School of Electrical Engineering and Information Technology

Computer Engineering Department

Bachelor's Thesis

Space Modulated Acoustic Communication System

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

Abbreviation	Meaning
ISR	Interrupt Service Routine
MIMO	Multiple Input Multiple Output
PCB	Printed Circuit Board
RF	Radio Frequency
SSK	Space Shift Keying
TDOA	Time Difference of Arrival
TTL	Transistor-Transistor Logic
TOA	Time of Arrival

ABSTRACT

This project aims to develop a simple and fast acoustic communication system by using a method called Delay Index Modulation. In this system, data is not encoded in the signal itself, but instead in the position of the transmitter that is active, a technique known as space modulation. At any given time, only one transmitter is active, and each transmitter is placed in a unique location.

To identify which transmitter is currently sending the signal, we use a technique called Time Difference of Arrival (TDOA). This involves measuring the slight differences in the time it takes for the signal to reach different receivers. By comparing these delays, we can determine the location of the active transmitter. For this purpose, we built a custom 4×4 ultrasonic array, which successfully demonstrated the concept. The system does not require complex processing, only accurate timing is needed.

CHAPTER I: INTRODUCTION

1.1 Aims and Objectives

The primary aim of this project is to design and implement a robust and energy-efficient acoustic communication system based on Space Shift Keying (SSK) using ultrasonic transducers. The key objectives are:

- To construct a custom ultrasonic transducer array optimized for precise signal transmission and reception.

- To implement reliable timing mechanisms using microcontrollers for accurate detection and differentiation of pulses.

- To accurately decode transmitter positions using Time Difference of Arrival (TDOA) at the receiver side.

- To utilize spatial modulation techniques for data transmission by activating only one transmitter at a time.

1.2 Problem Statement

Underwater communication is essential in a wide range of applications, including environmental monitoring, autonomous underwater vehicles (AUVs), and underwater sensor networks. However, traditional wireless communication methods, especially those that use radio frequency (RF) waves, fail to function effectively underwater because of the unique challenges of the environment, such as high signal attenuation and short propagation ranges. As a result, acoustic waves have become a more practical way to communicate underwater due to their ability to propagate over longer distances in water. Nevertheless, acoustic communication systems are limited by their bandwidth, high latency, and low data rates.

To overcome these challenges, advanced modulation techniques are being explored to enhance spectral efficiency and reliability in Underwater communication. One such promising technique is space modulation (SM). Spatially modulated systems have shown advantages in cost, power efficiency, and performance in RF applications [3].

This project presents the design and implementation of a system intended for testing space modulation techniques in air. While underwater trials were not conducted as part of this project, the work serves as a foundational step towards future underwater deployment.

1.3 Project Motivation

Environmental Monitoring: To effectively monitor ocean health over extended periods, sensors must be capable of transmitting data reliably across underwater distances.

Autonomous Underwater Vehicles (AUVs): There is a growing demand for reliable real-time communication with AUVs. However, most existing methods face challenges such as long-distance transmission, signal degradation, and limited bandwidth. The proposed system aims to address these issues and advance the communication capabilities of AUVs

CHAPTER II: LITERATURE REVIEW

2.1 Technical Background

2.1.1 Space Shift Keying (SSK)

Space Shift Keying (SSK) is a type of Index Modulation where the information is encoded in the spatial position of the active transmitter. SSK transmits data by activating one transmitter at a time from an array, each mapped to a unique bit pattern. In this project, SSK is applied to a 4×4 ultrasonic array, where only one transducer transmits at any moment. The receiver identifies the active transmitter by calculating the Time Difference Of Arrival (TDOA) between different sensors.

2.1.2 Multiple Input Multiple Output

Multiple Input Multiple Output (MIMO) systems employ multiple transmitters and receivers to improve communication capacity, robustness, and spatial diversity. In surface environments utilizing radio frequency (RF) signals, MIMO has attracted significant interest for next-generation applications due to its ability to exploit multipath channel properties. Compared to traditional single-antenna systems, MIMO offers enhanced data rates, improved error performance, and greater channel reliability [1].

