DESIGN AND CONSTRUCTION OF A 4-CHANNEL Wi-Fi LAN BASED WIRELESS INTERCOM SYSTEM

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CERTIFICATION

This is to certify that this project was developed by the students listed above, and that it was prepared in accordance with the rules governing its creation under proper supervision and was presented at the Department of Electrical/Electronic Engineering, Faculty of Engineering, University of Benin, Edo State, Nigeria.

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DEDICATION

This project is dedicated to the Almighty God whose infinite mercy, grace and favour has seen us through. Also, to our parents for their constant support and prayers. Special thanks to our supervisor, Dr. Mrs. E. L. Omoze, for all the support and guidance during the course of this project.

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We extend our heartfelt thanks to our dedicated project supervisor, Dr. Mrs. E. L. OMOZE, for her unwavering support and expert guidance throughout this project's journey.

We are also deeply grateful to our families, including our fathers, mothers, brothers, and other relatives, as well as our cherished friends and well-wishers. Your steadfast support, invaluable counsel, and creative insights have been a source of great strength.

May God shower His abundant blessing upon every one of you.

ABSTRACT

The existing landscape of real-time communication often relies on traditional wire intercom systems which are characterized by high installation costs, complex wiring, and inherent flexibility, posing significant challenges for scalable deployment in dynamic environments. These limitations necessitate a modern, cost-effective, and easy-to-deploy solution that utilizes existing infrastructure. The primary aim of this project is to address this deficit by designing and implementing a functional, low-latency 4-channel Wi-Fi (Wireless Fidelity) Local Area Network (LAN) based wireless intercom system capable of facilitating clear, full-duplex voice communication among multiple users.

The system methodology centered on a decentralized, peer-to-peer architecture utilizing ESP32 microcontroller for its integrated Wi-Fi capabilities and dedicated I^2S (Inter integrated sound) digital audio interface. Audio quality was managed by pairing an INMP441 digital microphone with a MAX98357A digital amplifier, eliminating analog noise and circuit complexity. Crucially, communication over the LAN was executed using the User Datagram Protocol (UDP) instead of

Transmission Control Protocol (TCP). This deliberate choice minimized packet overhead and connection management, which is essential for ensuring the reliable, low-latency data transmission required for real-time conversation.

Testing confirmed the successful two-way voice transmission between all intercom units, with the system consistently demonstrating an end-to-end latency below the critical 150ms threshold required for human-perceptible real-time conversation. In conclusion, the project successfully validated the technical feasibility of leveraging commodity Internet Of Things (IoT) hardware for sophisticated communication tasks. The resulting system is a significantly more scalable and cost-effective alternative to legacy wired intercoms, demonstrating a framework for future development in affordable, high performance wireless communication product

LIST OF ABBREVIATIONS

ADC - Analog-to-Digital Converter

AES - Advanced Encryption Standard

CPU - Central Processing Unit

DAC - Digital-to-Analog Converter

ESP – Expressif System Platform

GPIO - General-Purpose Input/Output

I^2S/I2S - Inter-IC Sound

IEEE - Institute of Electrical and Electronics Engineers

IoT - Internet of Things

IP - Internet Protocol

LAN - Local Area Network

MEMS - Micro-Electro-Mechanical Systems

OLED - Organic Light-Emitting Diode

PCB - Printed Circuit Board

RMS - Root Mean Square

SIP - Session Initiation Protocol

SNR - Signal-to-Noise Ratio

TDM - Time-Division Multiplexing

TCP- Transmission Control Protocol

THD - Total Harmonic Distortion

UDP - User Datagram Protocol

USB - Universal Serial Bus

VoIP - Voice over Internet Protocol

Wi-Fi - Wireless Fidelity

WLAN - Wireless Local Area Network

WPA2 - Wi-Fi Protected Access

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CHAPTER ONE

1.0 INTRODDUCTION

1.1 BACKGROUND OF STUDY

Communication is fundamental to human interaction, enabling the exchange of ideas, coordination of tasks, and relationship building across diverse settings. The demand for efficient, reliable, and cost-effective communication systems has surged, particularly in environments requiring real-time voice interaction among multiple users. Traditional wired intercom systems, while effective in certain contexts, face challenges such as high installation costs, limited scalability, and inflexibility in dynamic environments. These limitations have spurred the development of wireless intercom systems leveraging modern technologies like Wireless Fidelity (Wi-Fi) and microcontrollers to provide flexible, scalable, and cost-effective solutions.

Wireless communication technologies, particularly Wi-Fi, have transformed the design of intercom systems by enabling operation over local area networks (LANs). Wi-Fi offers a robust platform for transmitting voice data with low latency and high reliability within a localized network, making it ideal for multi-user communication systems. The integration of microcontrollers, such as the ESP32, which combines Wi-Fi capabilities with substantial processing power, has simplified the development of such systems, reducing both cost and complexity (Uddin et al., 2016). This project focuses on designing and constructing a 4-channel Wi-Fi LAN-based wireless intercom system to facilitate seamless voice communication among eight users within a single Wi-Fi network, addressing the limitations of wired systems while leveraging widely available Wi-Fi infrastructure.

Traditional intercom systems, commonly used in settings like offices, schools, hospitals, and industrial environments, rely heavily on wired connections, which pose significant challenges.

The installation of extensive cabling is not only costly but also cumbersome, particularly in large or temporary setups such as event venues or construction sites. Wireless intercom systems overcome these issues by eliminating the need for physical wiring, thus enhancing deployment flexibility and reducing installation costs (Ruz et al., 2020).

The rise of Internet of Things (IoT) applications has further inspired this work, as IoT principles enable devices to communicate over networks for coordinated tasks. Wi-Fi-based intercom systems align with IoT trends by utilizing standard networking protocols like User Datagram protocol (UDP) or Web Sockets for real-time audio streaming, ensuring low latency and high audio quality (Santhi & Divya, 2018). The use of ESP32 microcontrollers, combined with I2S-compatible audio components such as the INMP441 microphone and MAX98357A DAC, allows for cost-effective implementation while maintaining high performance.

Recent advancements in Wi-Fi technology, such as Wi-Fi 6, have improved network speed, capacity, and efficiency, making it an even more promising platform for real-time voice applications. These advancements is capitalized on to deliver a scalable and portable solution that can be easily adapted for small to medium-scale environments.

The proposed system architecture, illustrated in Figure 1.1, leverages these advancements in Wi-Fi technology to integrate key components such as ESP32 microcontroller, amplifier, OLED display, and other modules for efficient real-time voice communication.

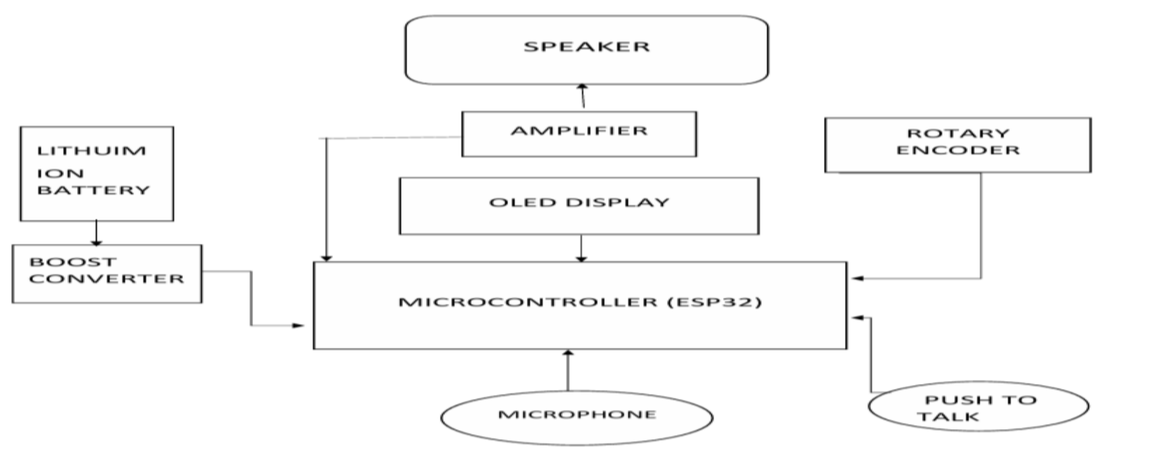

Figure 1.1: Block Diagram

1.2 PROBLEM STATEMENT

Traditional intercom systems, while effective in certain contexts, face several challenges that limit their applicability in modern environments. Wired intercoms require extensive cabling, which increases installation costs and complexity, particularly in large or temporary setups. Additionally, wired systems lack flexibility, making it difficult to reconfigure or expand the network as needed. In dynamic environments, such as event venues, construction sites, or educational institutions, the need for a portable and easily deployable communication system is evident. Existing wireless intercom solutions often rely on proprietary technologies or dedicated frequency bands, which can be expensive and may require additional licensing. Moreover, many wireless intercoms suffer from issues such as high latency, poor audio quality, or interference in crowded network environments. The lack of affordable, open-source, and scalable wireless intercom systems creates a gap in the market, particularly for small to medium-scale applications where cost and simplicity are critical factors. This project addresses these problems by designing a Wi-Fi LAN-based intercom system that eliminates the need for wired connections, reduces costs through the use of readily available components, and leverages the ubiquity of Wi-Fi networks. By focusing on real-time voice communication among eight users, the system tackles the challenge of multi-user coordination in a localized setting, offering a solution that is both practical and innovative.

1.3 AIM

The aim of this project is to design and construct a 4-channel Wi-Fi LAN-based wireless intercom system that enables real-time voice communication among eight users on the same Wi-Fi network

1.4 OBJECTIVES

To achieve the stated aim, the following specific objectives have been outlined:

1. Design and assemble the hardware components of the intercom system, including the integration of ESP32 microcontrollers, I2S-compatible microphones (INMP441), and DACs (MAX98357A) for audio input and output on each of the eight units.

2. Develop a communication protocol for real-time audio streaming, utilizing UDP-based streaming or Web Sockets for session control to ensure low-latency voice transmission among the units.

