
ULTRASONIC COMMUNICATION FRAMEWORK FOR IOT USING INAUDIBLE AUDIO FREQUENCIES

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ABSTRACT

Ultrasonic communication has emerged as a promising alternative medium for short-range, low-power data transmission in Internet of Things (IoT) applications. This project presents the design, development, and evaluation of an ultrasonic IoT communication framework capable of transmitting digital information using inaudible high-frequency sound waves (typically above 18 kHz). The primary objective is to establish a cost-effective, hardware-independent communication channel that operates using existing audio interfaces such as microphones and speakers, thereby eliminating the need for conventional wireless technologies like Wi-Fi, Bluetooth, or RF modules.

The proposed system employs modulation techniques such as Frequency Shift Keying (FSK) and Amplitude Shift Keying (ASK) to encode digital data into ultrasonic signals. These signals are transmitted through standard audio hardware and received by compatible devices, where demodulation and decoding processes reconstruct the original data. The architecture integrates microcontrollers, signal processing algorithms, and IoT interfaces to enable seamless device-to-device communication.

In the implemented phase of the project, ultrasonic signal generation and modulation were successfully achieved, and experimental validation demonstrated reliable data transmission over short indoor distances. A basic receiver module was developed to perform signal filtering, decoding, and error detection. Performance evaluation indicates that ultrasonic communication offers advantages such as low energy consumption, enhanced security due to

limited propagation range, and reduced interference compared to traditional RF-based systems.

Furthermore, the system shows potential for applications in secure authentication, proximity-based data exchange, indoor localization, and smart environments. Despite challenges such as environmental noise sensitivity and limited bandwidth, the results confirm the feasibility of ultrasonic communication as an innovative and efficient solution for next-generation IoT networks.

INTRODUCTION

IoT Communication and Its Importance

The Internet of Things represents an evolving ecosystem of interconnected devices that collect, process, and exchange data to enable automation and intelligent decision-making [1]. This connectivity is foundational to modern advancements in smart cities, industrial automation, healthcare, and home environments [1], [2]. For IoT to be effective, communication must be reliable and capable of operating within the constraints of low-cost, resource-limited devices that often rely on battery power [3], [4].

Limitations of Traditional Wireless Technologies

While Radio Frequency technologies currently dominate the IoT landscape, they face several inherent challenges:

- **Spectrum Congestion and Interference:** The 2.4 GHz ISM band is increasingly crowded with Wi-Fi, Bluetooth, and ZigBee signals [5], [6]. This congestion leads to packet collisions and degraded reliability for ultra-low-power radios [2], [6].
- **Power Consumption:** Standard Wi-Fi is optimized for high throughput rather than energy efficiency, making it ill-suited for long-term battery-operated sensors [2].
- **Security Vulnerabilities:** RF signals easily penetrate physical barriers like walls, making them susceptible to remote interception and cyberattacks [5], [7]. Security is frequently an "afterthought" in low-cost endpoint design, leaving devices vulnerable to malicious outages [5].
- **Hardware Complexity:** Traditional wireless protocols often require specialized transceivers and antennas, which can increase the form factor and bill-of-materials for small wearable devices [5].

Introduction to Ultrasonic Communication

Ultrasonic communication, or acoustic data transmission, offers an alternative by using sound waves at frequencies typically above 18–20 kHz, which are inaudible to most adults but detectable by standard consumer microphones and speakers [8], [9].

- **Acoustic Advantages:** Unlike RF, ultrasound is effectively blocked by solid barriers, significantly reducing the risk of signal leakage and unauthorized interception from outside a room [7].
- **Resource Efficiency:** It leverages existing audio hardware found in most smartphones and computers, potentially eliminating the need for dedicated RF chips in certain short-range applications [9], [10].
- **Environmentally Robust:** It operates independently of the RF spectrum, providing a reliable side-channel even in environments with extreme RF noise or congestion [6], [11].

Problem Statement

Traditional IoT communication frameworks are increasingly hampered by RF spectrum saturation and the high power demands of conventional wireless protocols. Furthermore, the "leaky" nature of RF signals creates significant security risks for sensitive short-range data exchange. While ultrasonic communication has been proposed as a solution, many existing implementations suffer from low data rates, high signal attenuation at higher frequencies, and a lack of standardized frameworks for seamless integration into the broader IoT ecosystem [7], [10].

