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RESEARCH ARTICLE

RTEPMS: Real-Time Environmental Parameters Monitoring System Using IoT-Based LoRa 868-MHz Wireless Communication Technology in Underground Mines

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ABSTRACT In underground mining, the real-time monitoring of environmental parameters plays a pivotal role in ensuring the safety of mining operations and personnel. This article explores the integration of Long Range (LoRa) wireless communication technology and the Internet of Things (IoT) to bolster safety measures and prevent potential accidents within underground mines. The environmental parameters in underground mines include Oxygen (O_2), Carbon Dioxide (CO_2), Carbon Monoxide (CO), Methane (CH_4), Nitric Oxide (NO), Nitrogen Dioxide (NO_2), Sulphur Dioxide (SO_2), Hydrogen Sulfide (H_2S), Ethylene Oxide (EO), Temperature and Humidity. Currently, underground mines in India use portable multi-gas detector devices to measure environmental parameters. HPD13A LoRa 868 MHz based Real Time Environmental Parameters Monitoring System (RTEPMS) is designed and developed to facilitate real-time data collection in underground mines. In addition, the developed RTEPMS system is tested and evaluated at the open surface level and in one of the underground mines in India. The experimental results represent successful LoRa-based wireless communication established in an underground mine with data acquisition and real-time processing. Major parameters exceeding threshold limits in the underground mine environment include O_2, CO, CO_2, NO_2, and EO. The data correlation between LoRa-based RTEPMS and multi-gas detector devices is 69.47% for CO_2 and 72.38% for CO, while the values for CH_4 and H_2S are nearly zero, indicating their presence in underground mines is almost negligible. The RTEPMS is an affordable solution for smaller and less affluent underground mines. It alerts mine workers if environmental parameters exceed threshold limits during emergencies.

INDEX TERMS Internet of Things, LoRa, wireless communication, sensors, environmental parameters, real time system, underground mine.

I. INTRODUCTION

Mining plays a pivotal role in fostering global socio-economic development and its indispensable position in meeting the high demand for mineral resources. However, the worldwide mining sector confronts various challenges, such as economic, initial investments, and the unpredictability of commodity prices. Underground mining operations are hazardous due to dust, flammable toxic gases, and geological conditions. The challenges of an underground mine environment are straight long and curved tunnels, unstable structures, poor lighting conditions, hazardous environmental parameters, and the movement of diesel-operated heavy machineries. The presence of toxic mine gases in underground mines is a significant danger, resulting in numerous fatalities among mine workers and the onset of health problems [1], [2], [3].

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These issues are exacerbated by elevated threshold limit values (TLV) of mine gas parameters and prolonged exposure [4].

The mining sector has adopted various emerging technologies to address these challenges to enhance work efficiency and safety. Like several other industries, mining is actively accepting digital transformation to achieve automation. Implementation of real-time monitoring of environmental and structural parameters, as well as tracking mine personnel, machines, and equipment, along with the installation of an alert system, can significantly improve underground mining operations in terms of productivity, efficiency, and safety [5], [6], [7].

The TLV of gas parameters are Carbon Dioxide (CO_2) - 5000 PPM, Carbon Monoxide (CO) - 50 PPM, Nitric Oxide (NO) - 25PPM, Nitrogen Dioxide (NO_2) - 5PPM, Sulphur Dioxide (SO_2) - 5 PPM, Hydrogen Sulfide (H_2S) - 5 PPM, Aldehydes or Ethylene Oxide (EO) - 10 PPM, Oxygen (O_2)-20.9% and methane (CH_4) -1.25% [8].

In this article, we focused on real-time monitoring of environmental parameters in an underground mine in India. The major variations of environmental parameters of CO_2, NO, NO_2, EO, and O_2 levels were observed in an underground mine. Currently, the process of measuring these environmental parameters in the underground mine relies on the use of portable multi-gas detector devices. The manual process is conducted by dedicated mine staff once in a daily shift, and updates by writing the measured data on the display board daily. Therefore, the implementation of a portable real-time environmental monitoring system becomes essential to accurately measure these parameters and promptly alert mine personnel to potential gas hazards. Portable devices are available to measure specific environmental parameters according to client needs. Still, they lack the capability to store and conduct basic analysis of the gathered data. These devices are expensive to equip for all underground mine workers.

This article aims to design and develop an RTEPMS utilizing affordable gas sensors, microcontroller processing units, and wireless communication technology. This system is designed for remote monitoring, data storage in a dedicated device or cloud platform, and triggering alerts when environmental parameters surpass predefined threshold limits.

The developed RTEPMS is a cost-effective, easy-to-use, portable type and small size, power efficient, calibration of gas sensors, assigned unique address in LoRa module communication to send and receive data, long distance communication, storage of data locally at RTEPMS transmitter and receiver, enclosures for sensors and RTEPMS devices. Deployment of RTEPMS devices in a harsh environment of underground mines is used as a portable real-time data acquisition system for a longer period.

This article is organized as follows after providing the background information on the underground mine and the requirement of wireless communication technology in the underground mine with the following contributions.

1. We reviewed the existing developed environmental parameters monitoring system and research activity in the underground mine applications (Section II).
2. We present LoRa-based RTEPMS to acquire data in real time by detailing its architecture, design, flowchart of the design methodology, its functionality, sensor calibration, and schematic diagram (Section III).
3. We describe the implementation details of LoRa-based RTEPMS at the surface level and underground mine (Section IV).
4. We evaluate the RTEPMS device performance compared with the multi-gas detector device in one of the underground mines in India (Section V).
5. Section VI describes the limitations of RTEPMS, and Section VII provides the conclusion.

II. APPLICATIONS OF ENVIRONMENTAL PARAMETERS MONITORING SYSTEM IN UNDERGROUND MINES

In underground mines, safe and healthy working conditions are required for mine workers to be productive. It is possible when the air quality in an underground mine environment is the same as on the surface, without any hazardous gases and with a comfortable temperature and humidity. Mining operations such as the use of heavy machinery, drilling, and blasting to excavate ore cause hazards such as changes in environmental parameters, ground vibrations, and air blasts. Most mines have implemented safety procedures and training programs to improve safety in underground mining. However, the dynamic nature of underground mining operations makes it difficult to use mining technology for adequate ventilation, and air quality can vary, affecting mine worker health. Because of underground mines' dynamic nature and harsh environment, it is challenging to deploy a reliable and robust wireless communication system to acquire environmental parameters [8]. To provide reliable and cost-effective wireless communication in underground mines, the following communication technologies are used as illustrated in Table 1. Table 2 describes the real-time environmental parameters monitoring system in underground mining applications. Reliable wireless communication plays a pivotal role in the success of underground mining operations. Yet, the challenge lies in wireless signal propagation within the confined, irregular structure, curved tunnels, and non-line-of-sight environment in mines. The limitation of network coverage significantly increases the complexity and cost of deploying a real-time wireless communication system for monitoring underground environmental parameters. Emerging radio frequency communication technologies like LoRa, LoRaWAN [9], [10], [11], and 5G technology are present cost-effective solutions for achieving seamless real-time communication in these underground mine environments [12].

TABLE 1. Summary of wireless communication technology in underground mine applications [12], [13], [14].

Technology	Type of Communication	Underground Mine Application
Fiber-optic communication	Wired communication	Underground Mine Communication
Leaky Feeder	Combination of wired and wireless communication	Ventilation control and rescue communication in underground mines
Radio Frequency Identification (RFID)	Wireless communication	Access control and positioning
Wireless Fidelity (Wi-Fi)	Wireless communication	Environmental Parameter Monitoring
Ultra-wideband (UWB)	Wireless communication	Positioning
ZigBee	Wireless communication	Wireless communication and Positioning
3G, LTE/4G	Wireless communication	Multi-Media Surveillance
Bluetooth Low Energy (BLE)	Wireless communication	Environmental Parameter Monitoring and Positioning
Long Range (LoRa)	Wireless communication	Control of explosive and communication, Environmental Parameter Monitoring
Narrowband-IoT (NB-IoT)	Wireless communication	Environmental Parameter Monitoring
5G - Positioning	Wireless communication	Unmanned operations and Remote control

TABLE 2. Applications of environmental parameters monitoring system in underground mines.

Refer ence	Deployment of Sensors	Technology	Parameters	Type of Sensors	Limitations
[7]	Fixed sensor	Bluetooth & IoT	CH_4, CO, CO_2, Temperature and Humidity	MQ4(CH_4), MQ9(CO), MQ135(CO_2) and DHT11	The lack of standardized processes and data transmission from the underground mine to the surface at a height of 23 m is recorded
[15]	Portable sensors connected to the system	Bluetooth	CO, H_2S, Temperature and Humidity	MQ9 (CO), MQ136 & ZE03 (H_2S) and DHT22	Lack of sensor calibration details
[16]	Portable sensors fixed to the helmet	NRF24L01 wireless module	CH_4, Temperature and Humidity	MQ4 (CH_4) and DHT11	Lack of experimentation details
[1]	Portable sensor	ZigBee	CH_4, CO, CO_2, Temperature and Humidity	MQ4(CH_4), MQ7(CO), MG811(CO_2) and DHT11	Lack of standardization, Data packet drops in NLOS, and the system is not suitable for harsh environment
[17]	Fixed sensor	ZigBee	CO_2, Temperature and Humidity	N/A	Insufficient provision of implementation specifics regarding data transmission to the surface
[18]	Fixed sensor	ZigBee	CH_4, CO_2, CO, O_2, H_2, H_2S, Temperature and Humidity	N/A	Lack of implementation and sensor details
[19]	Fixed sensor	ZigBee	CH_4, CO, O_2, Temperature, Humidity, and personnel positioning coordinates	MJC4_3.0L (CH_4), 7EFF(CO), KE-25(O_2) and DHT91	Simulation study
[20]	Fixed sensor	ZigBee	Gas Parameters	Gas Parameters	Lack of experimentation details
[21]	Fixed and Mobile sensor	ZigBee	CH_4, CO, O_2, Temperature and Humidity	N/A	Simulation study
[22]	Portable sensors fixed to the helmet	ZigBee	CH_4 and CO	MQ2 (CH_4) and MQ7(CO)	Implementation of the system at the laboratory level
[23]	Portable sensor	ZigBee	CO_2, Temperature and Humidity	MARTS-RMS sensor, digital temperature sensor	Lack of implementation details and data transmission to the gateway node
[24]	Portable sensor	ZigBee	Temperature, Humidity, and text message	SHT21	Focused only on communication establishment at the mine site
[6]	A portable sensor fixed to the helmet	ZigBee	CH_4, CO, Temperature and Humidity	MQ4 (CH_4), MQ7 (CO) and DHT11	Implementation at the laboratory level
[25]	Portable sensor	ZigBee	CO, CO_2, CH_4, H_2, NH_3, Temperature and Humidity	MQ2 (CH_4), MQ7(CO), MQ135 (CO_2) and DHT11	Implementation at the laboratory level
[26]	Portable sensor	LoRa	Temperature and Humidity	DHT 11	Implementation at surface level
[27]	Portable sensor	LoRa	Air Quality, Temperature and Humidity	MQ135 (Air Quality), DHT22	Implementation at the laboratory level
[28]	Portable sensor	LoRa	Temperature and Humidity	DHT 11	Implementation at the laboratory level

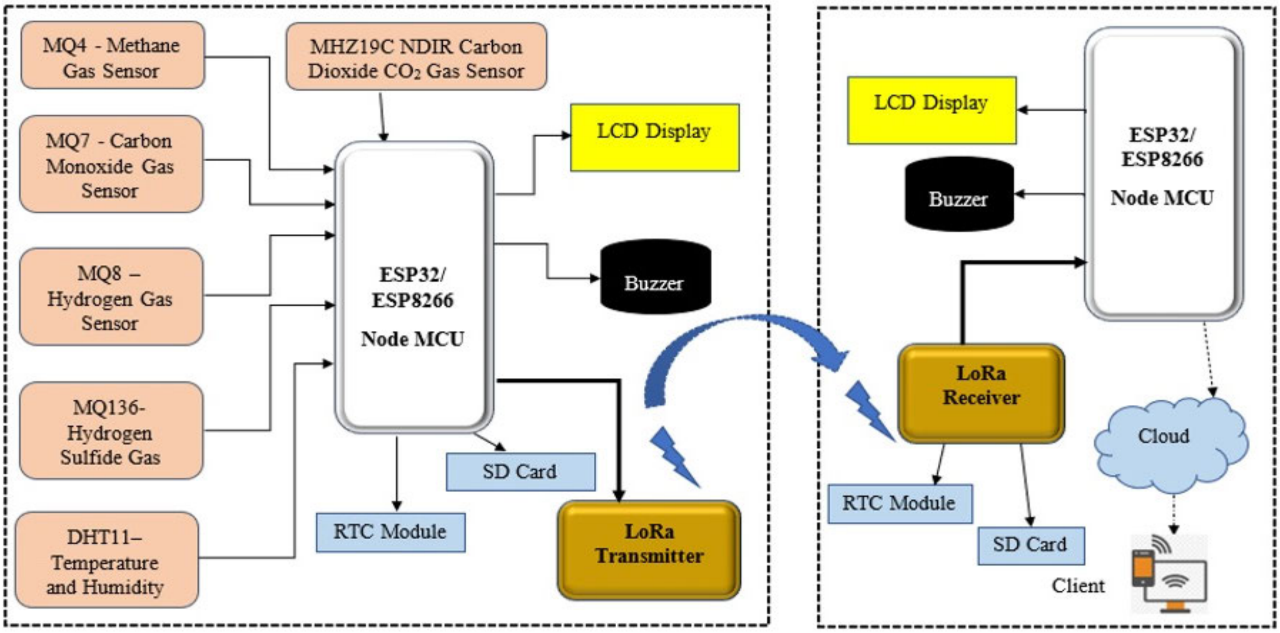


FIGURE 1. The architecture of the IoT-based RTEPMS with LoRa modules transmitter and receiver.

III. DEVELOPMENT OF PORTABLE REAL TIME ENVIRONMENTAL PARAMETERS MONITORING SYSTEM (RTEPMS)

We introduce IoT enabled LoRa based RTEPMS by describing an overview of the system architecture, details about the sensors and development board's features, a flowchart illustrating its operation, as well as schematic diagrams depicting the transmitter and receiver components of the RTEPMS.

A. ARCHITECTURE OF IOT ENABLED HPD13A - SX1276 (868 MHZ) LORA BASED RTEPMS

The LoRa module HPD13A-SX1276 is a wireless communication transceiver module that operates in the 868 MHz frequency band. It is based on the Semtech SX1276 chip, a highly integrated RF transceiver capable of operating in multiple frequency bands. LoRa is a long-range wireless communication technology ideal for applications that require long-range communication with low power consumption. The technology uses spread-spectrum modulation techniques to achieve long-range communication with low power consumption.

The architecture of the IoT-based RTEPMS with the LoRa module is shown in Figure 1. It consists of an ESP32 microcontroller-based development board, HPD13A LoRa module, DS1307 RTC module, Micro SD card module with the integration of MQ7(CO gas) sensor, MQ136 (H_2S gas) sensor, MQ8 (H_2 gas) sensor, MQ4 (CH_4 gas) sensor, MHZ19C NDIR CO_2 Module and DHT11/22 Temperature and Humidity Sensor. ESP 32 development board developed by the Espressif system is a low power based on a high-performance microcontroller with integrated Wi-Fi and Bluetooth capabilities [29]. It is an open-source platform, easy to use, and has a wide range of libraries and community users with a simple programming interface and a wide range of Input/Output options. ESP32 designed for advanced users has a wide range of capabilities including a high-speed processor, boot option, and flash encryption with a large amount of memory, more pins, and advanced peripherals, as shown in Figure 2(a).