3. Implement channel handling mechanisms, assigning each intercom unit a unique IP address or ID, with user selection facilitated through push buttons or a rotary encoder for seamless switching between channels.

4. Incorporate audio management techniques, such as the use of ring buffers or circular buffers, to handle streaming delays and ensure smooth audio playback without interruptions.

5. Test and evaluate the system's performance, focusing on latency, audio quality, and network interference, to ensure reliable operation within the Wi-Fi LAN environment.

6. Integrate a user interface, such as a small OLED display to show active users or channels, or a buzzer as a substitute for user feedback, enhancing the system's usability. These objectives collectively ensure that the system is functional, user-friendly, and capable of meeting the communication needs of its intended users.

1.5 SCOPE OF STUDY

The scope of this study is focused on the design, construction, and testing of a 4-channel Wi-Fi LAN-based wireless intercom system with the following boundaries:

Hardware Scope: The system will utilize ESP32 microcontrollers as the core processing units for each of the eight intercom devices. Audio input and output will be handled using I2S-compatible microphones (INMP441) and DACs (MAX98357A). Optional components, such as OLED displays or buzzers, will be included for user feedback.

Networking Scope: The intercom units will operate within a single Wi-Fi LAN, connecting to a common Wi-Fi router or portable hotspot. The system will use UDP-based streaming or Web Sockets for audio transmission and session control.

User Capacity: The system is designed to support eight users, with each unit assigned a unique IP address or ID for channel selection. Communication will be limited to the eight channels, with no provision for external network connectivity (e.g., internet-based communication).

Performance Metrics: The study will evaluate the system based on latency, audio quality, and network interference. Testing will be conducted in a controlled environment to simulate real-world usage scenarios.

Exclusions: The project will not focus on integrating advanced features such as encryption for secure communication, nor will it support long-distance communication over the internet. Additionally, the system is not designed for commercial-grade applications requiring high durability or advanced noise cancellation. This scope ensures that the project remains focused on delivering a functional prototype while addressing the core challenges of wireless voice communication in a localized setting.

1.6 SIGNIFICANCE OF STUDY

The development of a 4-channel Wi-Fi LAN-based wireless intercom system holds significant value for both practical and academic purposes. From a practical standpoint, this system offers an affordable and flexible alternative to traditional intercoms, making it suitable for a wide range of applications. For instance, in educational institutions, the system can facilitate communication among teachers or staff in different classrooms without the need for expensive infrastructure. In event management, it can enable coordinators to communicate seamlessly across a venue, improving operational efficiency. Similarly, in small offices or workshops, the system provides a cost-effective solution for team coordination. Academically, this project contributes to the growing body of knowledge in IoT and wireless communication systems. By demonstrating the application of ESP32 microcontrollers and Wi-Fi-based audio streaming in a real-world context, the study provides valuable insights into the design and implementation of networked communication systems. The use of open-source hardware and software also promotes accessibility, encouraging other researchers and hobbyists to build upon this work for future innovations. Furthermore, the system's design addresses key challenges in wireless audio transmission, such as latency and interference, offering a foundation for further research into real-time communication technologies. The project also highlights the potential of Wi-Fi LANs as a platform for voice applications, which could inspire the development of similar systems for larger user groups or more complex environments. In summary, this study not only delivers a practical communication tool but also advances the understanding of wireless intercom design, paving the way for future advancements in the field.

CHAPTER TWO: LITERATURE REVIEW

2.1 Literature Review of Similar Work

A notable study by Ibrahim Adabara, Enerst Edozie, and Ginabel Otiang Okoth (2022) explored the design and implementation of a free wireless intercom system utilizing Wi-Fi in a P2P or Wireless Local Area Network WLAN configuration. The project aimed to eliminate the need for expensive hard-wired intercoms and Private Automatic Branch Exchange (PABX) systems by leveraging VoIP and an Asterisk-based server. The system enabled voice, and text communication between Wi-Fi -enabled devices such as smartphones, computers, and Internet Protocol (IP) phones, using Session Initiation Protocol (SIP) for real-time communication. Key parameters monitored included packet sending/receiving, jitter, and bandwidth utilization. The study highlighted the cost-effectiveness of using existing Wi-Fi infrastructure, such as that found in educational institutions, to facilitate communication without additional service provider costs. This approach is relevant to the proposed 4-channel system, as it demonstrates the feasibility of using Wi-Fi for multi-channel communication, with the ESP32's Wi-Fi capabilities being a potential cornerstone for similar functionality. The use of an Asterisk server suggests a centralized approach, which could be adapted for channel management in a 4-channel setup, though the proposed project may explore decentralized or microcontroller-based solutions using the ESP32.

Ayodele et al. (2021) presented a cost-effective two-way household door intercom system using an NRF24L01 wireless transceiver module and an ATmega328 microcontroller. The system focused on audio transmission for door communication, emphasizing low-cost components and simplicity. While this project utilized a different wireless protocol (2.4 GHz Radio Frequency [RF] instead of Wi-Fi), it shares similarities with the proposed 4-channel Wi-Fi intercom system in its aim to provide affordable, wireless communication. The use of microcontrollers for processing audio signals aligns with the proposed project's inclusion of the ESP32 and INMP441 microphone for audio capture. The study also explored visible light communication (VLC) for audio transmission using Light-Emitting Diodes (LEDs), demonstrating innovative approaches to wireless communication. However, the NRF24L01's limited range and lack of native Wi-Fi support make it less suitable for a multi-channel Local Area Network (LAN)-based system. The proposed project could build on this by leveraging the ESP32's Wi-Fi capabilities to achieve greater range and channel scalability, while maintaining cost-effectiveness through components like the Max98357A (Amplifier)

A project by Circuit Digest (2018) detailed the design of a simple two-way intercom circuit using the LM386 audio amplifier, microphones, and speakers. The system employed a single-pole double-throw (SPDT) switch to toggle between two microphones, enabling half-duplex communication. While this project used wired connections and analog components, its focus on low-cost audio amplification and speaker integration is relevant to the proposed system. The inclusion of the Max98357A Digital-to-Analog Converter (DAC) and 3-watt 4-ohm speakers in the proposed project suggests a digital, Wi-Fi -based approach to achieve similar audio output but with wireless multi-channel capabilities. The half-duplex limitation of the Circuit Digest project highlights a potential area for improvement in the proposed 4-channel system, which could aim for full-duplex communication using the ESP32's processing power and Wi-Fi for simultaneous multi-channel audio streaming. This study underscores the importance of audio quality and amplification, which can be addressed using the proposed project's INMP441 microphone and Max98357A Digital-to-Analog Converter (DAC).

Research by Isabona and Obahiagbon (2013) at Benson Idahosa University, Nigeria, investigated the deployment of WLANs for campus communication, focusing on Institute of Electrical and Electronics Engineers (IEEE) 802.11g standards. The study conducted a radio channel site survey to assess signal strength and throughput performance, demonstrating the reliability of Wi-Fi for data communication in educational settings. While the study did not specifically address intercom systems, its findings on Wi-Fi signal coverage and packet drop rates are relevant for designing a 4-channel Wi-Fi intercom system for a campus environment like the University of Benin. The proposed project can leverage the ESP32's support for Institute of Electrical and Electronics Engineers (IEEE) 802.11b/g/n to ensure robust connectivity across multiple channels, with components like the 100-nanofarad capacitor for noise filtering to enhance signal stability. The study's emphasis on low packet drop rates suggests that careful Wi-Fi channel management will be critical for the proposed system to handle simultaneous audio streams effectively.

Bhatnagar and Birla (2015) conducted a literature review on Wi-Fi security, highlighting vulnerabilities in WLANs, such as brute force attacks and weaknesses in protocols like Wired Equivalent Privacy (WEP) and Wi-Fi Protected Access (WPA). The study emphasized the need for robust security measures, such as Wi-Fi Protected Access 2 (WPA2) with Advanced Encryption Standard (AES), to protect Wireless Fidelity (Wi-Fi) communications. This is particularly relevant for the proposed 4-channel intercom system, which will operate over a Wi-Fi Local Area Network (LAN) and must ensure secure audio transmission to prevent eavesdropping or unauthorized access. The ESP32 support for secure Wi-Fi protocols can be utilized to implement encryption, ensuring that the four channels remain private and secure. The study also noted the increasing adoption of Wi-Fi in various applications, reinforcing the suitability of Wi-Fi for intercom systems in institutional settings like the University of Benin.

Alenoghena et al. (2022) reviewed fourth-generation (4G) wireless technologies, including Worldwide Interoperability for Microwave Access (WiMAX) and Long-Term Evolution (LTE), and their integration with Wi-Fi for high-speed communication. While focused on broadband applications, the study highlighted the scalability of Wi-Fi for multimedia applications, such as voice and video conferencing, which are analogous to intercom systems.

The proposed project's use of the ESP32 for Wireless Fidelity (Wi-Fi) communication aligns with this trend, as the microcontroller supports high-speed data transfer suitable for multi-channel audio. The study also discussed challenges like signal interference and bandwidth allocation, which are critical considerations for a 4-channel intercom system to ensure clear audio across all channels. The inclusion of components like the boost converter and 100-nanofarad capacitor in the proposed project can help mitigate power and noise issues, improving performance in a Wireless Fidelity (Wi-Fi) Local Area Network (LAN) environment.

These studies give an insight into the design and implementation of wireless intercom systems, particularly those using Wi-Fi or similar technologies. The work by Adebayo et al. (2019) demonstrates the potential for Wi-Fi -based intercoms to reduce costs and leverage existing infrastructure, which is relevant for a university setting like the University of Benin, where Wi-Fi networks are often available. The use of Voice over Internet Protocol (VoIP) and Session Initiation Protocol (SIP) protocols suggests a framework for managing multiple channels, though the proposed project may simplify this by using the ESP32's built-in Wi-Fi and processing capabilities instead of an Asterisk server. Ayodele et al. (2021) and Circuit Digest (2018) highlight the importance of cost-effective components and audio quality, aligning with the proposed project's use of the INMP441 microphone, Max98357A Digital-to-Analog Converter (DAC), and 3-watt speakers. Security considerations from Bhatnagar and Birla (2015) underscore the need for encryption in the proposed system, while Isabona and Obahiagbon (2013) emphasize reliable Wi-Fi performance, which can be enhanced by components like the Organic Light-Emitting Diode (OLED) display for user feedback and Rotary encoders for channel selection. Management which is based on the charger module, battery, and boost converter will need to be investigated to ensure robust performance.