Objectives of the Project

This project aims to develop a robust ultrasonic communication framework that utilizes inaudible audio frequencies for secure, low-power IoT data exchange. The specific objectives include:

1. **Framework Design:** Develop a lightweight audio protocol stack capable of modulating and demodulating data in the 18 to 24 kHz range using standard audio transducers [11].
2. **Performance Optimization:** Implement signal processing techniques to maximize data throughput targeting rates comparable to experimental systems achieving 600 bps while mitigating multipath interference [7], [10].
3. **Security Evaluation:** Validate the framework's ability to prevent signal leakage through physical barriers, ensuring localized "air-gapped" communication [11].

4. **Hardware Compatibility:** Ensure the framework is compatible with common off-the-shelf IoT hardware to minimize deployment costs and complexity.

Literature Review

The development of communication frameworks for the Internet of Things has traditionally relied on radio frequency standards. However, the emergence of **ultrasonic communication** transmitting data via inaudible sound waves is gaining traction as a secure and hardware-agnostic alternative.

Review of Existing Ultrasonic Communication Systems

Existing research has demonstrated the viability of using standard audio hardware for data exchange.

- **Covert Networking:** The **MOSQUITO** system established that covert ultrasonic transmissions could occur between two air-gapped computers by repurposing speakers as microphones, highlighting the physical security benefits of acoustic signals [8], [11].
- **Smartphone-to-Smartphone Communication:** Systems like **BatNet** have successfully implemented data transmission over ultrasound between mobile devices, proving that specialized hardware is not required for short-range ad-hoc networking [10].
- **Modulation Techniques:** Early frameworks utilized quadrature modulation in air to achieve data rates around **600 bps**, focusing on optimizing signal-to-noise ratios within the 20 kHz range [7].
- **User Experience:** Research into acoustic data transmission has shown that while inaudibility is achievable, the user experience depends heavily on the reliability of the link in noisy real-world environments [9].

Comparison with RF-Based Communication

When compared to standard RF protocols like Bluetooth Low Energy or Wi-Fi, ultrasonic communication offers distinct trade-offs:

- **Spectrum Congestion:** Traditional wireless technologies suffer from severe interference in the crowded **2.4 GHz ISM band** [1], [6]. Ultrasound operates in the acoustic spectrum (typically 18–24 kHz), which is entirely free from RF noise [6], [7].
- **Security and Signal Leakage:** RF signals are "leaky" and can be intercepted through walls [5]. In contrast, ultrasonic waves are naturally confined by solid physical barriers,

making them ideal for secure, room-level localized communication and air-gapped systems [11].

- **Hardware and Energy:** While BLE is highly optimized for ultra-low power, it requires dedicated radio chips [1], [5]. Ultrasonic systems can utilize existing microphones and speakers, reducing the complexity of the IoT bill-of-materials [9], [10].

Recent Research Trends

Recent literature highlights several evolving trends in the field:

- **Smart Space Integration:** There is a growing focus on using acoustic signals within **AI-driven smart spaces** for indoor positioning and secure device pairing where traditional GPS or RF-based localization fails [2].
- **Multi-Device Connectivity:** Recent frameworks are moving toward "broadcast" models where one device can synchronize multiple sensors or wearables simultaneously using a single acoustic beacon [4].
- **Hybrid Systems:** Researchers are increasingly exploring hybrid models that use ultrasound for secure initial handshake/pairing followed by RF for high-speed data transfer [10].

Identification of Research Gaps

Despite its potential, several gaps remain in the current state of ultrasonic IoT research:

1. **Low Data Throughput:** Compared to RF, ultrasonic data rates remain extremely low (often <1 kbps), limiting their use to small sensor packets rather than rich data [7], [10].
2. **Environmental Noise Robustness:** While ultrasound avoids RF noise, it is susceptible to acoustic noise from machinery or ultrasonic sensors used in industrial settings, a factor that is often under-researched in consumer-focused studies [9].
3. **Distance and Attenuation:** High-frequency sound waves attenuate rapidly in air, severely limiting effective range compared to long-range RF technologies; current literature lacks standardized methods for extended-range ultrasonic communication [7].
4. **Protocol Standardization:** Unlike the highly standardized Bluetooth and Wi-Fi ecosystems, ultrasonic communication lacks a unified global protocol, leading to fragmentation and interoperability issues between different IoT vendors [5], [10].

