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Wireless Coal Mine Monitoring System based on ESP-NOW Protocol for Real-Time Data Acquisition and Analysis

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Abstract

Coal Mine monitoring is a critical task to ensure the safety of Miners and efficient mining operations. Traditional methods of monitoring rely on wired sensors, which are expensive to install and maintain. Wireless technologies offer a cost-effective and flexible solution to this problem. In this context, the use of the ESP-NOW protocol is proposed as a means of transmitting data from sensors in a Coal Mine to a central monitoring system where the data is processed and analysed in real time. ESP-NOW is a low-power wireless communication protocol that can be implemented on Node MCU. The proposed system can collect data from various sensors, including gas sensors, Temperature sensors, Particulate Matter sensors, and Humidity sensors, and send the data wirelessly to the nodes that are fixed at different locations on a tunnel surface that is connected to the central monitoring station. The system can detect potential safety hazards and provide early warning alerts to Mine operators as well as it is used in tracking the workers. The results demonstrate the effectiveness of ESP-NOW in Coal Mine monitoring where real-time data transmission is critical.

Keywords: ESP NOW, Coal Mine, Wireless Technology, Hazardous Gases, HTTP Server

1. Introduction

Coal mining is a critical industry that supports energy generation across the world. However, it is also a high-risk activity, with Miners exposed to numerous hazards such as cave-ins, explosions, and black lung disease. Exposure to Coal dust can have significant effects on the respiratory system and overall health. Inhaling Coal dust can cause respiratory diseases such as pneumoconiosis, silicosis, and chronic obstructive pulmonary disease [1]. These conditions can lead to shortness of breath, coughing, and reduced lung function. India has a significant number of mining accidents due to hazardous gas emissions. Coal mining is the most common type of mining in India, and it is often associated with Methane gas emissions [2]. According to a report by the Directorate General of Mines Safety one of the worst mining accidents in India due to hazardous gas emissions occurred in the Dhanbad Coal Mine in 1965. The accident was caused by an explosion of Methane gas that had accumulated in the Mine, and it resulted in the deaths of 375 Miners. More recently, in 2018, an explosion caused by Methane gas in a Coal Mine in Jharkhand claimed the lives of 18 Miners. Thus, monitoring of underground Mines is essential to reduce the Mine accidents [3]. Communication technology plays a critical role in monitoring Mine accidents due to hazardous gases, as it allows for real-time monitoring and quick communication with emergency responders. In earlier days Wired communication systems were used [4]. These hard-wired systems that use cables or wires to transmit communication signals between various locations in the Mine. Then they used Two-way radios which are handheld or mobile radios that allow workers to communicate directly with each other. These radios can be an effective means of communication in underground Mines but may be subject to interference and can be difficult to use in noisy environments. So, they communicated with the help of Leaky feeders, which act as an antenna that flows throughout the tunnel [5]. Another technique which was widely used is Through the Earth communication systems that utilize low-frequency electromagnetic waves or induction-based techniques to transmit signals through the solid earth, allowing communication between different points in the Mine [6]. These systems rely on the conductive properties of the earth to propagate the signals. Attenuation is a significant challenge in through-the-earth communication using radio waves. The attenuation of radio waves as they propagate through the earth is influenced by various factors, including the frequency of the radio wave, earth conductivity, transmission power, antenna type, and environmental noise. To minimize attenuation, lower frequency radio waves are typically used in through-the-earth communication systems. However, there are limitations to increasing the transmission power to compensate for attenuation. The Mine Safety and Health Administration (MSHA) regulations restrict the amount of power that can be transmitted through the earth in order to maintain a safe environment for Miners [7].

In the late 20th century, digital communication technology was introduced in Coal Mines, providing more advanced and sophisticated communication systems. This includes computer networks, wireless communication, and other digital technologies that have improved safety, efficiency, and productivity in mining operations. The Mines are monitored by the robots [8]. Not only for monitoring, now a days these robots are replacing the workers who works in extremely dangerous places and also used in rescue operations. Different communication Technologies used in Underground Mine are listed in Table 1.

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Table 1. Development of communication system in underground Mine.