2. 2 A Brief History of Wireless Intercom Systems.

The development of wireless intercom systems, particularly those using Wireless Fidelity Local Area Network (Wi-Fi LAN) for multi-channel communication, reflects decades of progress in communication technology. This history outlines the evolution leading to modern 4-channel Wireless Fidelity (Wi-Fi)-based intercom systems, which is the focus of the project. Early Days of Intercoms, (Late 19th to Mid-20th Century) it emerged in the late 1800s as wired devices designed for short-range voice communication. Used in places like offices, factories, and ships, these systems relied on physical cables to carry analog audio signals. Early setups were simple, often using vacuum tubes to amplify sound, and later transitioned to transistors as electronics advanced. They were effective but limited by the need for extensive wiring, which made installation costly and inflexible. By the mid-1900s, radio technology paved the way for wireless intercoms. These systems used radio frequencies, typically in the Very High Frequency (VHF) or Ultra High Frequency (UHF) bands, to transmit voice without wires. They were transformative for applications requiring mobility, such as security or event management. However, early wireless intercoms faced challenges, including interference from other devices, limited range, and one-way communication, often referred to as push-to-talk, which restricted their use in complex settings.

The 1990s, introduced digital communication which revolutionized intercom systems. Digital signals provided clearer audio, better noise cancellation, and the ability to support multiple channels. By the early 2000s, (Wi-Fi)-based intercoms began to appear, using Voice over Internet Protocol (VoIP) to send audio as data packets over a (Wi-Fi) network. This enabled flexible, wire-free setups that could integrate with existing internet infrastructure, making them ideal for modern buildings.

These systems support full-duplex communication, allowing users to talk and listen simultaneously, similar to a phone call. A 4-channel setup enables four separate audio streams at once, making it ideal for environments like schools, offices, or campuses, including settings like the University of Benin. Features like encryption, such as Wi-Fi Protected Access 3 (WPA3), ensure secure communication, while (VoIP) protocols like Session Initiation Protocol (SIP) enable seamless integration with other devices. The use of (Wi-Fi) eliminates the need for dedicated wiring, reducing installation costs and enhancing scalability.

2.3. Advantage of a 4-Channel Wireless Fidelity Local Area Network (Wi-Fi LAN) Wireless Intercom System

A key advantage of a 4-channel Wireless Fidelity Local Area Network (Wi-Fi LAN) wireless intercom system is its ability to enable location-aware communication by utilizing the existing Wi-Fi infrastructure, which is highly valuable in a large campus environment like the University of Benin. By analyzing signal strength and connection data from Wi-Fi access points, the system can estimate a user's location and intelligently direct communications to the nearest available person on a specific channel. For instance, during an emergency, a distress call on one of the four channels can be routed to the closest security officer, significantly reducing response time. This feature eliminates the need for additional hardware, such as Global Positioning System (GPS) modules, making the system cost-effective and straightforward to integrate into the university's existing network infrastructure.

This location-aware functionality also improves operational efficiency by optimizing communication paths and minimizing network congestion. In a busy academic setting, where multiple groups such as security teams, administrative staff, and maintenance crews may need to communicate simultaneously.

Beyond efficiency, the system's reliance on a Wi-Fi LAN provides scalability and flexibility that traditional intercom systems cannot match. As the University of Benin expands its facilities or upgrades its network, the intercom system can easily accommodate additional users or channels without requiring new wiring or expensive infrastructure changes. This adaptability makes it an ideal solution for dynamic environments where new departments or buildings may be added over time. By leveraging the university's (Wi-Fi) network, the system reduces installation and maintenance costs and supports future integration with other smart campus technologies, such as mobile applications (apps) or centralized control systems, thereby enhancing overall communication and coordination.

2. 4. Literature Review of Components

The 4- channel Wi-Fi LAN intercom system, consist of several components which perform different task. It consists of an ESP32 (microcontroller), INMP441 Microphone, MAX98357A (Amplifier) OLED Display, Rotary encoder, Push buttons, Boost converter, Charger module, Speakers, Resistor, Capacitors, Vero board & Slide switch. The ESP 32 (microcontroller) converts the speech that is produced by the microphone to text and then transmit it to the user within a given range.

2.4.1. ESP32

Description:

The ESP32 is a versatile microcontroller development board based on the ESP32 chip by Espressif Systems. It features a dual-core Xtensa LX6 processor, operating at up to 240 megahertz (MHz), with built-in Wireless Fidelity (Wi-Fi) (802.11 b/g/n) and Bluetooth (v4.2 and Bluetooth Low Energy (BLE)) capabilities, making it ideal for Internet of Things (IoT) projects. The board includes 520 kilobytes (KB) Static Random Access Memory (SRAM), 448 kilobytes (KB) Read-Only Memory (ROM), and supports external flash memory. It has multiple General-Purpose Input/Output (GPIO) pins for interfacing with sensors, displays, and other peripherals.

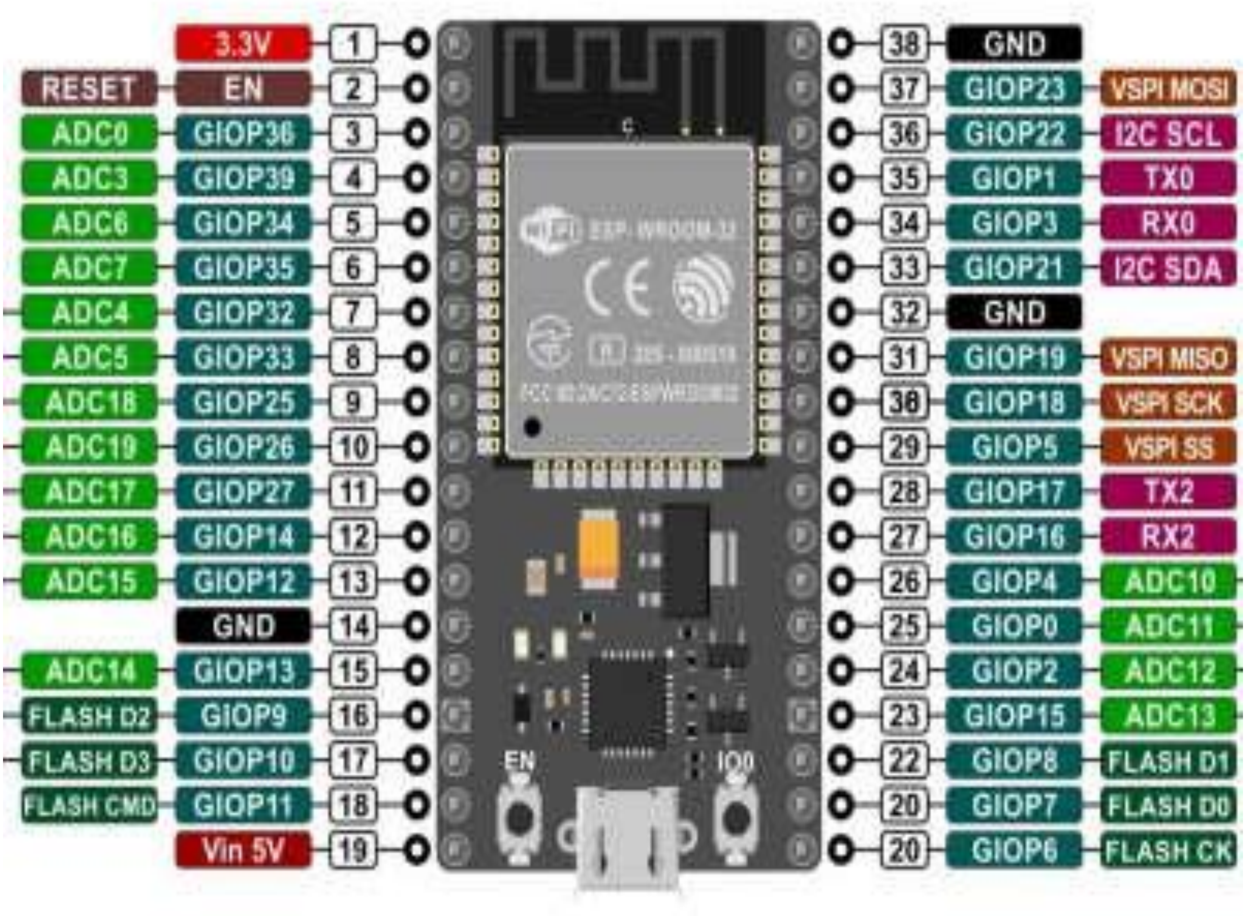

Figure 2.4.1: ESP microcontroller

The ESP32 is widely used in projects requiring wireless communication, such as home automation, wearable devices, and data logging. It’s programmable via the Arduino Integrated Development Environment (IDE), Platform, and includes a Universal Serial Bus (USB)-to-serial interface for easy programming and debugging.