METHODOLOGY

The methodology for implementing the ultrasonic communication framework focuses on utilizing existing hardware to facilitate secure, short-range data exchange within the 18–24 kHz frequency band [10], [11].

System Architecture

The framework is designed as a **simplex or half-duplex communication system** comprising two primary nodes: the **Transmitter** and the **Receiver** [10].

- **Transmitter Node:** Responsible for packetizing digital data, modulating it into an acoustic signal, and emitting it via a high-frequency transducer.
- **Communication Channel:** The medium is the ambient air within a confined space, ensuring that physical barriers like walls contain the signal for enhanced security [7], [11].
- **Receiver Node:** Continuously monitors the acoustic environment, filters out audible noise, and demodulates the ultrasonic signals back into digital data [9], [10].

Hardware Components

To ensure cost-effectiveness and scalability in IoT deployments, the system utilizes standard off-the-shelf components:

1. **Microcontroller:** An ultra-low-power MCU (such as an ARM-based processor) serves as the central processing unit, managing the timing and digital signal processing tasks [3], [5].
2. **Speaker/Transducer:** A standard piezo-electric speaker or high-fidelity micro-speaker capable of producing frequencies up to 24 kHz without significant distortion [9], [11].
3. **Microphone:** A MEMS microphone with a wide frequency response range to capture the inaudible data signals [10].
4. **Signal Conditioning Circuitry:** Includes a pre-amplifier to boost the low-voltage microphone output and a hardware-based high-pass filter to eliminate ambient audible noise below 18 kHz [7], [11].

Working Principle of Ultrasonic Communication

The system operates by translating binary information into mechanical pressure waves. Unlike RF-based systems that use electromagnetic waves, this framework uses **acoustic energy** [7]. Data is transmitted at frequencies above the human hearing threshold (typically

18 kHz+), allowing the framework to coexist with human activity without causing noise pollution [8], [9]. The limited range of these high-frequency sound waves in air due to high attenuation naturally creates a "security bubble" around the devices [7], [11].

Modulation Techniques

The framework primarily utilizes **Frequency Shift Keying** for data modulation due to its robustness in varying acoustic environments:

- **Binary FSK:** Data bits are represented by shifts between two distinct frequencies. For example, $f_1 = 19 \text{ kHz}$ may represent a '0', while $f_2 = 21 \text{ kHz}$ represents a '1' [10].
- **Alternative:** While **Amplitude Shift Keying** can be used for simpler hardware, it is often more susceptible to multipath interference and ambient echoes in indoor spaces, making FSK the preferred choice for reliable IoT links [7], [10].

