# DEVELOPMENT OF IOT ENABLED LORAWAN BASED REAL TIME EARLY WARNING MONITORING SYSTEM FOR UNDERGROUND MINE ENVIRONMENTAL PARAMETERS

Thesis

Submitted in partial fulfilment of the requirements for the degree of

## DOCTOR OF PHILOSOPHY

by

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# DECLARATION

*by the Ph.D Research Scholar*

I hereby declare that the Research Thesis entitled **"Development of IoT Enabled LoRaWAN based Real Time Early Warning Monitoring System for Underground Mine Environmental Parameters"** which is being submitted to the **National Institute of Technology Karnataka, Surathkal** in partial fulfillment of the requirements for the award of the Degree of **Doctor of Philosophy** in **Mining Engineering** is a bonafide report of the research work carried out by me. The material contained in this Research Thesis has not been submitted to any University or Institution for the award of any degree.

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# CERTIFICATE

This is to certify that the Research Thesis entitled "**Development of IoT Enabled LoRaWAN based Real Time Early Warning Monitoring System for Underground Mine Environmental Parameters**" submitted by **Mr. Anil S Naik (Registration Number:**2170088MN001 and **Roll Number:** 217MN001**)** as the record of the research work carried out by him, is accepted as the Research Thesis submission in partial fulfillment of the requirements for the award of the degree of **Doctor of Philosophy.**

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**DEDICATED TO**

**MY FAMILY,**

**MY TEACHERS AND**

**MY FRIENDS**

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**Anil S Naik**

# ABSTRACT

In underground mines, real time monitoring of environmental parameters is crucial for detecting hazardous scenarios during mining operations. This research study explores wireless communication technology and the Internet of Things (IoT) to enhance safety and prevent underground mining accidents, benefitting workers and organizations. Gas parameters like oxygen($O_2$), Carbon monoxide (CO), Carbon dioxide ($CO_2$), Methane ($CH_4$), Hydrogen sulfide ($H_2S$), Nitrous oxide (NO), Nitrogen dioxide ($NO_2$), Sulfur dioxide ($SO_2$), and Ethylene oxide (EO) and environmental factors like temperature and humidity are monitored using portable multi-gas detectors certified by DGMS and a hygrometer once per shift.

A hardware prototype employing IoT-enabled Sx1278 Ra-02 LoRa 433 MHz and ZigBee modules enables wireless communication from underground mine tunnels to the surface. This system was successfully tested in two Indian underground gold mines. Additionally, an IoT-enabled real-time monitoring system using HPD13A LoRa 868 MHz modules integrates CO, $CO_2$, $CH_4$, $H_2S$, $H_2$, temperature, and humidity sensors. Data is stored locally and uploaded to the cloud via LoRa receivers, providing a reliable, power-efficient solution for continuous real time monitoring in underground mines.

However, the developed hardware prototype communication range and sensor power consumption limit are deployed in underground mines, especially in harsh environmental conditions. To address these challenges, an IoT-enabled LoRaWAN Gateway based system is proposed. This system integrates industrial RS485 sensors, RS485-LN converter, and LoRaWAN Gateway to monitor environmental parameters from the surface continuously. The system promptly generates an email alert notification on the surface to the concerned authority and initiates an audible alarm alert sound in underground mine tunnels and at the surface when the specified parameters exceed the predetermined thresholds.

The developed LoRaWAN system was tested in an underground gold mine 832 meters below the surface, demonstrating effective wireless communication over distances up to 1000 meters. The system facilitates the transmission of

environmental parameters data of approximately 1800 meters from an underground mine of a specific location to the surface. Real-time data displayed in a surface control room dashboard offers immediate insights into underground mine environment conditions, complementing traditional multi-gas detectors' measurements.

The environmental parameters measured by the IoT-enabled LoRaWAN system are compared with those of DGMS-approved multi-gas detection devices. The measurement accuracy for gases like $CO_2$ and NO was recorded at 86.95% and 88.57%, respectively. CO levels spiked during blasting activities. The $H_2S$, $CH_4$, and $H_2$ concentrations were not detected in underground mine tunnels, while $N_2$ concentration was noted at 77.8%. Temperature and humidity readings from the IoT-enabled LoRaWAN system ranged between 28°C to 33°C and 55% to 61%, respectively. In contrast, a portable recorder device reported temperature variations from 31°C to 33.5°C and humidity levels from 58.9% to 61.5%. Environmental data gathered through an IoT-enabled LoRaWAN system is processed using the LSTM and XGBoost machine learning algorithm to predict environmental conditions accurately. The standard validation metric RMSE validates the accuracy of these predictions.

Furthermore, the system's design is robust, with intrinsic safety features, flameproof construction, and an IP65-rated panel, making it exceptionally suitable and secure for hazardous underground mine environments. The system design includes inherent safety features and IP65-rated panels for robustness in hazardous environments.

In conclusion, this research emphasizes the need for standardized strategies to manage and mitigate hazardous gases in underground mines, particularly from diesel vehicles. Implementation of the IoT-enabled LoRaWAN system proves cost-effective and efficient for continuous monitoring, ensuring safety and productivity in underground mining operations.

# TABLE OF CONTENTS

**CHAPTER 5 IMPLEMENTATION AND RESULT ANALYSIS OF THE DEVELOPED REAL TIME ENVIRONMENTAL PARAMETERS MONITORING SYSTEM (RTEPMS) IN UNDERGROUND MINES 93**

**CHAPTER 6** **CONCLUSIONS, LIMITATIONS, AND FUTURE SCOPE OF THE STUDY**

# LIST OF FIGURES

## LIST OF TABLES

# ACRONYMS

AI: Artificial Intelligence

BLE: Bluetooth Low Energy

BW: Bandwidth

CF: Carrier Frequency

$CH_4$: Methane gas

CO: Carbon Monoxide

$CO_2$: Carbon Dioxide

CR: Coding Rate

CRC: Cyclical Redundancy Check

CSS: Chirp Spread Spectrum

CSS: Chirp Spread Spectrum

DGMS: Directorate General of Mines Safety

EO: Ethylene Oxide

FSK: Frequency Shift Keying

GUI: Graphical User Interface

$H_2$: Hydrogen gas

$H_2S$: hydrogen sulfide gas

HTTPS: Hypertext Transfer Protocol Secure

HVAC: Heating, Ventilation, and Air Conditioning

IoT: Internet of Things

IR: Infrared Sensor

LHD: Load Haul Dump

LoRa: Long Range

LoRaWAN: Long Range Wide Area Network

LOS: Line of Sight

LPWAN: Low Power Wide Area Network

MAC: Medium Access Control

MQTT: Message Queuing Telemetry Transport

MTPA: Million Metric Tons Per Annum

$N_2$: Nitrogen gas

NB-IoT: Narrowband IoT

NDIR: non-dispersive infrared

NH3: Ammonia

NITK: National Institute of Technology Karnataka

NLOS: Non Line of Sight

NO: Nitrous Oxide

$NO_2$: Nitrogen Dioxide

$NO_x$: Oxides of Nitrogen

$O_2$: Oxygen

PCB: Printed Circuit Board

PoC: Proof of Concept

PPM: Parts Per Million

PSK: Phase Shift Keying

PWM: Pulse Width Modulation

$R^2$: R-squared Value

RFID: Radio Frequency Identification

RSSI: Received Signal Strength Indicator

RTC: Real Time Clock

RTEPMS LoRaWAN: LoRaWAN Gateway based Real-Time Environmental Parameters Monitoring System

RTEPMS: Real-Time Environmental Parameters Monitoring System

RTU: Remote Terminal Units

SF: Spreading Factor

$SnO_2$: Tin Dioxide

$SO_2$: Sulphur Dioxide

TCXO: Temperature Compensated Crystal Oscillator

TLV: Threshold Limit Values

TTA: Through The Air

TTE: Through The Earth

TTW: Through The Wire

UART: Universal Asynchronous Receiver Transmitter

UWB: Ultra Wide Band

WiFi: Wireless Fidelity

WSN: Wireless Sensor Networks

WUSNs: Wireless Underground Sensor Networks

XGBoost: Extreme Gradient Boosting

# CHAPTER 1

# 1. INTRODUCTION

## 1.1 Background

The mining industry is a cornerstone of global economic development, providing essential raw materials for various sectors, including manufacturing, energy, and construction. The mining industry primarily extracts valuable minerals from the earth's surface, which are then processed and utilized in many ways. India's mineral sector holds immense potential due to its abundant reserves of minerals such as coal, bauxite, and diamonds. Rajput et al. (2021) investigated the role of the mining sector as pivotal to India's economy, boasting substantial deposits of minerals.

Surface and underground mining are the primary excavation methods used by the mining industry. Unlike surface mining, which involves removing large sections of the Earth's crust, underground mining creates holes in the ground through drilling and blasting. Underground mining is generally more expensive than surface mining due to the need for extensive infrastructure, such as underground mine tunnel excavation, ventilation systems, and mining shafts.

Underground mining involves using heavy machinery for drilling, blasting, and transporting ore and other materials. Compared to open pit mining, it carries higher risks due to potential hazards such as toxic gas formation, unstable mine roofs leading to collapses, gas explosions, and exposure to dust and noise. Additionally, there are electrical hazards and variations in environmental conditions, such as oxygen levels, temperature, and humidity. Despite efforts to improve safety improvements, the unpredictable and dynamic nature of underground excavation means that risks can arise unexpectedly.

According to Naik et al. (2023), Mathioudakis et al. (2023), Mishra et al. (2013), and Montiel et al. (2018), some of the common minerals extracted through underground mining include gold, silver, copper, lead, zinc, iron ore, uranium, coal, nickel, tin, platinum, and diamonds. This extraction is essential to meet the rising demand for these minerals.

Tripathy et al. (2018) conducted a study to ensure safe working conditions in deep underground mines to minimize accidents, injuries to miners, and property damage, which pose significant challenges to mine management. During their work shifts in underground mines, workers face high-risk conditions that can result in severe bodily harm or loss of life.

The study was conducted by Verma et al. (2017) and analyzed the mining industry, which is globally recognized for its hazardous and risky work environments. Adopting advanced, highly mechanized vehicles and technologies to meet production demands has caused further concerns about the safety of workers and equipment in this sector.

Misra (1986) identified the primary gases present in underground mines as carbon monoxide (CO), carbon dioxide ($CO_2$), methane ($CH_4$), hydrogen ($H_2$), nitrogen ($N_2$), nitrogen oxides (NOx), and hydrogen sulfide ($H_2S$). These gases pose significant health risks to miners and are challenging to detect. The impurities within underground mines are classified as explosive but non-toxic gases, toxic gases, and other impurities such as dust and water vapor.

The hazards increase in underground mines, particularly at greater depths, highlighting significant safety concerns for miners. Prioritizing worker safety is paramount across all mining sectors, necessitating robust safety measures and protocols. The air at the Earth's surface contains oxygen, nitrogen, argon, carbon dioxide, and other gases in trace amounts. Human breathing is easy due to sufficient oxygen in the air, but oxygen levels drop, and breathing becomes problematic if the air is contaminated with other gases. Poor air quality in mining environments leads to long-term health problems, particularly in underground mines where toxic gases like carbon monoxide, hydrogen sulphide, methane, and increased carbon dioxide accumulate. It can't disperse due to narrow spaces or tunnel structures. These gases pose severe risks due to their combustible and explosive nature, and underground mines also contain impurities like coal dust and water vapor. Long-term exposure to these impurities, particularly toxic gases, can harm the health of mine workers. After mining activities, underground working locations become dangerous due to toxic and explosive gases and are restricted from entry. Exposure to these gases, dust, carbon dioxide, and nitrogen can harm the blood system and lead to health diseases.

In India, many underground mines have severe problems due to safety issues, sometimes leading to the shutdown. The mining industry consistently seeks ways to boost productivity and quality while adhering to safety standards to reduce expenses and safeguard the environment.

## 1.2 Problem Statement

Mining in underground mine tunnels is at high risk, with high accident rates due to environmental conditions that expose them to dust and toxic gases.

According to Anas et al. (2017), underground mining is one of the most hazardous work environments globally, characterized by inadequate safety measures and complex mining operations. These factors increase the inherent risks, leading to major accidents and significant challenges in formulating effective safety protocols. A critical aspect of safety in underground mines is air quality control, as highlighted by Bhaisak et al. (2017). Maintaining an optimal environmental conditions in underground mines is crucial for improving the efficiency of mine workers. To achieve this goal, mine management must guarantee that the air quality in the underground mine is similar to that of the surface, with a significant percentage or absence of toxic or flammable gases.

Gas monitoring is a vital component of safety in underground mines. Despite the presence of portable multi-gas detectors, they only provide periodic assessments, which is insufficient for dynamic and potentially volatile underground conditions. Dohare (2016) stresses that real-time monitoring is essential to detect sudden variation in gas concentrations, helping prevent accidents before they occur. However, as noted by Bandyopadya (2013), the current lack of effective real-time monitoring systems in many underground mines means workers often face dangerous conditions without adequate warning.

Health risks associated with prolonged exposure to hazardous gases are substantial. Michaud (2016) outlines the wide range of health issues miners face, from respiratory damage to long-term diseases, which underscores the need for strict control over environmental conditions. Moreover, continuous exposure to diesel fumes further heightens the risks of cancer and cardiopulmonary diseases, as noted by Debia et al. (2017).

Ramlu et al. (2006) describe Methane gas as highly flammable and explosive when its concentration in the air falls within the explosive range. It originates from coal seams formed during the coal formation, while carbon dioxide enters the coal seam through igneous intrusions.

During blasting operations in underground mines, large quantities of carbon monoxide and hydrogen sulphide gas are generated. Gas hazards in underground mines arise from the accumulation of gases in the mine environment. When gas levels exceed safe thresholds, it can lead to property damage, injuries to mine workers, and even fatalities. These incidents occur due to the absence of real-time monitoring systems and reliable communication infrastructure in underground mines. Currently, no effective technology is deployed for the real-time monitoring of environmental parameters of underground mines in India. Accidents in these environments are unpredictable events caused by unavoidable circumstances and human error. Unfortunately, such incidents occur globally and result in a significant number of worker fatalities every year.

Osunmakinde (2013) presented accidents involving underground mine gases as a significant safety concern in the mining industry. The explosive conditions in these mines arise from multiple factors, such as the production process, geological characteristics, and the type of mine, creating a high risk of explosions that can cause injuries and property damage.

Anas et al. (2017) emphasized that mining operations, which involve heavy machinery and ore extraction through drilling and blasting, pose safety risks. To improve safety standards in the mining industry, many mines have adopted safety protocols, provided comprehensive worker training, and focused on educational initiatives.

The safety and welfare of mine workers should be a top priority across all mining sectors. Mines have implemented various standard safety protocols and educational training sessions to enhance safety awareness in different mining environmental conditions. Currently, portable multi-gas detectors are used in India to measure the environmental parameters of underground mines on a shift or daily basis. However, real-time monitoring of environmental parameters is essential due to the diverse sources of mine gas in underground mine sites. Ensuring a safe and productive working environment is crucial for maintaining the efficiency of mine workers.

The structure of underground mines is inherently irregular, presenting challenges for communication due to its dynamic layout, bends, and crosscuts. A well-designed communication system is essential for exchanging real-time information on environmental parameters, tracking worker positions, and issuing alerts for safe and unsafe areas. Automation enhances worker health and safety by delivering a reliable and robust communication system. However, the unique geological structure of each mine presents challenges in adopting mining technology to monitor adequate ventilation and air quality in underground mines.

Zietek et al. (2020) and Hussain et al. (2017) discuss various methods the mining industry uses to measure environmental parameters in underground mines. Mine supervisors use handheld portable multi-gas detectors to gather environmental data once per shift. However, equipping every mine worker with these devices costs more, and these detectors typically do not store and perform any analysis of measured data.

Dohare et al. (2015) discuss the concept of hybrid communication systems in advanced automated mines. These systems incorporate a wireless real-time monitoring setup for collecting environmental data from underground mines. The hybrid communication setup can include wired and wireless components, such as complete cable wire communication or the use of portable devices at the mine site. However, the dynamic nature of working conditions in underground mines poses challenges for these systems. These challenges may include damage to cable wires, higher fault rates, difficulties in system maintenance, and other inconveniences.

According to the DGMS Circular of 2017, the Directorate General of Mines Safety (DGMS) in India recommends the implementation of real time environmental monitoring systems in mines to mitigate risks.

Moridi et al. (2014), Muduli et al. (2017), Jo et al. (2017), Suganthi et al. (2021), and Naik et al. (2024) have extensively researched wireless communication technology in underground mines. They recommend using technologies such as ZigBee and LoRa wireless communication modules, integrated with Wireless Sensor Networks (WSN) and the Internet of Things (IoT), to enable real-time monitoring of environmental parameters and other factors in underground mines.

The safety measures in underground mining must focus on comprehensive air quality control, real-time gas monitoring, and robust communication systems to ensure that miners work in a safe environment aims to enhance mining operations safety, efficiency, and productivity.

## 1.3 Objectives of the Research Study

The research study aims to develop a Real-Time Environmental Parameters Monitoring System (RTEPMS) capable of monitoring various gas parameters and temperature and humidity in an underground mine environment. Using an IoT-based architecture, this system facilitates the real-time transmission of measured environmental data from underground mine tunnels to the surface.

The main objectives of the proposed research work are as follows:

1) Design and development of a reliable and cost-effective wireless communication system (ZigBee or LoRa) for real time environmental parameters monitoring.
2) Development of an Internet of Things (IoT) enabled LoRaWAN based system to monitor real time environmental parameters in underground mining proximity.
3) Data acquisition and processing of real time environmental parameters in the underground mining proximity using LoRaWAN based wireless communication technology.
4) Development of a forewarning hazard monitoring of underground environmental parameters using machine learning techniques to prevent hazardous scenarios in an underground mine.
5) To suggest suitable environmental parameters for control or mitigation in the underground mining proximity.

## 1.4 Scope of the Research Work

To achieve the goals of this research, the study is divided into several key tasks.

- *Review of Related Literature:* Reviewing characteristics of mine gases, other environmental parameters such as temperature and humidity in underground mines, different environmental monitoring systems in underground mines, different types of sensor technologies, and real-time wireless communication systems to measure environmental data from underground mine tunnels.
- *Development of a Wireless Communication System:* Development of a reliable and cost-effective wireless communication system for monitoring and communication of real-time underground environmental parameters. First, select components for wireless communication, focusing on their ability to accurately measure and monitor different parameters in the mine environment, complying with legislative provisions applicable to underground mines by considering factors such as reliability, compatibility, sensor sensitivity, and communication technology. Choose sensors based on their durability in harsh mining conditions and their ability to detect low gas concentrations effectively. Incorporate communication modules like LoRa or ZigBee or LoRaWAN gateway for wireless data transmission over long distances. Microcontrollers like NodeMCU, ESP32, or RS485 technology are used for processing power, connectivity options, and ease of integration. A comprehensive solution for acquiring, processing, visualizing, and alerting data, ensuring efficient and real-time monitoring of mine gases through an IoT-enabled system.
- *Laboratory Testing and Calibration:* The developed real-time monitoring and communication system to comprehensive laboratory testing and sensor calibration to ensure accuracy, reliability, and optimal performance. Assess how well communication modules like ZigBee or LoRa or LoRaWAN gateway and Sensors perform in harsh underground environments.
- *Implementation and Testing:* Implement the developed real-time environmental monitoring system in the laboratory, model mines, and underground mines to carry out experimentation to test the accuracy of the gas sensors and the range

of communication devices for transmitting measured environmental data from underground mine tunnel to the surface.

- *Optimum Distance Determination:* Determine the optimum distance between underground mine sensors and the surface gateway device in an underground gold mine. The experimental investigations in an underground mine to understand the variation in RSSI (Received Signal Strength Indicator) concerning distance from the transmitter to the receiver under both line-of-sight (LOS) and non-line-of-sight (NLOS) conditions.
- *Machine Learning Algorithms to Forecast Hazards:* Process the environmental data gathered through the IoT-enabled system using machine learning algorithms to forecast hazardous environmental parameters in underground mines over extended periods.

## 1.5 Significance of the Research Study

The developed real-time monitoring of environmental parameters from underground mine tunnels to the surface is crucial for monitoring mine gases, temperature, and humidity. This research study aims to develop a system that continuously monitors the concentrations of gases such as $CO_2$, $CH_4$, CO, $NO_2$, and $H_2S$, as well as temperature and humidity, in real-time within underground gold mines near working areas within an underground mine tunnel. The system will transmit the measured environmental data from the underground mine tunnel to the surface, which will be monitored by competent persons and accessed by portable devices such as laptops, desktops, or mobile devices through a thingZmate applications. This allows the authorized mine manager or safety officer to take preventive measures by notifying the supervisor from any location, even remotely. Enhancing the accuracy and reliability of real-time monitoring systems for measuring environmental parameters will significantly improve the health and safety of underground miners. An effective early warning system will help promptly take preventive measures.

The development and proper implementation of real-time environmental parameters monitoring and communication in underground mines will fulfill the objectives of the research study.

## 1.6 Organization of the Thesis

The thesis comprises six chapters outlined below, each reflecting the objectives of the research work.

Chapter 1 begins with background details and information on the challenges related to underground mining situations. It further introduces the problem statement, primarily emphasizing environmental parameter concerns within underground mines. The chapter highlights the objectives, scope of the work, and importance of the study.

Chapter 2 presents a comprehensive literature review encompassing the entire research topic. This includes a review of the literature concerning various environmental gas parameters within underground mines. Additionally, it covers literature on different environmental monitoring systems designed for underground mines. Moreover, the chapter discusses literature related to wireless-based communication systems and real-time monitoring systems enabled by the Internet of Things (IoT).

Chapter 3 outlines the research design and the process of selecting components to develop a hardware prototype of a wireless Real-Time Environmental Parameters Monitoring System (RTEPMS) for use in underground mines. This system monitors environmental parameters within underground mines and integrates with LoRa and ZigBee wireless communication technology. Additionally, this chapter includes a discussion on comparing various wireless communication technologies for this purpose.

Chapter 4 focuses on developing a hardware prototype for the Real-Time Environmental Parameters Monitoring System (RTEPMS) designed to monitor environmental conditions within underground mines. This system is integrated with an IoT-enabled LoRaWAN Gateway communication system, facilitating the transmission of monitored data from underground mine tunnels/levels to the surface. The chapter also explores laboratory testing and calibration procedures for the developed system.

Chapter 5 presents the application of the developed IoT enabled LoRaWAN based Real-Time Environmental Parameters Monitoring System (RTEPMS- LoRaWAN) in underground gold mines in India and a Model Mine lab at the National Institute of

Technology Karnataka (NITK), Surathkal. The Model Mine Laboratory replicates the structural layout of an underground mine but does not simulate the harsh environmental conditions found in actual underground mines, as it is a surface-based laboratory setup. The model mine includes, Belt Conveyor of 23 m length, which operates with a 3 HP motor capacity, 58 RPM motor speed. The Direct Rope Haulage track length of 25 m, the track width of 0.66 m with a tub capacity of 1.5t, which operates on 2 HP motor power and 15 RPM motor speed. Variable speed fan with proper ventilation condition and power supply. At one of the underground gold mines, the system performance was evaluated at 832 m depth from the surface to monitor underground mine environmental parameters from the surface. A communication range for line-of-sight and non-line-of-sight was carried out. This chapter analyzes and discusses the results of monitored data and transmission range.

Chapter 6 presents a comprehensive discussion along with conclusions and recommendations based on the findings of this research. The chapter also highlights the limitations of the research study and discusses the future scope of the study in this area.

Each chapter concludes with a summary, and the references cited in the thesis are presented at the end of the thesis. Additionally, appendices are included at the end of the thesis.

# CHAPTER 2

# 2. LITERATURE REVIEW

## 2.1 Introduction

A literature review was conducted to gather information on issues in underground mines, explicitly focusing on environmental parameters, examining various environmental factors and associated safety concerns, and the safety of mine workers. It also covered topics such as gas explosions and the variation of environmental parameters influenced by different factors. The literature explores various monitoring systems that measure environmental parameters in underground mines and the communication technologies that transmit data from underground tunnels to the surface. This review aims to provide detailed insights into recent research on real-time monitoring systems in underground mining environments.

## 2.2 Safety Issues in Underground Mines

The growing population and economic growth, especially in Asian countries, have substantially increased the demand for minerals, coal, gold, and other resources. To meet this rising demand for different minerals, production must increase. However, boosting the production of coal, gold ore, copper ore, and other minerals from underground mines will also lead to an increase in various hazards. Therefore, according to Naik et al. (2024) and Vinay et al. (2022), ensuring safety is crucial alongside the production of different mineral ores from underground for the survival of the mining industry.

Paul and Maiti (2007) stated that it is essential to follow safety precautions to prevent workplace diseases and accidents in the mining industry. They emphasized that any production method prioritizing financial success over mine workers' health and lives is unethical and absurd. According to Akgun (2015), in the Parliamentary Research Commission Report 2010, the mining industry leads all other sectors in accidents that result in fatalities or serious injuries. The risk of fatal and occupational accidents is higher in the mining industry than in other sectors.

According to Asfaw et al. (2013) and Vinay et al. (2022), underground coal mining is a particularly hazardous occupation in the United States, with a high risk of accidents and workplace injuries. However, according to Chen et al. (2013), China is the most hazardous area for coal mining, with the world's highest number of coal miner deaths.

Yang et al. (2021) emphasized that the operational environment of an underground mine presents numerous risks to workers, such as exposure to mine gases and dust, close proximity to heavy machinery, electrical hazards, and the risk of roof falls. According to Ralston et al. (2015; 2017), the pressure to complete production tasks to meet demand forces underground mine workers to operate in hazardous environments. The mining industry is under increasing scrutiny due to a rising number of fatalities caused by harmful gases and gas explosions. The mining industry is under growing pressure as fatalities rise due to toxic gas exposure and explosions. Fig. 2.1 shows the accident reports from Indian coal mines between 2001 and 2024, showing that 4.8% occurred due to explosions and 5.1% occurred due to gas and dust. Smith (2013) analyzed that accidents and fatal injuries in underground mines remain a regular occurrence despite using advanced equipment in coal mines.

Bo et al. (2014) emphasized the necessity of implementing novel strategies to improve the health of underground miners, given the frequent presence of humans in these environments. They highlighted that exposure to various gas parameters can significantly impact the health of mine workers. On the other hand, Yang et al. (2021) analyzed that despite advancements such as safer underground mine tunnels and automation, accidents in underground mines continue to result in the loss of lives, time, and resources. Additionally, Naik et al. (2024) and Qiuping et al. (2011) concluded that adopting the Internet of Things (IoT) in underground mines can enable real-time monitoring of environmental parameters and early warning systems for variations in gas parameters, gas explosions, dust explosions, and other risk factors. According to Vinay et al. (2022), safety hazards in underground mines arise from various factors such as human errors, environmental conditions, operational challenges, equipment issues, and inadequate emergency response protocols. These factors need a workplace of monitoring and innovative strategies to reduce accidents in underground mines.

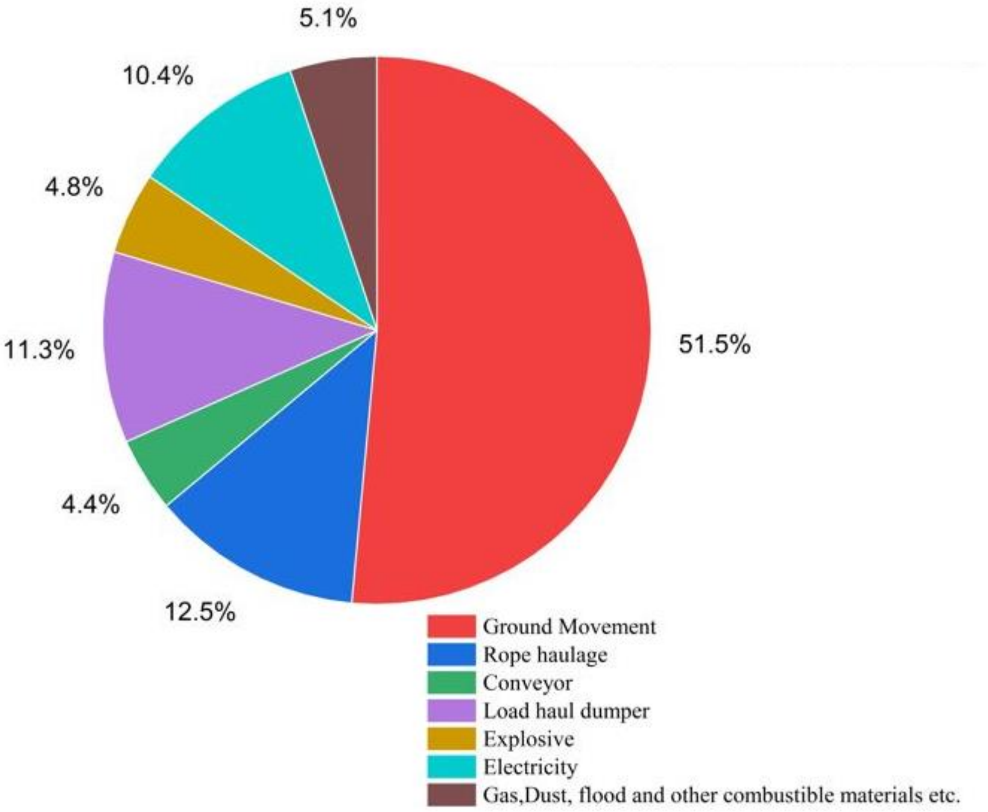


Fig. 2.1. Analysis of fatal accidents in coal mines from 2001 to 2024 (Source: Tripathy and Ala, (2018), EIACP (PC-RP) report (2023), Gogoi et al. (2024), Kulshrestha (2024))

### 2.3 Underground Mine Environment

Goswami (2014) highlighted that the combination of a constrained geological structure, darkness, suffocation, temperature, and humidity in underground mine environments has historically made working in Indian mines hazardous and risky. The author also pointed out that the reduced performance of mine workers is often a result of the intense thermal stress caused by high temperatures and humidity in deep underground mine tunnels. The underground mine environment is unsuitable for mine workers due to prolonged exposure to mine gases. Additionally, the production of NOx gas during subsurface blasting further adds to the challenges. Wathern (1988) described the underground mine environment as posing critical challenges for mine workers due to the release of methane gas during coal cutting, high temperature and humidity, and the production of fumes during coal blasting.

The mining processes, such as drilling, blasting, loading, and transportation, also impact the underground ecosystem. Over the last few decades, underground mining technology has significantly improved globally to enhance productivity and remain competitive.

### 2.3.1 Underground Mining: Activities and Impacts

The key activities involved in underground mining operations and their impacts are described here. As Goswami (2014) points out, methane gas explosions are triggered by ore excavation, drilling activities, noise pollution, blasting generates gases and fumes, and loading and transportation operations lead to dust and noise pollution. Paul and Maiti (2007) rightly emphasize the critical importance of safety measures. Executing immediate rescue operations for underground workers in hazardous environments prone to accidents is a significant concern for all stakeholders. According to Qinghua et al. (2009), addressing these concerns necessitates the implementation of comprehensive measures and advanced technologies to mitigate risks and safeguard the well-being of miners.

Ferie et al. (2016) emphasize the importance of gas detection in mines, advocating for the use of various sensors to measure the concentration of different environmental parameters. They emphasized the significance of understanding the mine environment, including the ignition temperature and flammable limits of gases, as crucial for ensuring safety. Additionally, temperature and humidity monitoring were noted to play vital roles in preventing underground mine disasters. Matijevic et al. (2009), stated that continuous real-time monitoring of gas concentrations and complex mine environmental conditions can effectively track potential hazards.

### 2.3.2 Underground Mines: Sources of Gases, Threshold Limit and Major Gas Hazardous

Different types of gases are released during the ore extraction process, which includes carbon monoxide, carbon dioxide, methane, hydrogen, nitrogen, nitrous oxides, and hydrogen sulphide. These mine gases affect the health of mine workers and are challenging for miners to detect. The impurities found in underground mine environments. Zipf et al. (2010) stated that the gas composition in the underground mine atmosphere is influenced by various factors, including mineral extraction, the breakdown of inorganic materials, underground water, ventilation systems, and the use of equipment.

The underground mining operation is riskier considering the health and safety of mining workers. These risks are more significant as the mining operation goes deep. Safety is an essential concern in any mining industry, and workers' safety should be an important consideration for all types of mining. Inhalation or exposure to toxic gases, dust, carbon dioxide, and nitrogen can severely impact miners' health, leading to long-term diseases. Additionally, exposure to emissions from diesel-powered vehicles in underground mines is a significant concern, as it raises the risk of cancer and cardiopulmonary diseases. Dense poisonous gases often prevent miners from entering certain areas, highlighting the need for enhanced safety measures in the mining industry. According to Dey et al. (2021), Table 2.1 Shows various mine gas and their effect on the health of mineworkers.

Underground mining operations emit toxic gases that need to be detected, and keeping them within the prescribed limits required to keep operations smooth and safe on a real-time basis is a requirement of the mining industry. Underground mine structures are not unique. The length and width of the mine depend on the type of mine and the orientation of the ore body. The excavation process makes a mine structure dynamic, with long side walls, curvature, bends, cross cuts, etc. The coal mine workings in gassy and fiery seams are addressed in DGMS Circulars-2017. The Directorate General of Mines Safety (DGMS) in India recommends implementing environmental monitoring systems in mines to address these risks, particularly emphasizing standards for diesel equipment to reduce hazards such as emissions and explosions.

The circulars outline the standards and safety protocols for diesel equipment used in underground coal and metalliferous mines. Equipment like diesel-operated trucks, high-capacity loaders/load haul dumps, drills, and others, which are common in underground mines, carry inherent health and safety risks such as diesel emissions, noise, dust, fire hazards from lubricants, explosions due to inflammable gases, and vehicle collisions.

Table 2.1 Various gas characteristics and their physiological effects

| **Toxic Mine Gases and Physiological Health Effects** | | | |
|---|---|---|---|
| **Environmental Parameters** | **Properties** | **Physiological effects** | **Explosive Limit (% by volume of air)** |
| Carbon dioxide ($CO_2$) | • Colourless and odourless<br>• Heavier than air and has an acidic taste at high concentrations | • At 5% concentration, it stimulates respiration.<br>• At 7% to 10% concentration, it can cause unconsciousness after a few minutes of exposure. | N/A |
| Carbon monoxide (CO) | • Flammable, colourless, tasteless and odourless<br>• Lighter than air | • Highly toxic and reduces the blood's capability to carry oxygen, at 200 ppm, causes a slight headache, tiredness, dizziness, and nausea after 2 to 3 hours<br>• At concentrations greater than 200 ppm, becomes life-threatening after 3 hours | 12.5 to 74.2 |
| Hydrogen ($H_2$) | • Colourless and reacts quickly with other chemical substances<br>• Explosive mixtures are easily formed and lighter than air | • High concentrations create an oxygen-deficient environment and can cause headaches, ringing in the ears, drowsiness, nausea<br>• Can cause the skin to turn blue (cyanosis) due to lack of oxygen | 4.1 to 74 |

| **Environmental Parameters** | **Properties** | **Physiological effects** | **Explosive Limit (% by volume of air)** |
|---|---|---|---|
| Methane ($CH_4$) | • Flammable, colourless, odourless and tasteless<br>• Lighter than air<br>• Largest component of fire-damp | • Causes breathing problems, asphyxiation, dizziness, and headache<br>• Not toxic, but high concentrations in confined spaces can reduce oxygen levels | 5 to 15 |
| Nitrogen Dioxide ($NO_2$) | • Reddish-brown color in high concentrations<br>• Nonflammable<br>• Heavier than air | • Toxic gas causes throat and lung infection<br>• At 1–13 ppm, irritates nose and throat<br>• At concentrations ≤80 ppm, causes tightness in the chest after 3 to 5 minutes<br>• At concentrations >80 ppm, causes pulmonary edema after 30 minutes | N/A |
| Hydrogen Sulphide ($H_2S$) | • Colourless and highly corrosive and flammable<br>• Poisonous gas | • Highly toxic and interferes with cellular metabolism<br>• Causes eye irritation, respiratory tract irritation, vomiting, headaches, and loss of sense of smell<br>• Can lead to unconsciousness, stopped breathing, and death | 4.3 to 45.5 |

Additionally, the DGMS circular specifies the minimum ventilation requirements and threshold limits for harmful and inflammable gases, as detailed in Table 2.2.

Table 2.2 Threshold limits of gases as per DGMS Circular (Shemshad et al. (2012), and DGMS Circulars (2017 & 2018))

| **Sr. No** | **Environmental Parameters** | **The maximum allowable concentration of gas TLV as per DGMS circular** | | **Undiluted exhaust gas emissions after treatment shall not contain more than as per DGMS circular** | |
|---|---|---|---|---|---|
| | | **Percentage (%) by volume** | **PPM** | **Percentage (%) by volume** | **PPM** |
| 1 | $CO_2$ | 0.5 | 5000 | NA | NA |
| 2 | CO | 0.005 | 50 | 0.11 | 1100 |
| | | | | 0.20 | 2000 (While 1 % $CH_4$ is injected into the intake) |
| 3 | NO | 0.0025 | 25 | 0.09 | 900 |
| 4 | $NO_2$ | 0.0005 | 5 | 0.010 | 100 |
| 5 | $SO_2$ | 0.0005 | 5 | NA | NA |
| 6 | $H_2S$ | 0.0005 | 5 | NA | NA |
| 7 | Aldehydes | 0.001 | 10 | NA | NA |

According to the DGMS Circular (2018), if the wet bulb temperature at any location in a mine exceeds $33.5^0$ Celsius or if it exceeds $30.5^0$ Celsius in the roadway, arrangements must be made to ventilate the area with an air current moving at a speed of at least 1 meter per second.

Safety is a significant concern and top priority, but mining remains inherently unpredictable and hazardous despite improving mine environment conditions.

Monitoring air quality and implementing robust safety measures, including thorough worker training and adoption of advanced technologies such as sensor-integrated gas detectors and wireless communication, are crucial for safeguarding the health and well-being of miners. The dynamic and complex nature of the environment of underground mines makes effective communication challenging yet necessary for ensuring safety.

Gas-related incidents in underground mines are widely recognized as the most dangerous hazards in the underground mining industry. A single gas accident can lead to multiple fatalities among underground mine miners. Yhoshu (2024) stated in an article about the recent underground mine incident in Ruchan village of Wokha district (India), which resulted in the death of six mine workers and four others injured in the year 2024, was caused by a methane gas fire and explosion.

Naik et al. (2023) stated several instances of gas explosions within underground mines in India, resulting in 287 fatalities and 34 injuries of mine workers. A few cases also stated by Chandravanshi (2016), a fire-damp explosion in 1973 at Jitput mines resulted in the deaths of 48 people. Similarly, at New Kenda mines in 1994, 55 individuals lost their lives due to suffocation from harmful and poisonous gases.

According to Debia et al. (2017), exposure to diesel engine exhaust is responsible for 6% of deaths among occupational mine workers in underground mines due to lung cancers. Mahdevari et al. (2016), found that individuals exposed to gas and dust for over five years at the Kerman coalfield in Iran are experiencing lung diseases. Their study focused on 460 persons who had worked at the coal mine, revealing that 72.30% were facing health issues related to shortness of breath.

Deng et al. (2019) stated abnormal hydrogen sulfide enrichment in coal and rock layers within China's coal mines. This phenomenon has led to numerous deaths and injuries among workers, as well as environmental pollution. Panhwar et al. (2017), investigated exposure to toxic gases and asphyxiation incidents at Lakhra Coal Mines from 2010 to 2014. Their study revealed that three mine workers were injured during this period, with three fatalities reported as well. Over an extended period, these incidents have presented substantial challenges for employees and employers. Researchers illustrate the trend of fatal accidents in underground mines. Kurlenya et al. (2017) identified that the primary causes of methane gas explosions in Russian coal mines between 2001 and 2007 were sparking from broken cables, friction during caving, and sparks from damaged power cables of machinery. These explosions resulted in the fatalities of 227 mine workers. Na et al. (2011), described 433 cases of gas explosions in Chinese coal mines from 1950 to 2006, which resulted in the fatalities of 10,056 mine workers. Shi et al. (2018), analyzed gas explosions in Chinese coal mines from 2006 to 2016, resulting in the fatalities of 741 mine workers. Wang et al. (2014) analyzed gas explosions in Chinese coal mines from 2006 to 2010, which resulted in the fatalities of 943 mine workers. Xiao et al. (2018), analyzed gas explosions in Chinese coal mines from 2000 to 2015, which resulted in the fatalities of 10,541 mine workers.

Fu et al. (2019), analyzed gas explosions in Chinese coal mines from 2007 to 2016, identifying 63 significant incidents that resulted in the fatalities of 1,443 mine workers. The authors proposed a "24Model" technique to analyze the causes of these explosions and implement adequate preventive measures in coal mines. Ke et al. (2020), analyzed 2,984 mine gas accidents in Chinese coal mines from 2003 to 2018, which resulted in the fatalities of 12,807 mine workers. Their analysis indicates that gas control policies significantly prevent such incidents. Shah et al. (2020), reported 65 fatal accidents at Cherat Coalfield, Pakistan, from 1998 to 2019. These incidents involved the collapse of the roof, followed by the presence of obnoxious gases, electric current hazards, and oxygen deficiency.

According to Khodabandeh et al. (2012), the use of diesel-powered vehicles in underground mines poses a significant risk of increased cancer and cardiopulmonary disease among workers. The presence of toxic gases makes entering certain areas inaccessible, highlighting the need for enhanced safety protocols in mining operations. Exposure to $CO_2$ gas can impact heart function and alter blood pressure in underground mine workers, resulting in lower mean diastolic blood pressure than non-mining workers.

It's crucial to systematically analyze gas-related accidents in underground mines and implement adequate preventive measures to avoid such incidents. According to Dohare et al. (2016), ensuring safety in underground mines requires careful consideration of factors such as toxic gas emissions during mining and monitoring temperature and humidity levels. Proper safety protocols, including monitoring of harmful gases, temperature, humidity, etc., must be consistently maintained to prevent accidents in underground mines. As per Le et al. (2017), exceeding the threshold limit of certain gases can result in a gas explosion. Such explosions represent a significant danger to underground mines globally, emphasizing the necessity for effective emergency protocols.

Zhang et al. (2014), highlighted that an increase in temperature and humidity levels in underground mine workplaces can reduce the productivity of mine workers. Enhanced surveillance and safety systems are crucial in the underground mining industry to boost worker safety and productivity and ensure a secure work environment. The safety of underground mining operations relies on improved surveillance and early warning systems for detecting gas hazards. The current safety standards at Indian underground mines are not appreciable, mainly due to the absence of a real-time monitoring system. Despite significant advancements in communication technology, particularly in wireless data transmission, the underground mining sector has yet to keep pace with these innovations due to inherent challenges. Implementing a real-time wireless communication system that provides real-time data on underground mine environment conditions is necessary.

According to Sunkpal et al. (2018), and a report by the U.S. Department of Labor (2012), the temperature and humidity in underground mines increase due to heat and water sources as air circulates through the mine galleries. Research indicates that mine workers in hot and humid conditions may struggle to maintain focus. Mines operating at temperatures below 70°F (21°C) have recorded fewer accidents, while those with temperatures above 80°F (27°C) have seen a higher incidence of accidents.

## 2.4 Evolution of Gas Monitoring Systems in the Mining Industry

Barry (2013) and Kaur (2012) mentioned that gas monitoring in underground mines initially relied on canaries. The distress signals of canaries were used to detect the presence of gases like methane or carbon monoxide. Until 30 years ago, underground miners depended on canaries to warn against harmful gases and pollutants. Suppose any signs of distress in the canaries, like difficulty breathing, alert miners to harmful gases and prompt immediate evaluation of the location. Historically, using canaries in mining pits served as a primary method for detecting the presence of toxic gases, thereby safeguarding miners from potential harm. Fig. 2.2 shows a canary mine workers use to detect hazardous gases in underground mines.

Fig. 2.2 Canaries served as an early warning system for miners in underground mines, (Kaur (2012))

By 1987, the government had stopped using canaries in mining sites to detect hazardous gases. Canaries were considered unreliable and unsafe for accurately identifying atmospheric gas pollutants in the underground mining environment. Consequently, more advanced and precise detection methods became necessary to ensure the safety and well-being of mine workers. As a result, alternative equipment and technologies were developed to provide more effective monitoring and detection of harmful gases in underground mines, offering a preferred and long-term cost-effective solution for gas monitoring.

According to Middleton et al. (2005), Unwin Ian (2021), and Mine Portal (2020), flame safety lamps were also utilized, and these lamps were specifically designed to detect harmful gases in the air. To detect the lowest possible levels, a technique was developed to reduce the large yellow illuminating flame by lowering the wick, creating a small, low-intensity testing flame. The components of a flame safety lamp are represented in Fig. 2.3.

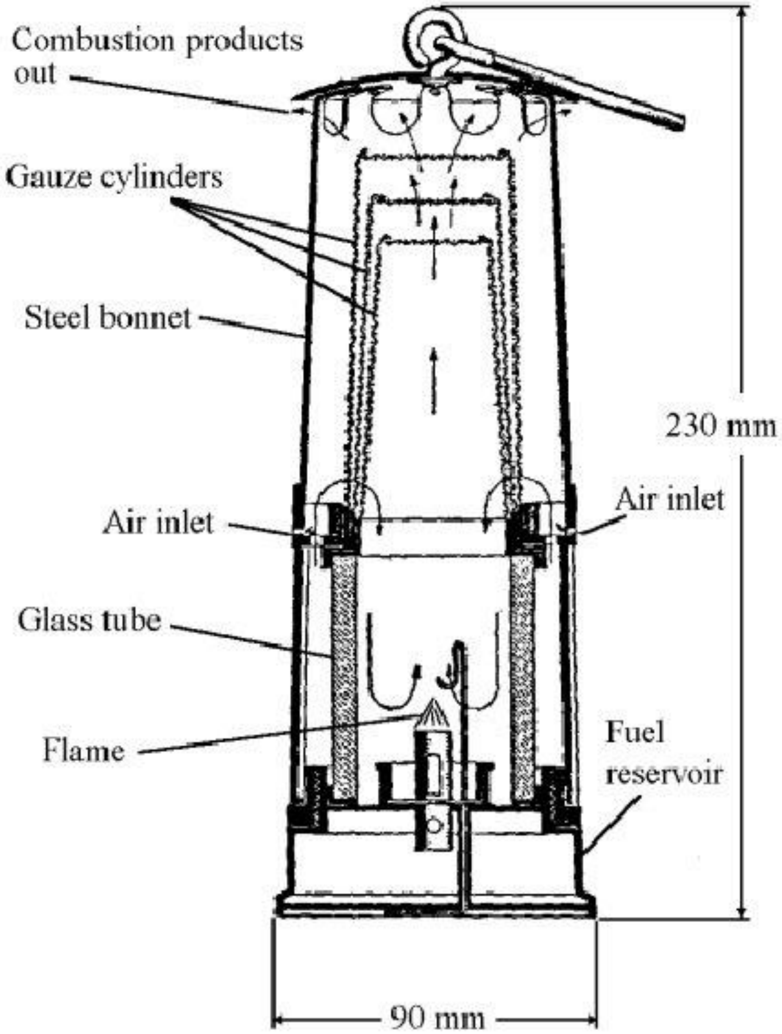


Fig. 2.3 A flame safety lamp (Unwin Ian, 2021)

According to Miller et al. (2005) and Kaur (2012), catalytic pellistors emerged as a significant improvement over canaries for detecting harmful gases in mines. These sensors pass an electric current through platinum wires, generating heat that triggers a catalytic reaction on the pellistor's surface. This reaction, particularly effective for carbon-based molecules like carbon monoxide, increases resistance within the metal coil, which can be measured to indicate gas presence. Fig. 2.4 shows the schematic of pellistors, which help to detect various gases. Pellistors are strategically placed in areas prone to hazardous gas pollution to maximize their efficiency. However, they have limitations, such as malfunctioning when exposed to substances containing metals like lead or silicon, as well as sulphur or chlorine compounds. Their sensitivity can be compromised by contamination from silicon. Additionally, pellistors require regular calibration and maintenance.

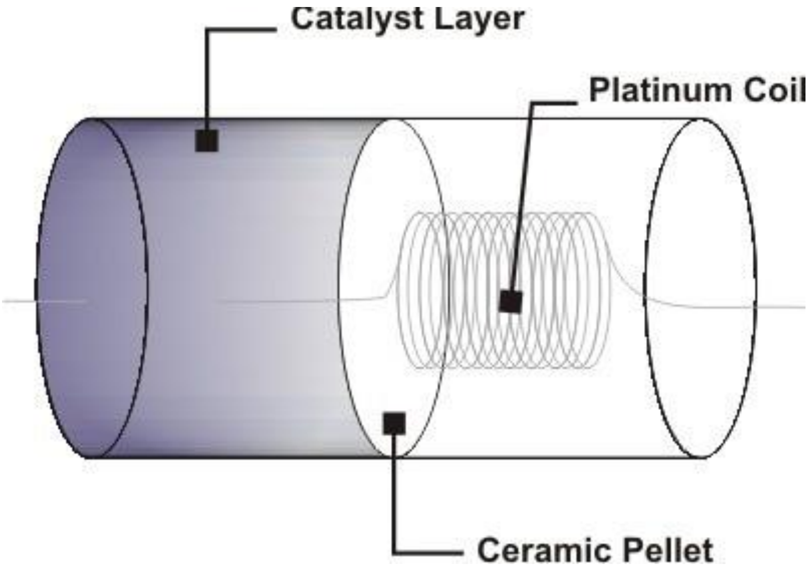


Fig. 2.4 Schematic of a basic pellistor, (Kaur (2012))

A methanometer is a portable device used to measure the concentration of methane gas in the air, particularly in underground mines. These devices use various technologies, such as catalytic combustion sensors or infrared absorption, to accurately detect methane and alert workers if dangerous levels are detected, allowing for timely preventive measures. Regular calibration and maintenance are essential for ensuring the reliability and accuracy of methanometers, according to Vermon (2012). Noack (1998) emphasized that an innovative technology based on catalytic combustion sensors was introduced in the 1960s to detect flammable gases like methane. As shown in Fig. 2.5, methanometers are used in the mining industry to detect methane gas and ensure safety.

Chaulya and Prasad (2016) describe a tube bundle system as a method for extracting gas samples from various underground mine locations. This system utilizes vacuum pumps to draw air samples through plastic tubes to the surface for analysis. Paramagnetic techniques are then employed to analyze the gas composition. Notably, tube bundle systems are particularly well-suited for long-term gas trend monitoring, provided they are properly maintained and configured to measure critical parameters like oxygen, carbon monoxide, carbon dioxide, and methane. Fig. 2.6 represents the Australian dynamic technologies tube bundle systems used in underground mines.

Fig. 2.5 Methanometer used at the Teralba Colliery 1972, (Story Place (2023))

Semiconductor technology was also incorporated to detect various gases such as methane, carbon monoxide, and hydrogen sulfide. These sensors detect specific gases through changes in the electrical resistance of semiconductor materials. Liu et al. (2018), highlighted the design of portable multigas detectors for simultaneous monitoring of various hazardous gases. These detectors achieve this through diverse sensors, including catalytic and semiconductor types. Anas et al. (2017), found that the evolution of wireless communication technology drove significant advancements in gas monitoring systems in recent years. This real-time monitoring capability empowers mine operators to receive environmental parameter data remotely, enabling them to react quickly to potential hazards.

Fig. 2.6 Australian Dynamic Technologies tube bundle systems for underground mines, (Australian Dynamic Technologies (2023))

Real-time environmental parameter monitoring in underground mines is an interdisciplinary effort crucial for underground mine worker safety. This approach allows for continuous data collection on critical parameters, enabling timely detection and mitigation of risks. Wireless communication technology plays a vital role in this system, with advancements offering even greater efficiency. It's important to remember that underground mines are inherently hazardous environments, often relying heavily on manual labour. Mine workers face continuous exposure to hazardous gases like methane, carbon monoxide, hydrogen sulphide, and oxygen and carbon dioxide variation.

A portable multi-gas detector device approved by DGMS, India, for use in the underground mine that measures the concentration of environmental parameters. DGMS, India (2018) notification states that portable hand-held multi-gas detectors are used to measure environmental parameters in underground mines in India. Three distinct multi-gas detectors collectively measure nine specific gases. The first detector measures Oxygen, Carbon dioxide, Hydrogen sulphide, Sulphur dioxide, and Methane levels. The second gas detector device is dedicated to measuring Nitrous oxides, while the third device is exclusively used to measure Ethylene oxide levels. All multi-gas detectors are periodically calibrated, and environmental parameters are measured on a shift basis. The multi-gas detectors and the place to update the gas parameters are shown in Fig. 2.7 (a & b).

(a) (b)

Fig. 2.7 Portable multi-gas detector device and board to display gas parameters (Naik et al. (2024))

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 during a daily shift, and updates are made 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.

Portable multigas detectors work by employing various sensors, each capable of detecting specific types of gases in the air. These detectors are comprised of several key components such as sensors for gas detection, a display unit for presenting readings, control buttons for user interaction, an alarm system to generate alerts, and a battery to power the entire unit. Portable multigas detectors employ a variety of sensors to identify and monitor the concentration of different gases in the air. These sensors are crucial in preventing hazards like fires, explosions, and toxic gas exposure.

- Electrochemical sensors utilize an electrochemical reaction to generate a current proportional to the gas concentration. They offer high sensitivity, low power consumption, and a long lifespan, making them suitable for detecting gases like oxygen, carbon monoxide, and hydrogen sulfide.
- Catalytic sensors feature a heated element coated with a catalyst that triggers an oxidation reaction with combustible gases (like methane) and produces heat. This heat change is measured by a thermocouple or circuit that generates a voltage that indicates gas concentration. These sensors are known for their fast response time, affordability, and broad detection range.

- Infrared sensors use an infrared light source and detector to measure the absorption of light by gas molecules. This method allows for highly accurate and selective detection of specific gases, commonly methane and carbon dioxide, with minimal interference from other gases in the environment.

Portable gas detectors significantly rise from traditional methods like canaries for monitoring environmental parameters in underground mines. These advanced devices, equipped with rechargeable batteries for extended operation, boast multi-gas detection capabilities using various sensors. These sensors are designed to measure specific gas types in precise units like parts per million (PPM) or percentages, ensuring accurate detection. Portable gas detectors play a vital role in safeguarding miners by enabling them to carry out immediate measurements of gas parameters. The devices generate alerts or warnings for gas accumulation, toxic gas presence, or oxygen level fluctuations. Additionally, they are lightweight, compact, and user-friendly, promoting easy integration into daily routines. These detectors contribute significantly to accident prevention by enabling continuous gas level monitoring. They protect mine workers from exposure to harmful gases and provide crucial early warnings of excess gas concentrations in specific mine tunnel locations before workers enter for tasks or maintenance work.

Portable gas detectors have become the standard for monitoring hazardous environments. These instruments, typically equipped with three or more sensors, are named "multi-gas detectors" as they can simultaneously detect various gases. Over the past two decades, advancements in sensor technology have driven the development of even more sophisticated portable detectors, offering broader gas detection capabilities tailored to specific needs and applications. Beyond portable units, fixed gas detection systems can be mounted strategically to monitor gas levels in a particular area continuously. These systems can also be equipped with wireless functionalities, enabling remote monitoring and data transmission for real-time analysis.

The shift towards advanced gas detection represents a significant improvement in workplace safety. In the past, the practice of using canaries in mines warned miners of danger, but at a tragic cost to the birds. Thankfully, this perspective has shifted dramatically. Today, workplace fatalities and accidents are no longer considered an acceptable cost of doing business. Advanced gas detectors represent a breakthrough in preventing workplace injuries and deaths. As these technologies evolve, we can expect even greater reductions in workplace accidents and a significant enhancement in overall safety. However, technology alone is not enough. Promoting awareness and training for mine workers regarding environmental parameters measurement is crucial. Equipping individuals working in potentially hazardous environments with the knowledge and skills to use gas detection devices effectively is essential. By prioritizing widespread awareness programs and comprehensive training, we can try to eliminate or drastically reduce workplace fatalities. This approach requires two efforts. First, proper training on the proper use of portable gas detectors is necessary. Second, ensuring regular calibration and maintenance of these devices is equally important.