The HPD13A-SX1276 module supports both LoRa and Frequency Shift Keying (FSK) modulation schemes and has a maximum output power of 20 dBm (100 mW). It has a built-in MCU (Microcontroller Unit) that can be programmed to control the module's functions and communicate with external devices through serial communication interfaces such as Universal Asynchronous Receiver-Transmitter (UART), Serial Peripheral Interface (SPI), and Inter-Integrated Circuit (I2C). The low-cost LoRa module is highly efficient and suitable for IoT applications. HPD13A - SX1276 based LoRa modules are used to monitor environmental parameters and to establish wireless communication between transmitter and receiver. HDP13A V1.1 LoRa Module, which is designed and developed by HPDTeK is used in RTEPMS as shown in Figure 3. LoRa stands for "Long Range" wireless data communication technology developed by Semtech. It uses a modulation technique called "Chirp Spread Spectrum" (CSS), which is distinct from the more common FSK or Phase Shift Keying (PSK) used in many other wireless systems. The LoRa module operates with the 868 MHz frequency band, offering a user-friendly, cost-effective, and high-efficiency solution suitable for real-time wireless applications [10], [30], [31].

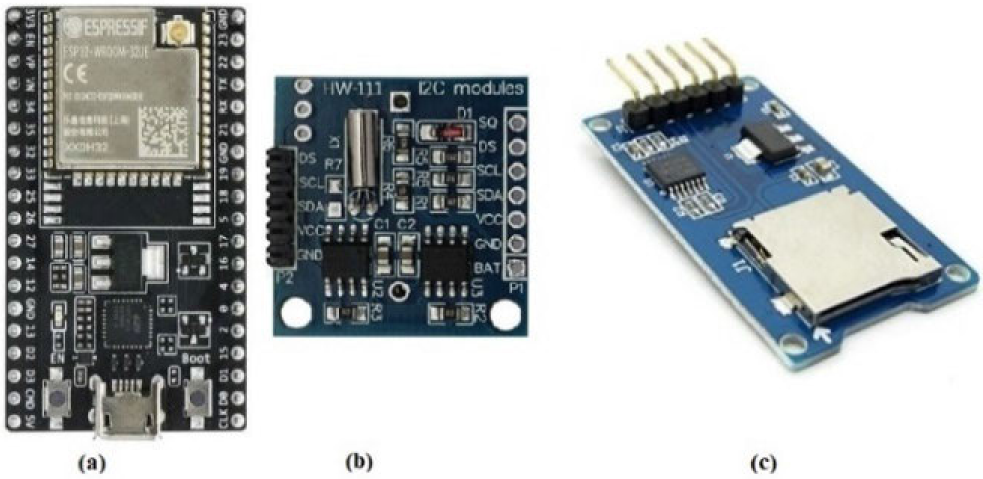


FIGURE 2. a) ESP32 development board, b) DS1307 RTC Module, c) Micro SD Card module.

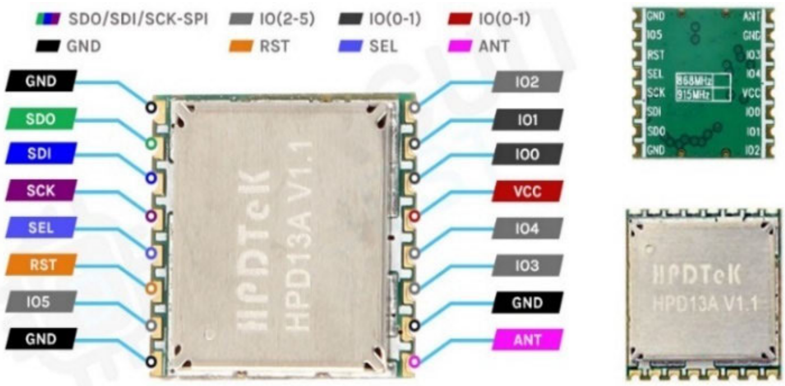


FIGURE 3. HDP13A V1.1 LoRa module pin configuration.

The SX1276 transceivers are equipped with the LoRaTM long-range modem that provides ultra-long range spread spectrum communication and high interference immunity while minimizing current consumption. SX1276 achieves a sensitivity of over (-134 dBm) and Spread Spectrum techniques spread the transmitted signal over a wide frequency band, much wider than the bandwidth (BW) of the original signal. This reduces the power density and makes the signal less prone to interference. The CSS used by LoRa spreads the signal across the spectrum using "chirps", which are signals that increase or decrease in frequency over time. The SX1276 transceivers are designed to be power-efficient. The sensitivity and coverage distance are based on the spreading factor (SF) and BW. Thus, the sensitivity of the LoRa module with SF = 12 is up to -134 dBm with BW of 125 KHz. The receiver sensitivity increases with the increase of SF and BW. A sensitivity of over -134 dBm refers to the minimum signal strength a receiver can detect and still successfully demodulate the information. A sensitivity of -134 dBm is extremely low, meaning the transceiver can pick up and decode very weak signals. This is a significant factor in its long-range capabilities [32], [33], [34], [35], [36].

LoRa transceiver module used to monitor underground mine environmental parameters is a good option compared to other wireless communication technology. It provides long-range wireless communication to transmit data over long distances. A microcontroller that acts as the brain of the system and controls communication with the LoRa module. The LoRa transceiver module is designed to transmit and receive data using the LoRa protocol. The RTC DS3231M module is a real-time clock (RTC) module that uses the DS3231M IC. The DS3231M is a low-cost, high-accuracy I2C real-time clock (RTC) with an integrated temperature-compensated crystal oscillator (TCXO) and crystal. The module provides accurate timekeeping for microcontroller-based projects, as shown in Figure 2(b). An SD card module for ESP 32 is a device that allows a microcontroller to communicate with an SD card. These modules include a slot for an SD card. A small circuit board with an SD card controller and a set of pins that can be connected to the ESP 32 to read and write data to the

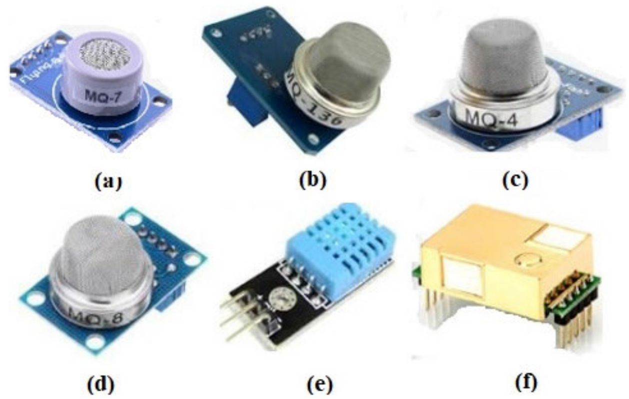


FIGURE 4. Sensors a) MQ7 (CO) Gas Sensor, b) MQ136 (H_2S) Gas Sensor, c) MQ4 (CH_4) Gas Sensor, d) MQ8 (H_2) Gas Sensor, e) DHT11–Temperature and Humidity Sensor, and f) MHZ19C NDIR CO_2 module.

SD card, which can be used for storing and retrieving sensor data, as shown in Figure 2(c). The sensors used to measure these gases are represented in Figure 4. Table 3 describes the characteristics of the sensors.

B. FLOWCHART OF RTEPMS TRANSMITTER AND RECEIVER

The RTEPMS transmitter device setup and operation flowchart are illustrated in Figure 5 and Figure 6.

- LoRa based RTEPMS Transmitter Setup:

The procedure for Initializing the RTEPMS LoRa based system is described in detail.

Step 1: Turn on the RTEPMS LoRa based system using a suitable power supply

Step 2: Verify if the LCD has successfully started. If "yes" then proceed to step 3, otherwise, initiate a manual system reset.

Step 3: Confirm whether the RTC module has initialized. If "yes" then proceed to step 4, otherwise, perform a manual system reset.

Step 4: Check the LoRa module is started. If "yes" proceed to step 5, otherwise, perform a manual system reset.

Step 5: Ensure that the SD card module has been initialized. If "yes" then proceed to step 6, otherwise, perform a manual system reset.

Step 6: Once all steps are completed successfully, fetch the sensor data and display it on the RTEPMS LCD of the transmitter.

- LoRa device operation cycle:

Step 1: Begin the LoRa device operation cycle upon successful setup.

Step 2: Retrieve the current timestamp from the RTC module.

Step 3: Fetch sensor data every minute o
r as per configuration

Step 4: If the current minute falls within the intervals of 20-22 or 40-42 or 00-02 then fetch the sensor data and create a CSV file on an SD card with a valid name.

TABLE 3. Characteristics of sensors [37].

Sensors	Details
MHZ19C NDIR CO_2 Module (CO_2)	The MH-Z19C NDIR infrared gas module is a commonly used sensor with a compact size designed for measuring CO_2 concentration in the air. It operates on the non-dispersive infrared (NDIR) principle to detect CO_2 presence in the air, offering excellent selectivity, independence from oxygen levels, and a long lifespan. This module features built-in temperature compensation, along with UART and PWM output capabilities.
MQ-4 Methane (CH_4)	To detect the presence of methane (CH_4) gas in the air. It operates on the principle of catalytic combustion, where the methane gas reacts with oxygen in the air to produce heat and carbon dioxide. The sensor is designed to detect the presence of methane gas in concentrations as low as 100 parts per million (ppm). It can be used in various applications such as natural gas leak detection, mine safety, and indoor air quality monitoring. The sensor responds quickly and is stable over various temperatures and humidity levels.
MQ-7 Carbon Monoxide (CO)	To detect the concentration of CO in the air. A metal oxide semiconductor (MOS) sensor uses a heated metal oxide film to detect CO. The sensor has a high sensitivity to CO and can detect concentrations as low as 20 parts per million (ppm). It is commonly used in applications for indoor air quality monitoring, portable gas detection devices, and home safety systems.
MQ8 Hydrogen (H_2)	The MQ8 Hydrogen (H_2) gas sensor is popular for detecting environmental hydrogen gas concentrations. The MQ8 sensor uses a metal oxide semiconductor, typically tin dioxide (SnO_2). When hydrogen gas comes in contact with the sensor, the resistance of the sensor changes. This change in resistance can be measured and correlated to the concentration of hydrogen gas in the air.
MQ-136 Hydrogen Sulfide (H_2S)	To measure the presence of hydrogen sulfide (H_2S) in the air. It is commonly used in industrial and environmental monitoring applications, such as sewage treatment plants, oil refineries, and chemical manufacturing facilities, to monitor dangerous levels of H_2S gas. The sensor typically produces an output voltage or current proportional to the concentration of H_2S in the air. It can be connected to a control system or data logger for monitoring and recording.
DHT 11 Temperature and Humidity	To monitor the temperature and humidity of the mine site to detect any changes that can create a problem with the ventilation system or mine infrastructure.

Step 5: If the current minute falls within the intervals 03-18 or 23-38 or 43-58 then display the sensor data. If the data surpasses predefined threshold values, then it generates an alert alarm sound.

Step 6: Send gathered sensor data using the LoRa module

Step 7: Store the data in the SD card module if the receiver receives the acknowledgment or response.

The flowchart of the RTEPMS receiver device setup and operation is illustrated in Figure 7 and Figure 8.

- LoRa enabled RTEPMS Receiver Setup:

Steps 1 to 5 are the same as stated in the RTEPMS Transmitter setup.

Step 6: Verify the status of internet connectivity. If the device is connected to the internet or internet access is unavailable, proceed to collect sensor data.

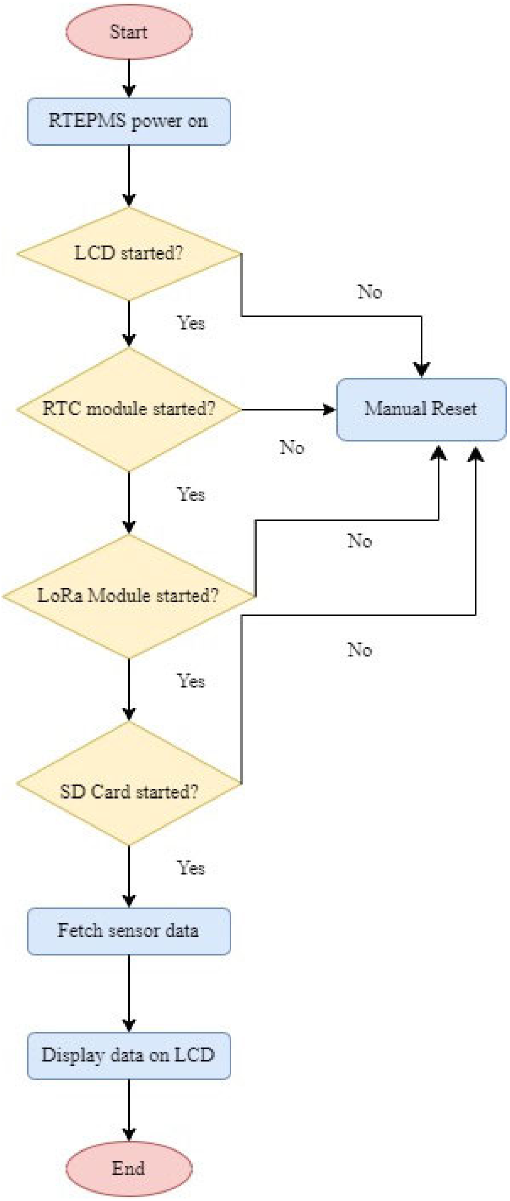


FIGURE 5. Flowchart of RTEPMS transmitter device setup.

Step 7: Display the collected data on the LCD.

- LoRa device operation cycle:

Steps 1 to 2 correspond to the procedures outlined in the RTEPMS Transmitter.

Step 3: If the data is received from the transmitter LoRa module, then send an acknowledgment or response to the transmitter

Step 4: If the current minute falls within the time intervals of 03-18 or 23-38 or 43-58, display the sensor data and generate an alert alarm sound if it exceeds the threshold limit.

Step 5: Save data to the cloud if the internet is connected, if the internet is not available, then save it to the SD card module.

