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Development of a wireless communication system for tracking environmental conditions from different locations of subterranean mines to the surface utilizing IoT based ZigBee modules

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Abstract

The mining sector is recognized for its precious minerals, which are extracted from beneath the earth's surface. Numerous industries have gained advantages by implementing automation, leading to improved management of operations, increased safety, continuous monitoring, and greater cost-efficiency. Given the challenges faced in underground mining, a dependable wireless communication and monitoring system is essential to improve safety and mitigate significant hazards. The conditions in underground mines are influenced by various environmental factors such as highly toxic gases, flammable and inflammable gases, and small dust particles. Fluctuations in the levels of hazardous gases pose a significant concern, potentially resulting in gas explosions and harming the mine's infrastructure. At present, most underground mines use traditional multi-gas detectors to manually check for mine gases at regular intervals or once daily. This paper suggests a real-time safety system for industrial environments in underground mines and it outlines the approach to implement IoT in subterranean mining environments to assess environmental variables, the configuration of sensor installation in underground locations, gas threshold limits, and disasters in underground mines resulting from gas explosions. The establishment of wireless message communication between two ZigBee modules is explained in detail, and radio range tests are investigated. Wireless connection can also be set up to keep an eye on the environmental conditions of subterranean mining levels from the surface. Additionally, wireless communication was set up to keep an eye on the environmental conditions of a underground mine's straight and curved tunnels.The experimental outcome suggests that ZigBee modules may successfully communicate wirelessly over straight tunnels between 100 and 120 meters apart, with a decrease in signal intensity and loss of data packets in underground mines' curving tubes. Furthermore, it demonstrate that the ZigBee-based system can be created is appropriate for assessing environmental factors in both underground and open surface mines.

Keywords: ZigBee; Wireless sensor network; Metal oxide semiconductor gas sensors; Environmental parameters; Monitoring system; Underground mine; IoT

1. Introduction

The numerous toxic gases, flammable and inflammable gases, and dust, are some of the reasons because of which underground mine operations have always been a dangerous and hazardous environment. The techniques used to extract various minerals, ventilation issues, roof collapses, and the usage of large machinery are the main causes of dangers in underground mines. There are more risks and safety concerns for mine workers in deeper underground mines. In underground coal and metal mines, safety concerns are crucial and extremely critical. All mining enterprises should be very concerned about the safety of their employees. All types of mines increase worker safety awareness by

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implementing a number of standard safety procedures, education, and training programs.Although mine gas properties allow it to originate from a variety of sources in underground mines, portable multi-gas detectors are currently utilised to test environmental parameters in underground mines and the data is recorded on a shift or daily basis. An environment that is safe and comfortable for a mine worker's body shouldn't interfere with his ability to work efficiently. It is only feasible if the underground mine's air is identical to that on the surface (normal breathing air contains 78% nitrogen, 21% oxygen, and 1% additional gases) [1]. The health of miners is at risk due to the poisonous and toxic gases present in underground mines.Carbon monoxide (CO), methane (CH4), carbon dioxide (CO2), nitrogen dioxide (NO2), and hydrogen sulphide (H2S) are the gases found in underground mines. These gases have different effects on human health and are produced in underground mines for a variety of causes. The incomplete burning of carbon compounds, fires, blasting, and explosions all produce Carbon monoxide , a poisonous gas. The human body's blood's capacity to carry oxygen is diminished when CO gas is inhaled. Internal combustion engines, blasts, welding, and odours all release nitrogen dioxide , a harmful gas. Lung infections are brought on by this gas's effects on the throat. The breakdown of organic compounds and acid water on sulphides results in the production of H2S, a highly poisonous gas, from strata [2].Coal mines are frequently the source of the flammable gas CH4. Strata and the breakdown of organic materials produce it. In an underground mine, the buildup of CH4 gas causes suffocation since there is not enough oxygen present. Explosions in the majority of mines are also caused by it. In addition to being found in the air we breathe, CO2 gas is created by burning fossil fuels, carbon oxidation, and explosion. Additionally, the human body's blood's capacity to carry oxygen is diminished by this gas [2- 4].The Directorate General of Mines Safety (DGMS) is an Indian regulatory agency that has promoted the establishment of an environmental monitoring system for underground coal mines, especially those with gassy and fiery coal seams. The circulars issued by DGMS specify the safety standards for diesel-powered equipment used in both underground coal and metal mines. Equipment such as trucks, high-capacity loaders/LHDs, drills, and other ancillary machinery powered by diesel, which are involved in underground operations, pose significant health and safety hazards, including diesel fumes, noise, dust, fire, lubricants, the potential for gas explosions, and vehicle accidents, among others. Additionally, the DGMS circular provided details on the necessary ventilation guidelines and the acceptable limits for dangerous and flammable gases, as outlined in Table 1. CO, CO2, H2S, NO, NO2, and O2 are among the gases whose threshold limit values are 0.005%, 0.5%, 0.0005%, 0.0025%, 0.0005%, and 19%, respectively. Less than 1.25% CH4 in the general body air and less than 0.75% methane in the return airways are the safe limits for humans. When driving large vehicles powered by diesel, the CH4 gas concentration should not be higher than 0.75%, and the engine should be turned off when it reaches this threshold [5].

Table 1 Maximum Allowable Concentration of gases as per DGMS circular

Sr.No.	Gas	Maximum Allowable Concentration	
		Percentage by Volume	**PPM**
1.	Carbon Dioxide	0.5	5000
2.	Carbon Monoxide	0.005	50
3.	Nitric Oxide (NO)	0.0025	25
4.	Nitrogen Dioxide (NO2)	0.0005	5
5.	Sulphur dioxide (SO2)	0.0005	5
6.	Hydrogen sulphide (H2S)	0.0005	5
7.	Aldehydes	0.001	10

The main means of communication between miners on the surface and those working underground in underground mines is wired telephone. A number of communication technologies are being tested in phase 1 from 2022 to 2024, with implementation in phase 2 from 2024 to 2026, according to a technology roadmap for the coal industry given by the Ministry of Coal, Government of India. Leaky feeder systems, wireless communication systems, node-based systems, and through-the-earth (TTE) mine communication systems are some examples of these technologies. TTE mine communication is a radio signalling technique that relays lower-frequency signals in underground mines using mesh network configurations, repeaters, or antennas. In a leaky feeder system, a base station or transceiver at the surface generates radio signals using a leaky feeder cable that "leaks" radio signals to produce a continuous coverage area along the tunnels, the technology provides a signal coverage throughout its length. Discrete antennas are linked to tiny transceivers known as nodes in node-based systems. The miner's radio range is detected by a microprocessor-based node, which then automatically establishes a network connection. Wi-Fi mesh network infrastructure, which includes wireless access points and switches in underground mines, is used by wireless communication systems.Wearable wrist devices with Wi-Fi link to the network, transmit signals, including a miner's location, and limit miners' access to the surface control room through tunnels. In order to improve safety and productivity in deep mines, flame safety lamps and multi-gas detectors are used to monitor environmental parameters and identify flammable gases, oxygen, and poisonous gases [6].