2.1.3 Time Of Arrival (TOA) & Time Difference Of Arrival (TDOA)

Time Difference of Arrival (TDOA) is a technique that measures the difference in time between the arrival of a signal at two or more receivers. TDOA is used to decode the data transmitted using SSK. By calculating the TDOA of the signals received at multiple receivers, the system can accurately identify the position of the active transmitter and decode the transmitted data bits. TDOA in particular relies on the time difference between signal arrival times and is typically more favourable than TOA. This is because TDOA, as opposed to TOA, does not require synchronization between the source and different destinations [1].

CHAPTER III: SYSTEM DESIGN

3.1 Hardware Design

3.1.1 Transmitter Circuit
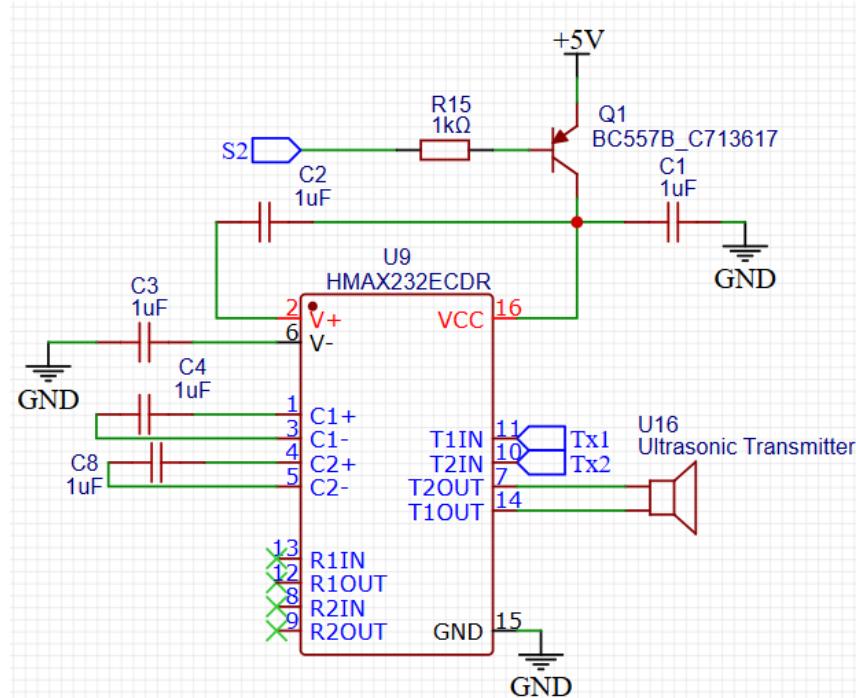
Figure 1: Transmitter Circuit

In the design of the transmitter circuit, we used the MAX232 chip. The MAX232 is an integrated circuit (IC) that converts TTL level signals into higher voltage RS-232 levels. Specifically, it takes TTL input signals on pins 10 (T1IN) and 11 (T2IN), and provides corresponding outputs on pins 7 (T1OUT) and 14 (T2OUT) with voltage levels of approximately ±15V. These higher voltages are used to create the maximum possible voltage difference across the ultrasonic transmitter, improving signal strength and transmission range.

