Zigbee-Based IoT Mining Safety System Using ESP32 for Continuous Environmental Monitoring and Worker Protection

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Abstract

In underground mines, coal mines, mineral extraction sites, and tunneling operations, there is a critical requirement for intelligent systems that can monitor environmental parameters in real time and provide immediate alerts during dangerous conditions. These environments demand reliable, wireless, and automated solutions capable of ensuring worker safety and preventing disasters. Traditional mining safety systems rely on periodic manual inspections and standalone detectors, which often fail to provide continuous monitoring or timely alerts, leading to delayed response and increased risk to miners. Furthermore, conventional systems lack integrated communication, remote monitoring, and data analysis capabilities, reducing their effectiveness in dynamic underground environments. To address these challenges, the proposed Zigbee Mining Safety System utilizes the ESP32 microcontroller to develop an intelligent and real-time safety monitoring solution. The system integrates CO_2 gas sensors, DHT11 temperature and humidity sensors, and vibration sensors to continuously monitor environmental conditions inside mines. The collected data is processed by the ESP32 and transmitted wirelessly using Zigbee communication to a receiver module, where another ESP32 displays the information on an LCD. A buzzer provides immediate alerts when any parameter exceeds safe limits, while IoT integration enables remote monitoring and data logging through cloud platforms. This smart system enhances miner safety, enables early hazard detection, reduces accident risks, and provides a scalable and reliable solution for modern mining safety management.

Keywords: DHT11 Sensor, ESP32, Hazard Detection, Internet of Things, Mining Safety, Real-Time Monitoring, Vibration Sensor, Wireless Communication, ZigBee Technology

1. Introduction

The mining industry is one of the most hazardous sectors globally, with reports indicating that over 15,000 fatalities occur annually due to unsafe working conditions [1], environmental hazards, and operational risks. Underground mining environments are particularly dangerous due to exposure to toxic gases, extreme temperatures, and unstable geological conditions [2]. Additionally, the adoption of smart mining safety technologies is growing at over 14% annually, driven by the need to enhance worker safety and operational efficiency [3]. In environments such as underground mines, coal extraction sites, and tunneling operations, there is a critical need for systems that provide real-time environmental monitoring, wireless communication, and instant alert mechanisms to prevent accidents and ensure miner safety.

Problem Statement: Traditional mining safety systems primarily rely on periodic manual inspections and standalone detection devices [4]. These methods are limited in their ability to provide continuous monitoring, as they depend on human intervention and scheduled checks. As a result, sudden changes in environmental conditions—such as gas leaks or temperature spikes—may go undetected until it is too late [5]. Additionally, conventional systems lack integrated communication and remote monitoring capabilities, making it difficult to transmit critical data to control centers in real time [6]. The absence of centralized data analysis further limits the ability to predict potential hazards and take preventive actions.

Motivation: In real-time scenarios, these limitations lead to several critical challenges that significantly increase risks in mining operations. The accumulation of toxic gases such as CO_2 can lead to suffocation and explosions, while extreme temperatures and humidity levels can affect worker health and equipment performance [7]. Unexpected vibrations may indicate structural instability, increasing the risk of collapses. Without continuous monitoring and immediate alerts, these hazards can escalate rapidly, resulting in severe accidents and loss of life. Furthermore, delayed communication and lack of remote monitoring hinder timely rescue operations [8]. These challenges highlight the need for an intelligent, IoT-based mining safety system capable of continuous environmental monitoring, real-time data transmission, and instant alert generation, ensuring improved safety, early hazard detection, and reliable mining operations.

2. Literature Survey

Gupta et al. [9] proposed a microcontroller-based mining safety monitoring system that utilized embedded systems for real-time parameter measurement and alert generation. Roy et al. [10] proposed an IoT-based smart mine monitoring system that enabled real-time data acquisition and cloud-based analysis for safety management. Rahman et al. [11] proposed an IoT-enabled mining safety monitoring system that integrated sensors and communication modules for continuous monitoring and alert generation.

Chen et al. [12] proposed a wireless monitoring system for underground mines that enabled reliable data communication and environmental sensing. Patel et al. [13] proposed a sensor-based environmental monitoring system that measured key safety parameters in industrial settings. Singh et al. [14] proposed a vibration-based mine safety monitoring system that detected abnormal vibrations to identify potential hazards.