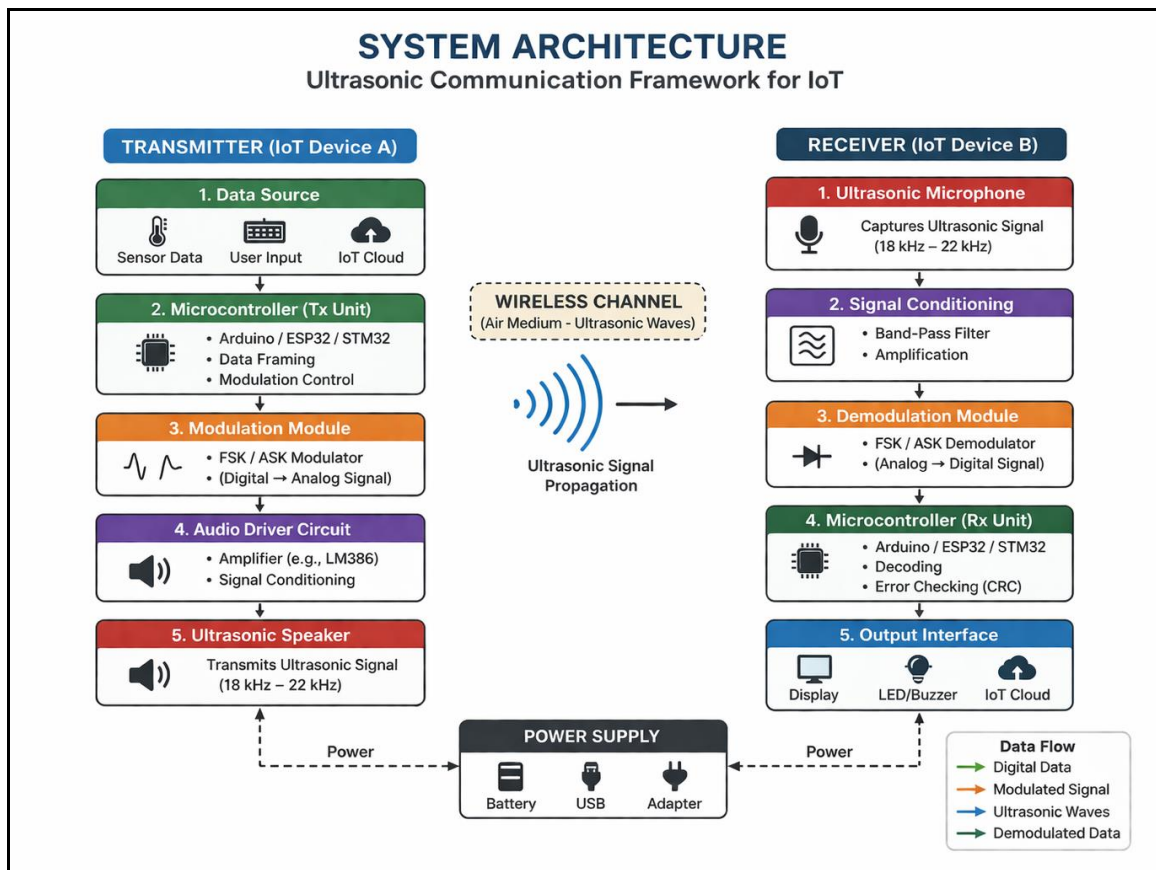


Figure 1. System Architecture.

Encoding and Decoding Process.

The digital logic follows a structured pipeline to ensure data integrity:

1. Encoding Process

- **Packetization:** Data is encapsulated into frames containing a preamble (for synchronization), a header (containing device IDs), the payload, and a Cyclic Redundancy Check for error detection [4].
- **Bit-to-Signal Mapping:** The MCU generates a continuous-phase signal where each bit is assigned a specific frequency duration (symbol time) to prevent phase discontinuities that could cause audible "clicks" [10].

2. Decoding Process

- **Sampling:** The receiver's microphone samples the incoming audio at a minimum of 44.1 kHz or 48 kHz to satisfy the Nyquist criterion for the 18–24 kHz range [11].
- **Frequency Analysis:** The system applies a **Fast Fourier Transform** or the **Goertzel algorithm** to detect the presence of the predefined "0" and "1" frequencies within each symbol window [10].
- **Thresholding and Verification:** If the signal strength exceeds a defined Signal-to-Noise Ratio threshold, the bits are extracted, and the CRC is calculated to verify the packet's validity [4], [7].

DISCUSSION

The implementation of an ultrasonic communication framework for IoT presents a specialized alternative to traditional wireless standards. The following analysis evaluates its operational performance, comparative standing, and overall viability for secure IoT ecosystems.

Analysis of System Performance

The performance of ultrasonic data transmission is primarily dictated by the constraints of the acoustic medium and the capabilities of standard audio transducers.

- **Data Throughput:** Experimental systems using quadrature modulation in air have achieved data rates of approximately **600 bps** within the 20 kHz range [7]. While this is significantly lower than the megabit-per-second speeds of Wi-Fi or Bluetooth, it is sufficient for the small telemetry packets (e.g., temperature, humidity, or status flags) typical of low-power IoT sensors [7], [10].

- **Range and Attenuation:** High-frequency sound waves (18–24 kHz) suffer from rapid atmospheric absorption and attenuation [7]. Performance is optimal within a "personal area network" range (0.5 to 5 meters). Beyond this, the signal-to-noise ratio drops significantly, requiring more complex error correction or higher transmission power [7], [10].
- **Inaudibility:** Utilizing the 18–24 kHz band ensures that the system remains inaudible to most human users, though environmental factors like speaker quality and sampling rates (typically 44.1 kHz or 48 kHz) are critical to preventing audible artifacts or "clicks" during transmission [9], [11].