For years, wired gas monitoring systems have been adopted in mining operations, ensuring worker safety and a healthy work environment. These systems involve strategically placed wired sensors throughout the mine, connected to a central control room for continuous monitoring and analysis of environmental parameters. A key advantage of wired systems is their reliable and stable data transmission to the control room. These strategically placed sensors can detect and measure crucial gases like methane, carbon monoxide, and hydrogen sulfide. Real-time data on gas levels allows operators to respond promptly to hazardous conditions and take necessary actions to ensure worker safety.  However, despite their effectiveness, wired gas monitoring systems face challenges in complex and large underground mines, as highlighted by Dohare (2016). The extensive wiring infrastructure required for installation is complex in underground mines.

Wired systems also present challenges related to maintenance and repair, particularly in hard-to-reach areas of underground mines. Furthermore, as mining operations delve deeper underground to meet growing resource demands, they encounter increasingly complex environments. Deep mine tunnels present significant challenges like higher temperatures, increased air pressure, and more harmful gases. These conditions necessitate more sophisticated and robust gas monitoring systems to ensure worker health and safety.

The mining industry should adopt advanced technologies and automation to address these limitations. Wireless real-time environmental monitoring systems utilizing the IoT and WSNs provide notable benefits. Their flexibility and scalability allow for real-time monitoring of environmental parameters without extensive wiring, streamlining deployment, and maintenance, particularly in deep underground mines. Additionally, integrating remote monitoring and control systems powered by Artificial Intelligence (AI) can significantly boost safety and efficiency. AI-driven systems can analyze real-time data, enabling informed decision-making and a proactive approach to safety and operational efficiency.

### 2.5 Underground Mine Communication Systems

According to Naik et al. (2024) and Reddy et al. (2023), wireless communication systems ensure miner safety in underground mines. Unlike surface environments, underground mines have complex, non-uniform structures with numerous intersections, cross-cuts, and tunnels. For stability, the rough surfaces and walls are often strengthened with wooden grids and metal frames. The establishment of reliable communication within underground mines is critical. However, several factors make this challenging, such as the dynamic structure of the mines with frequent changes due to excavation, the inherent instability of the geological environment, limited line-of-sight due to tunnels and bends, and harsh environmental conditions, including high temperature, humidity, dust and the presence of gases.

Murphy and Parkinson (1978), Bandyopadhyay et al. (2010), and Kennedy et al. (2011) categorize underground mine communication systems into four types: Through-the-Wire (TTW), Through-the-Earth (TTE), Through-the-Air (TTA), and Hybrid systems. TTE communication systems have been widely used for communication and emergency rescue due to their reliability. However, signal strength weakens in underground mines. TTW systems offer long-distance communication but are vulnerable to damage from incidents like roof falls and fires, causing communication breakdowns. Twisted pair cables and Fiber optics are used for signal transmission in TTW systems. TTA communication technology has drawn significant attention from researchers due to the increasing need for wireless communication and real-time monitoring of environmental parameters. However, underground mine environments pose substantial challenges for wireless signal propagation, impacting system performance.

The limitations of the TTW communication system, such as vulnerability to damage, have driven the mining industry to explore TTA technologies. TTA offers advantages like reliability, easier maintenance, and lower cost than TTW. Additionally, hybrid systems combine the strengths of TTW and TTA, resulting in a more widespread range of communication coverage for underground mines.

Reliable communication in underground mines is crucial for worker safety and operational efficiency. Fig. 2.8 illustrates the classification of communication systems. The TTE method utilizes the earth itself to transmit signals. Examples include PED Devices (for personnel emergency communication), TeleMag (for voice and data), Tram Guard (for avoiding collisions), and Subterranean Wireless Systems. TTW category relies on physical cables for signal transmission. It includes Magneto phones, Sound-powered phones, Bell signaling (simple alert system), Paging and Dial phones (for voice communication), Carrier current systems (utilizing power lines for communication), Hoist phones (connecting surface and underground), and Trolley current phones (using trolley wires for transmission). TTA method employs wireless technologies for communication. It encompasses Wireless Networks (i.e. WiFi for data transfer), Walkie-Talkies (for real-time voice communication), and Ultra-Wideband (UWB) communications (for short-range, high-bandwidth data).

Hybrid systems combine elements from different categories for improved coverage and functionality. Examples include RFID (Radio Frequency Identification) for asset tracking, Leaky Feeder Systems (using radiating cables for broader coverage), and Lamp Systems (integrating communication with mine lighting infrastructure). With these diverse communication systems, mine operators can select the most appropriate technology for their specific needs, ensuring a safe and efficient working environment for miners.

## 2.6 Recent Developments in Real Time Monitoring of Environmental Parameters and Communication Systems for Underground Mines

Recent advancements in wireless communication technologies have expanded their applications, enabling real-time monitoring of environmental parameters, tracking mine personnel, equipment, and vehicles, enhancing transportation and healthcare, and facilitating the installation of alert systems in underground mines.

According to Naik et. al (2024), the mining sector has incorporated emerging technologies to enhance work efficiency and safety. Like many other industries, mining is undergoing digital transformation to achieve automation and can significantly improve underground mining operations' productivity, efficiency, and safety. Reliable and cost-effective wireless communication is crucial for underground mines, and various technologies address this need. Fiber-optic communication supports underground mine communication, while Leaky Feeder systems are used for ventilation control and rescue communication.

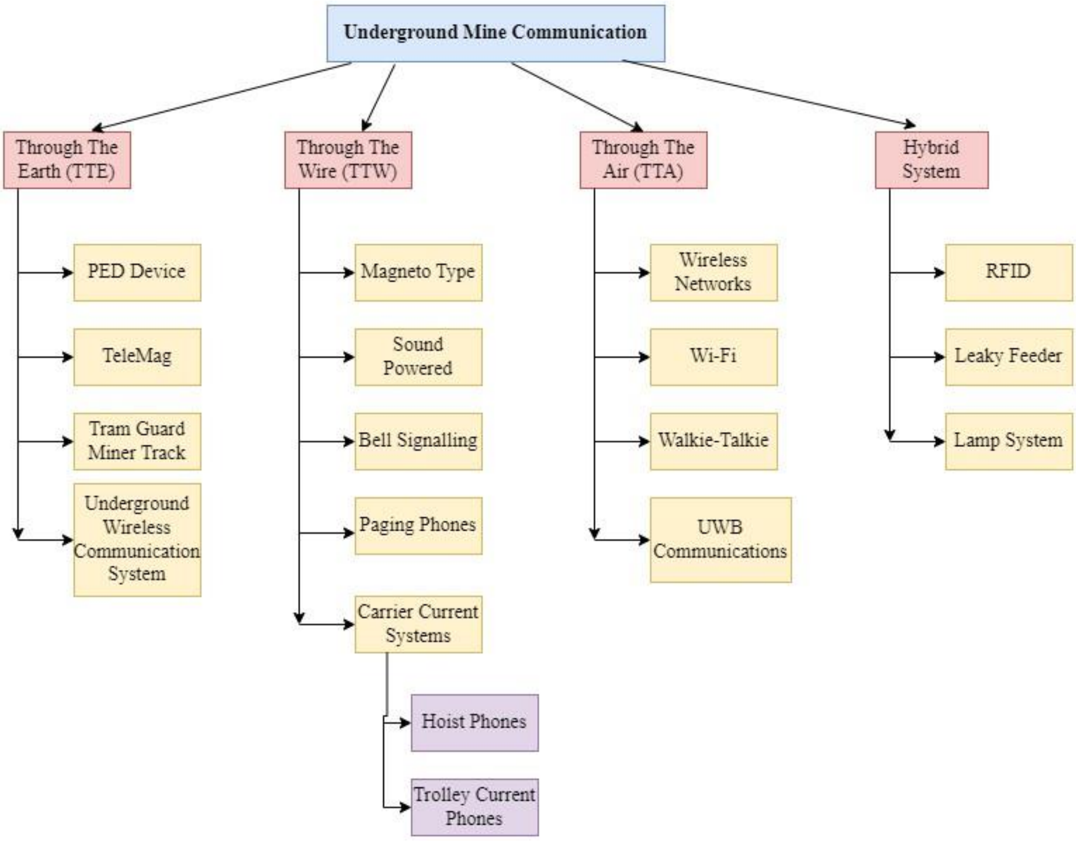


Fig. 2.8 Classification of communication systems in underground mines (Murphy and Parkinson (1978), Ranjan and Sahu (2014))

Radio Frequency Identification (RFID) aids access control and positioning, and Wireless Fidelity (Wi-Fi) monitors environmental parameters. Ultra Wide Band (UWB) technology is used for precise positioning, ZigBee for wireless communication and positioning, and 3G for multimedia surveillance. LTE/4G enhances environmental parameter monitoring and positioning, Bluetooth Low Energy (BLE) is utilized for explosive control and communication, and Long Range (LoRa) facilitates environmental parameter monitoring. Narrowband IoT (NB-IoT) supports unmanned operations and remote control. Reliable wireless communication is pivotal for successful underground mining operations.

However, challenges arise due to signal propagation issues in the confined, irregular structures and curved tunnels and the NLOS environment in underground mines. Limited network coverage significantly increases the complexity and cost of deploying real-time wireless communication systems for monitoring underground environmental parameters. Emerging radio frequency communication technologies, such as LoRa, LoRaWAN, and 5G, offer cost-effective solutions for achieving seamless real-time communication in these challenging underground environments.

Researchers have developed a Proof of Concept (POC) system enabled by ZigBee and LoRa technologies to monitor environmental parameters in underground mine sites and laboratory settings. They also proposed a methodology to facilitate data communication from the underground mine levels to the surface. The current solutions are summarized, including experimental evaluations, simulation results, proposed methodologies, and POC systems.

Moridi et al. (2014), investigated ZigBee-based wireless communication in underground mines. They achieved 100 meters of communication in straight tunnels and 70 meters in curved tunnels, observing data loss in curved tunnels of underground mines. Moridi et al. (2015), investigated a ZigBee-based PoC system to evaluate communication stability between ZigBee transmitter and receiver nodes in straight, curved underground mine tunnels. They found that branches and tunnel curvature affect packet loss and radio wave propagation. Sharifzadeh et al. (2015), analyzed radio wave propagation to determine path loss in various underground mine tunnel workplaces. This analysis aids in improving signal reception, sensor node localization, and miner tracking. Results may vary based on the mine site structure.

Patri and Nimaje et al. (2015), discuss a ZigBee-based system designed to monitor gas concentrations in coal mines using Wireless Sensor Networks (WSNs). However, the research study lacks essential detailed implementation. Gao et al. (2016), present a ZigBee-enabled smart helmet device designed to measure hazardous gas levels and use an infrared (IR) sensor to detect if mine workers remove their helmets. The system was implemented and tested in a laboratory setting, demonstrating its functionality in a controlled environment.

Behr et al. (2016), utilize a ZigBee communication module and Proteus simulation software to monitor changes in environmental parameters. Their study focuses on simulation results, with hardware implementation limited to the laboratory level. Joshi et al. (2017), investigate and analyze various sensor node arrangements in ZigBee networks with scenarios involving 12, 20, 30, 40, and 50 nodes. They conclude that a Wireless Sensor Network (WSN) design with a mesh topology is reliable for establishing a communication network. The study proposes a conceptual model and, based on simulation results, specifies the appropriate network topology for underground mining.

Moridi et al. (2018) propose a real-time wireless communication system using WSN and ZigBee to transfer data from underground mine sites to the surface. The paper presents a proposed model for this system. Chehri and Saadane et al. (2019) implemented a ZigBee-based system to measure temperature parameters in an underground mine site. However, the paper lacks detailed information about the implementation at the mine site.

Mishra et al. (2019), present a ZigBee-based IoT system with an IP-enabled gateway for real-time environmental monitoring of underground environments. The WSN system is implemented both in the laboratory and at a mine site, featuring a power management technique that achieved 140 meters of coverage between two routers. However, the research study lacks detailed information on the implementation at the mine site. Branch et al. (2020), designed a robust, low-complexity LoRaWAN system using LoRa relays in a mesh network configuration for controlling underground detonations. However, the system experiences signal strength drops due to non-line-of-sight conditions in underground mines.

Eldemerdash et al. (2020), implemented a ZigBee-based automated system that detects hazardous gases by attaching it to a mine worker’s helmet. This real-time monitoring system updates data in the control room and has been tested and implemented at the surface level. Reddy et al. (2023), developed a ZigBee-based system to monitor environmental parameters in underground mines. The system was tested in underground mines, but it was found that the communication range is short, and the signal strength significantly drops in curved tunnels.

Hidayat et al. (2019), implemented an air quality monitoring system using LoRa modules and a cloud platform in rural areas. The system establishes wireless communication over 800 meters between the transmitter and receiver, experiencing a

20% packet loss. The implementation was carried out at the surface level. Emmanuel et al. (2019), conducted a simulation study on the performance of LoRa wireless communication in mine areas, analyzing different frequency spread factors and multipath conditions. The study utilizes Rayleigh multipath and Additive White Gaussian Noise (AWGN) multipath channels for the simulation.

Tan et al. (2019), analyze the communication signal strength of LoRa modules using the Received Signal Strength Indicator (RSSI) value. They implement a LoRa-based system in an outdoor area to conduct this analysis. Anjum et al. (2019), implement a positioning system using LoRa RSSI fingerprinting, tested in LOS and NLOS environments to ensure reliable communication between the transmitter and receiver. The system is implemented at the surface level, with measurements taken to determine the path loss between the transmitter and receiver. Nikolakis et al. (2021), propose an IoT-based prototype using LoRa to monitor underground mine site data on a cloud platform. The system dynamically controls the ventilation system to reduce energy consumption. However, a more robust system is required to meet the safety aspects of underground mines.

Branch et al. (2020), developed a LoRa-based linear sensor network with relays and tags to transmit mine workers' location and equipment details in an underground mine. The system was tested on a small scale with two relays. Branch et al. (2020), designed a robust, low-complexity LoRaWAN system using LoRa relays in a mesh network configuration for controlling underground detonations. However, the system experiences signal strength drops due to NLOS conditions in underground mines.

Alam et al. (2021), implemented a LoRa-based system equipped with various sensors to transmit environmental parameters from one end to another. The system is tested and implemented at the open surface level. Reddy et al. (2022), developed a LoRa-based system designed to measure temperature and humidity parameters from one end to another. The system is implemented and tested at the open surface level. The studies reviewed focus on various implementations of ZigBee and LoRa-based systems for monitoring environmental parameters and ensuring safety in underground mines and other environments:

Research studies have investigated and evaluated the use of ZigBee and LoRa wireless communication technology in underground mines. These studies indicate that path loss occurs in branches and curved tunnels of underground mine levels, and non-line-of-sight situations impact communication. ZigBee-based wireless systems have been developed to sense and transfer environmental parameters within underground mines. The research highlights that mesh topology is the most effective choice for designing WSNs to monitor and communicate within these networks. Despite some studies lacking implementation details, the findings suggest that ZigBee-based wireless monitoring systems can be effectively used for data communication in underground mining environments. Additionally, LoRa, a small, low-power, and cost-effective wireless communication module, has been implemented at the surface level in outdoor environments to monitor environmental parameters. Various studies have also explored the implementation of wired and WSNs for monitoring environmental parameters in underground mines.

Overall, the interdisciplinary research study has advanced the development of reliable and robust systems for collecting and transmitting various environmental parameters in underground mines. There is a need to develop low-cost, custom-designed systems with specific architectures suitable for underground mine structures for real-time monitoring using wireless communication technologies. Additionally, integrating IoT-enabled gateway technology with industrial-standard gas sensors in underground mines can facilitate real-time data collection and transmission of parameters to the surface. This approach offers a more reliable and accurate method for preventing hazards in underground mines on a continuous 24x7 basis.

## 2.7 Summary

The literature review addresses the safety concerns of the underground mine environment, highlighting the sources of mine gases and their threshold limits. It emphasizes the necessity of real-time monitoring of environmental parameters to ensure the safety of mine workers. The review describes the development of gas monitoring systems and the evolution of monitoring systems in underground mines, from canary birds to modern wireless sensors. The adoption of advanced wireless communication technology offers significant benefits for monitoring underground mine conditions. However, the mining industry fails to adopt these technologies due to inherent challenges. Researchers have focused on developing wireless communication-based real-time systems for underground mines. IoT-based real-time monitoring systems are expected to aid the mining industry in monitoring environmental parameters and taking preventive measures to mitigate or eliminate abnormal incidents. The mining industry is undergoing a significant transformation with the application of Industry 4.0 principles.

Chapter 3 describes the design and development of a reliable and cost-effective real-time environmental parameters monitoring system (RTEPMS) for underground mines.

# CHAPTER 3

# 3. DESIGN AND DEVELOPMENT OF A RELIABLE AND COST-EFFECTIVE REAL-TIME ENVIRONMENTAL PARAMETER MONITORING SYSTEM (RTEPMS)

The existing systems for monitoring environmental parameters in underground mines have notably improved safety measures. However, the major limitation of the system is the manual measurement of environmental parameters in underground mines. Data collection can be risky and time-consuming for miners. This traditional approach involves periodic visits to specific areas for data measurement, leading to delayed detection of hazards due to the lack of real-time access. To address these issues, implementing a real-time environmental monitoring system in underground mines using IoT technologies offers significant advantages.

## 3.1 System Methodology to Implement Real Time Environmental Parameters Monitoring System (RTEPMS) in Underground Mines

The research study starts by defining the current work system and identifying the causes of gas hazards in underground mines through a systematic literature survey. This involved an in-depth study and field visits to underground mines to identify the components necessary for developing an IoT-enabled wireless real-time monitoring system. Research components such as sensors, microcontroller development boards, wireless communication modules, and storage media like cloud platforms or local storage SD cards were chosen based on several factors.

Following the selection of appropriate components, the development process for an IoT-enabled real-time monitoring system to measure environmental parameters is commenced.

The development process involves the integration of these components and establishing wireless communication between modules to transmit data in real time. Once the system is developed for real-time environmental parameter measurement, it undergoes testing in the laboratory to assess system performance, calibrate sensors, and check the performance of communication modules. After successful testing in the laboratory, the system is tested in two underground gold mines. The findings of this research study will provide recommendations for implementing the developed monitoring system in underground mines.

The development of IoT-enabled wireless communication systems for monitoring environmental parameters in underground mines involves integrating technological advancements to monitor changes at mine sites. The following methodology will guide the design and development of an environmental parameters monitoring system for underground mines. The detailed methodology is outlined in a flowchart, as shown in Fig. 3.1.

a) The first step involves the design and development of an IoT-enabled wireless communication system based on ZigBee communication modules or Long Range (LoRa) communication modules. This system will monitor environmental parameters in real time within a laboratory setup. A separate system is developed using ZigBee modules and LoRa modules to evaluate wireless communication modules' performance and communication range. Additionally, the values measured by sensors from this system will be validated using portable multi-gas detectors.

b) Selection of an underground mine for field investigations and to carry out experimentation at the mine site.

c) Experimental investigations will be conducted in the underground mines to establish reliable communication using ZigBee or LoRa wireless communication modules, considering controllable and uncontrollable environmental and communication parameters.

- Controllable parameters in underground mines include tunnel geometry (shape, size, tilt, turns, and curves) and ZigBee or LoRa wireless communication factors such as node deployment based on LOS and NLOS, network topology, throughput, and energy consumption.

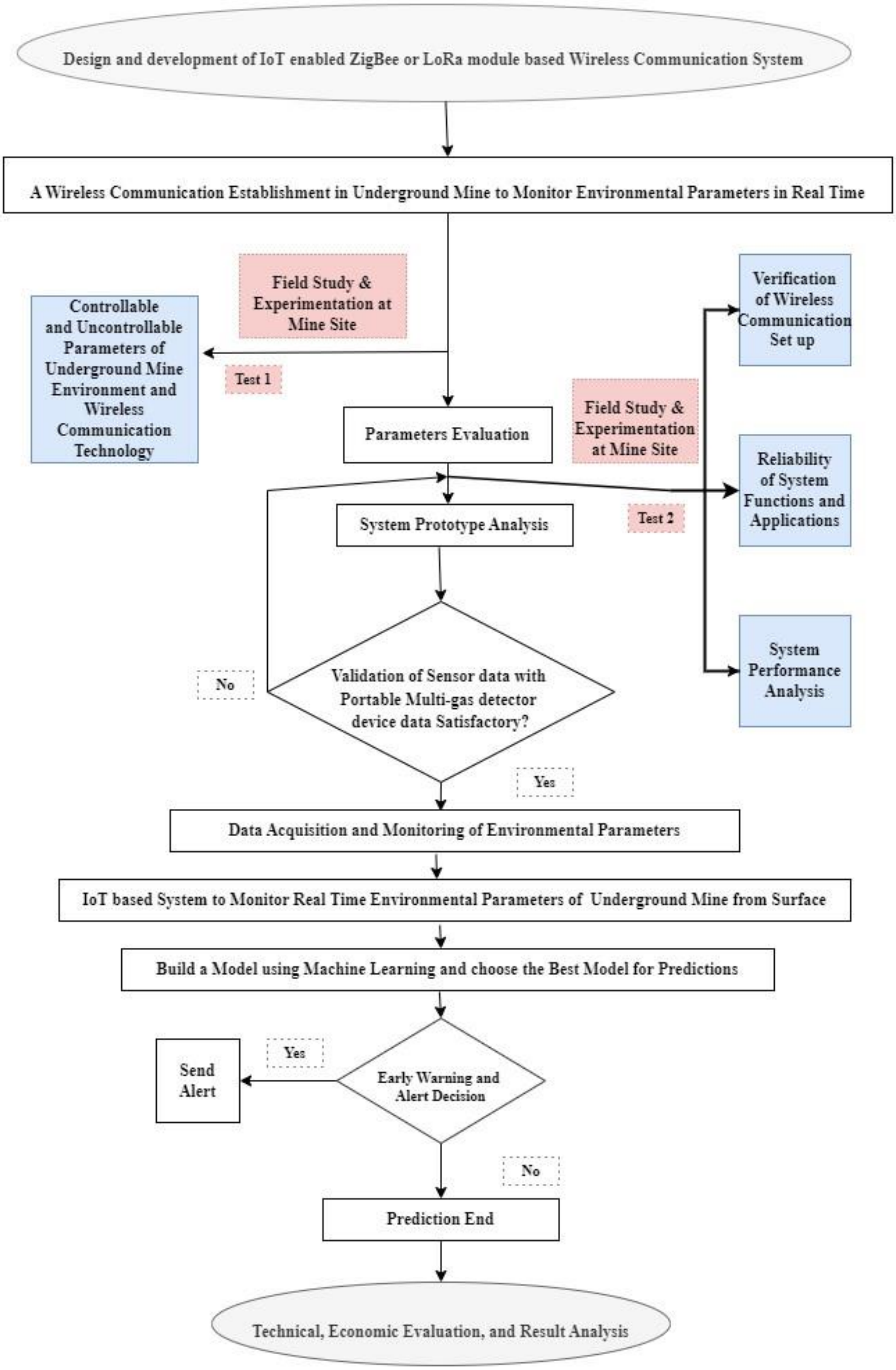


Fig. 3.1 System Methodology to Implement RTEPMS in Underground Mines

- Uncontrollable parameters in underground mines encompass tunnel wall characteristics (distortion, roughness), operating frequency, obstacles like dump trucks and LHD machines (Load Haul Dump), permeability, and rock mass conductivity. Similarly, ZigBee or LoRa wireless communication uncontrollable parameters involve data packet routing (number of hops), network congestion, and data packet reception failure.
- A separate ZigBee and LoRa module-based wireless communication system is utilized for real-time environmental parameter measurement in underground mines. Data transmitted by the module is continuously assessed at both the transmitter and receiver ends of the system.
- Experiments are conducted to determine the maximum distance in different areas of the underground mine tunnel with LOS and NLOS conditions. Received Signal Strength Indication (RSSI) value to analyze the signal strength between transmitter and receiver.
- In case sensor-measured environmental parameters exceed set thresholds, an alarm sound will activate to alert mine workers.

d) A separate ZigBee and LoRa module based wireless communication is established by identifying the underground mine key parameters affecting signal transmission and determining the maximum reliable communication distance between the transmitter and receiver communication modules at various underground mine locations.

- The system is designed to integrate multiple gas sensors and a temperature and humidity sensor for real-time environmental parameter monitoring.
- Experimentation is conducted to achieve real-time monitoring of environmental parameters in an underground mine. This includes evaluating communication technology at the system level, analyzing system performance, and performing data analysis on test results. Thus, quantifying these parameters is crucial for designing a reliable ZigBee or LoRa-based wireless communication system for underground mine proximity.

e) Validation of the sensor data measured from various gas sensors of ZigBee or LoRa modules based on a real-time wireless communication system with data measured from portable multi-gas detector devices in an underground mine.

f) Design and development of an extended wireless network for real-time monitoring of environmental parameters, taking into account factors like network topology, RSSI value between the Transmitter and Receiver, energy efficiency, frequency bandwidth, network performance, operating frequency range of LoRa or ZigBee modules, and specific requirements within underground mine locations.

g) Design and development of an IoT-enabled system based on ZigBee or LoRa communication modules to monitor real-time environmental parameters of the underground mine tunnel from the surface control room.

h) Analyzing real-time environmental data to build a predictive machine learning model for an early warning system against gaseous hazards in the underground mine.

i) A machine learning model is used to forecast gas concentrations and generate early warnings in the underground mine.

j) Systematically estimating technical and economic evaluations.

k) Utilizing the developed systems to recommend appropriate environmental parameter control or mitigation strategies in the vicinity of underground mining operations.

Real-time monitoring is crucial for improving safety in underground mines, especially with the integration of IoT technology. This IoT-enabled system comprises multiple gas sensors, temperature and humidity sensors, and a development board strategically placed within mine tunnels to instantly capture and transmit environmental data. This real-time system helps to identify hazardous situations and enables timely actions to safeguard mine workers. The IoT-based architecture of this real-time system allows data storage both locally, using an SD card, and on a cloud platform for convenient access when needed. Additionally, the adoption of IoT technology in underground mines enables supervisors to remotely monitor and control tasks like environmental parameters monitoring, ventilation management, and emergency responses. This system empowers mine workers, gives confidence in addressing safety incidents promptly, and reduces mine personnel entering hazardous areas, thus minimizing risks effectively.

### 3.2 Selection of Essential Research Components for the Development of a Real Time Environmental Parameters Monitoring System (RTEPMS)

Choosing the right components for a Real-Time Environmental Parameters Monitoring System (RTEPMS) is crucial for developing an effective monitoring system in underground mines. These components must accurately measure and monitor various parameters within the mine environment. Key considerations in selecting research components for IoT-enabled systems include their reliability, compatibility, sensitivity, and cost-effectiveness.

In developing the RTEPMS, sensor selection is based on their characteristics and responsiveness to detect specific parameters. Gas sensors like "MG811 Air carbon dioxide ($CO_2$)" and "MHZ19c NDIR $CO_2$" for $CO_2$ measurement, "MQ4 gas sensor" for Methane ($CH_4$), "MQ7 gas sensor" for carbon monoxide (CO), "MQ-136 gas sensor" for Hydrogen Sulphide ($H_2S$), "MQ-8 gas sensor" for Hydrogen ($H_2$), and "MQ-135 gas sensor" for air quality and smoke detection are chosen for their effectiveness in gas concentration detection. Temperature and humidity sensors like "DHT-11" or "DHT-22" are selected to measure temperature and humidity environmental conditions accurately.

These components are cost-effective and suitable for effectively measuring environmental parameters in underground mines. Compatibility with the system's data acquisition and processing abilities using Microcontroller development boards is also a crucial factor in their selection. Furthermore, communication modules such as LoRa or ZigBee are integrated into the system to enable long-distance data transmission. For RTEPMS development in underground mines, deploying a system with long-range wireless communication capabilities is recommended to efficiently transmit data from underground mine tunnels to the surface.

The components essential for the development of an IoT-enabled RTEPMS are as follows:

*a) Sensors*: Sensors are placed strategically within the underground mine to detect gases such as $CO_2$, CO, $CH_4$, $H_2S$, NO, and $H_2$, as well as temperature and humidity.

*b) Wireless Communication Modules*: LoRa modules operate at various frequencies and facilitate long-range communication between transmitter and receiver. ZigBee modules facilitate wireless communication between the transmitter and receiver. The transmission of data is possible with the integration of sensors and wireless communication modules such as ZigBee or LoRa with microcontroller boards to establish reliable wireless communication.

*c) Development Board:* Microcontrollers like ESP32, ESP8266, and Arduino boards are preferred due to their processing capabilities, connectivity with sensors, and ease of integration with necessary components.

*d) Storage device and cloud platform:* To store the sensor data locally or in a cloud platform for further analysis.

*e) User Interface:* The user interface enables mine personnel to monitor gas levels, set threshold values, and configure the alarm system.

### 3.2.1 Selection of Sensors for Monitoring Environmental Parameters in Underground Mines

According to Naik et al. (2024), the selection of suitable gas sensors is crucial for the development of RTEPMS to ensure accurate and reliable gas detection. The RTEPMS is designed to monitor gases commonly found in underground mines, such as carbon dioxide, carbon monoxide, methane, hydrogen sulfide, nitrogen dioxide, and oxygen, along with environmental factors like temperature and humidity.

The selection criteria for these sensors are sensitivity, response time, operating range, reliability, and stability. Moreover, they must operate in harsh mining conditions such as dust, temperature, and humidity variations and vibrations. Various sensor technologies exist to detect different gases. For instance, semiconductor sensors like metal oxide semiconductors (MOS) detect $CO_2$, CO, $CH_4$, $H_2S$, $NO_2$, $H_2$, temperature, and humidity.

These sensors detect target gases by changing their electrical resistance. Calibration is essential to ensure these sensors operate effectively. It involves exposing them to known gas concentrations and adjusting their output accordingly. Various sensor specification details are represented here.

- ***MG811 Air Carbon Dioxide ($CO_2$):*** To measure the concentration of $CO_2$ in the air. It consists of a sensor module containing a chemical element that reacts to $CO_2$ and an electronic circuit that converts the sensor's output into a measurable signal. A microcontroller or other electronic device can then read and interpret this signal. It is used in Heating, Ventilation, and Air Conditioning (HVAC) systems, greenhouses, and other real-time monitoring applications.
- ***MHZ19C NDIR $CO_2$ Module:*** 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 and UART and PWM output capabilities. Fig. 3.2 represents the carbon dioxide gas sensors.

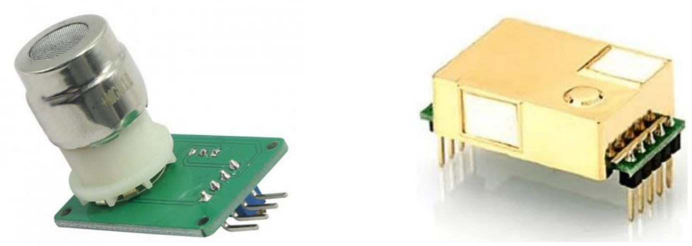
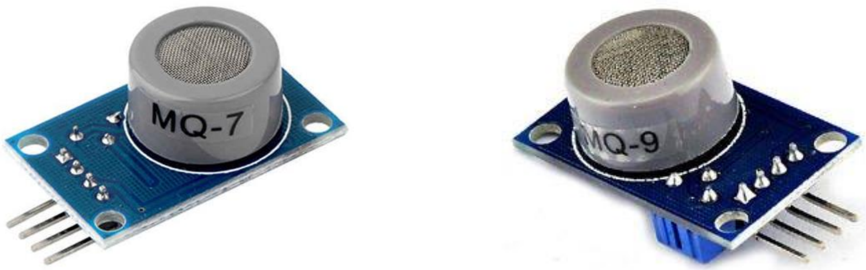

(a) (b)

Fig. 3.2 Sensors: (a) MG811 Air Carbon Dioxide Sensor and (b) MHZ19C NDIR $CO_2$ Module Sensor (Zaharudin et al. (2014))

- ***MQ4 - Methane Gas:*** To detect the presence of methane 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 variations of temperatures and humidity levels. Fig. 3.3 represents the methane gas sensor.

Fig. 3.3 MQ4 - Methane Gas Sensor (Fakra et al. (2020))

- ***MQ7 - 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.
- ***MQ9 - Carbon Monoxide (CO):*** Similarly, the MQ-9 gas sensor is highly sensitive to carbon monoxide, methane gas, and LPG gas. Fig. 3.4 represents the carbon monoxide gas sensors.



(a) (b)

Fig. 3.4 Sensors: (a) MQ-7 Carbon Monoxide Sensor and (b) MQ-9 Carbon Monoxide Sensor (Sai et al. (2019))

- ***MQ136-Hydrogen Sulfide ($H_2S$):*** To measure the presence of hydrogen sulfide 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. Fig. 3.5 represents the hydrogen sulfide gas sensor.

Fig. 3.5 MQ-136 Hydrogen sulfide Sensor (Sanger et al. (2019))

- ***MQ-8 Hydrogen:*** The MQ-8 Hydrogen ($H_2$) gas sensor is popular for detecting environmental hydrogen gas concentrations. The MQ-8 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. Fig. 3.6 represents the hydrogen gas sensor.

Fig. 3.6 MQ-8 Hydrogen Sensor (Ayub et al. (2020))

- ***MQ-135 Air Quality Gas Sensor:*** To detect various gases, including $NH_3$, NOx, alcohol, Benzene, smoke, and $CO_2$. It is a highly sensitive sensor that can detect low concentrations of these gases and is often used in air quality monitoring systems and other applications where air quality needs to be monitored. The sensor uses a heated metal oxide semiconductor to detect the gases, and the output is an analog voltage corresponding to the concentration of the gas being detected. Fig. 3.7 represents the air quality gas sensor sensor.

Fig. 3.7 MQ-135 Air Quality Sensor (Sai et al. (2019))

- ***DHT-11/22 Temperature and Humidity Sensor:*** 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. The DHT-11 temperature and humidity sensors contain NTC temperature and humidity measurement components. DHT-11 sensor 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. DHT-22 sensor to measure the temperature and humidity of an environment connected to an Arduino board. DHT 22 sensor contains a humidity sensing component and a thermistor temperature sensor. A semiconductor thermistor consists of a variable resistor, As the resistance changes with a change in the temperature. Fig. 3.8 represents DHT-11 and DHT-22 temperature and humidity sensors.

  According to the sensors datasheets, Table 3.1 represents the sensitivity of various MQ series gas sensors and other related sensors. The sensitivities are typically given in parts per million (ppm) or other relevant units based on available data from datasheets.


(a) (b)

Fig. 3.8 Sensors: (a) DHT-11 Temperature and Humidity Sensor and (b) DHT-22 Temperature and Humidity Sensor (Islam et al. (2020))

Table 3.1 Sensitivity of various MQ series gas sensors and other related sensors

| Sensor | Gas Detected | Sensitivity Range |
|---|---|---|
| MG811 | $CO_2$ | 400 to 5,000 ppm |
| MHZ19C NDIR $CO_2$ Module | $CO_2$ | 400 to 5,000 ppm |
| MQ-4 | $CH_4$ | 200 to 10,00 ppm |
| MQ-7 | CO | up to 100 ppm |
| MQ-9 | CO and $CH_4$ | CO: 10 to 100 ppm,<br>$CH_4$: 100 to 10,000 ppm |
| MQ-136 | $H_2S$ | 1 to 200 ppm |
| MQ-8 | $H_2$ | 100 to 1000 ppm |
| MQ-135 | Air Quality (NH3, Alcohol, Benzene, Smoke, $CO_2$) | 10 to 1,000 ppm for $NH_3$, Alcohol, Benzene, 300 to 5000 ppm for $CO_2$ |
| DHT-11 | Temperature and Humidity | Temperature: 0-50°C,<br>Humidity: 20-90% |
| DHT-22 | Temperature and Humidity | Temperature: -40-80°C,<br>Humidity: 0-100% |

### 3.2.2 Selection of Development Boards for Monitoring Environmental Parameters in Underground Mines

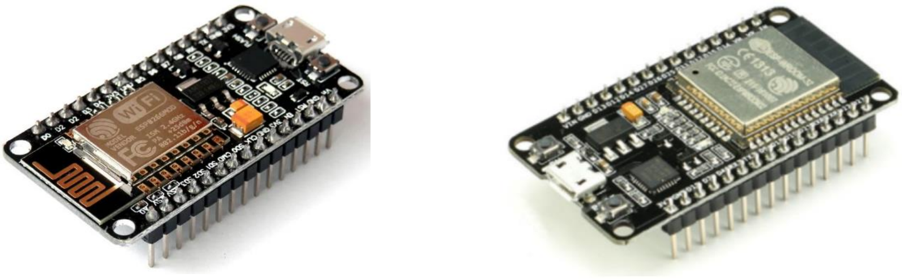
Arduino UNO, Arduino Nano, ESP32, and ESP8266 Node MCU are microcontroller-based development boards that are open-source platforms, easy to use, and have a wide range of libraries and community users. It has a simple programming interface and a wide range of Input/Output options.

- ***Arduino UNO and Arduino Nano boards:*** The Arduino Uno is a microcontroller based on ATmega328P. Arduino UNO and NANO is an open-source development board based on an 8-bit microcontroller. It facilitates communication by connecting it to a computer and programming with Arduino IDE software. Fig. 3.9 represents the Arduino UNO board and Arduino Nano board.

(a) (b)

Fig. 3.9 Development Boards: (a) Arduino UNO board and (b) Arduino Nano board (Suganthi et al. (2021))

- ***ESP32 Development Board (Wifi and Bluetooth) and ESP8266 Node MCU Wi-Fi module:*** The Wi-Fi enabled ESP32 development board transmits data to the cloud database to store and monitor real-time data anytime and anywhere. On the other hand, the ESP 32 development board developed by the Espressif system is low-power based on a high-performance microcontroller with integrated Wi-Fi and Bluetooth capabilities. 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 than Arduino board. The development board ESP 8266 NodeMCU Wi-Fi module enables the microcontroller to load data to the IoT platform. It Supports UART or GPIO data communication interface. Fig. 3.10 represents the ESP8266 Node MCU and ESP32 development board.



(a) (b)

Fig. 3.10 Development Boards: (a) ESP8266 Node MCU Wi-Fi module and (b) ESP32 Development Board (Wifi and Bluetooth) (Islam et al. (2020) and Anderies et al. (2020))

### 3.2.3 Selection of Wireless Communication Modules for Monitoring Environmental Parameters in Underground Mines

ZigBee is a low-power, low-data rate wireless communication technology suitable for use in underground mines where there may be limited power and limited connectivity. LoRa operates in unlicensed frequency bands that use a Low Power Wide Area Network (LPWAN) to transmit data long distances. LoRa modules are designed to integrate with Internet of Things (IoT) applications, including smart building, smart city, agriculture, and industrial automation applications. Smart building applications include HVAC control (Heating, Ventilation, and Air Conditioning), energy management, parking, and access control within the building. Smart city applications such as traffic monitoring, parking, and lighting. To monitor soil moisture, temperature, and water control applications in agriculture. Industrial automation includes monitoring industrial equipment, tracking and controlling machines, and monitoring environmental parameters.

ZigBee-based real-time environmental parameters monitoring system measures gas levels, temperature, and humidity to prevent accidents or significant hazards and improve working conditions for miners.

The LoRa module used to monitor underground mine environmental parameters is a good option compared to other wireless communication technologies. It provides long-range wireless communication to transmit data over large distances.

Different wireless communication modules, LoRa 433 MHz, ZigBee modules, and LoRa 868 MHz modules, are described here.

- ***XBEE_S2C Pro ZigBee module:*** XBee Pro S2C is an 802.15.4 Zigbee Radio Frequency Module with a 63mW, 3.2dBi Antenna is a wireless communication module that operates in the 2.4 GHz frequency band. The ZigBee module is cost-effective and supports multicasting for automation worldwide. XBee S2C Pro model contains SiliconLabs EM357 SoC Transceiver Chipset with a data rate of 250kbps maximum, as shown in Fig. 3.11. The Sensitivity of the model is -101 dBm, and the output power is 63mW with an SPI & UART interface Type. ZigBee module applications include remote industrial control and monitoring, wireless data acquisition, and long-range communication.

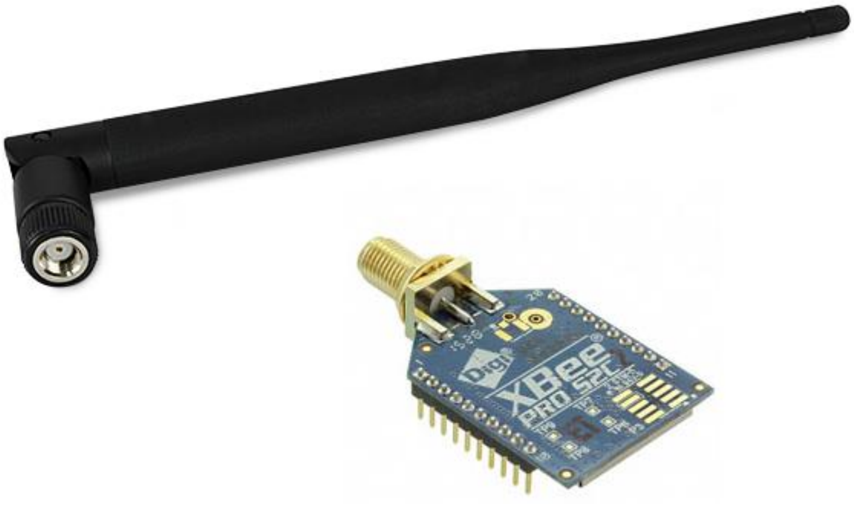
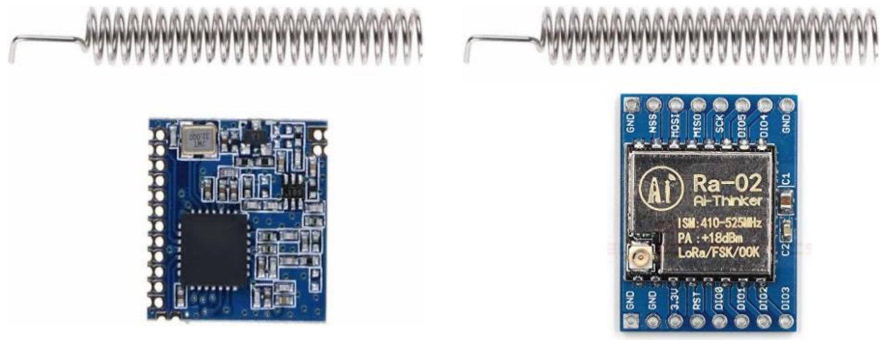


Fig. 3.11 XBee Pro S2C ZigBee Radio Frequency Module (Reddy et al. (2023))

- ***SX1278 (433 MHz) LoRa module & SX1278 Ra-02 (433 MHz) LoRa module:***

Sx1278 LoRa-02 Radio Frequency module is used for long-range wireless communication. Its low power (3.3 v) and high sensitivity is -148 dBm. In India, the unlicensed frequency range of the LoRa module is 865 MHz to 867 MHz, but the 433 MHz frequency-based LoRa modules can be used for academic purposes. The Sx1278 LoRa module has a high sensitivity of -148 dBm with a +20 dBm power output, as shown in Fig. 3.12.



(a) (b)

Fig. 3.12 LoRa Module: (a) SX1278 (433 MHz) LoRa Module and (b) SX1278 Ra-02 (433 MHz) LoRa Module (Reddy et al. (2023) and Moiroux-Arvis et al. (2022))

- ***HPD13A - SX1276 (868 MHz) LoRa module:***

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, high-efficiency solution for real-time wireless applications.

Moiroux-Arvis et al. (2022), described the LoRa wireless communication transceiver module HPD13A-SX1276 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 HPD13A-SX1276 module supports LoRa and Frequency Shift Keying (FSK) modulation schemes and has a maximum output power of 20 dBm (100 mW). 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, designed and developed by HPDTeK is used in RTEPMS as shown in Fig. 3.13.

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. Table 3.2 represents comparison of the various wireless communication modules.

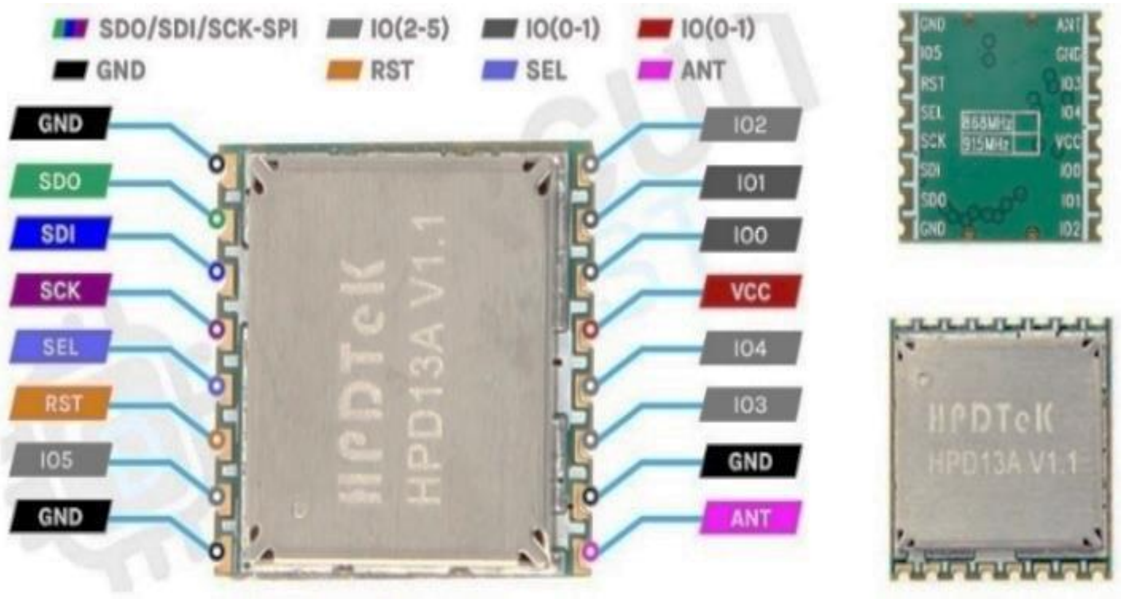


Fig. 3.13 HDP13A V1.1 LoRa Module Pin Configuration (Naik et al. (2024)

**Table 3.2 Comparison of the various wireless communication modules**

| **Feature/ Module** | **XBEE_S2C Pro ZigBee module** | **SX1278 (433 MHz) LoRa module** | **SX1278 Ra-02 (433 MHz) LoRa module** | **HPD13A - SX1276 (868 MHz) LoRa module** |
|---|---|---|---|---|
| Frequency | 2.4 GHz | 433 MHz | 433 MHz | 868 MHz |
| Technology | Zigbee (IEEE 802.15.4) | LoRa (Long Range) | LoRa (Long Range) | LoRa (Long Range) |
| Max Data Rate | 250 kbps | 300 kbps | 300 kbps | 300 kbps |
| Power Output | Up to 3 dBm | Up to 20 dBm | Up to 20 dBm | Up to 20 dBm |
| Sensitivity | -102 dBm | -148dBm | -148dBm | -148dBm |
| Modulation & Interface | DSSS (Direct Sequence Spread Spectrum) & UART, SPI | LoRa (Chirp Spread Spectrum) & SPI | LoRa (Chirp Spread Spectrum) & SPI | LoRa (Chirp Spread Spectrum) & SPI |
| Security | AES-128 Encryption | No native encryption | No native encryption | No native encryption |
| Antenna Type | External | External | External | External |
| Cost | Moderate | Low | Low | Moderate |

### 3.2.4 Selection of Cloud Platform for Monitoring Environmental Parameters in Underground Mines

Cloud platforms play a vital role in the Internet of Things (IoT) system by providing the infrastructure, services, and tools necessary for managing and analyzing the huge amounts of data generated by connected devices. These platforms offer scalable solutions for data storage, processing, visualization, and real-time analytics, enabling industries to develop and deploy IoT applications efficiently.

- ***ThingSpeak IoT Platform:***

Naik et al. (2024) used the ThingSpeak platform to visualize the real-time environmental parameters. ThingSpeak is an Internet of Things (IoT) analytics cloud platform that allows users to aggregate, visualize, and analyze real-time data in the cloud platform. The main key features of ThingSpeak are Data Collection, Real-Time Visualization, data analysis, and Event-Based Actions. Data collection is done through HTTP, MQTT, or other protocols. Data is stored in channels, each with up to eight fields and location and status fields. Real-time visualization by creating instant visualizations of live data, enabling real-time system monitoring. Data analysis allows the creation of predictive models directly on the platform. Event-based action can set triggers to execute code or send notifications based on specific data conditions. ThingSpeak platforms are utilized in environmental monitoring, energy usage tracking, smart farming, and academic research. It facilitates rapid prototyping and development of IoT applications without needing extensive backend infrastructure

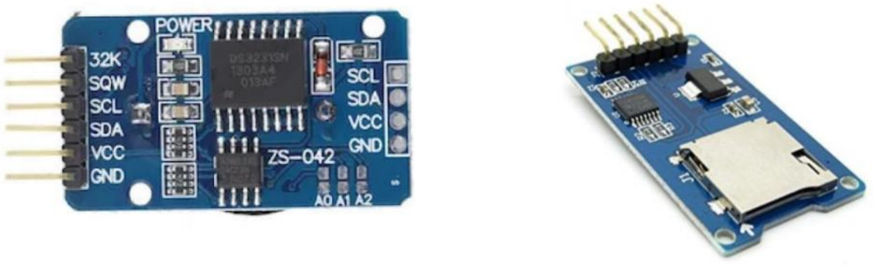
- ***Blynk IoT platform:***

Anderies et al. (2020) stated that Blynk is a comprehensive low-code IoT platform designed for businesses and developers to connect devices to the cloud, create mobile and web applications, and manage users and devices efficiently. The platform offers a suite of tools and features to streamline the development, deployment, and management of IoT projects.

### 3.2.5 Selection of Other Components for Monitoring Environmental Parameters in Underground Mines

The Real-Time Clock (RTC) module keeps track of the current time and date even when the processing device microcontroller is powered off. It typically uses a small battery to maintain the time. The SD card module provides a microcontroller or other device with a storage medium for large amounts of data.

- ***RTC module:*** The RTC DS3231M module is a real-time clock module that uses the DS3231M IC. The DS3231M is a low-cost, high-accuracy I2C real-time clock with an integrated temperature-compensated crystal oscillator (TCXO) and crystal. The module provides accurate timekeeping for microcontroller based projects.
- ***SD card module:*** An SD card module for Arduino is a device that allows an Arduino 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 Arduino to read and write data to the SD card can be used for storing and retrieving sensor data. Fig. 3.14 represents the RTC module and SD card module.



(a) (b)

Fig. 3.14 Other Modules: (a) RTC Module and (b) SD card Module
(Naik et al. (2024))

### 3.2.6 Consideration of RSSI, Spreading Factor, and Code Rate for Monitoring Environmental Parameters in Underground Mines Factors

The Received Signal Strength Indicator (RSSI) indicates the signal strength of wireless communication. The Semtech chip can use Chirp Spread Spectrum (CSS) or Frequency Shift Keying (FSK) as modulation techniques. LoRa, using CSS, excels in long-range communication and power efficiency, ideal for IoT applications. FSK offers higher speed but lower sensitivity and range. In CSS, the chirp signal's frequency changes linearly over time, influenced by the spreading factor (SF). LoRa data is encapsulated in a frame, with the payload data spread based on the SF. The SX1278 LoRa transceiver module was used with SF values from 7 to 12. Sensitivity and coverage distance depend on SF and bandwidth (BW), with sensitivity up to -135 dBm at SF 12 and BW 125 KHz. Increased bandwidth results in decreased sensitivity due to thermal noise. To achieve lower sensitivity, increase SF or decrease BW. Table 3.3 represents the Semtech SX1276/1278 LoRa modules receiver sensitivity in dBm.

Table 3.3 Semtech SX1276/1278 LoRa receiver sensitivity in dBm (Lavric et al. (2018))

| SF<br>BW | 6 | 7 | 8 | 9 | 10 | 11 | 12 |
|---|---|---|---|---|---|---|---|
| **125kHz** | -116 | -121 | -124 | -127 | -130 | -132.5 | -135 |
| **250kHz** | -113 | -118 | -121 | -124 | -127 | -129.5 | -132 |
| **500kHz** | -110 | -115 | -118 | -121 | -124 | -126.5 | -129 |

The other important parameter for communication is Code Rate (CR) because it is observed that the increase in BW increases the bit rate, but the coverage distance decreases. For instance, the LoRa-based system can be configured with SF=12, BW = 125 KHz, and CR = 4/6.

### 3.3 Development of a Real Time Environmental Parameters Monitoring System (RTEPMS) to Measure Environmental Parameters

The list of LoRa and ZigBee module-based hardware proof of concept (POC) developed for measuring environmental parameters in underground mines is described in the following subsections.

- SX1278 (433 MHz) LoRa module-based wireless communication system to measure Temperature and Humidity
- SX1278 Ra-02 (433 MHz) LoRa module-based IoT system with the Blynk application to measure Temperature and Humidity

- XBEE_S2C Pro ZigBee module-based wireless communication system to measure environmental parameters
- SX1278 Ra-02 (433 MHz) LoRa module-based IoT system to measure environmental parameters
- HPD13A - SX1276 (868 MHz) LoRa module-based IoT system to measure environmental parameters

### 3.3.1 SX1278 (433 MHz) LoRa module-based wireless communication system to measure Temperature and Humidity

LoRa-based system includes LoRa wireless communication modules SX1278 (433 MHz), DHT-22 sensor, and development modules. The LoRa transmitter module encodes and modulates the generated data to transmit through the antenna to the LoRa receiver module. A system prototype is designed with the integration of the DHT-22 sensor to Arduino UNO/Nano board to monitor the result in a serial monitor tool and 16X2 LCD. DHT 22 sensor can measure temperature up to $50^0$ C and humidity up to 90%. The architecture of the real-time environmental parameter monitoring system with the LoRa transmitter and LoRa receiver module with the integration of the sensor is shown in Fig. 3.15.

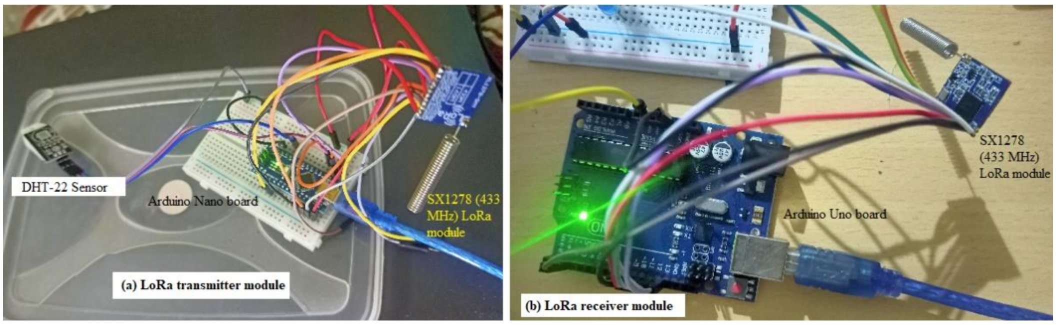
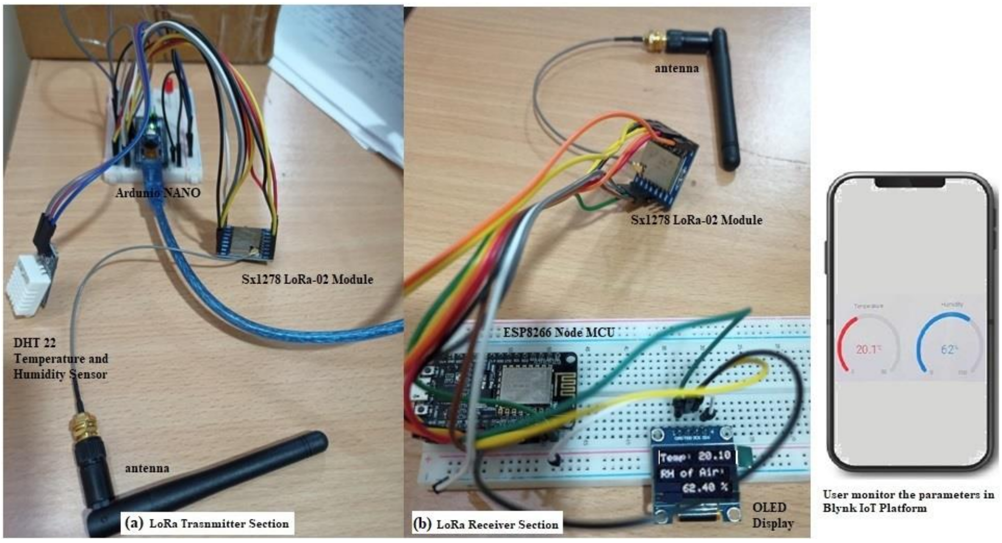


Fig. 3.15. SX1278 (433 MHz) LoRa module-based wireless communication to measure Temperature and Humidity (Reddy et al. (2022))

### 3.3.2 SX1278 Ra-02 (433 MHz) LoRa module-based IoT system with the Blynk application to measure Temperature and Humidity

Figure 3.16 illustrates the LoRa-based IoT system with the Blynk application in a laboratory setup. The transmitter section (a) has LoRa modules and a DHT-22 sensor connected to an Arduino NANO board. The receiver section (b) features a NodeMCU ESP8266 Wi-Fi module linked to a LoRa receiver module and an OLED display unit, which shows the sensed parameters. This data is also accessible on the Blynk IoT platform via a web or mobile application dashboard. The temperature and humidity values recorded were 20.1°C and 61.4%, respectively, displayed on both the display unit and the Blynk IoT mobile platform.



