this paper extends the completed Phase-1 network rather than repeating its routing comparison. The proposed routing concept from Phase-1 is treated as the network foundation, while the new contribution of Phase-2 is the multipath-aware acoustic link and receiver equalization.

A. Main Objectives

1. To extend the Phase-1 underwater environmental monitoring model with a multipath acoustic channel.
2. To observe the effect of delayed acoustic paths and ISI on received data.
3. To apply a simple trained linear equalizer at the receiver.
4. To compare the same multipath channel with and without equalization using BER and PDR.
5. To create a communication-layer improvement that can later be integrated with Phase-1 routing in the final project.

II. RECENT LITERATURE AND RESEARCH GAP

Recent underwater acoustic communication research shows that multipath, long delay spread, Doppler variation and noise can strongly affect received data. Channel tracking for moving transceivers [1], joint frequency-offset and channel estimation [2], and Doppler compensation [3] show why receiver processing is important.

Multipath is the main Phase-2 problem in this project. Time-reversal processing [4], chirp-based communication analysis [5], and experimental modulation comparison in multipath channels [6] all show that delayed acoustic arrivals can reduce communication quality.

Channel estimation is closely related to equalization. Recent IEEE work includes deep-learning-assisted estimation [7], model-driven estimation for uncertain channel sparsity [8], temporal-correlation and message-passing methods [9], VAMP-based MIMO-OFDM estimation [10], sparse OSDM estimation [11], and DenseNet-based estimation [12]. These methods are more advanced than the present project but support the need to account for underwater channel distortion.

Equalization directly addresses inter-symbol interference. Joint equalization and self-interference cancellation [13], low-complexity RLS decision-feedback equalization [14], and a multi-layer VAMP receiver evaluated on the WATERMARK benchmark [15] demonstrate different receiver approaches. The present paper intentionally uses a simpler trained linear equalizer so that its operation and improvement can be explained clearly.

Other physical-layer studies provide supporting context. Robust underwater OFDM synchronization [16], Doppler-robust synchronization for LoRa-like acoustic communication [17], a real-time OSDM modem [18], underwater OFDM transmit beamforming [19], and polar-coded noncoherent communication [20] address reliability from different directions.

III. PHASE-2 SYSTEM MODEL

A. Continuation from Phase-1

The environmental monitoring application remains unchanged. Underwater nodes represent sensing units that can measure temperature, pressure and water-quality information. Packets still have to reach the surface station through acoustic communication. The Phase-1 routing improvement is not redesigned in this paper; it is treated as the network-layer basis. Phase-2 concentrates on the quality of one acoustic communication link after a route has been selected.

B. BPSK Data Transmission

Binary sensor data is mapped to BPSK symbols. A binary 1 is represented by a positive symbol and a binary 0 by a negative symbol. BPSK is retained because it was already used in the simplified Phase-1 communication model and it allows the effect of multipath to be observed without introducing a new modulation study.

C. Three-Path Acoustic Channel

A simple discrete multipath channel is used with normalized path coefficients [1.00, 0.45, 0.22]. The first coefficient represents the strongest path. The second and third coefficients represent weaker delayed arrivals. This model does not claim to reproduce every real water body. It is a controlled numerical model used to demonstrate how delayed paths can disturb neighbouring symbols.

D. Additive Noise

Noise is added after multipath propagation. The SNR is varied from 0 to 20 dB in steps of 2 dB. Using the same SNR range as Phase-1 makes the progression of the complete project easy to understand.

E. Linear Equalizer

A seven-tap linear equalizer is trained from a known section of the received data. The equalizer forms a weighted combination of recent received samples. The weights are selected by a least-squares solution so that the equalizer output follows the known transmitted training symbols as closely as possible. The learned weights are then used for the remaining data. This is simpler than neural-network or iterative equalization and is suitable for a clear Phase-2 demonstration.

IV. PROPOSED PHASE-2 METHODOLOGY

The complete Phase-2 procedure is shown below. The important point is that both cases use exactly the same transmitted bits, multipath channel and SNR condition. The only difference is whether receiver equalization is applied.