Investigators	Particulars
Nicholas Damiano (2017), Thomas D.Barkand (2006)	Based on ultra-low-frequency (ULF) transmission that propagates through rock strata.
Michael D.Bedford (2020)	Developed a cost-effective Leaky feeder system for U/G
C.Shobana Nageswari (2021)	Developed a monitoring system using WSN and RFID
Xiodong Sun (2020)	Developed an escort watch based on Bluetooth mainly for rescue purpose
Mariya Tasneem (2014)	Uses Wi-Fi for data transmission and monitoring in U/G
K.Anitha (2019), Krithika N (2014)	Developed a monitoring system using Zigbee for communication
Vaibhav Pandit (2013), Pooja Kadu (2021)	Combines the Zigbee and GSM for monitoring and producing Alert
Asesh Kumar (2013)	Developed a Mine monitoring system that involves Zigbee and CAN bus
Mario Di Nardo (2021)	Ventilation system using Zigbee in U/G

2. Literature Review

A. WSN in Mine monitoring and Safety

Wireless technology has become increasingly important in the mining industry, including Coal mining, as it provides a means of improving safety and efficiency in the workplace. Different technologies used in Wireless Sensor Network for Underground Mines are mentioned below.

Radio Frequency Identification (RFID) technology can be used to track equipment and personnel in the Mine. RFID tags can be attached to equipment and to the workers and sensors can be installed at various points in the Mine to track their location and movement[9]. The RFID sensors senses the tags that are with the Mine workers. But the short-range and line of sight is must in this case which may reduce the systems reliability.

Bluetooth technology is used in underground Mines by providing the workers with a watch that monitors the heartbeat rate and the blood pressure of the personnel. In case of an emergency conditions the watch sends a Bluetooth broadcast signal for every 5 seconds that helps the rescuers, who carry the detecting device to monitor the surrounding Bluetooth information to find the Miners who are trapped in the underground Mine. Whenever the underground network fails, they extend by investing more nodes to achieve communication and as a matter of fact the theoretical transmission distance of Bluetooth is 300 meters. But practically they achieved less than 10 meters. This makes this technology less reliable in this application.

Wi-Fi networks are used in Coal Mines to provide workers with wireless access to data and communication systems. This can be particularly useful for workers who need to access information about safety procedures, equipment, and schedules while working underground. The structure of Wi-Fi in an underground Coal Mine typically involves the installation of wireless access points (WAPs) throughout the Mine, which are connected to a central controller that manages the network[10]. The WAPs are strategically placed in areas where Miners are likely to be working, such as near Coal seams, underground roadways, and work areas. In order to ensure reliable connectivity, the WAPs must be placed in locations with minimal interference from the surrounding environment, such as rock formations and machinery.

Zigbee is a wireless communication protocol that is commonly used in various industries, including underground mining. In underground Mines, Zigbee technology are used to monitor various aspects of the mining operation, including the condition of mining equipment, the presence of gases, and the location of Miners[11]–[17]. The Zigbee protocol can transmit data over a short- range thus, it is connected in a mesh network, to reach the most remote areas of the Mine. The positioning of the workers is calculated by strength indicator of a received signal. The structure of Zigbee in an underground Mine involves the installation of Zigbee nodes throughout the Mine, which are connected to a central controller that manages the network. The nodes can be placed in areas where data needs to be collected, such as equipment monitoring points, gas sensors, and personal safety equipment worn by Miners. Zigbee has become more complex as it is connected in mesh topology. Mesh networks require multiple hops to transmit data, which can result in increased latency and slower data transfer rates. Moreover, this mesh network technology is power hungry as it uses multiple hops to transfer data also the setup is complex. mesh networks require multiple hops to transmit data, which can result in increased latency and slower data transfer rates.

Considering the Mine monitoring in real-time communication approach, the technology chosen must satisfy the conditions like low latency, low power consumption and simplicity. These factors can be ensured by the ESP NOW protocol which can be used in Underground Mine monitoring and control.

B. Communication Over ESP-NOW

In 2018, the ESP-NOW protocol was introduced for ESP32/ESP8266 microcontrollers [18]. It enables peer-to-peer (P2P) and low-power communication without the need for a router or a joining state in a hierarchical network. ESP-NOW offers three main communication methods within the network they are broadcast, unicast, and multicast. Broadcast is efficient for our applications, allowing unlimited receivers without the need for pairing. Unicast and multicast require initial pairing, limited receivers (up to 20), and acknowledgement response. Broadcast is primarily used for group communication in the project. Every Device has its unique ID which is used to define the board in our application and to send ESP-NOW data, it employs a vendor-specific action frame. The vendor-specific action frame has the following format as shown in the Fig.1 and Fig.2. This ESP-NOW protocol enables the development of cost-effective and efficient residential monitoring solutions[19]. It provides a foundation for building smart homes that offer improved comfort, energy savings, and security for homeowners [20].