(a) (b)

Fig. 3.16 (a & b) SX1278 Ra-02 (433 MHz) LoRa module-based wireless communication to measure Temperature and Humidity (Reddy et al. (2022))

### 3.3.3 XBEE_S2C Pro ZigBee module-based Wireless Communication to Measure Environmental Parameters

The framework of the developed system, depicted in Fig. 3.17, includes ZigBee transceiver modules, an Arduino microcontroller board, and various sensors for measuring environmental parameters. This system is deployed in two underground mines to monitor environmental conditions, and the experimental measurement process is conducted accordingly. The system integrates Arduino UNO boards, ZigBee modules, and sensors for measuring target gases and other parameters to establish wireless communication. Detailed hardware components, various sensors, and schematic representation of the ZigBee transmitter and receiver modules are shown in Fig. 3.18. The ZigBee transmitter section comprises a microcontroller integrated with metal oxide semiconductor gas sensors such as the MQ-8, MQ-9, MQ-135, and DHT-11. The ZigBee receiver section includes a microcontroller, a ZigBee module, a display unit, and an alert buzzer to provide early warnings if gas levels exceed the threshold limit.

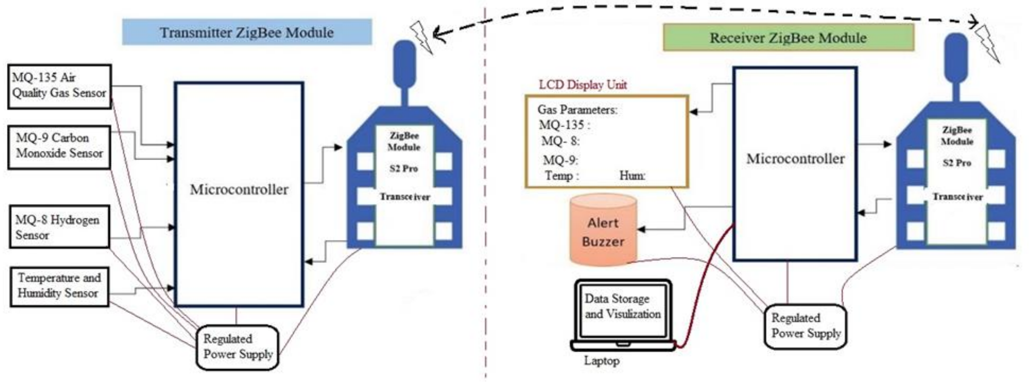
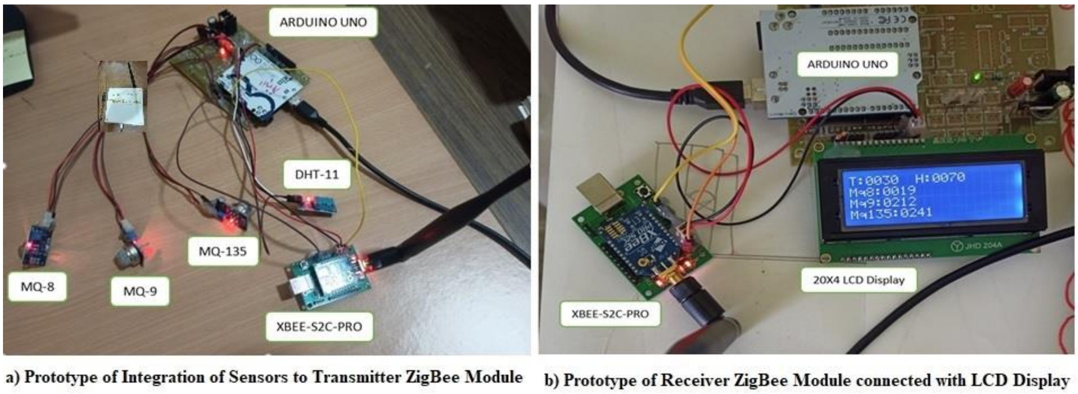


Fig. 3.17 A framework of the developed ZigBee-based System (Reddy et al. (2024))



a) Prototype of Integration of Sensors to Transmitter ZigBee Module

b) Prototype of Receiver ZigBee Module connected with LCD Display

(a) (b)

c) ZigBee Module and Sensors placed in a enclosures (Transmitter)

d) ZigBee Module and Sensors placed in a enclosures(Receiver)

(c) (d)

Fig. 3.18 (a, b, c & d) XBEE_S2C Pro ZigBee Module to Monitor Environmental Parameters (Reddy et al. (2024))

### 3.3.4 SX1278 Ra-02 (433 MHz) LoRa module-based IoT system to measure environmental parameters

The architecture of the IoT-based environmental monitoring system with the SX1278 Ra-02 LoRa module-based transmitter and receiver with the integration of sensors is shown in Fig. 3.19. A transmitter section includes an Arduino UNO development board with a LoRa module and Sensors MG811 Air Carbon Dioxide, MQ4 - Methane Gas, MQ7 - Carbon Monoxide, MQ135 - Air Quality Gas Sensor, MQ136-Hydrogen Sulfide, DHT11–Temperature and Humidity, RTC module, SD card module, and power supply components as illustrated in Fig. 3.20. The receiver section includes an ESP32 microcontroller with a LoRa transceiver module and the necessary components, as illustrated in Fig. 3.21. The sensors are selected to design and develop an IoT-enabled LoRa wireless communication system to monitor environmental parameters in underground mines.

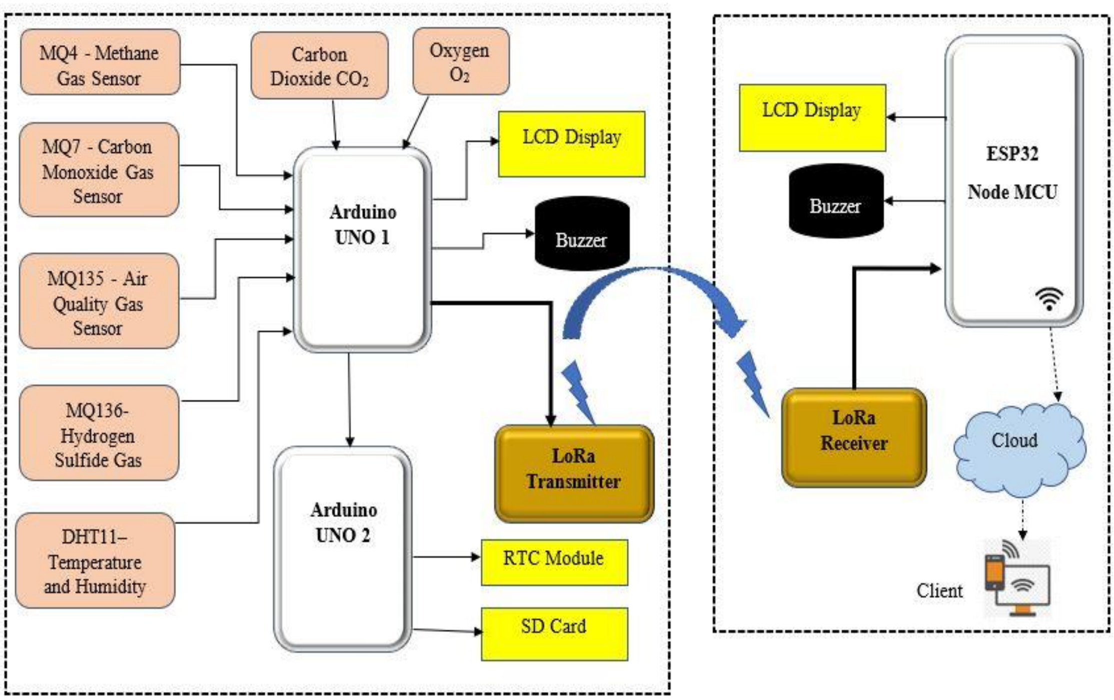


Fig. 3.19 The architecture of the IoT with LoRa module-based environmental monitoring system (Reddy et al. (2024))

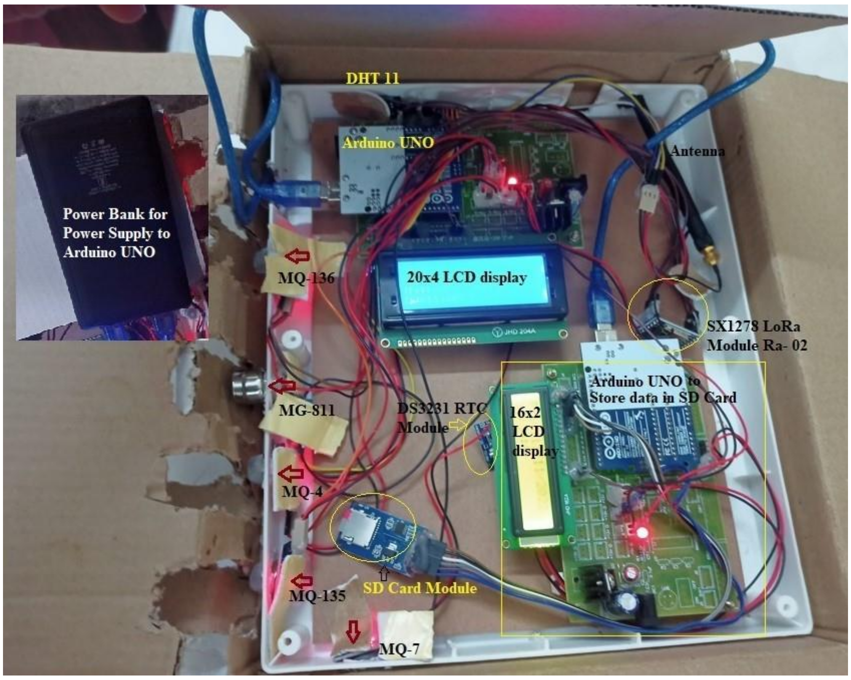


Fig. 3.20 Transmitter section: Integration of Sensors and Development board with Sx1278 Ra-02 LoRa Transmitter Module (Reddy et al. (2024))

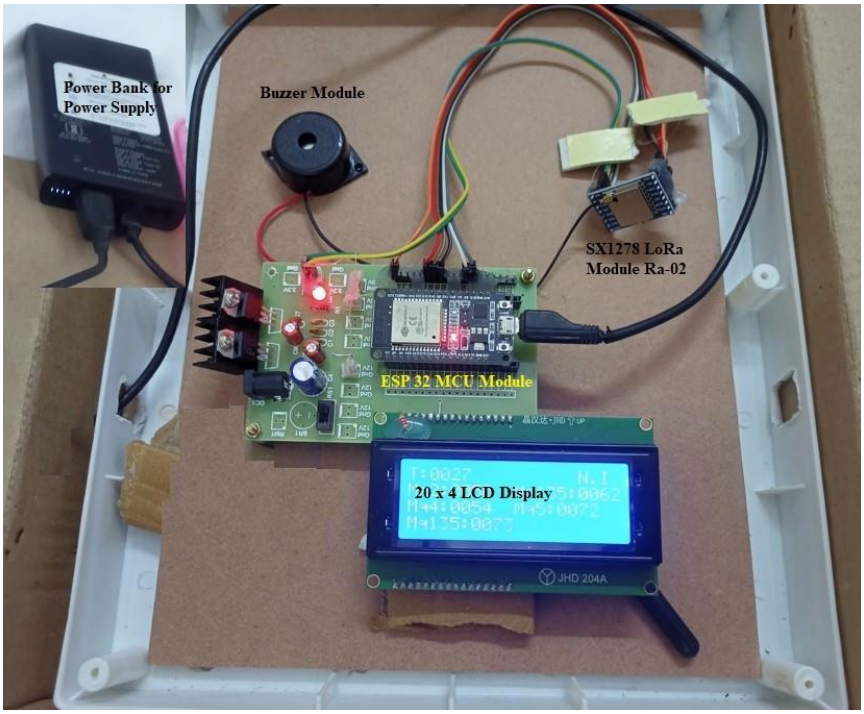


Fig. 3.21 Receiver section: Integration of Sensors and Development Board with Sx1278 Ra-02 LoRa Receiver Module (Reddy et al. (2024))

### 3.3.5 HPD13A - SX1276 (868 MHz) LoRa module-based IoT system to measure environmental parameters

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 Fig. 3.22. 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. HPD13A - SX1276 based LoRa modules are used to monitor environmental parameters and to establish wireless communication between transmitter and receiver.

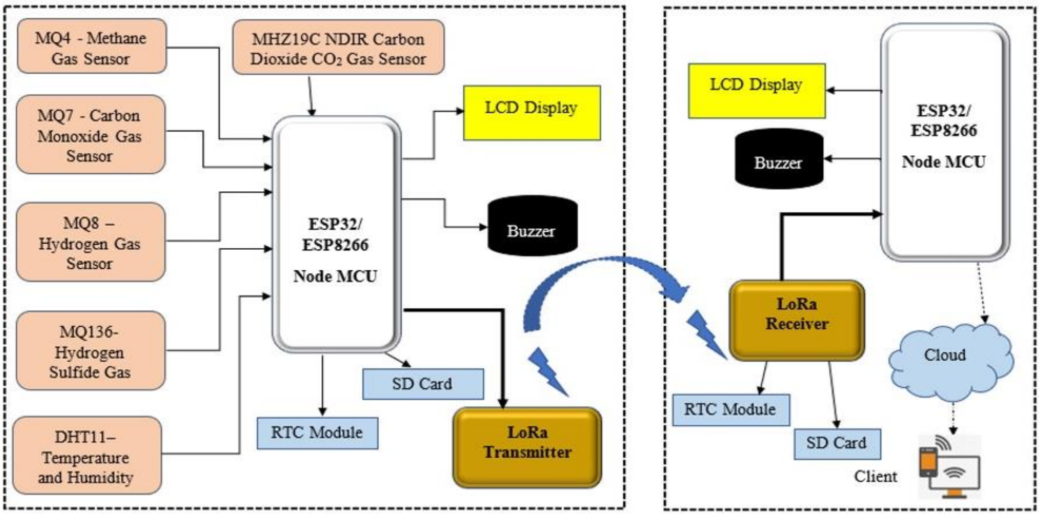


Fig. 3.22 The architecture of the IoT-based RTEPMS with LoRa Modules Transmitter and Receiver (Naik et al. (2024))

The external view of the portable LoRa-based RTEPMS transmitter and receiver is shown in Fig. 3.23 and Fig. 3.24. The inner view of the portable LoRa-based RTEPMS transmitter and LoRa receiver (LoRa SX1276 HD13A mounted on a PCB) is shown in Fig. 3.25 and Fig. 3.26. The developed portable RTEPMS transmitter and receiver, which integrates sensors and a development board, HPD13A - SX1276 (868 MHz) LoRa module, and power supply unit, are shown in Fig. 3.27.

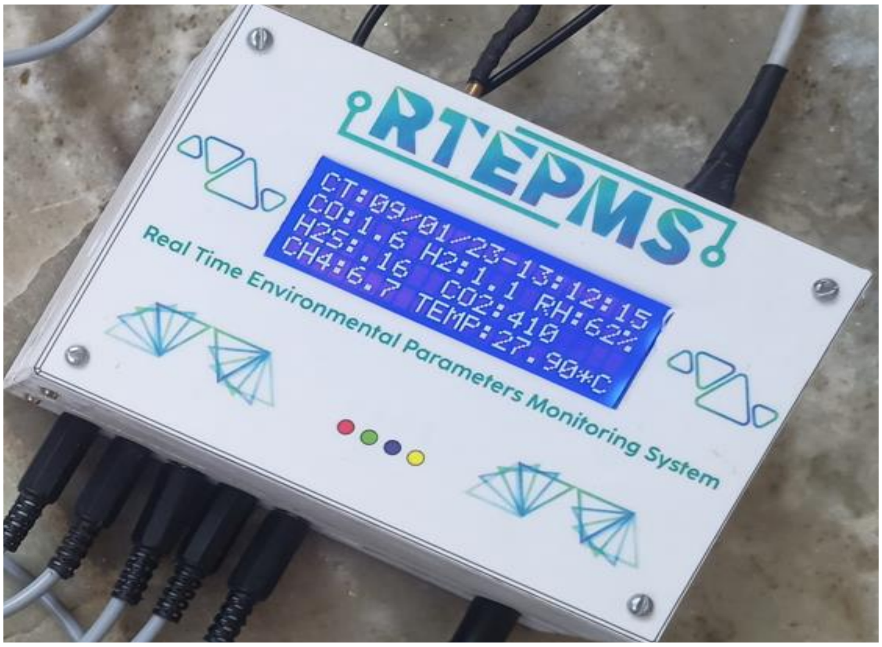


Fig. 3.23 External view of Portable RTEPMS LoRa Transmitter (Naik et al. (2024))

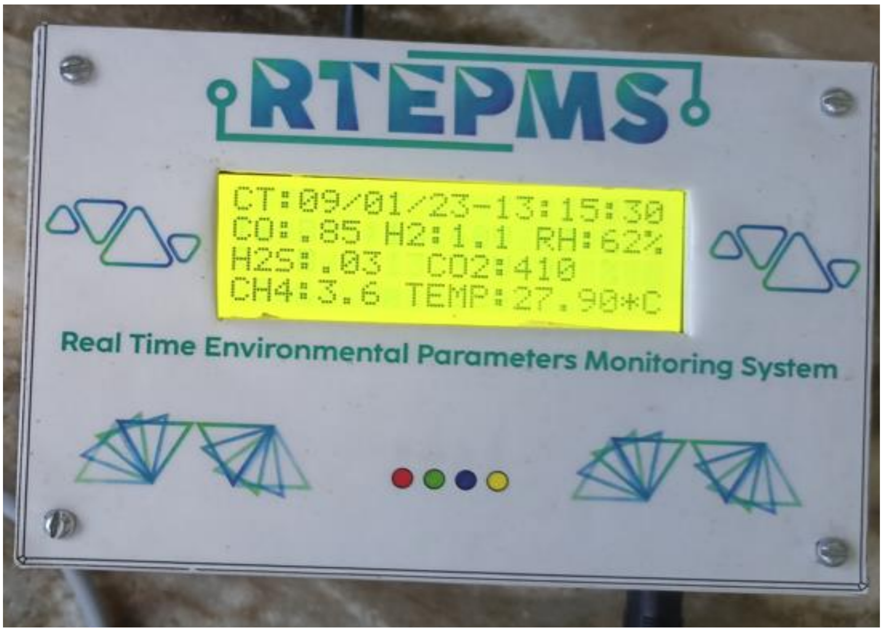


Fig. 3.24 External view of Portable RTEPMS LoRa Receiver (Naik et al. (2024))

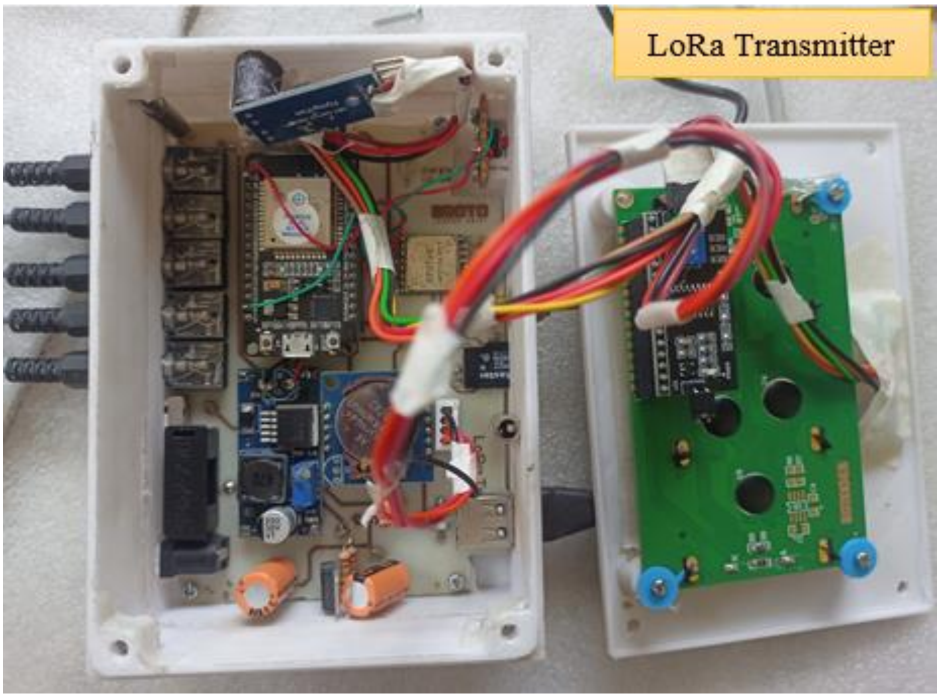


Fig. 3.25 Inner view of Portable RTEPMS LoRa Transmitter (LoRa SX1276 HD13A mounted on a PCB) (Naik et al. (2024))

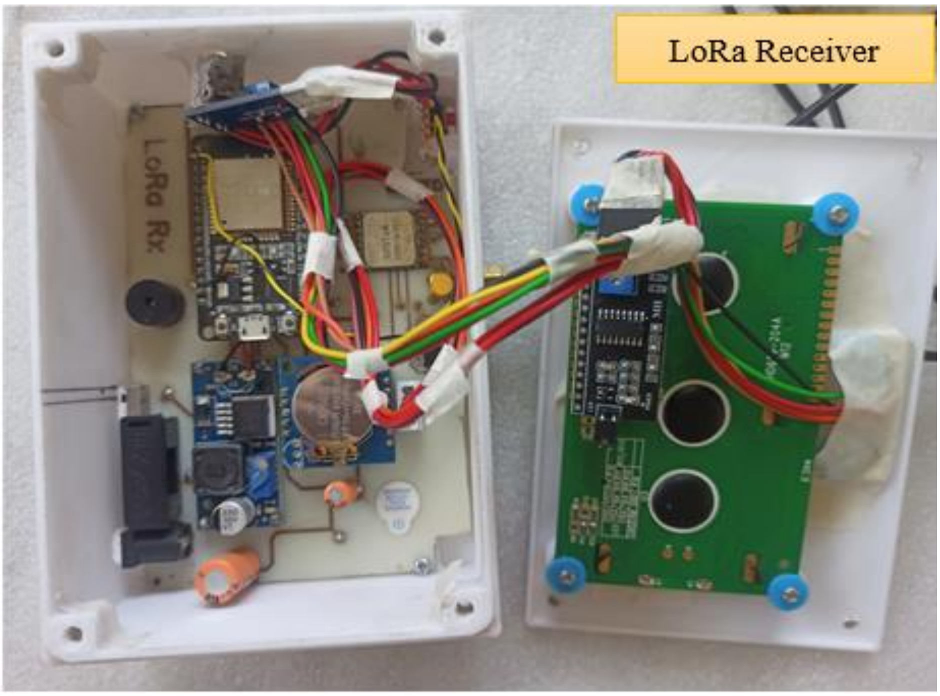


Fig. 3.26 Inner view of Portable RTEPMS LoRa Receiver (LoRa SX1276 HD13A mounted on a PCB) (Naik et al. (2024))

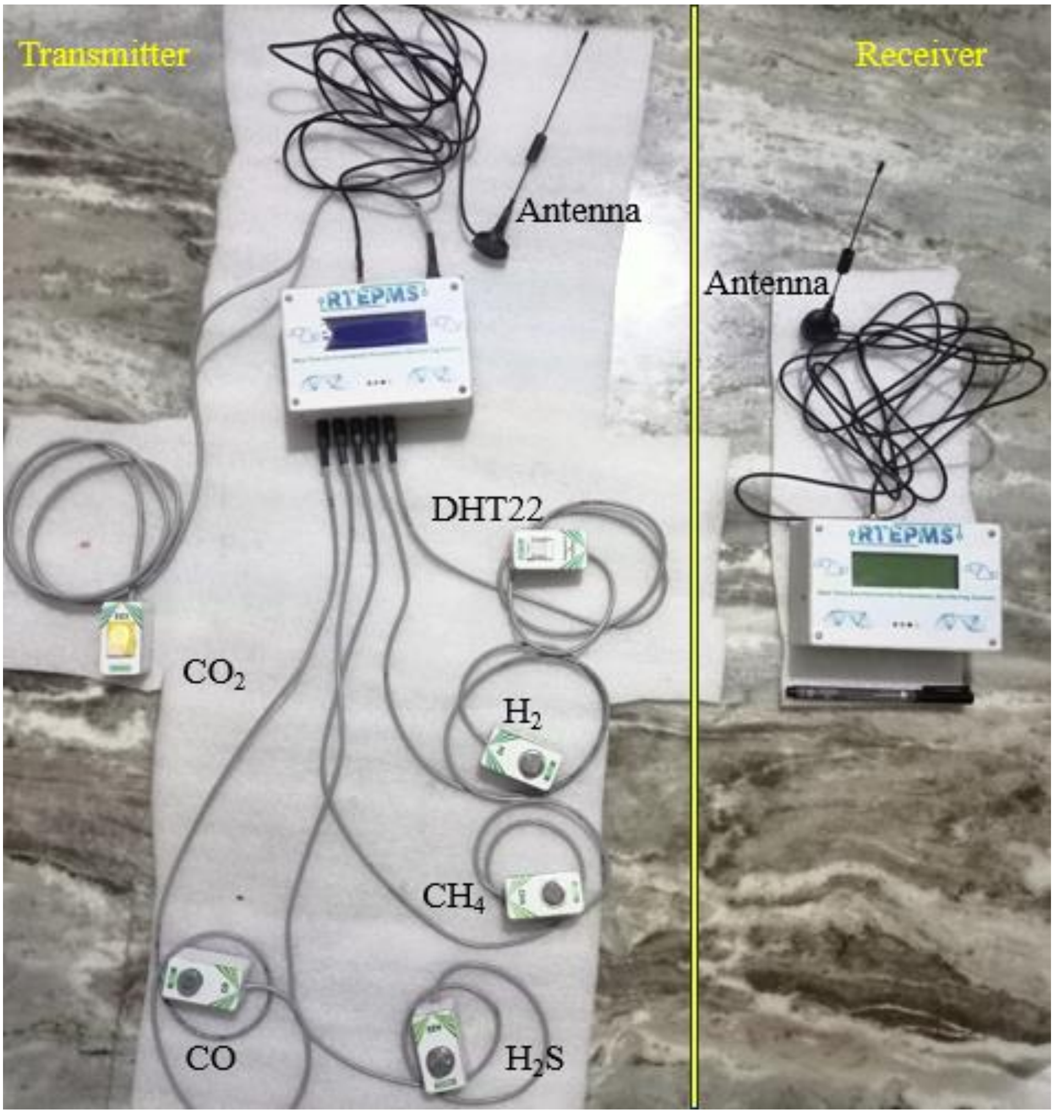


Fig. 3.27 Transmitter section: Sensors and development board integration with HPD13A - SX1276 and 868 MHz LoRa Transmitter Module. Receiver section: Integration of development board with HPD13A - SX1276 and 868 MHz LoRa Receiver Module (Naik et al. (2024))

### 3.3.6 HPD13A - SX1276 (868 MHz) LoRa module Vs LoRa 433 MHz and ZigBee module

Advantages of HPD13A - SX1276 (868 MHz) LoRa module-based IoT system compared with LoRa 433 MHz and ZigBee modules-based system.

- The design of the system is modified to deploy the portable system in an underground mine to monitor environmental parameters in harsh environment

- Reduced size of portable device
- Power Management of sensors and development board
- Calibration of gas sensors
- Considered sensors as per requirements in underground mine
- Assigned a unique address to send and receive data
- Easy to use and portable type
- Communication distance between LoRa transmitter and LoRa receiver is increased
- Storage of data locally at the transmitter and receiver
- Quality protective enclosures for sensors and development board
- Portable transmitter and receiver devices represent data signal notifications with LEDs

The performance analysis of different RTEPMS in terms of their effectiveness and limitations in measuring environmental parameters in underground mines are described in Table 3.4.

To overcome the limitations of LoRa and ZigBee-based systems in underground mines, particularly considering communication range and gas parameter sensitivity, a LoRaWAN gateway-based system with RS485 industrial gas sensors is more suitable for real-time monitoring of environmental parameters.

Table 3.5 presents the performance analysis of an IoT-enabled LoRaWAN Gateway-based system for real-time monitoring of environmental parameters over extended ranges. The system effectively transmits data over 1200 meters in line-of-sight (LOS) conditions and 600-650 meters in non-line-of-sight (NLOS) conditions, including from underground mine tunnels to the surface. This highlights its potential for comprehensive environmental monitoring in industrial settings.

### 3.4 Summary

The design and development of RTEPMS in underground mines describes the system methodology and outlines the steps necessary to establish an RTEPMS in underground mines with a focus on real-time monitoring of environmental parameters. The research design and component selection are crucial for the development of a system, encompassing the various sensors, development boards, wireless communication modules, cloud platforms, and other essential components with a consideration of factors such as RSSI, spreading factor, and code rate to optimize monitoring in a challenging underground mine harsh environment condition.

The development phase includes detailed descriptions of various LoRa and ZigBee module-based POC systems for comprehensive monitoring of environmental parameters in underground mines. Finally, the performance analysis compares the effectiveness of 433/868 MHz LoRa and ZigBee modules, highlighting their respective strengths and limitations in underground mining applications.

Chapter 4 discusses the comprehensive development of a hardware prototype for an IoT-enabled LoRaWAN Gateway-based system designed to monitor environmental parameters in underground mines. The primary objective is to transmit the monitored environmental parameters data from the underground workplace to the surface. This chapter also covers the laboratory testing and calibration of the developed system.

Table 3.4 Performance analysis of 433/868 MHz LoRa and ZigBee modules-based system

| **Sr.No** | **Wireless Communication module** | **Development Board & Integrated Sensors** | **LOS (meters) & NLOS (meters)** | **Depth from surface LOS in (meters) & Status of communication establishment** | **Test Location** | **Performance Analysis** |
|---|---|---|---|---|---|---|
| 1 | Sx1278 LoRa 433 MHz transceiver module | ESP8266 & DHT22 temperature and humidity sensor | 50 to 53 &<br>40 to 42 | NA | Surface and Laboratory scale | Established wireless communication and observed the variation in temperature and humidity values. |
| 2 | Sx1278 Ra-02 LoRa 433 MHz module | Arduino NANO and ESP 8266 board & DHT22 temperature and humidity sensor | 100 to 105 &<br>50 to 55 | NA | Surface and Laboratory scale | Established wireless communication and observed the variation in temperature and humidity values. |

| Sr.No | Wireless Communication module | Development Board & Integrated Sensors | LOS (meters) & NLOS (meters) | Depth from surface LOS in (meters) & Status of communication establishment | Test Location | Performance Analysis |
|---|---|---|---|---|---|---|
| 3 | XBee Pro S2C ZigBee radio frequency module | Arduino UNO & MQ-8, MQ-9, MQ-135 and DHT11 sensor | 100 to 120 & 60 to 70 | 60 & Communication established | Underground Mine ‘A’ | Noticed a spike in gas parameter values after explosive blast. DHT11 compared with HTC-1 digital temperature monitoring device, a positive correlation. |
| | | | | 832 & Communication is not established | Underground Mine ‘B’ | |
| 4 | Sx1278 Ra-02 LoRa 433 MHz module | MQ-4, MQ-7, MQ-135, MQ-136 and MG811 | 100 to 105 & 50 to 55 | 60 & Communication established | Underground Mine ‘A’ | $CO_2$ levels compared with a multi-gas detector. $R^2$ of 71.4% and 80% in underground mines 1 and 2, respectively. Store data in the SD card module and ThingSpeak IoT cloud platform |
| | | | | 832 & Communication is not established | Underground Mine ‘B’ | |

| Sr.No | Wireless Communication module | Development Board & Integrated Sensors | LOS (meters) & NLOS (meters) | Depth from surface LOS in (meters) & Status of communication establishment | Test Location | Performance Analysis |
|---|---|---|---|---|---|---|
| 5 | HPD13A, 868 MHz LoRa module | MQ-7, MQ-136, MQ-4, MQ-8, DHT11, MHZ19C NDIR CO2 module | Up to 300<br>&<br>180 to 200 | NA | Surface | Comparative measurements of $CO_2$, CO, $CH_4$, and $H_2S$ levels were taken using both the LoRa-based RTEPMS and traditional multi-gas detectors, revealing a correlation of 69.47% for $CO_2$ and 72.38% for CO, with negligible values for $CH_4$ and $H_2S$. The collected data analysis indicated rising $CO_2$, CO, EO, and $NO_2$ gases, as well as decreases in $O_2$ levels, emphasizing potential safety hazards. Store data in the SD card module and ThingSpeak IoT cloud platform |
| | | | | 832<br>& Communication is not established | Underground Mines 'B' | |

Table 3.5 Performance analysis of IoT enabled LoRaWAN Gateway based system

| **Sr.No** | **Wireless Communication module** | **Development Board & Integrated Sensors** | **LOS (meters) & NLOS (meters)** | **Depth from surface LOS in (meters) & Status of communication establishment** | **Test Location** | **Performance Analysis** |
|---|---|---|---|---|---|---|
| 1 | IoT-enabled LoRaWAN Gateway based system | RS485 industrial sensors ($CO_2$, CO, $CH_4$, $H_2S$, $H_2$, $N_2$, temperature and humidity), LoRaWAN gateway, RS485-LN converter and RS485 cable | up to 1200 & 600 to 650 | NA | Surface | IoT-enabled LoRaWAN setup monitors environmental parameters in real time. The System facilitates the transmission of environmental parameters data of approximately covers 1800 m distance from the underground mine of a specific location to the surface. |
| | | | Up to 1000 & 500 to 600 | 832 & Communication is established | Underground Mines ‘B’ | |

# CHAPTER 4

# 4. DEVELOPMENT OF AN IOT-ENABLED LORAWAN GATEWAY SYSTEM FOR REAL-TIME ENVIRONMENTAL PARAMETERS MONITORING (RTEPMS-LORAWAN)

The adoption of IoT in the mining industry significantly enhances safety, efficiency, and productivity by facilitating real-time monitoring of data and automation. Wearable IoT-enabled portable devices and location tracking enhance worker safety, while predictive maintenance and real-time monitoring optimize equipment performance and minimize downtime. IoT enables automated operations and fleet management, leading to precise and efficient resource utilization. The integration of IoT with technologies like Artificial Intelligence (AI), drones, and robotics further boosts operational efficiency, ensures regulatory compliance, and facilitates data-driven decision-making, transforming mining into a more sustainable, cost-effective, and safe industry.

Haxhibeqiri et al. (2018) and Augustin et al. (2016) describe an IoT-enabled LoRaWAN Gateway system that leverages Long Range Wide Area Network (LoRaWAN) technology, a type of Low-Power Wide-Area Network (LPWAN) designed for long-range communication and low power consumption. LoRaWAN operates in unlicensed ISM (Industrial, Scientific, and Medical) radio bands, which vary by region (e.g., 868 MHz in Europe, 915 MHz in North America). This technology is particularly advantageous for IoT applications where devices need to transmit small amounts of data over large distances with minimal power usage, making it suitable for battery-operated devices in remote locations.

Naik et al. (2023), proposed a real-time industrial smart safety system for underground mines using a LoRaWAN Gateway. Zhao et al. (2023), developed efficient protocols for LoRaWAN-based wireless underground sensor networks (WUSNs) to monitor underground environments, demonstrating their applicability in underground monitoring applications.

## 4.1 Selection of Hardware Components for Monitoring Environmental Parameters in Underground Mine

The IoT-based system for monitoring environmental parameters in underground mines operates in real time and utilizes multiple parameters sensors to enhance safety. This innovative solution incorporates RS485 sensors to detect Hydrogen sulphide ($H_2S$), Methane ($CH_4$), Carbon monoxide (CO), Carbon dioxide ($CO_2$), Nitrous oxide (NO), Nitrogen ($N_2$), Hydrogen ($H_2$), and Temperature (T) and Humidity (H) parameters as shown in Fig 4.1. The sensor features a gas detection hole with a polymer gas membrane that isolates it. This membrane is breathable and impermeable, allowing gas to permeate while blocking moisture. Damage of this membrane may affect the product's lifespan. Sensors can be positioned as needed, but precautions must be taken to ensure they are not in areas where vehicle movement could cause damage or where they could be affected by rock falls. A power supply is necessary for operation and portable battery can also be utilized. The working temperature environment of sensors is -30 ℃ to 50 ℃ and working humidity environment is 15 to 90% RH.

These sensors are linked to an RS485-LN converter device, as shown in Fig 4.2, which facilitates the transmission of sensor data to the LoRaWAN Gateway, as shown in Fig 4.3 (a & b). The multiple sensors interface with the RS485-LN converter device via wired connections, facilitating the wireless transmission of data to the LoRaWAN Gateway.

During the design stage, emphasis is placed on developing a system architecture tailored to the layout of underground mines, selecting appropriate hardware components, and choosing a communication technology to enable real-time monitoring of environmental conditions using LoRaWAN (RTEPMS-LoRaWAN).

The system integrates a LoRaWAN Gateway, an RS485-LN converter device, and RS485 industrial gas sensors to facilitate the continuous and immediate observation of the mine's environmental conditions from the surface. The system promptly generates an email alert notification on the surface to the concerned authority and initiates an audible alarm alert sound in underground mine tunnels or levels and at the surface when the specified parameters exceed the predetermined thresholds.

The technology, methodology, and materials used to develop and deploy a LoRaWAN Gateway based IoT system for monitoring environmental conditions in underground mines are described in the following sections. The approach is illustrated through a flowchart, as shown in Fig. 4.4, beginning with the identification of limitations and gaps in current real-time environmental monitoring systems.

The implementation and operationalization of the RTEPMS-LoRaWAN system involves LoRa technology, RS485 sensors, a LoRaWAN gateway, an RS485-LN converter, and an RS485 cable to facilitate real-time monitoring of environmental monitoring of the underground mine from the mine's surface.

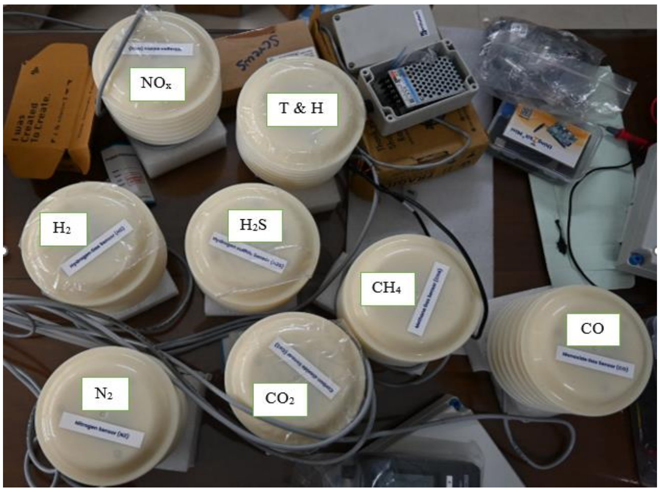
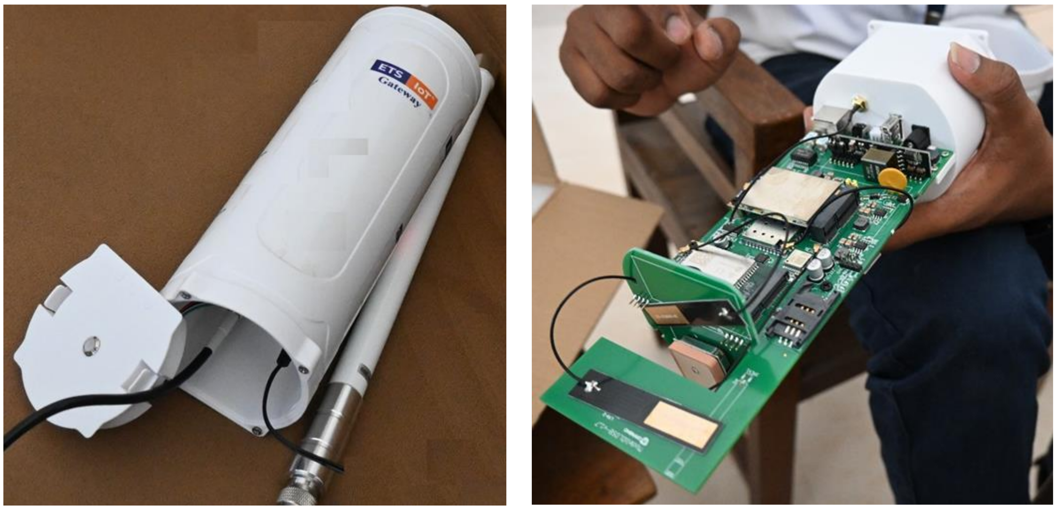


Fig. 4.1 RS485 Sensors $CO_2$, CO, $H_2S$, $H_2$, $N_2$, NO, Temperature(T) and Humidity(H)

Fig. 4.2 RS485-LN converter device



LoRaWAN Gatway External View (a)

LoRaWAN Gatway Internal View (b)

Fig. 4.3 (a & b) LoRaWAN Gateway device

The setup and testing of the system's components, including RS485 sensors, the RS485-LN converter, the LoRaWAN Gateway, power sources, and the IoT cloud platform, are thoroughly conducted. Following the hardware setup, software configuration, and GUI creation to manage the monitoring tasks in the IoT lab of the Mining Engineering Department, NITK Surathkal. The system undergoes a final review to ensure its functionality and to address any existing issues.

The completion of the RTEPMS-LoRaWAN system is marked by its ability to reliably transmit environmental data from the underground mine's tunnels/levels to the surface, alongside successful functionality tests. The data are accessible remotely via an IoT-based cloud platform, allowing monitoring from any location at any time. The practical deployment and effectiveness of the RTEPMS-LoRaWAN system are verified through performance evaluation.

The selection of hardware components for the envisioned system after conducting a comprehensive research study into current technologies, hardware options, materials, and costs. This investigation considered factors such as the type of communication technology (wireless or wired), environmental parameters to be monitored, operational conditions, and system reliability.

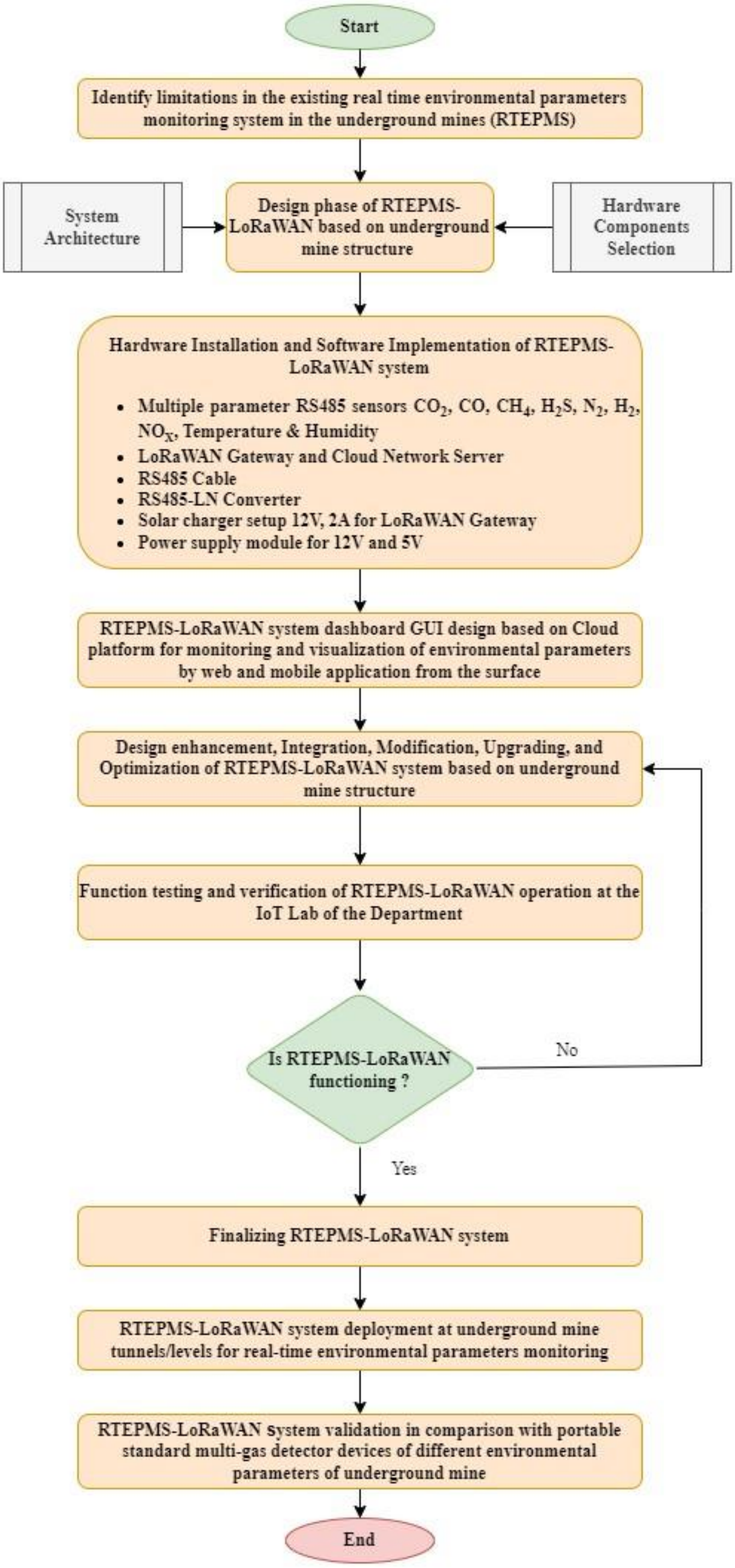


Fig. 4.4 Flowchart of Research Methodology for RTEPMS-LoRaWAN system

We thoroughly reviewed technologies for real-time monitoring of environmental conditions at the laboratory level, examining various sensor types and standard portable multi-gas detectors, including their specifications and pricing.

Based on this research, we choose the following hardware and software components for the system. The hardware components include a LoRaWAN gateway, an RS485-LN device (which converts RS485 signals to LoRaWAN), and industrial RS485 sensors for detecting $CO_2$, CO, $H_2S$, $H_2$, $N_2$, NO, as well as temperature and humidity. We also select RS485 standard cables, which facilitate point-to-point communication over long distances in environments with electrical noise and support multiple devices on the same bus. The RS485's capability for high-speed data transmission over extended distances makes it an ideal choice for many applications, necessitating a serial interface. Solar charge controllers (12V, 2A) for the LoRaWAN Gateway and power supply modules (12V and 5V) for the RS485-LN device and RS485 sensors were selected for powering the system, respectively.

RS485 gas sensors feature a detection hole equipped with a polymer gas membrane that isolates the sensing element. This membrane is both breathable and impermeable, allowing gas to permeate while insulating against moisture. It is crucial to maintain this membrane properly, as damage can impact the sensor's lifespan.

The RS485-LN converter device includes three buttons: ACT, RST, and PRO.

- ACT: If the RS485-LN device joined the network, press and hold this button for over one second. Following this action, the RS485 will transmit a data packet, and the SYSLED indicator will flash blue once.
- RST: This button is used to restart the RS485 device.
- PRO: This button is designated for uploading images.

On the software side, we opted for a private cloud platform thingZmate to enable the visualization and storage of real-time environmental data. Following the selection process, we proceeded to design, integrate, and implement all chosen hardware components, culminating in the development of the RTEPMS-LoRaWAN system.

The hardware for the RTEPMS-LoRaWAN was carefully chosen to ensure the system's cost-effectiveness, energy efficiency, and compatibility with both wired and wireless communication technologies while also considering the unique structural and operational demands of underground mines. Factors such as ease of integration, reliability, and the ability to adapt or upgrade components within the challenging environment of an underground mine were paramount. The selected components offer significant flexibility for system integration, modifications, or enhancements. The capacity to position sensors in various locations and the straightforward process for adding or replacing components enhance the system's adaptability. The reliance on standard, thoroughly tested components guarantees the system's reliability and simplifies installation, maintenance, or modifications for real-time environmental monitoring in underground mines.

## 4.2 Architecture of IoT-enabled LoRaWAN Gateway based Real-Time Environmental Parameters Monitoring in Underground Mines (RTEPMS-LORAWAN)

The architecture of the RTEPMS-LoRaWAN system is depicted in Fig. 4.5. It involves placing multiple sensors within the mine tunnels or levels of the underground mine at a depth of approximately 832 meters from the surface to gather data on various environmental conditions. These RS485 sensors are linked to an RS485-LN converter through an RS485 cable, facilitating data collection from the sensors. The data is then wirelessly sent from the RS485-LN converter to the LoRaWAN Gateway. RS4855-LN supports listening mode, it can listen to the sensor data, i.e., RS485 network packets and send them via LoRaWAN uplink. This LoRaWAN gateway establishes connectivity to a cloud-based platform using Wi-Fi, a cellular network, or an Ethernet connection. Through this setup, data from the mine's depths can be transmitted to the surface, allowing for real-time monitoring of environmental conditions via web or mobile applications.

Fig. 4.5 RTEPMS-LoRaWAN System Architecture

## 4.3 Development of IoT-Enabled LoRaWAN Gateway based Real-Time Environmental Parameters Monitoring (RTEPMS-LORAWAN)

Following the separate testing of the system's hardware components, the RTEPMS-LoRaWAN system was deployed in the underground mine through the integration of all RS485 sensors, the RS485-LN converter device, and the LoRaWAN Gateway into a unified system.

### 4.3.1 Functionality testing of multiple sensors and hardware implementation of RTEPMS-LoRaWAN in an IoT Laboratory

All sensor units underwent testing in the department's IoT Laboratory to verify the system's functionalities. This critical phase aims to improve system performance and detect issues with hardware connections or software coding. The configuration of the sensors, along with the functionality and capabilities of the sensing units, were initially tested in a laboratory setting, as depicted in Fig. 4.6.

IoT-based RTEPMS-LoRaWAN System components testing includes multiple sensors testing via the Serial monitor, Serial port, and Mod bus controller software. The installation of the system, in line with its architecture, was executed to identify any input/output issues. The LoRaWAN Gateway connects to the internet through a cellular network and is set up with the thingZmate private cloud platform for monitoring environmental parameters. The interaction among sensors, RS485-LN, and the

LoRaWAN gateway with the thingZmate platform is seamless. At this stage, the system undergoes evaluation to confirm the efficient operation of all sensors, RS485-LN, and the gateway.

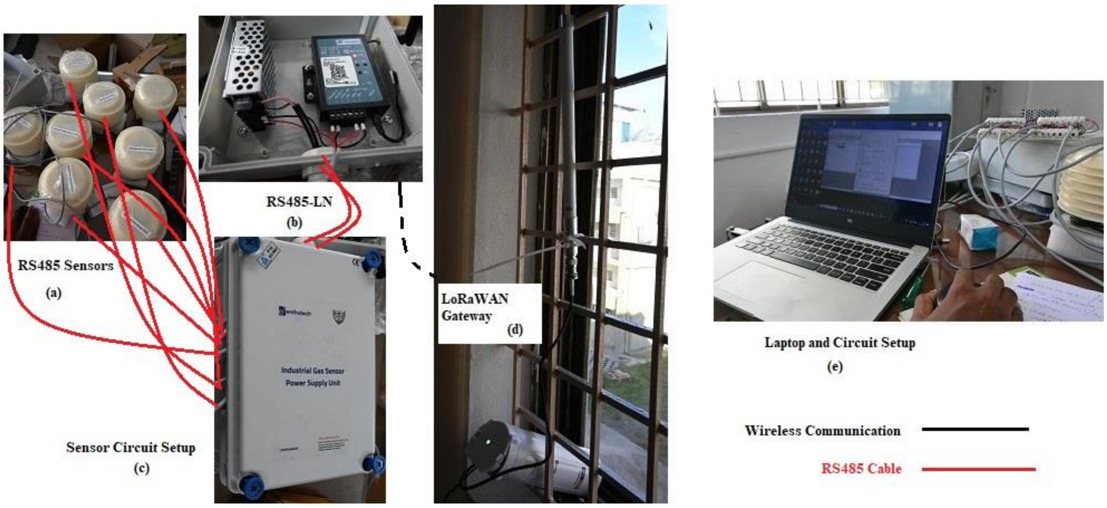


Fig. 4.6 IoT-based RTEPMS-LoRaWAN System Setup in an IoT Laboratory of the Mining Engineering Department, NITK Surathkal

Prior to finalizing the RTEPMS-LoRaWAN system, extensive testing and calibration settings were carried out on both individual and multiple sensor units within a laboratory setting. The calibration of sensors is performed at field trials and the frequency of calibration depends on the environmental conditions and sensor usage. The maintenance and calibration of sensor is same as portable multigas detector device. For every 6 months calibration of sensors are suggested to check the accuracy.

A notable characteristic of this system is its portability, which has been significantly enhanced by the inclusion of features that simplify the connection of components, thereby improving the system's modularity and user-friendliness. This aspect of the system's design not only makes the installation and swapping of different sensors straightforward but also integrates a power management system. The system is designed to operate on solar, battery power and AC-DC power supply, adapting to the available resources and requirements. Upon establishing a connection, the hardware modules automatically recognize the connected sensors, acquire their unique identifiers, and adjust the communication protocols as necessary.

This design significantly reduces the time required for setup and enables users to customize the system to meet their unique monitoring requirements. It is ideally suited for real-time monitoring of environmental parameters from underground mine tunnel to the surface.

### 4.3.2 Software Configuration

The software development focuses on collecting data from various sensors and consolidating it into a single packet for periodic transmission over the LoRaWAN network to the thingZmate server. This involves encoding the sensor data into a byte stream for upload via the LoRaWAN gateway. Multiple functions were created to facilitate data collection from each sensor. Within the LoRaWAN-based system, several parameters are configured to enhance data transmission efficiency and ensure collision-free communication. These configurations include:

- *Spreading Factor (SF):* Two different Spreading Factor (SF) configurations, SF7 and SF12, were explored to determine the optimal balance between communication range and data rate in various environmental settings.
- *Bandwidth (BW):* The bandwidth was set to 125 KHz, a common choice for LoRaWAN operations that effectively balance data rate and signal strength.
- *Coding Rate (CR):* Generally used a CR of 4/5, aiming for a middle ground between transmission durability and bandwidth utilization, ensuring data is reliably sent without overburdening the network.
- *Carrier Frequency (CF):* The CF was carefully chosen to comply with the standard frequency bands for LoRaWAN activities in India, ranging from 865-867 MHz, aligning with local regulations and maximizing signal transmission effectiveness.