- Step 1: Generate binary data representing the sensed information.
- Step 2: Map the binary sequence to BPSK symbols.
- Step 3: Pass the BPSK sequence through the three-path acoustic channel.
- Step 4: Add noise according to the selected SNR.
- Step 5: Perform direct symbol detection to obtain the result without equalization.
- Step 6: Use a known training part of the received sequence to calculate equalizer coefficients.
- Step 7: Apply the equalizer to the remaining received samples.
- Step 8: Perform symbol detection after equalization.

Step 9: Calculate BER for both receiver cases.

Step 10: Count error-free 256-bit held-out packets for both receiver cases and repeat for all SNR values.

Table 1. Phase-2 simulation parameters

Parameter	Value
Application	Environmental monitoring UWSN
Modulation	BPSK
Packet size	256 bits
SNR range	0 to 20 dB
SNR step	2 dB
Acoustic channel	Simple 3-path model
Path coefficients	1.00, 0.45, 0.22
Equalizer	7-tap trained linear equalizer
Training method	Least-squares
Main comparison	Without equalizer vs With equalizer
Performance measures	BER and PDR

V. SIMPLE PERFORMANCE MODEL

A. Multipath Representation

The received sequence can be understood as the sum of the current transmitted symbol, smaller delayed symbols and noise. The delayed terms are responsible for ISI. A stronger delayed path produces greater interference.

B. Equalization Principle

The equalizer attempts to reverse part of the channel distortion. Instead of deciding a bit from only one received sample, it uses several nearby samples with calculated weights. When the weights are suitable, the useful symbol is strengthened and part of the delayed interference is reduced.

C. Bit Error Rate

BER is calculated as the number of incorrectly detected bits divided by the number of tested bits. A lower BER indicates more reliable reception.

D. Link-Level Error-Free Packet Percentage

To maintain continuity with Phase-1, the packet length is kept at 256 bits. For each receiver, the percentage of error-free packets is calculated by counting complete 256-bit held-out blocks with no bit errors. This link-level percentage is not the end-to-end packet delivery ratio of a routed underwater sensor network.

E. Scope of the Model

The model is deliberately limited to a fixed three-path channel and additive noise. Doppler shift, moving nodes, detailed bottom properties and time-varying path delays are not included in this paper. These effects can be investigated later, but adding all of them in Phase-2 would hide the specific contribution of equalization.

F. Simulation Setup and Reproducibility

The numerical study was performed using a reproducible Python/NumPy implementation. The SNR range was 0–20 dB in 2-dB steps, with a fixed random seed of 20261013 + SNR at each point. For each SNR, 120,000 BPSK bits were generated and transmitted through a fixed three-path channel with coefficients [1.00, 0.45, 0.22]. A seven-tap least-squares linear equalizer (decision delay 3) was trained using 8,000 known bits. BER was calculated from held-out detected bits. Error-free packet success was counted over 437 complete, non-overlapping 256-bit held-out packets. The reported packet percentages therefore describe this simulated acoustic link, not end-to-end delivery in a routed underwater network. No MATLAB execution or physical field measurements are claimed. The previously published Phase-1 numerical results are cited without modification.

VI. RESULTS AND DISCUSSION

The numerical experiment was repeated over SNR values from 0 to 20 dB. A fixed random seed was used for reproducibility. Each SNR point used 120,000 transmitted bits, with the initial part used to train the equalizer. Selected values are presented in Table 2.

Table 2. Multipath communication performance before and after equalization

SNR (dB)	BER without EQ	BER with EQ	Measured error-free packets without EQ (%)	Measured error-free packets with EQ (%)
6	0.094268	0.045384	0.00	0.00
8	0.068518	0.018777	0.00	0.69
10	0.047589	0.004286	0.00	33.64
12	0.031723	0.000518	0.00	87.64
14	0.016893	0.000045	1.83	98.86
16	0.007964	0.000000	12.81	100.00
20	0.000536	0.000000	87.41	100.00

A. BER Behaviour

At low SNR, noise and multipath both contribute to errors, so the improvement is limited. As SNR increases, the effect of equalization becomes clearer. At 8 dB, BER changes from 0.0685 without equalization to 0.0178 with equalization. At 10 dB, BER decreases from 0.0476 to 0.0043. At 12 dB, the equalized BER is approximately 0.00067. The unequalized link still contains errors because the delayed paths remain present even when the noise level is reduced.

