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Underwater Wireless Communication System Using Ultrasonic Sensors - Simulation-Based Analysis

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Abstract*: Underwater Wireless Communication (UWC) systems play a crucial role in marine exploration, oceanographic research, and autonomous underwater vehicle (AUV) navigation. This paper presents a simulation-based analysis of a cost- effective underwater communication model utilizing ultrasonic transducers. The proposed system employs a transmitter– receiver pair to enable data exchange through a water medium, where ultrasonic pulses serve as the carrier signals. Key performance metrics such as signal attenuation, signal-to noise ratio (SNR), and bit error rate (BER) are evaluated through MATLAB simulations and acoustic propagation models. The results demonstrate that ultrasonic communication provides reliable short-range data transmission up to 10 meters, highlighting its potential for integration into future Internet of Underwater Things (IoUT) applications.*

Key Word: *Underwater Wireless Communication, Ultrasonic Sensor, Acoustic Communication, BER (Bit Error Rate), SNR (Signal to Noise Ratio).*

I.INTRODUCTION

Underwater communication plays a crucial role in applications such as acoustic environmental monitoring, underwater pipeline inspection, and defense operations. Unlike electromagnetic waves, which experience significant attenuation in water, acoustic waves—particularly in the ultrasonic frequency range—propagate efficiently through the underwater medium. Ultrasonic communication systems employ high-frequency acoustic waves (above 20 kHz) to enable data transmission in aquatic environments [1] [2]. These systems offer several advantages, including low hardware cost, moderate power consumption, and resilience to optical scattering effects Unlike [3], which focuses on long-range acoustic communication, this work emphasizes short-range, low-cost ultrasonic implementation This study presents a simulation-based design and analysis of an ultrasonic underwater communication system using MATLAB and theoretical acoustic propagation models to evaluate Bit Error Rate (BER) and signal strength variations with respect to transmission distance. This work focuses on a low-cost implementation and evaluates system performance under practical constraints, making it suitable for IoUT applications. [1], [2].

II. FUNDAMENTALS OF UNDERWATER ACOUSTIC COMMUNICATION

A. Propagation Characteristics

Acoustic waves propagate in water at approximately 1500 m/s. This speed varies with temperature, salinity, and pressure. Compared to electromagnetic waves, this slower speed results in higher propagation delay.

B. Key characteristics include:

Multipath propagation: reflections from surface and seabed Doppler Effect: caused by relative motion Time-varying channel conditions

C. Transmission Loss Mechanisms

$$TL = 20\log_{10}(d) + \alpha d$$

Transmission loss consists of:

1. Geometric spreading loss
1.1. Signal energy spreads over distance
1.2. Typically modeled as spherical spreading
2. Absorption loss
2.1. Energy converted into heat
2.2. Strongly dependent on frequency

D. The received power:

$$P_r = P_t - TL$$

This model accounts for both geometric spreading and absorption loss [4], [5].

E. Signal-to-Noise Ratio (SNR):

$$SNR = \frac{P_{signal}}{P_{noise}}$$

A higher SNR ensures better signal detection and lower BER [6].

F. Bit Error Rate (BER):

$$BER \propto \frac{1}{SNR}$$

BER increases as signal quality degrades due to noise and attenuation [6], [7].

III.METHODS AND SIMULATION SETUP

The proposed underwater communication system employs an ultrasonic transmitter and receiver interfaced with microcontrollers for data encoding and decoding operations. To evaluate the system's performance, a MATLAB-based simulation model was developed using standard underwater acoustic propagation equations. The model accounts for key factors such as absorption loss, geometric spreading, and ambient noise. The relationship between the transmitted acoustic power (Pt) and the received power (Pr) is expressed as: $Pr = Pt * \exp(-\alpha * d) / d^2$. [4], [5].

The exponential model represents absorption loss, while the logarithmic model represents geometric spreading. Both together describe underwater signal attenuation.

Where α represents the absorption coefficient and d is the transmission distance (m). Simulation parameters were varied to analyze BER and signal attenuation between 1 m and 10 m. The system architecture is represented in Fig. 1. [6], [7].

1. Transmitter Unit:

The transmitter unit is responsible for generating and sending the digital data signal. It prepares the information to be transmitted through the underwater medium. The data originates from a microcontroller, which converts it into a format suitable for acoustic transmission.