The gases in the mine have varying effects on people and, if they build up to a particular threshold, can explode. Researchers from all over the world have documented underground mine disasters brought on by gas explosions. Nine underground mine accidents were found in an analysis of gas explosion incidents in Indian coal mines between 1989 and 1998 [7].10,056 mine workers lost their lives in 433 gas mishaps in Chinese coal mines between 1950 and 2006, according to a statistical examination of gas explosions in these mines [8]. Illegal blasting at mines and inadequate ventilation systems caused gas explosions and outbursts in Chinese coal mines. Between 2006 and 2010, 943 mine worker fatalities were reported [9]. In a recent incident, the toxic carbon monoxide gas produced by burning a conveyor belt claimed the lives of two mine workers [10]. 227 worker fatalities were reported between 2001 and 2007 as a result of methane gas explosions in coal mines, which also caused 274 worker injuries [11].An analysis of 20 coal mine gas explosions from 2006 to 2016 shows that 741 mine worker fatalities occurred overall [12]. An analysis of 1679 gas mishaps in a Chinese coal mine from 2000-2015 shows that 10,541 mine workers lost their lives there [13]. 1443 mine workers were killed in 63 large gas explosions between 2007 and 2016, according to a statistical review of coal mine gas explosions [14]. 12,807 mine worker fatalities were reported in 2984 gas accidents that occurred in coal mines between 2003 and 2018 [15]. Due to asphyxiation, explosions, gas blasts, and leaks, there were 287 deaths among miners, along with 34 additional injuries occurring in the underground mine[16]. The Environmental Information System (ENVIS) reported statistics on mining disasters, indicating that a total of 284 mine worker deaths were recorded from gas accidents in underground mines in India. On February 16, 2022, two mine workers lost their lives due to asphyxiation at a coal mine in Meghalaya, India[17]. A gas explosion took place on October 14, 2022 in the Amasra coal mine located in Bartın Province, Turkey, resulting in the death of 42 people and the injury of 27 individuals. In a similar vein, on November 25, 2021, more than 40 miners perished due to suffocation from smoke in a ventilation shaft during the Listvyazhnaya mine disaster in Kemerovo Oblast, Russia. Another tragic event took place on December 1, 2020, in southwestern China, where 18 miners lost their lives due to a carbon monoxide leak at a coal mine. In Colombia, an accumulation of gas resulted in an explosion, fire, and subsequent tunnel collapse at the La Mestiza coal mine on May 30, 2022, claiming the lives of nine miners [18]. Every year, miners die in various mining accidents, especially in underground mines compared to open-pit operations.

It is essential for underground mines to improve safety measures by implementing wireless communication and monitoring systems to avert significant hazards [19]. To boost safety and efficiency in underground mines, wireless networks have been employed to lower operational expenses and to create dependable wireless communication [20,21]. A wireless sensor network (WSN) consists of sensor nodes that observe physical or environmental parameters, and in a wireless setting, the sensor data is transmitted via other sensor nodes to a central point known as a base station or gateway or a hub. The sensor nodes within the network utilize Industrial, Scientific, and Medical (ISM) unlicensed radio frequency bands for their communication. The use of unlicensed frequency bands facilitates deployment in various locations. Wireless communication technologies like Bluetooth, Wi-Fi, and ZigBee operate within a 2.4 GHz frequency band, while other wireless technologies such as SigFox and LoRa also use unlicensed frequency bands [22]. Bluetooth and ultra-wide band wireless technologies support very short ranges of communication [23]. Wi-Fi technology offers a reasonable communication range and higher speed but requires infrastructure for access points and cabling. ZigBee technology provides more advantages than other wireless technologies for establishing communication and monitoring systems in underground mines [24,25].

Currently, several companies such as, Rajant Corporation [26], Mine Site Technologies [27], CISCO [28], Carroll Technologies Group [29], and PBE Group [30] offer technological solutions and services for environmental monitoring systems in underground mines. The costs and reliability of each solution vary based on multiple factors, including the technology used, the specific type and complexity of the mine, and the client's unique requirements. The document outlines the creation of a wireless gas monitoring and communication system utilizing IoT and ZigBee technology, detailing the process of implementation, analysis of results, and discussion regarding the implications and limitations of this research, concluding with insights on future directions and work.

2. Proposed Real-Time Industrial Smart Safety System in Underground Mines

The proposed system is designed for deployment in an underground mine in India, where mining operations have reached a depth of approximately 832 meters below the surface. A general overview of an underground mine in India and the design of level 26 illustrates the positions of the ZigBee gateway/sensor controller, sensors, repeaters, and control room located on the surface. The implementation of an IoT-enabled ZigBee gateway smart safety environmental monitoring system in underground mines can improve safety measures and enhance operational efficiency in mining activities. A conventional industrial monitoring system is utilized to observe environmental parameters in the underground mine using a hybrid strategy. A variety of sensors, including those for CO2, CO, O2, H2S, CH4, as well as temperature and humidity sensors, can be installed at the mining site to evaluate the ambient conditions. The data collected can be transmitted to an IoT server through either a ZigBee gateway or a wireless communication method.

The proposed configuration can be divided into 3 components:

- Surface control room
- Sensor controller/IoT-enabled ZigBee gateway
- Sensors with their associated units

The surface control room manages the environmental data collected from various sensors via the ZigBee gateway. The programmable IoT-enabled ZigBee gateway/sensor controller acts as a remote station underground, facilitating real-time monitoring of environmental conditions and sending data to the surface control room via an Ethernet cable and repeater device. Industrial sensors monitor environmental factors and transmit the information to the control room in real time through the sensor controller or ZigBee gateway, enabling immediate data display or analysis to prevent dangerous situations at the underground site. The smart safety system may also include an alert mechanism that quickly notifies miners and managers of any hazardous or emergency circumstances. A ZigBee gateway can be configured to take required actions when the monitored parameter values exceed their preset limits. The environmental data stored on a cloud platform can be accessed by the supervisor or relevant personnel from the mining office for analysis to reduce risks. This strategy can greatly improve operational efficiency and productivity in mining operations, reduce downtime, and ensure compliance with safety standards. Additionally, the system can be enhanced by providing guidance and assistance to miners during emergencies, such as recommending the safest evacuation paths. Implementing an IoT-enabled smart safety monitoring system in underground mines can significantly strengthen safety protocols, increase productivity, and maintain compliance with safety regulations.