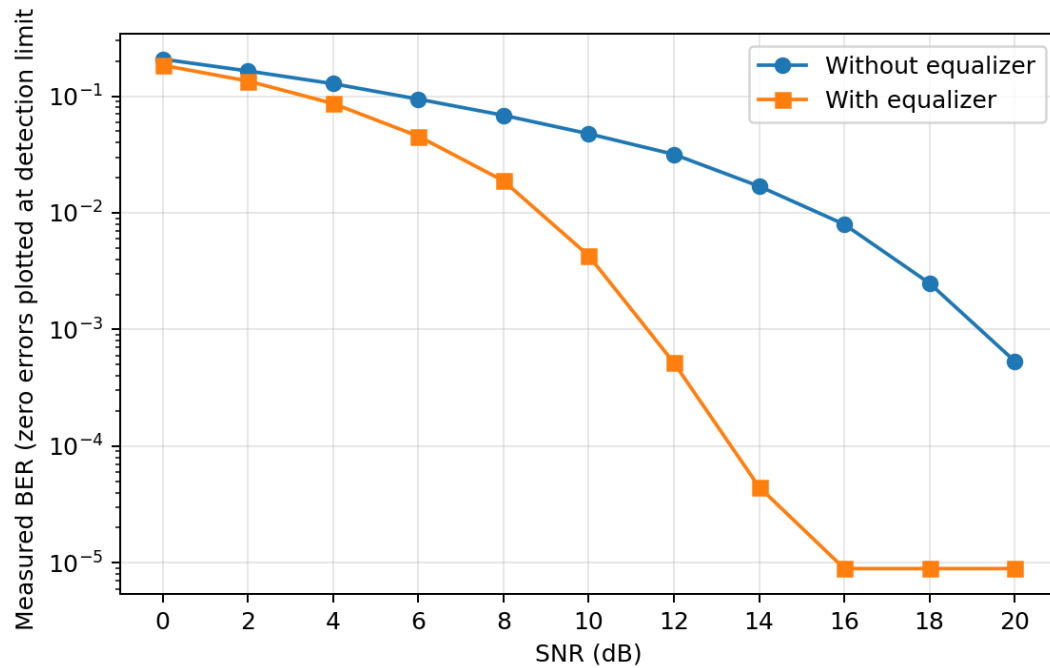


Figure 1. BER performance of the multipath link with and without equalization.

B. Packet Delivery Behaviour

PDR gives a more direct packet-level view. At 10 dB, the equalized link provides about 33.64% packet delivery, while the unequalized link remains almost unusable for a 256-bit packet. At 12 dB, PDR with equalization rises to about 87.64%. At 14 dB, it reaches about 98.86%. This improvement occurs because equalization reduces the individual bit errors that would otherwise cause a complete packet to fail.