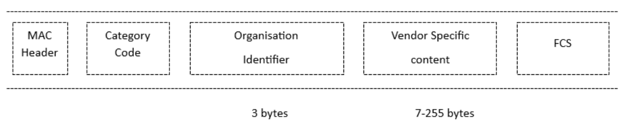


Fig. 1. Vendor-specific action Frame Format of ESP-NOW

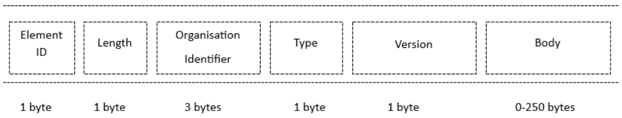


Fig. 2. Vendor Specific Content

3. Overview of the System

The proposed real-time monitoring and emergency alert system for underground Mines using ESP32/ESP8266 is divided into two node setups: fixed nodes and mobile nodes. The fixed nodes are installed on the surface of the Mine, connected to the internet, and equipped with ESP-NOW protocol. They collect data from mobile nodes carried by Mine workers, which are also equipped with ESP32/ ESP8266 microcontrollers and sensors for detecting Methane, carbon monoxide, Temperature, and Humidity levels. In case of any abnormality, the mobile nodes send an emergency message to the fixed nodes and to the central monitoring station. This system provides real-time monitoring of hazardous conditions in underground Mines and immediate alerts in case of emergencies to ensure the safety of Miners. The central monitoring station also stores and analyses the data for future analysis and decision making. The proposed system's user interface displays data collected from fixed and mobile nodes in real-time and provides a graphical representation of data to facilitate easy analysis. It also allows authorized personnel to configure the system settings and receive alerts on any abnormal levels detected in underground Mines. Fixed nodes collect data from mobile nodes using ESP-NOW protocol and transmit it to the central monitoring station through ethernet cables as shown in Fig. 3.

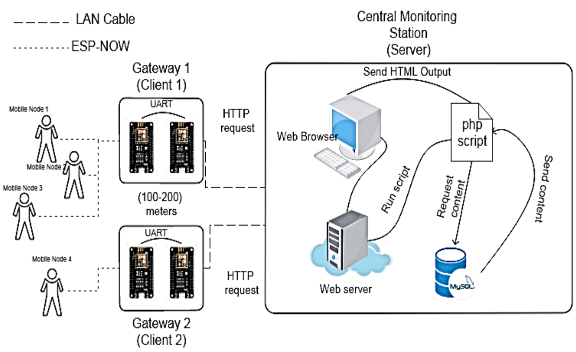


Fig. 3. Overview of the system Architecture

A. Hardware setup

ESP32 microcontrollers with sensors for detecting Methane, carbon monoxide, Temperature, Humidity and PM level. The Fixed nodes are the ESP32 microcontrollers installed on the surface of the Mine with a reliable power source, connected to the internet and equipped with ESP-NOW protocol. The block diagram of the fixed node and mobile node is shown in Fig.4 below. The fixed nodes are the responders that responds to the broadcasting message from the mobile nodes that are with the workers and alert the central monitoring station.

B. Data Collection and Transmission

The system uses ESP-NOW technology to ensure safety in an underground Mine application. The system consists of fixed nodes and dynamic nodes. The fixed nodes act as ESP-NOW access points and are installed in fixed locations throughout the Mine. The dynamic nodes are carried by Miners and move around the Mine. The dynamic nodes periodically send the sensor data to fixed node which acts as a gateway to the server. In case of an emergency, the dynamic nodes send data signals to the Fixed nodes. The monitoring station receives these signals from Fixed nodes, processes the data, and takes appropriate actions based on the emergency's severity. The workflow is mentioned in the Fig.5a, Fig.5b, Fig.5c below. Overall, the system uses ESP-NOW technology to enable real-time communication between fixed and dynamic nodes in the underground Mine, ensuring safety and preventing any potential emergencies.