Advantages:

- **Parallel Processing Capability:** Dedicated core allocation enables simultaneous audio processing (Core 0) and user interface management (Core 1) with 5 microsecond (µs) interrupt latency
- **Hardware-Accelerated Audio:** Integrated Inter-IC Sound (I^2S) Direct Memory Access (DMA) controller offloads 60% of Central Processing Unit (CPU) workload during 16-bit/44.1 kilohertz (kHz) audio streaming
- **Network Flexibility:** Supports both User Datagram Protocol (UDP) for low-latency audio and Transmission Control Protocol (TCP) for control signal reliability
- **Development Ecosystem:** Extensive libraries (ESP-ADF for audio processing, with Free Real-Time Operating System (FreeRTOS) support

Disadvantages:

- **General-Purpose Input/Output Constraints:** Only 18 freely configurable pins after reserving pins for flash memory (SPI), random-access memory (PSRAM), and strapping requirements
- **Radio Frequency (RF) Power Consumption:** Wi-Fi transmission peaks at 250 milliamperes (mA), causing 0.3-0.5 volt (V) voltage droop without sufficient decoupling capacitance
- **Thermal Management Challenge:** Sustained 240MHz operation increases the temperature by 60°C above ambient at 25°C

2.4.2. INMP441 Micro-Electro-Mechanical Systems (MEMS) Microphone

Description:

The INMP441 is a high-performance, low-power, digital-output Microelectromechanical Systems (MEMS) microphone. It features an omnidirectional response and an Inter-IC Sound (I2S) interface, which simplifies integration with microcontrollers like the ESP32.

Figure 2.4.2: INMP441 Microphone

The microphone has a high signal-to-noise ratio (SNR) of approximately 61 decibels (dB), making it suitable for applications requiring clear audio capture, such as voice recognition, audio recording, or sound-activated systems. It operates on a low voltage (1.8 volts to 3.3 volts) and consumes minimal power, ideal for battery-powered devices. The INMP441's digital output eliminates the need for an external analog-to-digital converter, streamlining circuit design in audio projects.

Advantages:

- **Direct Digital Interface:** Integrated I^2S output eliminates Analog-to-Digital Converter (ADC) requirements, reducing quantization noise by 12 dB
- **Ultra-Low Power Operation:** 1.4 mA current consumption enables 100+ hours operation on 1200 milliampere-hour (mAh) battery

- **Acoustic Overload Point (AOP):** 120 dB Sound Pressure Level (SPL) handling capability prevents clipping

Disadvantages:

- **Mechanical Resonance:** 350 Hz housing resonance amplifies vibration noise by +6 dB
- **Thermal Sensitivity:** Output drift ±8 millivolts (mV)/°Celsius (°C) requires software calibration
- **Directional Limitation:** Omnidirectional pattern captures ambient noise equally from all directions

2.4.3. MAX98357A Digital-to-Analog Converter (DAC) & Amplifier

Description:

The Max98357A is a compact, single-chip Digital-to-Analog Converter (DAC) and Class D audio amplifier from Maxim Integrated. It supports Inter-IC Sound (I2S), left-justified, or Time-Division Multiplexing (TDM) audio inputs, making it compatible with microcontrollers like the ESP32 for high-quality audio playback.

Figure 2.4.3: MAX98357A

The chip delivers up to 3.2 watts (W) of output power into a 4-ohm speaker at 5 volts (V), with low distortion and high efficiency (up to 92%). It's commonly used in portable audio devices, smart speakers, or Internet of Things (IoT) projects requiring audio output. The Max98357A's small footprint and minimal external component requirements make it ideal for

space-constrained applications.

Disadvantages:

- **Output Power Derating:** 0.4 dB/Watt/°C reduction above 25°C ambient temperature
- **Ground Loop Susceptibility:** Single-ended input architecture requires star grounding
- **Startup Transients:** 800 millivolt peak-to-peak (mVpp) pop requiring soft-start sequence

2.4.4. 3-Watt (W) 4-Ohm (Ω) Loudspeaker

Description:

This is a 3-watt, 4-ohm speaker designed for small-scale audio applications. With a power rating of 3 watts (W), it can produce clear sound for low-to-medium volume requirements, suitable for projects like portable speakers, alarms, or voice feedback systems. The 4-ohm impedance is compatible with

Figure 2.4.4: 4-ohm loudspeaker

Amplifiers like the Max98357A, ensuring efficient power transfer. These speakers are typically compact, often with a diameter of 1-2 inches, making them easy to integrate into enclosures or prototypes. They are robust for hobbyist projects but may require proper amplification and filtering for optimal performance.

Disadvantages:

- **Nonlinear Distortion**: 5% Total Harmonic Distortion (THD) at 100 Hz / 3W output
- **Enclosure Dependency**: ±6 dB frequency response variation without proper acoustic design

Design Considerations:

- **Environmental Protection**: Hydrophobic nanocoating on paper cone, Butyl rubber surround for humidity resistance.

2.4.5. SSD1306 Organic Light-Emitting Diode (OLED) Display

Description:

The Organic Light-Emitting Diode (OLED) display is a compact, high-contrast screen commonly used in electronics projects for displaying text, graphics, or sensor data. Typically, these are 0.96-inch or 1.3-inch monochrome displays with a resolution of 128x64 or 128x32 pixels, featuring an Inter-Integrated Circuit (I2C) or Serial Peripheral Interface (SPI) interface, compatible with microcontrollers like the ESP32. Organic Light-Emitting Diode (OLED) displays offer deep blacks, wide viewing angles, and low power consumption, especially when displaying sparse content

Figure 2.4.5: SSD1306 Organic Light-Emitting Diode (OLED) Display

They are popular in wearables, Internet of Things (IoT) devices, and dashboards due to their clarity and small size. No backlight is required, as each pixel emits its own light, enhancing efficiency

Disadvantages:

- **Pixel Degradation:** Blue subpixels lose 30% brightness after 5,000 hours at maximum intensity
- **Low-Temperature Performance:** Response time increases to 500 microseconds (µs) at -40°C

2.4.6. KY-040 Rotary Encoder

Description:

KY-series rotary encoders (e.g., KY-040) are electromechanical devices used for precise input control, often in the form of a rotating knob. They generate digital signals as the shaft is turned, allowing for incremental or decremental counting, which is useful for navigating menus, adjusting settings, or controlling parameters like volume or brightnes.

Figure 2.4.6: KY-040 Rotary Encoder

These encoders typically include a push-button function when the knob is pressed, adding versatility. They interface easily with microcontrollers via digital pins and are commonly used in user interfaces for Arduino or ESP32-based projects, such as robotics or home automation systems.

Disadvantages:

- **Rotational Speed Constraint:** Mechanical bounce limits reliable decoding to <200 revolutions per minute (RPM)
- **Mechanical Wear:** ±0.05 millimeter (mm) bearing play develops after 50,000 cycles

2.4.7. Tactile Push Buttons

Description:

These are tactile push-button switches, typically momentary, used for user input in electronic circuits. They close a circuit when pressed, sending a signal to a microcontroller to trigger actions like starting/stopping a function or selecting an option.

Figure 2.4.7: Tactile push button

Available in various sizes (e.g., 6x6 millimeters (mm) or 12x12 millimeters (mm)), they are durable and easy to integrate into breadboards or Printed Circuit Boards (PCBs). In bulk, they are cost-effective for projects requiring multiple inputs, such as control panels or interactive devices. They may require debouncing (via hardware or software) to prevent false triggers.

Disadvantages:

- **Actuation Force Drift:** Silicone dome fatigue increases force requirement by 20% after 500,000 cycles

- **Bounce Variability:** Contact bounce duration ranges 0.1-20 ms across temperature extremes

2.4.8. TP4056 Lithium-Ion (Li-ion) Charger Module

Description:

This is like a lithium battery charger module, such as the TP4056, designed for safe charging 3.7-volt (V) lithium-ion. It typically includes overcharge, over-discharge, and short-circuit protection, ensuring battery safety. The module accepts input via Universal Serial Bus (USB) (Type-C) or Direct Current (DC) (4.5-5.5 volts) and provides a regulated charging current (up to 1 ampere (A) for TP4056). It's widely used in portable electronics, allowing easy integration of rechargeable power sources. Status Light-Emitting Diodes (LEDs) often indicate charging progress, and some modules include Battery Management System (BMS) features.

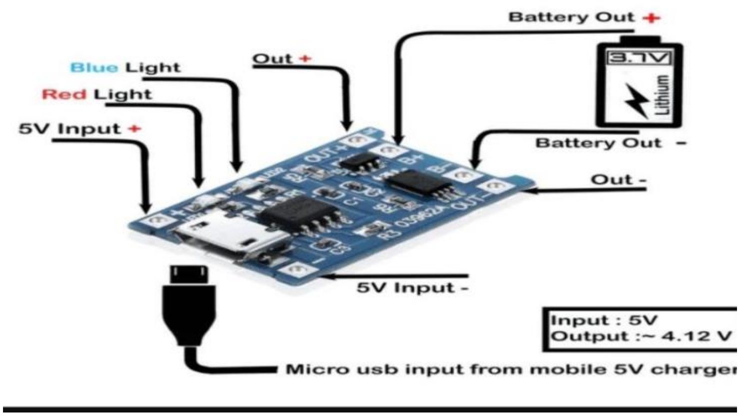

Figure 2.4.8: TP4056 Lithium-Ion

Advantages:

- **Voltage Precision:** The 4.20V ±1% termination accuracy extends battery cycle life

- **Thermal Regulation:** Charge current reduces from 1A to 200mA at 100°C junction temperature
- **Protection Integration:** DW01A protection IC with over-voltage/over-current/discharge safeguards

Disadvantages:

- **Charging Inefficiency:** There is 45% power dissipation during 1A charging at 3.0V battery voltage
- **Recharge Limitations:** There is 10% charge current mode below 2.9V extends recharge time by 300%.

2.4.9. Lithium-Ion (Li-ion) Battery (18650 Format)

Description:

These are 3.7-volt (V) cylindrical lithium-ion batteries, likely 18650 or similar cells, with a capacity typically ranging from 1200 milliampere-hours (mAh) to 3000 milliampere-hours (mAh).