Fernandes et al. [15] proposed a wireless monitoring system for mining safety using sensor networks for real-time data transmission. Verma et al. [16] proposed an IoT-based industrial safety monitoring system that integrated sensors and cloud platforms for real-time monitoring and alerting. Lee et al. [17] proposed a wireless sensor network for underground mining applications that enabled efficient data collection and communication.

Mehta et al. [18] proposed a microcontroller-based environmental monitoring system that utilized sensors for real-time safety parameter measurement. Kumar et al. [19] proposed an ESP32-based environmental monitoring system that enabled wireless data transmission and real-time monitoring. Sharma et al. [20] proposed a wireless sensor-based mine safety monitoring system that enabled continuous monitoring and alert generation in mining environments.

Zhang et al. [21] proposed a Zigbee-based sensor network for underground mining that enabled efficient communication and monitoring. Gupta et al. [22] proposed a smart mine safety monitoring system using embedded systems that integrated sensing and control mechanisms for hazard detection. Khan et al. [23] proposed an IoT-based mining safety monitoring system that enabled real-time monitoring and alert generation using connected devices.

Park et al. [24] proposed a sensor fusion-based mining safety monitoring system that combined multiple sensor inputs for improved decision-making. Roy et al. [25] proposed a wireless environmental monitoring system for industrial safety that enabled real-time monitoring and data transmission.

3. Proposed System

Figure 1 illustrates the transmitter module of a mine safety monitoring system built around the ESP32. This module is deployed inside the mining environment and is responsible for sensing and transmitting critical environmental parameters. It integrates sensors such as a vibration sensor for structural stability, CO_2 gas sensor for air quality monitoring, and DHT11 for temperature and humidity measurement. A regulated power supply ensures stable operation. The ESP32 processes all sensor data and transmits it wirelessly using a Zigbee transmitter, while also providing local alerts through an LCD and buzzer.

Step 1: Power Supply Initialization: The regulated power supply provides stable DC voltage to the ESP32 and all sensors, ensuring reliable system operation in harsh mining environments.

Step 2: Vibration Monitoring: The vibration sensor detects abnormal ground movements or structural instability, helping identify potential mine collapse risks.

Step 3: CO_2 Gas Monitoring: The CO_2 sensor continuously measures gas concentration levels. If the level exceeds safe limits, it indicates a hazardous condition for miners.

Step 4: Temperature and Humidity Monitoring: The DHT11 sensor monitors environmental conditions such as temperature and humidity, ensuring safe working conditions inside the mine.

Step 5: Data Processing Using ESP32: The ESP32 collects and processes all sensor data, compares it with safety thresholds, and determines whether conditions are normal or hazardous.

Step 6: Local Display and Alert System: The LCD displays real-time sensor readings, while the buzzer provides immediate audible alerts in case of abnormal conditions.

Step 7: Zigbee Data Transmission: The Zigbee transmitter (Tx) sends processed sensor data wirelessly to the receiver module located at the monitoring station.

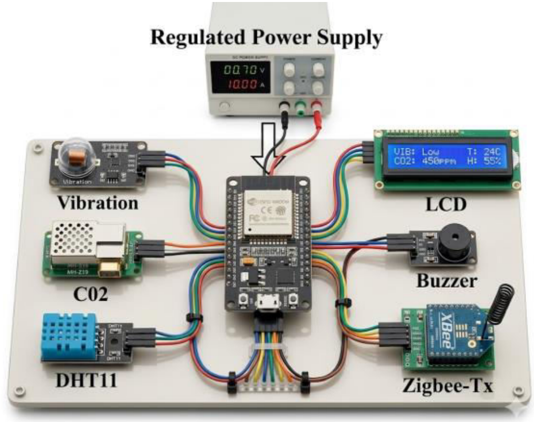

Figure 1. Mine Safety Monitoring System – Transmitter Module.

Figure 2 illustrates the receiver module of the mine safety monitoring system, where the ESP32 acts as the central processing unit. The Zigbee receiver collects transmitted data from the underground transmitter module. The ESP32 processes the received data, displays it on an LCD, and activates alerts through a buzzer when unsafe conditions are detected. Additionally, IoT integration enables remote monitoring of mine conditions through cloud platforms. This module ensures continuous supervision and safety management.