The LoRa parameters are customizable to balance data rate, transmission range, interference resilience, and energy consumption. LoRa, a physical layer modulation technique developed by Semtech, differs from LoRaWAN, an open standard that provides a Medium Access Control (MAC) layer protocol. This protocol allows multiple LoRa end devices to communicate efficiently with a gateway. Supported and promoted by the LoRa Alliance (2024), the global adoption of LoRaWAN is encouraged to ensure the interoperability of all LoRaWAN-compatible devices and technologies, thereby driving IoT towards a sustainable future.

The RS485-LN is compatible with the AT command set, allowing users to interface with the device using a USB to TTL adapter and a program cable. To utilize the AT command with the RS485-LN, it's necessary to configure the baud rate to 9600 for serial console access. Additionally, the RS485-LN operates on the IN865 frequency bands.

AT Command Configuration is carried out by Modbus controller software to configure the address of individual RS485 sensors is described below.

- *Read sensor data:* The RS485-LN is an RS485 to LoRaWAN converter that transforms RS485 signals into LoRaWAN wireless signals, simplifying IoT installations and reducing installation and maintenance costs. This device enables users to monitor and control RS485 devices over extensive distances. It offers long-range spread spectrum communication and high interference immunity while minimizing power consumption.
- *For data uplink:* The RS485-LN sends user-defined commands to RS485 devices and receives their responses. It processes these responses according to user-defined rules to generate the payload, which is then uploaded to the LoRaWAN server.
- *For data downlink:* The RS485-LN operates in LoRaWAN class C mode. When downlink commands are received from the LoRaWAN server, the RS485-LN forwards these commands to the RS485 devices.
- RS485-LN, RS485 alarm, and RS485 I/O are connected together Via RS485(A, B) interface.
    - RS485-LN will read RS485 I/O’s registers periodically and uplink to the LoRaWAN server.
    - The LoRaWAN server can send a downlink command to RS485-LN to control the RS485 Alarm.
- Each RS485-LN is a unique device EUI and joins the network. Configure RS485 devices/sensors using AT commands to read valid data and send it to the LoRaWAN

server. For example, set the baud rate for the RS485 connection. the default value is 9600. AT+BAUDR=9600

- Configure read commands for each sampling session. For each sampling, determine the specific commands to send to the RS485 sensors to read data. When the RS485 sensors return the data, it typically includes several bytes, but only a few are needed to create a shortened payload.
- To save the LoRaWAN network bandwidth, we might need to read data from different sensors and combine their valid value into a short payload.
- Each RS485 commands include two parts
  - RS485-LN will send to the RS485 sensors. There are a total of 15 commands from AT+COMMAND1, AT+COMMAND2, ……. to AT+COMMANDF.
  - We get the required value from the RS485 sensors returned by, there are a total of 15 AT Commands to handle the return commands AT+DATACUT1, AT+DATACUT2, …………AT+DATACUTF corresponds to the read commands.

Some RS485 devices might have a longer delay in reply, so the user can use AT+CMDDL to set the timeout for getting a reply after the RS485 command is sent. For example, AT+CMDDL1=1000 to send the open time to 1000 milliseconds.

- The following example describes how the AT commands work

    ***AT+COMMANDx:*** This command will be sent to RS485 devices during each sampling. The maximum command length is 14 bytes, and the grammar is, for ex: If we have an RS485 sensor, the command to get sensor value is: *01 03 0B B8 00 02 46 0A,* where *01 03 0B B8 00 02* is the Modbus command to read the register *0B B8* where stored the sensor value.

    The *46 0A* is the CRC-16/MODBUS, which is calculated manually.

    ***AT+COMMANDx:*** This command will be sent to RS485 devices during each sampling. Max command length is 14 bytes.

    ***AT+DATACUTx:*** This command defines how to handle the return from AT+COMMANDx. The maximum return length is 100 bytes.

*AT+DATACUTx = a, b, c*

Where,

*a* is the length for the return if AT+COMMAND

*b* is 1: grab valid value by byte, max 6 bytes, 2: grab valid value by byte section, max 3 sections

*c* defines the position for a valid value

AT+COMMAND1 = 01 03 0b b8 00 02,1

AT+DATACUT1= 8,2, 4~8

*a=8*, return a total of 8 bytes (20 20 20 20 2d 30 2e 00)

*b=2*

*c=4~8* (grab the 4th ~ 8th bytes from return, so COMMAND1 valid value is 20 2d 30 2e 00

*CMD1* = 01 03 0b b8 00 02 46 0a

*RETURN1*=20 20 20 20 2d 30 2e 00

*Payload* = 01

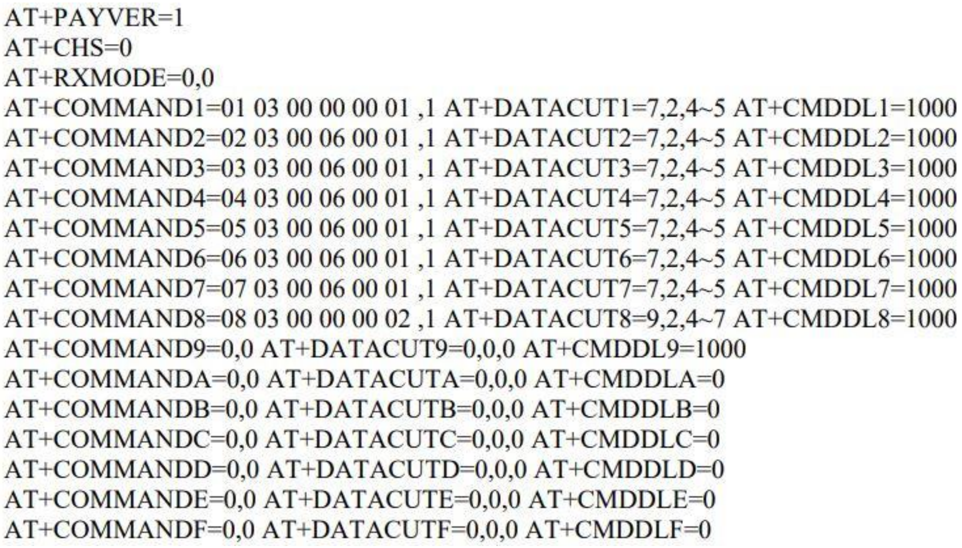
Configure read commands for each sampling, as shown in Fig. 4.7.

- Configure RS485-LN via AT or Downlink

Users can configure RS485-LN via AT commands or LoRaWAN Downlink commands.

There are two kinds of commands

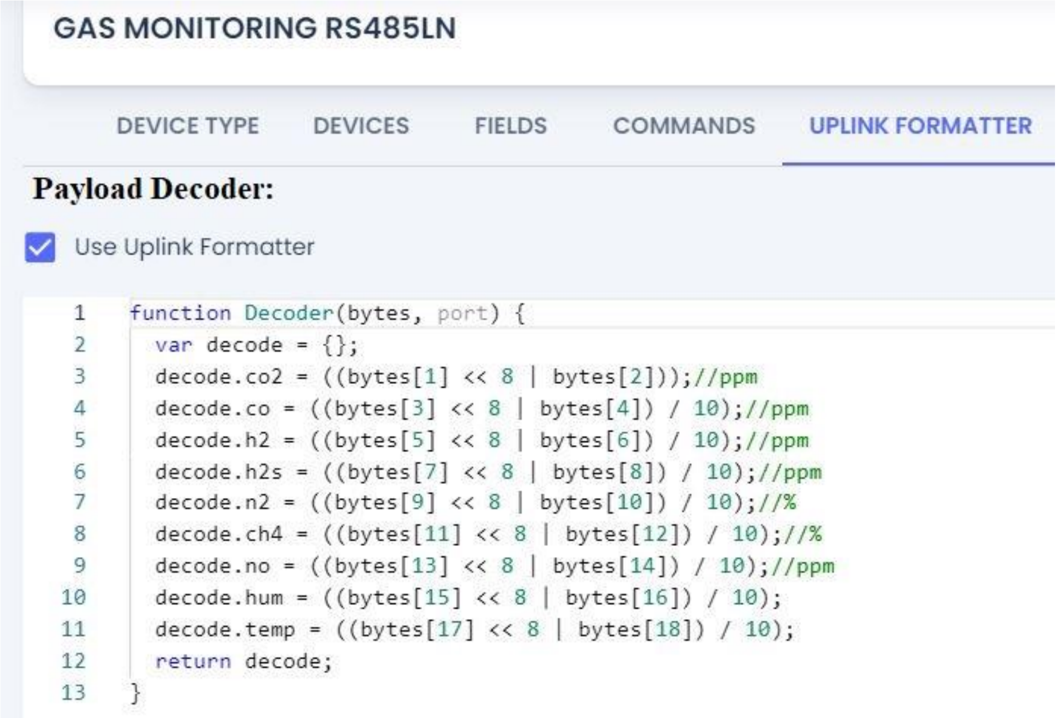
- Common commands are available for each sensor, such as changing the uplink interval, resetting the device, etc.
- Sensor related commands are specially designed for RS485-LN
  Ex: use the downlink command to control to RS485 Alarm



```
AT+PAYVER=1
AT+CHS=0
AT+RXMODE=0,0
AT+COMMAND1=01 03 00 00 00 01 ,1 AT+DATACUT1=7,2,4~5 AT+CMDDL1=1000
AT+COMMAND2=02 03 00 06 00 01 ,1 AT+DATACUT2=7,2,4~5 AT+CMDDL2=1000
AT+COMMAND3=03 03 00 06 00 01 ,1 AT+DATACUT3=7,2,4~5 AT+CMDDL3=1000
AT+COMMAND4=04 03 00 06 00 01 ,1 AT+DATACUT4=7,2,4~5 AT+CMDDL4=1000
AT+COMMAND5=05 03 00 06 00 01 ,1 AT+DATACUT5=7,2,4~5 AT+CMDDL5=1000
AT+COMMAND6=06 03 00 06 00 01 ,1 AT+DATACUT6=7,2,4~5 AT+CMDDL6=1000
AT+COMMAND7=07 03 00 06 00 01 ,1 AT+DATACUT7=7,2,4~5 AT+CMDDL7=1000
AT+COMMAND8=08 03 00 00 00 02 ,1 AT+DATACUT8=9,2,4~7 AT+CMDDL8=1000
AT+COMMAND9=0,0 AT+DATACUT9=0,0,0 AT+CMDDL9=1000
AT+COMMANDA=0,0 AT+DATACUTA=0,0,0 AT+CMDDLA=0
AT+COMMANDB=0,0 AT+DATACUTB=0,0,0 AT+CMDDLB=0
AT+COMMANDC=0,0 AT+DATACUTC=0,0,0 AT+CMDDLC=0
AT+COMMANDD=0,0 AT+DATACUTD=0,0,0 AT+CMDDLD=0
AT+COMMANDE=0,0 AT+DATACUTE=0,0,0 AT+CMDDLE=0
AT+COMMANDF=0,0 AT+DATACUTF=0,0,0 AT+CMDDLF=0
```

Fig. 4.7 Read command for sampling

  - ***Device Types:*** Device types function as templates, streamlining the setup process by eliminating repetitive configurations for similar devices. They encompass device protocols (such as HTTPS, LoRaWAN, and MQTT), various fields (like Payload and custom fields), and commands (e.g., On, Off, etc.), facilitating a single configuration for each specific device type.
  - ***Uplink Formatter:*** The “UPLINK FORMATTER” is designed to modify the data received from the uplink. For instance, devices using LoRaWAN transmit uplink data as hexadecimal values, necessitating the use of a formatter. This formatter should include a 'Decoder' function that takes an object as its parameter, as shown in Fig. 4.8. It's important to note that the formatter should output the data in JSON format.
- The LoRa packet's framework is designed for master-slave interaction among smart devices, using a message structure for communication. In a MODBUS message dispatched from a master device to a slave, the composition includes the slave's address, a command, data, and a checksum for verification, as illustrated in Fig. 4.9.



**Payload Decoder:**

☑ Use Uplink Formatter

```
function Decoder(bytes, port) {
  var decode = {};
  decode.co2 = ((bytes[1] << 8 | bytes[2]));//ppm
  decode.co = ((bytes[3] << 8 | bytes[4]) / 10);//ppm
  decode.h2 = ((bytes[5] << 8 | bytes[6]) / 10);//ppm
  decode.h2s = ((bytes[7] << 8 | bytes[8]) / 10);//ppm
  decode.n2 = ((bytes[9] << 8 | bytes[10]) / 10);//%
  decode.ch4 = ((bytes[11] << 8 | bytes[12]) / 10);//%
  decode.no = ((bytes[13] << 8 | bytes[14]) / 10);//ppm
  decode.hum = ((bytes[15] << 8 | bytes[16]) / 10);
  decode.temp = ((bytes[17] << 8 | bytes[18]) / 10);
  return decode;
}
```

Fig. 4.8. thingZmate Payload Decoder Function

- ***The Request:*** Within the request, the function code instructs the designated slave device on the action to execute. Additional details necessary for the slave to carry out this action are embedded in the data types. For instance, a function code of 03 prompts the slave to read holding registers and report back their values. The data field should specify the starting register and the number of registers to be read. An error check field is included to allow the slave to verify the accuracy of the message's content.
- ***The Response:*** In a standard response scenario, the function code mirrored in the response echoes that of the request, indicating continuity. The data byte in the response holds the information gathered by the slave, like register values or current status. Should there be an error, the function code is altered to signify an error response, and the data types include a specific code detailing the nature of the error. An error check field is also present, enabling the master to verify the integrity of the message's contents.

Controllers can be configured for Modbus network communication utilizing one of two modes: ASCII or RTU.

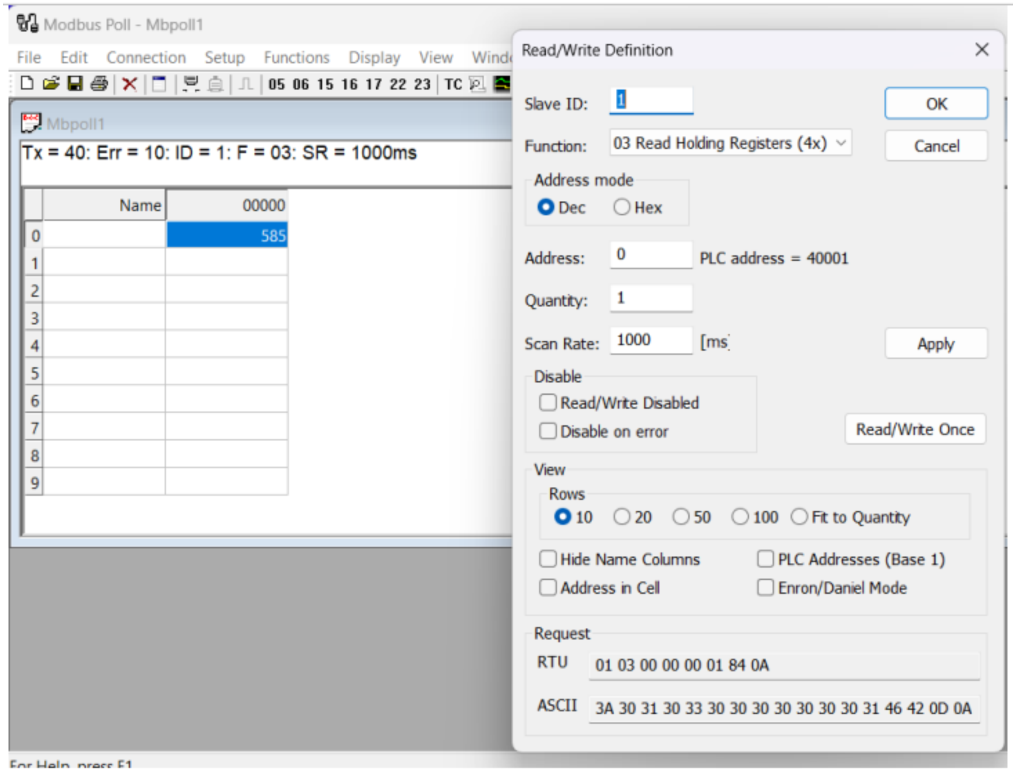
- ***RTU Mode:*** In RTU mode (Remote terminal units), character framing incorporates an error-checking mechanism where the error-check field consists of a 16-bit value divided into two eight-bit bytes. This value emerges from performing a cyclical redundancy check (CRC) on the message's data. The CRC field is attached at the end of the message, with the lower-order byte preceding the higher-order byte, making the CRC's high-order byte the final byte transmitted in the message. Table 4.1 presents the RTU Mode configuration.

Table 4.1. RTU Mode configuration

| **Field Name** | **RTU (hex)** |
|---|---|
| Header | None |
| Slave Address | 01 |
| Function | 03 |
| Starting Address Hi | 00 |
| Starting Address Lo | 00 |
| Quantity of Register Hi | 00 |
| Quantity of Register Lo | 02 |
| Error Check Lo | C4 |
| Error Check Hi | 0B |
| Trailer | None |
| Total bytes | 8 |

For instance, using Function 03 (03 HEX) to read holding registers involves querying the binary data from holding registers in the slave. The request message outlines the initial register and the number of registers to read, as demonstrated in specific figures and tables provided for reference.

The collected readings from the sensors are combined into a single payload packet to be sent to the LoRaWAN Gateway. Each sensor reading is represented within this packet. The combined payload is updated to thingZmate every five minutes. A payload decoder on the thingZmate platform interprets the received hexadecimal byte characters into human-readable information, as illustrated in Fig. 4.8.



Tx = 40: Err = 10: ID = 1: F = 03: SR = 1000ms

|  | Name | 00000 |
|---|---|---|
| 0 |  | 585 |
| 1 |  |  |
| 2 |  |  |
| 3 |  |  |
| 4 |  |  |
| 5 |  |  |
| 6 |  |  |
| 7 |  |  |
| 8 |  |  |
| 9 |  |  |

Slave ID: 1

Function: 03 Read Holding Registers (4x)

Address mode: ● Dec ○ Hex

Address: 0 PLC address = 40001

Quantity: 1

Scan Rate: 1000 [ms]

Disable
☐ Read/Write Disabled
☐ Disable on error

View
Rows: ● 10 ○ 20 ○ 50 ○ 100 ○ Fit to Quantity
☐ Hide Name Columns ☐ PLC Addresses (Base 1)
☐ Address in Cell ☐ Enron/Daniel Mode

Request
RTU 01 03 00 00 00 01 84 0A
ASCII 3A 30 31 30 33 30 30 30 30 30 30 30 31 46 42 0D 0A

Fig. 4.9 $CO_2$ (Carbon dioxide) gas configuration in Modbus software tool

### 4.3.3 The thingZmate Dashboard

The thingZmate dashboard offers a user-friendly interface with data visualization tools. This IoT server allows users to view collected data in various formats, including graphs, numerical displays, or trend graphs over specific periods daily, monthly, or yearly. To enhance visualization, 9 widgets have been introduced to showcase RTEPMS-LoRaWAN environmental parameter measurements. Additionally, private views for each created channel ensure the confidentiality of displayed data.

The thingZmate operates both as a web-based and mobile application, utilizing MQTT and HTTPS protocols for seamless communication. Users can customize their graphical user interface (GUI) with different configurations, such as colour schemes, timescales, types of charts, and the quantity of displayed results. This flexibility ensures that real-time environmental data is accessible and easily interpretable from anywhere, at any time, via these applications. With synchronized GUIs across platforms, users are offered two distinct methods for monitoring real-time environmental parameters, enhancing the convenience and efficiency of data interaction.

## 4.4 Summary

This chapter describes the development of an IoT-enabled system for real-time monitoring of environmental parameters in underground mines, aimed at enhancing safety and transmitting data from underground mine tunnel to surface. The system integrates a LoRaWAN Gateway, an RS485-LN converter, and RS485 industrial gas sensors to facilitate continuous monitoring from the surface. It outlines the selection of hardware components and a cloud platform, the architecture of the system, and the stages of development, including lab testing, hardware implementation, establishing wireless communication, software configuration using AT commands and the thingZmate Dashboard to visualize the environmental parameters data in a real-time. This IoT-enabled LoRaWAN Gateway based setup ensures real-time monitoring of underground mine conditions, promoting safety and operational efficiency.

Chapter 5 discusses the implementation of the developed RTEPMS based on LoRa, ZigBee modules and LoRaWAN Gateway settings in Model Mines and Underground Mines in detail.

# CHAPTER 5

# 5. IMPLEMENTATION AND RESULT ANALYSIS OF THE DEVELOPED REAL TIME ENVIRONMENTAL PARAMETERS MONITORING SYSTEM (RTEPMS) IN UNDERGROUND MINES

## 5.1 Introduction

The developed RTEPMS to monitor environmental parameters as detailed in Chapters 3 and 4, was tested at the Model Mine laboratory of the Mining Engineering Department at the National Institute of Technology Karnataka (NITK), Surathkal, India, and in two underground gold mines in India. These field investigations were conducted in four phases:

In the first phase, the investigations involved using a real-time monitoring system based on ZigBee wireless communication modules and LoRa 433 MHz modules at the NITK Surathkal Model Mine to assess the wireless communication range and sensor sensitivity.

In the second phase, the developed real-time system using ZigBee modules and LoRa 433 MHz modules was tested in underground mines ‘A’ and ‘B’, which are 90 meters and 832 meters in depth from the surface, respectively. This phase aimed to evaluate sensor sensitivity for measuring environmental parameters and the wireless communication range in both line-of-sight (LOS) and non-line-of-sight (NLOS) conditions in underground mine tunnels and data transmission from underground mine tunnels to the surface.

The third phase involved field investigation using an enhanced LoRa 868 MHz module-based real-time system in underground mine ‘B’, which is about 832 meters in depth from the surface. The focus remained on testing sensor sensitivity for environmental parameter measurements and establishing wireless communication in LOS and NLOS scenarios within the tunnels.

In the fourth phase, field investigations were conducted using enhanced industrial gas sensors and RS485 technology to transmit real-time data from the underground mine tunnels to the surface for continuous 24x7 monitoring to prevent hazardous situations. This phase also tested sensor sensitivity and wireless communication range in both LOS and NLOS conditions in underground mine tunnels and also from underground mine tunnels to the surface.

## 5.2 Field Investigation of the Developed RTEPMS in a Model Mine

The developed ZigBee wireless communication system was tested and validated at the surface and in a Model Mine laboratory at the Mining Engineering Department of the National Institute of Technology Karnataka (NITK), Surathkal, India. This laboratory replicates an underground mine setting. The ZigBee-based system is designed to wirelessly monitor environmental parameters. Experimental results suggest that the ZigBee network is suitable for real-time monitoring of environmental conditions in underground mines. Further details regarding the functioning, effectiveness, and potential applications of the ZigBee-based system in underground mining are discussed in the following sections.

The transmitter and receiver side ZigBee radio modules are fixed in an enclosure, as shown in Fig. 3.17. Fig. 5.1 depicts the layout of the Model Mine at the NITK, Surathkal, India. The model mine includes,

- Belt conveyor of 23 meters in length, which operates with a 3 HP motor capacity and 58 RPM motor speed.
- The Direct Rope Haulage track length is 25 meters, the track width is 0.66 meters, and the tub capacity is 1.5 t, which operates on 2 HP motor power and 15 RPM motor speed.
- Variable speed fan with proper ventilation condition and power supply.

The deployment of the ZigBee transmitter module in a Model Mine at the corner point is represented as shown in Fig. 5.2. The location of experimentation carried out at the Mining Engineering Department and Model Mine laboratory of the NITK, Surathkal, India, are cited in a google map, as shown in Fig. 5.3. The data collected from sensors using ZigBee modules at the Model Mine are represented in Fig. 5.11.

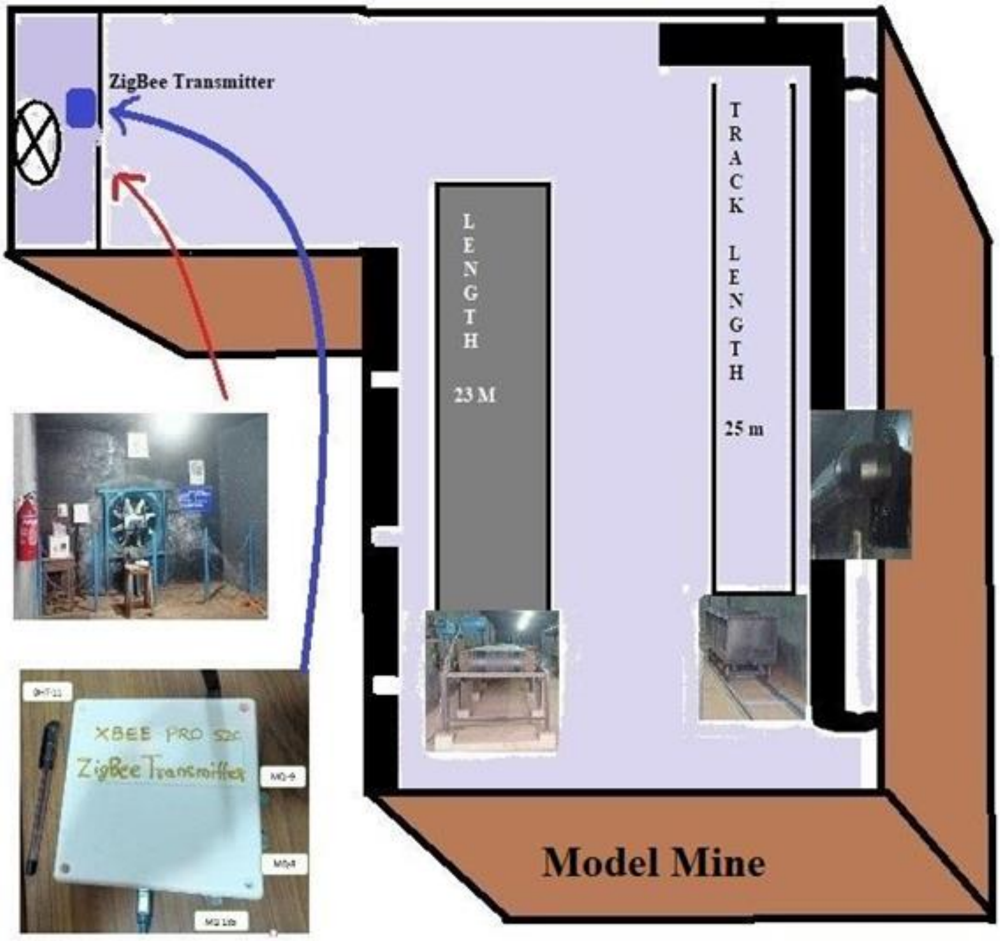
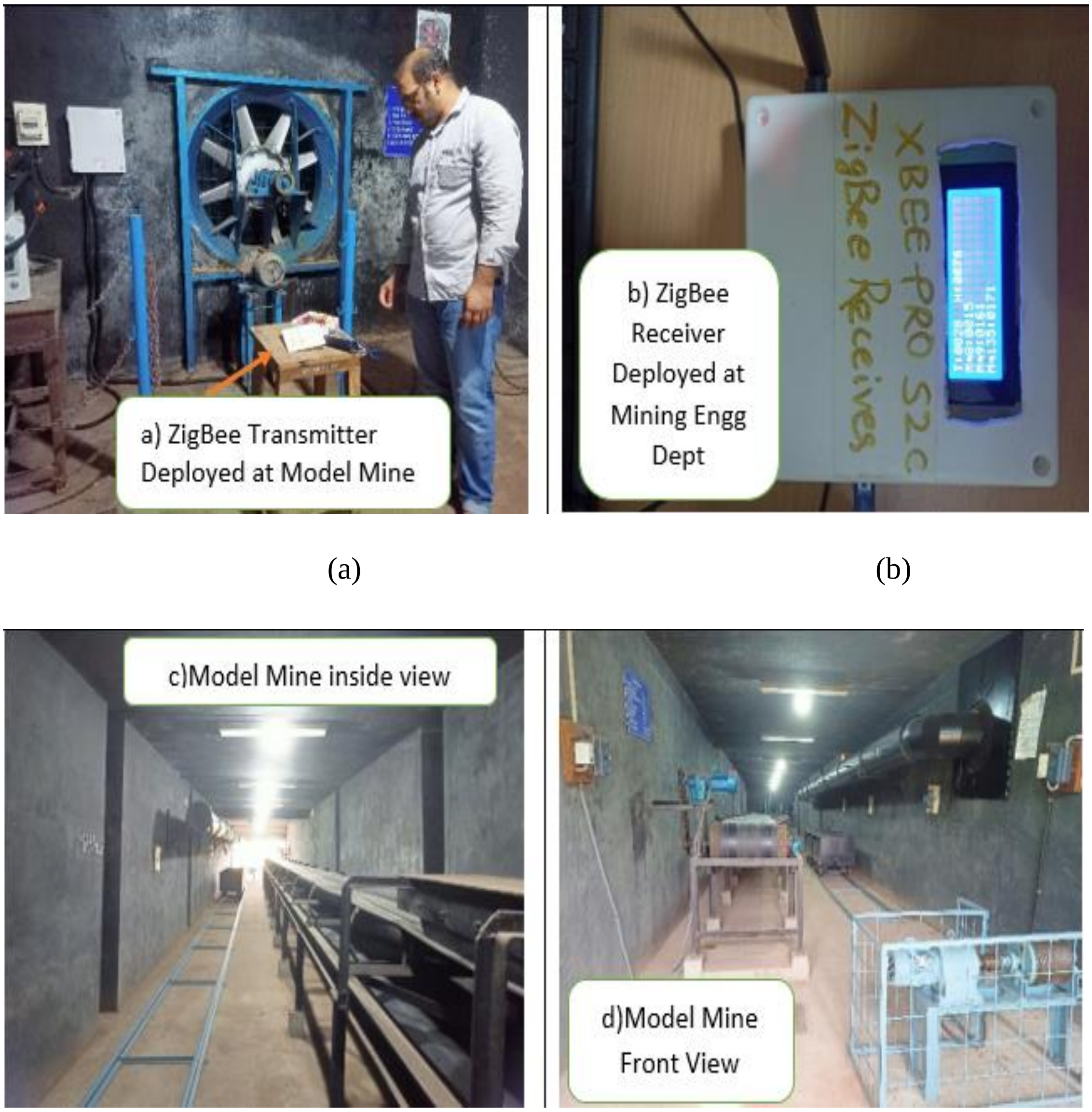


Fig. 5.1 A Schematic plan view of the Model Mine at the NITK Surathkal, India

The data is collected from 12:28 (hour: minute) to 14:54 (hour: minute) using the ZigBee-based system. The transmitter and receiver are deployed at a distance of 51 meters between the transmitter (Model Mine) and receiver (Mining Engineering Department), establishing a reliable signal strength to monitor data at the receiver.

The ZigBee-based portable real-time system was developed to monitor the environmental parameters in underground mines. The system is tested and evaluated in a Model Mine situated at a surface that replicates the underground mine structure. The developed system is reliable, power efficient, and cost-effective for monitoring the concentration of gases, temperature, and humidity. The system was tested at different locations and achieved a wireless communication distance between transmitter and receiver of more than 110 meters within the NITK, Surathkal campus, surrounded by college buildings and around 500 meters in open space without any obstacles. The transmitter and receiver are placed 51 meters apart to monitor real-time data from the model mine to the Mining Engineering Department of NITK, Surathkal.



(a) (b)

(c) (d)

Fig. 5.2 (a,b,c & d) Deployment of Transmitter ZigBee Module in a Model Mine and Receiver at the Mining Engineering Department, NITK Surathkal. a) ZigBee transmitter deployed at Model Mine, b) ZigBee receiver deployed at the mining engineering department, c) Inside view of Model Mine, d) Front view of Model Mine

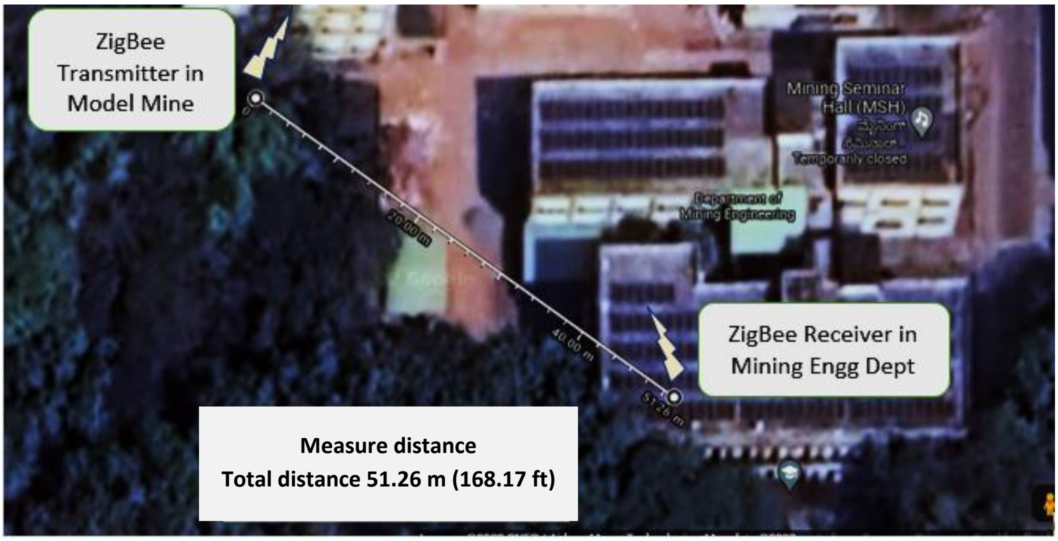


Fig. 5.3 Deployment of the Transmitter ZigBee Module in a model mine and Receiver at the Mining Engineering Department, NITK Surathkal is represented in a Google map

The developed system will benefit underground mine workers and organizations in terms of safety and productivity concerns. As a part of future work, the system can also be enhanced by embedding a gateway node at the receiver side of the ZigBee system to transmit data to the cloud platform to monitor the data in real time from anywhere and anytime. The developed system has been designed to be cost-effective and energy-efficient, making it accessible to smaller and less affluent underground mines.

### 5.3 Field Investigation of the developed RTEPMS in Underground Mines A and B

A real-time data communication system utilizing wireless ZigBee modules has been established and evaluated in two gold underground mines, identified as ‘A’ and ‘B’, in India. The process of establishing wireless communication between two ZigBee modules is detailed, including an investigation of radio range tests by measuring Received Signal Strength Indication (RSSI) parameters. These tests were conducted in underground mine ‘A’ at tunnel 3, with measurements taken at 10-meter intervals in a straight tunnel. Additionally, wireless communication was established to monitor environmental parameters from underground mine tunnels to the surface. The system was also tested in the second underground gold mine ‘B’, to monitor environmental parameters in both straight and curved tunnels. Experimental results indicate successful wireless communication between ZigBee modules over distances of 100 to 120 meters in straight tunnels, with a noted reduction in signal strength and increased data packet loss in curved tunnels. Overall, the results demonstrate that the ZigBee-based system is effective for measuring environmental parameters in underground mines.

### 5.3.1 Implementation of Developed ZigBee-based Wireless Communication System in Underground Mine ‘A’

Fig. 5.4 provides a typical view of the underground mine ‘A’ infrastructure. The attenuation of ZigBee radio waves in the straight tunnel at tunnel 3 of the mine was investigated at a frequency bandwidth of 2.4 GHz. The results and interpretations of the experiments conducted at tunnels 1, 2, and 3 of underground mine ‘A’ are as follows.

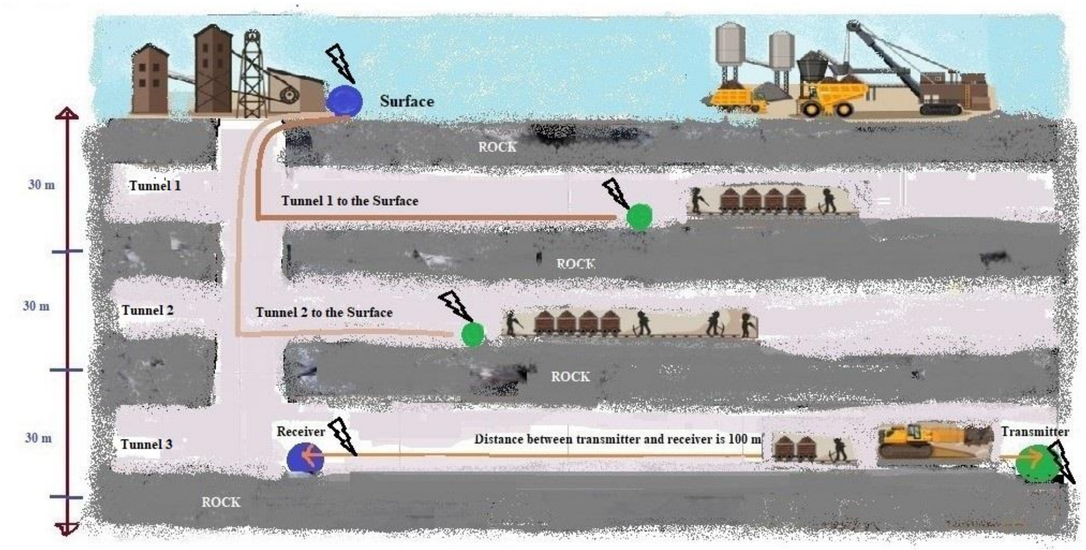


Fig. 5.4 Typical infrastructure of an Underground Mine ‘A’

#### *a) Establishment of Wireless Communication from Underground Mine ‘A’ Tunnel to the Surface*

The first experiment was conducted in an underground mine ‘A’ of tunnel 1, located 30 meters below the surface. The ZigBee transmitter and receiver modules successfully communicated at this depth, transmitting the sensed parameters from the tunnel 1 to the surface. The procedure was then repeated for an underground mine tunnel 2 situated 60 meters below the surface. The ZigBee transmitter was placed in tunnel 2, while the receiver remained at the surface level. Communication was successful, with a data packet success rate of 83%. Continuing the establishment of communication from the underground mine tunnel to the surface. The ZigBee transmitter again moved to underground mine tunnel 3, 90 meters below the surface. However, the modules failed to communicate due to a loss of signal strength. Additionally, the only available transmission path for radio waves from the underground mine tunnel to the surface was through a vertical opening called a shaft.

### *b) ZigBee Radio Range Test in an Underground Mine ‘A’*

The ZigBee radio range test was conducted in tunnel 3 of underground mine ‘A’, a straight tunnel 100 meters in length and 90 meters in depth. Fig. 5.5 presents a 3D layout of tunnel 3 of the underground mine straight tunnel, showing the placement of the ZigBee transmitter and receiver modules at a 100-meter distance. The test aimed to measure the Received Signal Strength Indication (RSSI), which indicates the strength of the wireless signal and the distance between devices. RSSI is expressed in decibels (dBm), where a higher value (closer to 0) indicates a stronger signal (e.g., -25 dBm is stronger than -80 dBm). The experiment was conducted in a line of sight (LOS) straight tunnel. The ZigBee receiver module was fixed near the shaft, while the ZigBee transmitter was moved at intervals (10 meters, 20 meters, 30 meters, ..., 100 meters) to measure RSSI values. The attenuation of ZigBee radio waves was analyzed based on the distance between the transmitter and receiver versus the logarithmic average of RSSI values, as illustrated in Fig. 5.6. The signal strength trend showed a decrease from -25 dBm at the shortest distance to -91 dBm at the longest distance, indicating weaker signal strength. The RSSI signal strength diminished as the distance increased, accompanied by data packet loss during successful packet transmission.

Fig. 5.5 3D map of tunnel 3 of the underground mine ‘A’

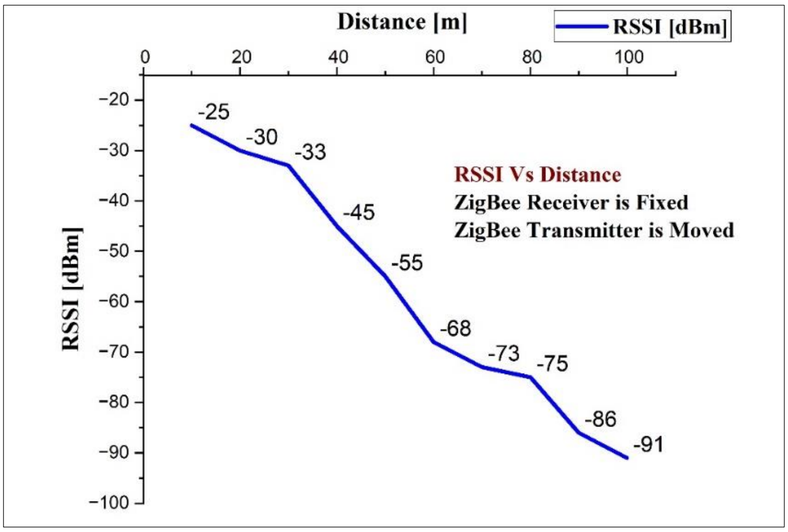
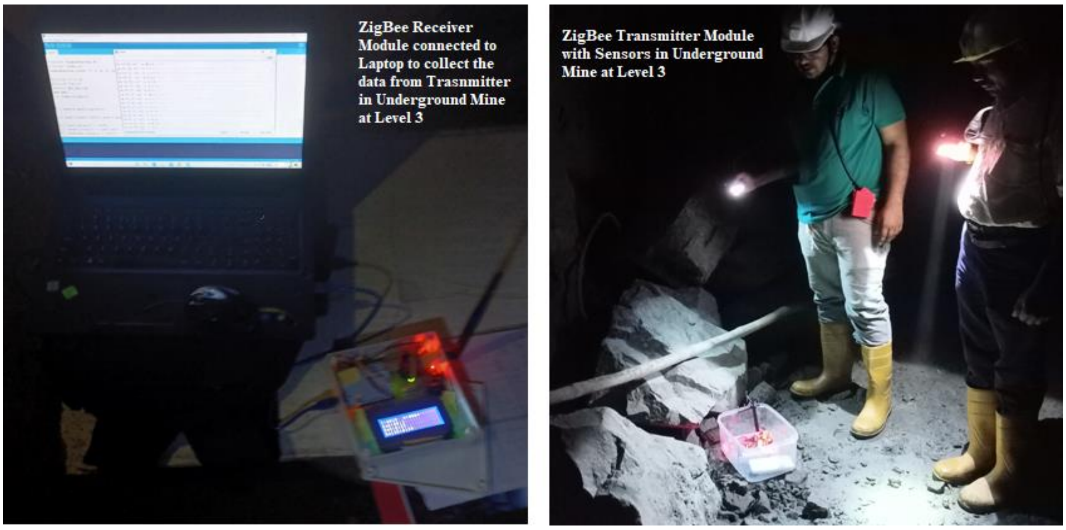


Fig. 5.6 ZigBee radio range RSSI test in an Underground Mine ‘A’

The experimental setup of deployment of the transmitter and receiver ZigBee modules in tunnel 3 of the underground mine ‘A’ straight tunnel of 100 meters in length to collect the environmental parameters is shown in Fig. 5.7. The ZigBee transmitter module is placed near the excavated ore body to collect the environmental parameters and sends data to the ZigBee receiver module in real-time. If the gas parameters exceed certain threshold limits, a receiver module will generate an alert buzzer sound to mine workers about variations in gas parameters.



(a) (b)

Fig. 5.7 (a & b) Deployment of ZigBee Transmitter and Receiver at the straight tunnel of tunnel 3 of Underground Mine ‘A’

### 5.3.2 Implementation of Developed ZigBee-based Wireless Communication System in Underground Mine ‘B’

Real-time monitoring of environmental parameters in underground mines involves the combination of communication modules and sensors. An experiment was conducted in an underground mine ‘B’ of tunnel 26, which contains straight and curved tunnels at an 832 meters depth from the surface. A section view of an underground mine and the ZigBee module’s positions where the experiment was performed is illustrated in Fig. 5.8.

The ZigBee receiver module is fixed at a specific location in an underground mine, and the transmitter module is placed in an LHD moving vehicle. The LHD vehicle is used to transport ore (ore that is fragmented after the blast) in underground mine tunnels. The ZigBee transmitter provides the sensed environmental parameters data to the receiver successfully with a distance of 100 meters to 110 meters in a straight tunnel of an underground mine. The signal strength drops in curved tunnels and data packets fail to receive at the receiver side. If the LHD vehicle comes in the straight tunnel, it continues to provide the sensed data to the receiver and drops data when it crosses the curved tunnel. The experimental setup of ZigBee transmitter and receiver modules was tested on underground mine tunnel 26 of an underground mine ‘B’ illustrated in Fig. 5.9.

After successful communication is established between ZigBee modules, then, the ZigBee transmitter is placed in a moving LHD vehicle (as the path represented in Fig. 5.8 on tunnel 26 of the underground mine is illustrated in Fig. 5.10. The sensed environmental parameters data is collected in real-time, and the variation in data is illustrated in Fig. 5.12 (a) and (b). The sensors at the transmitter ZigBee module sense the environmental gas parameters CO, $H_2$, Air quality smoke and dust, and other parameters like temperature and humidity.

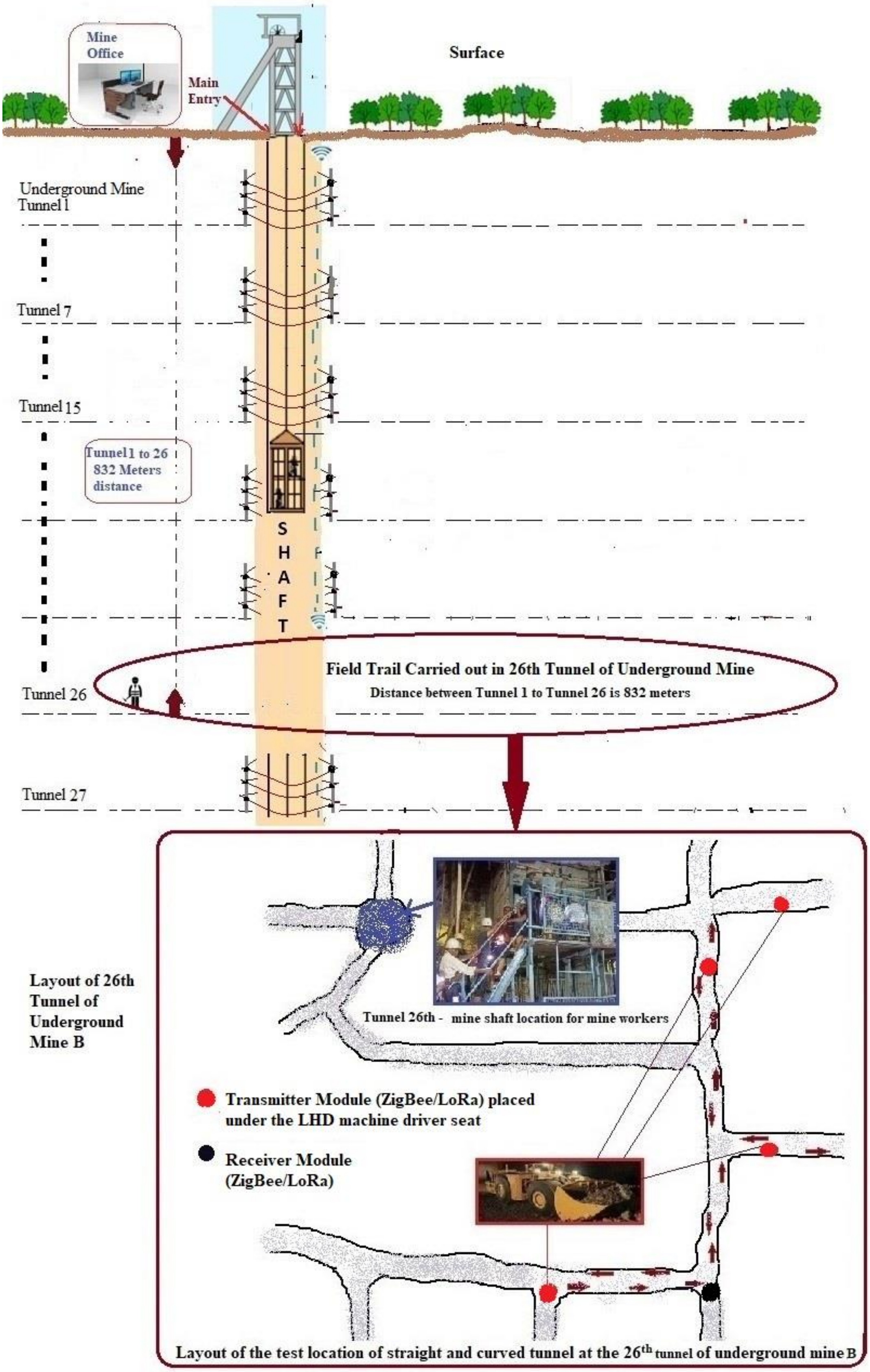


Fig. 5.8 Typical view of an Underground Mine ‘B’ infrastructure

Fig. 5.9 Experimental setup of ZigBee modules in tunnel 26 of Underground Mine ‘B’

(a) (b)

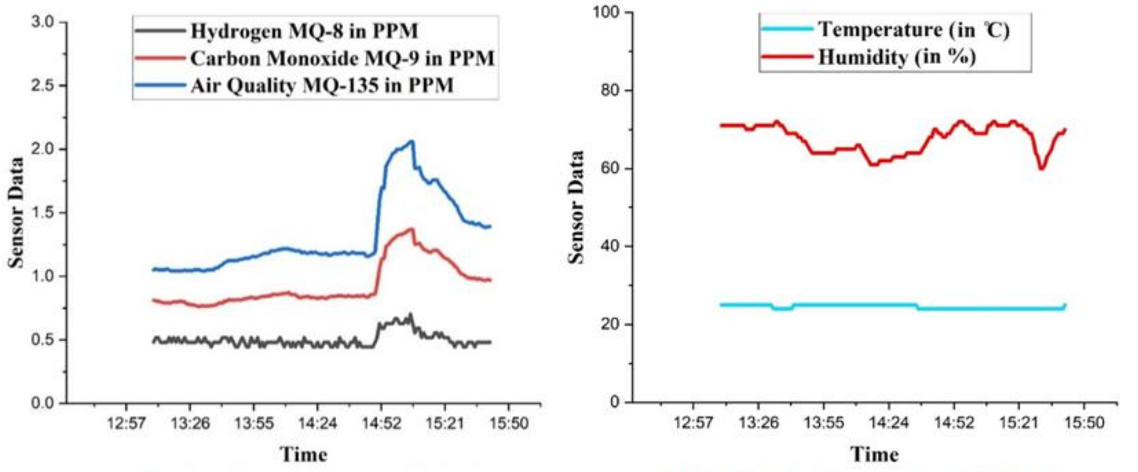
Fig. 5.10 (a & b) Placement of ZigBee transmitter module in LHD vehicle at tunnel 26 of Underground Mine ‘B’

### 5.3.3 Experimental Result Analysis and Discussion

#### *a) Analysis of Environmental Parameters Collected from Underground Mine 'A'*

The data collected by various sensors from underground mine 'A' is displayed over time in the graphs shown in Fig. 5.11 (a) and (b). During an experimental study at 14:50, an explosive blast was conducted to break the ore or mineral stone. This was done to test the sensitivity of the gas sensors on tunnel 3 of underground mine 'A', and a noticeable spike in gas parameter values was observed following the blast.

The analysis of the Air Quality MQ-135 sensor in PPM, the analysis of Carbon Monoxide MQ-9 in PPM and Hydrogen MQ-8, the analysis in PPM is illustrated in Fig. 5.11(a). The analysis of temperature and humidity is also shown in Fig. 5.11(b).



(a) Data collection from gas sensors using ZigBee modules

(b) Data collection from temperature and humidity sensors using ZigBee modules

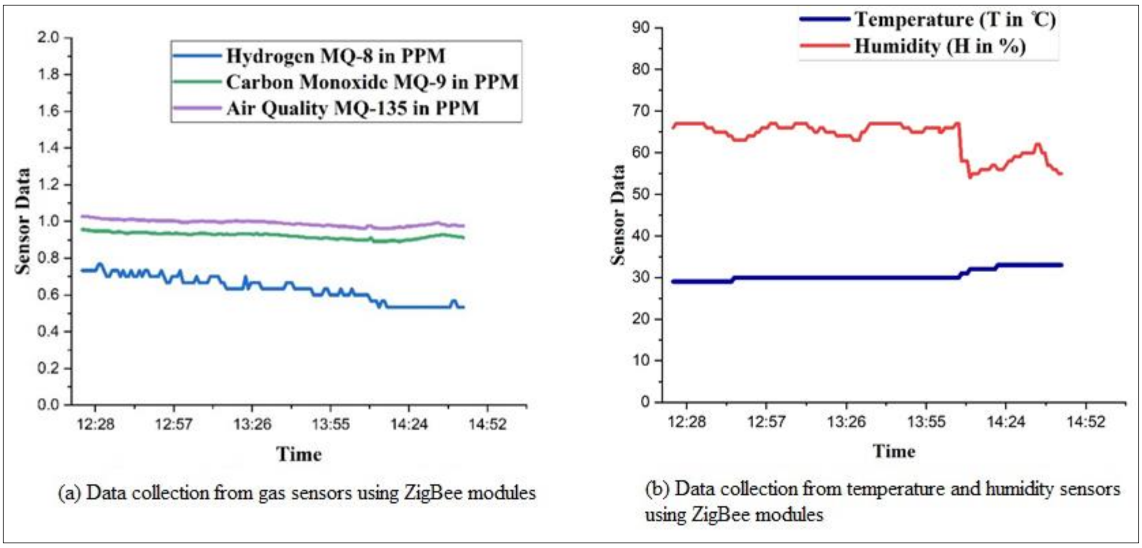
Fig. 5.11 Data collection from Underground Mine 'A' using ZigBee modules, a) Gas sensors b) Temperature and Humidity sensors

#### *b) Analysis of Environmental Parameters Collected from Underground Mine 'B'*

The continuous real-time data collected by various sensors from tunnel 26 of underground mine 'B' are displayed over time in the graphs shown in Fig. 5.12 (a) and (b). The ZigBee transmitter, placed on a moving LHD vehicle, captured the variations in gas parameter values and other environmental parameters.

### *c) Correlation between Sensor nodes attached to Zigbee modules and Portable Commercial Equipment*

To measure the correlation between the developed system and the HTC-1 Digital multi-monitoring system that includes a temperature thermometer and humidity hygrometer with a clock on the LCD display. The data was collected by HTC-1 digital temperature monitoring system and ZigBee-based system in underground mine ‘B’ during the process of mine excavation using LHD machines. The process involves preparation for material to be excavated, loading, hauling, and dumping.



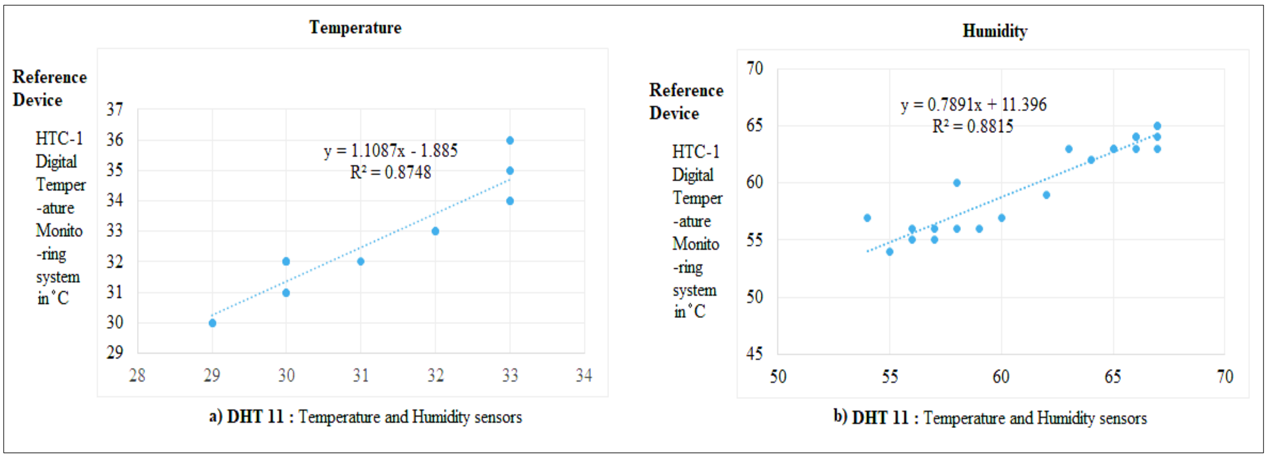
(a) Data collection from gas sensors using ZigBee modules

(b) Data collection from temperature and humidity sensors using ZigBee modules

Fig. 5.12 Data collection from Underground Mine ‘B’ using ZigBee modules, a) Gas sensors b) Temperature and Humidity sensors

Regression models describe the relationship between variables by fitting a straight line to observe data. Assuming the linearity between ZigBee-based system DHT 11 temperature sensor and reference device HTC-1 Digital Temperature Monitoring system responses. The performance of linear regression prediction is represented by the $R^2$ coefficient that describes the strength of the relationship on a 0 to 100% scale from 0 to 1. The linear regression graph for the Temperature and Humidity of environmental parameters in underground mine ‘B’ using measuring devices is shown in Fig. 5.13.