3.1.2 Receiver Circuit
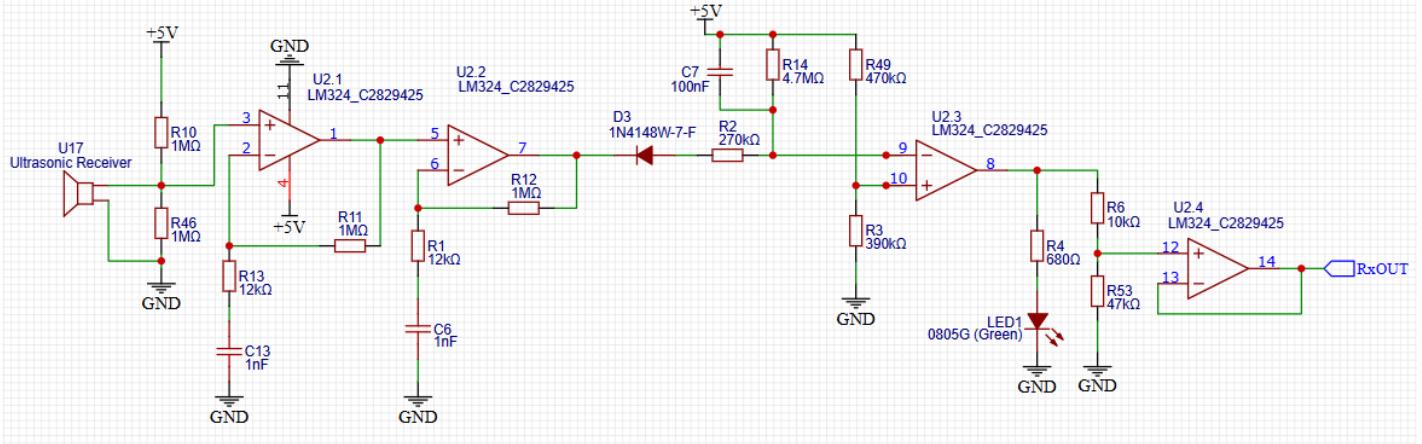
Figure 2: Receiver Circuit

This is the ultrasonic receiver circuit designed to detect and amplify ultrasonic signals received from the ultrasonic transmitter. It uses multiple op-amp stages from an LM324 op-amp IC to amplify the signal. The final output is a logic-level pulse (RxOUT) and a visual indicator (LED) that signals detection.

The first two op-amps (U2.1 and U2.2) are configured as a non-inverting amplifiers. Their purpose is to amplify the weak signal received from the ultrasonic transmitter while preserving its waveform and frequency characteristics. This ensures accurate signal processing at later stages.

The third op-amp (U2.3) functions as a comparator. It compares the amplified signal against a fixed threshold. When the input signal exceeds this threshold, the comparator output switches to a HIGH state. This output activates LED1, providing a clear visual indication that a signal has been detected.

The fourth op-amp (U2.4) is configured as a voltage follower. It does not change the signal voltage but helps match the output impedance of the circuit with the input impedance of the microcontroller, ensuring that the RxOUT signal is stable and not affected by the microcontroller's input impedance.

3.1.3 Multiplexer

We used the HCF4051 multiplexer to switch the operating mode of the ultrasonic transducer between transmitting and receiving. The mode is selected by setting the control bits of the multiplexer, which are sent from the microcontroller. This allows the same transducer to function as either a transmitter or a receiver, depending on the system's current operation.

3.1.4 Voltage Regulator
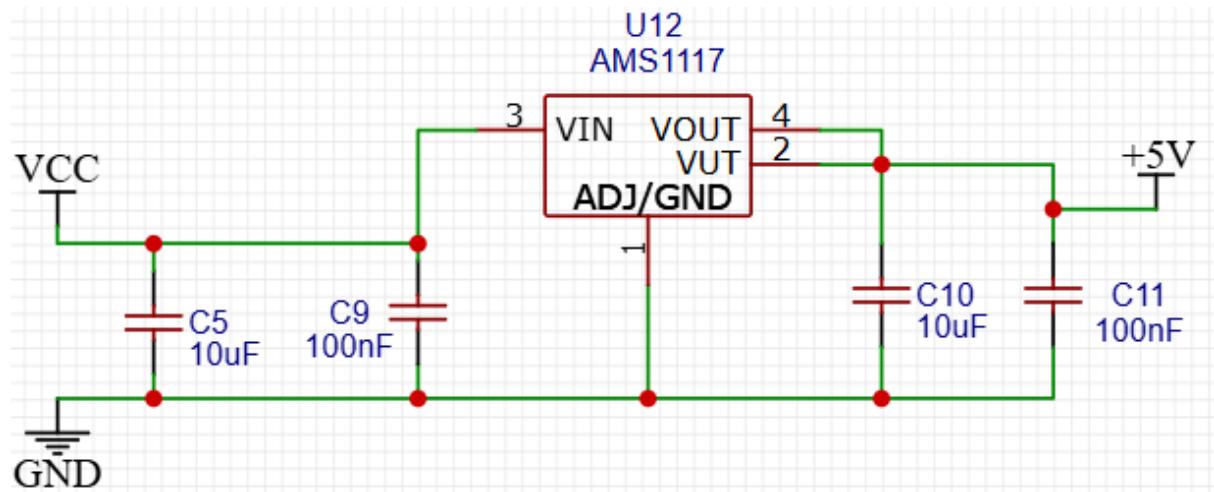
Figure 3: 5V Voltage Regulator Circuit

We used the AMS1117 voltage regulator IC to step down the input voltage (Vcc) to a stable +5V output. This regulated voltage is then used to safely power the circuit components.