2.1. The Architecture of Underground Mine IoT (UMIoT)

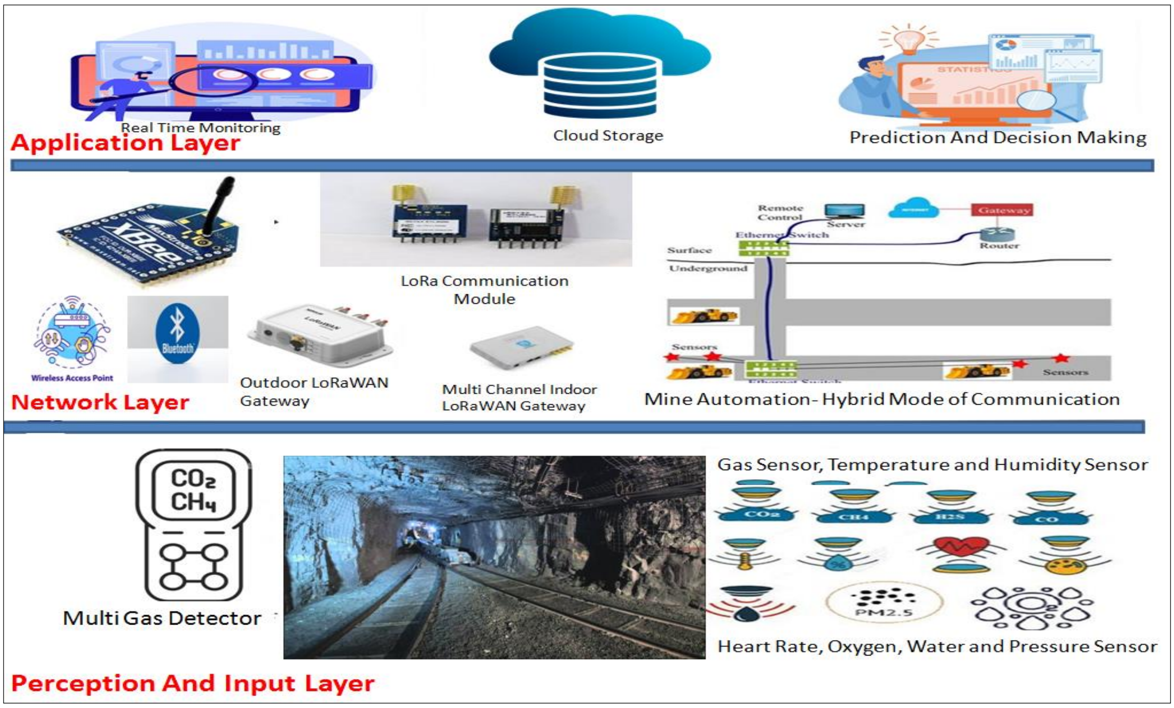

Figure 1 Architecture of UMIoT (Underground Mine IoT) System

The UMIoT framework details how environmental data is collected and sent from the underground mine to the surface.This framework consists of three layers: perception and input, network, and application, as depicted in Fig. 1[31]. This three-layer model acts as a guideline for creating and developing standardized industrial IoT systems for underground mining. The perception and input layer is tasked with collecting data from various sensors and sending it to the network layer. The network layer subsequently transmits the received sensor data to the application layer through a communication medium that can be either wireless, wired, or both. The application layer serves as the interface between users and applications. Data analysis from underground mining sites and forecasting of environmental parameters are conducted locally at the surface.

Sensors used in underground mines are divided into two categories: those that gauge environmental physical quantities and convert them into electrical signals for further processing to be sent to the upper layer, and those that connect with a microcontroller unit for data processing. A typical illustration of sensor placements in the walls of underground mine tunnels, along with some sensors attached to mine workers and equipment, is shown in Fig. 2[31]. To monitor environmental factors in underground mines, sensors for measuring gas, dust, temperature, humidity, health, position, and proximity detection are installed to ensure worker safety at the site. Various industries utilize different methods for measuring these parameters in underground mining settings, including multi-gas detectors, hybrid communication approaches (both wired and wireless), and fully wireless communication.

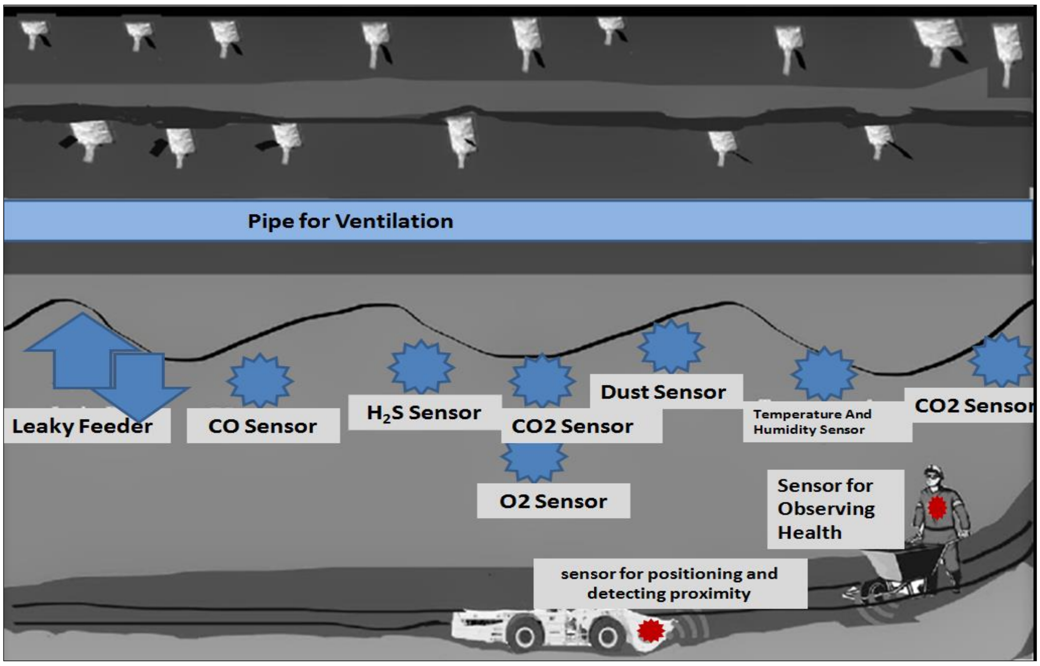

Figure 2 Common perspective of the setup of sensors within an underground mine passage

- Handheld portable multi-gas detectors: These are instruments employed by mine supervisors to monitor environmental parameters once per shift. It is expensive to equip every mine worker with these devices, and they do not perform any analysis on the collected data [32].
- Hybrid communication: In advanced automated mines, there exists a real-time wireless monitoring system that collects data on environmental parameters from underground mines. These systems employ both wired and wireless communication methods, relying on complete cable installations or portable devices used on-site. The constantly changing working conditions underground can result in cable damage, higher fault rates, and maintenance difficulties, among other issues [33, 34].
- Wireless communication technology: Technologies like Wi-Fi, ZigBee, or LoRa-based Wireless Sensor Networks (WSNs), along with IoT-enabled Low-power Wide Area Network (LoRaWAN) real-time systems, are used to monitor environmental parameters in underground mines, improving the safety, the efficiency, and the productivity [17–39].

