BLE MESH NETWORK AND INDOOR SENSOR DATA COLLECTION (PHYSARUM)
INFINIA

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Abstract. Considering communication constraints and safety risks in the mining industry, this project aims to provide an energy-efficient, reliable, and robust wireless communication solution without requiring Wi-Fi or cellular infrastructure. Utilizing BLE Mesh 1.1 technology, the system enables communication between mine workers and the central headquarter. Health data—blood oxygen saturation, ambient temperature, and acceleration; from oximeter, temperature sensor, and accelerometer-equipped ESP32-S3 nodes are monitored in real time via a central monitoring interface. The network comprises five transmitter nodes with sensors, four relay nodes to extend coverage, and one receiver node for data aggregation, enabling scalable node addition for increased workforce or area. Design and evaluation included simulations and tests of audio transmission, data reliability, latency, packet segmentation and reassembly, power consumption, PCB testing, and durability in low-signal tunnel-like environments. Software development used Python and C under ESP-IDF, while hardware design employed DipTrace. Results demonstrate robust node hopping, error correction, and low-latency performance with uninterrupted sensor and voice communication. The findings confirm the suitability of BLE Mesh technology for INFINIA's IoT applications and advocate for its deployment to enhance workplace safety through innovative, competitive, and energy-efficient solutions in high-risk mining environments.

PROJECT DESCRIPTION

Our project, developed in collaboration with INFINIA, addresses the theoretical research of Bluetooth Low Energy (BLE) Mesh Network, a low-energy, scalable communication protocol designed for environments lacking conventional infrastructure. To translate our theoretical research into a practical application, we focused on a critical real-world problem in the mining industry: enabling reliable communication and real-time health monitoring during emergencies, especially in environments where traditional infrastructure like Wi-Fi or cellular networks is unavailable. The company tasked us with creating a robust, energy-efficient system that enables voice and sensor data transmission in hazardous environments. To achieve this, we designed a BLE Mesh network using ESP32-S3 boards equipped with sensors (temperature, accelerometer, and pulse oximeter) and a microphone for real-time communication and monitoring. These devices communicate over a BLE Mesh architecture to relay data to a central interface, even when no direct connection is available. The ultimate outcome of our project is a functional and energy-efficient communication system that enhances worker safety and demonstrates the viability of BLE Mesh for INFINIA's future IoT-based solutions.

The motivation behind this project stems from the urgent need for dependable communication and health monitoring in environments where conventional networks are unreliable or nonexistent—such as underground mines or disaster zones. In such critical settings, ensuring worker safety and maintaining real-time contact is a top priority. While existing solutions like Wi-Fi mesh networks or long-range communication modules (e.g., LoRa, Zigbee) offer partial coverage, they often fall short due to limitations in scalability, latency, or energy consumption. Wi-Fi-based systems consume too much power and require infrastructure [**1**]; Zigbee networks lack native support for voice communication and have lower node capacity [**2**], while LoRa prioritizes range over real-time data, making it unsuitable for transmitting audio or vital health signals [**3**]. In contrast, BLE Mesh provides a low-power, decentralized, and scalable communication protocol capable of supporting dense networks with dynamic routing [**4**]. Its ability to handle real-time sensor data and voice transmission while preserving energy efficiency makes it an ideal candidate for challenging industrial applications like the one INFINIA aims to address. The novelty of our solution lies in integrating real-time voice communication and multiple health sensors into a decentralized BLE Mesh network, which is typically used only for small-scale data transfer. Unlike existing solutions such as Wi-Fi or Zigbee, which either require infrastructure or lack native support for voice, our system combines scalability, portability, and energy efficiency in a compact, deployable form. Moreover, our system operates autonomously and can forward data across multiple nodes without requiring a central hub, making it uniquely suitable for underground or remote applications where rapid deployment and robustness are essential.