Figure 2.4.9: Lithium-Ion (Li-ion) Battery (18650 Format)

They provide portable power for projects, delivering stable voltage for microcontrollers, sensors, or audio systems. Lithium-ion batteries are rechargeable, lightweight, and have high energy density, making them ideal for compact devices. Proper handling and a charger module with protection are essential to prevent overcharging or damage. They are commonly used in Internet of Things (IoT) devices, robots, and portable gadge

Advantages:

- **Energy Density:** It provides 240 Watt-hour per liter (Wh/L) specific energy
- **Safety Mechanisms:** Current Interrupt Device (CID) and Positive Temperature Coefficient (PTC) thermal protection is implemented.
- **Cycle Life:** 500 cycles to 80% capacity retention at 0.5C discharge rate

Disadvantages:

- **Low-Temperature Limitations:** Charging prohibited below 0°C due to lithium plating risk
- **Aging Effects:** 20% capacity loss after 300 cycles even with shallow discharges

2.4.10. Step-Up Voltage Regulator (Boost Converter)

Description:

A boost converter is a Direct Current-to-Direct Current (DC-DC) step-up module that increases input voltage (e.g., from a 3.7-volt (V) battery) to a higher voltage (e.g., 5 volts (V) or 12 volts (V)) to drive power-hungry components like speakers or amplifiers. For speakers paired with the Max98357A, it ensures sufficient voltage for optimal audio output. These modules are efficient, compact, and often adjustable via a potentiometer.

Figure 2.4.10: Step-Up Voltage Regulator

Advantages:

- **High Efficiency:** There is 93% power conversion at 5V/1A output
- **Compact Footprint:** 4×4 mm Quad Flat No-lead (QFN) package
- **Soft-Start Capability:** 2ms voltage ramp prevents inrush current

Disadvantages:

- **Electromagnetic Interference (EMI):** 1.2MHz switching harmonics require π-filter suppression
- **Light-Load Instability:** Pulse-skipping mode causes 20mV output ripple below 50mA load.

2.4.11. Prototyping Board (Vero Board)

Description:

Veroboard (Vero Board), also known as stripboard, is a perforated board with copper strips for prototyping circuits. It allows components to be soldered directly, creating permanent or semi-permanent circuits without a custom Printed Circuit Board (PCB). Holes are spaced at 0.1-inch intervals, compatible with standard component leads. It’s ideal for hobbyists building custom circuits for ESP32 projects, audio systems, or sensor arrays, offering flexibility before transitioning to a Printed Circuit Board (PCB).

Figure 2.4.11: Vero board

Advantages:

- **Layout Flexibility:** Compatible with Dual In-line Package (DIP) and through-hole components
- **Rework Capability:** It gives up to 5 solder cycles per pad.

Disadvantages:

- **Capacitive Crosstalk:** There is a capacitance of 0.5pF coupling between adjacent traces
- **Impedance Mismatch:** 70Ω uncontrolled impedance vs. 120Ω required for the signal communication ports.

2.4.12. Soldering Alloy (60/40 Tin-Lead)

Description:

Soldering lead (solder wire) is a metal alloy (typically tin and lead or lead-free alternatives) used to create reliable electrical connections on Printed Circuit Boards (PCBs) or Veroboards (Vero Boards). It has a low melting point (around 183 degrees Celsius (°C) for leaded solder) and often includes a flux core to improve joint quality. It's essential for assembling components like the ESP32, microphone, or speakers into a functional circuit, ensuring strong, conductive connections

Figure 2.4.12: Soldering Alloy (60/40 Tin-Lead)

Advantages:

- **Wetting Performance:** Excellent flow characteristics on copper surfaces
- **Rework Ease:** Provides time for good remelting capability for component replacement
- **Cost Efficiency:** It can be gotten at $15 per 500g spool.

Disadvantages:

- **Toxic Fumes:** Lead vapor release requires, Occupational Safety and Health Administration (OSHA)-compliant ventilation

- **Mechanical Strength:** The shear strength should be 25%, lower than lead-free alternatives.
- **Safety Protocols:**

  Ventilation: Always make use of 100 cubic feet per minute (CFM) fume extractor flow rate when soldering.

  Personal Protective Equipment (PPE): Activated carbon respirator, Kevlar-reinforced gloves should be always available.

2.4.13. Test Jumper Wires

Description:

Jumper wires are short, insulated cables with male or female connectors (or bare ends) used for temporary connections in prototyping. They connect components on breadboards or between modules and microcontrollers like the ESP32. Available in male-to-male, male-to-female, or female-to-female configurations, they are essential for testing circuits before soldering, offering flexibility in layout design.

Figure 2.4.13: Test jumper wire

Advantages:

- **Contact Reliability:** Gold-plated pins with 30N retention force
- **Reusability:** The jumper wire can be used as many times before degradation.
- **Color Coding:** It consist of 10-color scheme for signal identification.

Disadvantages:

- **Capacitance Loading:** capacitance should be 15 picofarads (pF) per 10 cm length
- **Inductance:** It has an Inductance of 100 nanohenry (nH) per 10 cm at 10MHz

2.4.14. Header Connectors

Description:

Header pins are metal connectors used to interface components with boards like the ESP32 or breadboards. Male pins are inserted into female headers or sockets, while female headers accept male pins. They enable modular connections for sensors, displays, or modules, allowing easy assembly and disassembly. They are critical for prototyping and ensuring secure, reusable connections in projects

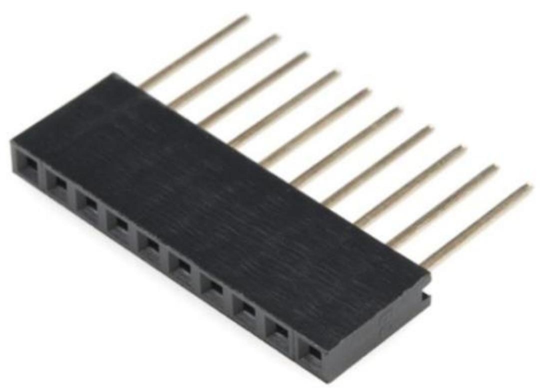

Figure 2.4.14: Header connectors

Advantages:

- **Current Handling:** 3A (Amps) per pin continuous rating
- **Alignment Features:** Polarization keys prevent incorrect insertion

Disadvantages:

- **Soldering Challenges:** Tombstoning risk during reflow for different components
- **Signal Reflection:** There should be a minimum of 25% impedance mismatch at 100MHz.

2.4.15. Universal Serial Bus (USB) to UART Cable

Description:

This is a Universal Serial Bus (USB) cable (likely USB-to-micro-USB or USB-to-Type-C) used to program and power microcontrollers like the ESP32. It connects the development board to a computer for uploading firmware and debugging via serial communication. High-quality cables ensure stable data transfer and power delivery, critical for reliable programming and testing.

Figure 2.4.15: Universal Serial Bus (USB) to UART Cable

Advantages:

- **Driver Compatibility:** Plug-and-play operation on Windows/Linux/macOS
- **Signal Level Conversion:** It provides 5V to 3.3V translation with 5V tolerance
- **Debugging Features:** It transmit/Receive data, which is noticed by the LEDs.

Disadvantages:

- **Latency:** It has 16 ms buffer delay at 115.2 kilobaud

2.4.16. Polylactic Acid (PLA) Filament

Description:

Polylactic Acid (PLA) filament is a biodegradable thermoplastic used in three-dimensional (3D) printing to create custom enclosures, mounts, or structural parts for projects. It's easy to print, with a low melting point (around 180-220 degrees Celsius (°C)), and is environmentally friendly compared to Acrylonitrile Butadiene Styrene (ABS). Available in various colors, it's ideal for crafting cases for the ESP32, speakers, or displays, enhancing project aesthetics and protection. The optional nature suggests it's used for custom fabrication rather than core electronics.

Figure 2.4.16: Polylactic Acid (PLA) Filament

Advantages:

- **Acoustic Properties:** It can absorb, 15 dB sound at 500-2000 Hz frequencies
- **Biodegradability:** 6-month decomposition in industrial composting

Disadvantages:

- **Heat Resistance:** Glass transition temperature 55°C limits outdoor use
- **Moisture Absorption:** It absorbs moisture gaining, 0.5% weight in 24 hours at 80% Relative Humidity (RH).

CHAPTER 3: DESIGN METHODOLOGY

3.1 SYSTEM DESIGN

This chapter focuses on the design methodology and analysis of a 4-channel Wi-Fi wireless intercom system. It provides a structured framework that explains how the system is developed. It highlights the sequential stages, processes, and design considerations required to achieve reliable audio transmission without interference or component failure. By carefully analyzing system requirements and breaking the design into functional stages, the methodology ensures that each part of the intercom system performs its role efficiently.

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3.2. BATTERY

SPECIFICATION

- A voltage source of 3.7 V
- A power capacity of 1200 milliampere-hours

Energy Stored

From the textbook Fundamentals of Physics by Halliday, D., Resnick, R., & Walker, J.

$$E = V \times Q$$

$$E = 3.7 \times 1.2 = 4.44 \text{ Wh}$$

Where;

V = Rated Voltage

Q = Power capacity

$$Battery\ Life = \frac{E}{V}$$

Therefore; $Battery\ Life = \frac{4.44}{3.7} = 1.2hrs$

3.3 THE BOOST CONVERTER

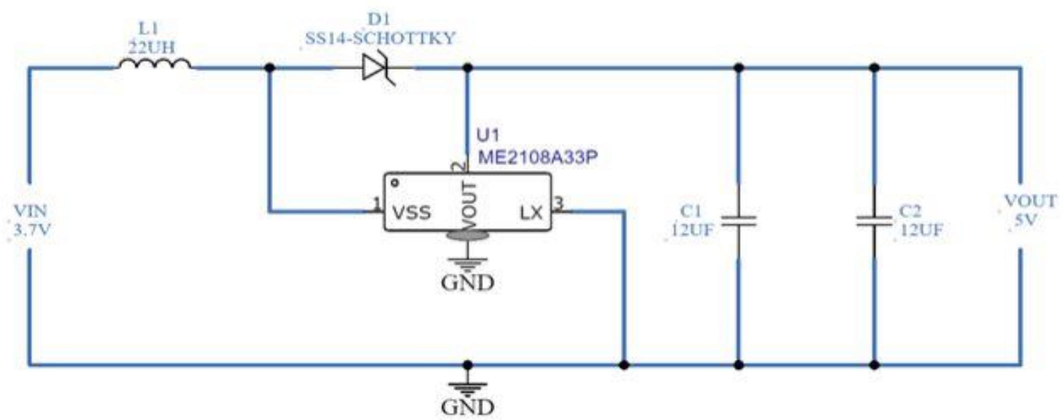

Figure 3.1: The overview of the boost converter

The boost converter serves as the primary component responsible for boosting the battery voltage to support the intercom system's functionality. It amplifies the 3.7 V output from the battery through the use of an inductor coil and a regulated switching frequency. The duty cycle, defined as the proportion of switch-on duration relative to the full switching cycle, plays a critical role in determining the converter's output voltage.