Step 6: Display data on LCD

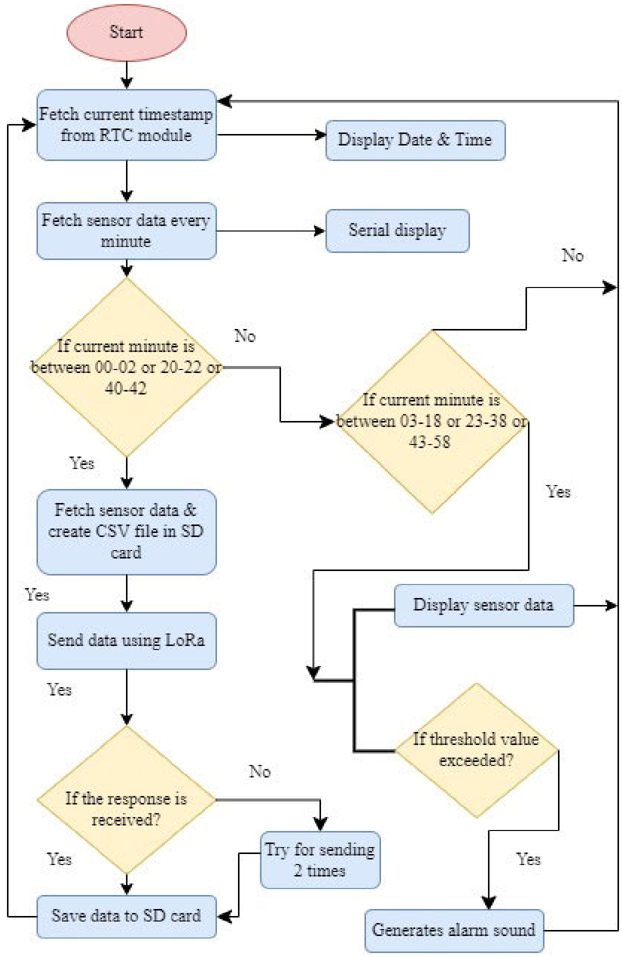


FIGURE 6. Flowchart of RTEPMS transmitter device operation.

Step 7: The process repeats for every fetched sensor data from Step 2

C. SCHEMATIC REPRESENTATION OF RTEPMS TRANSMITTER AND RECEIVER

A schematic representation of an RTEPMS transmitter and receiver section includes an ESP32 development board with a LoRa transceiver module and the necessary components as shown in Figure 9 and Figure 10. The LoRa transmitter section is integrated with an ESP 32 microcontroller, HPD13A LoRa Module, RTC Module, SD card Module, 16 × 4 LCD Display, Sensor sockets, External antenna and Power supply unit. The sensors are MH-Z19C (CO_2 gas) sensor, MQ-4 (CH_4 gas) sensor, MQ-7 (CO gas) sensor, MQ-8 (H_2 Gas) sensor, MQ-136 (H_2S gas) sensor and DHT 11/22 Temperature and Humidity sensor [37]. The LoRa transceiver module is designed to transmit and receive data using the LoRa protocol. The system comprises analog sensors (MQ-4, MQ-7, MQ-8, and MQ-136), an ESP32 development board, an LCD, and a digital MHZ19 CO_2 sensor, all operating on a 5V power supply. On the other hand,

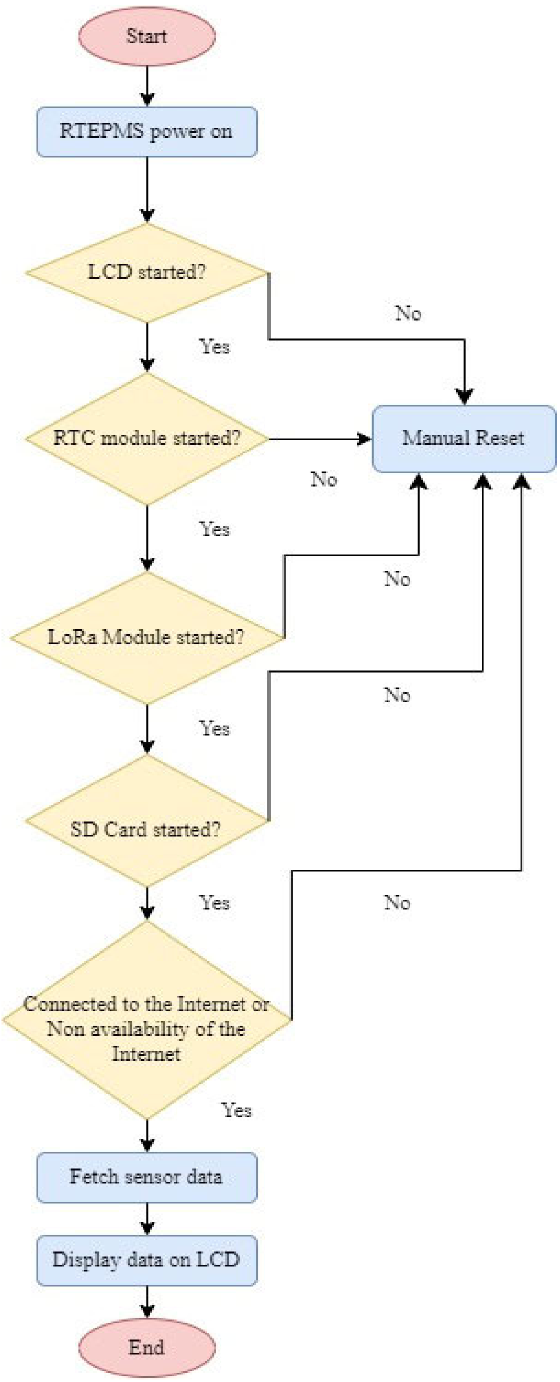


FIGURE 7. Flowchart of RTEPMS receiver device setup.

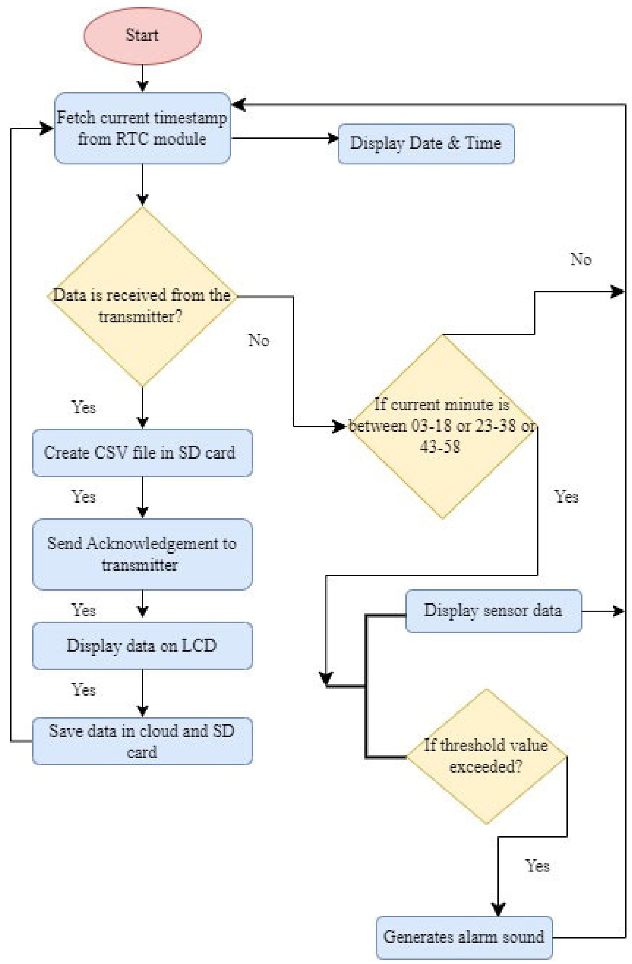


FIGURE 8. Flowchart of RTEPMS receiver device operation.

the 868 MHz LoRa module, DS1307 RTC module, and SD card module require a 3.3V power source.

To manage the power supply in the RTEPMS system, there is a dedicated section equipped with essential components that include a 0.5 Amp fuse, a Power on/off switch, and an LM2596 DC-DC converter module that transforms 12V power (sourced from an external rechargeable battery connected to RTEPMS for extended operation) into a stable 5V supply. The 5V supply is distributed to power the ESP32 development board, MQ series gas sensors MQ-4, MQ-7, MQ-8, and MQ-136, LCD display, CO_2 gas sensor, and LM317 voltage regulator. The developed RTEPMS is intrinsically safe to use in underground mines.

RTEPMS incorporates four MQ series analog gas sensors, each featuring a heating element with a total consumption of approximately 800 mA (200 mA each). The LM317 voltage regulator is employed to provide these MQ gas sensors with 5V, ensuring that the voltage hovers around 4.7 or 4.8V to maintain precise current control, with the current never exceeding 1A. Additionally, an AMS1117 voltage regulator is used to take the 5V input and convert it to the 3.3V required for the LoRa module. To ensure stability in this voltage supply, capacitors are effectively employed. The LoRa receiver section is also integrated with ESP 32 microcontroller, HPD13A LoRa Module, RTC Module, SD card Module, 16 × 4 LCD Display, External antenna, and Power supply unit.

The RTEPMS transmitter connectivity details of the ESP32 development board to various components, including the LoRa module, SD card module, Buzzer, CO_2 sensor, RTC

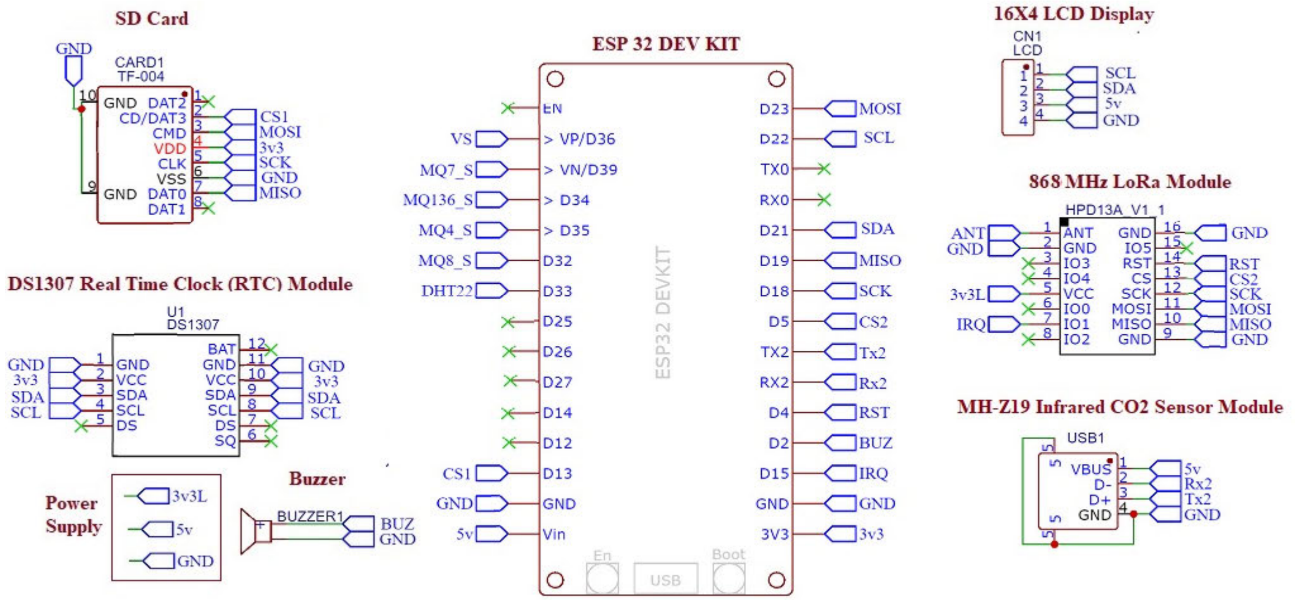


FIGURE 9. Schematic representation of transmitter section with 868 MHz LoRa transceiver module.

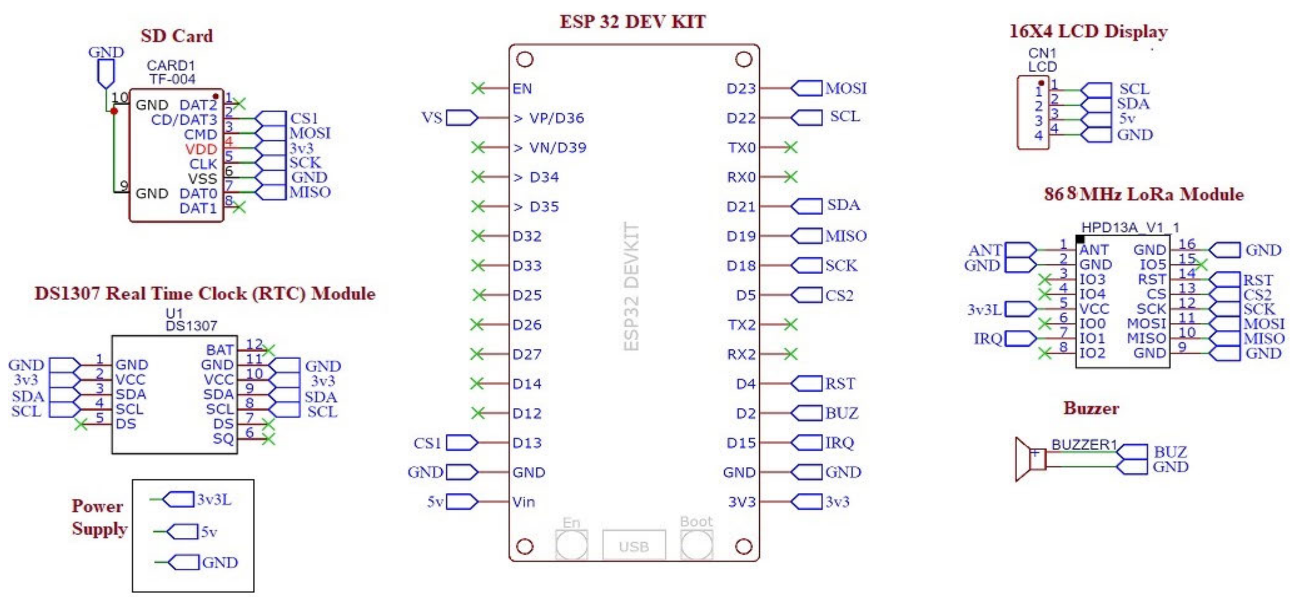


FIGURE 10. Schematic representation of receiver section with 868 MHz LoRa transceiver module.

module, and LCD, are represented in Table 4. Additionally, it illustrates the essential power supply links, connections to external sensors, and the antenna configuration. Table 5 represents the RTEPMS receiver connectivity details of the ESP32 development board to various components, including the LoRa module, SD card module, Buzzer, RTC module, and LCD.

D. SENSOR CALIBRATION

The sensitivity of analog gas sensors MQ-7, MQ-136, MQ-4, and MQ-8 relies on the heating element within the sensor package, where the heating element serves as the input while the sensing function serves as the output. Calibration for these gas sensors is established using data sheets and environmental parameters in an underground mine is measured by industry standard multi gas detector devices, which serves as the reference device. On the other hand, the DHT 11/22 is a digital sensor equipped with self-configuration capabilities based on the surrounding environmental conditions. For CO_2 gas sensors, configuration is achieved through commands to initiate operations according to the provided datasheet [6], [36].

TABLE 4. RTEPMS transmitter schematic tags connection of all components.

Tags	ESP32	LoRa module	SD card	Buzzer	CO_2 sensor	RTC module	LCD
ESP32	-	CS2 enabled MOSI MISO SCK IRQ RST	CS1 enabled MOSI MISO SCK	BUZ	RX2 TX2	SCL SDA	SCL SDA
Power supply: 5V/3.3V	5V VS	3.3V GND	3.3V GND	5V GND	5V GND	3.3V GND	5V GND
-	External Sensors: MQ7_S, MQ136_S, MQ4_S, MQ8_S, DHT22	External 6/7 dBi Antenna	-	-	-	-	-

TABLE 5. RTEPMS receiver schematic tags connection of all components.