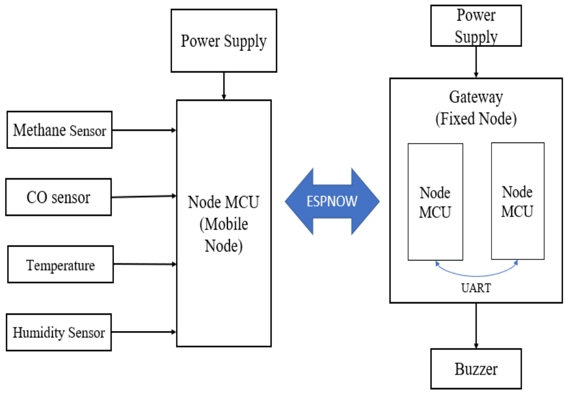
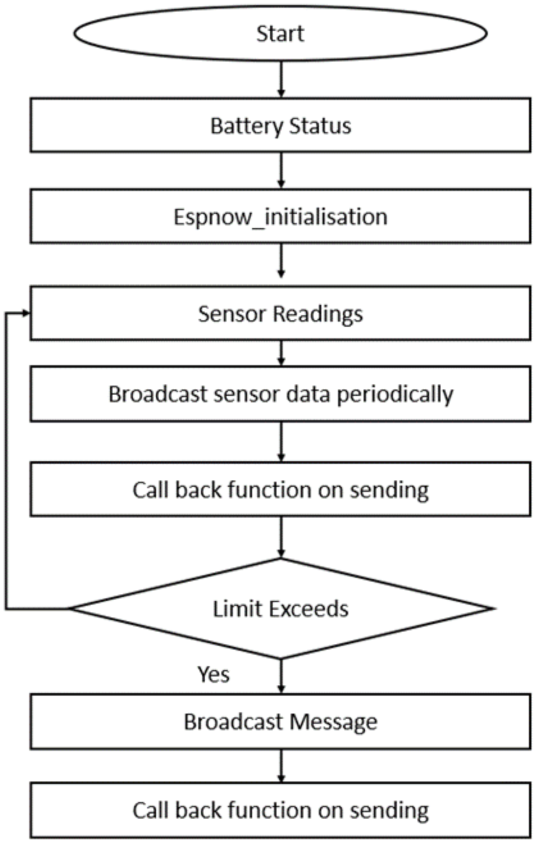
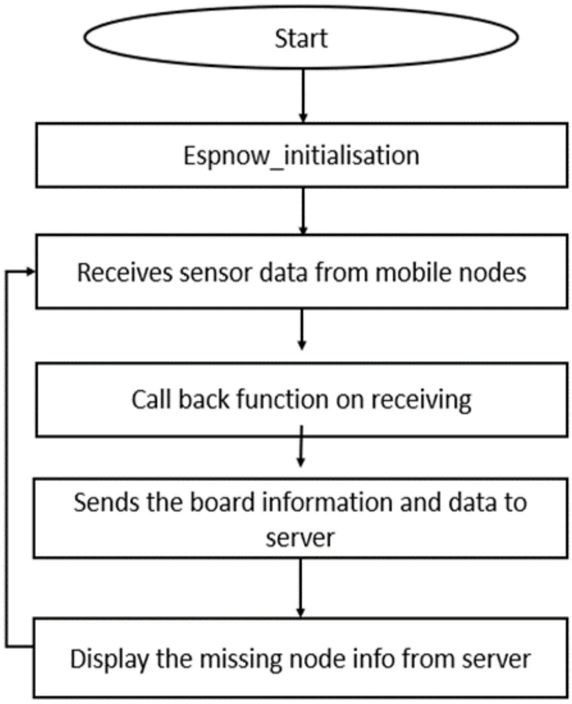


Fig. 4. Mobile node and Fixed node block diagram



(a)



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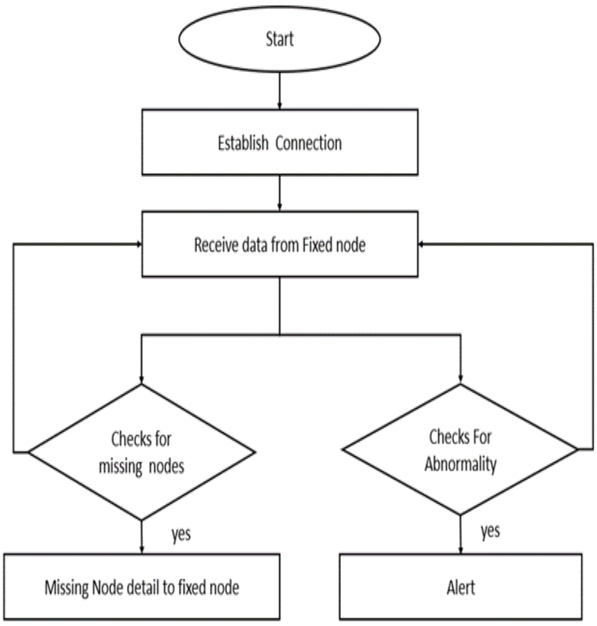


