# Adaptive Feedback Protocol for Underwater Vehicles via Software-Defined Acoustic Modems

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***Abstract*—Underwater acoustic communication provides great potential through aquatic robots that have use in scientific research, pollution monitoring, and maintenance of underwater facilities. However, the underwater channel poses a unique array of difficulties for acoustic communication, including path attenuation, colored noise, Doppler shifting, multipath propagation, and bandwidth limitations. Bidirectional communication utilizing a feedback channel can mitigate some of the impact of these challenges, but this feedback channel must be highly robust and reliable. This research proposes a new protocol for feedback transmissions that employs a software-defined, adaptive communication technique to achieve acceptable transmission rates without sacrificing the integrity of the data transmitted over this feedback link. The trade-off between transmission rate and accuracy is quantified via simulations to determine the most effective form of the proposed protocol.**

***Index Terms*—Modulation, underwater acoustic communications, software-defined modems.**

## I. Introduction

**Overview:** As the world of communication technologies advances, underwater transmission is emerging as a field of research due to the growing number of applications in aquatic environments, including maintenance, scientific discovery, and human safety. Specific applications of underwater transmission include remote oil rig inspections, oceanographic data collection, pollution monitoring, offshore exploration, tactical surveillance, and marine life research [1]–[3]. Autonomous underwater vehicles (AUVs) partake in these applications by monitoring and exploring underwater bodies as individual vehicles or as teams of vehicles. AUVs allow for exploration and data collection without the dangerous and arduous task of sending divers. However, AUVs are often limited in mobility by physical tethers, giving rise to the need for wireless underwater communication.

The nature of the underwater environment favors acoustic transmission for this application. Unlike radio frequency (RF) and optical waves, acoustic waves do not undergo severe absorption or scattering. Therefore, acoustics are the only feasible option for underwater transmissions [6]. However, utilization of acoustic waves leads to low-bandwidth, error prone, and slow communications [7].

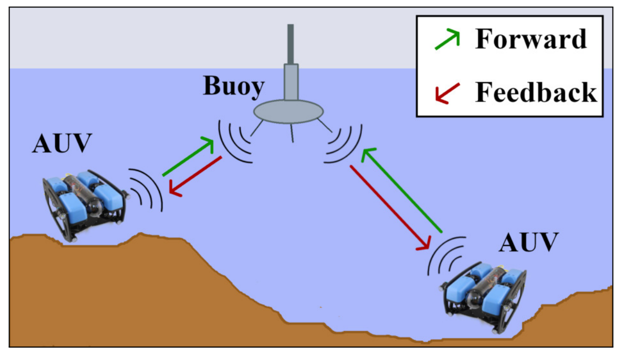


Figure 1. A simple setup with communication between a buoy at the surface and an AUV operating deeper underwater. The AUV transmits video and sensor data to the buoy in the forward direction, while the buoy sends commands, channel state information, and package acknowledgements to the AUV in the feedback channel. This figure depicts BlueROV2 ROVs [4] which have been adapted for use as AUVs by authors in [5].

Consistent accuracy is crucial in underwater data transmission, where the properties of the underwater environment pose unique challenges that could potentially result in communication errors [8], [9]. Miscommunication often has critical implications in underwater applications, such as sending faulty commands to costly underwater robots. Thus, relevant research is necessary to address these concerns. To achieve these goals, the possibility of replacing the traditional underwater hardware-based acoustic modems with software-defined modems should be explored. Software-defined modems are highly flexible, reconfigurable, and reprogrammable [10]. They use minimal hardware, and depend on the host's general processor (i.e. CPU) to modulate and demodulate the data. The flexibility of a software-defined modem enables the use of an adaptive protocol which takes into consideration the current environmental conditions as well as the acceptable level of error in a transmission to choose the most optimal set of parameters for the communication link.

**Motivation:** Authors in [11] develop a real-time software-defined multi-antenna communication system between AUVs and remote transmitters/receivers on the buoy/land station. The

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main goal of their research is to create high-speed acoustic links between the robots and the buoy/land station so that underwater videos, captured by the robots, can be processed, compressed, and transmitted through these high-speed links in a timely manner and up to a certain level of quality. Achieving this goal requires a closed-loop communication algorithm that includes a reliable feedback channel, where different encoding tools can reduce potential errors.

**Contribution:** To have bidirectional communication and to guarantee data delivery, a reliable feedback system is required in the reverse direction of the video transmission (i.e. from buoy/land station to robot) to issue new commands to the AUV and to acknowledge received data packets. Without a robust feedback channel, the system would accumulate errors in the feedback transmission while attempting to detect or correct errors in the data transmission. The current research aims to investigate and optimize a reliable method of feedback by developing a protocol that adapts to the conditions of the channel as well as to the relative importance of the information being transmitted.