Tags	ESP32	LoRa module	SD card	Buzzer	RTC module	LCD
ESP32	-	CS2 enabled MOSI MISO SCK IRQ RST	CS1 enabled MOSI MISO SCK	BUZ	SCL SDA	SCL SDA
Power supply: 5V/3.3V	5V GND VS	3.3V GND	3.3V GND	5V GND	3.3V GND	5V GND
-	-	External 6/7 dBi Antenna	-	-	-	-

1. Initialization of sensor pins with ESP 32 development board

#define PIN_4 35 //ESP 32 – Pin 35
#define PIN_8 39 //ESP 32 – Pin 39
#define PIN_7 32 //ESP 32 – Pin 32
#define PIN_136 34 //ESP 32 – Pin 34
#define PIN_DHT 33 //ESP 32 – Pin 33

2. Calibration factors of sensors considered based on the datasheet and with a comparison of the standard industrial multi-gas detector device

#define R04 50000
#define R08 0.28
#define R07 900
#define R0136 2500
#define V_{IN} *3.30*

- DHT temperature sensor initialization

SimpleDHT22 dht22(PIN_DHT);

- MHZ19 CO_2 gas sensor sends 9 bytes of command to initialize operation

byte cmd [9] =
{0xFF,0 × 01.0×86,0 × 00.0×00,0 × 00.0×00,0 × 00.0×79};
unsigned char response [9];
float Temp = 0, Hum = 0;

- MQ 136 (H_2S) gas sensor calibration

float MQ_136()
{
float V_{SEN}, R_S;

$$\mathrm{V_{SEN}} = \mathrm{analogRead\ (PIN\_136)} \times \frac{V_{IN}}{4095};$$

$$\mathrm{Rs} = \left(\frac{(V_{IN} - V_{SEN})}{V_{SEN}}\right) \times 20000;$$

$$\mathrm{return}\left(100 \times \mathrm{pow}\left((1.25 \times \frac{Rs}{R07}), -3.7\right)\right);$$

}

- MQ-7 (CO) gas sensor calibration

float MQ_7()
{
float V_{SEN}, R_S;

$$V_{SEN} = analogRead\ (PIN\_7) \times \frac{V_{IN}}{4095};$$

$$Rs = \left(\frac{(V_{IN} - V_{SEN})}{V_{SEN}}\right) \times 10000;$$

$$return\left(100 \times pow\left(\frac{Rs}{R07}, -1.474\right)\right);$$

}

- MQ 4 (CH_4) gas sensor calibration

float MQ_4()
{

float V_{SEN}, R_S;

$$V_{SEN} = analogRead\,(PIN\_4) \times \frac{V_{IN}}{4095};$$

$$Rs = \left(\frac{(V_{IN} - V_{SEN})}{V_{SEN}}\right) \times 10000;$$

$$return\left(100 \times pow\left(\frac{Rs}{R04}, -3.84\right)\right);$$

}

- MQ 8 (H_2) gas sensor calibration

```
float MQ_8()
 {
 float VSEN, RS;
```

$$V_{SEN} = analogRead\,(PIN\_8) \times \frac{V_{IN}}{4095};$$

$$Rs = \left(\frac{(V_{IN} - V_{SEN})}{V_{SEN}}\right) \times 20000;$$

$$return\left(1000 \times pow\left(\frac{Rs}{R08}, -0.73\right)\right);$$

- MHZ19 Carbon dioxide gas sensor is a digital sensor has a controller that control the value (Self calibration)

```
unsigned int MHZ19()
 {
  mySerial.write(cmd,9);
  mySerial.readBytes(response, 9);
  unsigned int responseHigh = (unsigned int) response [2];
  unsigned int responseLow = (unsigned int) response [3];
  return (float)((256×responseHigh)+responseLow);
 }
```

- DHT 22 Temperature and Humidity is a digital sensor has a controller that control the value (Self calibration)

```
void DHT()
 {
  int err = SimpleDHTErrSuccess;
  if ((err = dht22.read2(&Temp, &Hum, NULL)) != SimpleDHTErrSuccess)
  {
  Serial.print("Read DHT22 failed, err=");
  Serial.print(SimpleDHTErrCode(err));
  Serial.print(",");
  Serial.println(SimpleDHTErrDuration(err));
  delay(2000);
  return;
  }
  float Temp = (float)Temp;
  float Hum = (float)Hum;
  }
```

E. PORTABLE HPD13A - SX1276 LORA BASED RTEPMS

The RTEPMS transmitter and receiver sections of PCB components are enclosed in enclosures. The external view of portable LoRa based RTEPMS transmitter and LoRa receiver as shown in Figure 11 and Figure 12. The inner view of portable LoRa based RTEPMS transmitter and LoRa receiver (LoRa SX1276 HD13A mounted on a PCB) as shown in Figure 13 and Figure 14.

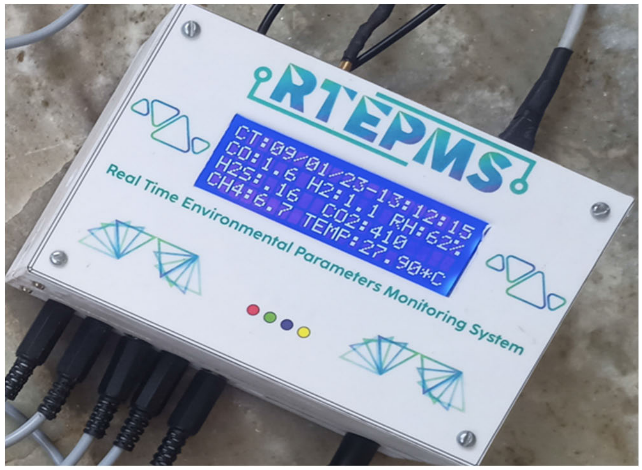


FIGURE 11. External view of portable RTEPMS LoRa transmitter.

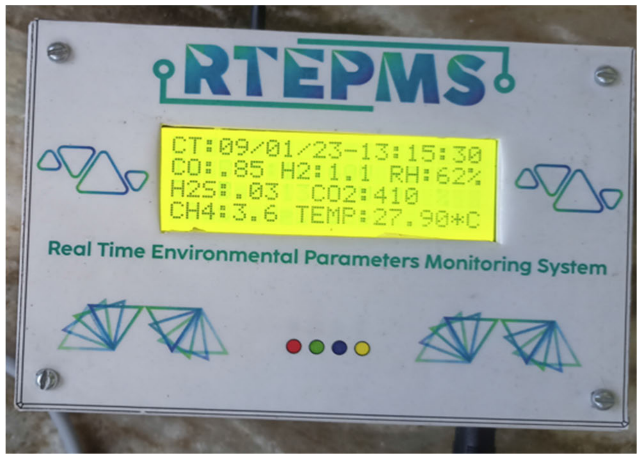


FIGURE 12. External view of portable RTEPMS LoRa receiver.

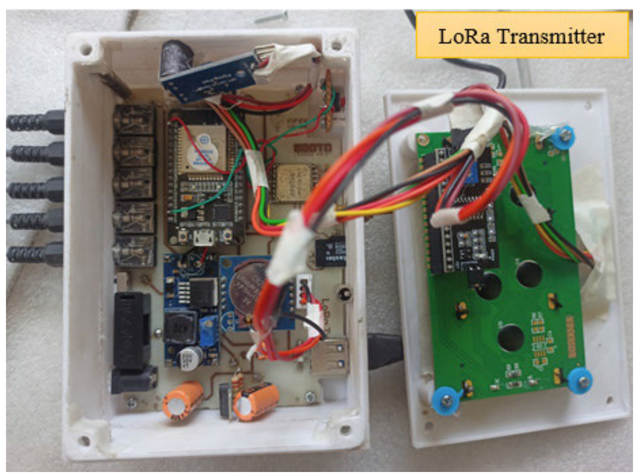


FIGURE 13. Inner view of portable RTEPMS LoRa Transmitter (LoRa SX1276 HD13A mounted on a PCB).

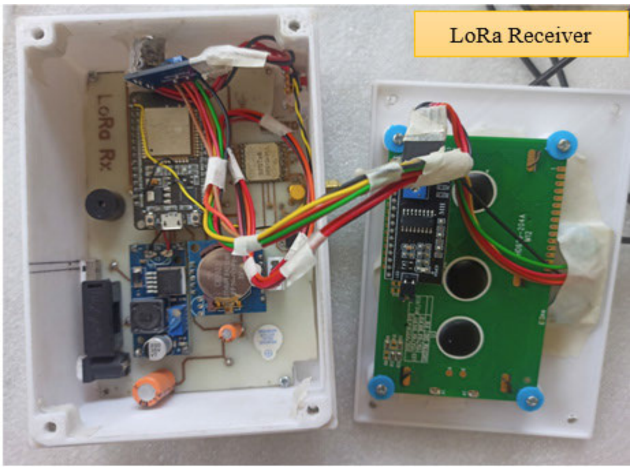


FIGURE 14. Inner view of portable RTEPMS LoRa Receiver (LoRa SX1276 HD13A mounted on a PCB).

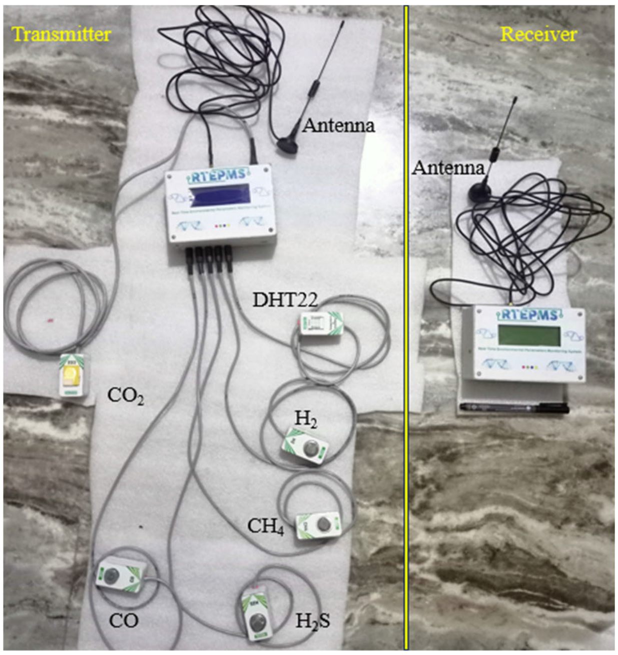


FIGURE 15. Transmitter section: Sensors and development board integration with HPD13A - SX1276 and 868 MHz LoRa transmitter module. Receiver section: Integration of development board with HPD13A - SX1276 and 868 MHz LoRa receiver module.

The developed portable RTEPMS transmitter and receiver with the integration of sensors and development board, HPD13A - SX1276 (868 MHz) LoRa module, and power supply unit are shown in Figure 15.

IV. IMPLEMENTATION OF DEVELOPED IOT-ENABLED RTEPMS WITH LORA-BASED WIRELESS COMMUNICATION SYSTEM

We provide details of the implementation of RTEPMS at the surface level and within an underground mine. In addition, details of underground mine structure and deployment locations to acquire the environmental parameters data.

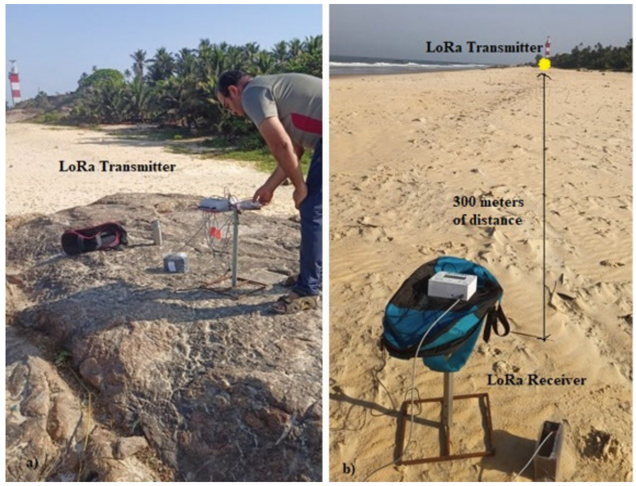


FIGURE 16. Establishment of wireless communication between RTEPMS transmitter and receiver.

A. IMPLEMENTATION OF IOT ENABLED RTEPMS WITH LORA AT THE SURFACE LEVEL

The IOT enabled RTEPMSwith LoRa module is developed, tested, and evaluated at a surface level to collect environmental parameters data in a real-time. The system was tested at different locations and achieved a wireless communication distance between transmitter and receiver of around 300 m in open space without any obstacles and with obstacles 180 to 200 m. The system is designed to store data in an SD card at both the transmitter and receiver. If the receiver has an active internet connection, then the LoRa receiver module transmits the sensor data to the open source Thingspeak cloud server. The establishment of wireless communication between RTEPMS with LoRa based transmitter and RTEPMS receiver is represented in Figure 16.

B. MEASUREMENT OF ENVIRONMENTAL PARAMETERS USING MULTI-GAS DETECTOR IN AN UNDERGROUND MINE

Portable hand-held multi-gas detectors are used to measure environmental parameters in one of the underground mines in India. Three distinct multi-gas detectors collectively measure nine specific gases. The first detector evaluates levels of O_2, CO_2, H_2S, SO_2, and CH_4. The second is dedicated to measuring NO and NO_2, while the third exclusively detects EO levels. All multi-gas detectors are periodically calibrated and measure environmental parameters on a shift basis. The multi-gas detectors and the place to update the gas parameters are shown in Figure 17.

C. IMPLEMENTATION OF RTEPMS WITH LORA BASED WIRELESS COMMUNICATION SYSTEM IN AN UNDERGROUND MINE

The real-time monitoring of environmental parameters within underground mines involves the integration of communication modules and sensors. An experimental investigation was

FIGURE 17. (a) Multi-gas detector device, (b) Board to display gas parameter.

carried out in Level 26 of an underground mine, situated at a depth of 832 meters below the surface, as depicted in Figure 18. The establishment of wireless communication between the transmitter and receiver of the RTEPMS using LoRa transceiver modules in Level 26 is visualized in Figure 19.

The layout of Level 26 in the underground mine exhibits various key elements, including mine tunnels, rock break chambers, shafts, underground mine passages, and ventilation fans. The RTEPMS transmitter successfully transmits collected environmental parameter data to the receiver, covering distances of 180 to 200 m within straight tunnels, with a gradual decrease in signal strength and occasional data packet loss occurring in curved sections of the underground mine tunnels. The experimental configuration of the RTEPMS, featuring LoRa-based transmitters and receivers on Level 26 of the underground mine, is illustrated in Figures 20 and 21.

V. EXPERIMENTAL RESULTS

We briefly describe environmental parameters collected from a surface level using an IoT-enabled RTEPMS with LoRa Module and from an underground mine using RTEPMS with LoRa Module. In addition, we discussed a comparison of data collected from an underground mine using a multi-gas detector device and a LoRa-based RTEPMS wireless communication system. The wireless communication distance between RTEPMS-based LoRa transmitter and receiver at the surface level and underground mine is described in Table 6 and Table 7, respectively.

A. DATA ANALYSIS OF ENVIRONMENTAL PARAMETERS COLLECTED FROM A SURFACE LEVEL USING AN IOT ENABLED RTEPMS WITH LORA MODULE

Once successful wireless communication is established between RTEPMS based LoRa transmitter and receiver, the receiver LoRa module uploads the sensor data to the Thingspeak cloud server. This sensor data can be monitored and accessed on the Thingspeak cloud server in real-time and also in the serial monitor. Moreover, Thingspeak private view provides the sensor data in a graphical format. The graphical representation of individual environmental parameters CO gas, CO_2 gas, CH_4 gas, H_2S gas, H_2 gas, Temperature

TABLE 6. Experimental results of communication distance between LoRa nodes in different scenarios at surface level.