The linear regression graph for CO concentrations of environmental parameters monitored by MQ-9 gas sensor and the Drager Xam 5600 multi-gas detector instrument to monitor the gases in the underground mines is shown in Fig. 5.14. When the Linear Regression graphs are examined, it is observed that the temperature measurement devices have a high coefficient of determination for temperature $R^2 > 0.874$, humidity $R^2 > 0.881$, and $R^2 > 0.788$ for carbon monoxide gas.



**a) DHT 11 :** Temperature and Humidity sensors

**b) DHT 11 :** Temperature and Humidity sensors

Fig. 5.13 Correlation between readings of temperature at underground mine ‘B’ by developed system and HTC-1 Digital Temperature Monitoring system

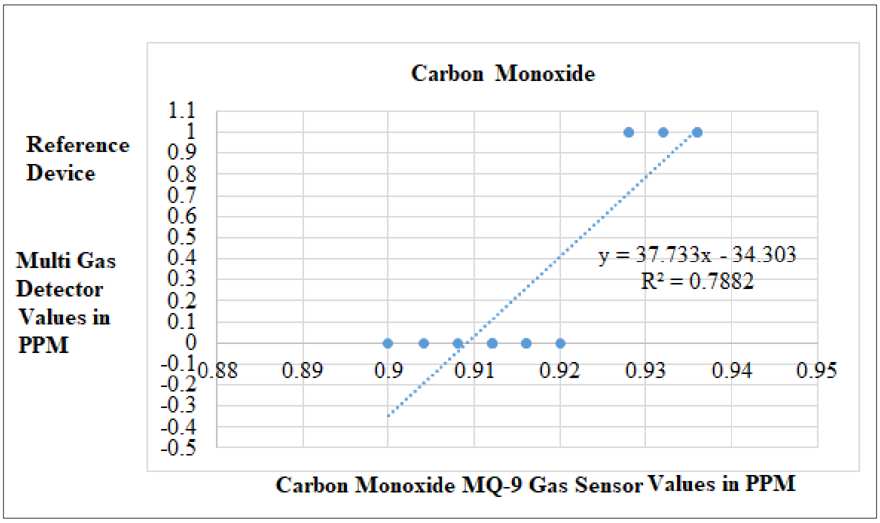


Fig. 5.14 Correlation between readings of MQ-9 carbon monoxide gas sensor at underground mine ‘B’ by developed system and Multi-Gas Detector

The ZigBee-based wireless monitoring system is designed and developed to measure environmental parameters in underground mines. This portable, reliable, and robust system monitors gas concentration levels, temperature, and humidity in underground mines. It utilizes open-source technologies, low-cost sensors, and wireless communication modules to enhance safety, operational management, and productivity by preventing major hazards. In this study, wireless communication was established between two ZigBee modules. The system was implemented in two underground mines, demonstrating that ZigBee modules are suitable for wireless monitoring and communication in such environments. The communication range of the ZigBee module in straight tunnels was analyzed using the RSSI test, and the experimental results of the collected environmental parameters were evaluated. A positive correlation was observed between the temperature and humidity data from the developed ZigBee-based system and the HTC-1 digital temperature monitoring system. Successful communication was established between underground mine levels and the surface at a height of 60 meters, with communication ranges of 100 to 120 meters in straight tunnels and 60 to 70 meters in curved tunnels with some data packet loss. This system is useful for real-time monitoring of environmental parameters, providing faster alerts to mine workers if parameters exceed the threshold limits. The ZigBee-based system can be enhanced by incorporating the gateway/IoT at the receiver section of the ZigBee transceiver module to collect data from the transmitter section and send it to cloud platforms such as ThingSpeak or Blynk IoT. This allows real-time analysis of monitoring data by mine supervisors from the mining office, enabling immediate mitigation measures if hazardous gases are detected. This developed product is cost-effective and significantly enhances safety in underground mines on a real-time basis.

### 5.3.4 Establishment of Real-Time communication with IoT-enabled LoRa module from Underground Mine ‘A’ to the Surface

Underground Mine ‘A’ infrastructure is illustrated in Fig. 5.4. The LoRa-based wireless communication from tunnels 1, 2, and 3 of Underground Mine ‘A’ to the surface is established and tested.

#### *a) Establishment of IoT Enabled 433 MHz LoRa module-based wireless communication from the tunnels of Underground Mine ‘A’ to the Surface*

Wireless communication between the LoRa transmitter in tunnel 1 and the LoRa receiver at the surface was successfully established, allowing the transmission of sensed parameters from the underground tunnel to the surface. The Wi-Fi-enabled LoRa receiver module then stores the acquired data on a cloud server.

The test was repeated to measure environmental parameters sensed by the sensors in tunnel 2 of Underground Mine 'A', located 60 meters below the surface. The hardware setup of the LoRa transmitter module was relocated to tunnel 2, while the receiver LoRa module remained at the surface. Wireless communication between the transmitter and receiver was successfully established, achieving an 85% success rate for data packet transmission to the LoRa receiver (gateway) and cloud server, as shown in Fig. 5.15.

(a) (b)

Fig. 5.15 (a & b) Experimental hardware setup of LoRa transmitter and LoRa receiver module at tunnel 2 of an Underground Mine 'A' to surface

To further test the wireless communication between the LoRa transmitter and receiver, the hardware setup of the LoRa transmitter module was moved to tunnel 3 of the underground mine, located 90 meters below the surface, while the LoRa receiver remained at the surface. Unfortunately, the transmitter and receiver failed to communicate due to weak signal strength and intervening obstacles.

### b) Establishment of wireless communication at the straight tunnel of underground mine tunnel 3 of an Underground Mine ‘A’

The developed LoRa-based hardware prototype was deployed in tunnel 3 of Underground Mine ‘A’ to measure environmental parameters, as shown in Fig. 5.16. The selected testing site is a 100-meter-long straight tunnel. The LoRa transmitter module was placed near the excavated ore body, where ore extraction is ongoing, to collect environmental data and transmit it in real time to the LoRa receiver module. The LoRa transmitter modules store collected data in an SD card module and send it to the LoRa receiver module, which can be viewed using the Arduino serial monitor tools. As part of the experimental study, an explosive blast was conducted by experts at a specific location in tunnel 3 to observe variations in environmental parameters detected by the sensors at the mine working site, as shown in Fig. 5.16. A typical layout map of tunnel 3, indicating the deployment of LoRa transmitter and receiver modules 100 meters apart, is shown in Fig. 5.5. The data collected by the receiver is represented in Fig. 5.20. The LoRa-based system is configured to generate an alert buzzer sound at the mine site if gas parameters vary or exceed certain threshold limits, helping to prevent hazards.

(a) (b)

Fig. 5.16 (a & b) Experimental hardware setup of LoRa transmitter and LoRa receiver module at tunnel 3 of an Underground Mine ‘A’

(c) (d)

Fig. 5.17 (a & b) LoRa transmitter and receiver module at tunnel 3 of an Underground Mine ‘A’

### *c) Establishment of LoRa-based wireless communication in Mine Tunnel 26 of the Underground Mine ‘B’*

The developed LoRa module hardware setup was deployed in tunnel 26 of Underground Mine ‘B’ to monitor and collect environmental parameters from both straight and curved tunnel sections located approximately 832 meters below the surface. A layout map of tunnel 26, along with the positions of the LoRa transmitter and receiver modules during the experimental test, is illustrated in Fig. 5.8. The LoRa receiver module was fixed at a specific location in tunnel 26, while the LoRa transmitter module was placed in an LHD vehicle operating in the same tunnel. These LHD vehicles are used to transport ore fragmented after blasting in the underground mine tunnels. The experimental hardware setup for the LoRa transmitter and receiver modules in tunnel 26 of Underground Mine ‘B’ is depicted in Fig. 5.18.

### 5.3.5 Experimental Result Analysis and Discussion

The developed LoRa-based environmental monitoring system is designed for use in underground mine sites to detect various environmental parameters. As a reference device, the multi-gas detector instrument “Drager Xam 5600” was used along with calibrated gas sensors to collect environmental data. This multi-gas detector can identify six gases: $CO_2$ (%), $CH_4$ (%), $SO_2$ (ppm), $H_2S$ (ppm), and $O_2$ (%), as shown in Fig. 5.22. The LoRa-based system detects parameters including $CO_2$ (ppm), CO (ppm), $CH_4$ (ppm), $H_2S$ (ppm), air quality (ppm), and temperature (°C). The data collected by the LoRa-based system under different scenarios are described in this section.

(a) (b)

Fig. 5.18 (a) Experimental hardware setup of LoRa modules in mine tunnel 26 of Underground Mine 'B', (b) LoRa transmitter modules in LHD vehicle and LoRa receiver at the specific location of mine tunnel 26 of the Underground Mine 'B'

### *a) Data Analysis of Underground Mine 'A'*

The IoT with LoRa-based environmental monitoring system uses sensors to measure various environmental parameters and sends the data to a receiver (Gateway). The Wi-Fi or Bluetooth-enabled receiver development board, ESP32, transmits the data to a private cloud for analysis and storage. Data collected from tunnels 1 and 2 of Underground Mine 'A' is shown in Fig. 5.21. To test wireless communication, data was collected for 20 minutes from Underground Mine 'A' to the surface. From tunnel 1, data was collected and transmitted to the cloud server from 13:10:05 to 13:20:16, and from tunnel 2, from 13:21:38 to 13:30:06. Successful wireless communication was established from a depth of 60 meters to the surface, despite some data packet drops due to weak signal strength. However, communication from tunnel 3, at a depth of 90 meters, failed, and no data was transferred to the cloud server. The percentage of data packets received at the surface from Underground Mine 'A' is represented in Table 5.1.

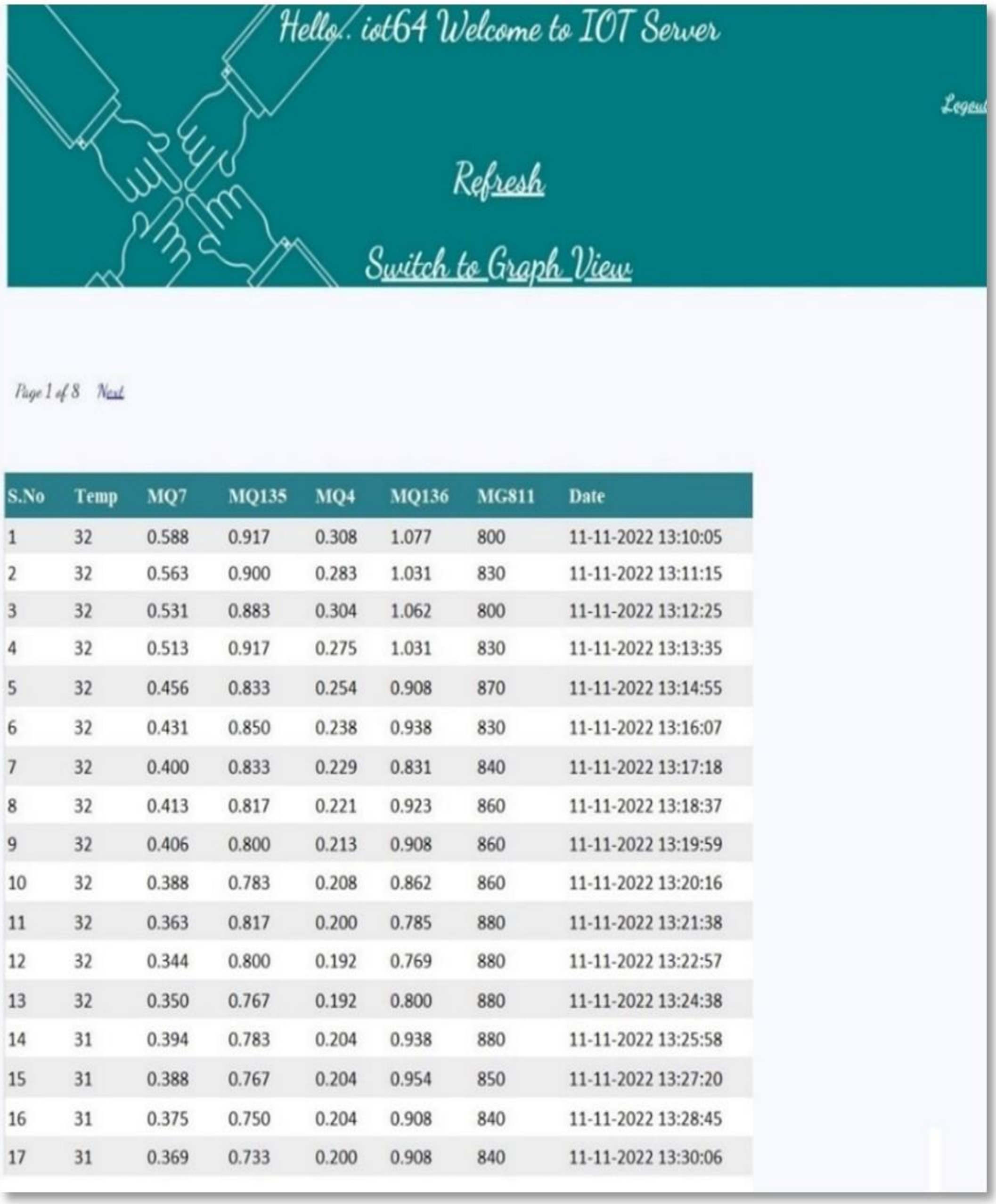
Data from the LoRa transmitter module, deployed at a working site in tunnel 3, is stored in an SD card module connected to the transmitter, as shown in Fig. 5.20. This data can be viewed in real-time on a laptop or a 20x4 LCD at the receiver end. At 14:50, an explosive blast was conducted in tunnel 3 to test the sensors' sensitivity, resulting in a noticeable spike in the environmental parameter values.

Table 5.1 Percentage of data packets received at the surface in an Underground Mine ‘A’

| **Underground Mine ‘A’** | **Distance from surface** | **Time** | **Percentage of data packets received** |
|---|---|---|---|
| Mine Tunnel 1 | 30 m | 13:10:05 to 13:20:16 | 100% |
| Mine Tunnel 2 | 60 m | 13:21:38 to 13:30:06 | 70% |
| Mine Tunnel 3 | 90 m | 13:31:00 to 13:40:00 | No communication |

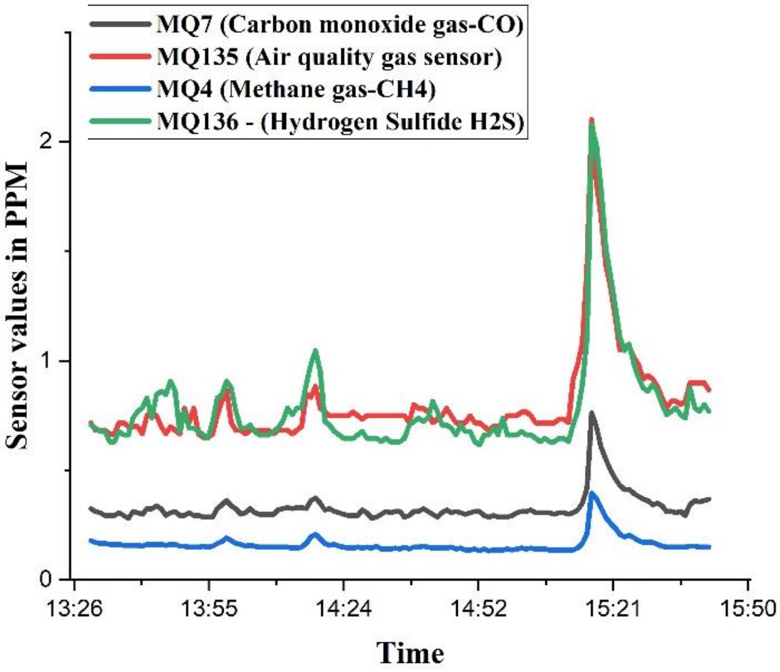
### *b) Data Analysis of Underground Mine ‘B’*

The sensor data collected from tunnel 26 of Underground Mine-B is illustrated in Fig. 5.21. The LoRa transmitter successfully transmitted data to the LoRa receiver over distances of 100 to 105 meters in a straight tunnel and 50 to 55 meters in a curved tunnel. Data packet loss occurred in the curved tunnels due to weak signal strength and NLOS (non-line-of-sight) conditions between the transmitter and receiver. The LoRa transmitter module was placed in a moving LHD vehicle, capturing variations in environmental parameters. Meanwhile, the LoRa receiver module was stationed at a specific location within the same tunnel to monitor the data. The system successfully transmitted sensed data in straight underground tunnels, but data packet loss was observed when crossing curved tunnels. Variations in $H_2S$ gas sensor data, air quality sensor data, and temperature were noted due to the deployment of the LoRa system in the moving LHD vehicle.

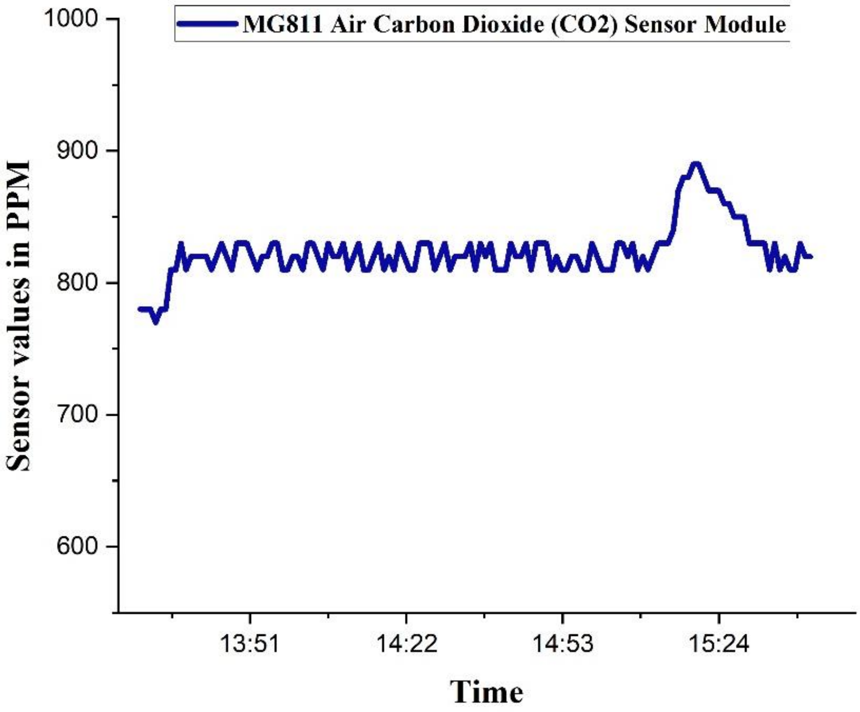


| S.No | Temp | MQ7 | MQ135 | MQ4 | MQ136 | MG811 | Date |
|---|---|---|---|---|---|---|---|
| 1 | 32 | 0.588 | 0.917 | 0.308 | 1.077 | 800 | 11-11-2022 13:10:05 |
| 2 | 32 | 0.563 | 0.900 | 0.283 | 1.031 | 830 | 11-11-2022 13:11:15 |
| 3 | 32 | 0.531 | 0.883 | 0.304 | 1.062 | 800 | 11-11-2022 13:12:25 |
| 4 | 32 | 0.513 | 0.917 | 0.275 | 1.031 | 830 | 11-11-2022 13:13:35 |
| 5 | 32 | 0.456 | 0.833 | 0.254 | 0.908 | 870 | 11-11-2022 13:14:55 |
| 6 | 32 | 0.431 | 0.850 | 0.238 | 0.938 | 830 | 11-11-2022 13:16:07 |
| 7 | 32 | 0.400 | 0.833 | 0.229 | 0.831 | 840 | 11-11-2022 13:17:18 |
| 8 | 32 | 0.413 | 0.817 | 0.221 | 0.923 | 860 | 11-11-2022 13:18:37 |
| 9 | 32 | 0.406 | 0.800 | 0.213 | 0.908 | 860 | 11-11-2022 13:19:59 |
| 10 | 32 | 0.388 | 0.783 | 0.208 | 0.862 | 860 | 11-11-2022 13:20:16 |
| 11 | 32 | 0.363 | 0.817 | 0.200 | 0.785 | 880 | 11-11-2022 13:21:38 |
| 12 | 32 | 0.344 | 0.800 | 0.192 | 0.769 | 880 | 11-11-2022 13:22:57 |
| 13 | 32 | 0.350 | 0.767 | 0.192 | 0.800 | 880 | 11-11-2022 13:24:38 |
| 14 | 31 | 0.394 | 0.783 | 0.204 | 0.938 | 880 | 11-11-2022 13:25:58 |
| 15 | 31 | 0.388 | 0.767 | 0.204 | 0.954 | 850 | 11-11-2022 13:27:20 |
| 16 | 31 | 0.375 | 0.750 | 0.204 | 0.908 | 840 | 11-11-2022 13:28:45 |
| 17 | 31 | 0.369 | 0.733 | 0.200 | 0.908 | 840 | 11-11-2022 13:30:06 |

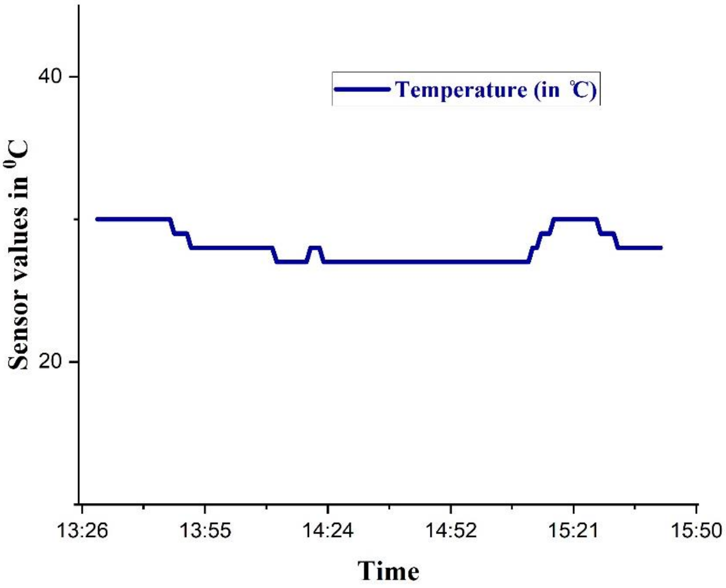
Fig. 5.19 IoT-based web user interface of the environmental parameters from the tunnel 1 and 2 of Underground Mine ‘A’



(a) $CH_4$, CO, $H_2S$, Air quality Gas sensors

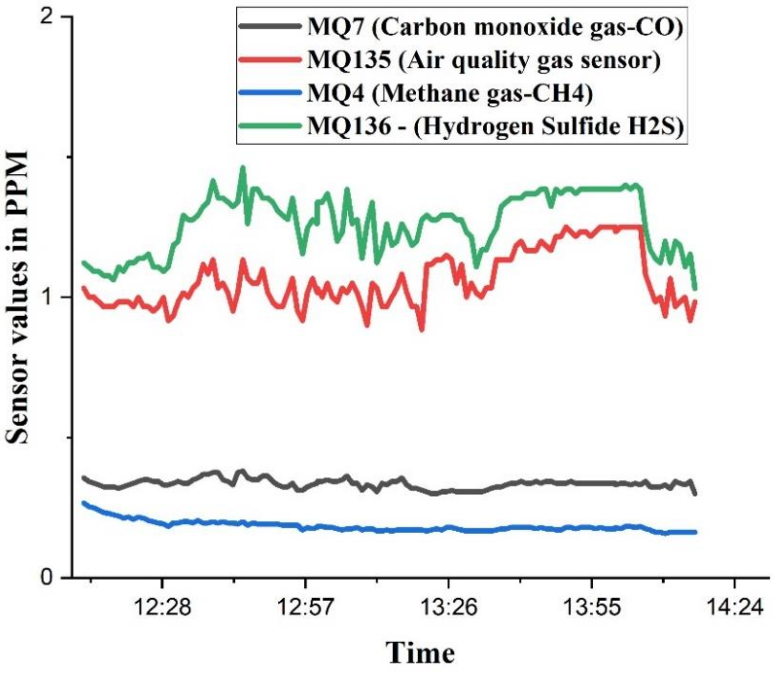


(b) $CO_2$ sensor

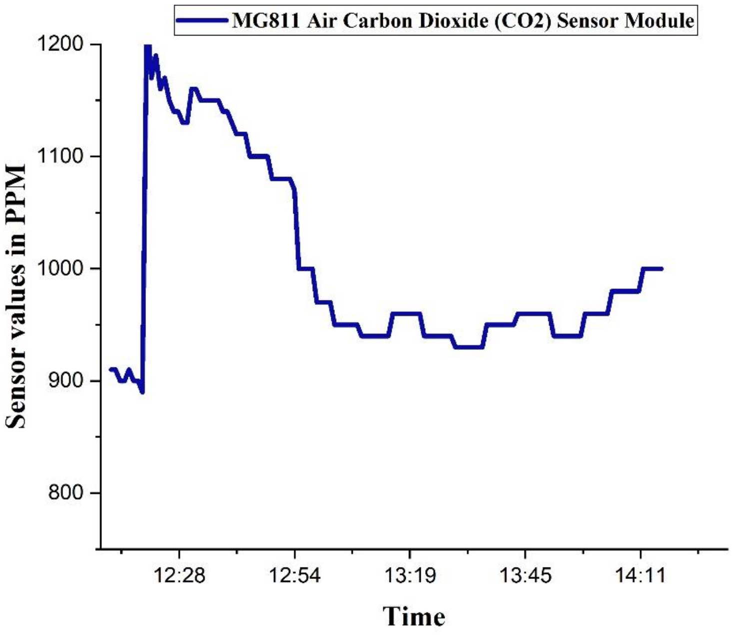


(c) Temperature and Humidity sensor

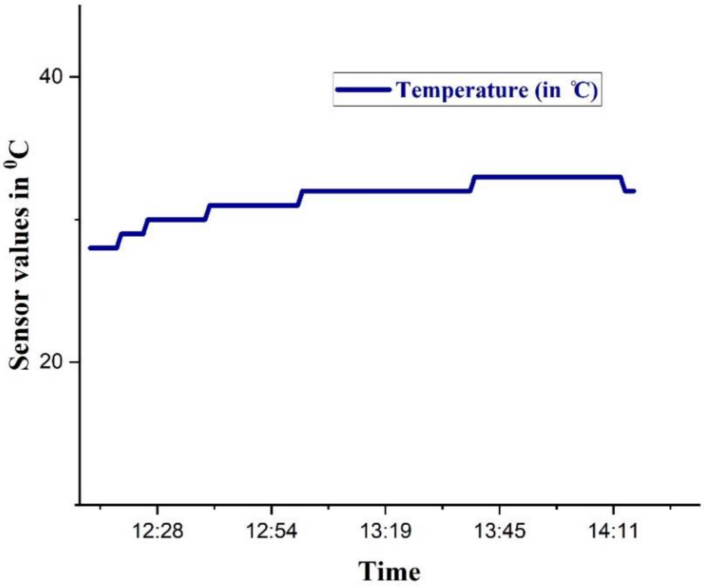
Fig. 5.20 Concentrations of environmental parameters from sensors deployed in a working mine site of mine tunnel 3 of Underground Mine ‘A’ (a) $CH_4$, CO, $H_2S$, Air quality Gas sensors, (b) $CO_2$ sensor, (c) Temperature and Humidity sensor



(a) $CH_4$, CO, $H_2S$, Air quality Gas sensors



(b) $CO_2$ sensor



(c) Temperature and Humidity sensor

Fig. 5.21 Concentrations of environmental parameters from sensors in an Underground Mine ‘B’ (a) $CH_4$, CO, $H_2S$, Air quality Gas sensors, (b) $CO_2$ sensor, (c) Temperature and Humidity sensor

### 5.3.6 Data Validation of Sensor Values with Multi Gas Detectors of Underground Mines ‘A’ and ‘B’

The comparison between the LoRa-based system sensors and the multi-gas detector responses is also presented. The performance of the linear regression model prediction is indicated by the $R^2$ coefficient, which describes the strength of the relationship on a scale from 0 to 1. The linear regression graph for $CO_2$ concentrations measured by the devices is shown in Figures 5.23 and 5.24. Upon examination, it is observed that the coefficient of determination for $CO_2$ measurement in Underground Mine ‘A’ is $R^2 = 0.714$, and in Underground Mine ‘B’, it is $R^2 = 0.800$.

(a) (b)

Fig. 5.22 (a & b): Data monitor by the portable multi-gas detector in underground mines ‘A’ and ‘B’

The hardware prototype of an IoT with a LoRa module-based real-time environmental monitoring system has been developed for underground mines. This system is portable and reliable, designed to monitor environmental parameters in underground mines and enhance safety and productivity by preventing significant hazards. It generates alerts if parameters exceed threshold limits at the mine site. The system was deployed, tested, and evaluated in two underground mines in India. The results showed that LoRa transceiver modules (433 MHz) are suitable for wireless communication and monitoring environmental parameters in underground mines.

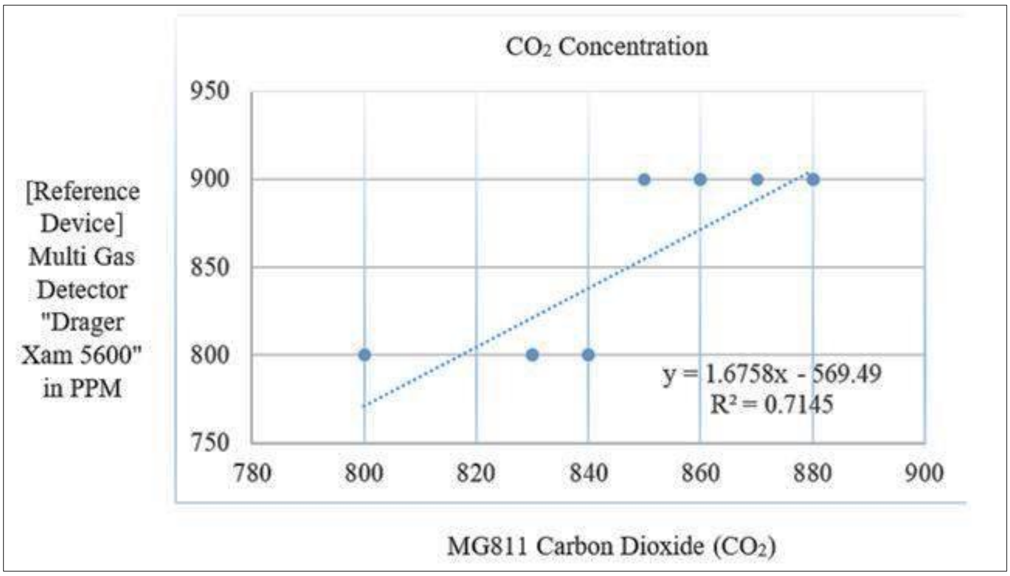


Fig. 5.23 Linear regression graphs of the devices for $CO_2$ gas concentration in Underground Mine ‘A’

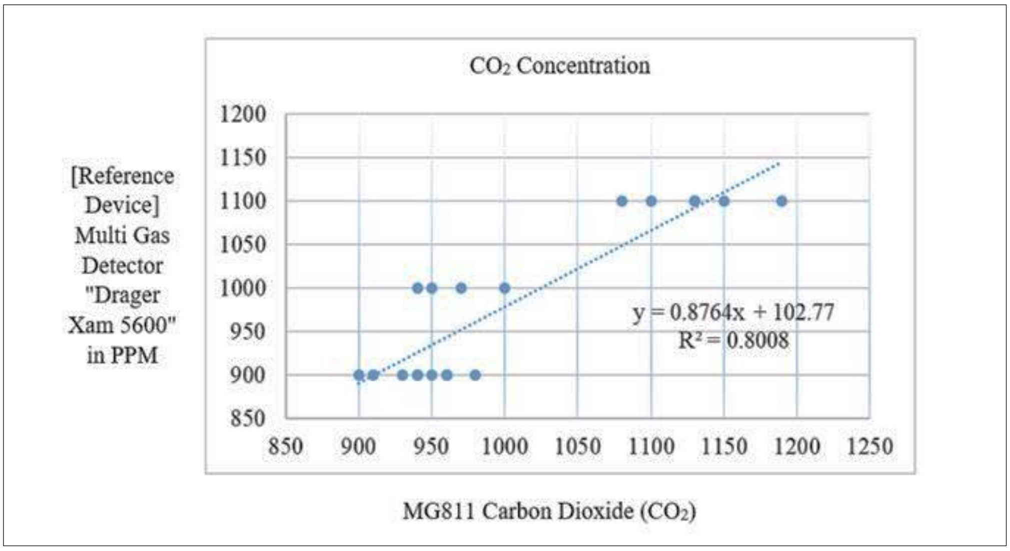


Fig. 5.24 Linear regression graphs of the devices for $CO_2$ gas concentration in Underground Mine ‘B’

The radio range test using the RSSI factor between LoRa modules was analyzed in a straight tunnel. Successful wireless communication was established between tunnel 2 and the surface at a depth of 60 meters, with data stored in a cloud database. Wireless communication distances between LoRa modules were 100 to 105 meters in straight tunnels and 50 to 55 meters in curved tunnels, with some data packet loss. A portable multi-gas detector was used in underground mines (‘A’ and ‘B’) to measure environmental parameters and compare the data with the developed LoRa system, showing very close results. The LoRa-based system is programmed to send receiver data to a cloud platform such as ThingSpeak IoT or a private cloud whenever the LoRa receiver module is connected to Wi-Fi or the Internet. If Wi-Fi or the Internet is unavailable, data is stored in an SD card module. The received data from the cloud platform or SD card is analyzed by the mine supervisor from the mining office. The developed IoT with LoRa transceiver Ra-02 (433 MHz) module-based product enhances safety in underground mines in real-time and cost-effective.

## 5.4 Field Investigation of the developed RTEPMS based on LoRa 868 MHz module in Underground Mine ‘B’

The HPD13A LoRa 868 MHz based RTEPMS is designed and developed to facilitate real-time data collection in underground mines. The RTEPMS was tested and evaluated both at the surface and in an underground mine in India. The experimental results demonstrate successful LoRa-based wireless communication in the underground mine, with effective data acquisition and real-time processing. Key environmental parameters monitored include $O_2$, CO, $CO_2$, $NO_2$, and EO, with alerts generated when these exceed threshold limits. The data correlation between the LoRa-based RTEPMS and multi-gas detector devices was 69.47% for $CO_2$ and 72.38% for CO, while the values for $CH_4$ and $H_2S$ were nearly zero, indicating their negligible presence in the underground mines. The RTEPMS provides an affordable solution for smaller and less affluent underground mines, alerting workers if environmental parameters exceed safe limits during emergencies.

Details of the implementation of the RTEPMS within an underground mine are provided, including information on the mine's structure and the deployment locations used to acquire environmental parameter data.

The real-time monitoring of environmental parameters within underground mines involves the integration of communication modules and sensors. An experimental investigation was conducted at tunnel 26 of an underground mine, situated 832 meters below the surface. The layout of tunnel 26 includes key elements such as mine tunnels, rock break chambers, shafts, underground passages, and ventilation fans as shown in

Fig. 5.25. The RTEPMS transmitter successfully transmitted environmental data to the receiver over distances of 180 to 200 meters in straight tunnels, with a gradual decrease in signal strength and occasional data packet loss in curved sections. The experimental setup of the RTEPMS, featuring LoRa-based transmitters and receivers at tunnel 26, is illustrated in Fig. 5.26 and Fig. 5.27.

### 5.4.1 Experimental Results and Analysis

We briefly describe the environmental parameters collected from an underground mine tunnel 26 using an IoT-enabled RTEPMS with a LoRa Module. Additionally, the collected data is compared from the underground mine using a multi-gas detector device that was obtained from the LoRa-based RTEPMS wireless communication system. The wireless communication distances between the RTEPMS-based LoRa transmitter and receiver in the underground mine are detailed in Table 5.2.

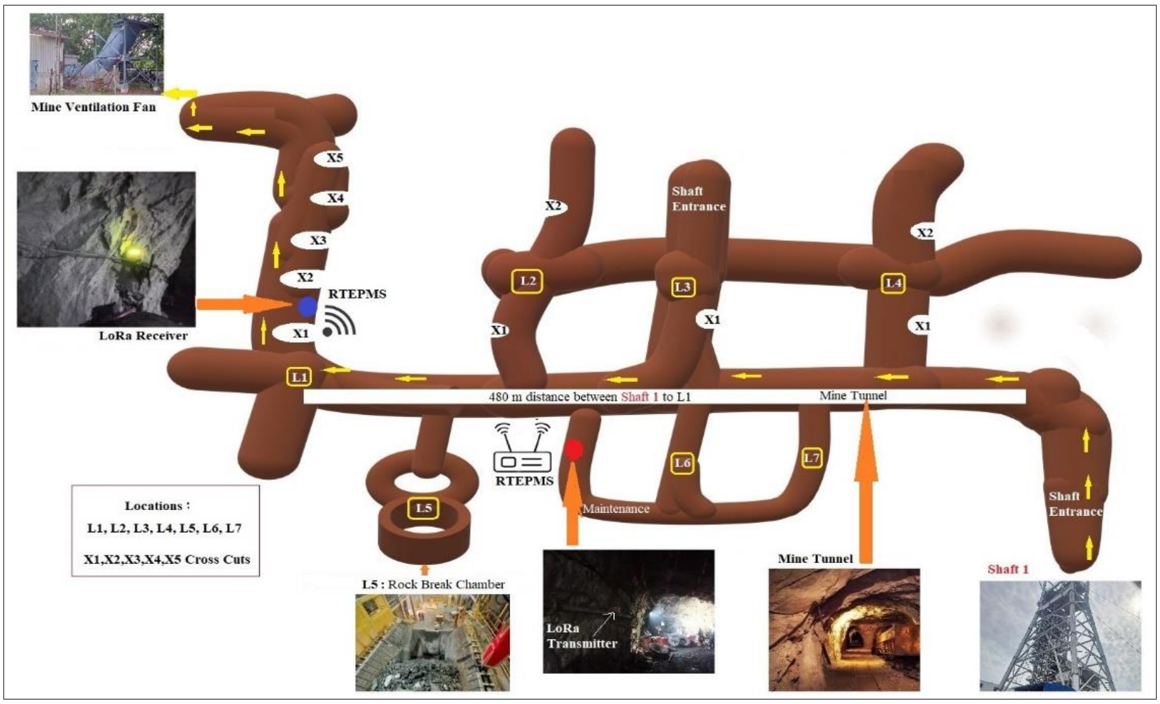
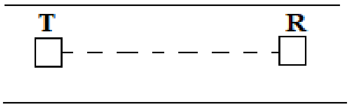
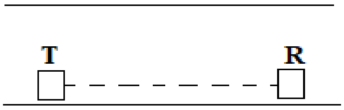
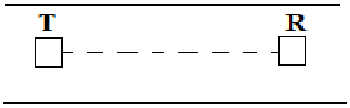
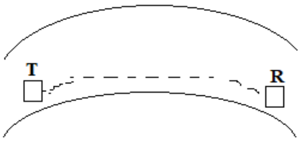


Fig. 5.25 Layout view of tunnel 26 of the Underground Mine ‘B’ Infrastructure

Fig. 5.26 RTEPMS with LoRa transmitter deployment at tunnel 26 of the underground mine ‘B’

Fig. 5.27 RTEPMS with LoRa receiver deployment at tunnel 26 of the underground mine ‘B’

Table 5.2 Experimental Results of Communication distance between LoRa modules 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 |  |

### *a) Data Analysis of Environmental Parameters Collected from an Underground Mine using RTEPMS with LoRa Module*

The environmental parameters were collected in real-time using a LoRa 868 MHz-based RTEPMS with a LoRa module in an underground mine. Table 5.3 provides the dataset statistics of these parameters. The gas concentrations are depicted in a time series chart to examine variations in levels. Fig. 5.28 shows the $CO_2$ gas concentration measured by the LoRa-based RTEPMS, with periodic rises above the baseline likely due to the movement of diesel-operated LHD vehicles, which release significant amounts of $CO_2$ during combustion. These peaks correspond to times of increased vehicle activity, indicating that diesel vehicle movement noticeably impacts $CO_2$ levels.

The CO levels exhibit a periodic pattern similar to $CO_2$, suggesting influence from diesel-operated LHD vehicle movement. $CH_4$, $H_2S$, and $H_2$ levels remain relatively low with minor fluctuations.

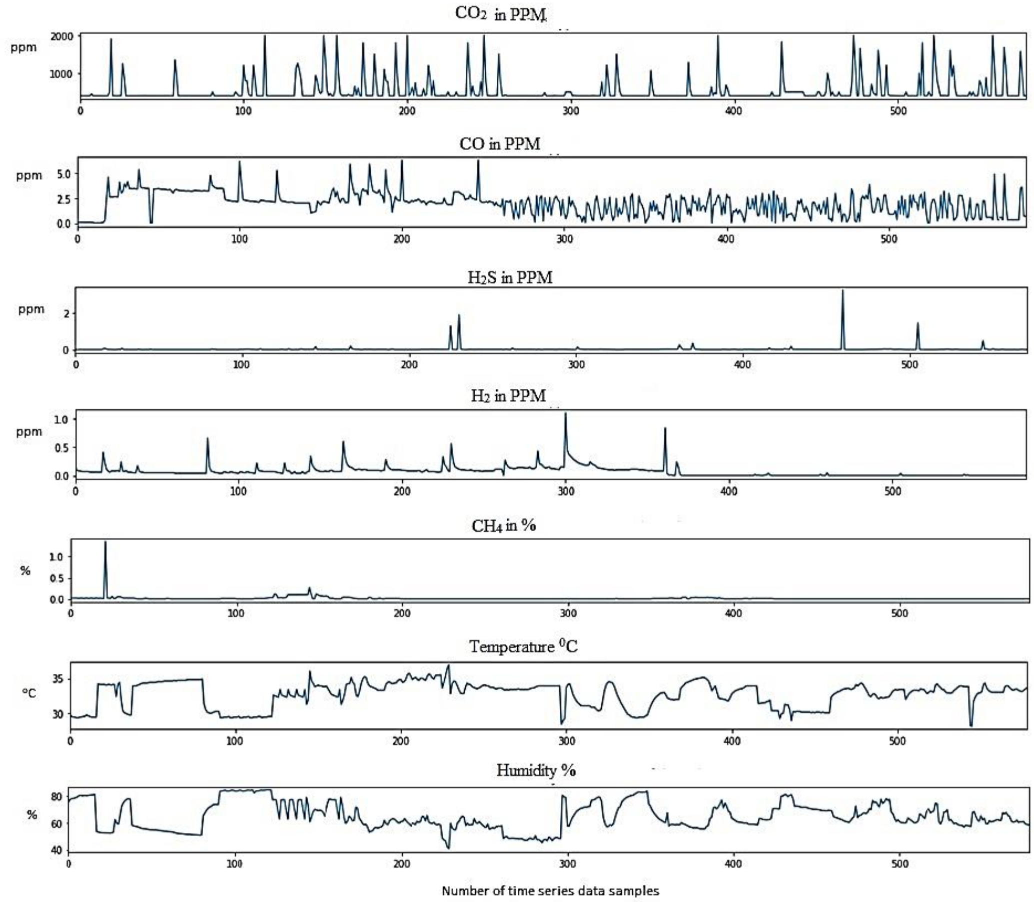


Fig. 5.28 Time Series real time data representation of environmental parameters $CO_2$, CO, $H_2S$, $H_2$, $CH_4$, Temperature $^0$C, and Humidity %

Temperature and humidity fluctuations, measured by the LoRa device suggest that the mine's ventilation system is functioning efficiently. Proper ventilation is crucial for regulating temperature and removing harmful gases in underground mines. High humidity and temperatures can be uncomfortable and dangerous for miners, leading to heat stress or other heat-related illnesses. The inverse relationship between temperature and humidity observed here is a positive sign, indicating lower relative humidity at higher temperatures, potentially reducing the risk of heat-related issues.

Data was collected at tunnel Level 26 of the underground mine, at a depth of 832 meters from the surface, encompassing parameters such as $CO_2$, CO, $H_2S$, $H_2$, $CH_4$’ temperature, and humidity.

Table 5.3 Dataset Statistics of Environmental Parameters Measured by using the LoRa Device

| **Parameters** | **CO by LoRa PPM** | **$CO_2$ by LoRa PPM** | **$CH_4$ by LoRa %** | **$H_2S$ LoRa PPM** | **$H_2$ LoRa PPM** | **Temperature in °C** | **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 |

- **Gas Concentrations**

*$CO_2$:* Periodic fluctuations in $CO_2$ levels, particularly 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 impair miners' cognitive abilities.

*CO:* Periodic spikes in CO levels suggest bursts of CO emissions, possibly from machinery or combustion processes. CO is a toxic gas, and even low concentrations can be harmful over prolonged exposure.

*$H_2S$:* Although $H_2S$ levels are relatively low, they are still significant. $H_2S$ is a toxic gas with a characteristic rotten egg smell, and even low concentrations can be harmful.

*$H_2$:* The presence of hydrogen gas indicates potential chemical reactions or processes within the mine. Hydrogen is flammable, and its accumulation can pose explosion risks.

*$CH_4$:* Methane, a common gas in coal mines, is highly flammable. Although the levels are low, continuous monitoring of $CH_4$ is crucial to prevent any explosive mixtures.

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 meters presents a challenging environment with potential risks from various gases and environmental conditions.

The observed time series data showcases the actual recorded values over time. The underground mine environment appears relatively stable in terms of gas concentrations and environmental conditions. Clear daily patterns in most parameters suggest consistent daily activities, machinery operations, and ventilation patterns influencing the mine's environment. The stable trends in gas concentrations are a positive sign for safety, but continuous monitoring is essential to promptly detect any sudden changes or anomalies.

### *b) Data Analysis of Environmental Parameters Collected from Underground Mine Using Multi Gas Detector Device and Lora-Based RTEPMS Wireless Communication System*

Environmental parameters were collected using a multi-gas detector device and a real-time LoRa module-based RTEPMS in an underground mine. Data measured using the multi-gas detector was recorded once per shift, while the RTEPMS device collected data continuously. These measurements are illustrated in Table 5.4 and Table 5.5.

The trends and distributions observed for similar gases (e.g., CO, $CO_2$) using both the multi-gas detector and the LoRa-based RTEPMS are somewhat consistent, indicating reliable measurements from both devices. The temperature and humidity readings from the LoRa-based RTEPMS reflect typical indoor or ambient conditions, suggesting that extreme conditions (very high or low temperatures/humidities) were not encountered during the measurement period. Comparison plots for gas parameters measured by both devices—CO (PPM), $CO_2$ (PPM), $CH_4$ (%), and $H_2S$ (PPM)—with date and time on the x-axis are shown in Fig. 5.29, 5.30, 5.31, and 5.32 respectively.

- **Observations from the time series real time data representation of environmental parameters**

  *CO (PPM):* Both devices show similar trends, with some variations in measurements.

*$CO_2$ (PPM):* Trends are consistent between the two devices, though the LoRa device sometimes measures slightly higher values.

*$CH_4$ (%):* Both devices consistently measure 0% for $CH_4$ across all data points.

*$H_2S$ (PPM):* Both devices consistently measure 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.

Table 5.4 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 5.5 Dataset Statistics of Environmental Parameters Measured by using the LoRa 868 MHz Based RTEPMS

| **Parameters** | **CO by LoRa PPM** | **$CO_2$ by LoRa PPM** | **$CH_4$ by LoRa %** | **$H_2S$ by LoRa PPM** | **$H_2$ by LoRa PPM** | **Temperature in °C** | **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 |

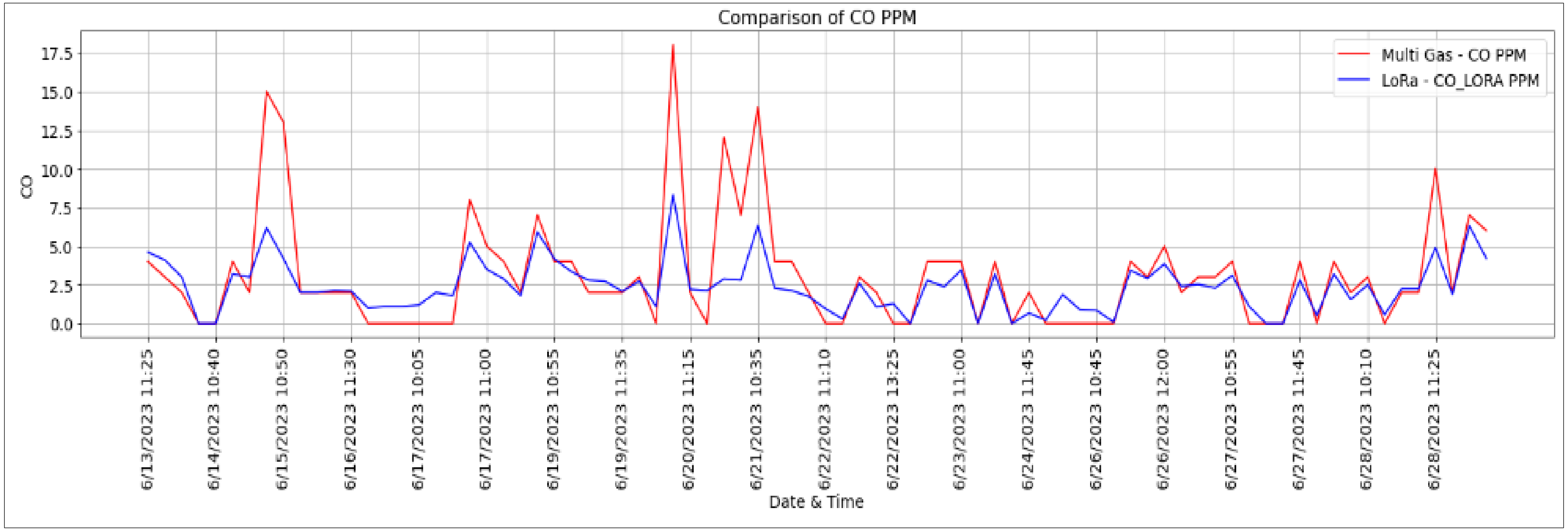


Fig. 5.29 Comparison of Multi Gas detector CO (PPM) with LoRa based RTEPMS device CO (PPM)

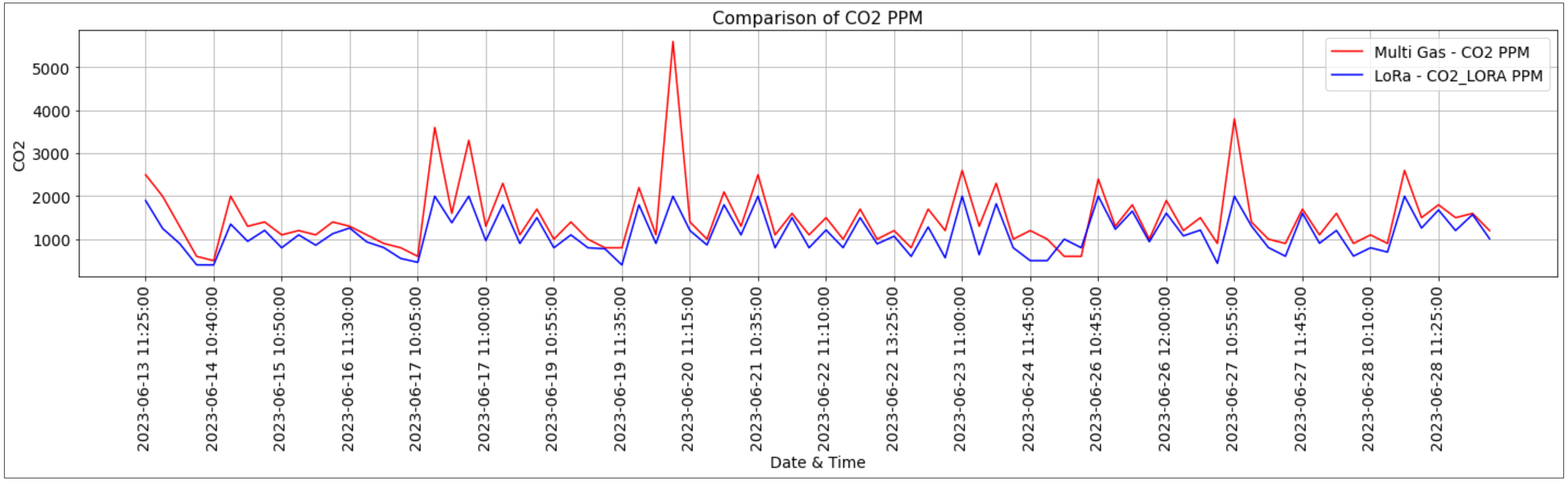


Fig. 5.30 Comparison of Multi Gas detector $CO_2$ (PPM) with LoRa based RTEPMS device $CO_2$ (PPM)

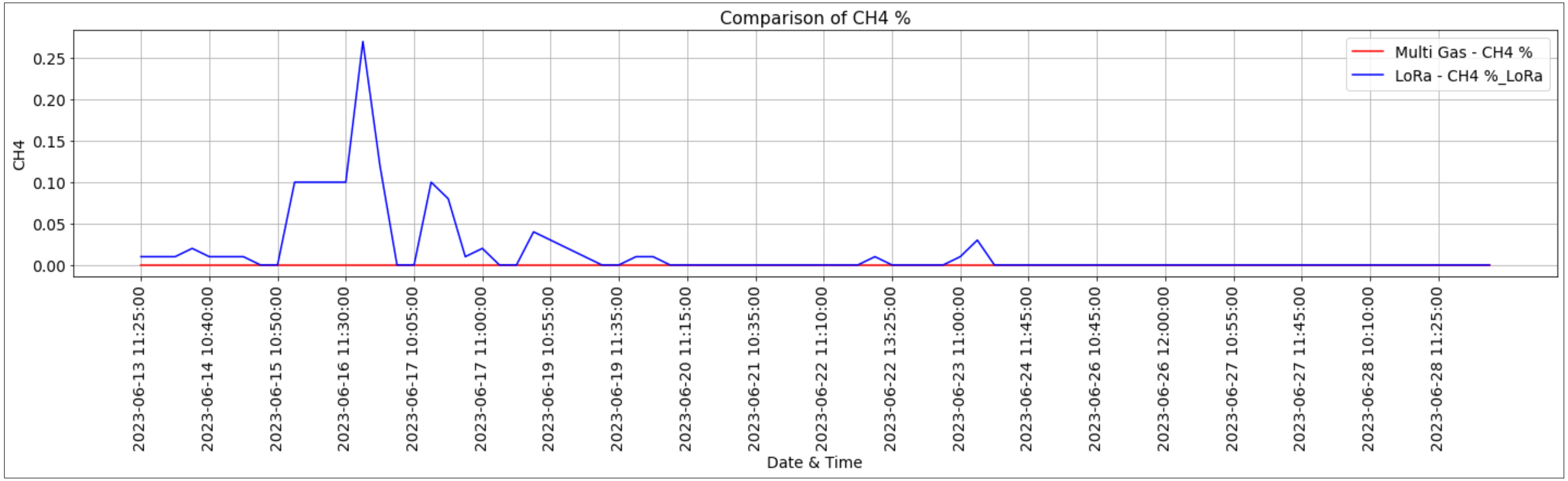


Fig. 5.31 Comparison of Multi Gas detector $CH_4$ (%) with LoRa based RTEPMS device $CH_4$ (%)

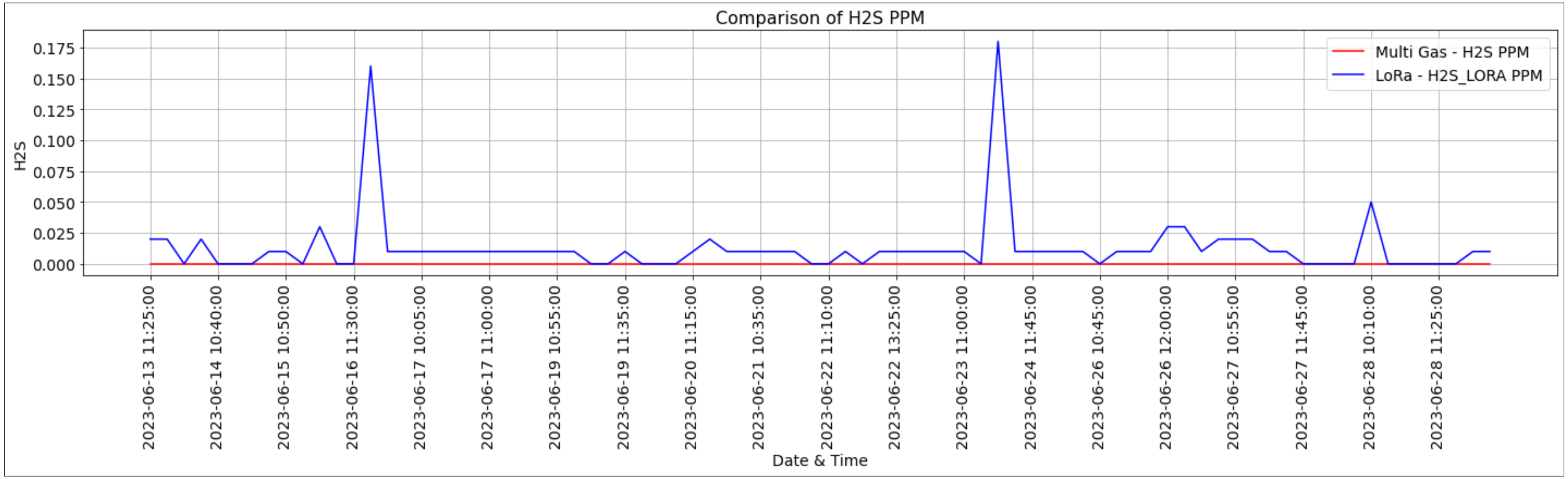


Fig. 5.32 Comparison of Multi Gas detector $H_2S$ (PPM) with LoRa based RTEPMS device $H_2S$ (PPM)

### *c) Comparison of $O_2$ Gas with $CO_2$, CO, and EO Gas Parameters Measured using Multi Gas Detectors.*

In an underground mine, increased concentrations of gases like $CO_2$, CO, and EO typically reduce $O_2$ levels, as shown in Figures 5.33, 5.34, 5.35, and 5.36, respectively.