To continually evaluate environmental factors, a reliable and cost-effective real-time monitoring system is required in underground mines. This need arises from the fact that underground mining activities pose greater risks to the health and safety of workers, particularly since these mines often use diesel-powered machinery and extend to greater depths. Ensuring worker safety in mining is of utmost importance, as exposure to harmful gases, dust, carbon dioxide, and nitrogen can result in chronic health issues. Furthermore, interactions with diesel-operated vehicles increase the risk of cancer and cardiopulmonary diseases [40]. To improve safety protocols, it is vital to monitor toxic gas levels and keep them within safe limits in real-time, which requires low-power wireless communication technologies [41]. Considering the unpredictable layout of underground mines, communication can be challenging due to their ever-changing nature, curves, and intersections. An effective communication system is essential for disseminating information about environmental conditions, tracking worker locations, and indicating safe and hazardous areas. The implementation of automation can enhance worker health and safety by establishing a dependable and resilient communication infrastructure.

3. Creation of a Wireless Gas Monitoring and Communication System based on ZigBee technology

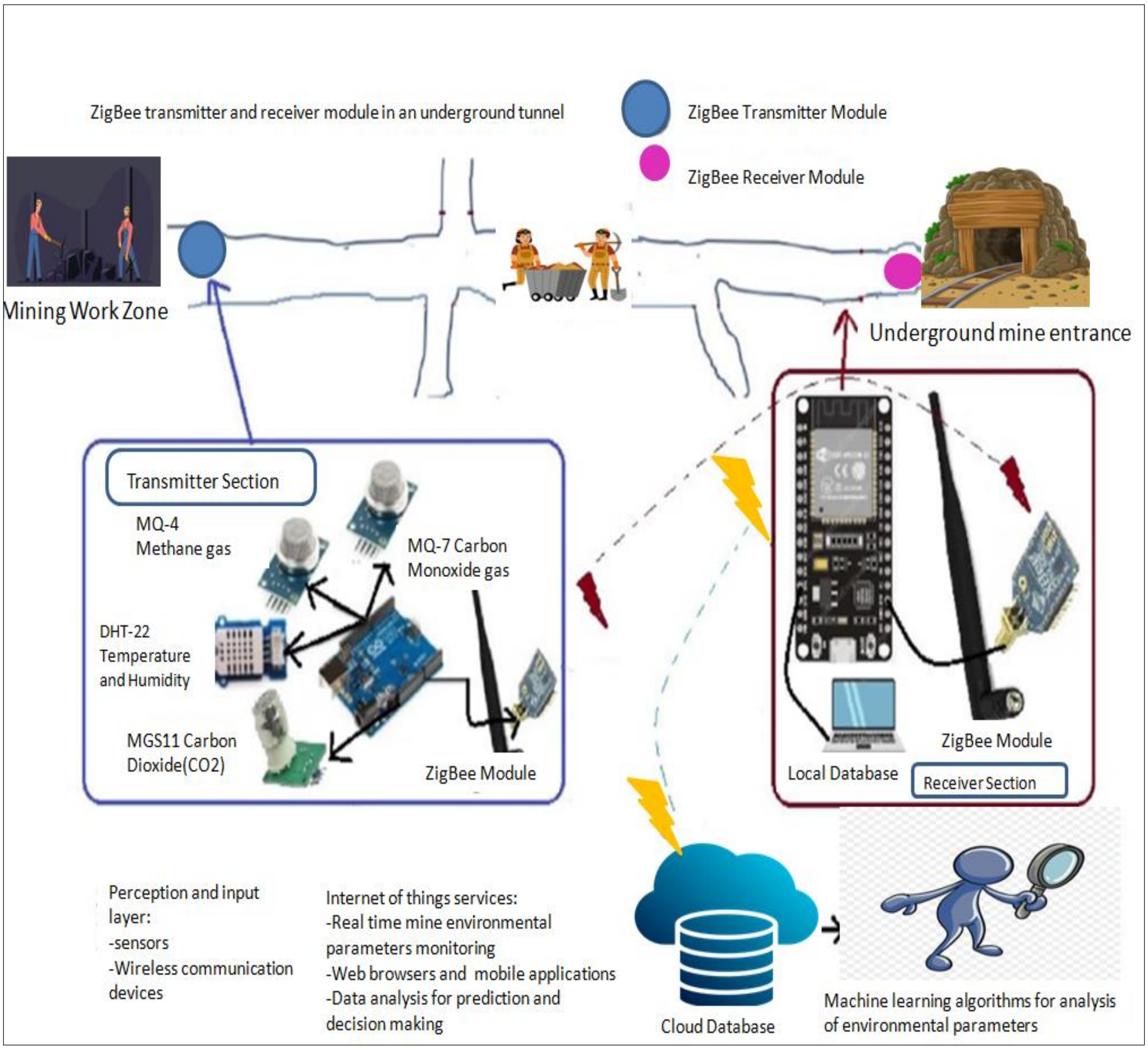

Figure 3 The system architecture features an Arduino and ESP32 serving as a development platform for monitoring environmental factors in underground mines, utilizing machine learning (ML) for predicting environmental parameters

Wireless communication plays a vital role in underground mining for safety reasons, as it enables miners to maintain contact with one another and with those on the surface, which is essential during emergencies. The implementation of wireless communication systems at mine locations enhances coordination among miners and surface personnel, boosts efficiency, and minimizes accident risks [2]. It also delivers real-time information, including environmental data and production updates, which aids in enhancing decision-making and overall management of the mine. Installing wired communication systems in underground mines is costly and challenging. On the other hand, wireless systems are generally more economical and simpler to set up, resulting in cost savings for mines and enhancing their financial performance. The Internet of Things (IoT) with ZigBee is particularly important in underground mines, as it contributes to improved safety and efficiency in mining activities [42-44]. ZigBee is a low-power, low-data rate wireless communication technology that is well-suited for underground mine environments, where power sources and connectivity may be limited. The system incorporates various sensors into development boards within an underground mine, and ZigBee facilitates the real-time monitoring of environmental factors such as gas levels, temperature, and humidity to avert accidents or significant dangers and enhance working conditions for miners [44]. Furthermore, ZigBee-based systems boost the efficiency of mining operations by enabling remote monitoring and management of equipment, which can decrease downtime and maintenance expenses while increasing the overall productivity of the mine. In summary, utilizing IoT alongside ZigBee in underground mining offers numerous advantages that can enhance safety, efficiency, and productivity.The fundamental structure of the suggested Internet of Things (IoT) system, using ZigBee technology for governing environmental conditions in underground mines, is illustrated in Fig. 3. The primary aim of the system involves collecting data from multiple sources, transmitting this data via wireless communication, and processing the information with a machine learning algorithm for environmental parameter analysis and forecasting [46].