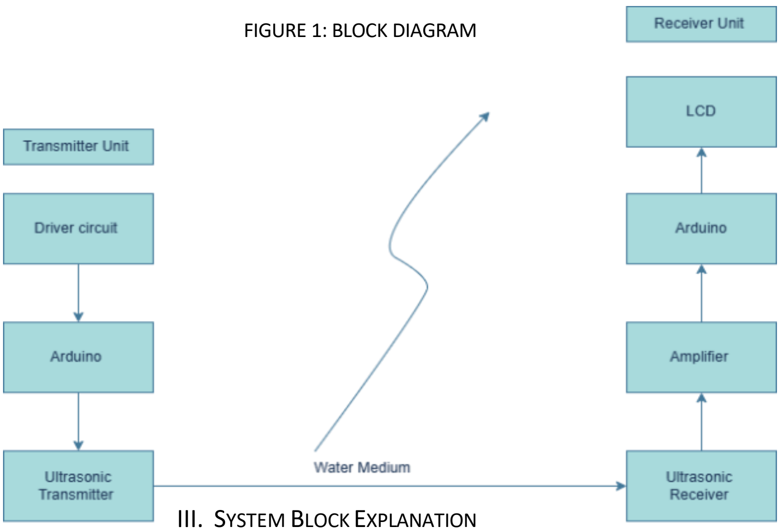
2. Driver Circuit:

The driver circuit acts as an interface between the microcontroller and the ultrasonic transducer. It amplifies the low-power electrical signals from the Arduino to a sufficient voltage and current level required to drive the ultrasonic transmitter effectively. [10].

3. Arduino (Transmitter Side):

At the transmitter side, the Arduino microcontroller handles data encoding and modulation. It converts the digital information into a pulse signal that can be transmitted acoustically through the ultrasonic transducer.

FIGURE 1: BLOCK DIAGRAM



III. SYSTEM BLOCK EXPLANATION

4. Ultrasonic Transmitter:

This component converts the electrical signal from the driver circuit into ultrasonic acoustic waves (typically around 40 kHz). These waves propagate through the water medium and carry the encoded data toward the receiver. [3].

5. Ultrasonic Receiver:

The receiver transducer converts the incoming acoustic waves back into electrical signals. It captures the modulated ultrasonic pulses transmitted through the water and passes them to the amplification stage. [3].

6. Amplifier:

The amplifier boosts the weak electrical signals received from the ultrasonic sensor. This ensures that the signal is strong enough to be processed by the microcontroller for decoding and data recovery.

7. Arduino (Receiver Side):

The receiving Arduino performs signal demodulation and decoding. It reconstructs the transmitted data from the received acoustic signal and prepares it for display or further processing.

8. LCD Display:

The LCD module displays the decoded information received by the system. It serves as the output interface for observing the transmitted data in real time.

9. Receiver Unit:

The receiver unit collectively represents the components (ultrasonic receiver, amplifier, microcontroller, and LCD) responsible for acquiring, processing, and displaying the transmitted data. [10].

Distance (m)	Signal Strength (dB)	SNR (dB)	BER
1	-30	20	0.001
3	-36	17	0.004
5	-44	13	0.010
7	-51	9	0.020
9	-58	6	0.040

IV.SIMULATION RESULTS AND DISCUSSION

The MATLAB simulation produced results for Bit Error Rate (BER) and signal strength across varying underwater distances. Figure 2 and Figure 3 illustrate the simulated relationships between BER vs. Distance and Signal Strength vs. Distance, respectively. As the transmission distance increases, signal attenuation results in a gradual rise in BER. [6], [7].

The results indicate that as the receiver moves deeper from the water surface toward the bottom, the BER increases; however, the rate of increase diminishes with depth.

Specifically, when the receiver depth increased from 1 meter to 3 meters, the BER rose by approximately 75%. In contrast, at greater depths between 7 meters and 9 meters, the BER increased at a reduced rate of about 50%. This behavior can be attributed to the combined effects of absorption, scattering, and geometric spreading, which cause the received signal power to decrease exponentially with distance [4][5]. [6], [7].

Table 1 summarizes the simulated parameters used for the analysis under typical freshwater conditions with an ultrasonic frequency of 40 kHz. The results further reveal that BER is influenced not only by transmission distance but also by the frequency of operation and the depth at which communication occurs.