Step 1: Power Supply Initialization: The regulated power supply ensures stable voltage supply to the ESP32 and all receiver components.

Step 2: Data Reception via Zigbee: The Zigbee receiver (Rx) receives real-time environmental data transmitted from the underground transmitter module.

Step 3: Data Processing Using ESP32: The ESP32 processes incoming data and analyzes it to detect unsafe conditions such as high CO_2 levels, abnormal temperature, or vibration alerts.

Step 4: LCD Display for Monitoring: The LCD displays real-time environmental parameters, allowing monitoring by safety personnel at the control station.

Step 5: Buzzer Alert System: If any parameter exceeds safe limits, the buzzer is activated to alert authorities for immediate action.

Step 6: IoT-Based Remote Monitoring: The ESP32 sends the processed data to cloud platforms via IoT, enabling remote monitoring, data logging, and analysis from anywhere.

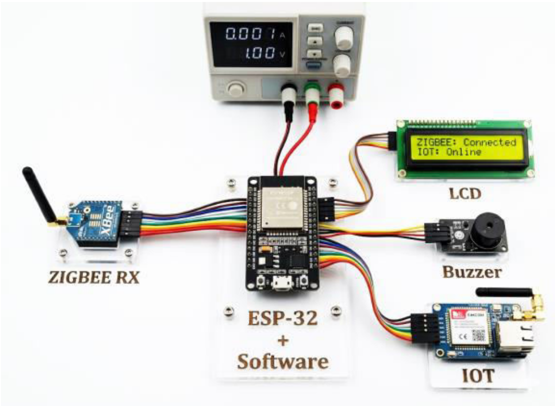

Figure 2. Mine Safety Monitoring System – Receiver Module.

3.1 Working Procedure

The proposed system as shown in Figure 3, Zigbee Mining Safety System, is designed to continuously monitor environmental conditions in underground mining environments and provide early warnings when hazardous situations occur. The system uses wireless communication technology along with embedded sensors to ensure the safety of miners working in dangerous underground locations. The system consists of two major modules: a Transmitter Module placed inside the mine and a Receiver Module located at the monitoring station. The transmitter module is responsible for collecting environmental data from various sensors installed inside the mining area. Sensors such as the CO_2 gas sensor, DHT11 temperature and humidity sensor, and vibration sensor continuously monitor the surrounding conditions.

The collected data is processed by the ESP32 microcontroller, which acts as the central controller of the transmitter module. If any environmental parameter exceeds its safe limit, the system immediately activates a buzzer to alert the workers inside the mine.

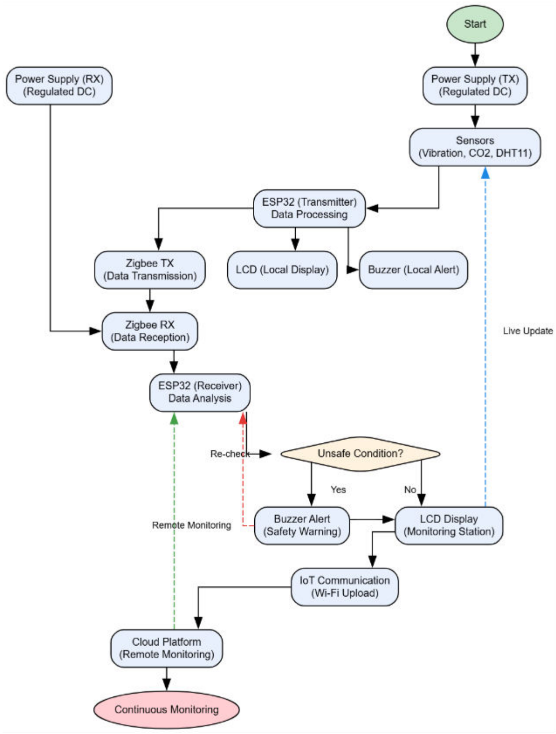

Figure 3. Proposed Flowchart.

After processing the sensor data, the ESP32 sends the information wirelessly using a Zigbee transmitter module. Zigbee technology is widely used in wireless sensor networks because it provides reliable communication, low power consumption, and good coverage in industrial environments. This allows the sensor data collected inside the mine to be transmitted safely to the monitoring station.