The sensing units consist of sensors interfaced with Arduino UNO development boards at the transmitter end and ESP32 boards at the receiver end. The sensor node gathers environmental data at the mine location and relays it to the base station or local database using ZigBee communication modules. The Wi-Fi-enabled ESP32 board sends data to a cloud database, allowing for the storage and monitoring of real-time information from anywhere at any time. Details regarding each component of the proposed IoT configuration will be elaborated on in the subsequent sections. Various factors like signal strength degradation, multi-path fading, noise, and the architecture of underground mine tunnels influence the constraints of the suggested IoT-based wireless communication system. The layout of tunnels within underground mines, including cross-cuts and the application of roof support systems, leads to increased attenuation of radio frequencies, thereby enhancing path loss. Furthermore, the distance between the sender and receiver impacts signal strength, as reflective mechanisms underground contribute to greater path loss. Additionally, the existence of mining equipment, vehicles, and other reflective surfaces causes variations and fading in the signal strength. The noise arising from mining operations and vehicles within the tunnels also affects signal quality, diminishing the communication range. Choosing the appropriate operating frequency is challenging for signal transmission in underground mine tunnels due to several elements, including the inclination of side walls, curves, cross-cuts, and the ever-evolving structure of the mine. The communication system must be engineered to endure the harsh conditions found in underground mines, such as elevated temperatures, high humidity, gas concentrations, and the risk of explosions and dust. Moreover, the dynamic nature of mineral extraction processes in underground mines complicates the communication system's ability to ensure complete mine coverage and effectively monitor environmental parameters as the area of signal coverage expands.

The architecture of the created system is composed of ZigBee transceiver modules, an Arduino microcontroller board, and different sensors designed to measure environmental parameters, as illustrated in Fig. 4.

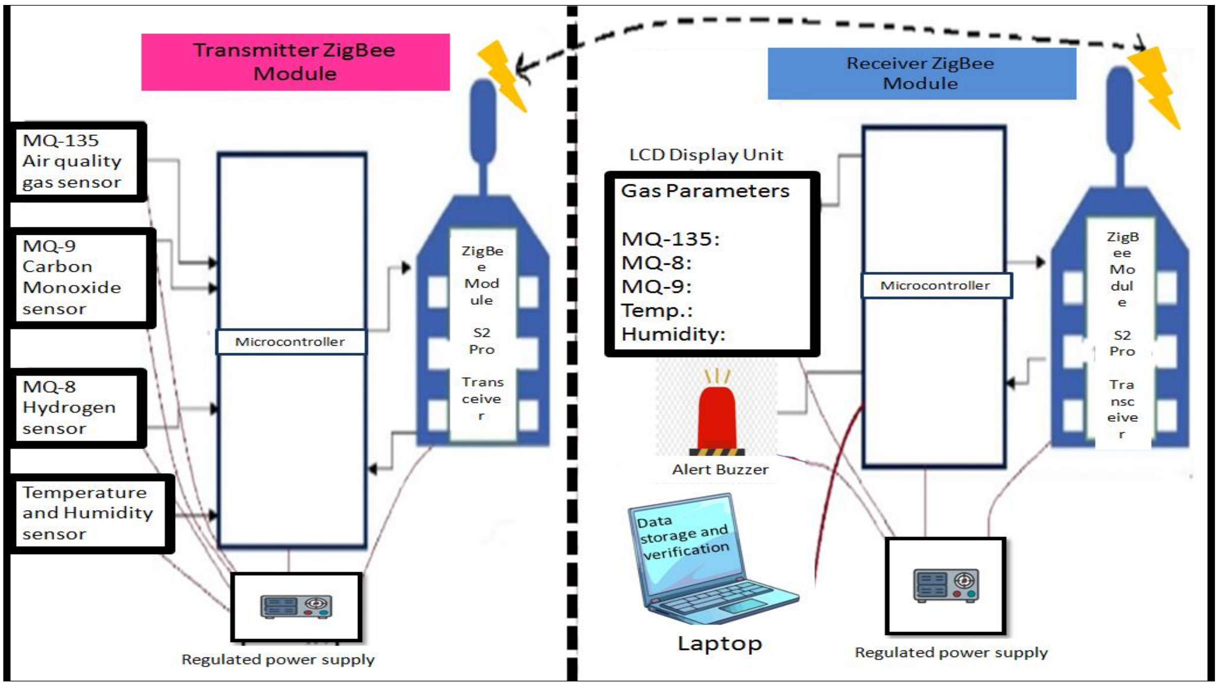

Figure 4 Framework of the developed ZigBee-based system

The schematic diagram illustrating the transmitter and receiver ZigBee modules is presented in Fig. 5a and 5b. The transmitter section of the ZigBee includes a microcontroller that is integrated with metal oxide semiconductor gas sensors like the MQ-8, MQ-9, MQ-135, and DHT-11. On the other hand, the receiver section comprises a microcontroller, a ZigBee module, a display unit, and a buzzer to provide an early warning when the gas concentration surpasses the threshold limit value [47].

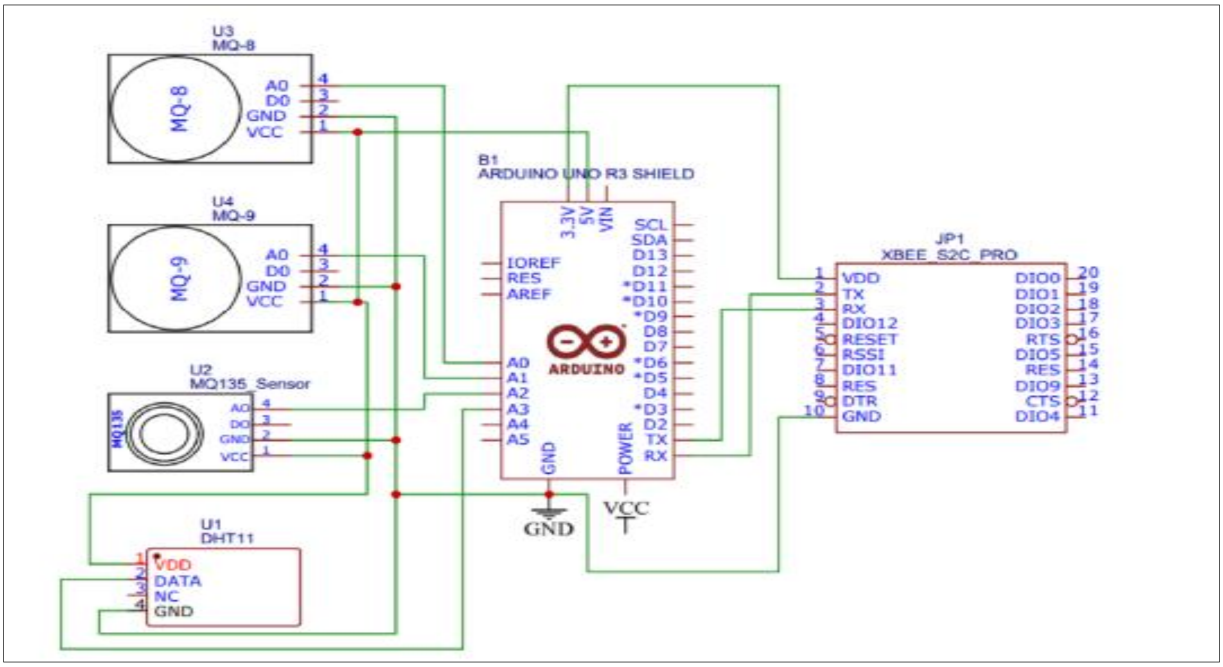

Figure 5a Diagrammatic illustration of the transmitter segment featuring a ZigBee module**.**