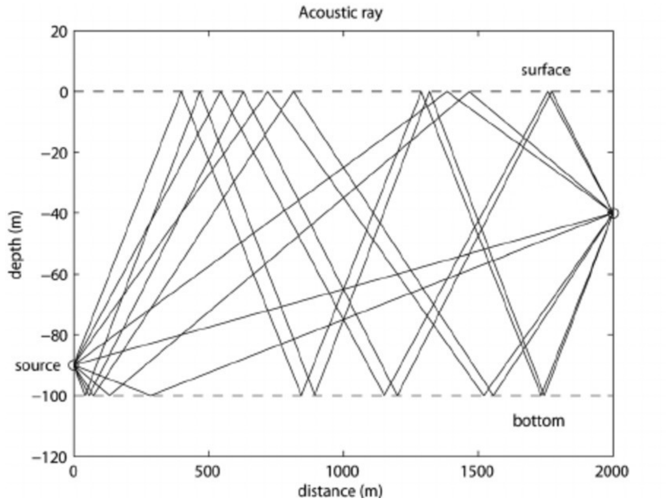


Figure 2. Diagram depicting multipath propagation. The various lines illustrate multiple paths from transmitter to receiver, including the direct path from transmitter to receiver and the indirect paths which reflect off of the surface and ocean floor before reaching the receiver [15].

## II. Background and Problem Definition

**Underwater Acoustic Challenges:** The complexity of underwater transmission lies in the variance of the underwater environment. Small changes in temperature, salinity, and pressure can greatly impact the characteristics of the aquatic channel. A secondary challenge inherent to this environment is bandwidth limitation. The available bandwidth for underwater acoustic communications is limited to 100 kHz, an extremely small range that limits the maximum data transmission rate. Combinations of these challenges further complicate transmission, and together they pose a variety of issues to overcome. Overall, this research focused on three major issues for underwater transmission: noise, the Doppler effect, and multipath propagation.

*Background Noise:* Background noise is always present in any system. Underwater background noise is highly dependent on the specific environment, which introduces complications for transmissions. Man-made sea vessels, flows or currents, and sea life can all be sources of background noise [1]. In general, underwater background noise is characterizable as additive Brownian noise, containing more noise at lower frequencies than higher frequencies [12].

A signal must be distinguished from this background noise to be decoded. The relative intensity of the carrier signal compared to background noise is measurable as the signal-to-noise ratio (SNR). In general, the lower the SNR, the more difficult demodulation becomes. As the carrier signal propagates, the amplitude of the signal decreases, a phenomenon known as path loss or path attenuation [13]. Thus, the SNR decreases as the signal travels farther from its source, until the SNR is too low for the signal to be accurately interpreted.

*Doppler Effect:* The Doppler effect refers to frequency shifts in waveforms as the result of the transmitter and receiver moving relative to the transmission medium, resulting in a difference between the transmitted signal frequency and the received signal frequency [14]. An unexpected Doppler shift could impact all types of modulation because of small but significant effects on phase, symbol duration, carrier frequency, etc. over long periods of continuous communication.

*Multipath Propagation:* Multipath propagation describes the reflections of a signal (e.g. off of the surface or the ocean floor) which interfere with one another and with the main signal, depicted in Figure 2. Reflections can cause amplitude and phase changes through constructive or destructive interference, while leaving frequencies unaffected. However, the reflections can interfere constructively or destructively, making demodulation difficult regardless of the modulation scheme. Furthermore, inter-symbol interference (ISI) may occur if the multipath propagation spread is longer than the signal duration [16]. In this scenario, symbols carried by reflected signals are delayed enough to interfere with subsequent symbols and can confuse the demodulator as to which symbol is 'correct'.

**Modulation Schemes:** Common modulation schemes include phase shift keying (PSK), amplitude shift keying (ASK), and frequency shift keying (FSK). Due to the previously noted issues, this research focuses on optimizing FSK for underwater acoustic transmission. As aforementioned, multipath propagation can cause amplitude and phase shifts, making ASK and PSK less reliable. On the other hand, FSK may be more resistant to multipath propagation because frequencies remain unchanged by reflections. Moreover, this research utilizes adaptive modulation in which the feedback channel changes modulation technique and other parameters depending on the environment and circumstance. In shallow waters, for instance, where multipath propagation may be especially disruptive, the land or surface link and AUV can adapt to use a more reliable modulation scheme (such as BFSK) to improve transmission accuracy. On the other hand, in amenable conditions the link can utilize less robust schemes (such as higher order FSK) in

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order to improve transmission speed.