Regression analysis of $CO_2$ gas parameters measured using the Multi-Gas Detector and the LoRa device is depicted in Fig. 5.37. The R-squared value of 0.6947 means that approximately 69.47% of the variance in $CO_2$ measurements from the LoRa device can be explained by the $CO_2$ measurements from the Multi-Gas Detector.

Regression analysis of CO gas parameters measured by the Multi-Gas Detector and the LoRa device is shown in Fig. 5.38. The R-squared value of 0.7238 means that approximately 72.38% of the variance in CO measurements from the LoRa device can be explained by the CO measurements from the Multi-Gas Detector. The close alignment of most data points with the regression line demonstrates consistent measurements between the two devices for CO gas.

For $CH_4$ and $H_2S$ measurements, both the Multi-Gas Detector and the LoRa-based device consistently measure a value of 0% for CH4 across all data points, indicating 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 $H_2S$.

### *d) Limitations of LoRa-based RTEPMS*

The LoRa-based RTEPMS wireless communication system has limitations, including data packet drops due to weak signal strength in non-line-of-sight conditions. Additionally, the system uses various analog and digital sensors, which consume significant power, and some require preheating before deployment. Harsh environments and extreme weather conditions can damage the sensors and other components, potentially leading to communication failures. Consequently, the installation of LoRa-based wireless communication technology is not feasible for prolonged periods in underground mines.

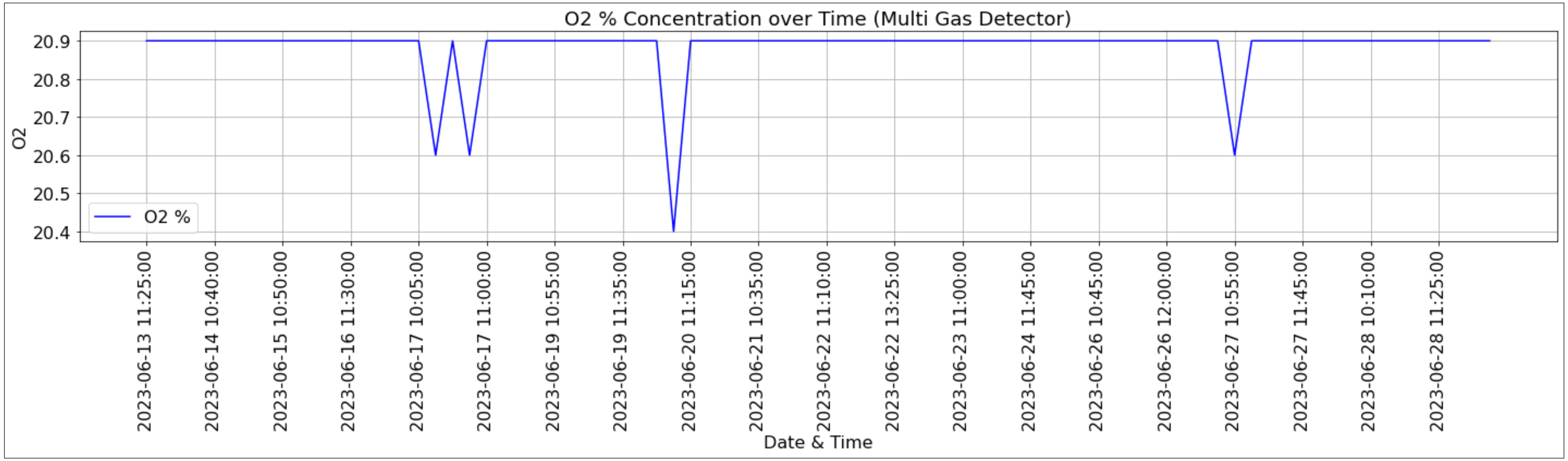


Fig 5.33 Concentrations of $O_2$ measured by using Multi Gas detector

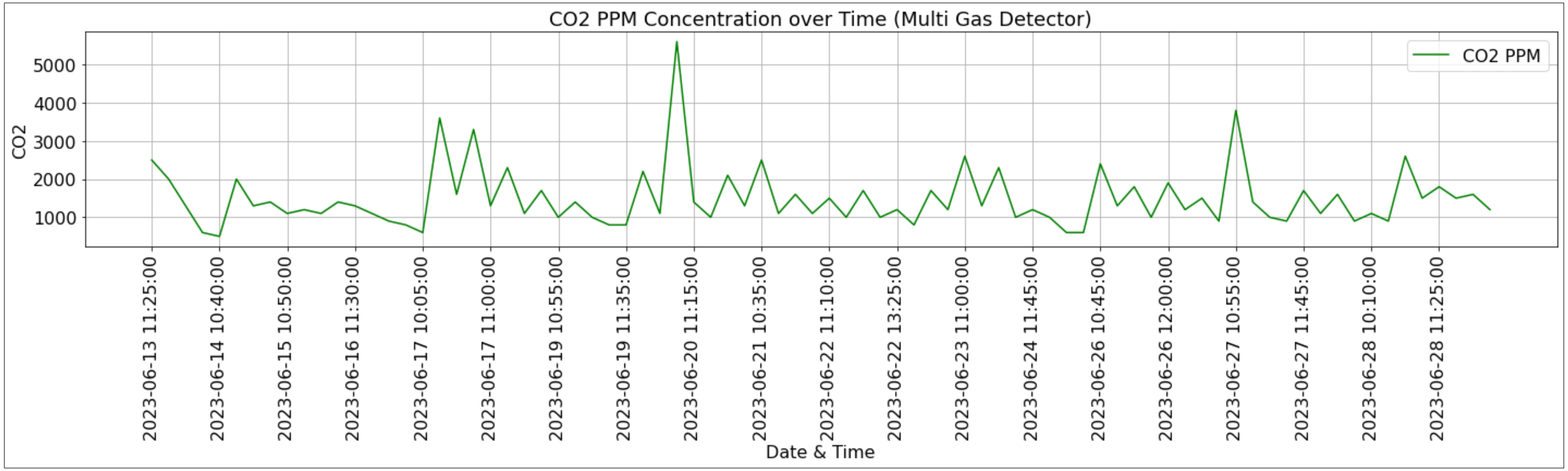


Fig 5.34 Concentrations of $CO_2$ measured by using a Multi Gas detector

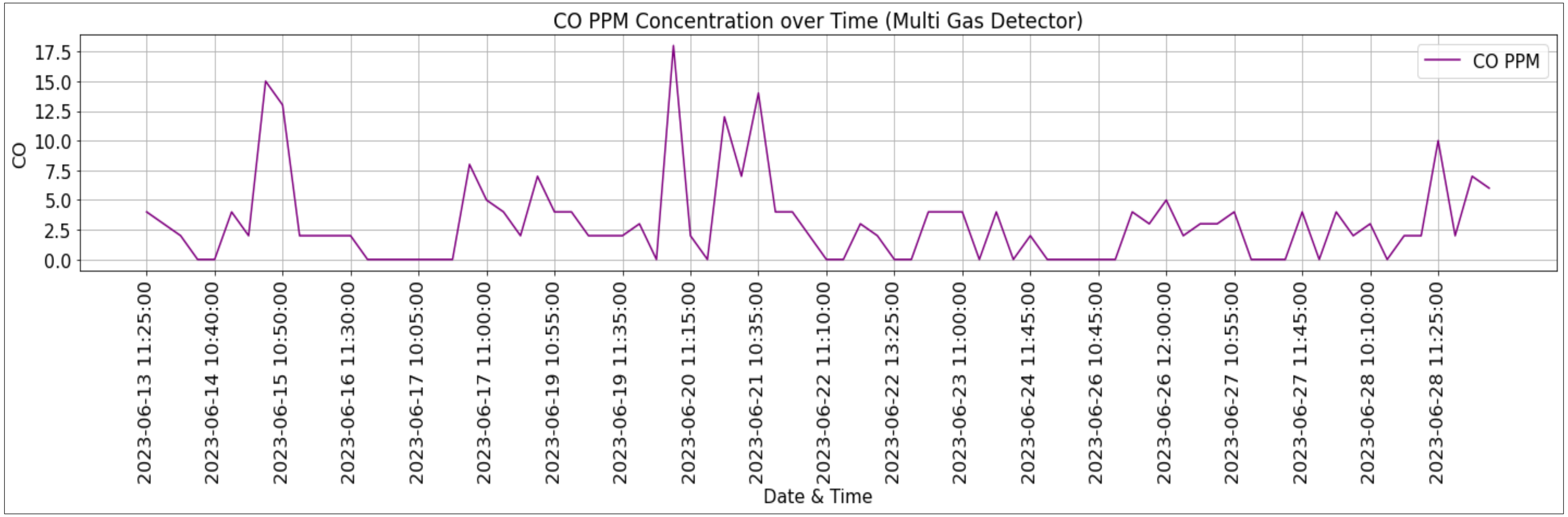


Fig 5.35 Concentrations of CO measured by using Multi Gas detector

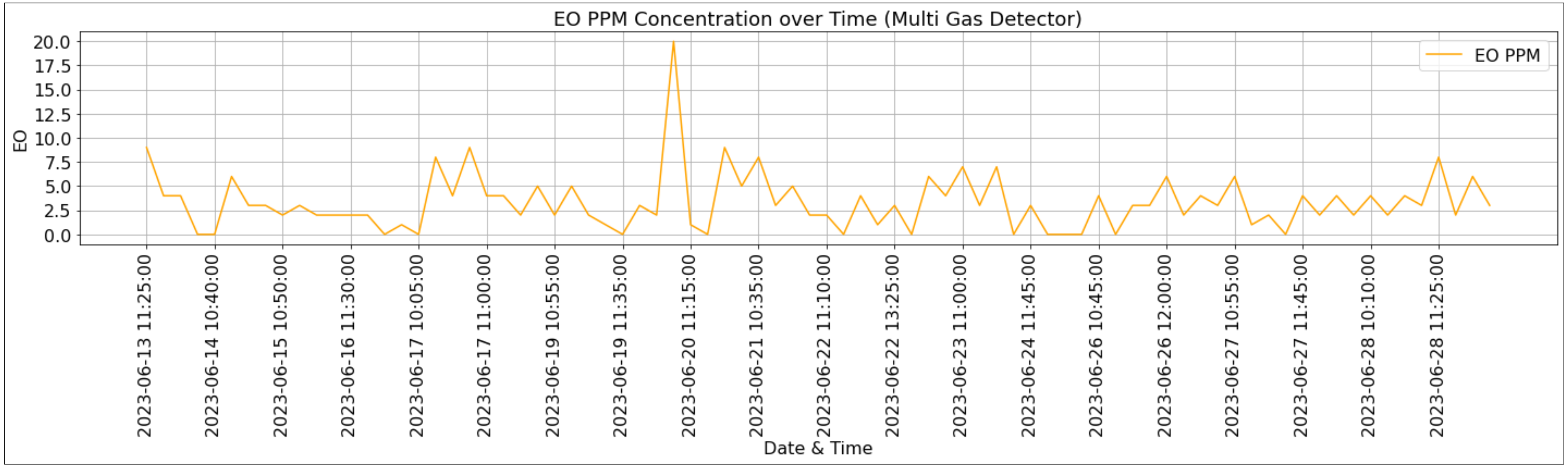


Fig 5.36 Concentrations of EO measured by using Multi Gas Detector

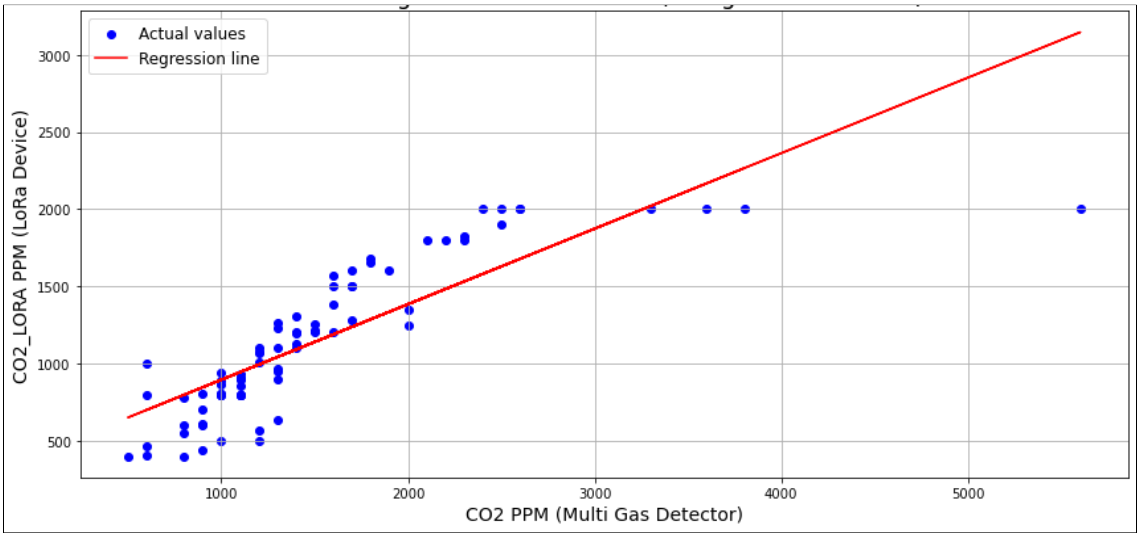


Fig 5.37 Regression plot of $CO_2$ measurements from the two devices

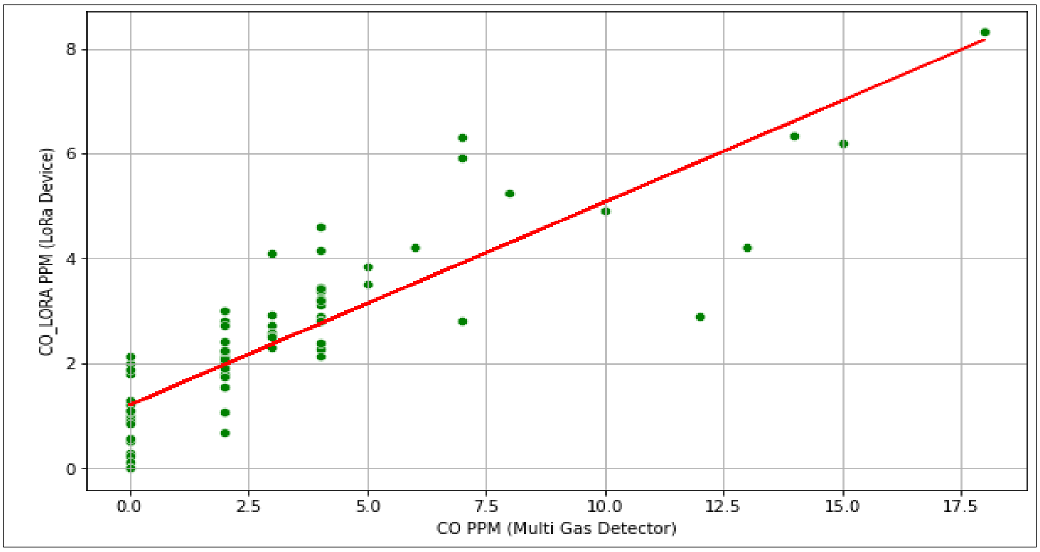


Fig 5.38 Regression plot of CO measurements from the two devices

In the underground mining industry, real-time monitoring of environmental parameters is essential for identifying and managing potential hazards during mining activities. Adopting wireless communication technology and IoT in mining operations can significantly enhance safety and prevent accidents. Gas parameters such as $O_2$, CO, $CO_2$, $CH_4$, $H_2S$, NO, $NO_2$, $SO_2$, and EO are measured using three portable multi-gas detectors, along with a hygrometer for temperature and humidity, once every shift. Hazardous gases are generated continuously through machinery and blast operations, necessitating a real-time monitoring system to ensure safety.

The portable LoRa module HPD13A, an 868 MHz based RTEPMS device, integrates gas sensors for CO, $CO_2$, $CH_4$, $H_2S$, $H_2$, and temperature and humidity sensors to measure environmental parameters. This system has been designed, developed, and tested in both open surface environments and an underground mine in India for real-time monitoring. Key features and results include:

- The system stores data on an SD card at both the transmitter and receiver. The LoRa receiver module uploads sensor data to the Thingspeak cloud server.
- Testing at various open surface locations achieved a wireless communication distance of around 300 meters in open space without obstacles and 180 to 200 meters with obstacles.
- In underground mines, wireless communication was tested in straight and curved tunnels at the 26th level, approximately 832 meters from the surface. The results showed successful communication over 180 to 200 meters in straight tunnels, with reduced signal strength and data packet loss in curved tunnels, achieving 125 to 130 meters.
- Major gases exceeding the threshold limits in the mine environment include $O_2$, CO, $CO_2$, $NO_2$, and EO.
- Both the LoRa-based RTEPMS and multi-gas detector devices measure $CO_2$, CO, $CH_4$, and $H_2S$. The data correlation between the two devices is 69.47% for $CO_2$ and 72.38% for CO, with nearly zero values for $CH_4$ and $H_2S$, indicating their minimal presence in underground mines.
- Data analysis indicated a rise in $CO_2$, CO, EO, and $NO_2$ levels, with a corresponding decrease in $O_2$ levels.
- The LoRa-based RTEPMS is a cost-effective solution for long-range wireless communication in low-power applications, alerting mine workers if environmental parameters exceed threshold limits during emergencies.
- The system is cost-effective and energy-efficient, making it accessible for smaller, less affluent underground mines.

To address the limitations, adopting an IoT-enabled LoRaWAN gateway-based environmental monitoring system can significantly enhance the productivity and safety of underground mine personnel and organizations over extended periods. Additionally, a real-time monitoring dashboard in the surface control room provides intuitive insights into the underground mining environment. Machine learning techniques will be utilized to analyze collected data, identify hazardous areas, and facilitate proactive measures, reducing potential risks and improving working conditions. Deploying 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.

## 5.5 Field Investigation of the developed IoT enabled RTEPMS-LORAWAN in Underground Mine 'B'

The RTEPMS-LoRaWAN system has been successfully tested and deployed in an underground mine 'B' located in India. An illustration of the mine's structure is provided in Fig. 5.39.

Underground mines are highly stressful environments conditions, with workers exposed to numerous hazards. Ensuring the safety of miners requires thorough monitoring and evaluation of the environmental conditions within mines. This proactive approach helps to identify hazards and take action in advance to avoid any disastrous conditions in underground mines. The nature of the underground mining process carries a considerable risk of incidents that may damage the mine's infrastructure, lead to fatalities, and interrupt communication. The primary reason for accidents or disasters in underground mines due to the explosion of various flammable gases.

As of now, the underground mine structure, where experimentation is carried out on tunnels below the surface, consists of 29 levels, and it is planned to extend deeper in the future to continue extracting ores or minerals, with each level being approximately 31 to 33 meters in height. Notably, research activities are carried out on the level 26. To monitor environmental conditions, RS485 sensors are strategically placed at certain points within the activities of heavy diesel-powered LHD vehicles and ore excavation to monitor environmental parameters. Workers in the mine navigate through these levels and use the mine shaft to enter into the mine. Consequently, diesel-powered LHD vehicles transport materials and equipment at tunnel 26. Specifically, the deepest part of the mine is Level 29, which is situated approximately 965 meters from the surface.

The RTEPMS-LoRaWAN system employs an RS485 cable to connect the sensor setups to an RS485-LN device, which converts RS485 signals to LoRaWAN. These cables can transmit data over distances ranging from 900 meters to 1 kilometer. The RS485-LN device then sends this data to a LoRaWAN gateway via wireless communication mode, capable of receiving information up to 1000 meters in Line of Sight (LOS) configurations and from 500 to 600 meters in Non-Line of Sight (NLOS) setups. The RS485-LN device, positioned for LOS communication from inside the mine at Level 26 to the surface, connects through a 900 meters long RS485 cable to the RS485 sensor setup. The LoRaWAN gateway is compatible with Ethernet or Wi-Fi or cellular network which operates on the IN865 – 867 MHz frequency band for LoRa communication and is located at the surface for optimal connectivity.

The challenge in the underground mine is to establish wireless communication to transmit data from the underground mine tunnel to the surface, which is about 832 meters depth from the surface. The deployment of the RTEPMS-LoRaWAN system within the underground mine was executed with attention to specific criteria. These include:

- The type of the underground mine and structure of underground mine tunnels/levels
- The establishment of wireless communication from the mine's tunnels/levels to the surface
- The placement of sensors throughout the mine's tunnels/levels
- The continuous real-time monitoring of environmental parameters around the clock

As a result, the components of the system are strategically positioned and organized within the underground mine environment.

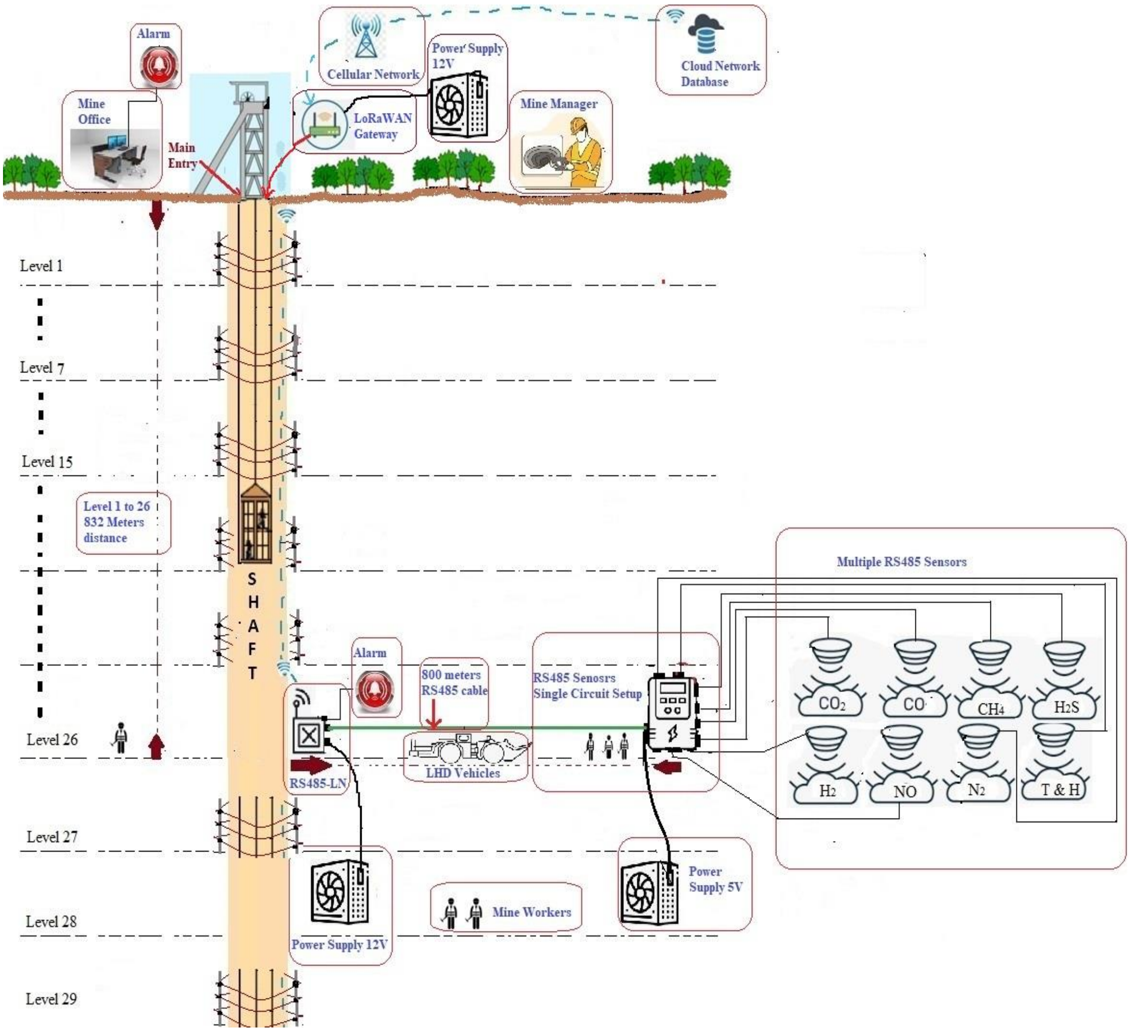


Fig. 5.39 Underground mine ‘B’ structure with the deployment of hardware components

### 5.5.1 Implementation of the RTEPMS-LoRaWAN system in the Underground Mine ‘B’

The implementation of the RTEPMS-LoRaWAN system in the underground mine ‘B’ is illustrated in Fig 5.40, 5.41, 5.42, and 5.43.

### 5.5.2 Steps carried out to establish wireless communication

The establishment of wireless communication between RS485 sensors and the LoRaWAN gateway is illustrated in Fig. 5.39. The requirement to monitor the environmental parameters from tunnel 26 is challenging, and the LoRaWAN gateway device, which is internet-enabled by the cellular network, is fixed on the surface.

Once the wireless communication is established between the RS485-LN device and LoRaWAN gateway server, the trial is conducted to fix the RS485-LN for reliable transmission of sensor data to the server as illustrated in Fig. 5.44, with different cases and their received signal strength indication (RSSI) values with respect to spreading factor (SF) are represented in Table 5.6 and illustrated in Fig. 5.45.

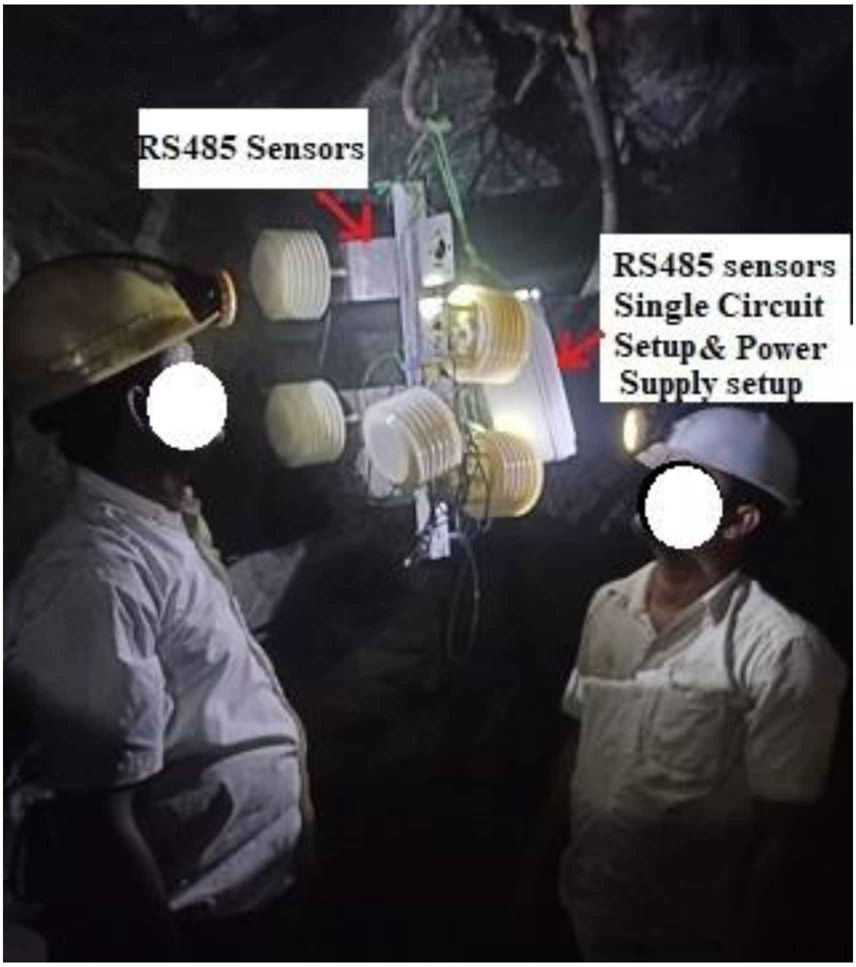


Fig. 5.40 Multiple RS485 Sensor Node Setup in an Underground Mine ‘B’

Fig. 5.41 Installation of Multiple RS485 Sensor Node and Connection to RS485-LN device

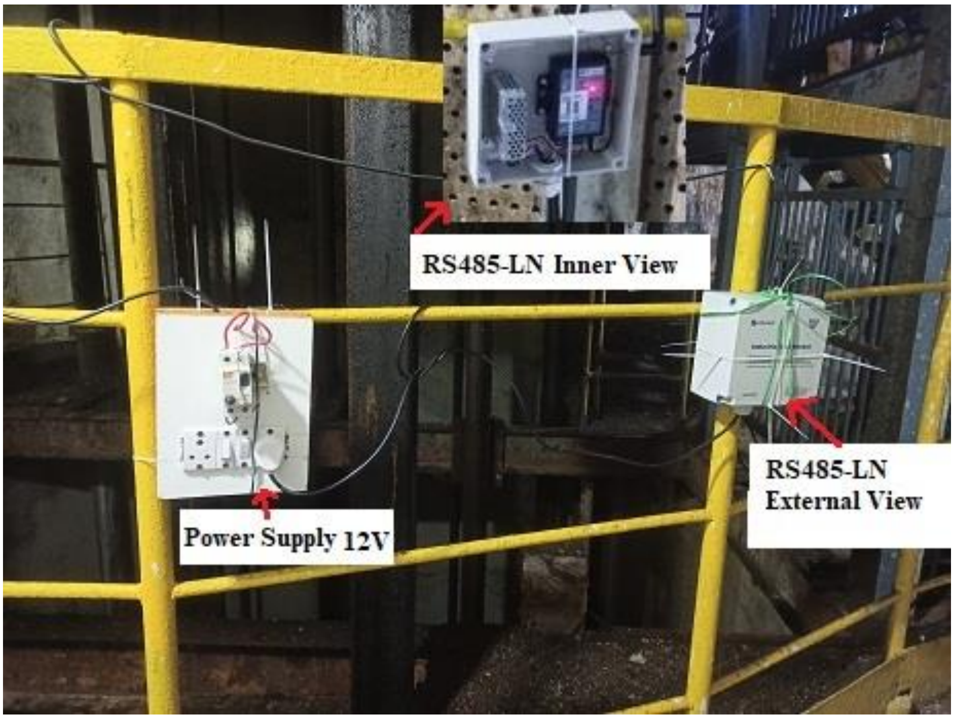


Fig. 5.42 Installation of RS485-LN (RS485 to LoRaWAN Converter) device

Fig. 5.43 Installation of LoRaWAN Gateway device

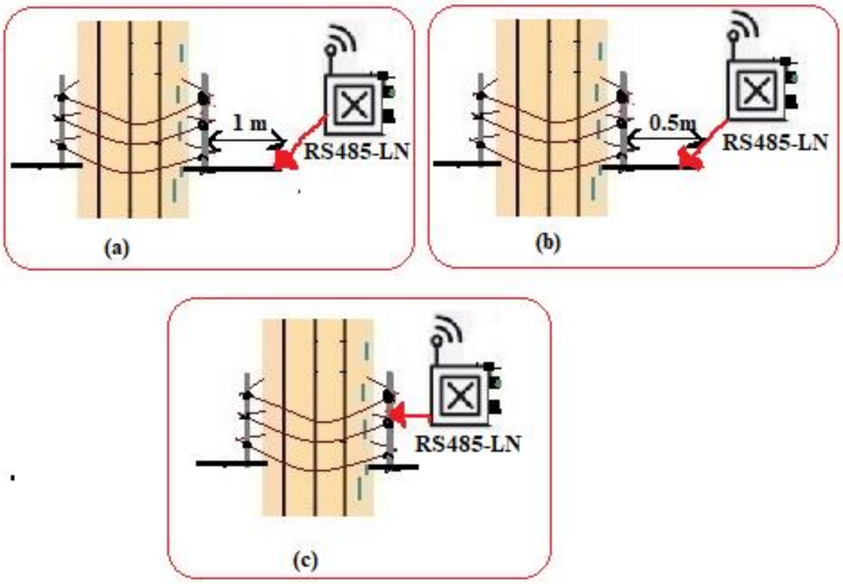


Fig. 5.44 RS485-LN device position at tunnel 26 in underground mine 'B' (a) Case 1, (b) Case 2, and (c) Case 3

The RS485-LN device is strategically positioned on tunnel 26 within an underground mine to establish a direct Line of Sight (LoS) connection with the LoRaWAN gateway device. Specifically, the RS485-LN device is installed at distances of 1 meter and 0.5

meters from the barricades of the underground mine tunnel shaft, as depicted in Fig 5.45. Following signal strength testing, it was determined that the optimal location for the RS485-LN device is fixed directly at the barricade.

The RSSI value, measured in dBm, indicates the strength of the signal received by a receiver from a sender. It is a negative value, where a value closer to zero indicates a stronger signal. The minimum RSSI value is -120 dBm. For instance, an RSSI value of -40 dBm signifies a strong signal, while an RSSI value of -120 dBm suggests a very weak signal.

The signal-to-noise ratio (SNR) is measured in dB and represents the ratio of received signal power to the noise level. The noise is an undesired interference and can corrupt transmitted signals, leading to signal retransmission. A positive SNR value indicates that the received signal operates above the noise level, while a negative SNR value indicates operation below the noise level.

Table 5.6 RSSI values of wireless signal establishment between Tunnel 26 to surface

| | **Case 1** | | **Case 2** | | **Case 3** | |
|---|---|---|---|---|---|---|
| **SF** | **RSSI** | **SNR** | **RSSI** | **SNR** | **RSSI** | **SNR** |
| 12 | -118 | -5.5 | -114 | -12.2 | -107 | 3.8 |
| 12 | -111 | -0.5 | -113 | -9.2 | -104 | 5.5 |
| 12 | -115 | -18 | -115 | -20 | -117 | -3.5 |
| 12 | -114 | -6.8 | -114 | -19.8 | -105 | 4.2 |
| 12 | -119 | -19.5 | -115 | -20 | -116 | -1.2 |
| 12 | -110 | -0.8 | -113 | -7.2 | -106 | 2 |
| 12 | -118 | -6.5 | -119 | -20 | -113 | 1.8 |
| 12 | -119 | -19.2 | -111 | -7.5 | -105 | 4.2 |
| 12 | -112 | -1.5 | -113 | -8.5 | -116 | -1.5 |
| 12 | -115 | -17 | -113 | -8.2 | -109 | 1.5 |
| 12 | -118 | -4.8 | -115 | -19 | -118 | -3.8 |
| 12 | -117 | -2.5 | -114 | -18.8 | -106 | 4.5 |
| 12 | -119 | -5.5 | -113 | -8.5 | -110 | -0.2 |

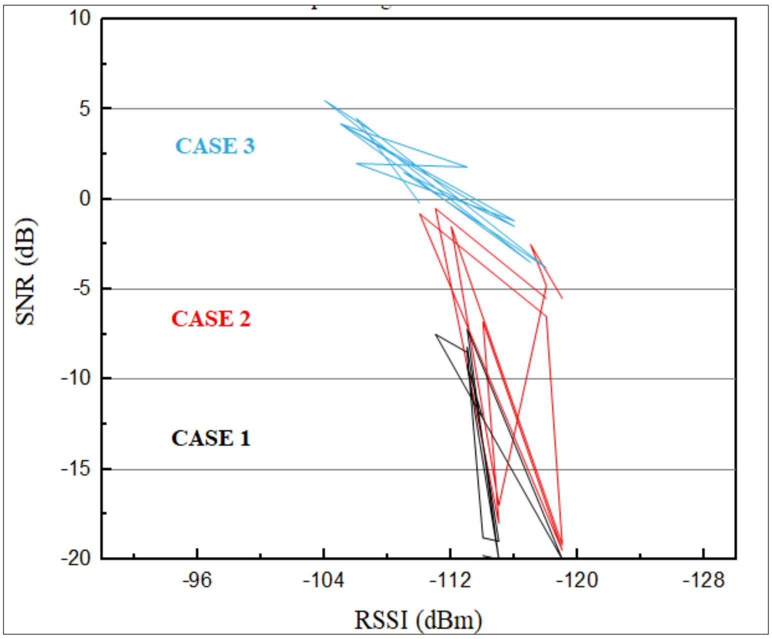


Fig. 5.45 RSSI and SNR values between tunnel 26 of the underground mine ‘B’ to the surface with SF=12

In the case of LoRa, it typically operates below the noise level, with SNR values ranging between -20 dB and +10 dB. An SNR value close to -10 dB suggests that the received signal is less corrupted. LoRa modulation involves cyclically shifting chirps and frequency jumps to encode data onto them. Each symbol, such as "1011111" (decimal 95), represents a certain number of bits, in this case, ‘7’. This is equivalent to having a spreading factor (SF) of ‘7’, indicating that the symbol contains $2^7$ values. For SF=7, these values range from 0 to 127, and they are encoded onto a sweep signal, known as an up-chirp, which is divided into $2^{SF}=2^7 = 128$ chips.

When SF=12, each symbol can carry 12 raw bits, resulting in $2^{12}=4096$ unique values ranging from 0 to 4095. A symbol consists of $2^{SF}$ chips, and chirps are essentially ramps from a lower frequency ($f_{low}$) to a higher frequency ($f_{high}$) for up-chirps, or from $f_{high}$ to $f_{low}$ for down-chirps as illustrated in Fig. 5.46.

### 5.5.3 Experimental Result Analysis and Validation

This section outlines the key findings and confirms the performance of the RTEPMS-LoRaWAN system, which underwent initial laboratory testing before being deployed in an underground mine ‘B’ for evaluation.

The system's testing was conducted within the challenging environment of an underground mine, where its results were validated by comparison against those obtained from portable multi-gas detectors used on-site. Despite the limited duration of the RTEPMS-LoRaWAN system's testing in the mine, it's crucial to highlight the practical aspects of our study. The system was subjected to comprehensive testing and demonstrated its robustness in an underground mine located in India.

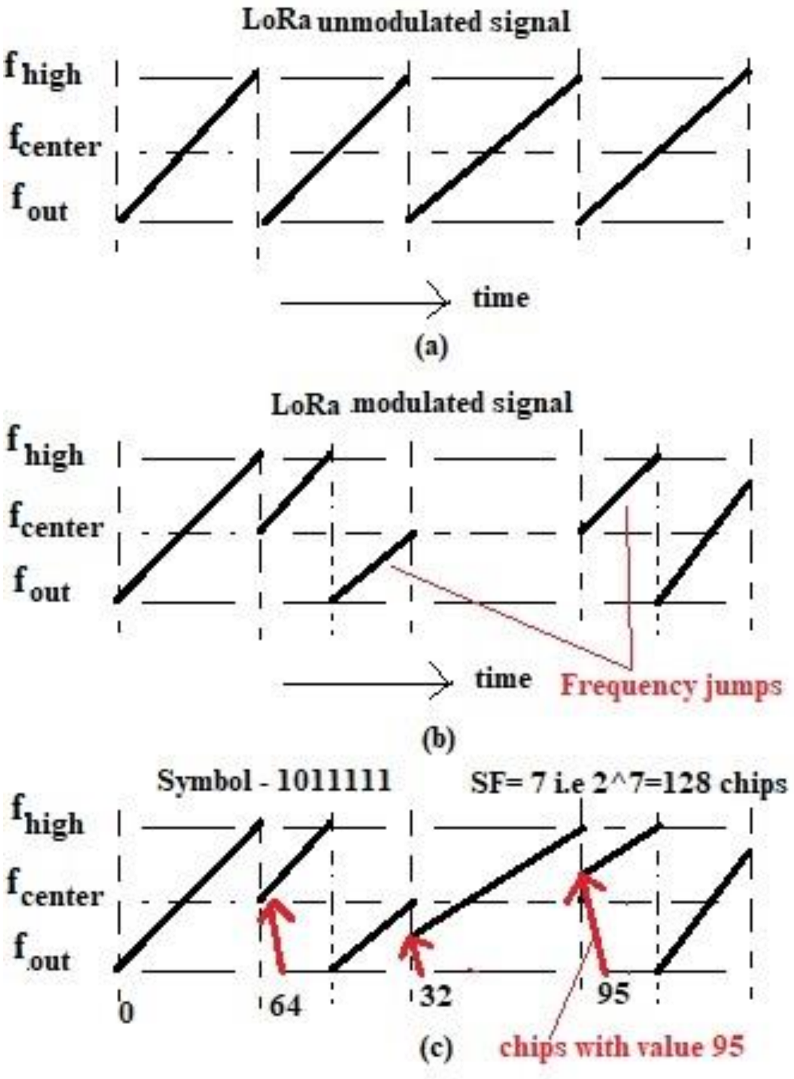


Fig. 5.46 LoRa modulation and unmodulated signal

The test result represents the system's capability to monitor environmental parameters in real-time. Data was efficiently relayed to the IoT cloud through the LoRaWAN network, fulfilling the study's primary goal to evaluate the IoT system's performance under both controlled laboratory conditions and real deployment situations.

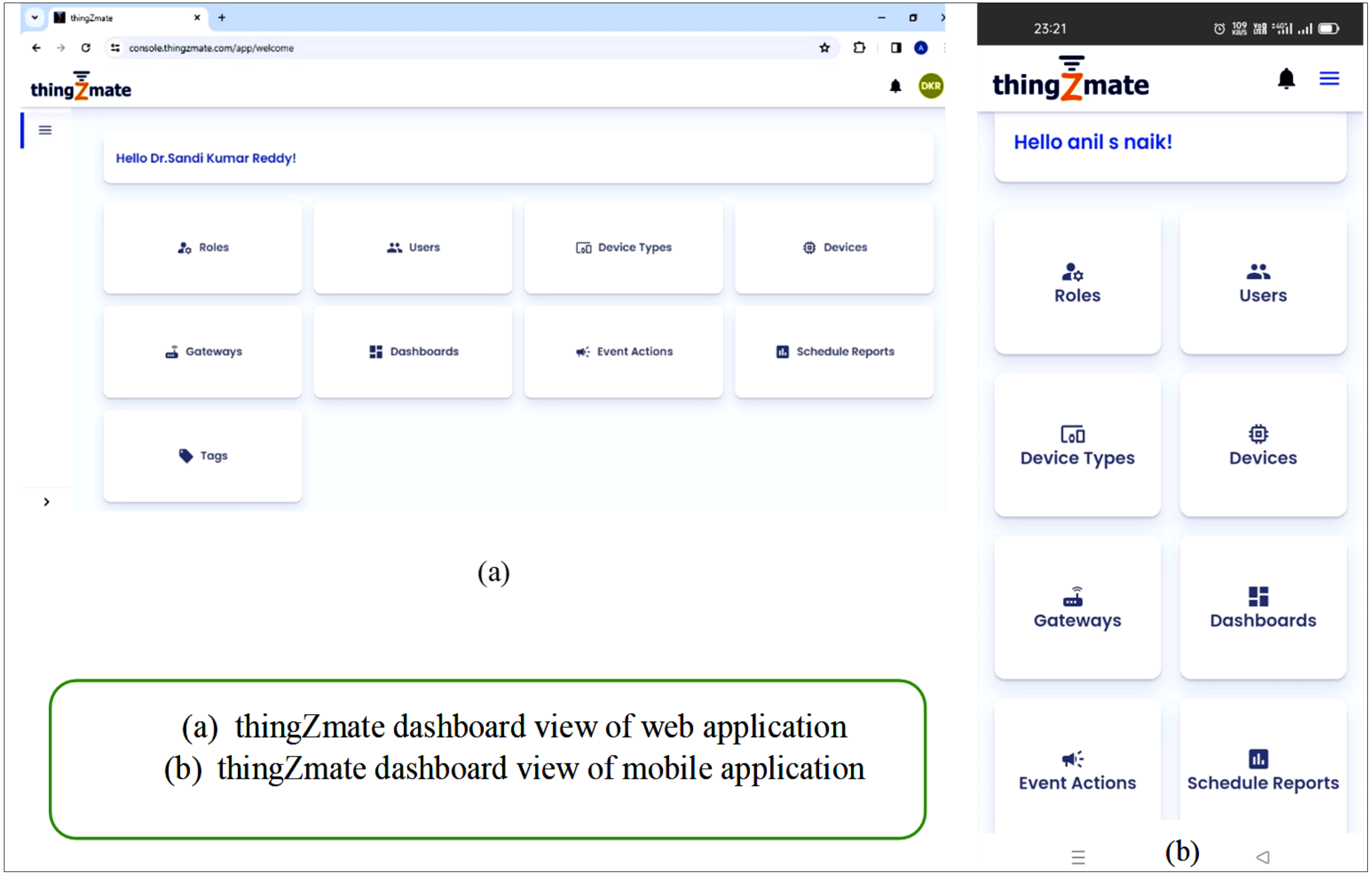
For effective real-time monitoring in underground mines, deploying multiple RS485 sensors across various sections and levels of the mine is advisable. This strategy ensures a thorough assessment of environmental conditions across different mine areas, with data centralized on servers for immediate analysis.

Throughout the mine testing phase, we evaluated the network's connectivity and the system's ability to update environmental data promptly on IoT platform, highlighting the system's potential for enhancing safety and operational efficiency in such critical environments.

Multiple sensor nodes, including RS485-LN and RS485 cables, were deployed in underground mine shafts to facilitate the collection of real-time data from the surface. During the trial of the RTEPMS-LoRaWAN system in an underground setting, the main goals involved evaluating network connectivity and ensuring prompt data updates to our IoT platform. LoRaWAN gateway, positioned on the surface and connected via the cellular network, successfully received data from sensors placed at tunnel 26 of the mine, situated approximately 832 meters below the surface. The system was operational in the mine for a 24-hour period, during which we monitored various parameters such as $CO_2$, CO, NO, temperature, and humidity using a multi-gas detector. Sensor data was periodically transmitted to our LoRaWAN Gateway by the RS485-LN, which then uploaded the information to the thingZmate platform. This data was available for real-time access on the thingZmate platform and could be viewed on internet-enabled devices, including laptops, desktop computers, and smartphones. The purpose of this test was to conduct a focused assessment of the system's network performance, sensor precision, and data transmission reliability, rather than a comprehensive implementation. Ultimately, the trial confirmed the functionality of our system and established a foundation for its future deployment across various locations.

For a comprehensive and permanent monitoring setup, deploying numerous sensors throughout various locations in underground mine tunnels/levels is crucial. Such a strategy ensures broader coverage and facilitates a deeper understanding of environmental conditions across different areas simultaneously.

Within the thingZmate platform, environmental data is periodically refreshed based on the necessary time intervals to connect with the gateway. This platform enables real-time tracking of environmental conditions and presents the data in both graphical and numerical formats, including historical trends for each sensor's readings, as illustrated in Fig. 5.47. Data stored on the thingZmate platform can be downloaded for additional analysis. This real-time information can also be accessed on smartphones or through web applications, and the recent events can also be viewed as depicted in Fig. 5.48 and Fig. 5.49.



Hello Dr.Sandi Kumar Reddy!

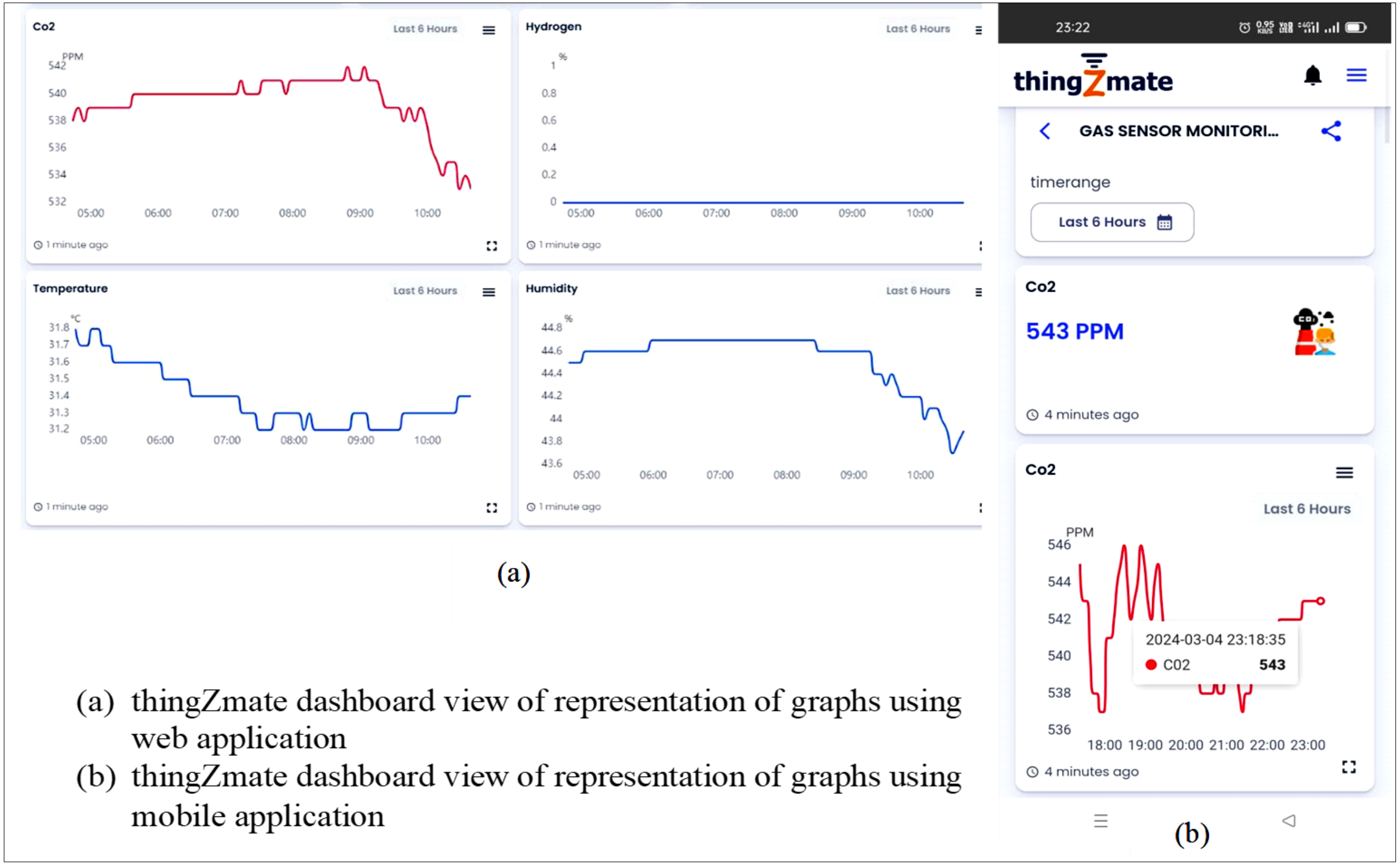
(a)

Hello anil s naik!