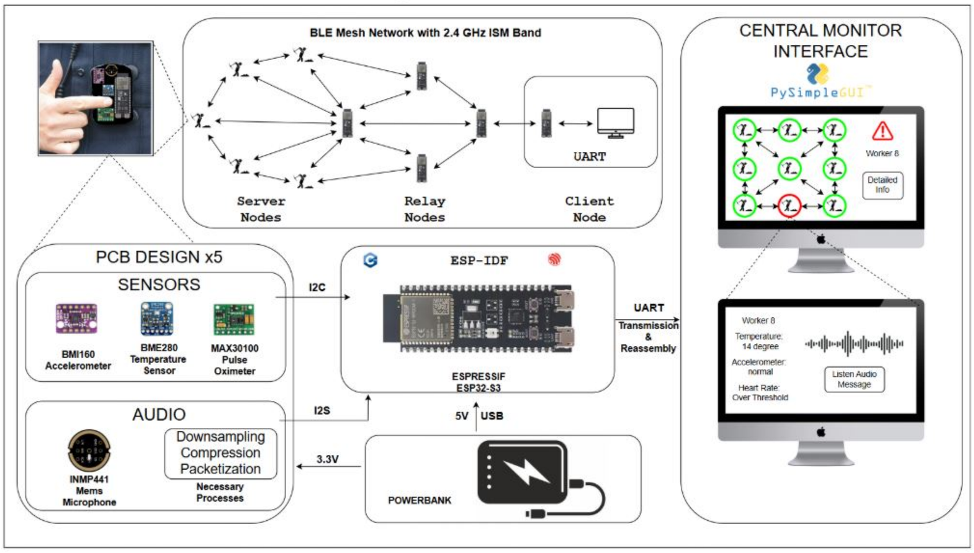

FIGURE 1. Big Picture of the Project

In the big picture, the architecture of the BLE Mesh network and the hardware design of the portable PCB—intended to be worn on the collars of mine workers—are illustrated. Each portable unit features an ESP32-S3 microcontroller connected to a custom-designed PCB powered by a USB power bank. The board integrates multiple sensors, including a BMI160 accelerometer, BME280 temperature sensor, and MAX30100 pulse oximeter, all interfaced via the I2C protocol. Additionally, an INMP441 MEMS microphone is connected via I2S to capture real-time audio. The ESP32-S3 modules form a BLE Mesh network operating on the 2.4 GHz ISM band, where nodes are categorized as server nodes (miners' boards), relay nodes (extending signal range), and a client node. The client node is represented on the right side of the diagram as an ESP32-S3 connected to a computer via UART. This computer runs a graphical user interface (GUI), which visualizes the health status of workers and provides access to live sensor data and recorded audio messages for emergency response and monitoring purposes.

MILESTONES

- **Milestone 1 - Research, Program Setup, and Initial Trials:** Background research was conducted to comprehend the basics of BLE Mesh and conventional BLE mesh tests, such as lighting up LEDs.
- **Milestone 2 - BLE Mesh Trials and Audio Transmission:** After successfully setting up the initial mesh, tests covered distance, Tx power, relay enabling, and sensor data transmission.
- **Milestone 3 - Multi-Server Node Hopping and PCB Design:** PCB design was completed in DipTrace and 5 PCBs were produced in-house. Furthermore, additional servers were ready to be added to the node network.

- **Milestone 4 - PCB Integration and UI Design:** Soldered PCBs were introduced as servers and the UI display was designed to monitor sensor data.
- **Milestone 5 - Network Finalization and Testing:** After several demo runs with improvements, the network transmits data smoothly.

DESIGN DESCRIPTION

The project was developed using a milestone-driven approach where each functional block is detailed in the WBS. The design strategy began with the preparation phase and literature research on BLE Mesh technology, ESP32-S3 boards, audio transmission protocols, and sensor integration, along with software environment setup using ESP-IDF and Visual Studio Code (Milestone 1). Early experiments involved implementing conventional BLE Mesh tests such as LED lighting, to verify provisioning and basic communication. The next phase focused on BLE Mesh trials and UART-based audio transmission (Milestone 2), where the team evaluated mesh connectivity, adjusted Tx power levels, and measured communication ranges. Sensor data from BME280 and BMI160 modules was transmitted over a mesh network, while INMP441 microphone data was captured, visualized through UART, and analyzed in MATLAB. During Milestone 3, the BLE Mesh was extended to support multiple server nodes and node-hopping capabilities. Relay nodes were tested in indoor environments by limiting RF range through transmission power tuning. Simultaneously, schematic and PCB design were completed in DipTrace, and 5 PCBs were produced, each integrating temperature, accelerometer, pulse oximeter sensors, and microphone modules. The integrated PCBs were deployed as mobile server nodes within the BLE Mesh network, enabling real-time transmission of sensor and audio data to the central client node and displayed on a Python-based GUI (Milestone 4). The GUI interface visualized node statuses, incoming sensor streams, and message hops. During finalization and functional testing (Milestone 5), the architecture transitioned from pull-based to push-based transmission for real-time emergency communication.