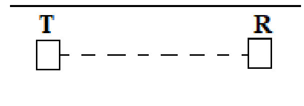
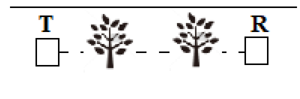
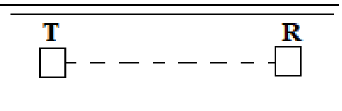
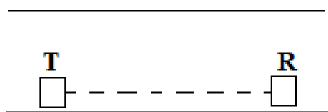
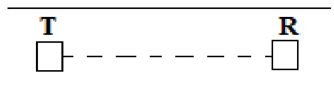
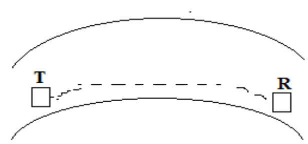
LoRa node deployment	Communication distance	Surface Level
Line of Sight (LOS) without any obstacles between Transmitter (T) and Receiver (R)	300 m	
Non line of sight (NLOS) with an obstacles between Transmitter (T) and Receiver (R)	180 to 200 m	

TABLE 7. Experimental results of communication distance between LoRa nodes at different scenarios in underground mines.

LoRa node deployment	Communication distance	Underground Mine (Tunnel plan view)
Straight tunnel (Center axis) with LOS	180 to 200 m	
Straight tunnel on the wall with LOS	190 to 200 m	
Straight tunnel on the floor with LOS	170 to 180 m	
Curved tunnel with NLOS	125 to 130 m	

and Humidity as shown in Figure 22, Figure 23, Figure 24, Figure 25, Figure 26, Figure 27 and Figure 28 respectively. Users also have the option to export the uploaded sensor data from the Thingspeak server in CSV file format through the data import/export function to perform data analysis.

B. DATA ANALYSIS OF ENVIRONMENTAL PARAMETERS COLLECTED FROM AN UNDERGROUND MINE USING RTEPMS WITH LORA MODULE

The environmental parameters are collected from a real-time RTEPMS with LoRa module in an underground mine. Table 8 describes the dataset statistics of environmental parameters.

The gas parameter concentrations are depicted in a time series chart to examine variations in gas parameter levels. The concentration of CO_2 gas measured by the RTEPMS-based LoRa device is represented in Figure 29. The periodic rise

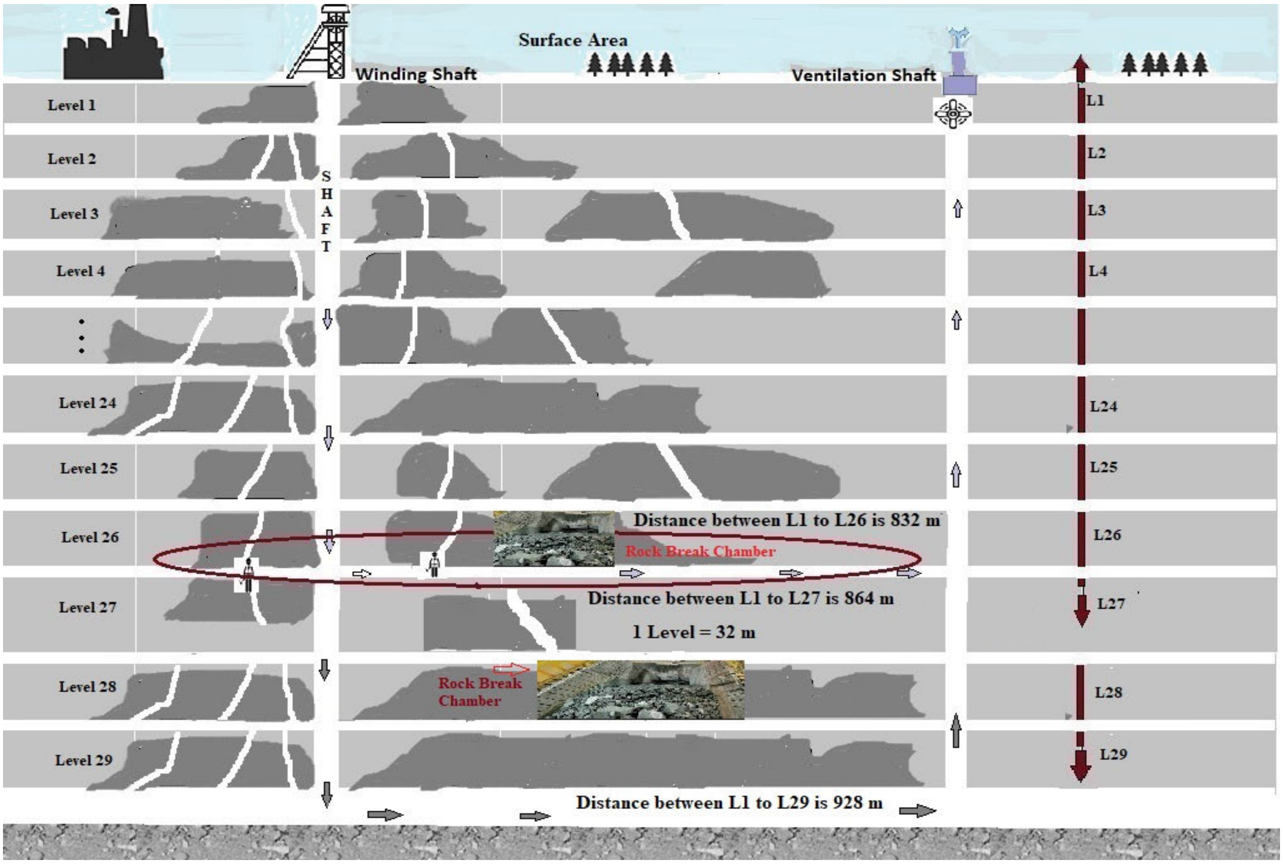


FIGURE 18. Visualization of an underground mine infrastructure.

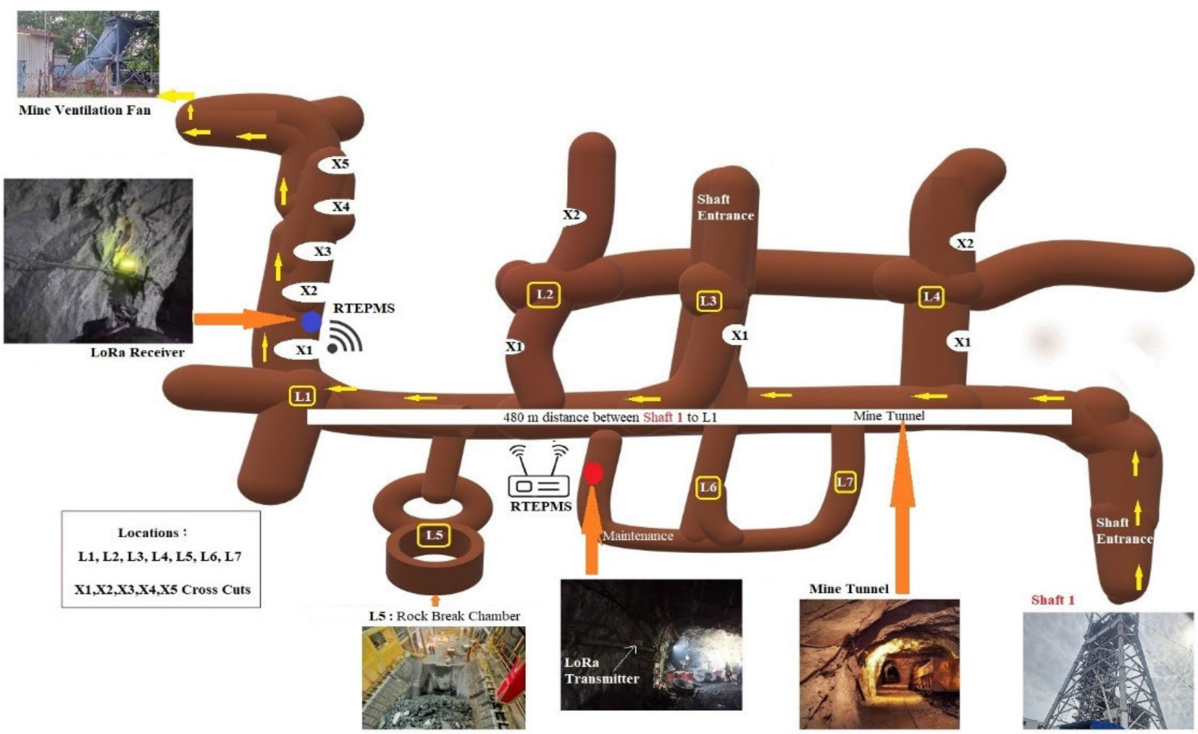


FIGURE 19. Layout view of level 26 of the underground mine infrastructure.

FIGURE 20. RTEPMS with LoRa transmitter deployment at level 26 of the underground mine.

FIGURE 21. RTEPMS with LoRa receiver deployment at level 26 of the underground mine.

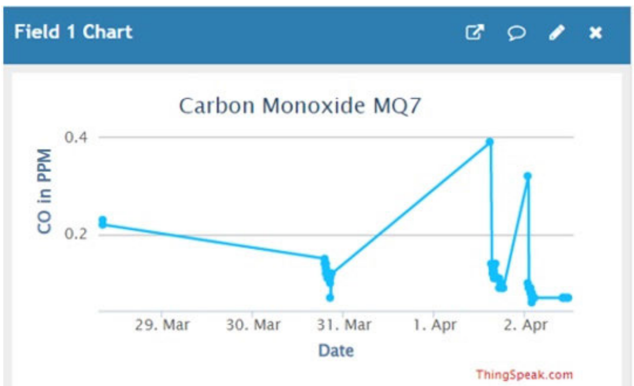


FIGURE 22. CO gas monitoring over the Internet using ThingSpeak.

in CO_2 gas levels above the baseline can be attributed to the movement of diesel-operated LHD vehicles. Diesel combustion releases a significant amount of CO_2, and the peaks in the graph likely correspond to times of increased vehicle activity. The consistent rise above the baseline indicates that diesel-operated vehicle movement has a noticeable impact on CO_2 levels.

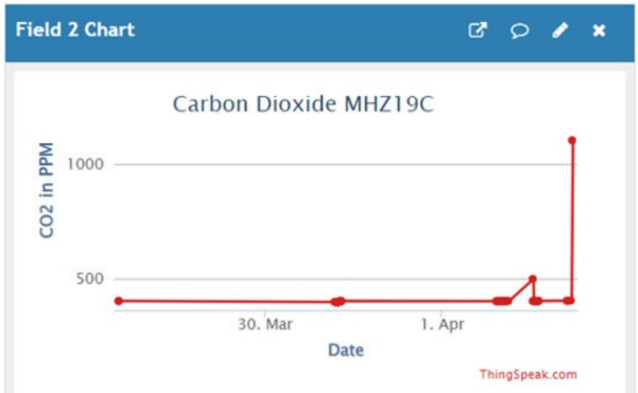


FIGURE 23. CO_2 gas monitoring over the Internet using ThingSpeak.

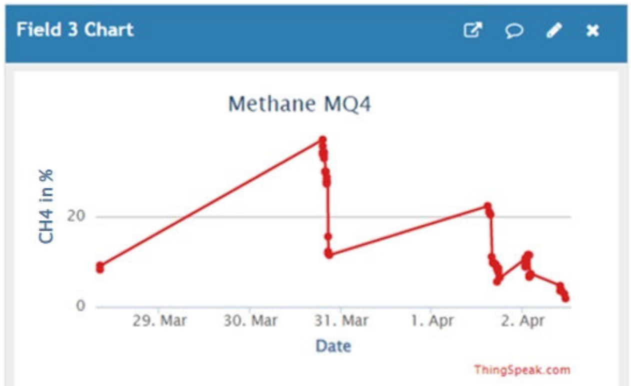


FIGURE 24. CH_4 gas monitoring over the Internet using ThingSpeak.

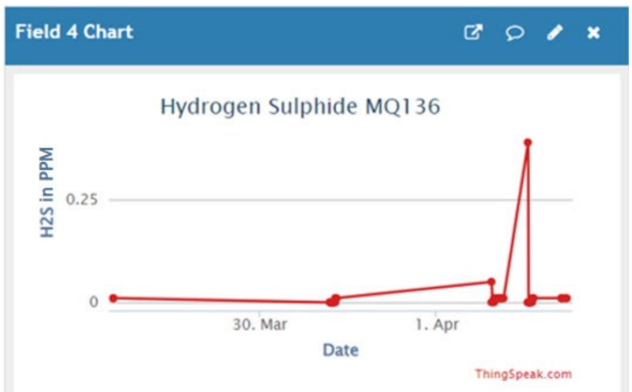


FIGURE 25. H_2S gas monitoring over the internet using ThingSpeak.

The concentration of CH_4, H_2S, and H_2 gas measured by the LoRa-based RTEPMS is represented in Figure 31. CO levels show a clear periodic pattern similar to CO_2, suggesting it is also influenced by diesel-operated LHD vehicle movement. CH_4, H_2S, and H_2 levels are relatively low, with minor fluctuations. The periodic fluctuations in temperature and humidity suggest that the mine's ventilation system is working efficiently. Temperature and Humidity parameters measured by the LoRa device are represented in Figure 32.

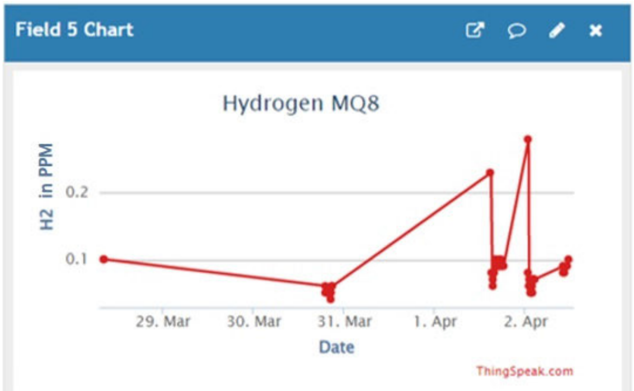


FIGURE 26. H_2 gas monitoring over the Internet using ThingSpeak.

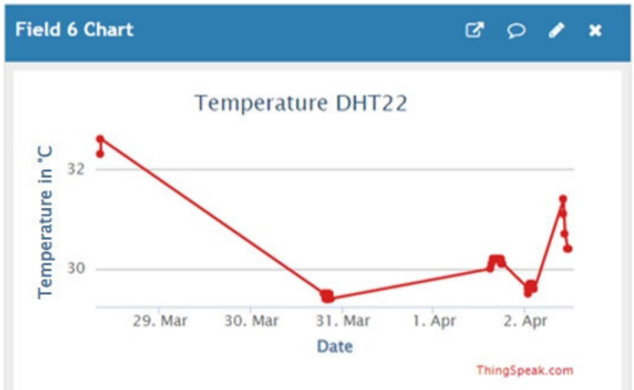


FIGURE 27. Temperature monitoring over the internet using ThingSpeak.