The receiver module is installed at the control station where authorities can monitor the mining conditions in real time. This module consists of a Zigbee receiver, an ESP32 microcontroller, an LCD display, and a buzzer. The Zigbee receiver receives the transmitted sensor data from the transmitter module and sends it to the ESP32 for processing. The ESP32 then displays the environmental information on the LCD screen and triggers alerts if dangerous conditions are detected. Additionally, the system integrates IoT technology, enabling remote monitoring of mining conditions through the internet.

By combining wireless communication, environmental sensors, and IoT technology, the proposed system provides a reliable and efficient solution for improving mining safety and preventing accidents.

Figure 4 illustrates the transmitter section of a ZigBee-based mining safety system designed for real-time environmental monitoring in hazardous mining environments. The system is powered by a regulated power supply unit comprising a step-down transformer, bridge rectifier, filter capacitors, and a 7805-voltage regulator to provide a stable +5V output. The ESP32 microcontroller acts as the central processing unit, interfacing with sensors such as a DHT11 sensor for temperature and humidity monitoring, a CO_2 sensor for gas detection, and a vibration sensor for detecting ground instability or seismic activity. The collected sensor data is processed and transmitted wirelessly through a ZigBee transmitter module. A 16×2 LCD displays real-time environmental parameters, while a buzzer provides immediate alerts when unsafe conditions are detected. This system ensures continuous monitoring and early warning for miner safety.

Figure 5 presents the receiver section of the ZigBee-based mining safety system, which is responsible for receiving and displaying data transmitted from the mining environment. Like the transmitter, the system is powered using a regulated power supply with a transformer, rectifier, and voltage regulator. The ESP32 microcontroller receives data via a ZigBee receiver module and processes it for monitoring and alerting purposes. An IoT module is integrated to enable remote data access and cloud-based monitoring, enhancing real-time supervision. The 16×2 LCD displays received environmental parameters, and a buzzer generates alerts when abnormal or hazardous conditions are detected. This receiver unit provides centralized monitoring, improving safety management and enabling quick response in mining operations.