(b)

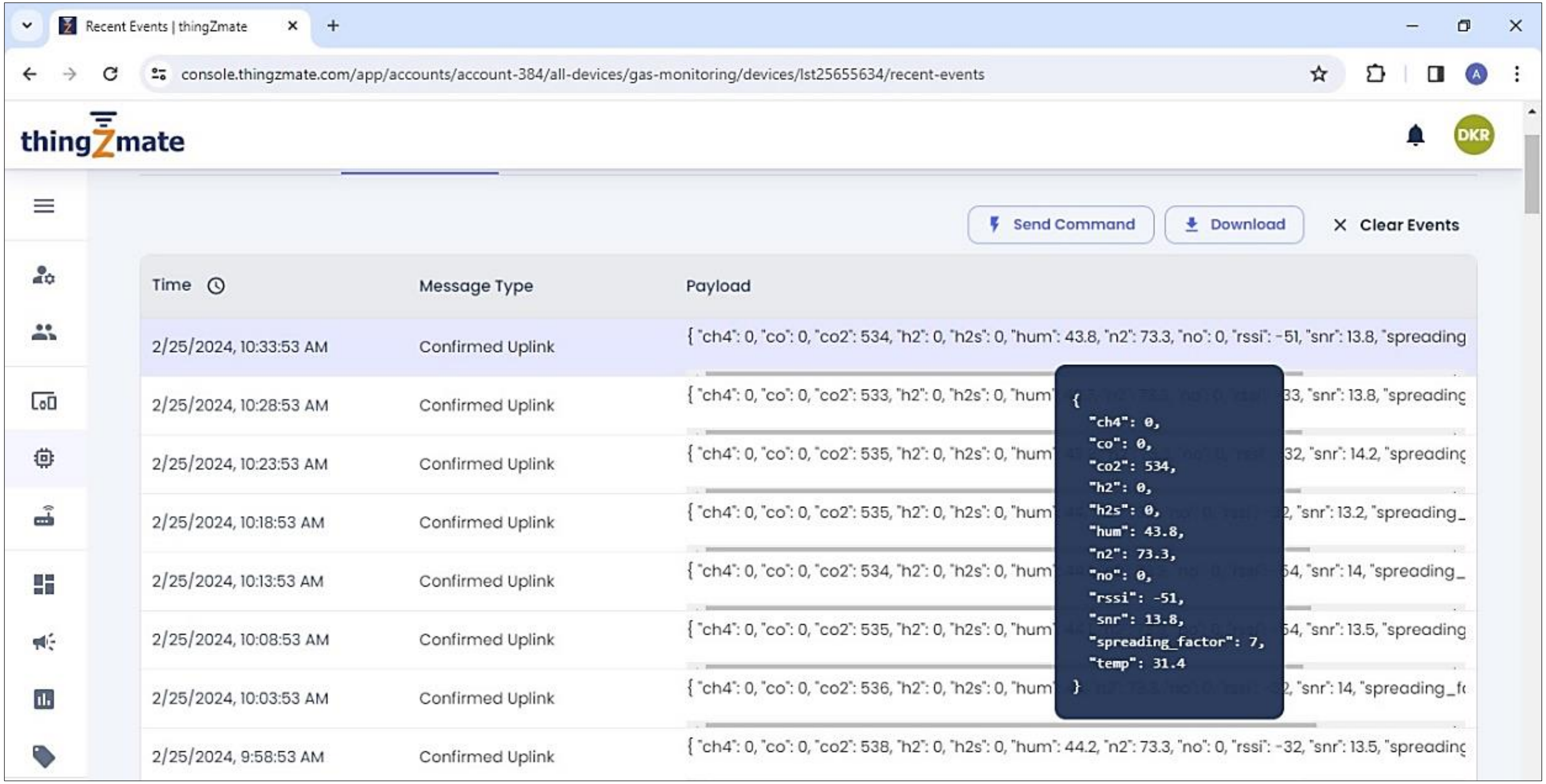
(a) thingZmate dashboard view of web application
(b) thingZmate dashboard view of mobile application

Fig. 5.47 thingZmate platform dashboard view



(a) thingZmate dashboard view of representation of graphs using web application
(b) thingZmate dashboard view of representation of graphs using mobile application

Fig. 5.48 thingZmate platform dashboard view of web and mobile applications



| Time | Message Type | Payload |
|---|---|---|
| 2/25/2024, 10:33:53 AM | Confirmed Uplink | { "ch4": 0, "co": 0, "co2": 534, "h2": 0, "h2s": 0, "hum": 43.8, "n2": 73.3, "no": 0, "rssi": -51, "snr": 13.8, "spreading |
| 2/25/2024, 10:28:53 AM | Confirmed Uplink | { "ch4": 0, "co": 0, "co2": 533, "h2": 0, "h2s": 0, "hum [illegible] 33, "snr": 13.8, "spreading |
| 2/25/2024, 10:23:53 AM | Confirmed Uplink | { "ch4": 0, "co": 0, "co2": 535, "h2": 0, "h2s": 0, "hum [illegible] 32, "snr": 14.2, "spreading |
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| 2/25/2024, 10:13:53 AM | Confirmed Uplink | { "ch4": 0, "co": 0, "co2": 534, "h2": 0, "h2s": 0, "hum [illegible] 54, "snr": 14, "spreading_ |
| 2/25/2024, 10:08:53 AM | Confirmed Uplink | { "ch4": 0, "co": 0, "co2": 535, "h2": 0, "h2s": 0, "hum [illegible] 54, "snr": 13.5, "spreading |
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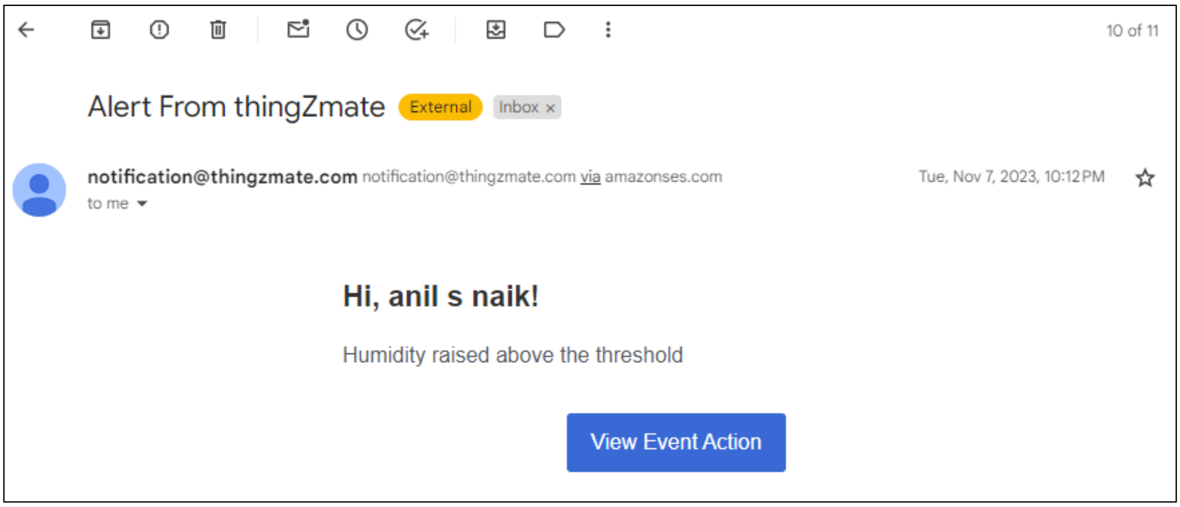
| 2/25/2024, 9:58:53 AM | Confirmed Uplink | { "ch4": 0, "co": 0, "co2": 538, "h2": 0, "h2s": 0, "hum": 44.2, "n2": 73.3, "no": 0, "rssi": -32, "snr": 13.5, "spreading |

```
{
  "ch4": 0,
  "co": 0,
  "co2": 534,
  "h2": 0,
  "h2s": 0,
  "hum": 43.8,
  "n2": 73.3,
  "no": 0,
  "rssi": -51,
  "snr": 13.8,
  "spreading_factor": 7,
  "temp": 31.4
}
```

Fig.5.49 thingZmate platform dashboard to view recent events

The system is designed to alert relevant authorities about environmental conditions by sending email notifications and triggering alarms both underground and on the surface, as illustrated in Fig. 5.50.



Alert From thingZmate

**notification@thingzmate.com** notification@thingzmate.com via amazonses.com
to me
Tue, Nov 7, 2023, 10:12 PM

**Hi, anil s naik!**

Humidity raised above the threshold

Fig. 5.50 Email Alert notification to the concerned authority

The application will continue to display data as long as there is a stable connection between the gateway and the RS485-LN converter device.

Extensive testing, both on-site and in the lab, has been carried out to evaluate the RTEPMS-LoRaWAN system's performance. The results presented in this document reflect real-time observations of the environmental parameters over a 24-hour testing period, with information sent to the cloud every 5 minutes.

### *a) Comparison of data collected by the RTEPMS-LoRaWAN system and Multi-gas detector*

To assess the system's accuracy, we compared environmental parameters measured from RS485 sensors with a portable multi-gas detector device used in the underground mine and a Temperature and Humidity data recorder, as illustrated in Fig. 5.51. The data collected by the RTEPMS-LoRaWAN system was aligned with readings from the multi-gas detector, which validated its efficacy.

The figure displays data gathered by the RTEPMS-LoRaWAN system and a portable temperature and humidity data recorder. The readings from the data recorder were slightly higher than those from the RTEPMS-LoRaWAN, indicating a small discrepancy between the real-time data and the portable device measurements.

Environmental parameters measured by the RTEPMS LoRaWAN system and Multigas detector at a particular instant of time are represented in Table 5.7. $CO_2$, CO, NO, Temperature and Humidity, $CH_4$, $H_2S$ are measured from RTEPMS-LoRaWAN and Multi gas detector device as illustrated in Figures 5.52 to 5.56 and $N_2$ gas parameter measured using RTEPMS-LoRaWAN system as illustrated in Fig. 5.57.

(a) (b)

Fig. 5.51 (a &b) Portable Multi Gas Detector Device and Temperature and Humidity Data Recorder

Table 5.7 Parameters Recorded by RTEPMS-LoRaWAN System and Multigas Detector at a Specific Time Point

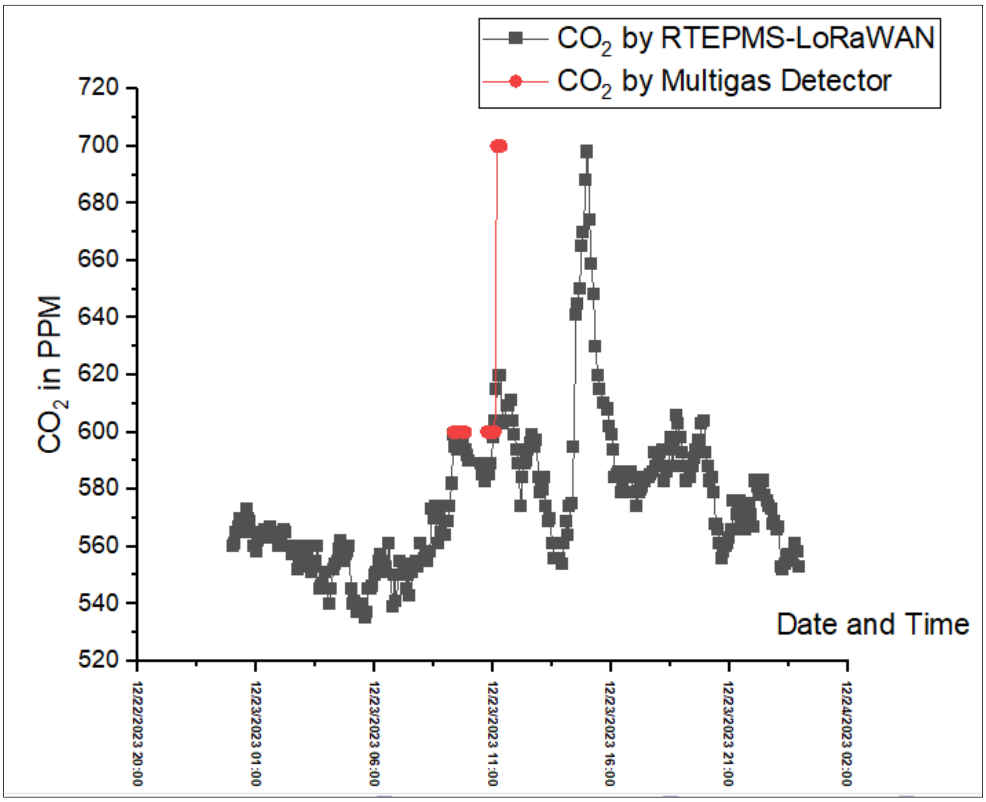
| **Date &Time** | **$CO_2$_L** | **$CO_2$_M** | **CO_L** | **CO_M** | **NO_L** | **NO_M** | **T_L** | **H_L** | **T_R** | **H-R** |
|---|---|---|---|---|---|---|---|---|---|---|
| 12/23/2023 9:20 | 600 | 596 | 6 | 5 | 31 | 60 | 30.4 | 57.2 | NA | NA |
| 12/23/2023 9:25 | 600 | 595 | 7 | 8 | 31 | 59 | 30.4 | 57.3 | NA | NA |
| 12/23/2023 9:30 | 600 | 617 | 6 | 7 | 31 | 60 | 30.3 | 57.4 | NA | NA |
| 12/23/2023 9:45 | 600 | 615 | 6 | 6 | 31 | 57 | 30.4 | 57.3 | NA | NA |
| 12/23/2023 9:50 | 594 | 600 | 0 | 0 | 5 | 0 | 30.4 | 57.1 | 31.5 | 60.5 |
| 12/23/2023 9:55 | 592 | NA | 0 | NA | 6 | NA | 30.4 | 57.2 | 31.8 | 60.8 |
| 12/23/2023 10:00 | 590 | NA | 0 | NA | 4 | NA | 30.4 | 57.3 | 32.1 | 61.1 |

*Multi-Gas Detector: $CO_2$_M, CO_M, NO_M

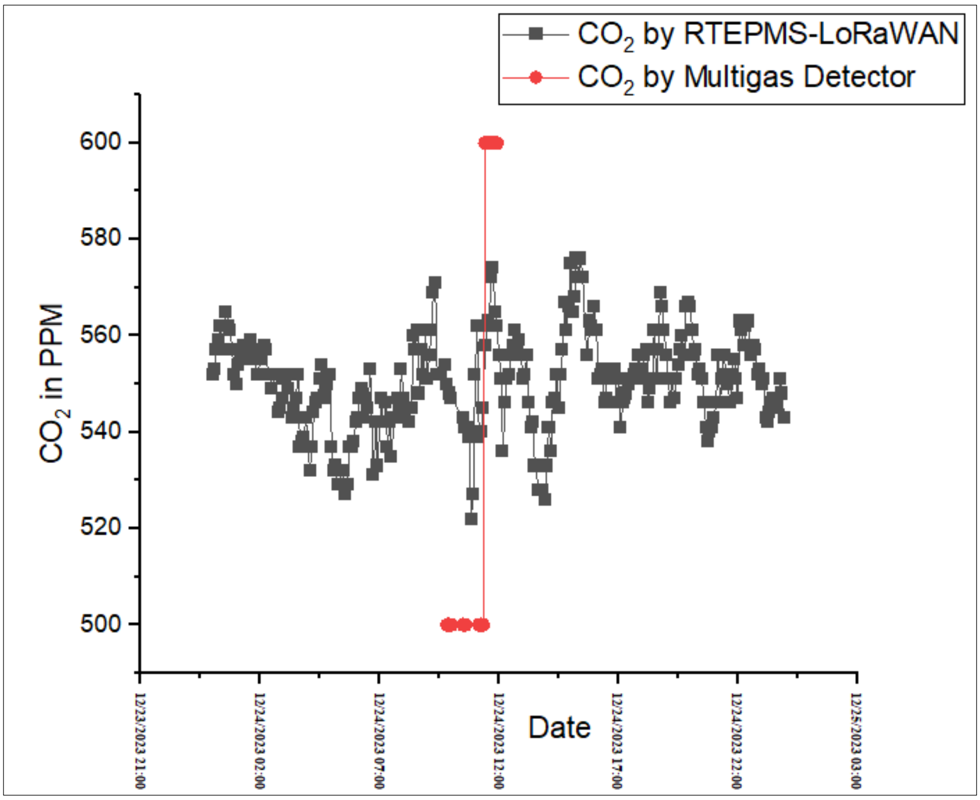
*Temperature and Humidity Data Recorder Device: T_R, H_R

* RTEPMS-LoRaWAN: $CO_2$_L, CO_L, NO_L , T_L, H_L

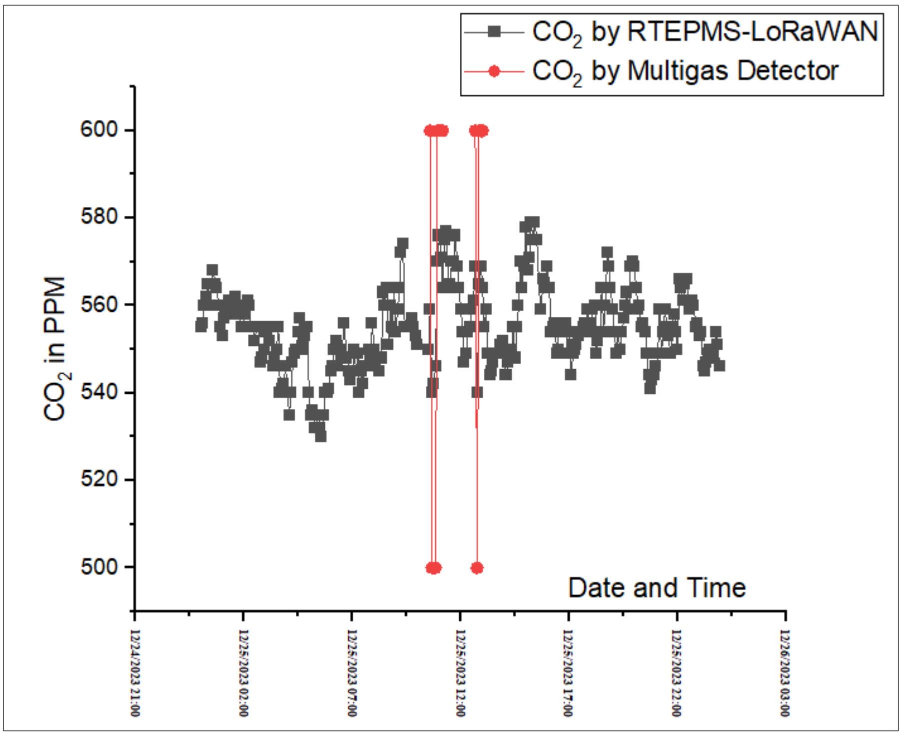
*NA: Not Applicable (Data is not recorded)


CO$_2$ by RTEPMS-LoRaWAN
CO$_2$ by Multigas Detector
CO$_2$ in PPM
720
700
680
660
640
620
600
580
560
540
520
Date and Time
12/22/2023 20:00
12/23/2023 01:00
12/23/2023 06:00
12/23/2023 11:00
12/23/2023 16:00
12/23/2023 21:00
12/24/2023 02:00

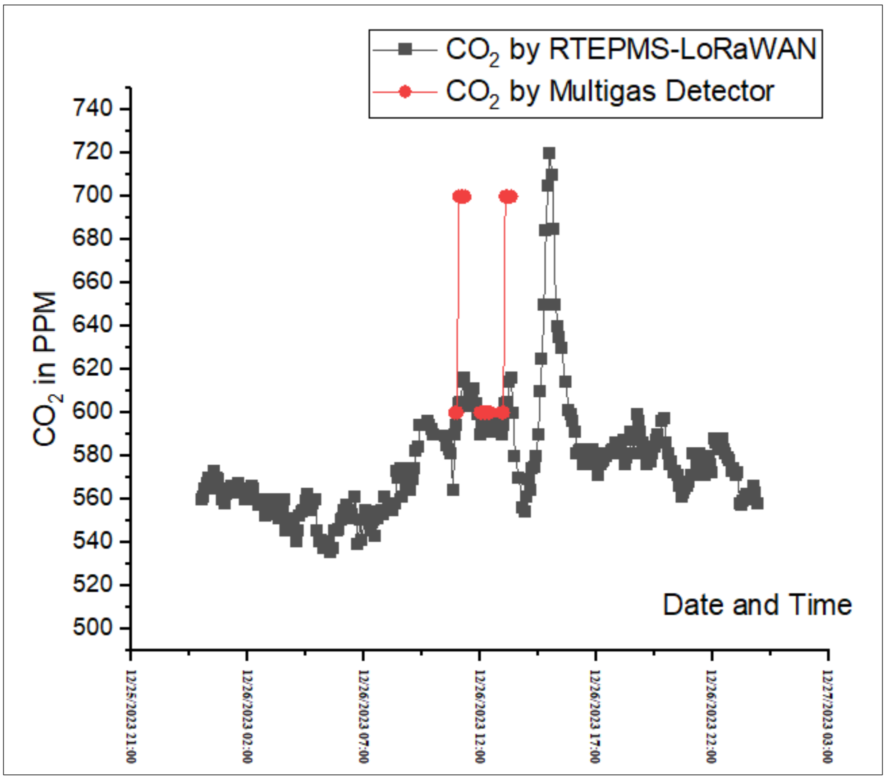
(a)


CO$_2$ by RTEPMS-LoRaWAN
CO$_2$ by Multigas Detector
CO$_2$ in PPM
600
580
560
540
520
500
Date
12/23/2023 21:00
12/24/2023 02:00
12/24/2023 07:00
12/24/2023 12:00
12/24/2023 17:00
12/24/2023 22:00
12/25/2023 03:00

(b)

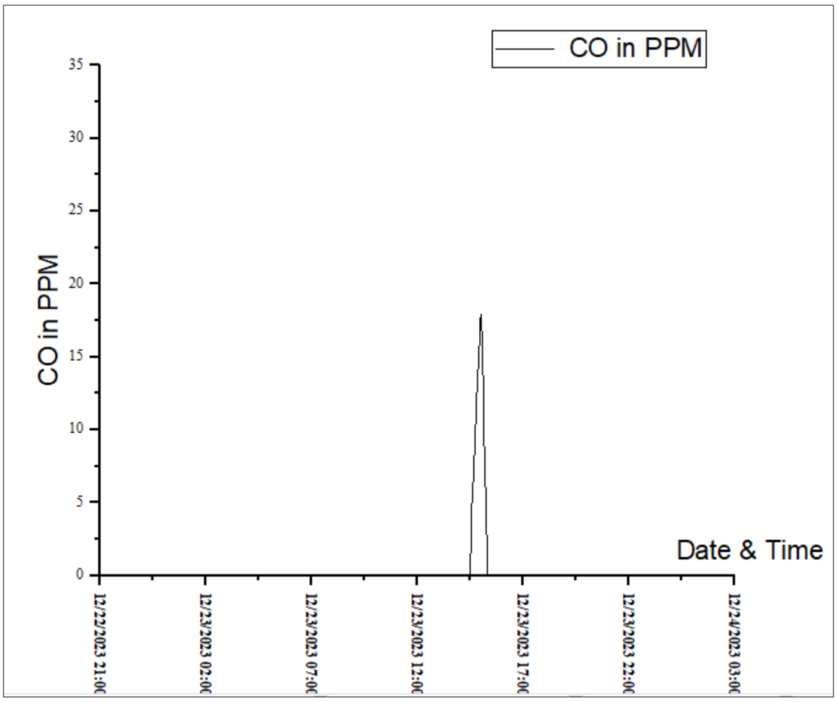


(c)

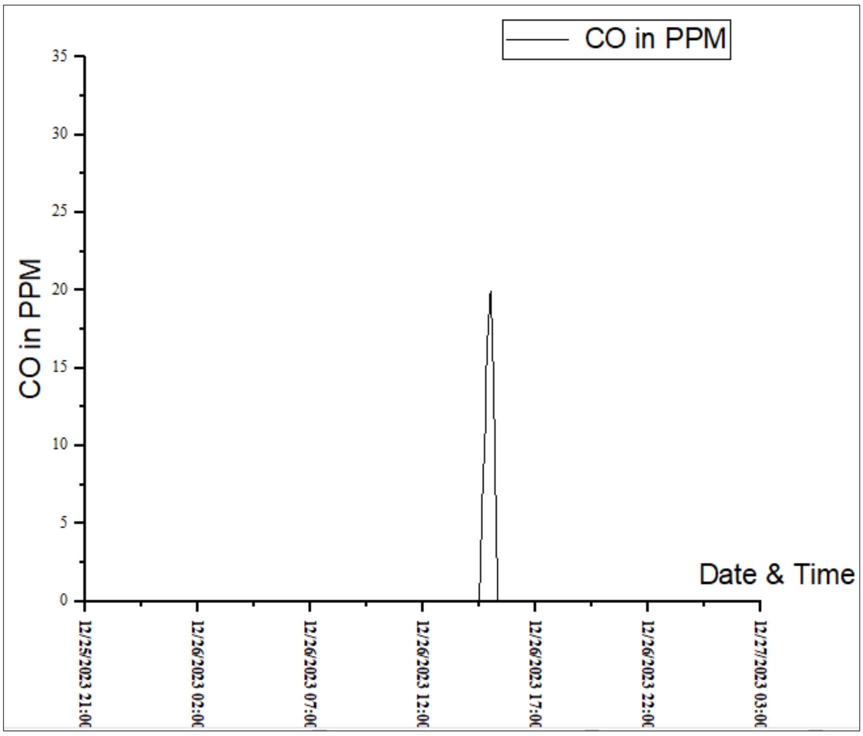


(d)

Fig. 5.52 $CO_2$ measured from RTEPMS-LoRaWAN and Multi gas detector (a, b, c & d)

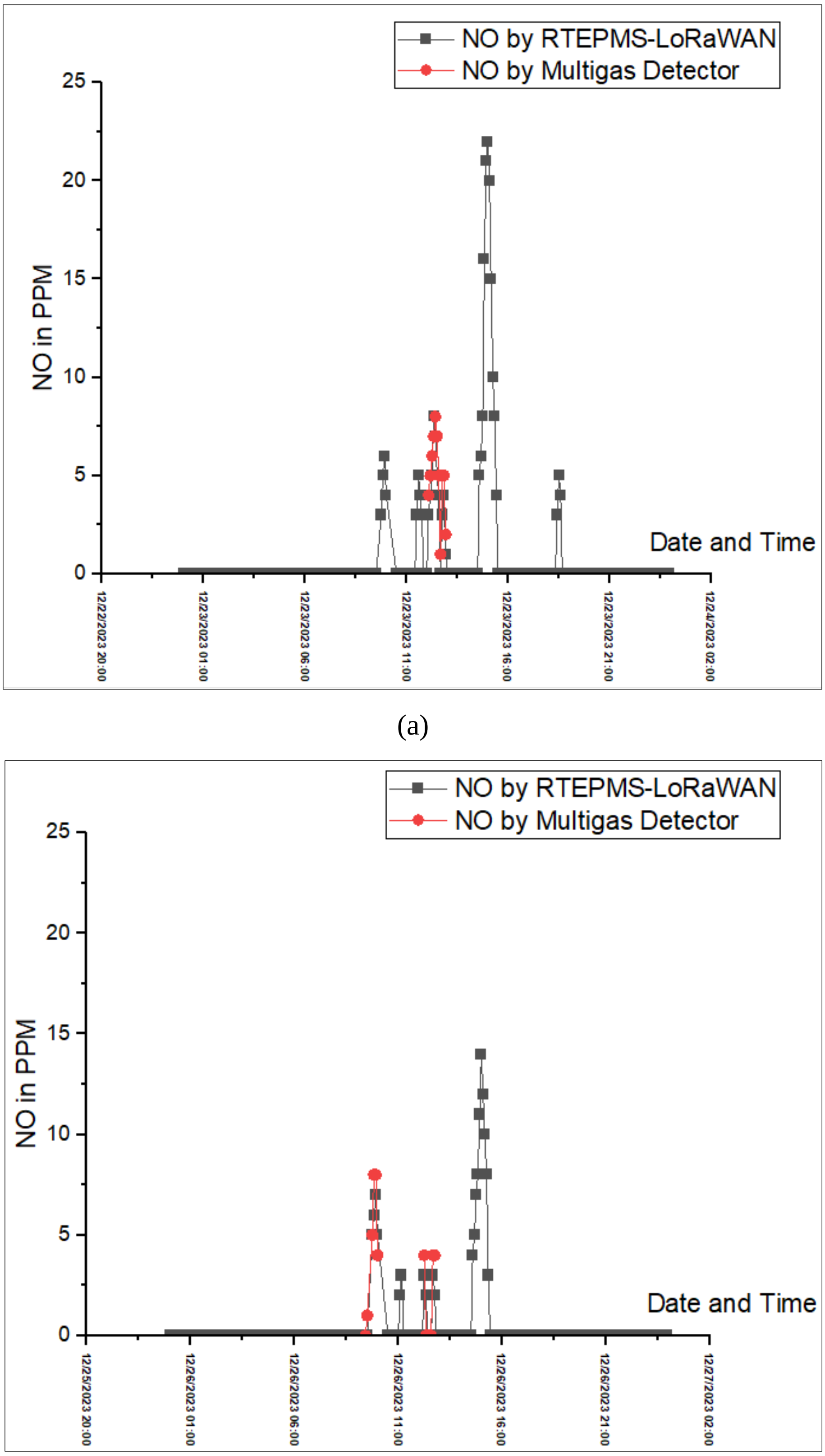


(a)



(b)

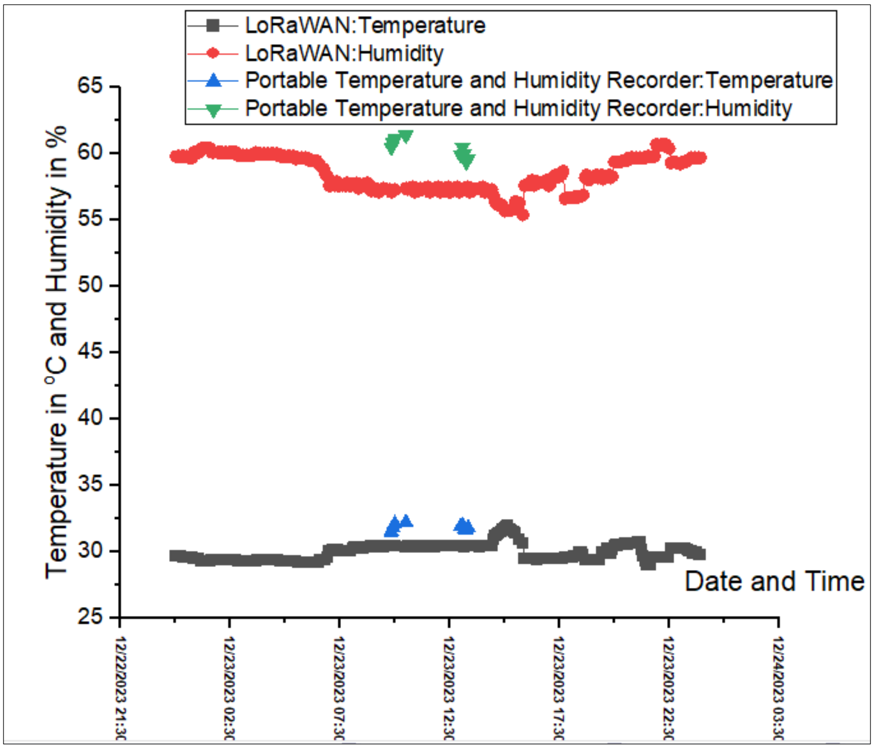
Fig. 5.53 CO measured from RTEPMS-LoRaWAN and Multi gas detector (a & b)



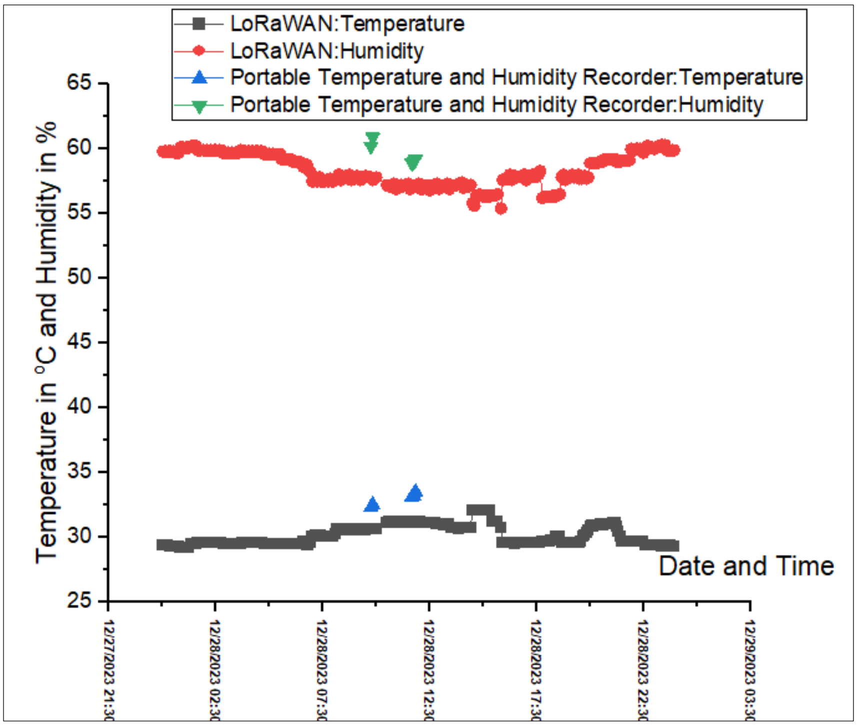
(a)

(b)

Fig. 5.54 NO measured from RTEPMS-LoRaWAN and Multi gas detector (a & b)



(a)



(b)

Fig. 5.55 Temperature and Humidity measured from RTEPMS-LoRaWAN and temperature and humidity data recorder (a & b)

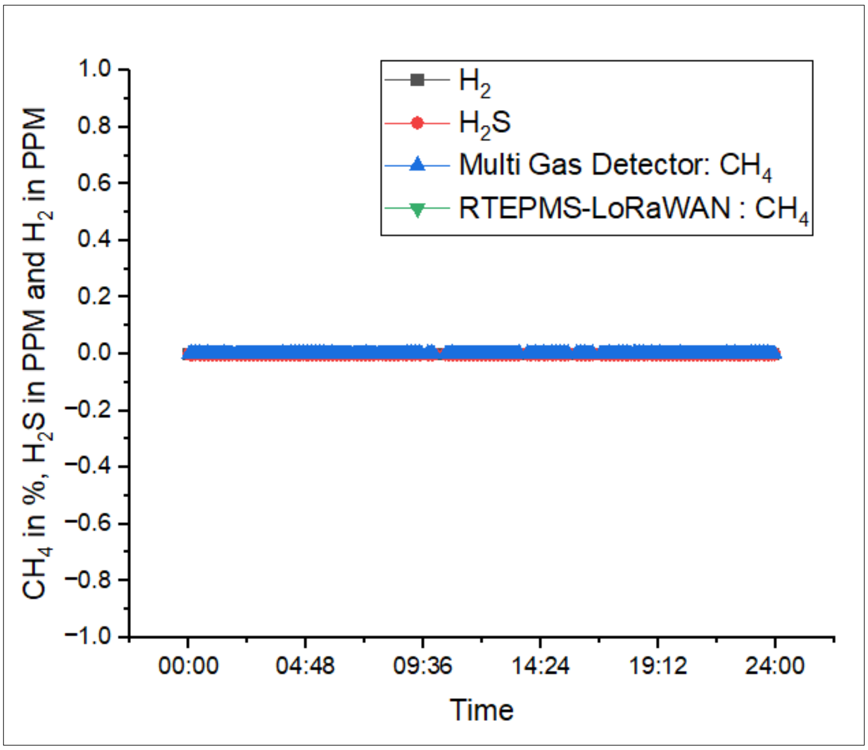


Fig. 5.56 $CH_4$, $H_2$ and $H_2S$ measured from RTEPMS-LoRaWAN and multigas detector device.

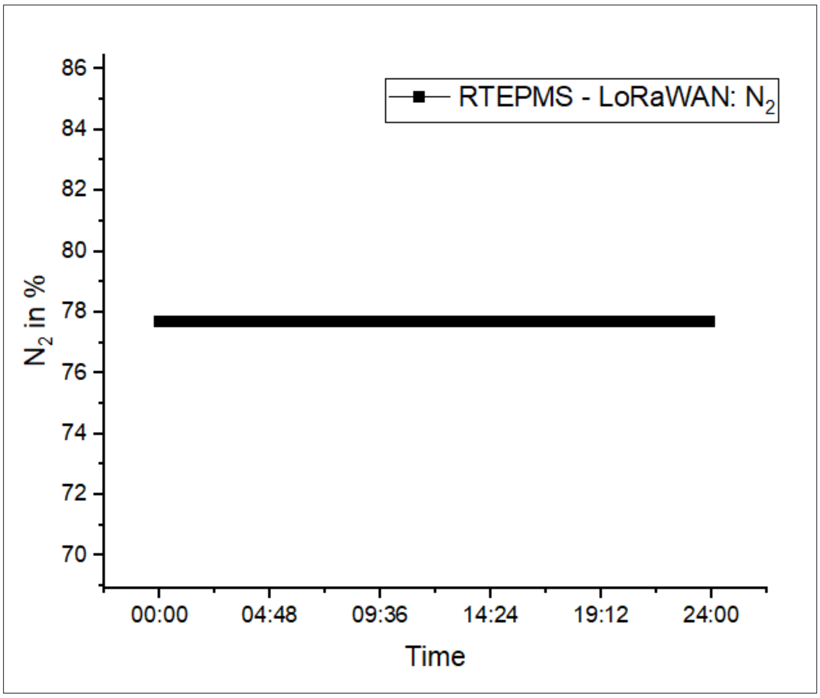


Fig. 5.57 $N_2$ measured from RTEPMS-LoRaWAN system

### 5.5.4 Time Series Forecasting Analysis by LSTM

A comprehensive analysis of environmental parameters collected from underground mines is carried out by using a time series forecasting machine learning algorithm. Machine learning algorithms Long Short-Term Memory (LSTM) predict future values of environmental parameters and gain insights into temporal patterns and trends. By doing so, we aim to provide actionable insights for maintaining optimal environmental conditions and mitigating potential risks. Ultimately, our goal is to enhance the safety, productivity, and sustainability of underground mining operations. The objective is to perform time series forecasting and analysis on major environmental parameters $CO_2$, CO, NO, temperature, and humidity collected from underground mines.

The dataset contains 40 days of environmental parameters data collected from sensors. it contains date and time and environmental parameters such as $CO_2$, CO, NO, Temperature and Humidity. Table 5.8 represents the maximum, minimum, and average values of each parameter. Based on 40 days of data, forecast the next 1 or 2 days as shown in the graph. This method is also applicable to all parameters.

Table 5.8 Maximum, Minimum and Average Values of Environmental Parameters

| **Environmental Parameters** | **Maximum** | **Minimum** | **Average** |
|---|---|---|---|
| $CO_2$ | 736 | 522 | 573.23 |
| CO | 32 | 0 | 0.256 |
| NO | 35 | 0 | 0.529 |
| Temperature | 33 | 28.8 | 30.07 |
| Humidity | 61.4 | 55.3 | 58.4 |

Long Short-Term Memory (LSTM) model offers a sophisticated framework for understanding and forecasting sequential data. At the heart of the univariate LSTM architecture lie memory cells, each equipped with hidden states and cell states. The hidden state serves as the network’s memory, retaining crucial information from past time steps, while the cell state facilitates selective retention or forgetting of data, enabling the model to grasp long-term dependencies effectively.

Integral to the functionality of univariate LSTM models are gates, including the input, forget, and output gates. These gates regulate the flow of information within the model, controlling the entry of new data, determining what information to discard, and managing the output of the model's predictions. Using activation functions like the hyperbolic tangent (tanh), LSTM cells transform inputs and gate outputs, capturing the nonlinear relationships inherent in time series data. During training, LSTM models update their parameters through backpropagation and gradient descent optimization, aiming to minimize the discrepancy between predicted and actual values in the time series. Once trained, these models can generate accurate forecasts for future time steps, making them indispensable tools for predictive analytics in various fields.

### *a) Data Preprocessing*

Here are the datasets for December 2023 and January 2024 months of $CO_2$, CO, NO, Temperature, and Humidity were pre-processed. The visualization of the data is represented as shown in Fig. 5.58 to 5.62.

Upon processing the entire data frame, the function returns two NumPy arrays. one containing the input sequences (X) and another containing the corresponding output values (y). These arrays can then be utilized directly in the training process of an LSTM model, providing the necessary input data and target labels for supervised learning. By encapsulating this data preparation process into a function, users can easily transform their time series data into a format suitable for LSTM model training, streamlining the overall workflow of time series analysis and prediction tasks.

**$CO_2$ in PPM**

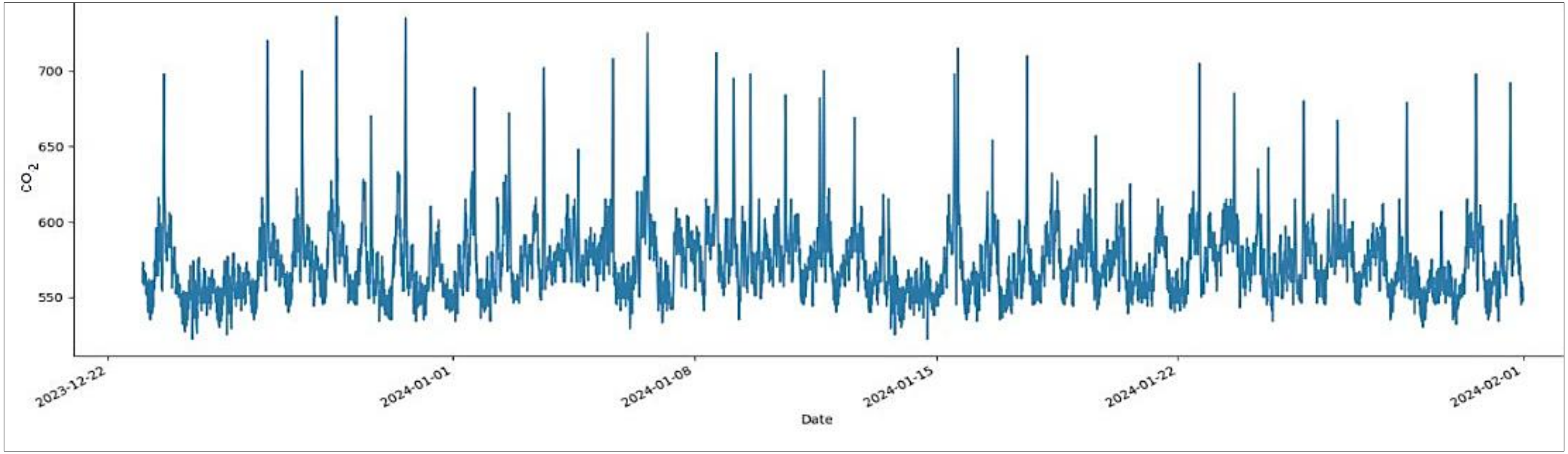


Fig. 5.58 Visualization of the $CO_2$ in PPM data

### CO in PPM

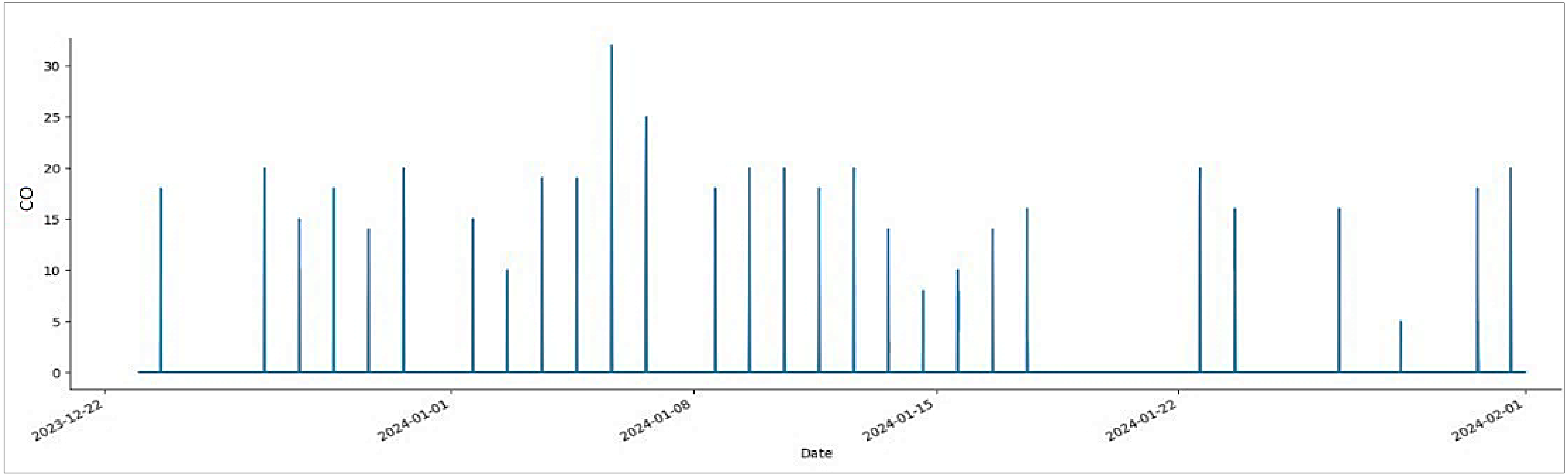


Fig. 5.59 Visualization of the CO data

**NO in PPM**

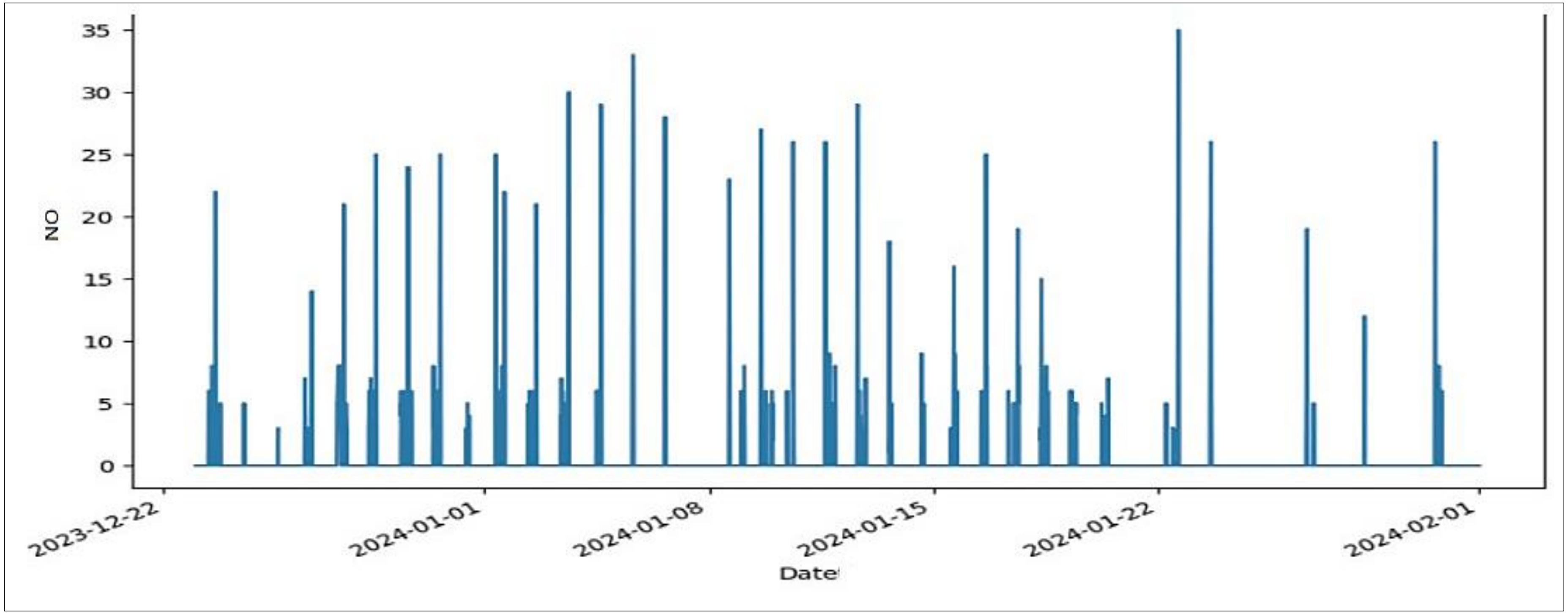


Fig. 5.60 Visualization of the NO data

**Temperature in $^{0}$C**

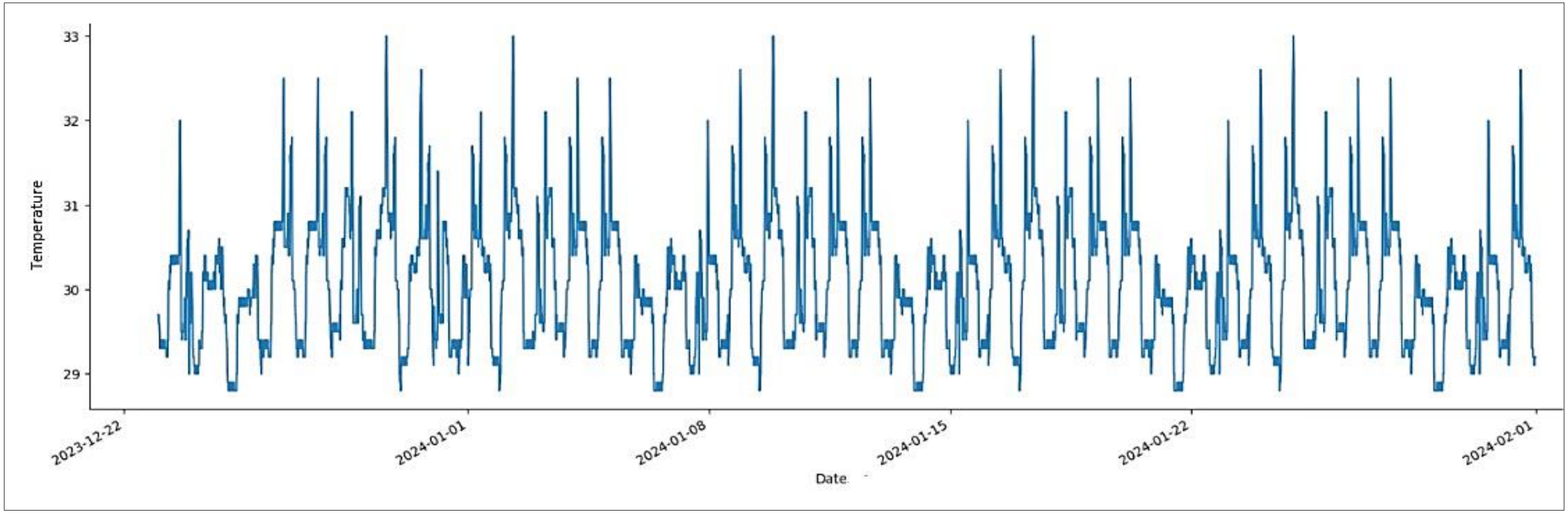


Fig. 5.61 Visualization of the Temperature data

**Humidity in %**

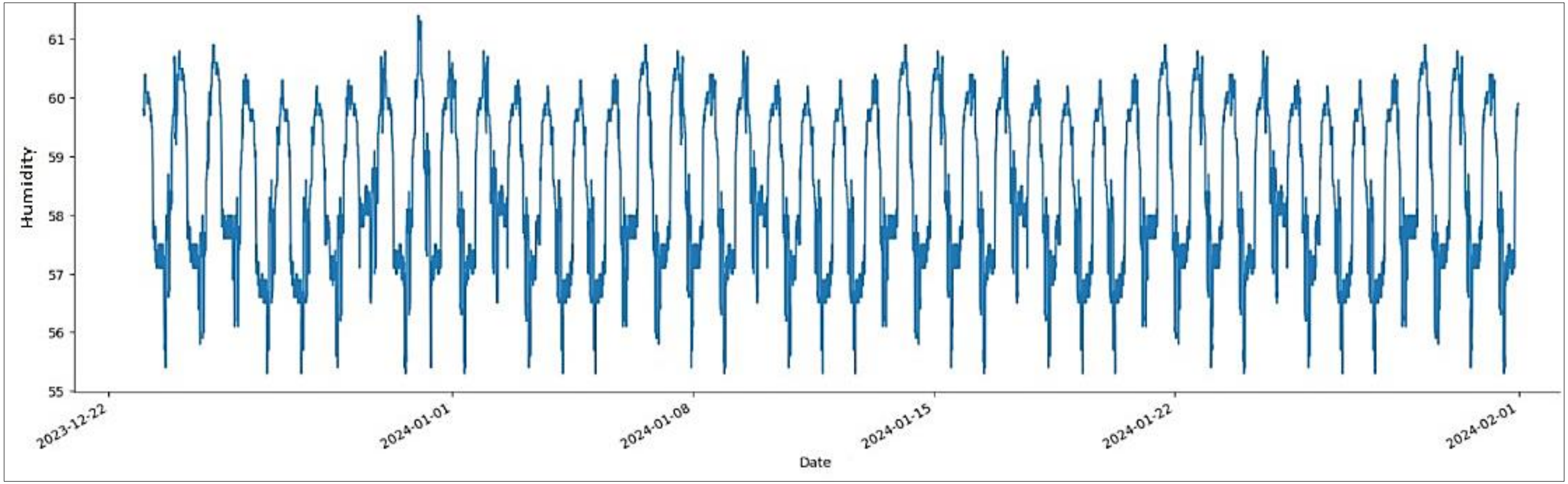


Fig. 5.62 Visualization of the Humidity data

### ***b) Splitting Dataset for Training, Validation and Testing***

After splitting datasets, the X1 and y1 data frames after using the defined function for data distribution, then the data frame X1 is divided into three subsets: training, validation, and testing. These subsets are crucial for training, tuning, and evaluating machine learning models, respectively.

- Training Set (X *train1*, y *train1*): It contains the initial portion of the data frame X1, consisting of the first 5000 samples. X *train1* comprises the input features used for training the model. y *train1* contains the corresponding target labels or output values associated with the input features in X *train1*.
- Validation Set (X *val1*, y *val1*): The validation set is utilized for fine-tuning the model's hyperparameters and assessing its performance during training. It consists of samples from the data frame X1 ranging from the 5000th to the 8999th index, a total of 4000 samples. Similar to the training set, X *val1* comprises input features, while y *val1* contains the corresponding target labels.
- Testing Set (X *test1*, y *test1*): The testing set serves as an independent dataset to evaluate the trained model's performance and generalization ability It includes the remaining samples of the data frame X1 starting from the 9000th index until the end. X test1 consists of input features, while y *test1* holds the corresponding target labels.

By partitioning the data frame X1 into these distinct subsets, practitioners can effectively train, validate, and test machine learning models, ensuring robustness and reliability in their predictive capabilities. This division enables comprehensive model assessment, aiding in the identification of potential overfitting or underfitting issues and facilitating the selection of optimal model configurations.

### ***c) LSTM model built for training time series data***

The neural network model developed here specializes in predicting levels of carbon dioxide ($CO_2$), carbon monoxide (CO), nitrogen oxide (NO), temperature, and humidity using historical time series data. It begins with an input layer designed to accommodate sequences of data, each consisting of five consecutive observations. This structure allows the model to incorporate contextual information, which is essential for identifying patterns and trends over time. Following the input layer is a Long Short-Term Memory (LSTM) layer, a crucial component of the model architecture. Known for its ability to capture temporal dependencies, the LSTM layer processes the input sequences, effectively handling the complex and dynamic nature of the data.

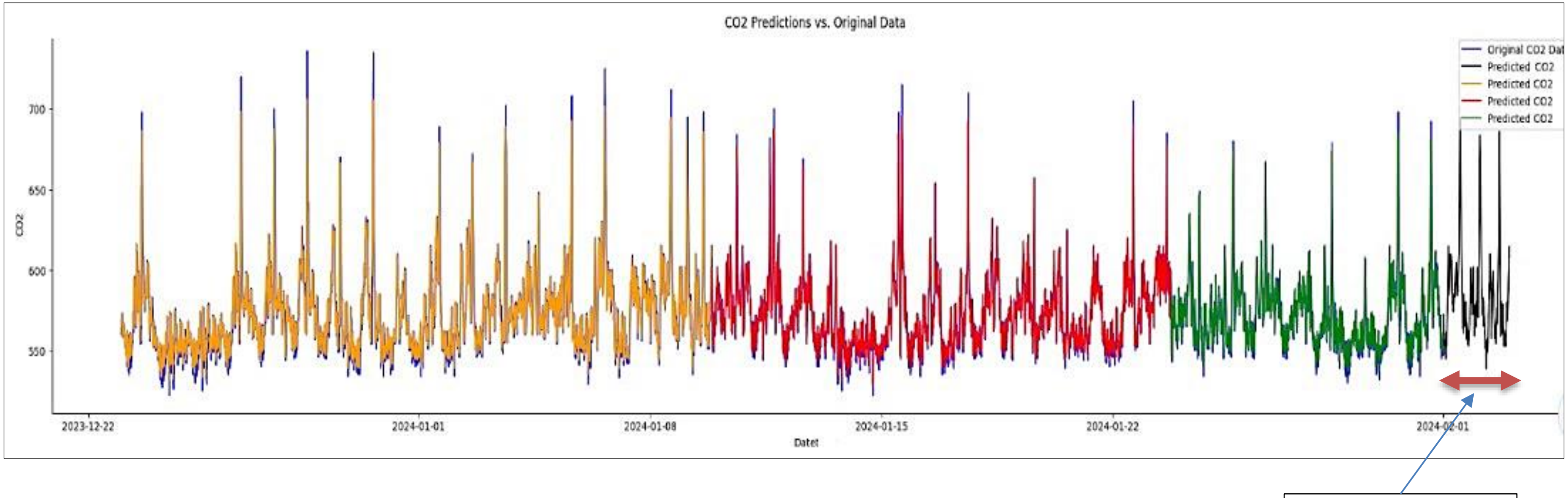
Following the LSTM layer, the model incorporates two dense layers to further refine the learned representations and enhance prediction accuracy. The first dense layer, with eight units and using the Rectified Linear Unit (ReLU) activation function, introduces non-linearity to the model's transformations. This non-linearity enables the model to capture intricate relationships within the $CO_2$ data, improving its ability to identify subtle patterns and fluctuations. Finally, the second dense layer serves as the output layer and consists of a single unit with a linear activation function. This layer is crucial for generating predictions of future $CO_2$ levels based on the processed representations learned by the model. In essence, the architectural design of the model, which includes input, LSTM, and dense layers, enables it to effectively learn and identify meaningful patterns within the input data. By utilizing historical time series data, the model can accurately predict future levels, providing valuable insights for environmental monitoring and climate research. The model's robustness and predictive accuracy highlight its potential utility in addressing real-world challenges related to forecasting variable levels and developing mitigation strategies. A checkpoint mechanism is implemented to save the best-performing model during the training phase using TensorFlow's Keras library. This is accomplished with the ModelCheckpoint callback, which is configured to save only the best model encountered during training based on a predefined criterion, typically the validation loss.