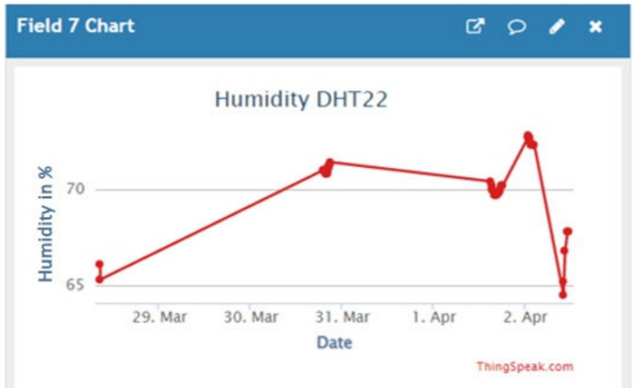


FIGURE 28. Humidity monitoring over the Internet using ThingSpeak.

Proper ventilation is crucial in underground mines to regulate temperature and ensure the removal of harmful gases. High humidity and high temperatures can be uncomfortable and even dangerous for miners. Prolonged exposure to such conditions can lead to heat stress or other heat-related illnesses. The inverse relationship observed between temperature and humidity is a positive sign in this context, as it means that when the temperature is high, the relative humidity is lower, potentially reducing the risk of heat-related issues. An underground mine with a 26^{th} level, where the data is collected at a depth of 832 m from the surface and considering all the parameters (CO_2, CO, H_2S, H_2, CH_4, Temperature, and Humidity).

The concentration of CO gas measured by LoRa-based RTEPMS in an underground mine at level 26 located at 832 m distance from the surface is represented in Figure 30.

1) GAS CONCENTRATIONS

- CO_2: The periodic fluctuations in CO_2 levels, especially those above the baseline of 400 ppm, are likely influenced by diesel-operated machinery and LHD vehicles within the mine. Elevated CO_2 levels can lead to difficulty breathing and affect the miners' cognitive abilities.
- CO: The periodic spikes in CO levels suggest bursts of CO emissions, possibly from machinery or combustion processes. CO is a toxic gas. Even low concentrations can be harmful over prolonged exposure.
- H_2S: The levels of H_2S, although relatively low, are significant. H_2S is a toxic gas. Even at low concentrations, it can be harmful and has a characteristic rotten egg smell.
- H_2: Hydrogen gas suggests potential chemical reactions or processes within the mine. Hydrogen is flammable, and its accumulation can pose explosion risks.
- CH_4: Methane is a common gas in coal mines and is highly flammable. Even though the levels are low, it's crucial to monitor CH_4 continuously to prevent any explosive mixtures.

2) ENVIRONMENTAL CONDITIONS

- **Temperature**: The periodic fluctuations in temperature suggest that the mine's cooling system is working, but the depth of 864 meters means the mine is naturally warmer due to geothermal gradients and the movement of LHD vehicles. High temperatures can lead to heat stress and other health issues for miners.
- **Humidity:** The inverse relationship between temperature and humidity is a positive sign in terms of comfort. However, high humidity can affect equipment functionality and the structural integrity of the mine walls.

The combined effects of gas concentrations and environmental conditions can pose health risks to miners. Proper ventilation is crucial to remove harmful gases and regulate temperature and humidity. The underground mine at a depth of 832 m presents a challenging environment with potential risks from various gases and environmental conditions.

3) TIME SERIES REPRESENTATION OF REAL-TIME ENVIRONMENTAL PARAMETERS IN UNDERGROUND MINE

Time Series real-time data representation of environmental parameters CO_2, CO, H_2S, H_2, CH_4, Temperature, and Humidity collected from the RTEPMS system is represented in Figure 33.

The observed time series data for environmental parameter levels. It represents the actual recorded values over time.

TABLE 8. Dataset statistics of environmental parameters measured by using the LoRa device.

Parameters	CO_LoRa PPM	CO_2_LoRa PPM	CH_4_LoRa %	H_2S_LoRa PPM	H_2_LoRa PPM	Temperature in ºC	Humidity in %
count	579	579	579	579	579	579	579
mean	1.98	526.32	0.01	0.02	0.06	32.71	64.75
min	0.0	400.00	0.0	0.0	0.0	28.20	40.50
max	8.31	2000.00	1.36	3.26	1.11	36.90	84.70

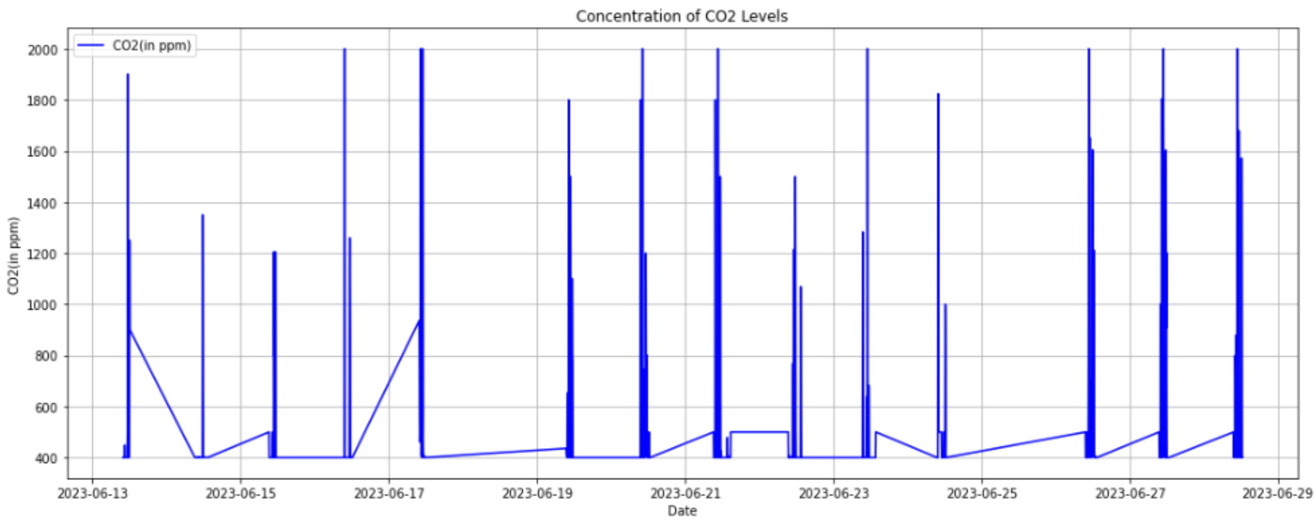


FIGURE 29. Concentration of CO_2 gas measured by LoRa-based RTEPMS.

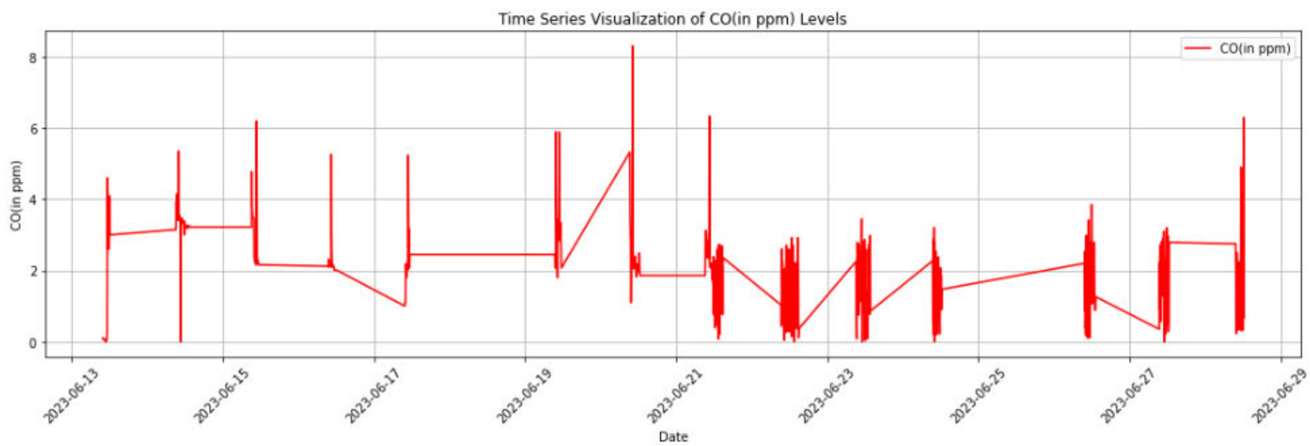


FIGURE 30. Concentration of CO gas measured by LoRa based RTEPMS.

The underground mine environment is relatively stable in terms of gas concentrations and environmental conditions. The clear daily patterns in most parameters suggest consistent daily activities, machinery operations, ventilation patterns, or influences on the mine's environment. The stable trends in gas concentrations are a positive sign in terms of safety, but continuous monitoring is essential to ensure that any sudden changes or anomalies are detected promptly.

C. DATA ANALYSIS OF ENVIRONMENTAL PARAMETERS COLLECTED FROM UNDERGROUND MINE USING MULTI GAS DETECTOR DEVICE AND LORA-BASED RTEPMS WIRELESS COMMUNICATION SYSTEM

The environmental parameters are collected from a multi-gas detector device and a real-time LoRa module based RTEPMS in an underground mine. The data measured using an multi gas detector once in a shift at a particular instance of time and

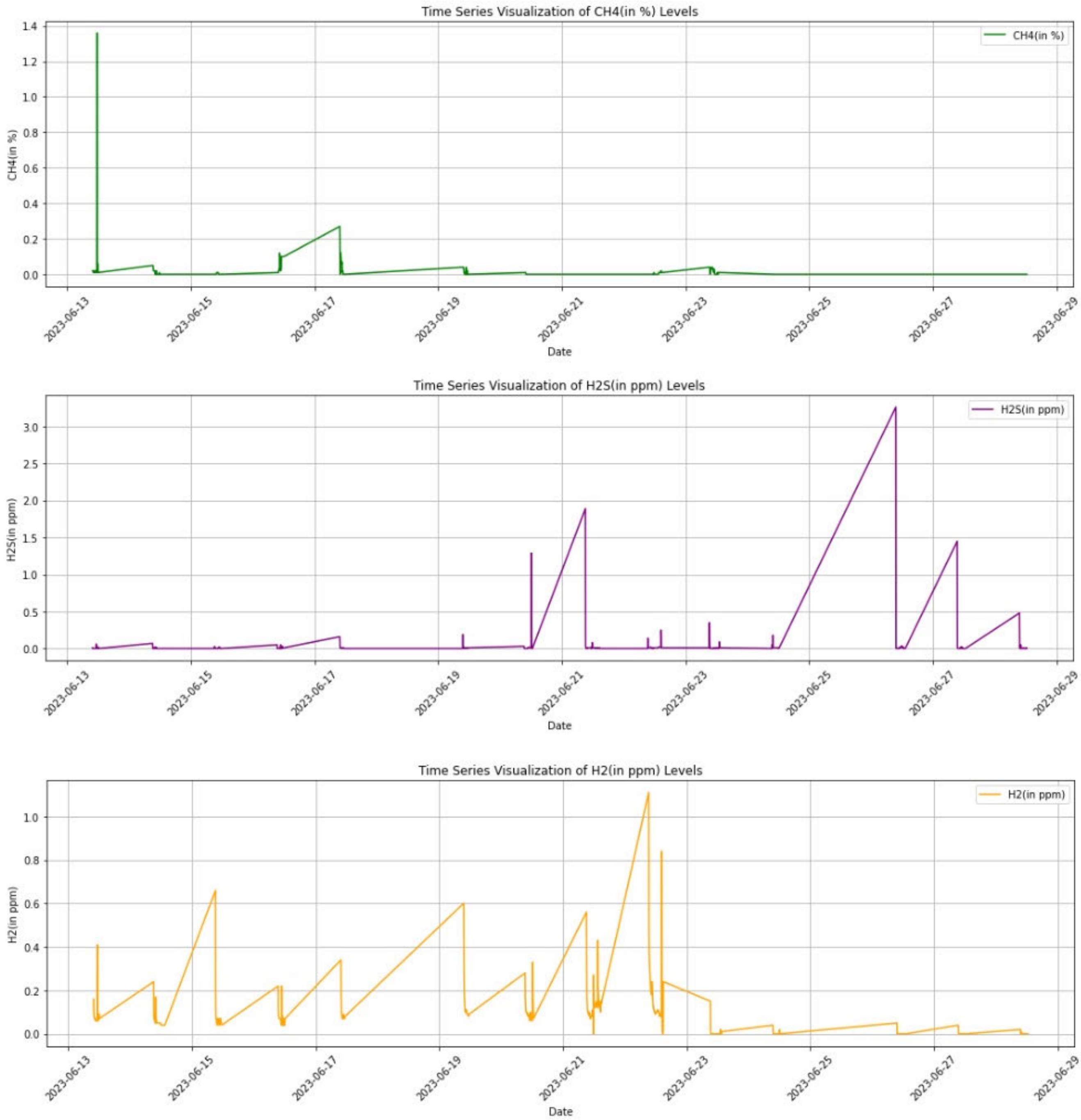


FIGURE 31. Concentration of CH_4, H_2S, H_2 gas measured by LoRa based RTEPMS.

at the same time, data collected by using RTEPMS device is illustrated in Table 9 and Table 10.

The trends and distributions observed in the Multi Gas Detector device and LoRa-based RTEPMS for similar gases (e.g., CO, CO_2) are somewhat consistent, indicating that both devices provide reliable measurements. The temperature and humidity readings from the LoRa-based RTEPMS device show typical indoor or ambient conditions, which suggests that extreme conditions (very high or low temperatures/ humidities) were not encountered during the measurement period. Comparison plots for gas parameters of both multi-gas detector and LoRa based RTEPMS device for CO PPM, CO_2 PPM, CH_4 %, H_2S PPM with date_time on x-axis is represented in Figure 34, Figure 35, Figure 36 and Figure 37, respectively. The graph represents the environmental parameters measured by multi gas

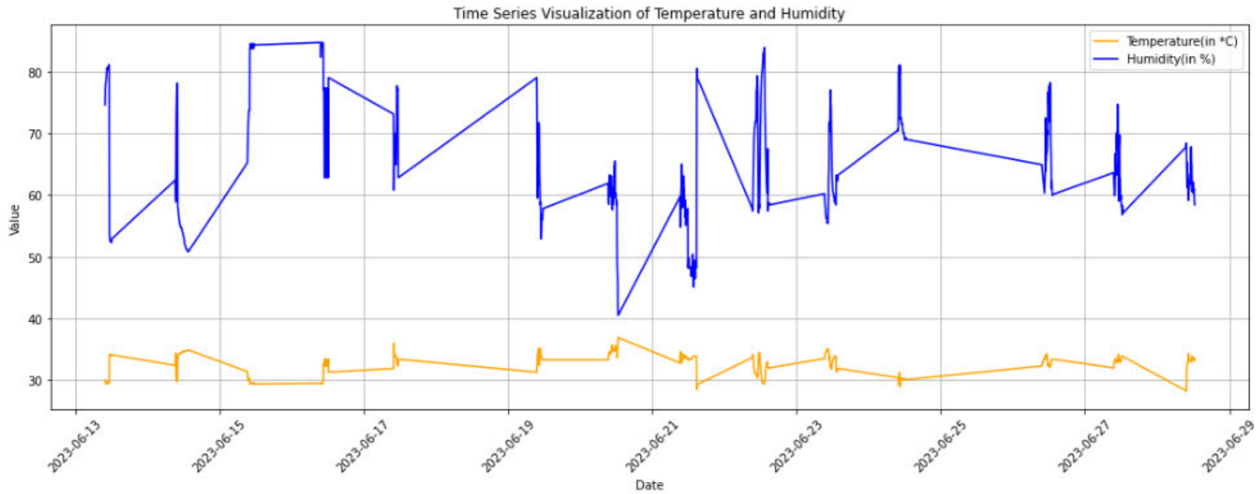


FIGURE 32. Temperature and humidity measured by LoRa based RTEPMS in an underground mine.