**Channel Coding:** On top of these modulation schemes, error correcting codes (ECCs) can further reduce the error rate by adding redundant information to the actual message, which is then used to detect and correct errors at the receiver. This replaces any need to retransmit data corrupted by noise, which is a costly operation in slow channels, such as with underwater transmission. ECCs each have unique properties regarding the cost and benefit of their use, but for the purpose of this research two linear ECCs will be chosen to demonstrate their use in this application. The first, weaker code will be assumed to be a Hamming(7,4) code; the second, stronger code will be assumed to be a Hadamard(16,5,8) code. Both codes have well-defined behavior which will be used to predict their impact on the error rate of a transmission.

**Problem Definition and Significance:** Transmitting signals through underwater acoustic channels can often be unreliable. Techniques such as ECC and robust modulation schemes can reduce the error, but at the cost of a lower transmission rate. An adaptive protocol processes data differently based on the acceptable error level; critical transmissions can be heavily protected from error, while the integrity of noncritical data can be sacrificed for faster transmission.

In the underwater communication system that this research targets, there are three types of data that must be sent via the feedback channel: commands (CMD), describing the actions the AUV should take; channel state information (CSI), summarizing the conditions of the underwater communication channel; and acknowledgements (ACK), indicating whether or not data packets (e.g. video frames) were received.

Commands are critical to the functioning of the system. The AUV must receive accurate command data, such as maneuvering instructions or motor inputs, to carry out its necessary tasks. CSI is less critical than CMD. CSI data sent in the feedback channel describes the current properties of the forward communication channel. Having access to this data in real-time enables the system to correct for the external environment, improving the reliability of the data being sent from the AUV. However, CSI data is not absolutely essential to the drone's ability to operate, so it is deemed as less critical information. Acknowledgement messages (ACK), generally a simple response to each packet received from the AUV, are comparably non-critical, as they only serve to request that the AUV resend individual packets of video/sensor information that were lost.

For this research, acceptable error rates were chosen for each of the three types of feedback data based on the priority of the information. Command transmissions, being highly critical, were assigned a target bit error rate on the order of $10^{-9}$ errors per bit; CSI data, $10^{-6}$; and acknowledgements, $10^{-3}$.

## III. Procedure

**Protocol:** A simple implementation of a flexible protocol will be outlined as follows. Transmissions occur in short packets, under around 100 bits long after channel coding. Each packet transmits data of a single type (CMD, CSI, ACK). The packet structure (see Figure III) begins with a header, which specifies the data type and the parameters of transmission for the body. The header will always be modulated in the most robust manner applicable (i.e. with a strong ECC and a lower-order modulation scheme) to ensure that the receiver properly interprets the header. The header is as compact as possible to minimize the time spent transmitting with a robust communication method.

A header implementation could use as few as four bits: two to specify the data type (CMD, CSI, or ACK), one to choose between a slow and a fast modulation scheme, and one to choose between a strong ECC and a weak ECC. By choosing an applicable set of parameters, the target error rate for each type of data can be achieved. The transmitter is responsible for determining the optimal parameters based on the target error rate, the overall load on the feedback channel (i.e. the amount of data queued for transmission), and the current channel conditions.

| Packet | | | | |
|---|---|---|---|---|
| Header (fixed 4 bits) | | | Body (<50 bits) | |
| Type | Codec | Modem | Meta-Data | Data |

Figure 3. Example implementation of a feedback packet structure for a flexible feedback protocol. Each packet consists of a 4-bit long header followed by a variable-length body. The header includes information about the data type (CMD, CSI, or ACK), the channel coding used (weak or strong ECC), and the modulation scheme used (lower or higher order). The body structure varies by data type, but generally includes any meta-data such as the body's length, followed by the raw data. The body is transmitted with the encoding and modulation scheme specified in the packet header.

After the header is transmitted, the body of the packet is sent using the modulation and channel coding specified in the header. Depending on the data type, this body may include meta-data such as the length of the body. However, any meta-data is considered part of the body, and as such should be transmitted using the same parameters as the rest of the body.

On the AUV, the receiver initially expects transmission in the most robust method to receive the header. Once the header is received and interpreted, the receiver switches to the specified modulation scheme and channel coding to receive the body. On reaching the end of the body packet, the receiver returns to expecting a packet header transmission.

Under heavy load or in especially poor conditions, the feedback channel may be unable to reliably transmit all of the CMD, CSI, and ACK packets being generated. In such a case, low-priority packets (e.g. ACK packets or potentially CSI packets) should be dropped from the queue to allow for higher priority packets to be transmitted in a timely manner.