3.1.4 PCB Design
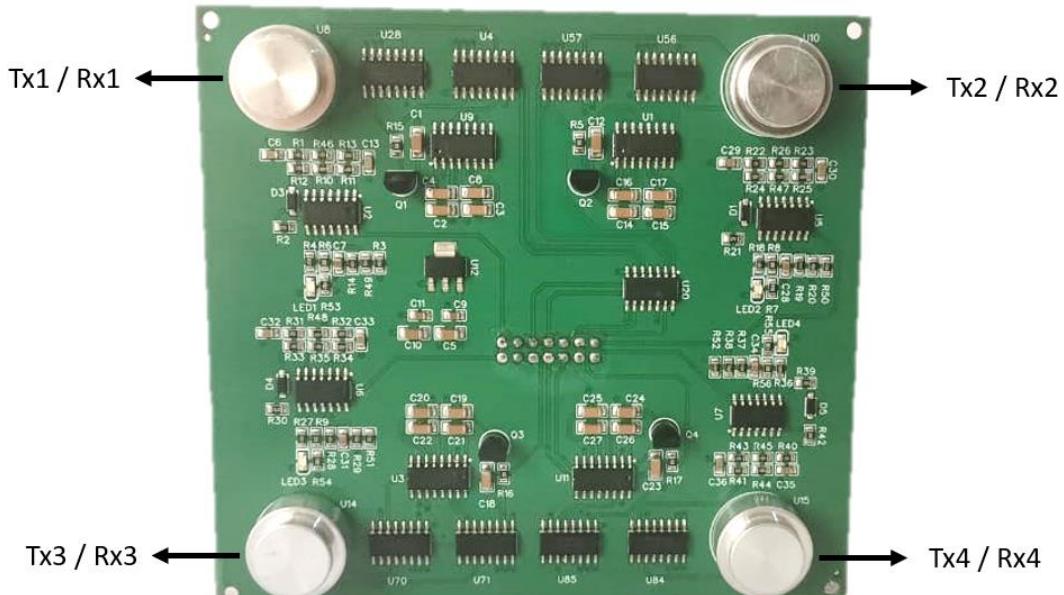
Figure 4: PCB Board

After verifying the functionality of the transmitter and receiver circuits on a breadboard, we proceeded to design a 4×4 PCB ultrasonic transducer array. This transition to a printed circuit board significantly improved the reliability and organization of the setup, making experimental testing more efficient and consistent.

3.1.5 Arduino UNO

Figure 5: Arduino UNO Microcontroller

We used the Arduino UNO on the transmitter side to generate a 40 kHz TTL +5V square wave signal, which was then supplied to the MAX232 IC.

3.1.6 ESP32
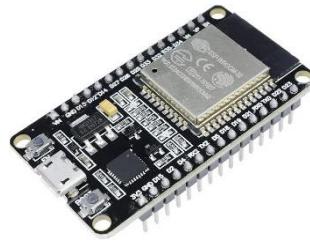
Figure 6: ESP32 Microcontroller

We used the ESP32 on the receiver side because it has a faster clock compared to the Arduino UNO, allowing for more precise timing measurements of signal arrival. Additionally, the ESP32 offers more GPIO pins, many of which support hardware interrupts, making it well-suited for handling multiple input signals efficiently.

3.2 Software Design
3.2.1 EasyEDA

Figure 7: EasyEDA

EasyEDA is a free, web-based tool that allows users to design circuit schematics, simulate them, and create PCB layouts. It offers an easy-to-use interface with access to a large library of components and supports exporting Gerber files for PCB manufacturing.

3.2.2 Arduino IDE

The Arduino IDE is a free, open-source platform used to write, compile, and upload code to Arduino boards. It supports C/C++ and provides a simple interface for programming microcontrollers, making it beginner-friendly and widely used in electronics and embedded systems projects.