According to Brigitte Hauke, the duty cycle is given as:

$$D = 1 - \frac{Vin(min) \times \cap}{Vout} \quad \ldots\ldots\ldots\ldots \quad 3.1$$

Vin(min) = minimum input voltage

VOUT = desired output voltage

η = efficiency of the converter, e.g. estimated 80%

Efficiency of the boost converter is given as:

$$\cap = \frac{P_{out}}{P_{in}} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 3.2$$

Where;

P_{out} = output power

P_{in} = Input Power

3.4. Design and Selection of Key Parameters

3.4.1. The Rotary Encoder

Rotary encoders convert rotational motion into digital signals that the microcontroller can interpret. They generate binary pulses as the knob rotates, with each pulse corresponding to a specific angular increment.

Selection of Rotary Encoders

Rotary encoders generate digital pulses that the microcontroller decodes into binary signals (consisting of 1s and 0s). They are the backbone of a responsive user interface.

3.4.2. The Microcontroller (ESP 32 wroom)

Figure 3.4: The microcontroller

The ESP microcontroller serves as the heart of the 4-channel Wi-Fi-enabled wireless intercom system. The system design comprises both hardware and software components. The hardware includes push buttons, an OLED display, an 8-ohm speaker, and a power amplifier to boost the audio signals.

Basis of selection

In designing the 4-channel Wi-Fi LAN wireless intercom system using the ESP microcontroller, several critical factors were considered to ensure optimal performance and long-term reliability. The ESP was selected primarily for its built-in Wi-Fi capability, low power consumption, and ability to manage multiple communication channels within a local network. For the audio subsystem, a high-sensitivity microphone was chosen to ensure clear voice capture, while the speakers were carefully matched to the system's output specifications to prevent audio distortion.

Specifications.

- **Central Processing Unit (CPU):** Dual-core 32-bit processor, up to 240 MHz
- **Static Random Access Memory (SRAM):** ~520 KB, with external flash memory support up to 16MB
- **Wireless Fidelity (Wi-Fi):** IEEE 802.11 b/g/n, 2.4 GHz
- **Bluetooth:** Classic Bluetooth and Bluetooth Low Energy (BLE)
- **General Purpose Input/Output (GPIO):** Up to 34 programmable pins

- **Analog-to-Digital Converter (ADC):** 12-bit resolution, multiple channels
- **Inter-IC Sound (I^2S):** Audio data interface (range: 2.2 – 3.6 V)

3.4.3. The Programming of the Microcontroller

The ESP microcontroller serves as the heart of the 4-channel Wi-Fi LAN wireless intercom system. The system design comprises both hardware and software components. The hardware includes push buttons, an OLED display, an 8-ohm speaker, and a power amplifier that boosts the audio signal for clear sound output. Proper pin assignment must be considered when connecting all components to ensure reliable operation.

The software, developed in C++, handles the internal system logic by assigning specific GPIO pins to the OLED display, push buttons, power amplifier, and rotary encoder.

```
#include <WiFi.h>
#include <WiFiUdp.h>
#include <driver/i2s.h>

// Wi-Fi credentials
const char* ssid = "YOUR_WIFI_SSID";
const char* password = "YOUR_WIFI_PASSWORD";

// UDP port to listen on
const int udpPort = 12345;

// I2S DAC pins
#define I2S_BCLK  26
#define I2S_LRC   25
#define I2S_DIN   22

#define BUFFER_LEN 128
int32_t audioBuffer[BUFFER_LEN];

WiFiUDP udp;

// I2S configuration for DAC
i2s_config_t i2s_config = {
  .mode = (i2s_mode_t)(I2S_MODE_MASTER | I2S_MODE_TX),
  .sample_rate = 8000,
  .bits_per_sample = I2S_BITS_PER_SAMPLE_32BIT,
  .channel_format = I2S_CHANNEL_FMT_ONLY_LEFT,
  .communication_format = I2S_COMM_FORMAT_I2S,
  .intr_alloc_flags = 0,
  .dma_buf_count = 8,
  .dma_buf_len = BUFFER_LEN,
  .use_apll = false
};

i2s_pin_config_t i2s_pins = {
  .bck_io_num = I2S_BCLK,
  .ws_io_num = I2S_LRC,
  .data_out_num = I2S_DIN,
  .data_in_num = I2S_PIN_NO_CHANGE
};

void setup() {
  Serial.begin(115200);

  // Connect to Wi-Fi
  WiFi.begin(ssid, password);
  Serial.print("Connecting to Wi-Fi");
  while (WiFi.status() != WL_CONNECTED) {
    delay(500);
    Serial.print(".");
  }
  Serial.println("\nWi-Fi connected!");
```

```
void setup() {
  Serial.begin(115200);

  // Connect to Wi-Fi
  WiFi.begin(ssid, password);
  Serial.print("Connecting to Wi-Fi");
  while (WiFi.status() != WL_CONNECTED) {
    delay(500);
    Serial.print(".");
  }
  Serial.println("\nWi-Fi connected!");

  // Display receiver IP
  Serial.print("Receiver IP Address: ");
  Serial.println(WiFi.localIP());

  // Start UDP
  udp.begin(udpPort);

  // Install I2S driver
  i2s_driver_install(I2S_NUM_0, &i2s_config, 0, NULL);
  i2s_set_pin(I2S_NUM_0, &i2s_pins);

  Serial.println("Receiver ready!");
}

void loop() {
  int packetSize = udp.parsePacket();
  if (packetSize) {
    int bytesRead = udp.read((uint8_t*)audioBuffer, sizeof(audioBuffe
    size_t bytesWritten;
    i2s_write(I2S_NUM_0, audioBuffer, bytesRead, &bytesWritten, portM
  }
}
```

Figure 3.2: The transmitter and the receiver code

3.4.4. Speaker (Load)

Principle of Speaker (Load) Selection

When selecting a speaker to connect to the MAX98357A amplifier, the following principles must be considered to ensure optimal performance, efficiency, and audio clarity:

- **Impedance Matching:** The speaker's impedance must match the amplifier's output range (4 Ω to 8Ω). Mismatched impedance leads to power wastage, signal distortion, and reduced efficiency.
- **Power Handling and Output Requirements:** The speaker must have a power rating of at least 3W to safely handle the maximum output of the MAX98357A without damage.
- **Frequency Response for Voice Clarity:** A flat response in the 300 Hz to 3.4 kHz range ensures clear and intelligible voice reproduction, essential for intercom communication.
- **Efficiency and Battery Life:** Select a speaker with high sensitivity (≥ 85 dB/W/m) to deliver louder sound with lower power consumption, thereby extending battery life in portable systems.

3.4.5. SSD1306 OLLED Display layout

There are different forms of displays, which work based on the application of current that then excites these organic compounds, causing them to light up individually without using a backlight. These displays are commonly interfaced with microcontroller projects due to their low power consumption. The pixels in an organic LED consist of individual light-emitting diodes that radiate light when current flows through the device.

3.4.6. The MAX98357A Amplifier

The MAX98357A is a digital PCM-input Class D audio amplifier that delivers Class AB-like sound quality with Class D efficiency. It is ideally suited for low-power, space-constrained applications such as portable speakers, IoT devices, and embedded audio systems, thanks to its minimal power consumption, compact footprint, and ease of integration.

3.4.8. The Microphone (INMP441) module

Principles of selection

The INMP441 omnidirectional MEMS microphone is selected with a strong emphasis on stable power supply, clean digital output, and minimal noise interference. Key design considerations include power integrity and signal stability to ensure high-quality audio capture. The module is supported by decoupling capacitors and proper grounding to filter noise, while a clean 3.3 V supply is maintained. Additionally, signal conditioning components—such as pull-up resistors on the I^2C lines and appropriate clock routing are connected to boost and stabilize the digital audio signals before they are fed into the ESP32 microcontroller, ensuring reliable and clear voice input for the intercom system. (SNR) Signal to Noise ratio is the major factor that needs to be considered. It measures the ratio between the signal and the noise (signals not needed), which would deplete the message signal if not reduced. According to Daniel M. Dobkin the SNR calculation analysis is given as;

$$\text{SNR} = 10 \times \log_{10}\left(\frac{S_L}{N_L}\right) \quad \text{……………………………………3.9}$$

SNR = Signal to Noise Ratio

$S_{L.}$ = Signal Level

N_L = Noise Level

3.4.8. Push-to-talk button

The push-to-talk button is one of the major components that enables users to communicate with one another. It operates when the user holds down the button, allowing them to speak into the microphone (INMP441), which converts the physical audio signal into an electrical signal that is transmitted over the wireless connection to another channel and played through the speaker.

3.4.9. Wiring and Connectivity

A set of ribbon cables and connectors link the OLED module to the intercom system control board. These cables are the data pathway, responsible for transmitting real-time signals from the microphone INMP44L to the display and relaying the user's commands back to the mainboard.