(c)

Fig. 5. (a) Flow chart of the Mobile node, (b) Flow chart of fixed node and (c) Flow chart of Server node

4. Hardware Design

The hardware setup for the coal mine monitoring project comprises several essential components that work together to ensure accurate data collection and seamless communication. The key hardware components include the NodeMCU module, DHT11 sensor, MQ2 sensor, power supply, wiring and connectors, coal mine infrastructure, internet connection, and an HTTP server. The Hardware setup is shown in the Fig. below

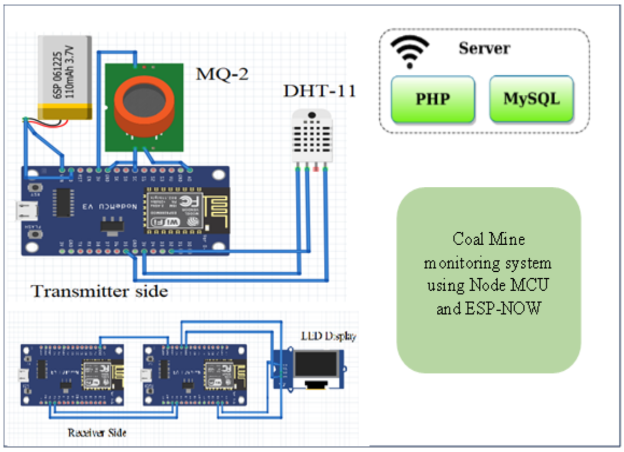


Fig. 6. Hardware setup of a coal mine monitoring system

A. NodeMCU module:

The NodeMCU module plays a crucial role as a gateway device in your coal mine monitoring system. It serves as a bridge between the sensor nodes and the HTTP server, facilitating the seamless transmission of data. NodeMCU is an open-source IoT development board based on the ESP8266 Wi-Fi module. It provides a user-friendly environment for programming and integrating various sensors and actuators. The key features of NodeMCU include its compact size, low power consumption, and built-in Wi-Fi capabilities. In this system, two NodeMCU modules are deployed as gateway devices within the coal mine. These gateway devices are responsible for receiving sensor data from multiple sensor nodes, such as DHT11 and MQ2 sensors, through the ESP-NOW protocol. ESP-NOW is a lightweight communication protocol designed for low-power devices, allowing efficient broadcasting and transmission of data between NodeMCU devices.

B. MQ-2 Sensor

In coal mine monitoring, the MQ2 sensor is a crucial component for detecting and monitoring the concentration of combustible gases, including methane, which is a significant concern in coal mines due to its flammability and potential for explosions. The MQ2 sensor's ability to detect methane gas accurately helps ensure the safety of the mining environment and the workers involved. When connected to the NodeMCU module, the MQ2 sensor provides analog or digital output, depending on the specific module used. The analog output indicates the gas concentration as a voltage level, while the digital output provides a binary signal indicating the presence or absence of the target gas above a certain threshold.

C. Temperature/Humidity Sensor

The DHT11 sensor is a basic digital temperature and humidity sensor. It provides accurate readings of temperature and humidity levels in the coal mine environment. The DHT11 sensor consists of a humidity sensing component and a thermistor for temperature measurement. The humidity sensing component utilizes a moisture-absorbing substrate that changes its electrical resistance based on the surrounding humidity. Meanwhile, the thermistor measures temperature by detecting changes in its electrical resistance as the temperature fluctuates. When connected to the NodeMCU module, the DHT11 sensor provides digital output in the form of a serial data signal. The NodeMCU module communicates with the sensor using a specific protocol to request data, which is then transmitted in a standardized format.

D. OLED Display

In the event of a hazardous situation such as a gas leak or excessive temperature, the gateway NodeMCU can receive alerts from the HTTP server. These alerts can be immediately displayed on the screen, notifying miners of the emergency, and providing them with relevant instructions, evacuation routes, or safety protocols.