3.3 State Machines

3.3.1 Transmitter State Machine
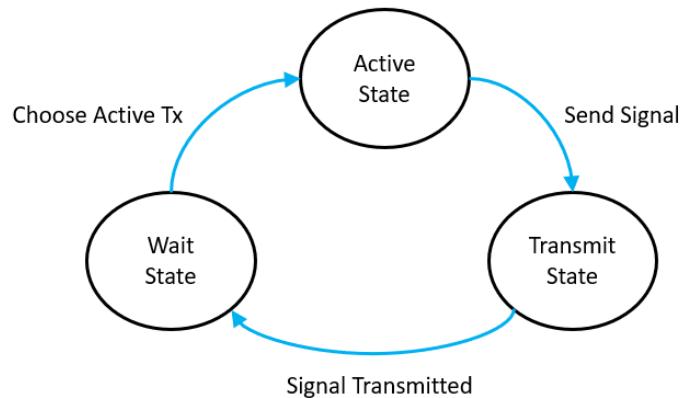
Figure 8: Transmitter State Machine

Initially, all transducers remain in an idle or **Wait State**. When a specific transducer is selected, it transitions to the **Active State**, where it awaits the transmission trigger. Upon receiving the trigger signal, it enters the **Transmit State** and begins emitting the ultrasonic pulse. Once the transmission is complete, the transducer returns to the wait state, remaining inactive until it is selected again for the next transmission cycle.

3.3.2 Receiver State Machine
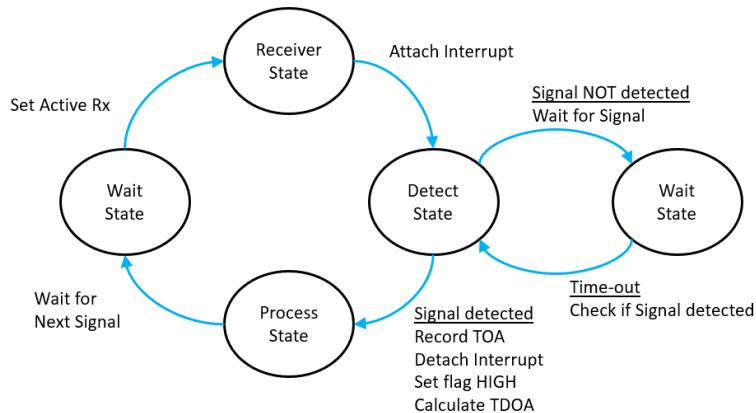
Figure 9: Receiver State Machine

Similar to the transmitter state machine, the system starts in the **Wait State**. When one or more transducers are activated, they move to the **Receiver State**. At this point, an interrupt is

attached to the corresponding GPIO pin on the ESP32 to detect the arrival of the signal, and the transducer enters the **Detect State**. If no signal is detected within a certain time, the system returns to the **Wait State** and then after time-out the system re-enters the **Detect State** to check again.

When a signal is successfully received, the system transitions to the **Process State**. Here, the Time of Arrival (TOA) is recorded, the interrupt is detached to prevent multiple triggers in the same cycle, and a flag is set to HIGH to confirm that a signal was detected. The Time Difference of Arrival (TDOA) is then calculated, and the results are shown on the serial monitor. After processing, the system returns to the **Wait State**, ready for the next detection cycle.

CHAPTER IV: METHODOLOGY

4.1 System Implementation

4.1.1 Theoretical Calculations

Assuming Tx1 is the active transmitter at a given moment, the closest receiver would be Rx1, the one directly aligned horizontally with Tx1. The distance between Tx1 and Rx1 corresponds to the physical spacing between the two PCB boards, with no additional vector components involved. Therefore, the ultrasonic signal emitted by Tx1 should first be detected by Rx1.

Tx1   Rx1

40 cm
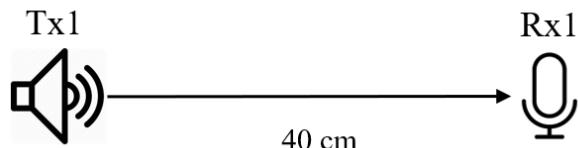
Figure 10: Tx1 to Rx1 Alignment

Since the speed of sound in air is known and the distance between Tx1 and Rx1 is given, we can calculate the time it takes for the signal to reach Rx1, referred to as the **Time Of Arrival** at Rx1 (TOA_{Rx1}).

Speed of sound in air (**c**) = 343 m/s

Distance between Tx1 & Rx1 (d_{Tx1Rx1}) = 40 cm = 0.40 m

Time Of Arrival at Rx1 (TOA_{Rx1}) = $\dfrac{d_{Tx1Rx1}}{c} = \dfrac{0.4}{343} = 1166.18\ \mu s$

The next closest receivers are Rx2 and Rx3, which are positioned at 90° angles relative to Rx1. Due to their symmetrical placement, the signal from Tx1 is expected to reach both Rx2 and Rx3 simultaneously under ideal conditions. The distance from Rx1 to Rx2 is 6 cm, which is equal to the distance from Rx1 to Rx3.