Audio data was segmented into 11-byte packets, sequenced, and transmitted over the mesh using adaptive buffering and error-handling strategies. Functional tests included delay measurements, audio intelligibility assessments, and packet reliability checks, ensuring a robust, scalable, and low-latency system suitable for underground mining environments. All test results validated the system's ability to support real-time audio and health data transmission, achieving the overarching goal of an energy-efficient, multi-node BLE Mesh network.

RESULTS AND PERFORMANCE EVALUATION

BLE Mesh Network Establishment Results: The designed BLE Mesh system includes 5 server nodes, 4 relay nodes, and a client node. Each server node is equipped with a temperature sensor, oximeter, and accelerometer. Client node is used as a central monitor and it receives all sensor data and visualizes node health status through the GUI. Furthermore, relay nodes are used to extend the mesh communication range and support multi-hop transmission. The designed BLE mesh system was tested in an indoor environment, replicating multi-hop data transmission across mobile and stationary nodes. The results were collected to evaluate the capabilities of the mesh in supporting real-time sensor data transmission, dynamic path management, scalability, and provisioning.

- **Multi-hop multi-server communication:** A stable multi-hop BLE Mesh network was established with both server and relay nodes. The data was successfully transmitted over more than two hops without interruption. Oximeter, accelerometer, and temperature sensor data were simultaneously collected from multiple server nodes and successfully displayed on the central GUI in real time.
- **Dynamic node hopping:** Even when a relay node was disabled, data packets were rerouted through alternate paths. This dynamic path adjustment confirmed the mesh network's fault tolerance and self-healing ability.
- **Push-based system:** Instead of a less efficient pull-based architecture, the system was changed into push-based architecture where server nodes send data without waiting for client requests.
- **Live visualization of node states:** The connection status of the nodes (on/off) was clearly visualized through LED indicators and the GUI, allowing us to observe whether the nodes were properly connected to the mesh network.
- **Provisioning:** Each ESP32-S3 node was securely provisioned into the BLE Mesh network using a central provisioner device. During provisioning, each node was assigned a unique unicast address and securely received the network and application keys. All server, relay, and relay nodes were successfully bound to application keys. The provisioning process also included setting publish/subscribe addresses for group communication and configuring the relay feature on intermediate nodes.
- **Scalability:** The BLE Mesh structure was extended with additional nodes, and communication performance was preserved.
- **Reliable data transmission:** The GUI consistently received and updated data with minimal latency, validating real-time mesh capabilities.
- **Path-finding:** Path estimation and the map of the network was displayed in the UI using the time to live (TTL) value of messages.

```
I (55151) EXAMPLE: --------------------------------------------
I (55151) EXAMPLE: Received sensor data from server 0x0005:
I (55151) EXAMPLE: TTL: 3 for 0x0005
I (55161) EXAMPLE: MORT NOT: 0x0005
I (55161) EXAMPLE: Temperature: 25 °C from 0x0005
I (55171) EXAMPLE: SpO2: 96.9% from 0x0005
I (56111) EXAMPLE: --------------------------------------------
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FIGURE 2. Multi-server real-time data

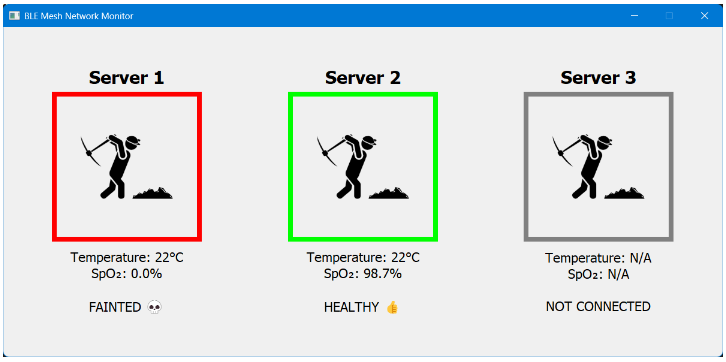

FIGURE 3. UI showing health status of mine workers