The hardware components work to create a robust and reliable coal mine monitoring system. By leveraging the capabilities of the NodeMCU module, DHT11 and MQ2 sensors, power supply, wiring and connectors, coal mine infrastructure, internet connection, and an HTTP server, the system ensures accurate data collection, effective communication, and enhanced safety measures within the coal mine environment.

5. Software Used

A. Arduino IDE

The Arduino Software (IDE), also known as the Arduino Integrated Development Environment, is equipped with various features. It includes a text editor for code writing, a message area, a text console, a toolbar with commonly used functions, and a range of menus. Its purpose is to establish a connection with Arduino hardware, enabling the uploading of programs and facilitating communication with the devices. The ESP-32 utilizes this platform to upload programs and communicate with other nodes within its network.

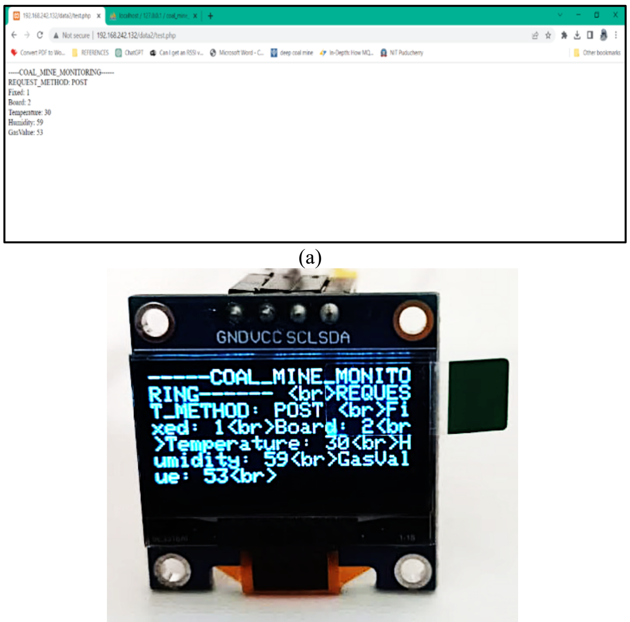
B. **XAMPP Software**

XAMPP is a comprehensive software package designed to create a web development environment on your personal computer. The name "XAMPP" originates from its core components: Apache, MySQL, PHP, and Perl. Apache is a widely used open-source web server software that facilitates website hosting and serves web pages to clients. MySQL is an open-source relational database management system (RDBMS) that enables the creation, management, and manipulation of databases. It offers a dependable backend solution for storing and retrieving data in web applications. PHP is a server-side scripting language that is widely used for web development. It allows you to embed PHP code within HTML files to create dynamic web pages and interact with databases. Perl is a powerful scripting language that can be used for various purposes, including web development, text processing, system administration, and more. XAMPP combines these components into a single package, making it easy to set up a local web server environment on your computer. It is available for Windows, macOS, Linux, and Solaris operating systems, making it a cross-platform solution.

6. Result and Discussion

The results obtained from the coal mine monitoring project using mobile nodes communicating with a gateway and storing data in a MySQL database are both informative and promising. Through the implementation of this system, we have successfully established a robust monitoring infrastructure that ensures real-time data collection and transmission from the coal mine site. The collected data, such as temperature, humidity, gas levels, and worker location, have been efficiently transmitted from the mobile nodes to the gateway using appropriate communication protocols. This seamless transmission ensures that vital information is relayed to the centralized system without delay or loss. Upon reaching the gateway, the data is processed and securely transferred to an HTTP server. This step allows for convenient storage and retrieval of the collected information, facilitating easy access for monitoring and analysis purposes. By utilizing a MySQL database, we have ensured the organization and persistence of data, enabling efficient data management and retrieval. The Data sent from the mobile node (miners' Helmet) to the Node MCU gateway is displayed in the OLED Display as shown in Fig.7(a) and Fig.7(b) and the information posted on the server is displayed on the screen for guiding the miners in Underground as shown in Fig.8(a), (b), (c), (d). Also, the sensor values along with the id is stored in the MySql Database for future reference as shown in Fig.9.The display chart in the phpMyAdmin displays the sensor data across every mobile node as shown in Fig.10(a) and Fig.10(b).