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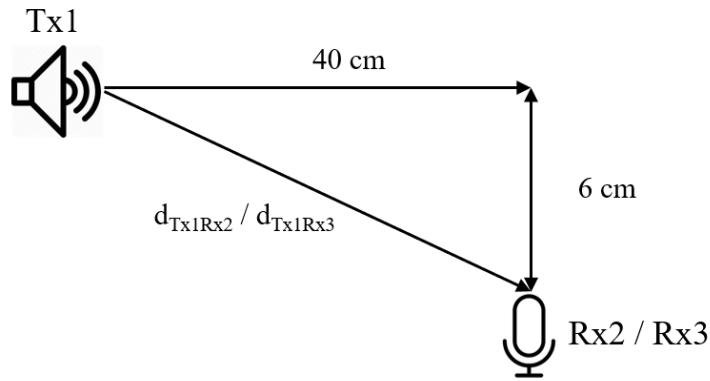
Figure 11: Tx1 to Rx2 / Rx3 Alignment

The following calculation determines TOA_{Rx2}. Note that the same calculation applies to TOA_{Rx3}, as Rx2 and Rx3 have the same aligned with respect to Tx1.

To find $\mathbf{d_{Tx1Rx2}}$ we apply Pythagorean Theorem:

$$\mathbf{d_{Tx1Rx2}} = \sqrt{40^2 + 6^2} = 40.45 \; cm$$

To find TOA_{Rx2}:

$$\mathbf{TOA_{Rx2}} = \frac{d_{Tx1Rx2}}{c} = \frac{0.4045}{343} = 1179.23 \; \mu s$$

To find the **Time Difference Of Arrival** (TDOA) between Rx1 and Rx2:

$$\mathbf{TDOA_{Rx1Rx2}} = TOA_{Rx2} - TOA_{Rx1} = 1179.23 \; \mu s - 1166.18 \; \mu s = 13.05 \; \mu s$$

The farthest receiver from Tx1 is Rx4, located diagonally at a 45° angle from Rx1. As a result, the signal from Tx1 would take the longest time to reach Rx4, making it the last to detect the transmission.

4.1.2 Transmission Timing

To avoid overlap and interference during transmission and reception, precise signal timing is crucial. According to initial testing, the receiver misinterpreted the data because it detected several edges from a single pulse.

The solution was to match pulse detection with exact timing windows, hardware timers were implemented and fixed delays were also added in order to guarantee that only one legitimate edge was recorded per cycle. This change improved the accuracy of pulse detection and successfully reduced false triggers.

4.1.3 Delay

In order to control the timing of transmitted pulse signals and guarantee that each pulse is unique and detectable separately, delays were used. By creating separation between pulses, delays help in preventing signal overlap, which is crucial in ultrasonic communication.

4.1.4 Interrupts & Timers

The system's ability to react precisely to signals received was significantly enhanced by the combination of timers and interrupts. While timers made sure that the system precisely controlled timing and prevented errors caused on by repeated activation from a single pulse, interrupts enabled the system to detect and process incoming pulses instantly in real-time, making the system faster and reliable.

4.2 Results & Delay Matrix

4.2.1 Results

The following results show the Time Difference of Arrival (TDOA) measurements at various receivers (Rx) for each transmitter (Tx) when activated individually at a distance of 40 cm.

Tx1 Active	
Receive Order	TDOA / µs
Rx1	X
Rx2	13.36
Rx3	54.66
Rx4	57.63

Table 1: Tx1 Active

Tx2 Active	
Receive Order	TDOA / µs
Rx2	X
Rx4	13.60
Rx1	32.55
Rx3	120.32

Table 1: Tx2 Active

Tx3 Active	
Receive Order	TDOA / µs
Rx3	X
Rx4	13.63
Rx1	43.78
Rx2	44.10

Table 3: Tx3 Active

Tx4 Active	
Receive Order	TDOA / µs
Rx4	X
Rx2	13.63
Rx3	30.19
Rx1	77.44

Table 4: Tx4 Active

The discrepancy in the TDOA readings may be attributed to two primary causes:

1. Multipath Propagation: The ultrasonic signal may reflect off nearby surfaces before reaching a receiver. These reflected paths are longer than the direct path, resulting in delayed signal arrival times and introducing error into the measurements.