Audio Transmission Results: Our audio transmission efforts yielded several key achievements. Initially, we established a serial connection between the ESP32 and the INMP441 microphone module and after succeeding in transitioning into a push-based system, sending back-to-back audio packets through the BLE Mesh protocol was possible. Although early trials resulted in inaudible output, once these issues were resolved, we successfully saved clear audio as a .wav file. The final recordings provided us a proof of concept that the recorded 4-5 second sequence was understandable, marking a significant milestone in our project's progress.

Hardware Results: Our final hardware design, validated through both LTSpice simulations and empirical tests, confirms that our PCB, integrating the BME280, BMI160, MAX30100, and INMP441, meets the rigorous demands of emergency communication in mining environments. The prototype tests, including rigorous ICT and FCT, showed high sensor accuracy (±1°C for the BME280 and 16,384 LSB/g for the BMI160) and reliable pulse oximeter within a ±2% range. An iterative redesign reduced the footprint of the PCB while minimizing interference.

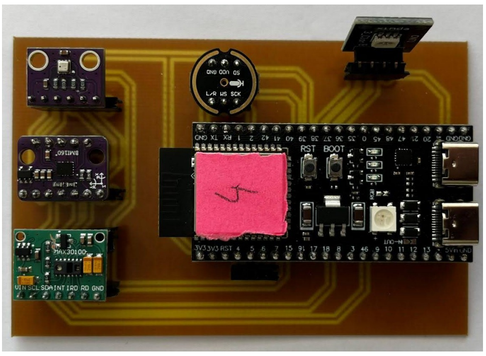

FIGURE 4. The final PCB

Comparison with Existing Literature: Philips Hue, which demonstrates BLE Mesh in energy-efficient lighting control, and the Malmö University study that showcases precise indoor tracking, our approach addresses the dual need for health monitoring. In comparison to Texas Instruments' demonstration of a scalable and ultra-low power mesh network, our design leverages similar principles of power efficiency and reliability, but with the added complexity of managing IoT over a constrained network. Additionally, while ESP32-based Wi-Fi audio transmission systems illustrate high-quality audio streaming, our project's use of BLE Mesh represents a novel attempt to merge these capabilities in a decentralized, emergency-focused framework. Overall, our solution stands out by synthesizing elements from these diverse applications to meet specific industrial safety requirements, laying the groundwork for potential innovation and future patent opportunities.

CONCLUSIONS AND FUTURE DIRECTIONS

In this project a BLE Mesh-based communication and health monitoring system specifically designed for mining environments, where traditional networks like Wi-Fi and cellular services are often unreliable or unavailable was developed. In collaboration with INFINIA, the system comprises multiple sensor-equipped server nodes, relay nodes for extended range, and a central monitor node for data collection. Utilizing Bluetooth Mesh 1.1 technology, our implementation supports multi-hop, fault-tolerant, scalable, and energy-efficient communication. The primary goal was enhancing safety by enabling continuous monitoring of vital signs and environmental conditions via a decentralized network. The hardware design, creating a compact and lightweight custom PCB that integrates sensors, intended to be worn comfortably by mine workers was successfully designed. Key achievements include establishing a robust multi-hop BLE Mesh topology with ESP32-S3 boards, provisioning and configuring nodes effectively, and ensuring simultaneous and continuous sensor data transmission. A user-friendly graphical interface was developed, providing real-time visualization of sensor readings and node connection statuses, significantly improving situational awareness. Although BLE Mesh presented challenges for audio transmission, the feasibility of transmitting understandable audio messages through packetization and compression was successfully demonstrated. Possible future directions may include real-life applications in the mining field. Increasing the relays and maximizing the Tx power could further extend the network's range, ensuring robust multi-hop communication even in extensive and confined mining environments. These improvements, along with refining RF power calibration and optimizing node placement, have the potential to enhance both sensor data and audio transmission in real time. Future work should also incorporate extensive field testing and additional integration of advanced sensing capabilities to fully validate performance under actual mining conditions and to further support emergency responses and safety monitoring.

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BEHIND THE SCENES