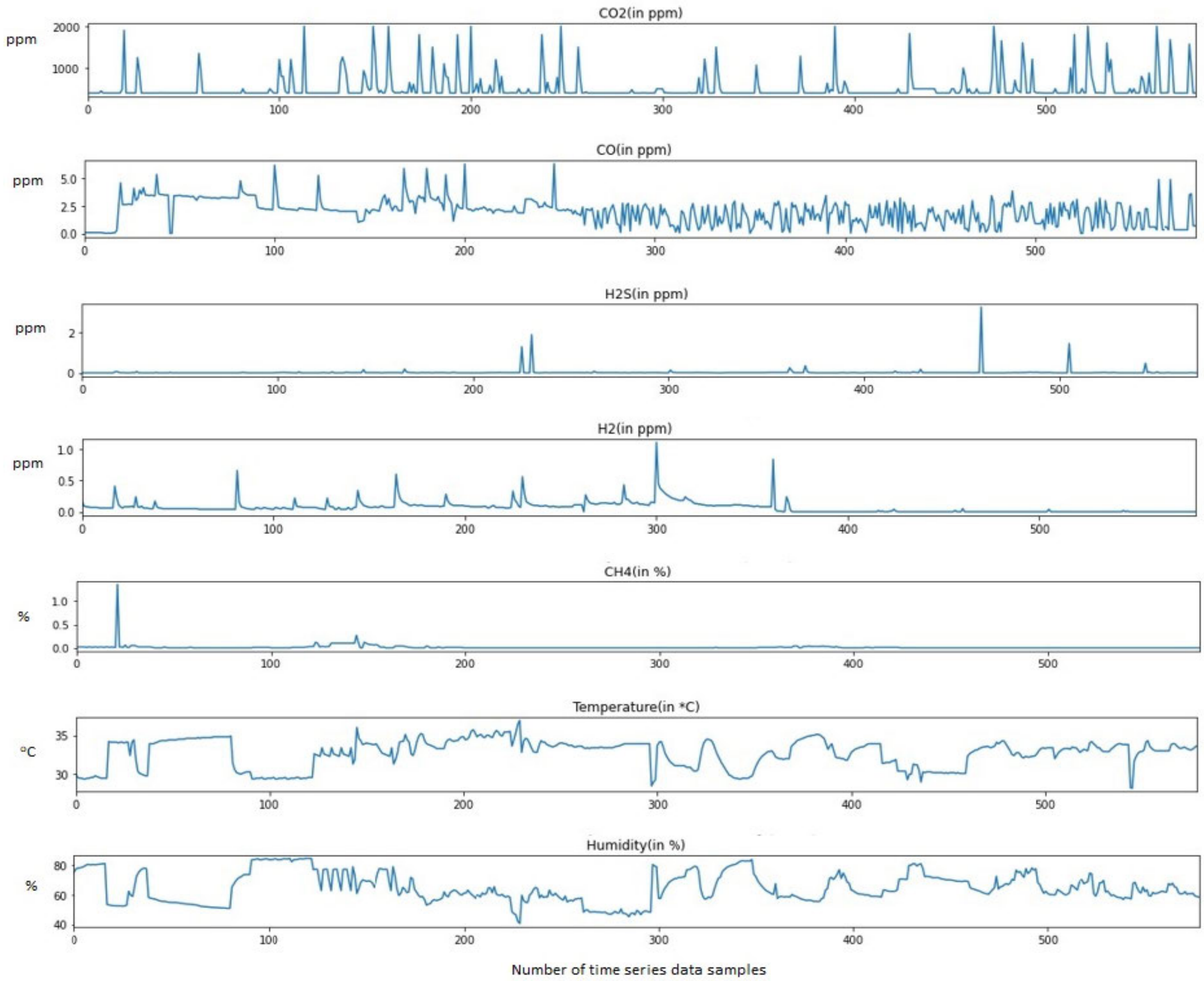


FIGURE 33. Time Series real time data representation of environmental parameters CO_2, CO, H_2S, H_2, CH_4, Temperature, and Humidity.

TABLE 9. Dataset statistics of environmental parameters measured by using the multi gas detector device.

Parameters	O_2	CO PPM	CO_2 PPM	CH_4 %	H_2S PPM	NO PPM	NO_2 PPM	SO_2 PPM	EO PPM
count	80	80	80	80	80	80	80	80	80
mean	20.88	3.07	1491.25	0.0	0.0	2.97	0.25	0.13	3.31
min	20.40	0.0	500.0	0.0	0.0	0.0	0.0	0.0	0.0
max	20.90	18.00	5600.00	0.0	0.0	10.40	4.50	1.00	20.00

TABLE 10. Dataset statistics of environmental parameters measured by using the LoRa based RTEPMS.

Parameters	CO_LoRa PPM	CO_2_LoRa PPM	CH_4_LoRa %	H_2S_LoRa PPM	H_2_LoRa PPM	Temperature in ºC	Humidity in %
count	80	80	80	80	80	80	80
mean	2.38	1135.50	0.01	0.01	0.05	32.95	67.71
min	0.0	400.00	0.0	0.0	0.0	29.30	52.90
max	8.31	2000.00	0.27	0.18	0.34	35.10	84.00

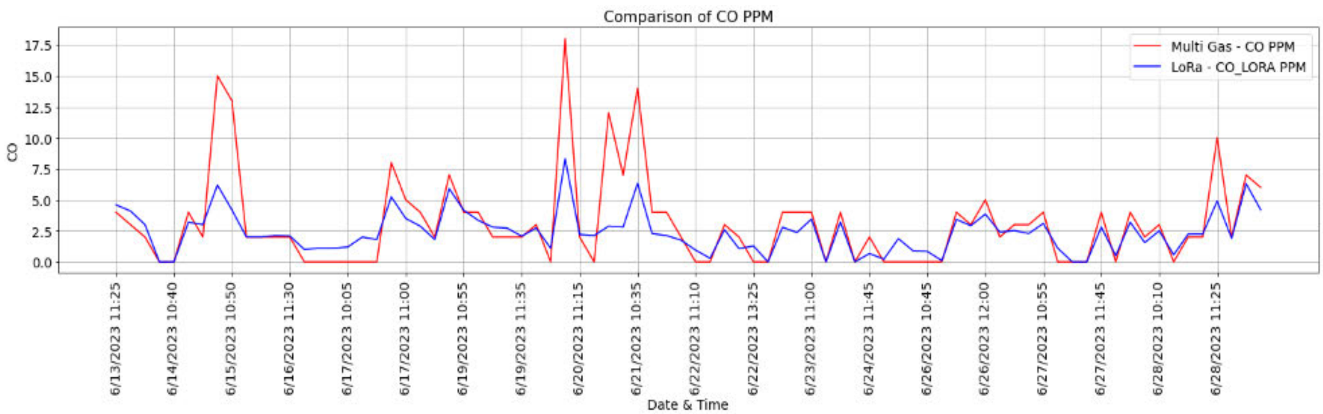


FIGURE 34. Comparison of multi gas detector CO (PPM) with LoRa based RTEPMS device CO (PPM).

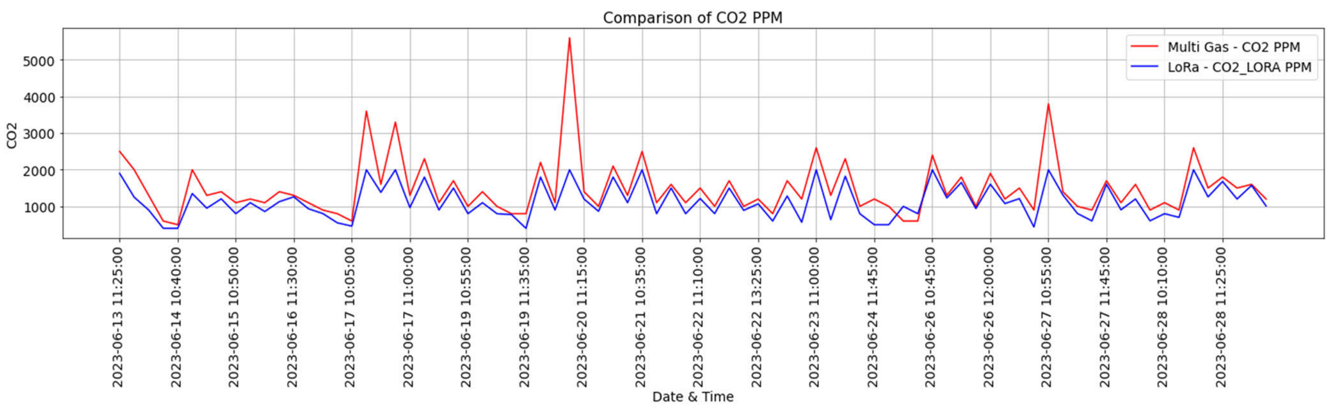


FIGURE 35. Comparison of multi gas detector CO_2 (PPM) with LoRa based RTEPMS device CO_2 (PPM).

detectors and LoRa based RTEPMS device at the same time.

Observations from the plots:

- CO(PPM): Both devices show similar trends, with some variations in the measurements.
- CO_2(PPM): The trends are consistent between the two devices, but the LoRa device tends to measure slightly higher values in some instances.
- CH_4 (%): Both devices consistently measure a value of 0% for CH_4 across all data points.

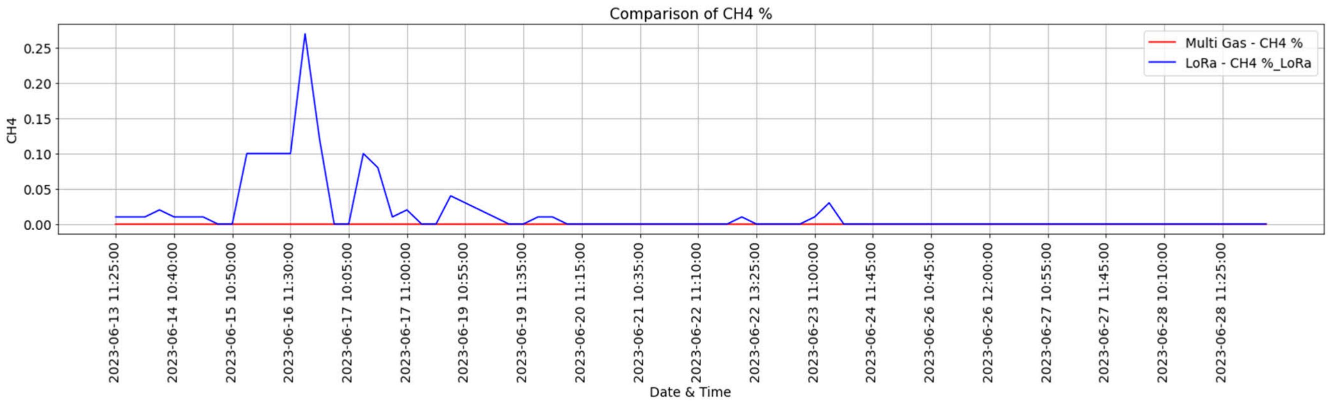


FIGURE 36. Comparison of multi gas detector CH_4 (%) with LoRa based RTEPMS device CH_4 (%).

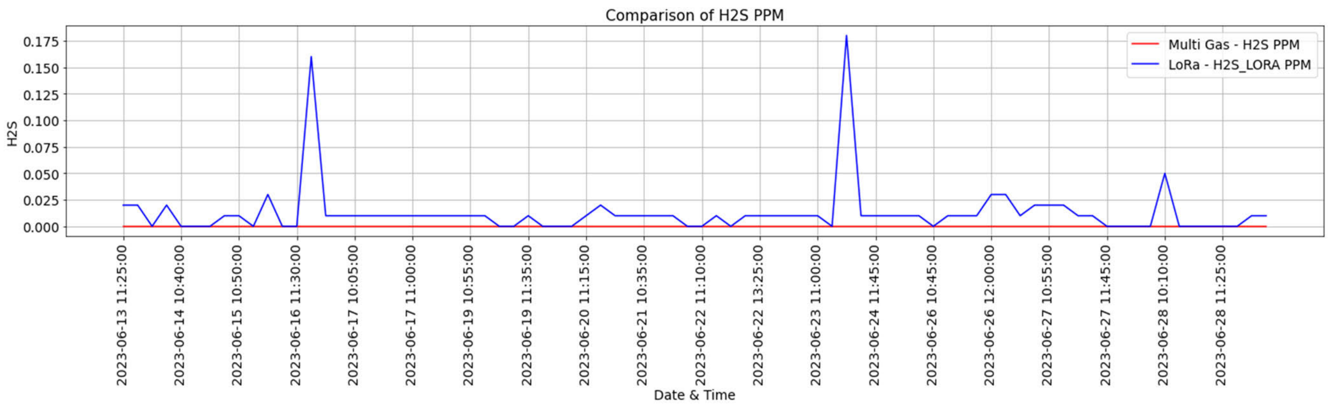


FIGURE 37. Comparison of multi gas detector H_2S (PPM) with LoRa based RTEPMS device H_2S (PPM).

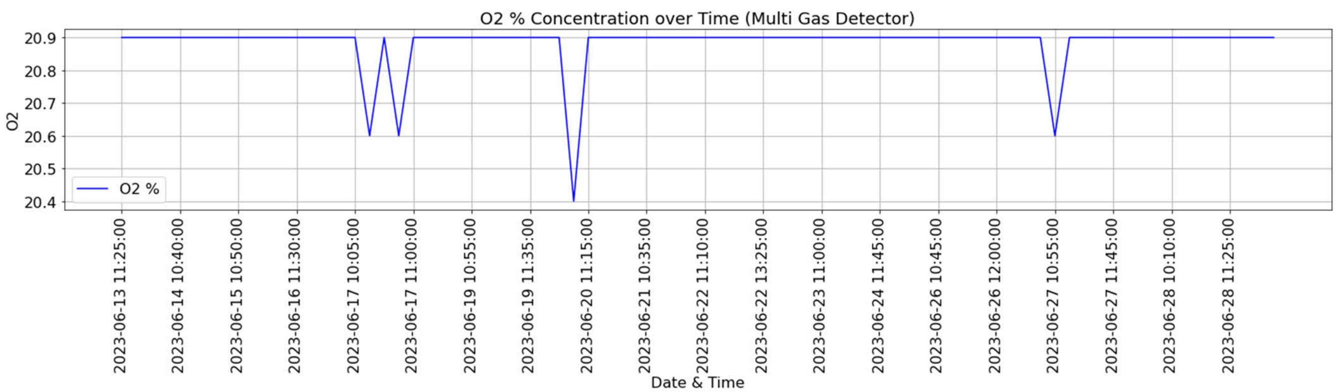


FIGURE 38. Concentrations of O_2 measured by using multi gas detector.