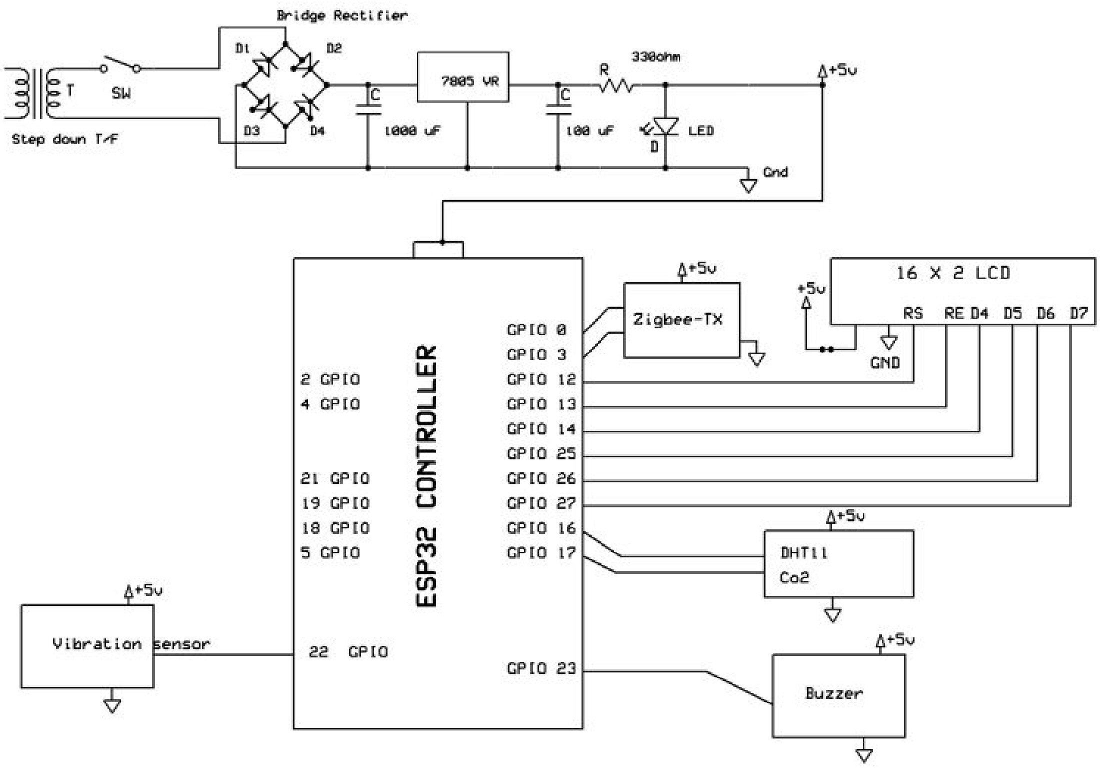

Figure 4. Circuit Diagram of ZigBee-Based Mining Safety System (Transmitter Section).

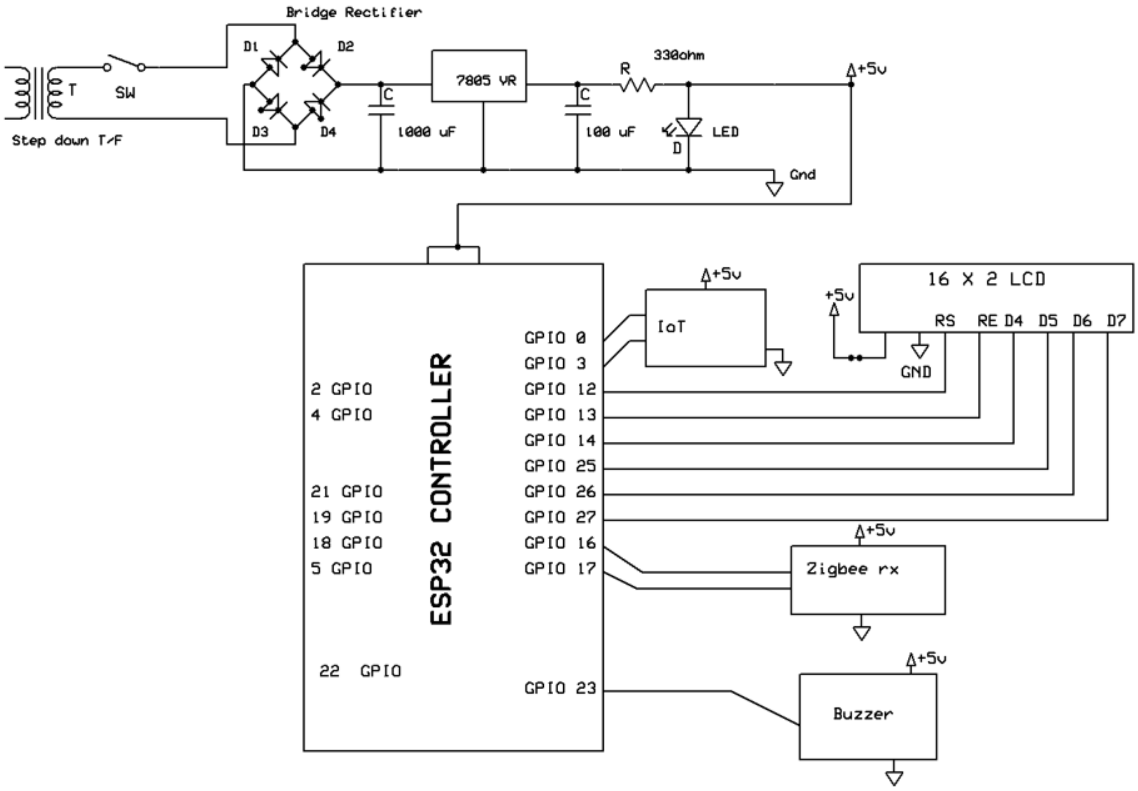

Figure 5. Circuit Diagram of ZigBee-Based Mining Safety System (Receiver Section).