Advantages and Limitations

The framework offers several strategic advantages while facing inherent physical constraints:

Advantages

- **Physical Security:** A defining advantage is that ultrasonic signals do not penetrate solid walls [7]. This provides a natural "air-gap" security layer, preventing remote sniffing or unauthorized access from outside the physical room a major vulnerability in RF-based systems [8], [11].
- **Hardware Agnosticism:** By leveraging standard microphones and speakers, the system can be deployed on billions of existing smartphones and computers without requiring new silicon or specialized antennas [9], [10].
- **RF Immunity:** The system is entirely immune to the extreme congestion found in the **2.4 GHz ISM band**, allowing it to function reliably in environments where Wi-Fi and Bluetooth are saturated [6], [7].

Limitations

- **Low Bandwidth:** It cannot support high-data applications like video streaming or large file transfers [7].
- **Acoustic Interference:** While immune to RF noise, the system can be disrupted by loud high-pitched ambient sounds or ultrasonic noise from specialized industrial equipment [7], [9].
- **Multipath Echoes:** In small, reflective rooms, acoustic echoes can cause inter-symbol interference, necessitating robust modulation like Frequency Shift Keying to maintain link stability [10].

Comparison with Traditional Communication Methods

Unlike Bluetooth Low Energy or ZigBee, which prioritize high throughput and long-range connectivity, ultrasonic communication prioritizes **containment and accessibility** [1], [5].

- **Security Model:** Traditional RF technologies require complex encryption layers because their signals "leak" through boundaries [5]. Ultrasound uses physical containment as a primary security feature [11].
- **Deployment Cost:** Implementing BLE requires a dedicated radio chip on the IoT device [5]. In contrast, the ultrasonic framework can be implemented as a software-defined radio using a device's built-in audio codec, potentially lowering the bill-of-materials for simple IoT nodes [9], [10].

Reliability and Efficiency

The reliability of the system is highly dependent on the chosen modulation scheme. **Frequency Shift Keying** has proven more robust than Amplitude Shift Keying for indoor environments because it is less affected by fluctuating volume levels and background noise [10].

In terms of efficiency, the system is ideal for "trigger-based" IoT tasks such as secure pairing, localized broadcasting of sensor data, or proximity-based authentication [4], [10]. While the CPU cycles required for Real-Time Fast Fourier Transform on the receiver can be demanding, modern low-power microcontrollers can handle these tasks efficiently enough to support battery-operated operation in short bursts [3], [5]. For the transmitter, the power consumption is largely limited to the energy required to drive the speaker, which is comparable to low-power RF transmissions during active states [10].

CONCLUSION

The development of an **Ultrasonic Communication Framework** for the Internet of Things addresses critical vulnerabilities in modern wireless connectivity. By shifting data transmission to the inaudible acoustic spectrum, this framework provides a specialized solution for secure, short-range, and hardware-agnostic communication.

Summary of Key Findings

Research into ultrasonic data transmission reveals several transformative capabilities:

- **Acoustic Viability:** Utilizing frequencies in the **18–24 kHz** range allows for the successful transmission of digital data using standard consumer-grade microphones and speakers [10], [11].

- **Localized Security:** Unlike Radio Frequency signals, ultrasonic waves do not penetrate solid physical barriers, creating a natural "air-gap" that prevents remote signal interception from outside a room [7], [8].
- **Operational Throughput:** While data rates are modest typically around **600 bps** they are functionally adequate for the small data packets and telemetry required by low-power IoT sensors [7], [10].
- **Protocol Robustness:** The use of **Frequency Shift Keying** modulation offers a reliable method for mitigating the effects of ambient acoustic noise and multipath echoes in indoor environments [7], [10].

Importance of Ultrasonic Communication in IoT

As the IoT ecosystem grows, the importance of non-RF communication channels becomes more pronounced:

1. **Spectrum Relief:** By operating in the acoustic domain, this framework bypasses the severe congestion of the **2.4 GHz ISM band**, which is increasingly saturated by Wi-Fi and Bluetooth devices [1], [6].
2. **Cost and Accessibility:** Because it leverages existing audio hardware, the framework eliminates the need for dedicated radio chips in certain applications, reducing the overall complexity and bill-of-materials for simple IoT nodes [5], [10].
3. **Secure Pairing and Proximity:** It serves as a superior alternative for secure device pairing and localized "broadcast" beacons, where proximity is a prerequisite for trust [4], [11].

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