- H_2S (PPM): Both devices consistently measure a value of 0 PPM for H_2S across all data points.

The x-axis represents the date and time (Timestamp) and the y-axis represents the measurement values for each parameter.

D. COMPARISON OF O_2 GAS WITH CO_2, CO, AND EO GAS PARAMETERS MEASURED USING MULTI GAS DETECTORS

In an underground mine, increased gas concentrations like CO_2, CO, and EO typically reduce O_2 levels, represented in Figure 38, Figure 39, Figure 40, and Figure 41, respectively.

Regression analysis of CO_2 gas parameters measured using the Multi-Gas Detector device and the LoRa device are repre-

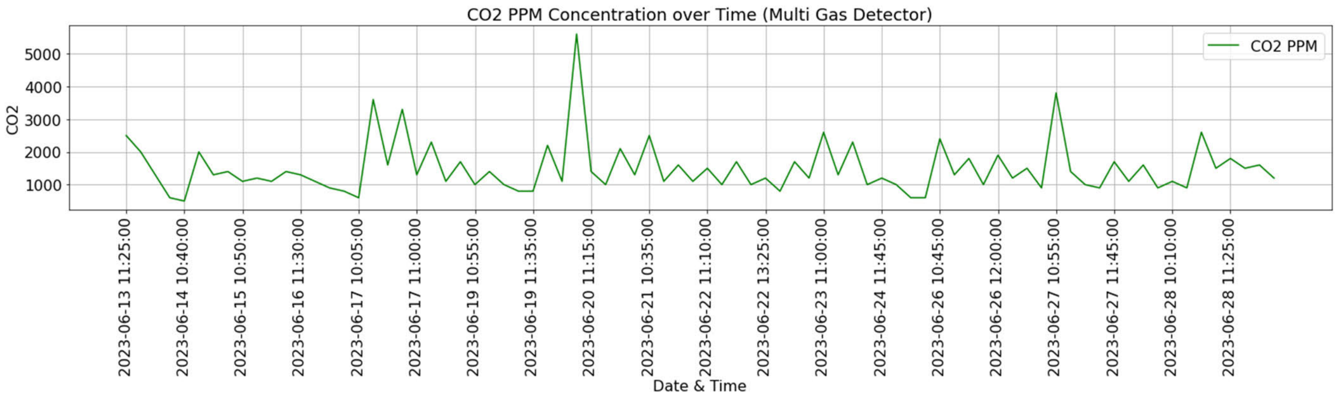


FIGURE 39. **Concentrations of CO_2 measured by using multi gas detector.**

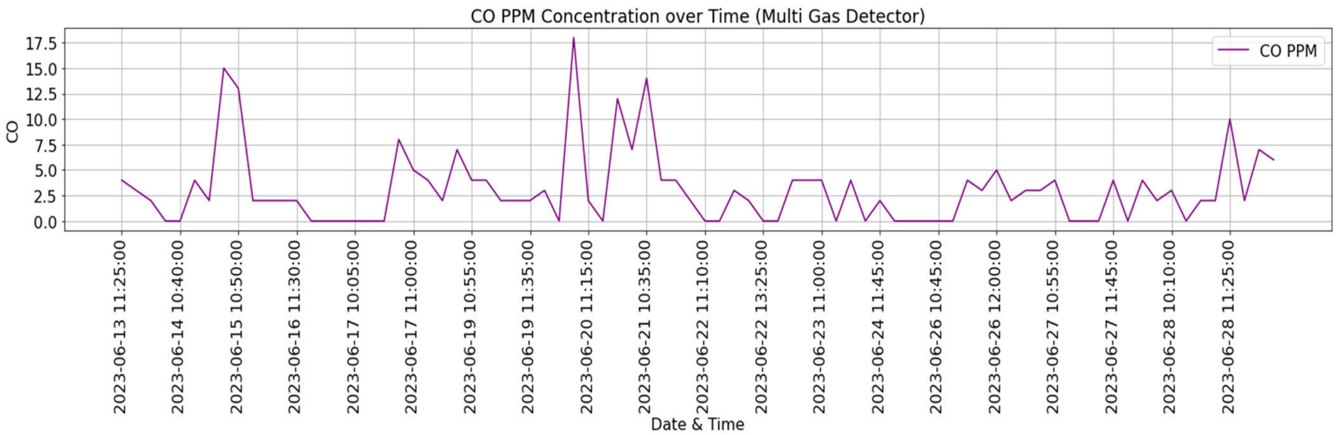


FIGURE 40. **Concentrations of CO measured by using multi gas detector.**

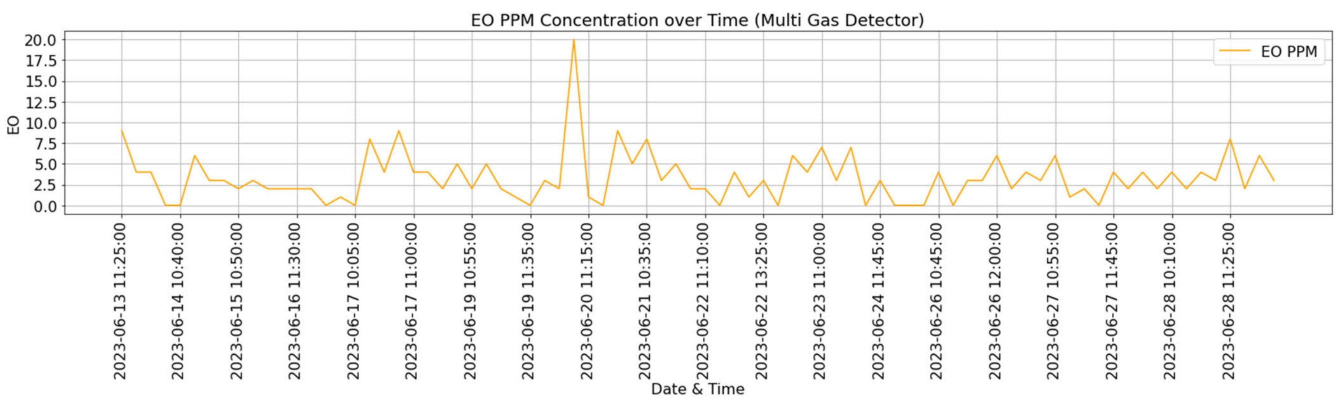


FIGURE 41. **Concentrations of EO measured by using multi gas detector.**

sented in Figure 42. The data (blue dots) represent the actual data points, and the red line is the regression line that best fits the data. Correlation Coefficient: 0.8335 indicates a strong positive linear relationship between the CO_2 measurements from the two devices. R-squared Value: 0.6947. This means that approximately 69.47% of the variance in the CO_2_LORA PPM can be explained by the CO_2 PPM from the Multi Gas Detector.

Regression analysis of CO gas parameters measured by using the Multi-Gas Detector device and the LoRa device are

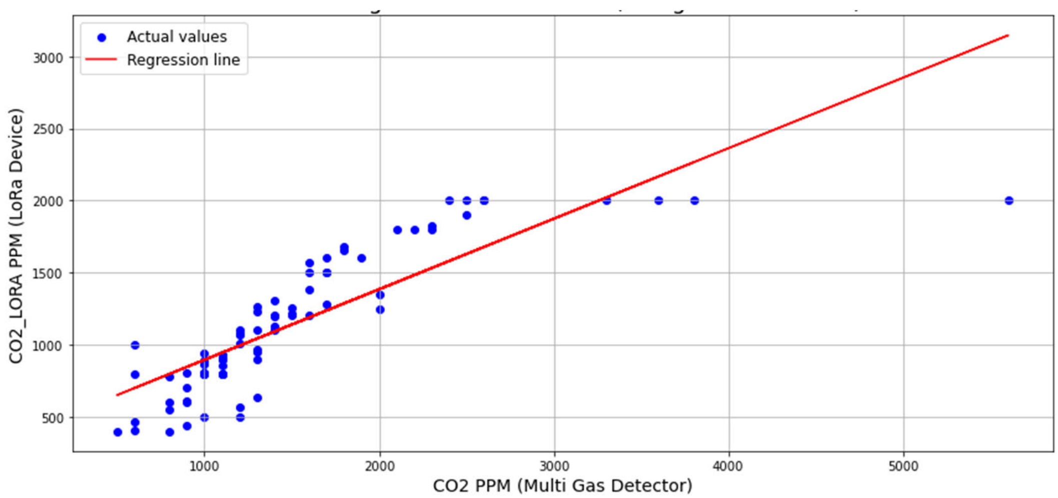


FIGURE 42. Regression plot of CO_2 measurements from the two devices.

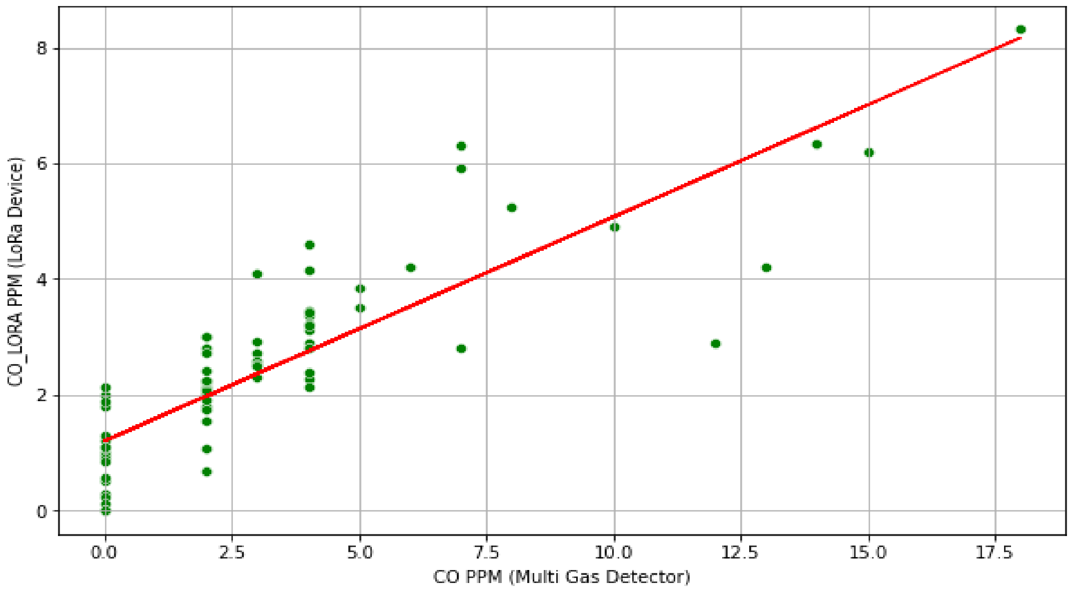


FIGURE 43. Regression plot of CO measurements from the two devices.

represented in Figure 43. The data (green dots) represents the actual data points, and the red line is the regression line that best fits the data. The regression analysis for CO measurements with a correlation coefficient of 0.8508 indicates a strong positive linear relationship between the CO measurements from the two devices. A value closer to 1 suggests that the measurements from the two devices are closely related. R-squared Value of 0.7238. This means that approximately 72.38% of the variance in the CO_LORA PPM can be explained by the CO PPM from the Multi Gas Detector. This high R-squared value indicates that the regression model provides a good fit for the observed data. The CO measurements from the two devices show a strong positive correlation, suggesting that they increase or decrease together. The regression model captures a significant portion of the variability in the CO_LORA PPM measurements based on the CO PPM measurements. The close alignment of most data points with the regression line indicates consistent measurements between the two devices for CO gas. CH_4 measurements and H_2S measurements both the Multi Gas Detector and the LoRa-based device consistently measure a value of 0% for CH_4 across all data points. This indicates the absence of CH_4 gas in the mine environment during the measurement period. Similarly, both devices consistently measure a value of 0 PPM for H_2S across all data points, suggesting the absence of H_2S.

VI. LIMITATIONS

The limitation of LoRa based RTEPMS wireless communication system is data packet drops due to weak signal strength in non-line of sight. Additionally, the system is equipped with different analog and digital sensors. The gas sensors consume more power and few are preheated before being deployed in a mine site. Furthermore, harsh environments and extremely bad weather conditions can damage the sensors and other components, leading to communication failure. The installation of LoRa based wireless communication technology is not feasible for prolonged periods in underground mines.

VII. CONCLUSION AND FUTURE WORK

In the underground mining industry, it's essential to have a system that monitors environmental parameters in real-time. This is crucial for identifying and managing potential hazards during mining activities. The adoption of wireless communication technology and IoT in mining operations would be advantageous for mine workers and organizations to increase safety and avoid accidents in underground mines. The gas parameters such as O_2, CO, CO_2, CH_4, H_2S, NO, NO_2, SO_2, and EO in underground mines are measured by using three portable multi-gas detectors, along with a hygrometer for temperature and humidity, once in every shift. The underground mines generate hazardous gases through machinery and blast operations round the clock in three shifts daily. A continuous real-time monitoring system is required to enhance safety.

Portable LoRa module HPD13A, 868 MHz based RTEPMS device with integration of gas sensors such as CO, CO_2, CH_4, H_2S, H_2, and Temperature and humidity sensors to measure environmental parameters has been designed, developed, and tested in both open surface and one of the underground mines in India to monitor environmental parameters in real-time.

- The system is designed to store data in an SD card at the transmitter and receiver. The LoRa receiver module uploads the sensor data to the cloud Thingspeak server.
- The RTEPMS was tested at different locations on an open surface and achieved a wireless communication distance between transmitter and receiver of around 300 m in open space without any obstacles and with obstacles of 180 to 200 m.
- The wireless communication testing is carried out at the straight and curved tunnels of the underground mine at the 26th level, which is around 832 m from the surface. The experimental results show successful wireless communication of 180 m to 200 m in straight tunnels and a reduction in signal strength and data packet loss in curved tunnels of underground mines with wireless communication of 125 to 130 m.
- The gas parameters such as O_2, CO, CO_2, NO_2, and EO are major gases exceeding the mine environment's threshold limit.
- LoRa-based RTEPMS and multi-gas detector devices measure CO_2, CO, CH_4, and H_2S. The correlation for the data from both devices is 69.47% for CO_2 and 72.38% for CO, while the values for CH_4 and H_2S are nearly zero (CH_4 and H_2S gases presence are nearly zero in underground mines).
- Data analysis from the LoRa-based RTEPMS system and multi-gas detector also indicated a rise in CO_2, CO, EO, and NO_2 gas levels, decreasing O_2 levels.
- The LoRa based RTEPMS is a cost-effective solution for long-range wireless communication in low-power applications. The system alerts the mine workers if the environmental parameters exceed the threshold limit during emergencies.
- The developed system is cost-effective and energy-efficient, making it accessible to smaller, less affluent underground mines.

To address these limitations, the adoption of an IoT-enabled LoRaWAN gateway-based environmental monitoring system holds the potential to significantly enhance the productivity of underground mine personnel and organizations over an extended timeframe. Furthermore, the inclusion of a real-time monitoring dashboard in the surface control room offers a more intuitive insight into the underground mining environment. Machine learning techniques will be harnessed to analyze the collected data, identify hazardous areas, and facilitate proactive measures, thereby reducing potential risks and enhancing working conditions. The deployment of this industrial IoT-based system promises cost-efficiency and effectiveness in ensuring continuous, real-time monitoring of environmental parameters within underground mines for prolonged durations.

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CONFLICTS OF INTEREST

The authors declare no competing interests.

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