**Testing:** To test this protocol, the overall research process consists of simulating three underwater-specific issues using MATLAB, analyzing their effects on transmission accuracy, and utilizing the results to quantify the trade-off between speed and accuracy in this setting. Given the advantages posed by FSK schemes in handling multipath propagation, this research tests multiple FSK schemes (BFSK, QFSK, 8-FSK, and 16-FSK), as well as BPSK as a control to compare FSK schemes

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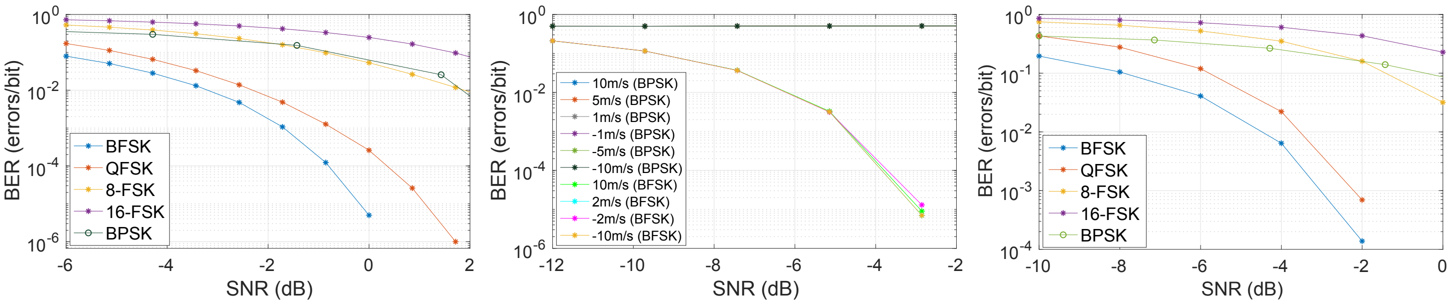


(a) (b) (c)

Figure 4. (a) Simulated BER vs. SNR with Brownian noise; (b) Simulated BER vs. SNR with Doppler shifts calculated according to various relative velocities; (c) Simulated BER vs. SNR after simulated multipath propagation using a Rician channel.

to a non-FSK scheme. All five modulation schemes are tested under 1) Only Brownian Noise, 2) Doppler Effect, and 3) Multipath. Given that underwater settings always contain some level of background noise, Brownian noise is also included in tests 2 and 3. Additionally, the inherent limitations of the channel regarding frequency band and power are obeyed in all simulations: a maximum bandwidth of $100$ kHz and signal to noise ratios below $20$ dB are used.

## IV. Results

**Simulations:** Raw Brownian noise generated by the Digital Signal Processing toolbox is adjusted to conform to the selected SNRs based on the relative root mean squares of the noise and the signal, before being added directly to the signal sample. Six realistic relative velocities, ranging from -10 m/s and 10 m/s, are used in the Doppler equation to calculate frequency shifts between the transmitter and receiver. These shifts are then applied individually to the modulated signals. The Rician channel function is utilized to simulate multipath propagation and path attenuation, with the path delays and average path gains set empirically to represent relatively heavy multipath propagation. The sampling frequency of the path is set at $200$ kHz, derived from the Nyquist rate [17], and the Doppler shift component of the Rician channel is set to $0$ in order to analyze Doppler Shifts' effects separately.

**BER vs. SNR:** To visualize and evaluate the quality of the channel under a set of conditions, BER vs SNR graphs are generated. The shape of these graphs depicts the error rate at a variety of SNRs. This research specifically focuses on comparing the SNRs required to reach an acceptable error rate. For a given set of conditions, a modulation scheme which requires a lower SNR to achieve an acceptable error rate is considered more robust, because this modulation scheme can withstand more noise. Figure 4 includes three BER vs. SNR graphs.

**Noise-Only Test:** BFSK, QFSK, 8FSK, 16FSK, and BPSK are tested with Brownian noise (see Figure 4a). When Brownian noise is introduced to the signal, all of the tested modulation schemes handle the issue relatively well. However, the BER for BFSK and QFSK drop off significantly more quickly than other tested schemes, indicating these are much more resilient against high levels of noise.

At an SNR of 2dB, BFSK and QFSK have error rates below $10^{-6}$. In comparison, the higher order FSK schemes (8-FSK and 16-FSK) as well as BPSK have error rates above $1\%$. Though the simulations do not offer a complete image of the performance of these schemes at much higher SNRs, it is evident that BFSK and QFSK perform far better in a noisy environment than higher order FSKs and BPSK.