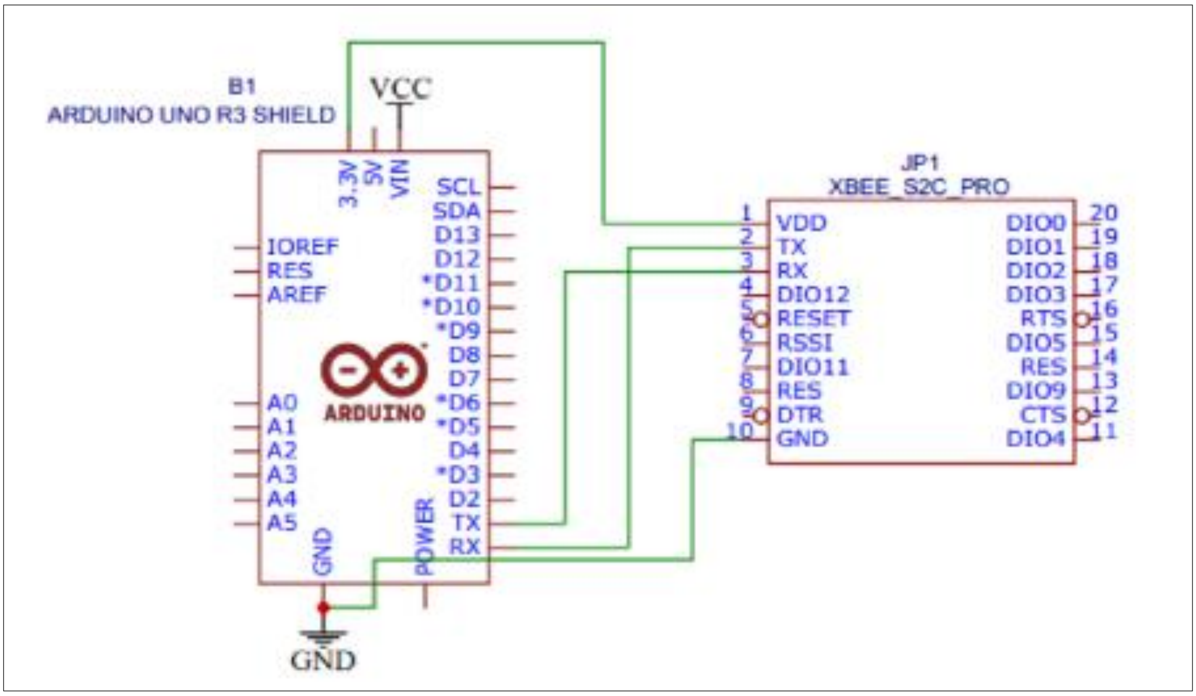

Figure 5b Diagrammatic illustration of the receiver segment featuring a ZigBee module

3.1. Establishment of Wireless Communication among ZigBee modules

To enable wireless communication between ZigBee radio modules, the initial step involves setting up the ZigBee modules with the XCTU software application and conducting text communication between the transmitter and receiver modules to confirm the wireless connection.

3.1.1. Setting up a ZigBee device with the XCTU software application.

The ZigBee radio module which can be utilized for experimentation is of the XBee Pro S2C type. To begin using ZigBee for the first time, it is necessary to update the firmware by connecting the ZigBee module to a laptop and employing the XCTU software application to configure and setup the ZigBee device for reliable wireless communication [48]. The default ZigBee device selected is a "ZIGBEE TH Reg function," and updating the firmware in XCTU is required. To facilitate communication between two ZigBee modules, one should be set to router mode while the other is configured in coordinator mode, ensuring that both ZigBee devices share the same PAN ID, such as "1234," and then update the relevant field.

3.1.2. Configuration of ZigBee Coordinator .

To set up ZigBee as a coordinator, perform the following steps.

- Assign the "PAN ID" as "1234" and save the changes.
- Leave the "JV Channel Verification" option unchanged for the coordinator and stick with the default setting of "Disabled [0]".
- Activate the "CE Coordinator Enable" setting by selecting "Enabled [1]", allowing the ZigBee to function as a coordinator, and update the field.
- Change the value in the "NI Node Identifier" field to "Coordinator" as illustrated in Fig. 5.
- Choose the "AP API Enable" field and set it to "API enabled [1]", then save the changes.

3.1.3. Confguration of ZigBee router

To set up ZigBee as a coordinator, carry out the following steps.

- Configure the "ID PAN ID" to "1234" and refresh the field.
- Leave the "JV Channel Verification" unchanged for the coordinator, sticking with the default setting of "Disabled [0]."
- Activate the "Coordinator Enable" option by selecting "Enabled [1]," allowing ZigBee to function as a coordinator and then saving the changes.
- Modify the "NI Node Identifier" field to "Coordinator".
- Choose the "API Enable" field and set it to "API enabled [1]," then update the field.

Both ZigBee modules have been configured for coordinator and router modes. Once the module configurations are successfully completed, select the coordinator ZigBee, then click the "Switch to console working mode" icon located in the upper right corner. The console mode enables message exchange between the two ZigBee modules, ensuring they can communicate wirelessly. To transmit a message from the ZigBee router to the ZigBee coordinator in both directions, follow the same procedure and configure the router with the MAC address of the coordinator. Now we can execute the Designed ZigBee-Based Wireless Communication System in Subterranean Mining Operations.