2. Interrupt Handling Latency on the ESP32: When a signal is detected, the ESP32 triggers an interrupt to timestamp the event. However, delays can occur between the signal detection and the execution of the interrupt service routine (ISR). These delays may result from ISR prioritization, queued interrupts, or slow execution of existing ISRs, leading to inaccuracies in the recorded arrival time.

4.2.2 Delay Matrix

Given the number of receivers (N_{Rx}) and transmitters (N_{Tx}), we can construct a channel delay matrix D, where each element $\text{TDOA}_{i,j}$ represents the Time Difference of Arrival between the signal received at receiver i when transmitter j is active. That is:

$$D_{i\,j} = \text{TDOA}_{i\,j} \qquad \text{where } i = 1 \dots N_{Rx},\ j = 1 \dots N_{Tx}$$

In each column j of D, corresponding to a specific active transmitter Tx, at least one element must be zero. This zero represents the first arrived signal at the receiver that is closest to Tx or has the shortest propagation path.

$$D = \begin{bmatrix} 0 & 32.55 & 43.78 & 77.44 \\ 13.36 & 0 & 44.10 & 13.63 \\ 54.66 & 120.32 & 0 & 30.19 \\ 57.63 & 13.60 & 13.63 & 0 \end{bmatrix}$$

4.3 2x2 Data Transmission

4.3.1 System Set-up

To test our system with data transmission we have implemented a simple 2x2 data transmission system. The below figure shows the implemented set-up:
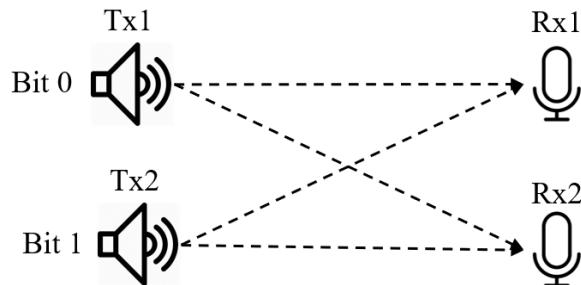

Figure 12: 2x2 Data Transmission Set-up

To calculate the TDOA between the two receivers we used the following formula:

$$\text{TDOA} = \text{TOA}_{Rx1} - \text{TOA}_{Rx2}$$

If TDOA is less than 0 this means that the receiver Rx1 received the signal before Rx2, which implies that the transmitter Tx1 was the sender, that indicates Bit 0 was transmitted.

If TDOA is greater than 0 this means that the receiver Rx2 received the signal before Rx1, which implies that the transmitter Tx2 was the sender, that indicates Bit 1 was transmitted.

4.3.2 2x2 Transmitter State Machine
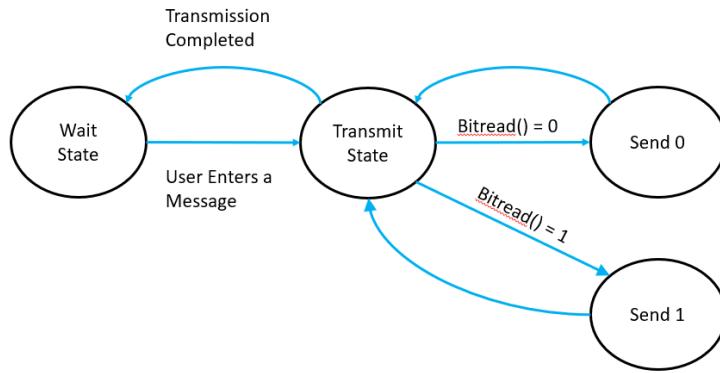
Figure 13: 2x2 Transmitter State Machine

Initially, all transmitters are in the **Wait State,** waiting for the user to enter a message through the serial monitor. Once a message is entered the transmitters enter the **Transmit State** and start transmitting. For each bit in the message: if the bit is 0, Bit 0 is transmitted; if the bit is 1, Bit 1 is transmitted. This process continues sequentially until the entire message has been sent. After the message has been transmitted, the transmitters return to the wait state wating for the next message.