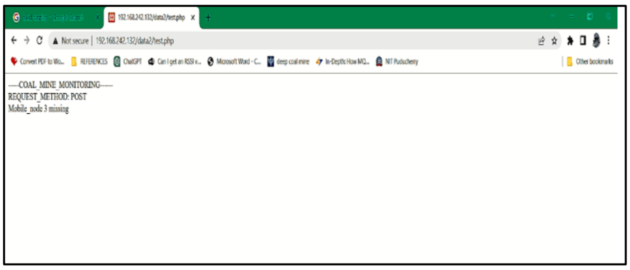
The concentration of gases represented in this graph is determined by applying calculations to the sensor values obtained from the gas sensors. These calculations convert the raw sensor readings into gas concentration values, which are then plotted on the graph shown in Fig. 14 (c) to provide a clear visualization of the gas levels over time. The challenges and packet loss in an ESP-NOW communication can be influenced by various factors, including the range between the devices. When it comes to the range of ESP-NOW communication, it depends on several factors such as the transmit power, environmental conditions, obstacles, and interference. In general, the range of ESP-NOW can vary from a few meters to several hundred meters, depending on these factors. If the range between the devices exceeds the effective range of ESP-NOW, packet loss is more likely to occur. Packet loss can happen due to weak signal strength, interference, or obstacles obstructing the wireless signal. Here the packet loss is calculated by sending an incremented value to the receiver and checking the corresponding data received by the receiver at different range is shown in the Fig.11 below and values are shown in Table 2. This can be reduced with increasing the transmit power and by improving antenna design.



(a)

(b)

Fig. 7. (a) Web page displaying the sensor values from the Gateway and (b) Displaying the response of the server in the Gateway (Fixed Node)



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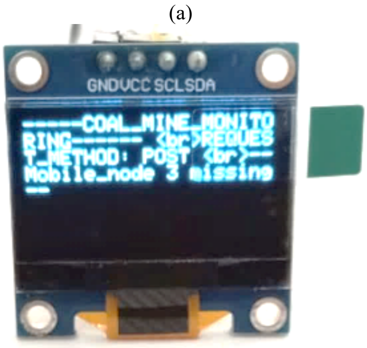

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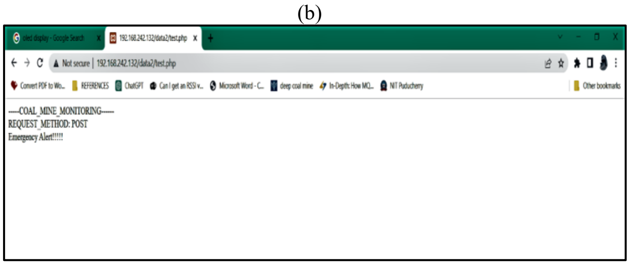

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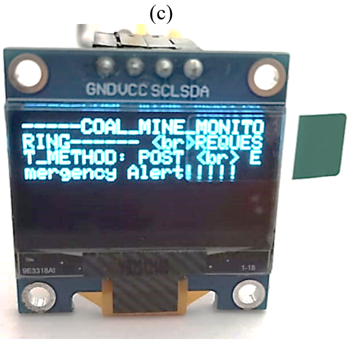


(d)

Fig. 8. (a)Web page displaying the Missing node, (b) Displaying the response of the server in the Gateway (Fixed Node), (c) Web page displaying the Alert Message and (d) Web page displaying the Alert Message

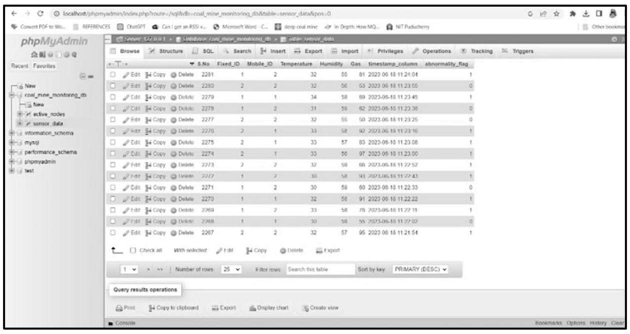
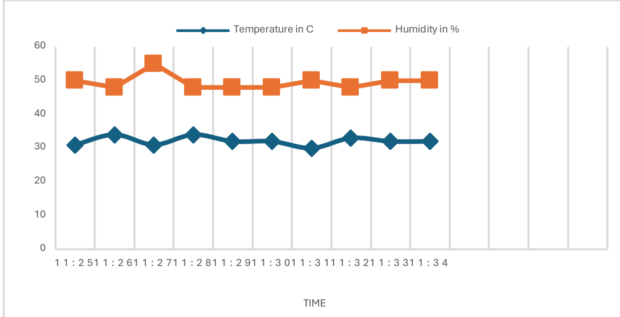
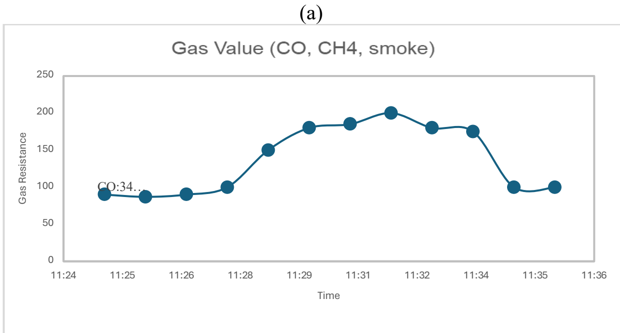