**Doppler Effect Test:** BFSK and BPSK are tested under the Doppler effect with a range of relative velocities between -10 and $10$ m/s. For each scheme, the resulting graphs for the six relative velocities were almost indistinguishable from each other, as shown in Figure 4b. The similarity among the plots indicates that Doppler shifting at these velocities has minimal impact on BFSK transmissions. It is unclear whether the effect would be more pronounced on other FSK schemes, as only BFSK was tested in this case. With higher modulation orders, frequencies are closer together, so these small frequency shifts may cause a more noticeable change. BPSK did not perform well after the signal was distorted by the Doppler Shift. The error rate for all the Doppler shifts remained at around $0.5$ regardless of the SNR, indicating that the demodulated data is random.

**Multipath Propagation Test:** Multipath propagation significantly impacted the accuracy of signals across the board, seen in Figure 4c. The relative performance of all five schemes closely follows the trends seen in the noise only test in Figure 4a. BFSK and QFSK dip off faster than all other tested schemes, approaching error rates below $10^{-3}$ at an SNR of $-2$dB. At this SNR, the other tested modulation schemes still have simulated error rates above $10\%$, far too high to be usable. These data are rearranged in Figure 5 to more clearly illustrate the trade-off between transmission rate and error rate at a set SNR in a highly turbulent channel.

**Summary:** Simulation results indicate that low order FSK is effective at low SNRs. The signal can resist high levels of noise, suggesting high reliability. FSKs of higher order are less successful in a very noisy environment, requiring significantly higher SNRs to achieve acceptable error rates. BPSK performs similarly to these higher order FSKs in a noisy channel. BFSK is resistant to Doppler shifting at the speeds reached by AUVs, whereas BPSK is more susceptible to these frequency shifts.

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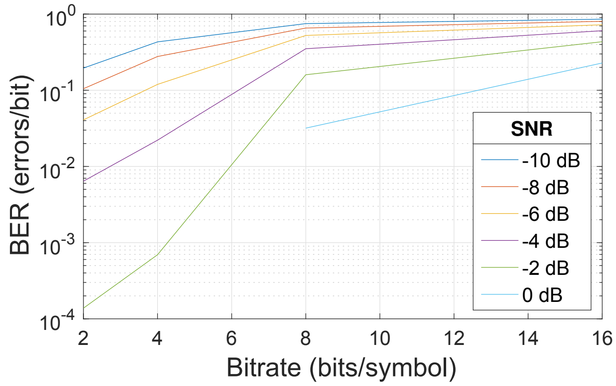


Figure 5. BER trends for tested FSKs under multipathing at various SNRs, derived from data in Figure 4c. The data are grouped by SNR, with the bits per symbol (2, 4, 8, or 16) on the horizontal axis. At a set SNR, the error rate increases dramatically as the bit rate increases, suggesting that acceptable error rates in this environment are only feasible with low order FSKs.

It is unclear what results would be produced by higher order FSKs. However, given the relatively low speeds of objects traveling underwater, it is presumable that other FSKs would also be resilient to these small shifts. Moreover, multipath propagation drastically increases error in transmissions across the board, but does not significantly alter the general trends seen in the noise-only test. There is a strong inverse correlation between speed and accuracy for FSKs, shown in Figure 5. Across all tested SNRs in the multipath test, the error rate increases dramatically for bitrates above $4$ bits per symbol (i.e., FSKs beyond QFSK).

## V. Conclusions

In this short paper, a reliable method of feedback was investigated that adapts to the conditions of the channel as well as to the importance of the information being transmitted. Overall, the results indicate that BFSK and QFSK result in acceptable error rates for reliable underwater transmission. BFSK transmissions are highly robust, capable of reaching error rates below $10^{-3}$ in most conditions. By applying a strong ECC such as Hadamard(16,5,8), this error rate could be decreased to below $10^{-9}$, acceptable for packet headers and for high priority command packets. Given that command data should be limited to only a few bytes, the cost of using such a slow transmission method is mitigated. In different systems, the amount of CSI information being transmitted on the feedback channel will vary, which will in turn vary the length of the CSI packet. For shorter CSI packets, use of BFSK is still reasonable, and in good conditions a weak ECC such as Hamming (8,4) would transform a BER on the scale of $10^{-4}$ to below $10^{-7}$, which us sufficient for CSI. For longer CSI packets, which may take too long to transmit under BFSK, QFSK would be more efficient and would reach an acceptable error rate with a weak ECC in good conditions or with a strong ECC in poor conditions. For ACK packets, QFSK combined with a weak ECC in even poor conditions would provide BERs on the order of $10^{-3}$. These BERs are acceptable for these packets since they are of the lowest priority.

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