4. Results and Discussion

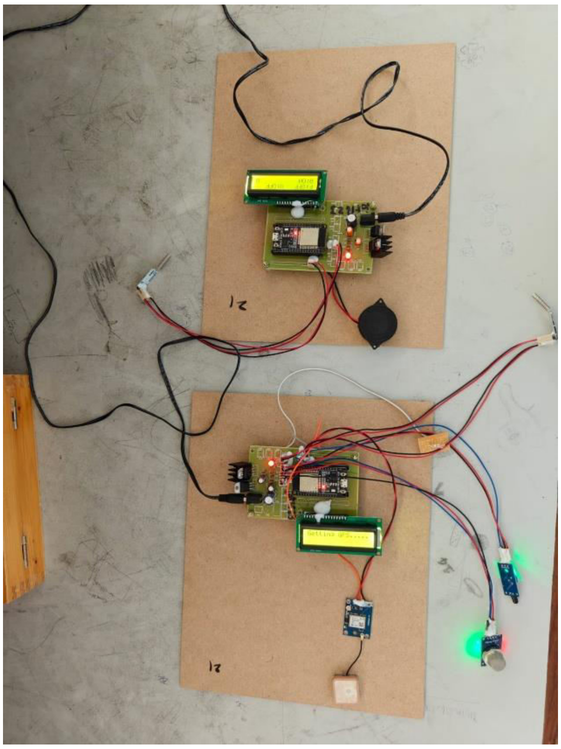

Figure 6. Hardware Implementation of Zigbee Mining Safety System

Figure 6 shows the complete hardware setup of the Zigbee Mining Safety System. The system consists of ESP32 microcontrollers, Zigbee communication modules, sensors such as CO_2 gas sensor, DHT11 temperature and humidity sensor, vibration sensor, LCD display, and buzzer used to monitor environmental conditions in mining areas.

Figure 7. LCD Display Showing Zigbee Mining Safety System Initialization

Figure 7 shows the LCD display output of the Zigbee Mining Safety System during system initialization. The display indicates that the system has started and is ready to monitor environmental parameters such as gas levels, temperature, humidity, and vibration.

S.No	Temperature	Humidity	Vib	Co2	Date
1	29	42	OFF	OFF	2026-02-10 12:54:02
2	29	42	ON	OFF	2026-02-10 12:53:42
3	29	41	OFF	OFF	2026-02-10 12:52:54
4	29	41	OFF	OFF	2026-02-10 12:51:58
5	29	40	OFF	OFF	2026-02-10 12:51:44
6	32	95	OFF	OFF	2026-02-05 18:45:12
7	32	92	OFF	OFF	2026-02-05 18:45:02
8	26	42	OFF	OFF	2026-01-30 12:27:37
9	26	42	OFF	OFF	2026-01-30 12:27:13
10	26	43	OFF	OFF	2026-01-30 12:26:49
11	26	43	OFF	OFF	2026-01-30 12:26:22
12	26	43	OFF	OFF	2026-01-30 12:25:56
13	26	43	OFF	OFF	2026-01-30 12:25:30
14	26	43	OFF	OFF	2026-01-30 12:25:03
15	26	43	OFF	OFF	2026-01-30 12:24:37
16	26	43	OFF	OFF	2026-01-30 12:24:10
17	26	43	OFF	OFF	2026-01-30 12:23:45

Figure 8. IoT Server Monitoring Interface

Figure 8 shows the IoT web server interface used for remote monitoring of mining safety parameters. The dashboard displays real-time values of temperature, humidity, vibration status, CO_2 levels, and timestamps for continuous monitoring and safety management.

5. Conclusion

The proposed Zigbee Mining Safety System provides a reliable and intelligent solution for enhancing safety in hazardous underground environments by integrating real-time monitoring, wireless communication, and automated alert mechanisms. By utilizing the ESP32 microcontroller along with CO_2 gas, temperature, humidity, and vibration sensors, the system continuously tracks critical environmental parameters and detects potential hazards at an early stage. The use of Zigbee communication ensures low-power and reliable data transmission to a remote monitoring unit, while LCD display and buzzer alerts enable immediate local awareness and response. Additionally, IoT integration facilitates remote monitoring, data logging, and analysis, improving decision-making and preventive measures. This system overcomes the limitations of traditional manual inspection methods by providing continuous, automated, and real-time safety monitoring. Finally, it significantly enhances miner safety, reduces accident risks, and supports the development of advanced, scalable, and efficient mining safety management systems.

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