4. Implications and Limitations of the Research

The prototype ZigBee-based system employs XBee Pro S2C radio frequency wireless communication modules to ensure dependable communication.This system boasts several benefits, including cost-effectiveness, low power consumption, compact module and sensor size, and the capability to form a mesh network.It is designed to fit within a handheld enclosure, making it easy to deploy in a mining environment for transmitting data from underground levels to the surface by positioning signal boosters at regular intervals. The exchange of information between ZigBee modules is more rapid, allowing for quicker alerts to mine workers if environmental conditions surpass the threshold limits during an emergency.The underground system has been equipped with gas and temperature-humidity sensors to monitor substances like carbon monoxide, hydrogen, and air quality.Any increase in these gases beyond the threshold limits can be promptly detected by the proposed system in real time.Such hazardous conditions within the underground workings will trigger immediate alerts to mine personnel, allowing for effective preventive measures to reduce risks and enhance safety in underground mines.However, this system does have limitations, such as a decrease in radio signal strength in non-line of sight situations, potential sensor damage requiring preheating before site deployment, and communicationfailures in extreme weather conditions with poor temperature and humidity.For optimal functioning, the system needs a rechargeable external power supply for both the transmitter and receiver units.An Arduino development board is utilized for both the transmitter and receiver of the ZigBee-based system, which lacks Wi-Fi capability, thus limiting its ability to send data to a cloud server.Nevertheless, the transmitter portion of the system can function as a portable multi-gas detector for individual mine workers.It also has the potential to track the location of mine workers and detect additional toxic gases by integrating more gas sensors into the existing setup.Furthermore, an ultrasonic sensor can be added to measure the distance to nearby objects.

5. Conclusions and Future Work

The wireless monitoring system based on ZigBee technology has been created to assess environmental conditions in both open and underground mining sites. This system is portable, dependable, and sturdy, making it suitable for tracking gas concentration and additional metrics, including temperature and humidity, within underground mines. It employs open-source technologies alongside affordable sensors and wireless communication modules to improve safety, streamline operational management, and boost productivity by mitigating significant risks. In this research, wireless communication was successfully established between two ZigBee modules, demonstrating their effectiveness for wireless monitoring and communication within underground mining environments. Using ZigBee reliable communication can be achieved from underground mine levels to the surface at distances of up to 60 m, with direct tunnel communication reaching between 100 m to 120 m, and 60 m to 70 m in curvy tunnels, albeit with some data packet loss. The system developed is advantageous for real-time monitoring of environmental parameters, providing quicker alerts to mine workers when levels exceed safety thresholds. The ZigBee-based system can be further improved by integrating the Internet of Things (IoT) at the receiving end of the ZigBee transceiver module, which would facilitate data collection from the transmitter and upload it to a cloud platform like ThingSpeak or BlynkIoT situated on the surface. The data gathered from underground can be analyzed in real time by mine supervisors in the office, allowing for immediate action to address any detected gases and prevent accidents or hazardous situations within the mine. This innovative product serves to enhance safety in underground mining operations on a real-time basis and is a cost-efficient solution.

Compliance with ethical standards

Disclosure of conflict of interest

There is no conflict of interest.

References

[1] G. B. Misra, Mine environment and ventilation. Oxford University Press (1986)

[2] O. Isaac, Towards safety from toxic gases in underground mines using wireless sensor networks and ambient intelligence. Int. J. Distrib. Sensor Netw. 9(2), 159273 (2013). https://doi.org/10. 1155/2013/159273

[3] B. Beatriz, A. Rafael Colombo, P. Carolina Pereira, P. Marçal Jose Rodrigues, G. Cleber Jose Baldoni, CH4 and CO2 monitoring in the air of underground coal mines in southern Brazil and GHG emission estimation. REM Int. Eng. J. 72, 635–642 (2019)

[4] F. Zhao, X. Fanyu, Health risks of occupational exposure to toxic chemicals in coal mine workplaces based on risk assessment mathematical model based on deep learning. Environ. Technol. Innov. 22(101500), 1–11 (2021)

[5] Directorate General of Mines Safety, Ministry of Labour and Employment. DGMS Circulars - 2017,2018.https://bit.ly/3z7ya ZK https://bit.ly/3lF1SSD Accessed 8 December 2022

[6] Technology Road Map for the Coal Sector (Volume- I, Part-A), Ministry of Coal, Government of India. https://coal.nic.in/sites/ default/fles/2022-05/09-05-2022vp1.pdf Accessed on 22 Mar 2023

[7] A. Mandal, D. Sengupta, The analysis of fatal accidents in Indian coal mines. Calcutta Statist. Assoc. Bull. 50(1–2), 95–120 (2000). https://doi.org/10.1177/0008068320000109

[8] N. Chen Na, Y. Mao, Specifc statistics and control method study on unsafe behavior in Chinese coal mines. Procedia Eng. 26, 2222–2229 (2011). https://doi.org/10.1016/j.proeng.2011.11.2428

[9] W. Lei, C. Yuan-Ping, L. Hong-Yong, An analysis of fatal gas accidents in Chinese coal mines. Saf. Sci. 62, 107–113 (2014). https://doi.org/10.1016/j.ssci.2013.08.010

[10] Y. Liming, Z. Lihong, S. Alex, Modeling carbon monoxide spread in underground mine fres. Appl. Thermal Eng. 100, 1319–1326 (2016)

[11] M.V. Kurlenya, V.A. Skritsky, Methane explosions and causes of their origin in highly productive sections of coal mines. J. Min. Sci. 53(5), 861–867 (2017). https://doi.org/10.1134/S106273911 7052886

[12] S. Shulei, J. Bingyou, M. Xiangrui, Y. Li, Fuzzy fault tree analysis for gas explosion of coal mining and heading faces in underground coal mines. Adv. Mech. Eng. 10(8), 1–9 (2018). https://doi.org/ 10.1177/1687814018792318

[13] W. Xiao, X. Jianfei, L. Xuejiao, Establishing a georeferencedspatio-temporal database for Chinese coal mining accidents between 2000 and 2015. Geomat. Nat. Hazards Risk (2018). https://doi. org/10.1080/19475705.2018.1521476

[14] F. Gui, Z. Ziqi, H. Chuanbo, W. Qiang, The accident path of coal mine gas explosion based on 24Model: a case study of the ruizhiyuan gas explosion accident. Processes 7(2)(73), 1–18 (2019)

[15] K. Wei, W. Kai, Impact of gas control policy on the gas accidents in coal mine. Processes 8(11)(1405), 1–20 (2020)

[16] ENVIS Centre on Environmental Problems of Mining, Hosted by Indian Institute of Technology (ISM), Dhanbad, Jharkhand, Sponsored by Ministry of Environment, Forest & Climate Change, Govt of India. http://ismenvis.nic.in/Database/Mining_Accidents_ in_India_24483.aspx. Accessed on 8 December 2022

[17] S. K. Reddy, A.S. Naik, M. Govinda Raj, Wireless Monitoring of Environmental Parameters for Underground Mining using Internet of Things with LoRa Transceiver Module. IEEE 7th International Conference on Recent Advances and Innovations in Engineering (ICRAIE), 224–229, (2022) https://ieeexplore.ieee.org/ abstract/document/10054280

[18] Mining accident. https://en.wikipedia.org/wiki/Mining_accident Accessed on 23 Mar 2023