4.3.3 2x2 Receiver State Machine
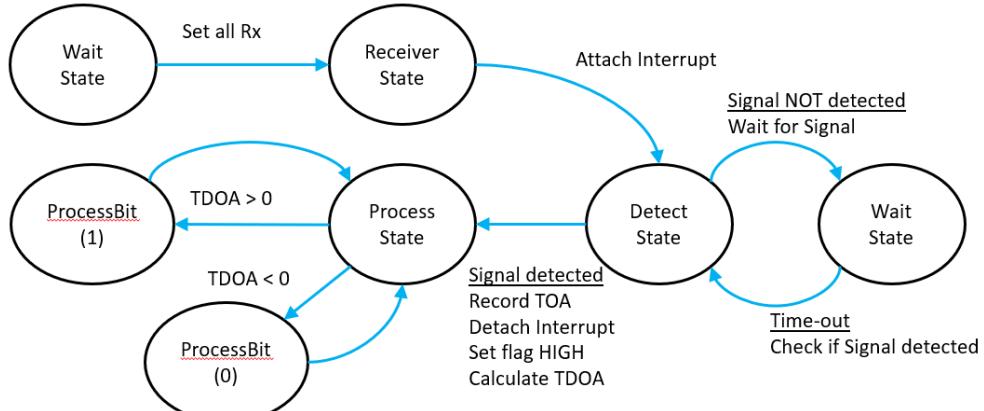
Figure 14: 2x2 Receiver State Machine

The 2×2 receiver state machine operates similarly to the previous design, with the addition of a **Process State** after signal detection. Once a signal is detected, the system transitions to the Process State, where the TDOA is evaluated. If TDOA < 0, the ProcessBit(0) function is called to process Bit 0. If TDOA > 0, the ProcessBit(1) function is called to process Bit 1.

4.3.4 2x2 Data Transmission Results

Testing demonstrates that a 2×2 data transmission was successfully achieved with a 0% error rate at the receiver over a distance of 40 cm.

CHAPTER V: DISCUSSION

5.1 Accuracy Enhancement Methods

5.1.1 MCPWM Capture

For recording signal timestamps, the ESP32's MCPWM (Motor Control Pulse Width Modulation) capture feature provides noticeably greater accuracy than conventional hardware interrupts. as opposed to interrupts, which depend on the CPU reading a timestamp after executing an interrupt service routine (ISR). MCPWM capture uses a specialized hardware timer to record the precise moment a signal edge occurs. Because of this, timestamps can be recorded regardless of CPU load or ISR latency, which makes it perfect for applications requiring precise timing, like TDOA measurements.

5.1.2 Timestamp Averaging and Redundancy

In order to reduce the impact of noise and outliers, timestamp averaging and redundancy involve collecting multiple TDOA samples and statistically filtering them. For example, a median or mode-based method can be used to average or filter the corresponding arrival times at each receiver. A more stable and precise estimation of the signal arrival time results from the system's ability to ignore unusual values caused by redundant measurements. Those methods can reduce the outliers in TDOA measurements that were caused by processing delays and multipath propagation.

5.2 Future Work

Two main areas of future research can be pursued based on this project:

4x4 Data Transmission: Having successfully achieved 2×2 data transmission, the next step is to expand the system for 4×4 data transmission. This expansion will significantly increase data throughput and allow the system to handle more complex messages. The previously obtained delay matrix can be used to facilitate accurate TDOA calculations across the larger grid, aiding in the correct identification of each transmitter during the 4×4 transmission process.

Underwater Data Transmission: After verifying the functionality of the system in air, the next step is to begin the deployment of underwater data transmission.

CHAPTER VI: CONCLUSION

This project successfully demonstrated the design and implementation of a space-modulated acoustic communication system based on Space Shift Keying (SSK) and Time Difference of Arrival (TDOA) techniques. The system avoids conventional waveform modulation and uses straightforward signal timing analysis to achieve dependable communication by encoding data in the spatial position of the active transmitter.

The experimental results confirmed that a 2×2 data transmission system could operate with a 0% error rate at a range of 40 cm, validating the effectiveness of spatial modulation for short-range acoustic communication. While testing was conducted in air, the system provides a strong foundation for future underwater deployment.

This work establishes the core principles of space-modulated communication and opens the path for further development, including expanding to a 4×4 transmission system and adapting the approach to underwater environments where traditional communication methods are less effective.

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