During model training, after each epoch, the model's performance on the validation set is evaluated. If the current model achieves a lower validation loss than any previous model, the checkpoint mechanism saves the current model’s weights and architecture to a specified directory. By setting `save_best_only=True`, the checkpoint ensures that only the best-performing model is saved, preventing the overwriting of previous checkpoints with inferior models.

The model is then compiled using the specified loss function `MeanSquaredError()`, optimizer `Adam` with a learning rate of 0.0001, and evaluation metrics (`mae`, `mape`, and `RootMeanSquaredError()`). Subsequently, the model is trained using the `fit` method with the training data (`Xtrain1`, `ytrain1`) and validation data (`Xval1`, `yval1`). The training process is set to run for 450 epochs and includes the `cp1` callback, which activates the checkpoint mechanism to save the best model encountered during training. Overall, the checkpoint mechanism ensures that the best-performing model is saved during the training process, enabling practitioners to retain the model and the configuration that yields optimal performance on the validation set for subsequent evaluation or deployment. Forecasted data for $CO_2$ for the next two days using the trained LSTM Model represented a shown in Fig. 5.63. Forecasted data for CO, NO, Temperature, and Humidity for the next two days using the trained LSTM Model represented as shown in Figures 5.64 to 5.67.

RMSE and MAE serve as crucial evaluation metrics for predictive models in regression analysis or forecasting. RMSE assesses the average discrepancy between predicted and actual values, with an emphasis on larger errors due to the squared differences. Meanwhile, MAE quantifies the average absolute difference between predicted and actual values, offering a straightforward interpretation of error magnitude. These metrics collectively aid in understanding model performance, guiding decision-making processes, and facilitating model refinement endeavors. Table 5.9 represents the error analysis of data by the LSTM model.

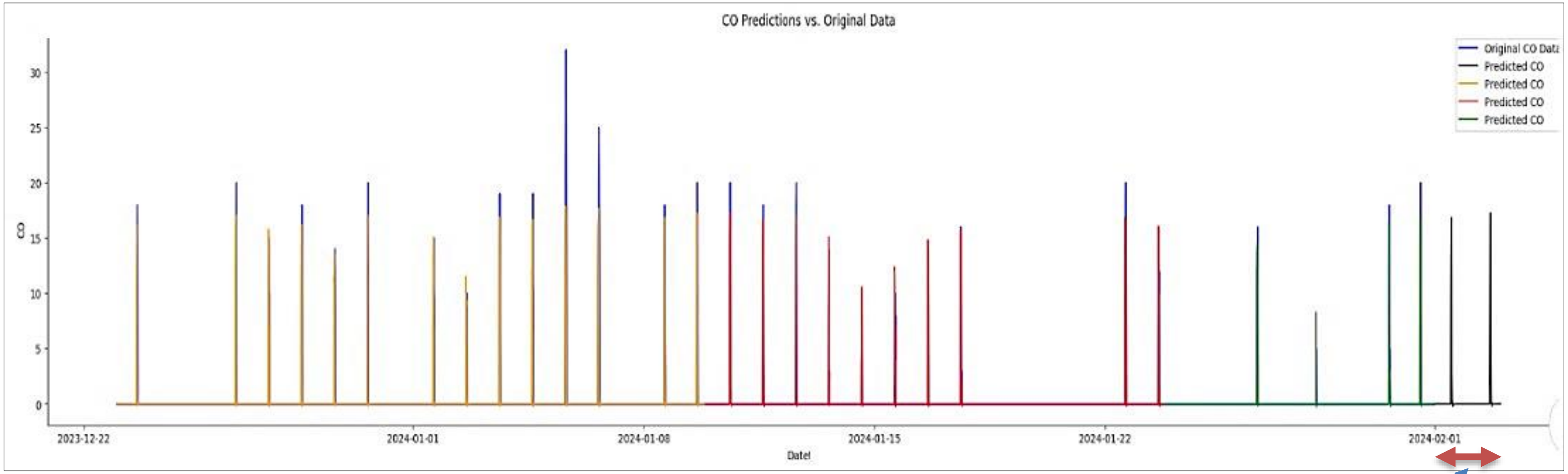
### $CO_2$ in PPM



Forecasting $CO_2$

Fig. 5.63 Forecasting data For $CO_2$ prediction vs original data

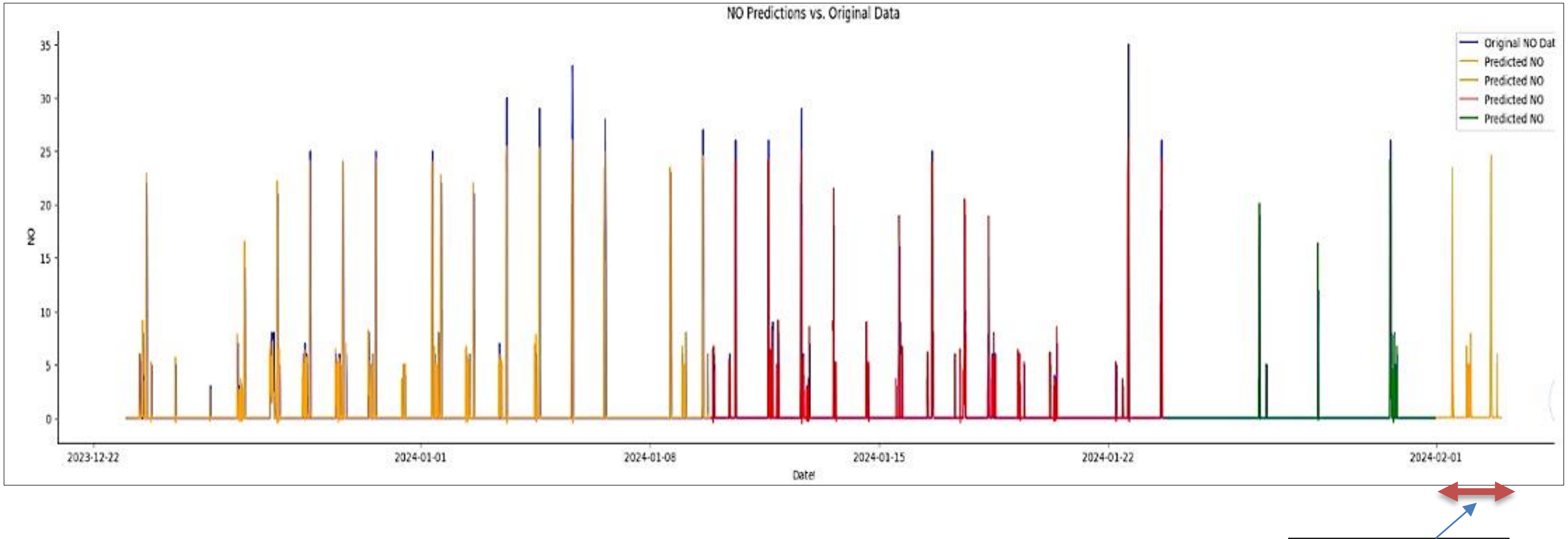
## CO in PPM



Forecasting CO

Fig. 5.64 Forecasting data For CO for the next two days prediction vs original data

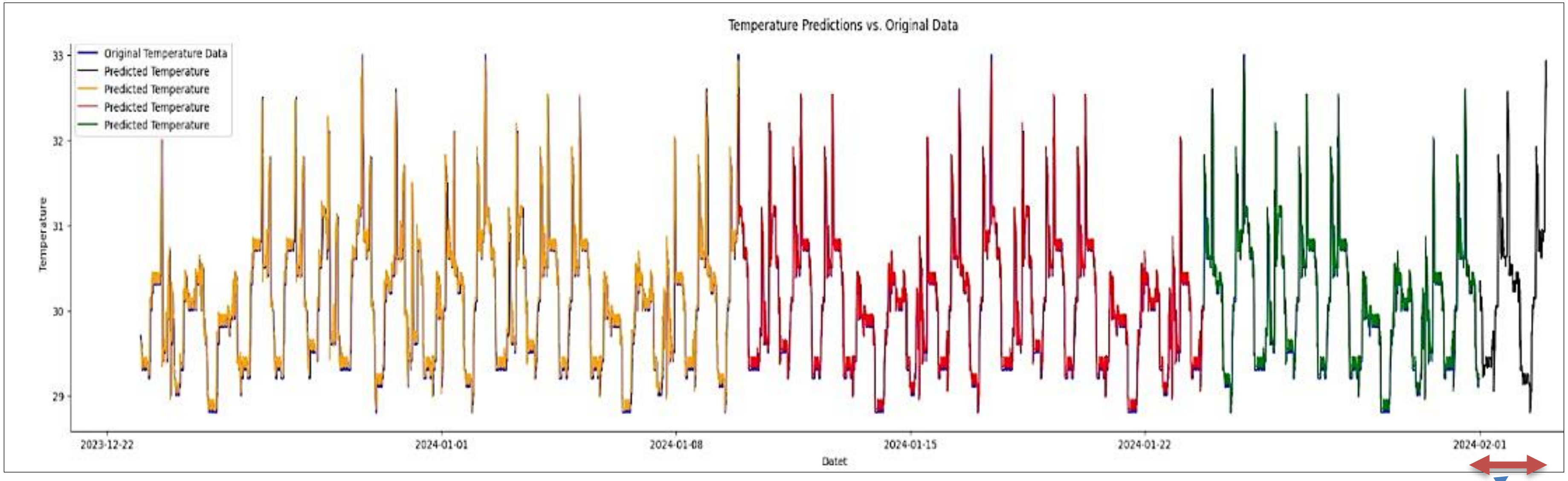
**NO in PPM**



Forecasting NO

Fig. 5.65 Forecasting data for NO for the next two days prediction vs Original Data

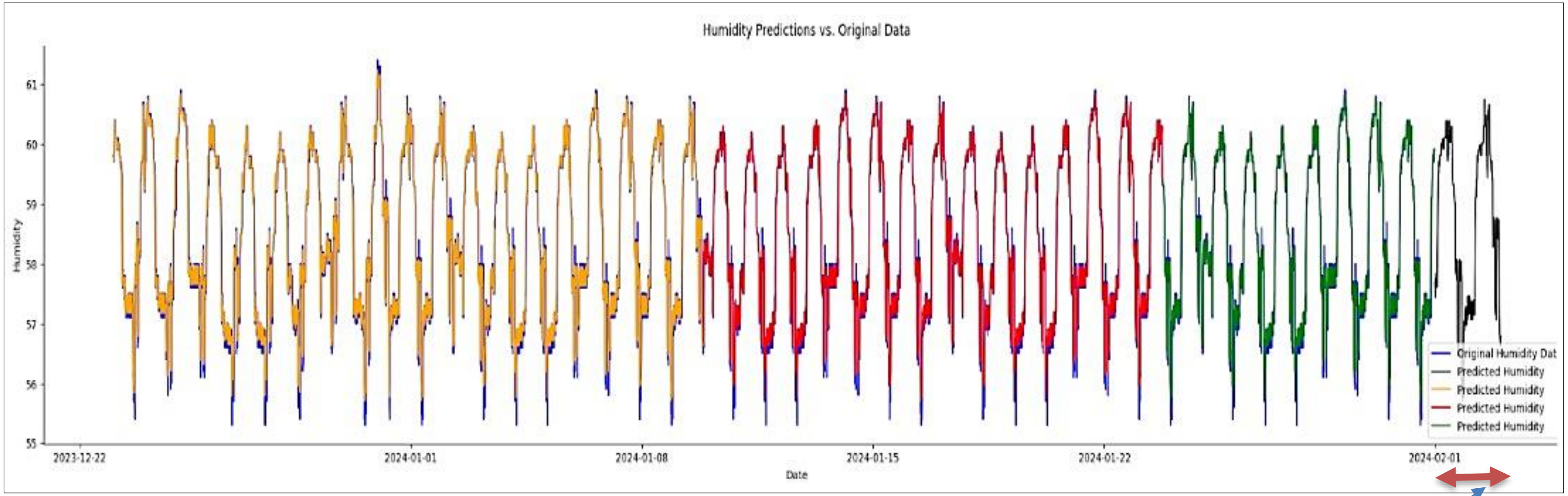
**Temperature in $^0$C**



Forecasting Temperature $^0$C

Fig. 5.66 Forecasting data for Temperature for the next two days prediction vs Original Data

**Humidity in $^0$C**



Forecasting Humidity in %

Fig. 5.67 Forecasting data for Humidity for the next two days Prediction vs Original Data

Table 5.9 Error Analysis

| **Environmental Variables** | **RMSE** | **MAE** |
|---|---|---|
| $CO_2$ | 6.8972 | 4.8408 |
| CO | 0.3788 | 0.0678 |
| NO | 0.7363 | 0.2202 |
| Temperature | 0.1294 | 0.0686 |
| Humidity | 0.3020 | 0.1901 |

LSTM model has the ability to learn from sequential data, remember past information, and capture complex patterns, making it well-suited for time series forecasting tasks. The lower error values RMSE and MAE obtained with LSTM indicate its capability to provide more accurate predictions and preferred choice for time series forecasting tasks.

### 5.5.5 Time Series Forecasting Analysis by XGBoost

XGBoost (Extreme Gradient Boosting) is a powerful machine learning algorithm that builds an ensemble of decision trees sequentially to improve prediction accuracy. The XGBoost algorithm to predict $CO_2$, CO, NO, temperature, and humidity levels using environmental parameters by merging various datasets ($CO_2$, CO, NO, temperature, and humidity) and formatting the data for time-series analysis. It performs feature engineering by creating lag features, applying a rolling mean, and using Fourier transformation to capture trends and periodic patterns. The data is split into training and testing sets, and hyperparameter tuning is done using GridSearchCV to optimize the model.

The XGBRegressor model is then trained with the best parameters, and its performance is evaluated using metrics such as RMSE, MAE, $R^2$, and MAPE. The visualization of the actual versus predicted $CO_2$ values and extends the dataset by two days to forecast future $CO_2$ levels, dynamically updating features for continuous predictions as shown in Fig. 5.68 to 5.72.

RMSE and MAE serve as crucial evaluation metrics for predictive models in regression analysis or forecasting. Table 5.10 represents the error analysis of data by the XGBoost model.

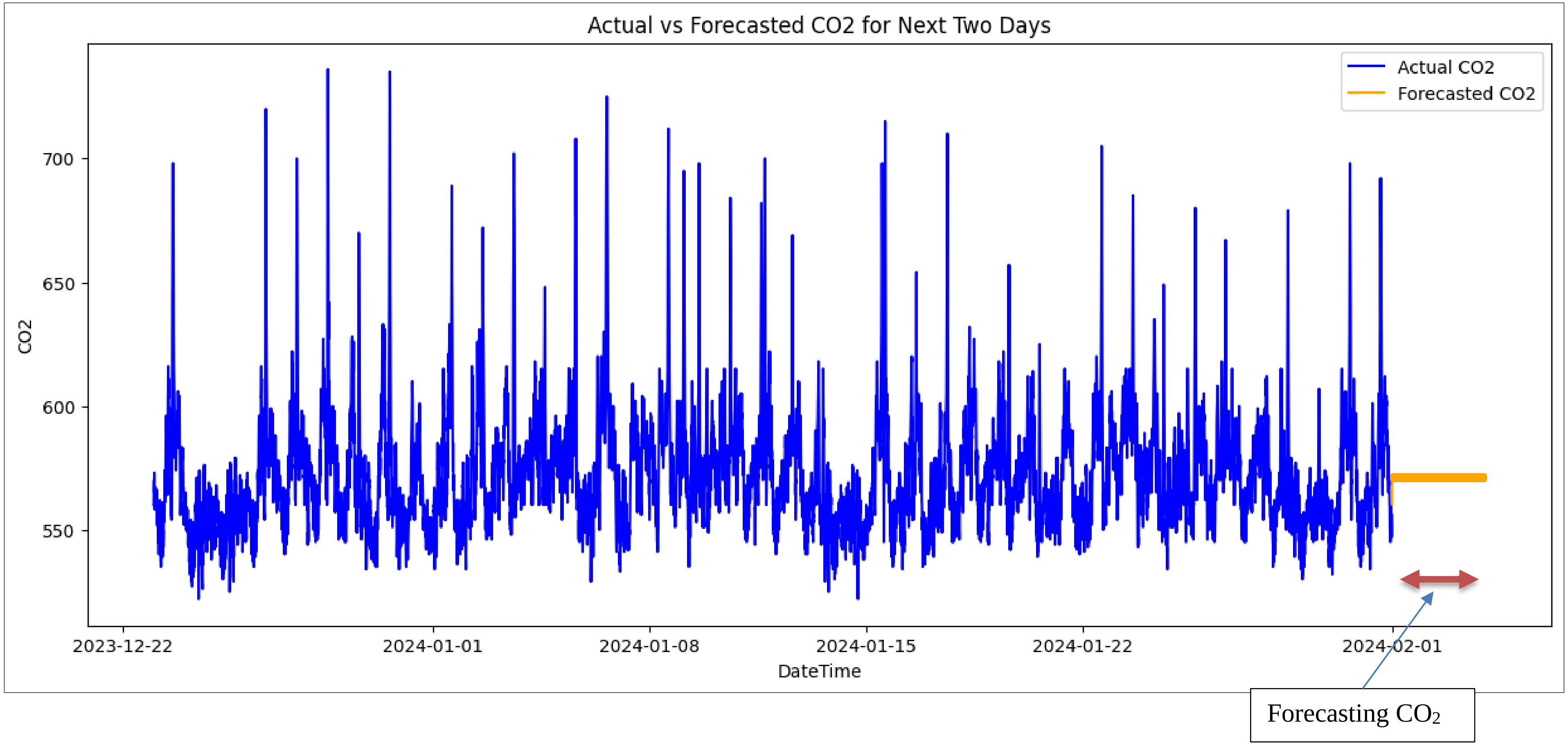
Errors in time series data can result from various sources like missing values, outliers, or measurement errors. Addressing these errors is crucial for meaningful analysis. Techniques such as Linear, Spline, and Polynomial interpolation help estimate missing values, while Z-score analysis measures deviations from the mean, and the IQR method sets thresholds for identifying outliers.

To effectively manage noise, techniques like Moving Averages and Wavelet Transforms are employed to smooth data. For error correction and forecasting, statistical methods like ARIMA are used, and machine learning models like LSTM and XGBoost model handle complex patterns in time series data.

Table 5.10 Error Analysis

| Environmental Variables | RMSE | MAE |
|---|---|---|
| $CO_2$ | 9.0962 | 6.8874 |
| CO | 0.7241 | 0.1769 |
| NO | 0.7173 | 0.3112 |
| Temperature | 0.2976 | 0.24 |
| Humidity | 0.5170 | 0.4543 |

## **$CO_2$ in PPM**



Forecasting $CO_2$

Fig. 5.68 Forecasting data For $CO_2$ prediction vs original data

**CO in PPM**

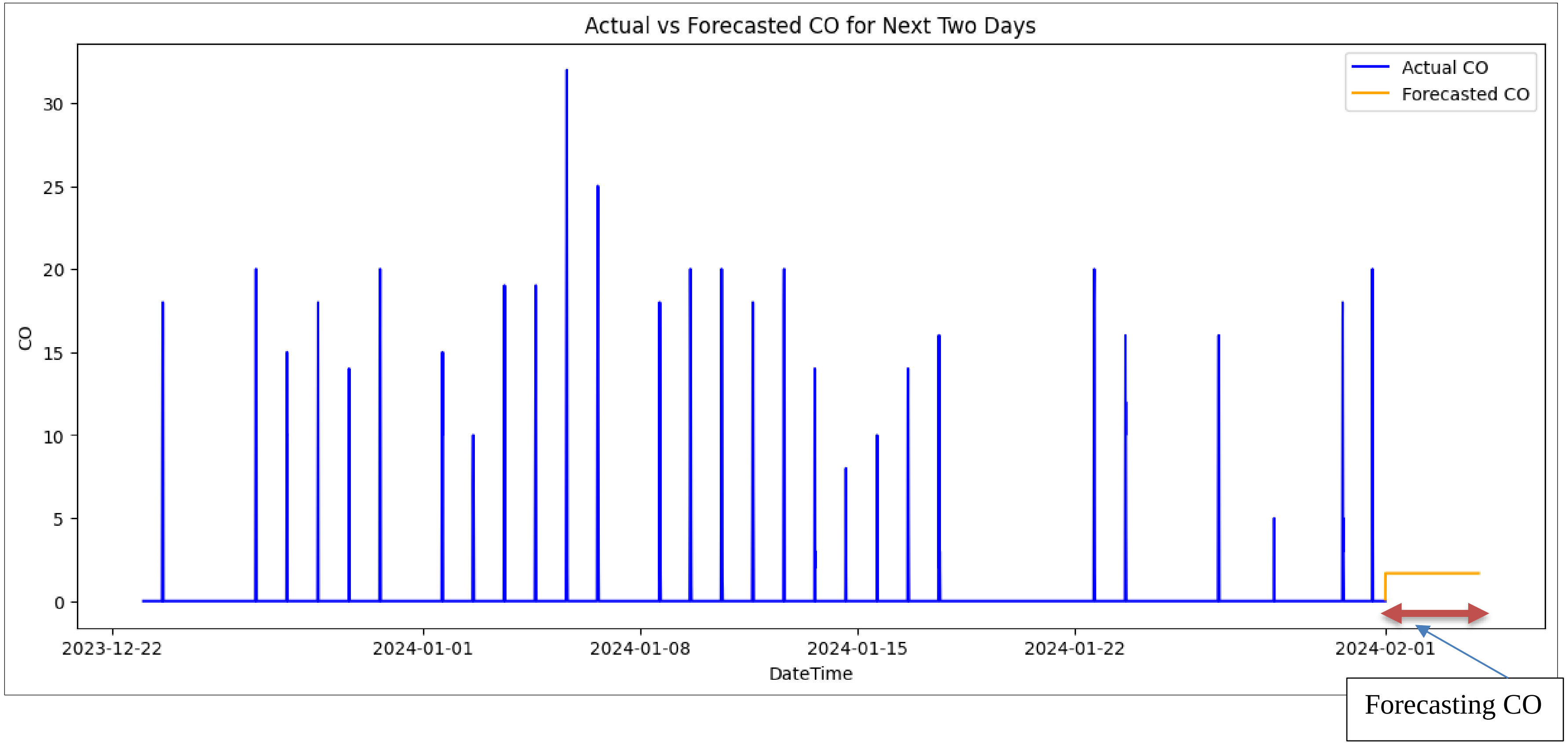


Fig. 5.69 Forecasting data For CO for the next two days prediction vs original data

**NO in PPM**

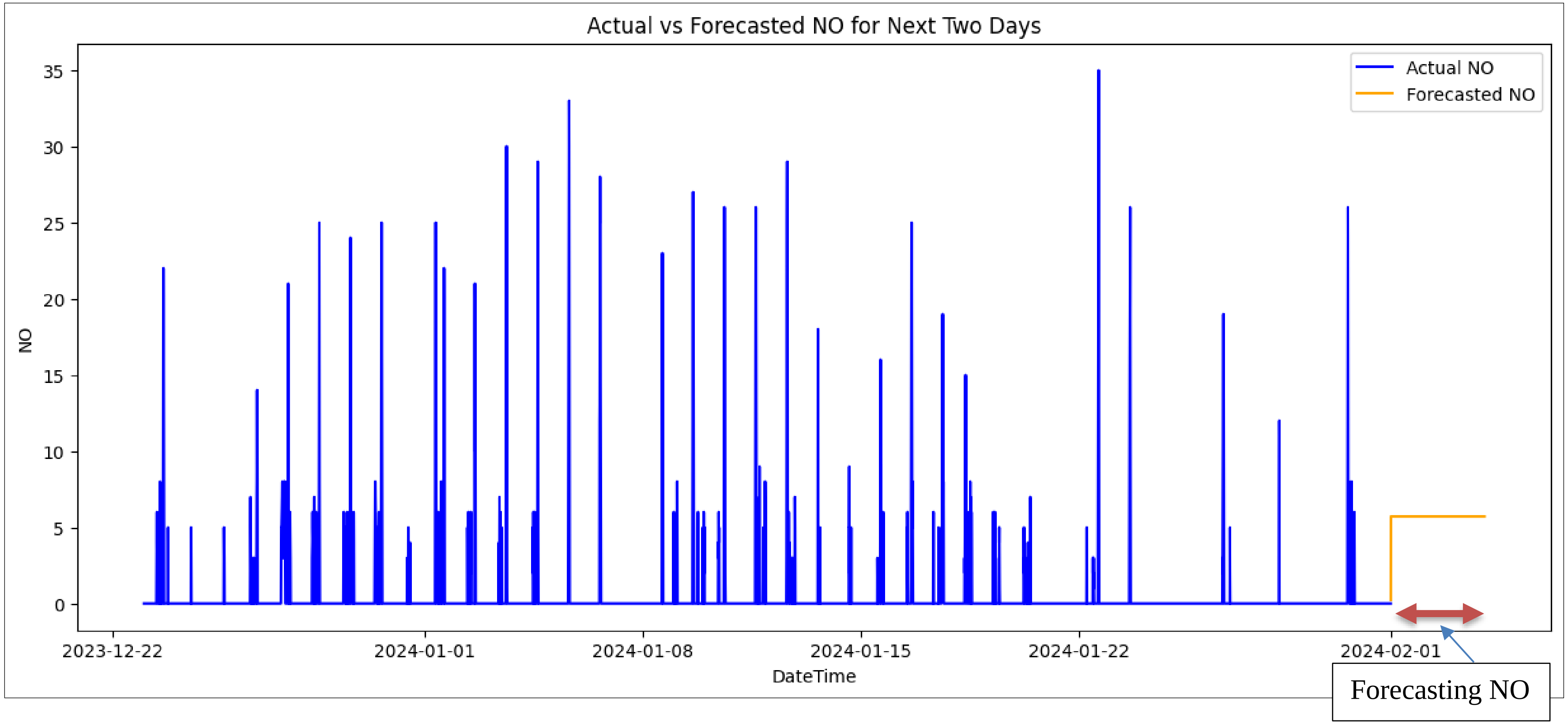
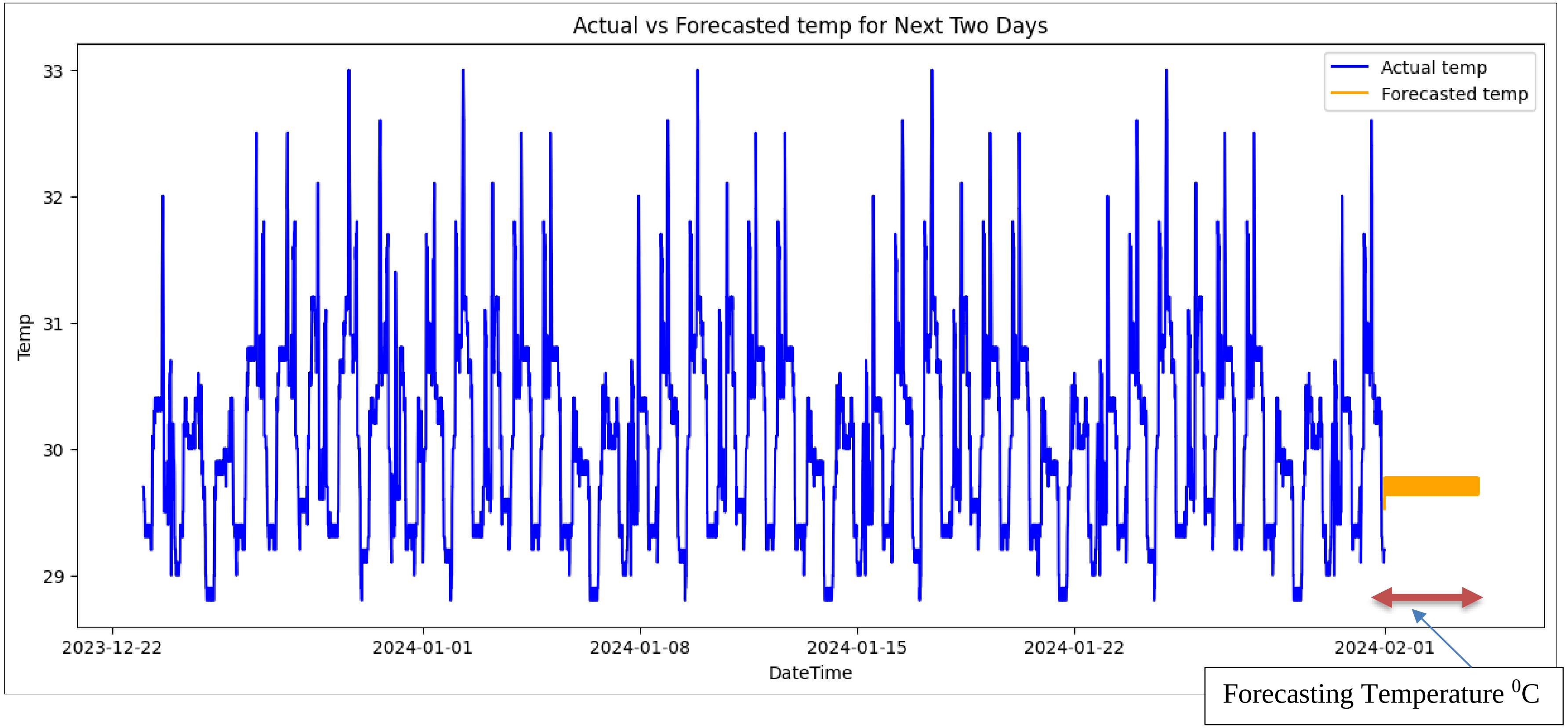


Fig. 5.70 Forecasting data for NO for the next two days prediction vs Original Data

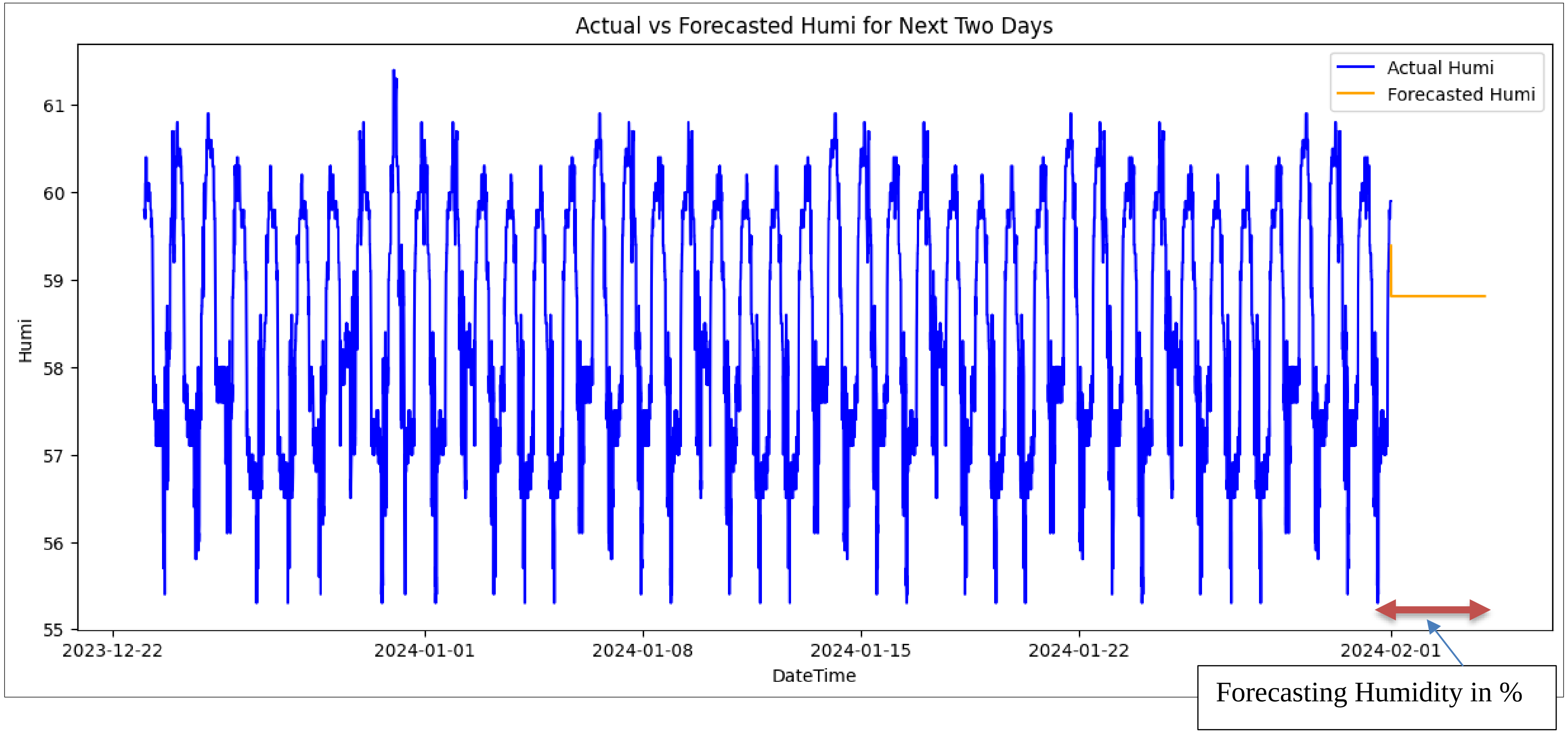
**Temperature in $^0$C**



Forecasting Temperature $^0$C

Fig. 5.71 Forecasting data for Temperature for the next two days prediction vs Original Data

**Humidity in $^0$C**



Forecasting Humidity in %

Fig. 5.72 Forecasting data for Humidity for the next two days Prediction vs Original Data

## 5.6 Advantages and Potential Improvements of the RTEPMS

The design and development of the RTEPMS system, incorporating LoRaWAN technology, provides several advantages compared to ZigBee and basic LoRa systems:

- **Extended Range:** The IoT-enabled LoRaWAN gateway-based system can transmit data over distances of up to 1800 meters in underground mines, significantly exceeding the range of LoRa and ZigBee systems.
- **Data Accuracy and Reliability:** While ZigBee or LoRa based systems had communication failures at deeper underground depths, the RTEPMS with IoT enabled LoRaWAN maintained a stable connection over long distances, allowing real-time monitoring of environmental parameters.
- **Cost-effective and Efficient:** The development of the IoT-based system is cost-effective and efficient for continuous 24/7 real-time monitoring of environmental parameters of underground mines from the surface. There is some trade-off in accuracy compared to traditional multi-gas detectors. However, the IoT enabled LoRaWAN system's capability to continuously collect and transmit environmental data in real time overcomes this limitation, especially in large-scale mining operations.
- **Energy Efficiency:** The IoT-enabled LoRaWAN gateway system is designed with low-power sensors and LoRaWAN communication modules, which are known for their energy efficiency. LoRa technology allows for long-range data transmission with minimal energy use, making the system ideal for environments where power supply may be limited or inconsistent.
- **System Design:** The system's design is a reliable, robust and wireless communication technology for real-time forewarning hazard monitoring of environmental parameters with intrinsic safety features, flameproof construction, and an IP65-rated panel, making it exceptionally suitable and secure for hazardous underground mine environments.

## 5.7 Cost Estimation of RTEPMS System

The LoRa-based RTEPMS system, which integrates ESP32 development boards, HDP13A LoRa Modules, a $CO_2$ Module, MQ7 Carbon Monoxide Sensor, MQ136 Hydrogen Sulfide Gas Sensor, MQ4 Methane ($CH_4$) Gas Sensor, MQ8 Hydrogen ($H_2$)

Gas Sensor, DHT11 Temperature and Humidity Sensor, and 12V batteries, costs a total of Rs. 20,500/-. Additionally, the PCB and fabrication for 2 units cost Rs. 20,000, bringing the overall total for all components to Rs. 40,500/-.

In contrast, the installation and deployment of the IoT-enabled LoRaWAN system for a single set of sensors, which includes 8 sensors, 1 LoRaWAN gateway, and 1 RS485-LN converter with accessories, is approximately Rs. 4,53,671/-.

## 5.8 Summary

The Real-Time Environmental Parameters Monitoring System (RTEPMS) was initially tested in a Model Mine, followed by field trials in Underground Mines ‘A’ and ‘B’. A notable field trial in Underground Mine ‘B’ using the LoRa 868 MHz module and the IoT-enabled LoRaWAN system was carried out. The data measured from ZigBee, 433 MHz LoRa modules, 868 MHz LoRa modules, and LoRaWAN Gateway-based systems are compared against a portable multi-gas detector and temperature and humidity devices. Additionally, the RTEPMS-LoRaWAN system was implemented in Underground Mine ‘B’ to monitor data of the underground mine tunnel from the surface. Time series forecasting analysis was performed using the LSTM and XGBoost algorithm to forecast the environmental parameters to avoid any hazardous scenarios. The next chapter, 6, presents a conclusion, and the limitations of this study and the scope of future research in this interdisciplinary area are also discussed.

# CHAPTER 6

# 6. CONCLUSIONS, LIMITATIONS, AND FUTURE SCOPE OF THE STUDY

## 6.1 Conclusions

This research study focused on the design and development of an advanced industrial Internet of Things (IoT) system for real time monitoring of environmental parameters in underground mines from the surface. The objective is to develop a cutting-edge solution to overcome the limitations of current environmental parameters monitoring systems in underground mines, thereby enhancing the safety and well-being of mine workers in challenging underground mine environments.

The research aimed to integrate IoT technology, incorporating multiple RS485 sensors, an RS485-LN converter device, and a LoRaWAN gateway. This setup is intends for the real-time monitoring of environmental conditions, enabling data transmission and storage on a cloud platform, and facilitating the monitoring of this data from the surface via web and mobile applications. In response to variations in environmental parameters, an alarm system was installed both within the mine tunnels and on the surface, alerting workers to evacuate to safe locations promptly. The system also generates an email notification to the concerned authority. The IoT-enabled LoRaWAN Gateway based system was developed after extensive calibration of sensors and trials in a laboratory. The RTEPMS-LoRaWAN system is tested and evaluated in an underground mine in India, which is approximately 832 meters below the surface, to determine the effectiveness of this innovative approach.

The IoT-enabled RTEPMS-LoRaWAN system for monitoring environmental parameters in underground mines operates in real-time and utilizes multiple parameter sensors to enhance safety. The RS485 sensors interface with the RS485-LN converter device via wired connections, facilitating the wireless transmission of data to the LoRaWAN Gateway. This wireless transmission occurs between the RS485-LN device location and the LoRaWAN Gateway, maintaining a line of sight over distances ranging up to 1000 meters. The system facilitates the transmission of environmental parameters data of approximately covers 1800 meters distance from the underground mine of a specific location to the surface. Further, the system's design is a reliable, robust, cost-effective wireless communication technology for real-time forewarning hazard monitoring of environmental parameters with intrinsic safety features, flameproof construction, and an IP65-rated panel, making it exceptionally suitable and secure for hazardous underground mine environments.

IoT-enabled LoRaWAN setup monitors environmental parameters in real-time such as $CO_2$, CO, NO, $H_2S$, $CH_4$, $H_2$, $N_2$, temperature, and humidity in real-time, comparing the results with those from DGMS-approved multi-gas detection devices. The measurement accuracy for gases like $CO_2$ and NO was recorded at 86.95% and 88.57%, respectively. This margin of accuracy error is attributed to the instantaneous measurement of environmental parameters by the multi-gas detectors. CO gas levels spiked 20 ppm during blasting activities. The $H_2S$, $CH_4$, and $H_2$ concentrations were not detected in underground mine tunnels, while $N_2$ concentration recorded at 77.8%. Temperature and humidity readings from the IoT-enabled LoRaWAN system ranged between 29°C to 32°C and 55% to 61%, respectively. In contrast, a portable recorder device reported temperature variations from 31°C to 33.5°C and humidity levels from 58.9% to 61.5%. In constructing the forecasting model, Integrate an LSTM layer consisting of 64 units, defining the output space's dimensionality and uses ReLU activation function. Subsequently, a Dense layer is incorporated into the model. For the compilation phase, the model utilizes the adam optimizer to enhance its performance. The calculation of the error employs the mean_squared_error metric. The performance metric RMSE of CO achieves 0.38, $CO_2$ is 6.89, NO is 0.73, Temperature is 0.12 and Humidity is 0.30. The performance of the XGBoost forecasting algorithm shows an RMSE of 0.72 for CO, 9.09 for $CO_2$, 0.71 for NO, 0.29 for Temperature, and 0.51 for Humidity. In comparison, the LSTM algorithm, lower RMSE values indicate that the model provides more accurate predictions and fits the data effectively. The developed IoT enabled LoRaWAN product enables to monitor in real time.

The development of the IoT-based system is cost-effective and efficient for continuous 24/7 real-time monitoring of environmental parameters of underground mines from the surface. Mitigating and controlling excess gases in underground mines, especially due to diesel-operated vehicles, requires a standard approach that focuses on both prevention and real-time monitoring. During and post-blasting periods, a strict no-entry time frame of 30 minutes must be enforced to ensure the dissipation of toxic gases. In any workplace where diesel equipment is operated, keeping the air velocity above 45 meters per minute is essential to ensure a safe and healthy environment. Maintenance and regular check-ups of Load-Haul-Dump (LHD) vehicles are crucial to prevent excessive emissions.

## 6.2 Challenges and Limitations of the Developed System

The industrial IoT-enabled LoRaWAN system has demonstrated significant improvements in monitoring environmental parameters within underground mines. However, it is crucial to recognize the system's limitations and the challenges encountered during its development and deployment in underground gold mine sites. Key Limitations of the IoT-Enabled LoRaWAN System:

- The system's design and development heavily depend on the underground mine structure. The experimental studies were conducted in metal mines, featuring long, narrow, and curved tunnels. However, coal mines have a different tunnel structure and environment, necessitating custom system designs. The IoT enable system has to be designed based on the structure of underground mines.
- Establishing wireless communication from the depths of underground mines to the surface presents challenges, especially in positioning the RS485-LN device and LoRaWAN Gateway to maintain a line of sight. The system can reliably provide wireless communication over distances of up to 1000 meters for data transmission to the cloud database. However, the movement of the shaft cage, which is used for transporting materials and excavated ores, and mine workers may intermittently block the signal.
- The mine tunnels are often long, narrow, and curved, lacking a direct line of sight. To deploy RS485 sensors in specific locations within these tunnels for environmental monitoring, RS485 cables are necessary. The system supports a maximum cable length of 900 meters for transmitting data from the RS485 sensor setup to the RS485-LN converter. This limitation restricts sensor deployment to within 900 meters of the RS485-LN device for effective data transmission to the cloud database.

- RS485 cables are required to be fixed carefully in underground mine tunnels because heavy vehicle movement can damage the cable wires.

### 6.3 Future Scope of Study

The Real-time monitoring of environmental parameters in underground mines continues to evolve; several promising future directions can enhance the capabilities of IoT-enabled LoRaWAN systems in underground mines.

- Exploring advanced RS485 sensor technology presents an opportunity to significantly enhance the detection accuracy and sensitivity for environmental parameters.
- Customizing the sensor setup to meet the specific requirements of underground mines, including the integration of RS485 sensors for oxygen ($O_2$) levels and air quality monitoring dust sensors (PM2.5, PM10), smoke sensors, water level detector sensors, and vibration sensors.
- The current IoT system supports up to 32 sensors, allowing for a diverse array of sensors to be integrated and strategically placed throughout the mine for comprehensive coverage.
- Enhancing the dashboard to efficiently store, visualize, and manage real-time data from up to 32 parameters, along with providing precise sensor locations, would streamline monitoring processes.
- Employing artificial intelligence (AI) for data analysis could revolutionize the understanding of environmental parameter variations and gas dynamics within mines. AI-enhanced predictive analytics could forecast potential hazards, facilitate preventive safety protocols, and improve mine planning and design.
- Ongoing research and development are essential for the development of real-time environmental parameters monitoring technologies in mining industry. Collaboration between researchers, practice engineers, and mining industry stakeholders will provide valuable insights into the operational demands of mines, guiding the customization and improvement of IoT-enabled systems to address specific mining challenges.

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# NATIONAL INSTITUTE OF TECHNOLOGY KARNATAKA, SURATHKAL

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## List of Publications based on Ph.D. Work

| Si. No. | Title of the paper | Authors (in the same order as in the paper. Underline the Research Scholar's name) | Name of the Journal/ Conference/ Symposium, Vol., No., Pages | Month & Year of Publication | Category * |
|---|---|---|---|---|---|
| 1 | RTEPMS: Real-Time Environmental Parameters Monitoring System Using IoT-Based LoRa 868-MHz Wireless Communication Technology in Underground Mines | **Anil S Naik**, Sandi Kumar Reddy, and Mandela Govinda Raj | IEEE Access<br>Volume 12, 2024, Pages 7430-7455<br>DOI: 10.1109/ACCESS.2024.3350429 | January 2024 | 1 |
| 2 | A Systematic Review on Implementation of Internet-of-Things-Based System in Underground Mines to Monitor Environmental Parameters | **Anil S Naik**, Sandi Kumar Reddy, and Mandela Govinda Raj | Journal of The Institution of Engineers (India): Series D<br>Pages 17<br>DOI:10.1007/s40033-023-00541-3 | 05 September 2023 | 1 |

## List of Publications based on Ph.D. Work

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|---|---|---|---|---|---|
| 3 | Development of a Novel Real-Time Environmental Parameters Monitoring System Based on the Internet of Things with LoRa Modules in Underground Mines | Sandi Kumar Reddy, **Anil S Naik**, and Mandela Govinda Raj | Wireless Personal Communications Volume 133, pages 1517–1546, (2023)<br>DOI: 10.1007/s11277-023-10827-0 | January 2024 | 1 |
| 4 | Development of a Reliable Wireless Communication System to Monitor Environmental Parameters from Various Positions of Underground Mines to the Surface using ZigBee Modules | Sandi Kumar Reddy, **Anil S Naik**, and Mandela Govinda Raj | Journal of The Institution of Engineers (India): Series D<br>Pages 25<br>DOI: 10.1007/s40033-023-00486-7 | 18 April 2023 | 1 |
| 5 | ZigBee based Real Time System for Environmental Parameters Monitoring in Model Mine: An Experimental Study | **Anil S Naik**, Sandi Kumar Reddy, and Mandela Govinda Raj | International Conference on Mining for a Greener Future: Technological Developments and Sustainable Practices", Dept. of Mining Engineering, NITK Surathkal<br>Date: 16 - 17 February 2024 | February 2024 | 3 |

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|---|---|---|---|---|---|
| 6 | Wireless Monitoring of Environmental Parameters for Underground Mining using Internet of Things with LoRa Transceiver Module | Sandi Kumar Reddy, **Anil S Naik,** and Mandela Govinda Raj | 2022 IEEE 7th International Conference on Recent Advances and Innovations in Engineering (ICRAIE) Date of Conference: 01-03 December 2022, Pages 224-229, IEEE Xplore DOI: 10.1109/ICRAIE56454.2022.10054280 | 02 March 2023 | 3 |
| 7 | Implementation of Environmental Parameters Monitoring and Alert System for Underground Mining Using Internet of Things with LoRa Technology | Sandi Kumar Reddy, **Anil S Naik,** and Mandela Govinda Raj | Techno-Societal 2016, International Conference on Advanced Technologies for Societal Applications<br>ICATSA 2022: Techno-societal 2022<br>Pages 69–76<br>DOI:10.1007/978-3-031-34644-6_8 | 23 September 2023 | 3 |
| 8 | An Enhanced IoT and LoRa-Based Communication System for Underground Mines | Sandi Kumar Reddy and **Anil S Naik** | International Conference on Signals, Machines, and Automation SIGMA 2022, Part of the Lecture Notes in Electrical Engineering book series (LNEE, volume 1023)<br>DOI:10.1007/978-981-99-0969-8_53 | 23 May 2023 | 3 |

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|---|---|---|---|---|---|
| 9 | Implementations of IoT Applications for Environmental and Safety Monitoring in Underground Mines | Sandi Kumar Reddy, **Anil S Naik,** and Mandela Govinda Raj | 4th International Conference on Advanced Technology in Exploration and Exploitation of Minerals, Jodhpur,<br>8-10th 2024 January. Mining Engineers Association of India, Rajasthan Chapter, Jodhpur, India | January 2024 | 3 |
| 10 | A Comprehensive Review on Role of Internet of Things in Wireless Environmental Monitoring System for Underground Mining | **Anil S Naik** and Sandi Kumar Reddy | Diamond Jubilee Conference on Challenges in Safety and Environmental Management in Mines (CSEMM - 2022), Department of Mining Engineering, NITK Rourkela, June 17-19, 2022 | June 2022 | 3 |
| 11 | **Details of Patent Filed:**<br>Patent Title: An IoT enabled Real Time Early Warning Hazard Monitoring System for Underground Mine Environmental Parameters | Sandi Kumar Reddy,<br>**Anil S Naik,**<br>M Aruna,<br>Mandela Govinda Raj | Date of publication: 14/06/2024<br>Application Number:202441042240 | June 2024 | 5 |

## NATIONAL INSTITUTE OF TECHNOLOGY KARNATAKA, SURATHKAL

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## List of Publications based on Ph.D. Work

* Category: 1: Journal paper, full paper reviewed
2: Journal paper, Abstract reviewed
3: Conference/Symposium paper, full paper reviewed
4: Conference/Symposium paper, abstract reviewed
5: others (including papers in Workshops, NITK Research Bulletins, Short notes etc.) (If the paper has been accepted for publication but yet to be published, the supporting documents must be attached.)

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# BIO DATA

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## Education

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| Master of Technology (M.Tech) | Information Technology | AMC Engineering College, Bangalore, VTU, Belgaum, Karnataka. | 2012 |
| Bachelor of Engineering (BE) | Electronics & Communication Engineering | Basaveshwar Engineering College, Bagalkot, VTU, Belgaum, Karnataka. | 2009 |

## Work Experience

- Assistant Professor, Department of Computer Science and Engineering (Cyber Security), National Forensic Sciences University (NFSU), Dharwad. (*An Institution of National Importance, Ministry of Home Affairs, Government of India*) (April 2024 to till date)
- Assistant Professor, Department of Information Technology, Walchand Institute of Technology, Solapur, Maharashtra, India. (From Jan-2012 to Sep 2021) Teaching Experience: (9 years 8 months)

## Professional Qualification

- UGC NET Qualified in Computer Science and Applications
- GATE Qualified in Computer Science and Information Technology

## Honours and Awards

- Professional Learning Community, e-Learning Center, Walchand Institute of Technology, Solapur
  Honorarium towards Appreciation for e-Content generation in the form of Videos Date:2020-03-04
- Use of ICT in Education for Online and Blended Learning - (Top 253 out of 4051 registered participants) by IIT Bombay and SAP India Pvt. Ltd through CSR grants, Date:2016-07-10
- Runner up in Content Guru event of Inspire Faculty Excellence Awards 2016, Infosys Campus Connect, Date:2016-07-01

## Membership of Professional Bodies

- ISC Indian Science Congress Association membership - Membership No: L34481

## Patent details

- Application Number:202441042240
- Patent Title: An IoT enabled Real Time Early Warning Hazard Monitoring System for Underground Mine Environmental Parameters

## Peer-Reviewed Journal Articles

1. Anil S Naik, Sandi Kumar Reddy, Mandela Govinda Raj. (2024). RTEPMS: Real Time Environmental Parameters Monitoring System using IoT based LoRa 868 MHz Wireless Communication Technology in Underground Mines. IEEE Access.

2. Anil S Naik, Sandi Kumar Reddy, Govinda Raj Mandela. (2023). A systematic review on implementation of Internet-of-Things-based system in underground mines to monitor environmental parameters. Journal of The Institution of Engineers (India): Series D, 1-17.
3. Sandi Kumar Reddy, Anil S Naik, Govinda Raj Mandela. (2023). Development of a Novel Real-Time Environmental Parameters Monitoring System Based on the Internet of Things with LoRa Modules in Underground Mines. Wireless Personal Communications, 133(3), 1517-1546.
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5. Anil S Naik. (2020). Text and Voice Based Emotion Monitoring System. Oriental Journal of Computer Science and Technology, 12(4), 194-200.
6. Anil S Naik, R Murugan. (2018). Security attacks and energy efficiency in wireless sensor networks: A survey. International Journal of Applied Engineering Research, 13(1), 107-112.
7. Nirgude Manisha, Anil S Naik. (2017). WhatsApp application: An effective tool for out-of-class activity. Journal of Engineering Education Transformations, 30, 1-5.
8. Anil S Naik, Prakash Pawar, Santosh Pawar. (2014). Fast Transmission to the Remote Co-Operative Group: A New Key Management VPN and Security Policy Enforcement., (IJCSIT) International Journal of Computer Science and Information Technologies, Vol. 5 (3), 4054-4056
9. Shivappa M Metagar, Praveenkumar D Hasalkar, Anil S Naik. (2014). Case study of data mining models and warehousing. International Journal of Innovative Research in Computer and Communication Engineering, 2(5), 4408-4412.
10. Anil S Naik. (2013). User Query Processing Using Distance Oracle for Road Networks. International Journal of Engineering Research & Technology (IJERT), (pp. 1-6). 2278-0181.

## Refereed Book Chapter & International Conference: Oral Presentations

1. Sandi Kumar Reddy, Anil S Naik, Govinda Raj Mandela. (2022, December). Wireless Monitoring of Environmental Parameters for Underground Mining using Internet of Things with LoRa Transceiver Module. In 2022 IEEE 7th International Conference on Recent Advances and Innovations in Engineering (ICRAIE) (Vol. 7, pp. 224-229). IEEE.
2. Sandi Kumar Reddy, Anil S. Naik (2022, August). An Enhanced IoT and LoRa-Based Communication System for Underground Mines. In International Conference on Signals, Machines, and Automation (pp. 513-521). Singapore: Springer Nature Singapore.
3. Sandi Kumar Reddy, Anil S Naik, Mandela Govinda Raj. (2022, December). Implementation of Environmental Parameters Monitoring and Alert System for Underground Mining Using Internet of Things with LoRa Technology. In Techno-Societal 2016, International Conference on Advanced Technologies for Societal Applications (pp. 69-76). Cham: Springer International Publishing.
4. Anil S. Naik, Pravin N. Kathavate, Shivappa M. Metagar. (2022). Nearpod: An Effective Interactive ICT Tool for Teaching and Learning Through Google Meet. In IOT with Smart Systems: Proceedings of ICTIS 2021, Volume 2 (pp. 269-276). Springer Singapore.
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## National Conference: Oral Presentations

1. Anil S Naik, Sandi Kumar Reddy. (2022). A Comprehensive Review on Role of Internet of Things in Wireless Environmental Monitoring System for Underground Mining, Diamond Jubilee Conference on Challenges in Safety and Environmental Management in Mines(CSEMM - 2022), National Institute of Technology Rourkela.

2. Sandi Kumar Reddy, Anil S Naik. (2022). Proceedings of National Conference on Recent Trends in Intelligent Control Communications and Computing Technologies in Mining (RTIC3TM -2022),University College of Engineering, Kakatiya University, Kothagudem.
3. Anil S Naik, Sandi Kumar Reddy. (2022). The Role of the Internet of Things in Mining Industry, 3rd SME(Society of Mining Engineers), National Institute of Technology Karnataka, Surathkal.

## Teaching and Training

- Computer Organization and Architecture (*Theory & Tutorial*)
- Microprocessor 8085, 8086 *(Theory & Lab)*
- Switching Theory and Logic Design *(Theory & Lab)*
- Software engineering (*Theory & Tutorial*)
- Software Testing and Quality Assurance (*Theory & Tutorial*)
- Web programming *(Theory & Lab)*
- Internet of Things (*Theory*)
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## Administrative Services

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**Declaration:**

I, Anil S Naik, hereby declare that all the above mentioned information about me is correct to the best of my knowledge.

Anil S Naik