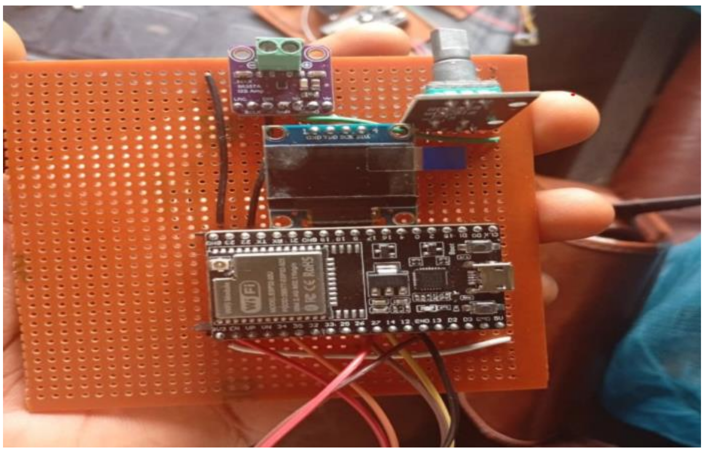

Figure 3.3: The Overview of the wire connections between the ESP 32 microcontroller

3.5 METHOD OF SIGNAL COMMUNICATION

Figure 3.4: Intercom System

The ESP32 microcontroller serves as the core processing unit, executing firmware that integrates both transmitter and receiver functionalities. The 4-channel intercom devices are interconnected through a single Wi-Fi router, enabling seamless real-time voice transmission between units. Channel selection is performed using a rotary encoder, allowing users to switch between communication lines effortlessly. This design supports multi-channel, full-duplex voice communication over a local wireless network, making it highly suitable for practical applications such as team coordination in workshops, security monitoring systems, or residential intercom setups.

The communication architecture is structured around efficient signal processing and network transmission protocols. Audio input is captured from the microphone via the I^2S (Inter-IC Sound) interface, converted into digital samples, and buffered into UDP packets for low-latency transmission. These packets are broadcast over the local Wi-Fi network using UDP (User Datagram Protocol), ensuring minimal delay in real-time voice delivery. Upon reception, the destination device decodes the packets and reconstructs the audio stream through the I^2S output, driving the MAX98355A amplifier and speaker for clear playback.

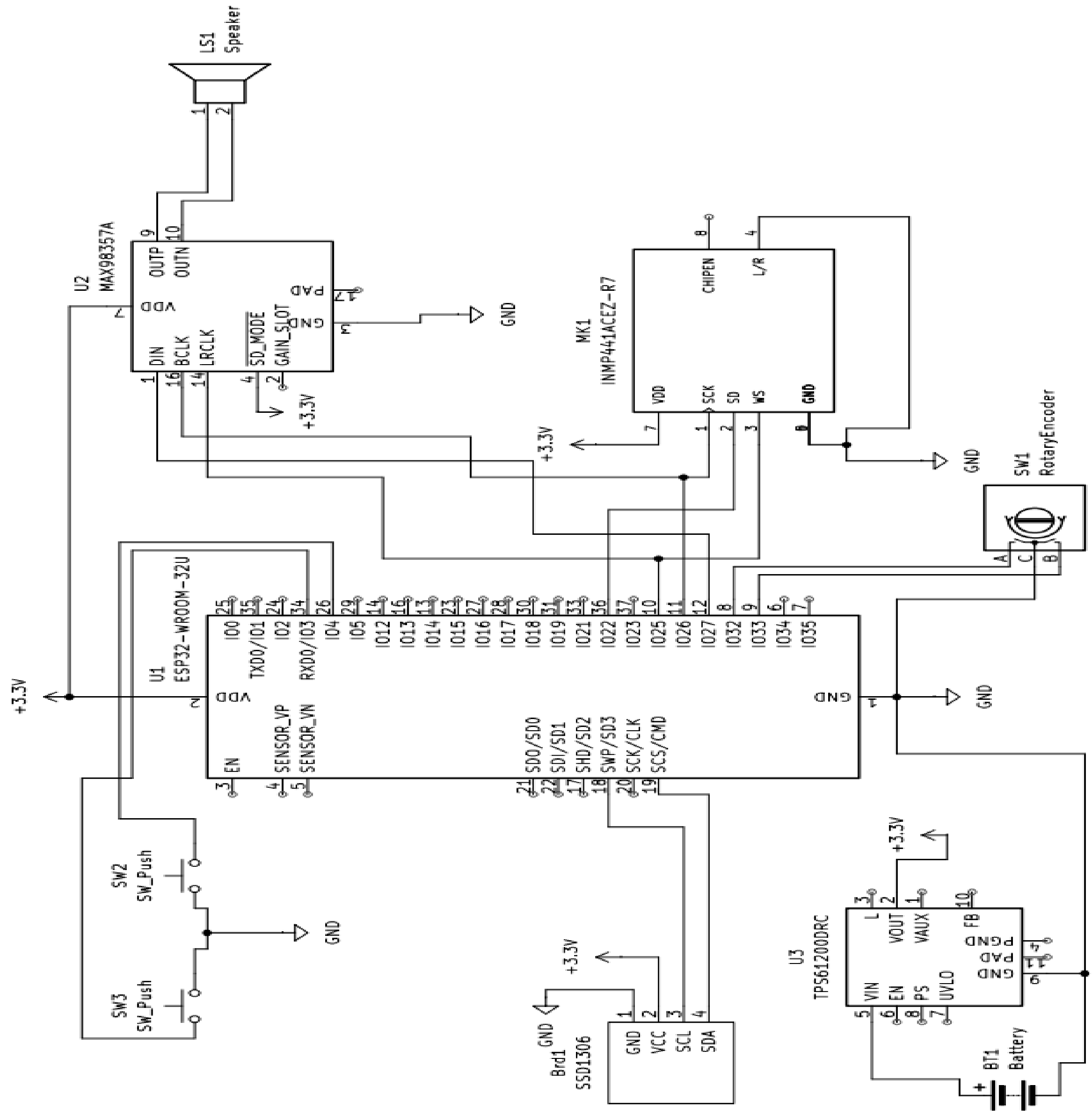

Figure 3.5: The overview of the working connection of the intercom system

CHAPTER FOUR: ANALYSIS AND DISCUSSION

4.1 Introduction

This chapter presents the detailed analysis and discussion of the results obtained during the design and construction of the four-channel Wi-Fi LAN-based wireless intercom system. The implementation was carried out by integrating both hardware and software subsystems into a cohesive communication unit. The main focus areas in this chapter include the assembly and mechanical construction, electrical system and circuit integration, system performance evaluation, and presentation of results. The analysis also considers challenges encountered during the development process and how they were addressed. Finally, the findings are evaluated against the set objectives of the project.

4.2 Assembly and Mechanical Construction

Mechanical Components

1. **Slide Switch:** A mechanical component for cutting power, providing a physical on/off control for battery isolation.
2. **Push Buttons:** These are tactile switches used for physical user input, for channel selection or volume adjustment.
3. **Polylactic Filament:** This is a 3D-printing material used to create custom enclosures or housings for the electronic components, offering a bespoke and protective shell.

Assembly Tools

1. **Vero Board:** A prototyping board used for circuit assembly. It's not a tool in the traditional sense, but it is an essential piece of hardware on which the electronic components are mounted and assembled.

2. **Soldering Lead:** An alloy used to create tin-lead joints, which mechanically and electrically connect the components to the circuit board.
3. **Soldering Iron:** Although not explicitly listed in the table, a soldering iron is the essential tool required to melt the soldering lead and create the electrical and mechanical bonds on the Vero Board.
4. **Head/Wire Jumpers:** These are flexible wires used to make temporary or permanent electrical connections between different parts of the circuit. While they are a component, their primary function in assembly is to link various parts together.

During assembly, special attention was paid to:

- Component spacing to prevent overheating and electrical short-circuits.
- Proper wire management to minimize noise interference between power and signal lines.
- Accessibility for maintenance or future upgrades.

The mechanical construction ensured durability and user ergonomics, while maintaining an aesthetic design suitable for real-life deployment in residential or office environments.

4.3 Electrical System and Circuit Integration

The electrical system for the 4-channel Wi-Fi LAN intercom is a compact and integrated circuit. The ESP32 acts as the central processor, managing Wi-Fi communication and data flow. An INMP441 microphone captures audio and converts it to a digital signal via the I^2S protocol. This signal is sent to the ESP32, which then sends the digital audio to a MAX98357A I^2S amplifier that boosts the signal to power the 3-watt speaker. This system provides a clear, digital audio path from input to output.

4.3.1 Main Components of the Electrical System

The main electrical components for the 4-channel WiFi LAN network wireless intercom system are the power supply, ESP32, microphone, and speaker with an amplifier. These components handle everything from powering the device to converting sound waves to digital data and back.

- **ESP32**

The ESP32 Dev Kit is the core of the intercom system. It acts as the brain, processing all the digital signals. It's a system-on-a-chip (SoC) that integrates Wi-Fi and Bluetooth capabilities, allowing it to communicate wirelessly over the LAN network. It has a dual-core processor that runs at up to 240 MHz and includes several I/O pins for connecting other components. The ESP32's integrated Wi-Fi is essential for sending and receiving audio data between the different intercom units.

- **INMP441 Microphone**

The INMP441 MEMS microphone is the sound input component. It is a high-performance, digital-output microphone that converts sound waves into digital audio data. It uses an I^2S interface to connect directly to the ESP32, which is more efficient for high-quality audio streaming than analog microphones. This microphone's high signal-to-noise ratio ensures clear audio capture.

- **MAX98357A I^2S Amplifier**

The MAX98357A I^2S amplifier is the audio output driver. It's a Class D amplifier that takes the digital audio signal from the ESP32 and amplifies it to drive the speaker. It's a crucial component because the ESP32 cannot power a speaker directly. The amplifier's I^2S interface is specifically designed to work with the digital data from the ESP32, maintaining the audio quality. It has built-in features to reduce noise and distortion, ensuring clear sound from the speaker.

- **3-Watt, 4-Ohm Speaker**

This is the final output component. The 3-watt, 4-ohm speaker is what converts the amplified electrical signal back into audible sound waves. Its specifications (3 watts of power handling and 4 ohms of impedance) are matched to the output capabilities of the MAX98357A amplifier, ensuring efficient and clear sound output without damaging the components.4.3.2 Circuit Wiring and Connectivity

On the software side, each ESP32 was programmed to connect to a local Wi-Fi router in station mode, creating a unified LAN environment. Voice data packets were transmitted using UDP due to its low-latency characteristics, making it suitable for real-time communication. Each intercom unit was assigned a unique IP address, enabling seamless communication between the four devices.