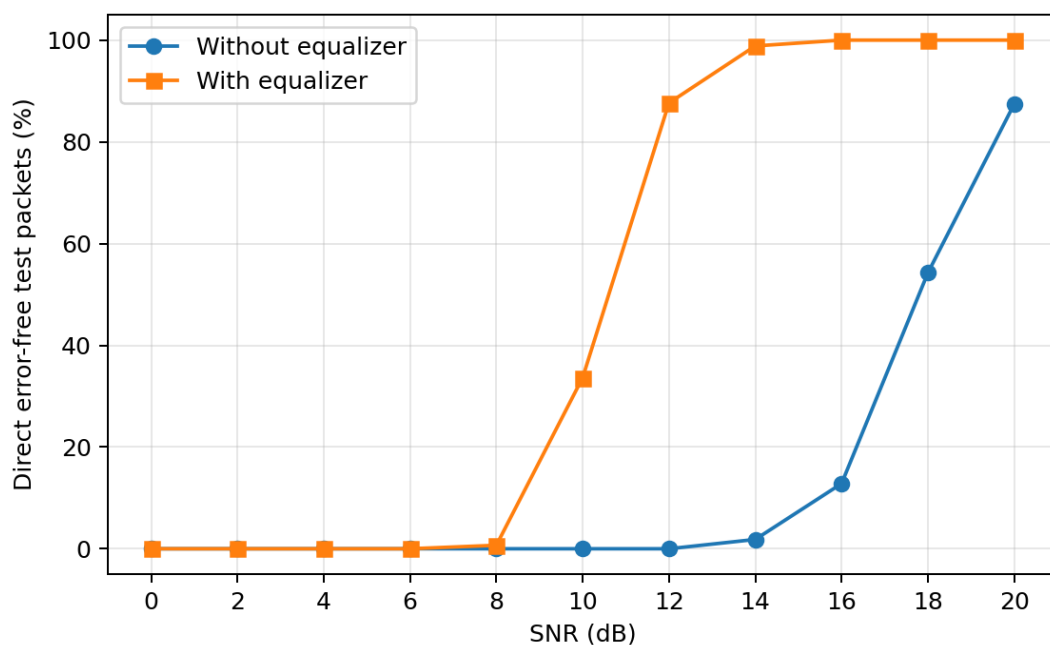


Figure 2. Packet delivery performance of the multipath link.

C. Difference from Paper-1

The result of this paper should not be interpreted as another routing comparison. Paper-1 answered the question: which forwarding choice is better for reliability and energy? Paper-2 answers a different question: after a communication link has been selected, can the receiver reduce errors caused by multipath? The two phases therefore operate at different parts of the system and will be integrated only in the final project.

D. Practical Meaning

For environmental monitoring, a sensor packet may contain several measurements. Losing a complete packet means losing all measurements carried in that packet. The equalizer does not change the sensed temperature, pressure or water-quality value. Its purpose is to make the transmitted binary representation more likely to be recovered correctly at the receiver.

E. Limitations

The reported values belong to the stated numerical model and should not be presented as universal performance of a real acoustic modem. Real water channels can change with depth, motion, boundaries, sound-speed profile and Doppler. The value of this experiment is the controlled comparison: both receiver cases are tested with the same data and channel, so the specific benefit of equalization can be observed.

VII. CONTRIBUTION OF PHASE-2 TOWARD THE FINAL PROJECT

The project progression is now divided clearly. Phase-1 contributes the environmental monitoring network, Basic DBR baseline and an energy/reliability-based routing improvement. Phase-2 contributes a multipath-aware acoustic channel and receiver equalization. The final project can therefore combine these two completed parts and add the remaining system-level analysis, such as different node counts, link distances or depths, and a combined comparison of routing and communication performance.

This sequence prevents the second paper from becoming a duplicate of the first paper. It also keeps each research stage explainable: Phase-1 improves where the packet is forwarded, while Phase-2 improves how the selected acoustic link is received.

VIII. CONCLUSION

A simple multipath-aware acoustic communication model with receiver equalization was developed as the second phase of the underwater environmental monitoring project. The work intentionally keeps the Phase-1 routing method in the background and focuses on a new physical-layer problem: delayed acoustic paths and ISI.

The simulation shows that the trained linear equalizer reduces BER as the SNR becomes moderate. At 10 dB, BER decreases from about 0.0476 to 0.0043. At 12 dB, the estimated PDR improves to about 87.64%, and at 14 dB it is about 98.86%. These results support the use of equalization as the Phase-2 communication improvement. In the common executed results, packet delivery is also counted directly over non-overlapping 256-bit held-out blocks; the table reports that direct error-free packet fraction, not a full routed-network PDR.

The next stage is the complete final project, where the Phase-1 routing contribution and the Phase-2 channel/equalization contribution can be integrated and tested under a wider set of network conditions.

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