Fig. 9. Database for storing the received values from sensor nodes



(a)



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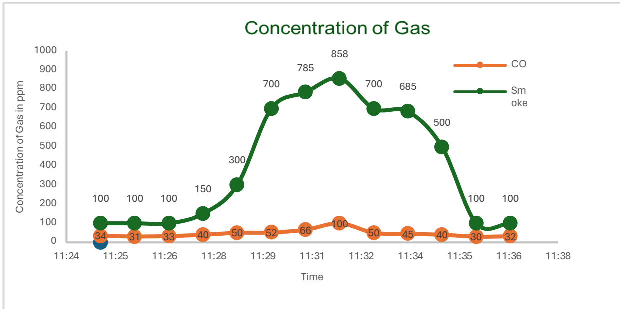

(c)

Fig. 10. (a) Humidity and Temperature value, (b) Analog value obtained by MQ-2 and (c) Concentration of CO and Smoke

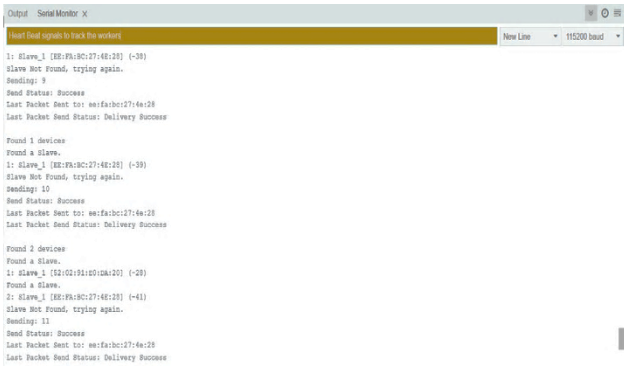

Fig. 11. Checking for packet received at different range.

Table 2. Calculation of Packet loss with respect to range

S. No	Data Sent	Data Received	Range (m)	Packet Loss (%)
1	100	100	1	0
2	100	100	5	0
3	100	100	10	0
4	100	99	20	1
5	100	99	30	1
6	100	98	40	2
7	100	97	50	3
8	100	95	70	5
9	100	93	80	7
10	100	93	100	7

7. Conclusion

This System is aimed to develop an efficient and reliable coal mine monitoring system by employing mobile nodes, fixed nodes, ESP-NOW communication, and HTTP requests for data transmission to a server. Through the implementation of this system, several significant outcomes were achieved, and key objectives were successfully addressed. By establishing a robust communication network between mobile and fixed nodes using ESP-NOW, real-time data transfer was made possible within the coal mine environment. This approach overcame challenges such as limited connectivity and interference, ensuring seamless and reliable communication throughout the monitoring system. The utilization of ESP-NOW offered numerous advantages, including low power consumption and reduced latency. These benefits are vital in the context of coal mine monitoring, where energy efficiency and real-time data are critical for ensuring the safety and efficiency of mining operations. The system demonstrated its ability to collect and analyze data promptly, enabling timely decision-making for mine operators and personnel. Furthermore, the integration of HTTP requests facilitated the transmission of collected data from fixed nodes to a centralized server. This centralized storage and management of monitoring data allowed for comprehensive analysis and generated valuable insights. Additionally, the use of HTTP requests enabled remote monitoring and access to data, enhancing the overall efficiency and accessibility of the system.

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