[19] S. Sadeghi, N. Soltanmohammadlou, F. Nasirzadeh, Applications of wireless sensor networks to improve occupational safety and health in underground mines. J. Safety Res. 83, 8–25 (2022). https://doi.org/10.1016/j.jsr.2022.07.016

[20] M. Mohammad Ali, K. Youhei, S. Mostafa, C. Emmanuel Knox, J. Hyongdoo, An investigation of underground monitoring and communication system based on radio waves attenuation using ZigBee. Tunnell. Undergr. Sp. Technol. 43, 362–369 (2014)

[21] Y. Zhang, W. Yang, H. Dongsheng Han, K. Young, An integrated environment monitoring system for underground coal mines— wireless sensor network subsystem with multi-parameter monitoring. Sensors 14(7), 13149–13170 (2014)

[22] Q. Cheng Qiang, J. Sun, Z. Zhang, F. Zhang, ZigBee Based Intelligent Helmet For Coal Miners. 2009 WRI World Congress on Computer Science and Information Engineering, 433–435, (2009). https://ieeexplore.ieee.org/document/5170878

[23] M. Paavola, P. Seppala, Wireless Networks in Underground Mines. In Industrial Wireless Sensor Networks, Woodhead Publishing, (2016), pp. 107–123, https://www.sciencedirect.com/science/artic le/pii/B9781782422303000064

[24] J. Coert, M. Reza, Design of a monitoring and safety system for underground mines using wireless sensor networks. Int. J. Ad Hoc Ubiquitous Comput. 32(1), 14–28 (2019)

[25] A. Moridi Mohammad, Y. Kawamura, M. Sharifzadeh, K. Chanda Emmanuel, M. Wagner, H. Jang, H. Okawa, Development of wireless sensor networks for underground communication and monitoring systems (the cases of underground mine environments). Tunnell. Undergr. Sp. Technol. 73, 127–138 (2018)

[26] Rajant Corporation https://rajant.com/underground-mining-netwo rk-2/Accessed on 22 Mar 2023

[27] MST Global https://mstglobal.com/industry/underground-coalmining/ Accessed on 22 Mar 2023

[28] Cisco for Mining https://www.cisco.com/c/en/us/solutions/indus tries/materials-mining.htmlAccessed on 22 Mar 2023

[29] Carroll Technologies Group https://www.carrolltechnologiesg roup.com/products-monitoring/Accessed on 22 Mar 2023

[30] PBE Group https://tinyurl.com/4x2ah4c5Accessed on 23 Mar 2023

[31] Jogekar, A., & Sinha, P. (2025). A comprehensive review on the use of Internet-of-Things-based systems in underground mining for monitoring environmental conditions. World Journal of Advanced Engineering Technology and Sciences, 14(1), 001-019.

[32] B. Zietek, A. Banasiewicz, R. Zimroz, J. Szrek, S. Gola, A portable environmental data-monitoring system for air hazard evaluation in deep underground mines. Energies 13(23), 6331 (2020)

[33] Y.S. Dohare, T. Maity, P.S. Das, P.S. Paul, Wireless communication and environment monitoring in underground coal mines– review. IETE Tech. Rev. 32(2), 140–150 (2015)

[34] I. Hussain, F. Cawood, R. Olst, Efect of tunnel geometry and antenna parameters on through-the-air communication systems in underground mines: survey and open research areas. Phys. Commun. 23, 84–94 (2017)

[35] M.A. Moridi, Y. Kawamura, M. Sharifzadeh, E.K. Chanda, H. Jang, An investigation of underground monitoring and communication system based on radio waves attenuation using ZigBee. Tunn. Undergr. Space Technol. 43, 362–369 (2014)

[36] L. Muduli, P.K. Janaa, D.P. Mishra, A novel wireless sensor network deployment scheme for environmental monitoring in longwall coal mines. Process Saf. Environ. Prot. 109, 564–576 (2017)

[37] B. Jo, R.M.A. Khan, An internet of things system for underground mine air quality pollutant prediction based on azure machine learning. Sensors 18(4), 930 (2018)

[38] B.W. Jo, R.M.A. Khan, O. Javaid, Arduino-based intelligent gases monitoring and information sharing Internet-ofThings system for underground coal mines. J. Ambient Intell. Smart Environ. 11(2), 183–194 (2019). https://doi.org/10.3233/AIS-190518

[39] S.U. Suganthi, G. Valarmathi, V. Subashini, R. Janaki, R. Prabha, Coal mine safety system for mining workers using LORA and WUSN. Mater. Today: Proc. 46, 3803–3808 (2021)

[40] D. Maximilien, C. Caroline, N. Pierre-Eric, N. Eve, L. Guillaume, C. Hugo, H. Stephane, A. Simon, Diesel engine exhaust exposures in two underground mines. Int. J. Min. Sci. Technol. 27(4), 641–645 (2017)

[41] Y.S. Dohare, T. Maity, P.S. Paul, H. Prasad, Smart low power wireless sensor network for underground mine environment monitoring, in 3rd International Conference on Recent Advances in Information Technology (RAIT) (2016), pp. 112–116. https://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=7507885

[42] D. Gao, L. Weiwei, K. Dai, Design of coal mine intelligent monitoring system based on ZigBee wireless sensor network. In International Conference on Mechanics, Materials and Structural Engineering (ICMMSE), Atlantis Press, (2016), pp. 182–187 https:// www.atlantis-press.com/proceedings/icmmse-16/25854549

[43] J. Byung Wan, K. Rana Muhammad Asad, An event reporting and early-warning safety system based on the internet of things for underground coal mines: a case study. Appl. Sci. 7(9), 925 (2017)

[44] F. Molaei, E. Rahimi, H. Siavoshi, S.G. Afrouz, V. Tenorio, A comprehensive review on internet of things (IoT) and its implications in the mining industry. Am. J. Eng. Appl. Sci. 13(3), 499– 515 (2020). https://doi.org/10.3844/ajeassp.2020.499.515

[45] D. YogendraS, M. Tanmoy, P.S. Das, P.S. Paul, Wireless communication and environment monitoring in underground coal mines–review. IETE Tech. Rev. 32(2), 140–150 (2015). https:// doi.org/10.1080/02564602.2014.995142

[46] J. Ankit, V. Alex, T. Purushotham, Internet of things–based command center to improve emergency response in underground mines. Safety Health Work 13(1), 40–50 (2022)

[47] L. Shilpa, C. Punam, B. Vishal, An Efcient Implementation of Wireless Sensor Network for Performing Rescue & Safety Operation in Underground Coal Mines. International Conference for Emerging Technology (INCET), 1–6, (2020). https://ieeexplore. ieee.org/document/9154150

[48] DigiXBeeZigbee, https://www.digi.com/products/embeddedsystems/digi-xbee/rf-modules/2-4-ghz-rf-modules/xbee-zigbee Accessed on 23 Mar 2023