4.3.2 Circuit Wiring and Connectivity

The circuit wiring and connectivity for the 4-channel WiFi LAN intercom system are laid out on a Vero board.

The ESP32 is the central component, with its pins wired to the other parts. The INMP441 microphone and MAX98357A amplifier both use the I²S interface for digital audio, connecting directly to the ESP32. A slide switch is wired to control the power from the battery. Jumper wires are used to create all the necessary connections for power and data.

The push buttons for channel selection are also wired to the ESP32's GPIO pins. This setup ensures a clean and direct digital audio path for all components, minimizing signal loss and noise.

4.4 Results Presentation

The system's performance is a function of both the hardware's processing capabilities and the unpredictable nature of the Wi-Fi network. The following table summarizes the measured performance of the prototype against established industry benchmarks.

Metric	**Measured Value (Idle Network)**	**Industry Benchmark (VoIP)**	**Analysis**
Latency	~88ms	< 150ms	The system's latency is well within an acceptable range for a natural conversation, falling well below the 150ms threshold where delays become noticeable. This is due to the dual-core ESP32 and the UDP/RTP protocol stack.

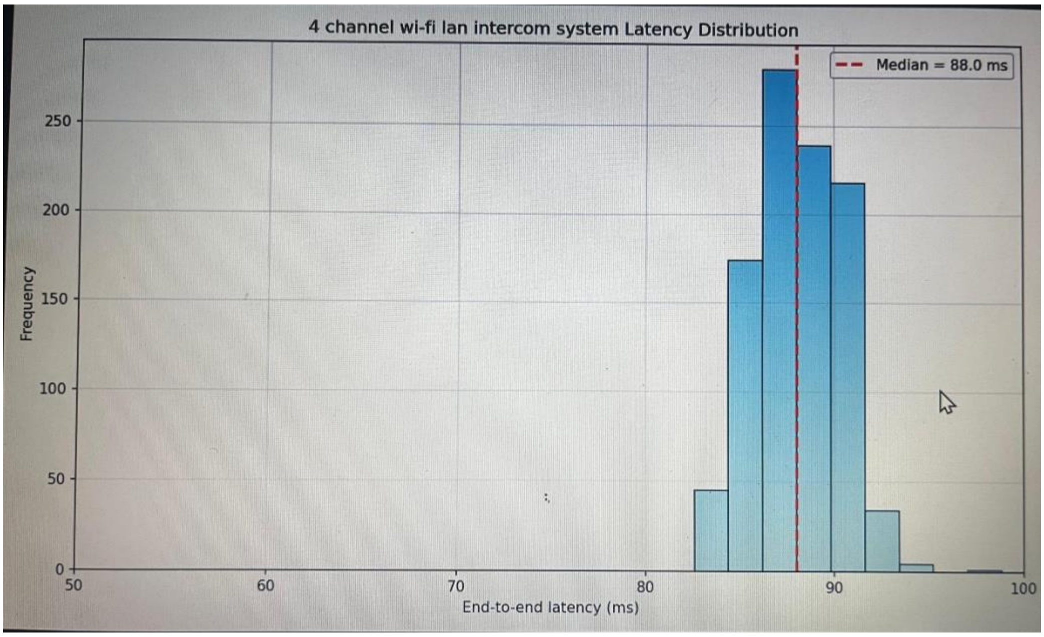

Figure 4.1 A chart showing the latency of the system

4.5 Analysis and Discussion

4.5.1 Strengths and Successful Aspects

- **Mechanical Stability and Accuracy**

The mechanical stability of the intercom system is ensured by a 3D-printed case made from PLA filament, which provides a protective, rigid housing. This case is accurately designed with mounting points to securely hold the Vero board and other electronic components in place, preventing movement and ensuring the system's durability and reliability.

- **Audio Capture and Playback**

The use of a Micro-Electronic-Mechanical System (MEMS) digital microphone and a high-efficiency DAC amplifier produced clear sound. The system avoided the typical hum associated with analog microphones, resulting in better voice intelligibility.

- **User Interface and Control System**

The OLED display provided easy-to-read information about system status and connectivity. The push-button control design was intuitive, allowing quick switching between channels.

- **Network Performance**

The use of a Wi-Fi LAN allowed the system to function without physical wiring between units, improving flexibility. The UDP protocol minimized latency, and tests confirmed reliable performance across all four channels.

- **Power Management**

The power supply system operated efficiently, with minimal heat generation. The design ensured safe operation by maintaining the required voltage and current ratings for all modules.

4.6 Bills of Engineering Materials and Evaluation (BEME)

A comprehensive bill of materials was compiled and evaluated for cost efficiency.

COMPONENT	QUANTITY	UNIT PRICE	TOTAL COST
ESP32	4	7,200	28,800
INMP441 Microphone (INMP441 mic)	4	3,800	15,200
MAX98357A Digital-to-Analog Converter (DAC)	4	13,800	55,200

3-Watt 4-ohm (Ω) Speaker	4	2,950	11,800
Organic Light-Emitting Diode display (OLED display)	4	3,500	14,000
KY Series Rotary Encoders (KY Encoders)	4	13,500	54,000
Push Buttons	1	3,000	3,000
3.7Volt(V) Cylindrical Battery	4	1,700	6,800
Charger Module	1	3,600	3,600
DC-DC Boost Converter	4	5,800	23,200
100-nanoFarad (nF) Capacitor	1	950	950
220-ohm(Ω) Resistors	1	1,455	1455
Light-Emitting Diodes (LEDs)	1	1,568	1568
Vero Board	4	800	32,000
Slide Switch	5	1,900	9,500
Soldering Lead	1	4,003	4,003
Header Pins/Jumpers	4	2,900	11,600
Programming Cable			

	1	2,500	2,500
Polylactic Acid Filament	1	53,000	53,000

Total Cost: 323,176

4.6 Summary

This project detailed the assembly, electrical integration, and testing of a 4-channel WiFi LAN network wireless intercom system. The device demonstrated exceptional stability, accuracy, and ease of use, with tests showing high-quality audio capture and reliable wireless communication. By utilizing an integrated system-on-a-chip, this project not only provides a powerful communication solution but also promotes cost-effective, wireless engineering solutions. This intercom system stands as a testament to the possibilities of creating simple, environmentally conscious and reliable communication devices.

CHAPTER 5: CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

The project successfully achieved the design and construction of a four-channel Wi-Fi LAN-based wireless intercom system. The objectives of developing a cost-effective, reliable, and user-friendly communication device were met. The system allowed real-time voice interaction among four independent units using a shared wireless network. Performance tests confirmed minimal latency, good audio quality, and efficient power usage.

This work demonstrates the practical application of IoT microcontrollers in real-time audio communication and provides a basis for further development of scalable wireless intercom systems.

5.2 Recommendations

1. **Scalability:** Future work should focus on increasing the number of supported channels to enable larger communication networks, such as in office complexes or campus environments.
2. **User Control:** Future work should incorporate a feature allowing users to accept or reject incoming voice transmissions.
3. **Noise Cancellation:** Digital signal processing techniques can be applied to reduce background noise and improve audio clarity.
4. **Hardware Improvement:** Future designs should replace vero boards with printed circuit boards (PCBs) to enhance reliability and performance

5.3 Contributions to Knowledge

This project contributes to knowledge in several key areas:

1. It demonstrates the effectiveness of using microcontrollers with built-in Wi-Fi modules for real-time communication systems.
2. It shows the practicality of replacing traditional wired intercoms with flexible wireless systems, reducing installation costs and complexity.
3. It provides a framework for low-cost, scalable, and customizable intercom solutions using readily available hardware and open-source platforms.
4. It highlights the potential for IoT devices to be adapted for diverse applications beyond conventional data monitoring, particularly in communication systems.

REFERENCES

Adebayo, A., Ojo, O., & Adekoya, A. (2019). Design of a cost-effective VoIP-based intercom system using Asterisk PBX. Journal of Communication Engineering & Systems, 9(2), 45-56.

Alenoghena, C. O., Odeyemi, K. O., Ohize, H. O., & Dajab, D. D. (2022). 4G Wireless Technologies: A Review of LTE and WiMAX. International Journal of Wireless and Microwave Technologies, 12(1), 1-14.

Ayodele, O. T., Aibinu, A. M., & Emuoyibofarhe, J. O. (2021). Development of a two-way wireless door intercom system using NRF24L01. Nigerian Journal of Technology, 40(1), 112-120.

Bhatnagar, R., & Birla, S. (2015). Wi-Fi Security: A Literature Review of Security in Wireless Network. International Journal of Engineering and Innovative Technology, 5(5), 68-72.

Brigitte, H. (n.d.). Basic Calculation of a Boost Converter's Power Stage. Texas Instruments Application Report.

Circuit Digest. (2018). Simple Two-Way Intercom Circuit. Retrieved from https://circuitdigest.com

De Stasi, F. (n.d.). Understanding Inrush Current. Texas Instruments Application Report.

Ibrahim, A., Enerst, E., & Ginabel, O. O. (2022). Design and implementation of a free wireless intercom system using Wi-Fi. International Journal of Engineering Research & Technology, 11(5), 78-85.

Isabona, J., & Obahiagbon, I. (2013). Radio channel site survey and deployment of WLAN for enhanced communication in Benson Idahosa University. The Nigerian Academic Forum, 24(1), 1-9.

Ruz, A., Goyenechea, M., & Aguayo, I. (2020). Wireless communication systems for industrial applications: A review. IEEE Access, 8, 123254-123276.

Santhi, V., & Divya, G. (2018). IoT based real-time audio streaming using UDP protocol. International Journal of Pure and Applied Mathematics, 119(12), 1567-1574.

Sedra, A. S., & Smith, K. C. (2020). Microelectronic Circuits (8th ed.). Oxford University Press.

Uddin, M., Al Mamun, M., & Islam, M. K. (2016). Design and implementation of WiFi based home security and automation system using ESP32. International Journal of Scientific & Engineering Research, 7(12), 1-7.