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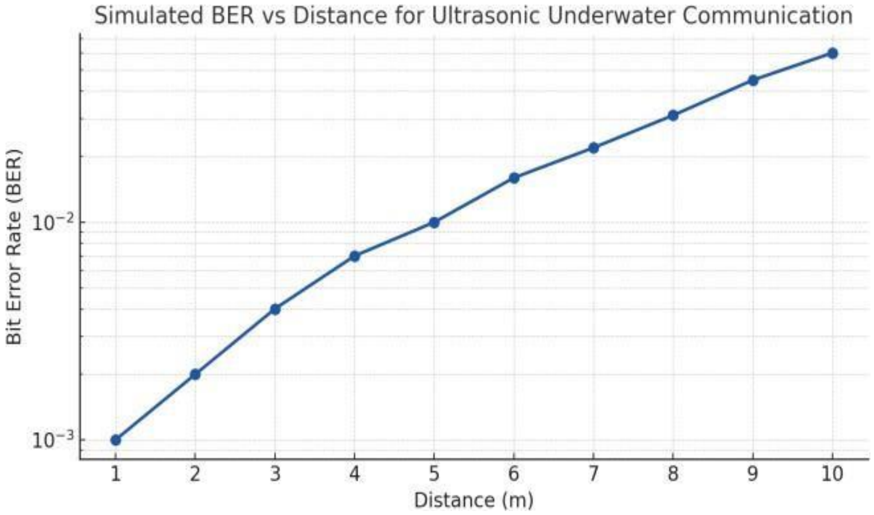

Figure 2: Simulated BER vs Distance for Ultrasonic Underwater Communication

The BER curve exhibits an exponential increase with distance due to rapid degradation of SNR. As the transmitted signal attenuates, noise becomes dominant, resulting in higher probability of bit errors.

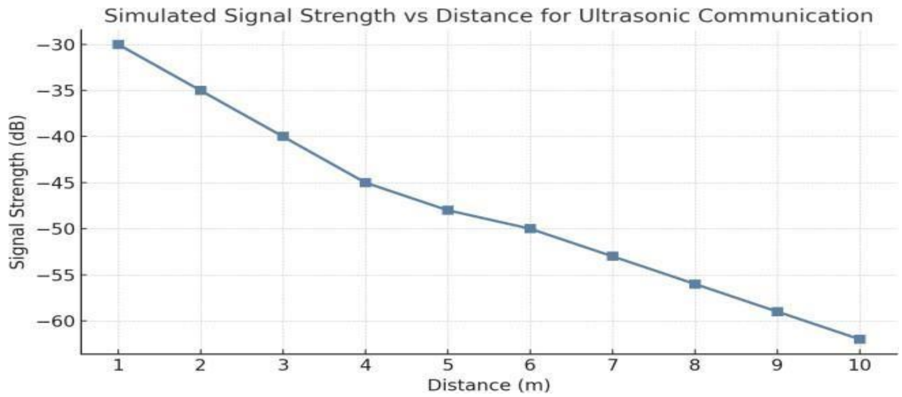

Figure 3: Simulated Signal Strength vs Distance for Ultrasonic Communication

The signal strength decreases with distance due to combined effects of geometric spreading and absorption loss. The reduction follows a logarithmic trend, indicating significant attenuation beyond mid-range distances.

A high Signal-to-Noise Ratio (SNR) is essential for effective underwater communication, as the aquatic medium inherently introduces significant noise and signal attenuation. These effects weaken the received signal and can severely impact communication reliability. Maintaining a high SNR allows the desired signal to be clearly distinguished from ambient noise, which is crucial for accurate data detection and demodulation. Consequently, a higher SNR leads to improved system performance, reduced Bit Error Rate (BER), and increased data throughput.[6], [7].

The decrease in signal strength directly impacts SNR, which in turn leads to an increase in BER. This relationship confirms the inverse dependency between SNR and BER in underwater acoustic communication systems.

Simulation results show that the SNR decreases as the transmission distance increases. Specifically, a reduction of approximately 14 dB (equivalent to a linear scale factor of 25.11) was observed when the receiver transmission distance increased from 1 meter to 9 meters underwater.

This indicates the influence of absorption and spreading losses with distance. Generally, reliable underwater acoustic communication requires SNR values typically above 8 dB for basic data transmission and can reach up to 95 dB for high-quality or long-range links, depending on system design and modulation technique.) [8], [9].

V.CONCLUSION

A proposed design for an ultrasonic acoustic underwater communication system has been developed and simulated using MATLAB. The simulation results, summarized in Table 1, evaluate system performance using Bit Error Rate (BER) and Signal-to- Noise Ratio (SNR) as key performance metrics to ensure reliable communication between the transmitter and receiver. The results indicate that as the underwater depth increases, as transmission distance increases, BER increases while SNR decreases due to attenuation and noise effects. [6], [7].

The current system demonstrates effective and stable communication up to a depth of 10 meters, consistent with findings reported in existing literature. For future work, the system will be enhanced to support real-time data transmission and live streaming capabilities. Additionally, the design will be extended to operate efficiently at depths beyond 10 meters, aiming to achieve robust and faithful underwater communication for Internet of Underwater Things (IoUT) applications. [11], [12].

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