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A comprehensive review on the use of Internet-of-Things-based systems in underground mining for monitoring environmental conditions

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Abstract

The implementation of Internet of Things (IoT) technology in the mining sector has immense potential to enhance both safety and efficiency. The mining industry is globally acknowledged for its valuable resources, including gold, coal, and iron ore, which are extracted from beneath the Earth's surface. Several environmental factors in underground mines affect the productivity and safety of mine workers, such as the presence of toxic gases, flammable gases, elevated carbon dioxide (CO2) levels, and reduced oxygen (O2) levels. Managing these gases is a critical concern that requires appropriate measures. There are multiple techniques available to monitor gas percentages and ensure an appropriate response is enacted when gas levels exceed the acceptable limit. Every system has its own constraints. Wireless monitoring systems play a crucial role in underground mines. This paper 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. Additionally, it analyzes wireless sensor network (WSN) technologies such as ZigBee and LoRa for applications within underground mines. Finally, it suggests a real-time safety system for industrial environments in underground mines, discussing its functionality, effectiveness, and potential applications.

Keywords: Internet of Things; Wireless communication; Industrial automation; Underground mines; Mine safety; Environmental monitoring

1. Introduction

The mining sector mainly retrieves valuable minerals from the earth's surface through techniques such as ore extraction and solid mineral processing, resulting in products like gold, diamonds, platinum, coal, and metal ores. Underground mining entails activities like blasting, drilling, and the movement of ore and materials utilizing heavy equipment. Nonetheless, underground mining presents greater risks compared to open-pit mining due to the potential for toxic gas build-up, possible roof collapses, gas explosions, exposure to dust and noise, electrical dangers, and fluctuating levels of oxygen, temperature, and humidity. Although steps have been taken to enhance safety, mines can still be unpredictable, and hazards may arise at any moment due to the ever-changing nature of excavation. The atmosphere at the earth's surface comprises oxygen (21%), nitrogen, carbon dioxide, argon, and trace amounts of other gases. Humans can breathe easily because of the ample supply of oxygen in the air; however, if the air becomes polluted with different gases, the oxygen levels drop, resulting in difficulties in breathing. Poor air quality in mining settings results in chronic health issues, especially in subterranean mines where hazardous gases such as carbon monoxide (CO), hydrogen sulfide (H2S), methane (CH4), and elevated levels of carbon dioxide (CO2) build up and cannot disperse due to the confined spaces or tunnel designs. These gases present significant dangers because of their flammable and explosive

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characteristics, and underground mines also harbor contaminants like coal dust and water vapour. Prolonged exposure to these contaminants, particularly harmful gases, can adversely affect the health of miners [1]. Following mining operations, locations underground can become perilous due to the presence of toxic and explosive gases, resulting in restricted access. Contact with these gases, as well as dust, CO2, and nitrogen, can be detrimental to the circulatory system and lead to various health issues. Diesel-operated vehicles found within underground mines significantly contribute to an elevated risk of cancer and cardiopulmonary ailments [2]. The existence of hazardous gases renders certain areas inaccessible, emphasizing the need for enhanced safety protocols within the mining sector. Breathing in CO2 gas can adversely impact the cardiac function of coal mine workers and alter their blood pressure. Furthermore, it leads to a lower mean diastolic blood pressure when compared to individuals not exposed to such conditions [3]. In underground mining, maintaining safe and healthy environmental conditions is essential for improving the work efficiency of miners, particularly if the air quality at the underground site matches that of the surface, free from harmful gases [4]. Mining activities, which involve heavy machinery as well as ore extraction through drilling and blasting, introduce safety risks. To bolster safety in both underground and open-pit mining operations, many mines have adopted safety protocols, along with training and educational initiatives for workers [5]. Nevertheless, the distinct layout of each mine poses challenges in applying mining technologies for adequate ventilation, which can result in variability in air quality affecting the health of workers. Gas incidents in subterranean mines pose significant risks due to the explosive environment generated by various factors such as production methods, geological circumstances, and the specific type of mine, resulting in injuries and property losses. When mine gases exceed a certain threshold limit value (TLV), they can adversely impact the health of mine workers. The gases found in underground mines affect the human body differently and can lead to chronic health problems. Possible effects of exposure to toxic gases include difficulty in breathing, suffocation, loss of consciousness, respiratory system damage, nausea, headaches, loss of smell, fatigue, and dizziness [6]. The Directorate General of Mines Safety (DGMS) is a regulatory body in India that has advocated for the implementation of an environmental monitoring system in underground coal mines, particularly in gassy and fiery coal seams [7]. The circulars issued by DGMS outline the safety protocols for diesel equipment utilized in both underground coal and metalliferous mines. Equipment powered by diesel, such as trucks, high-capacity loaders/LHDs, drills, and other ancillary machinery used in underground operations present inherent health and safety risks, including diesel fumes, noise, dust, fire, lubricants, the risk of flammable gas explosions, and vehicle collisions, among others. Furthermore, the DGMS circular outlined the essential ventilation standards and the permissible limits for harmful and flammable gases, as detailed in Table 1 [8, 9].

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

To tackle mining hazards, the mining sector is incorporating new technologies to enhance safety at excavation sites. Implementing an intelligent mining framework in underground operations guarantees the effective and secure extraction of minerals. This strategy focuses on increasing machine autonomy and continuously monitoring environmental conditions in deep mines [10]. The utilization of Internet of Things (IoT) technology enables real-time tracking of these environmental metrics, creating a global network that links devices together [11]. The Industrial Internet of Things (IIoT) is a subset of IoT, integrating electronic components, sensors, wireless communication technologies, and gateways to facilitate data transmission from sensors to the cloud [12]. The Underground Mine IoT (UMIoT) is part of the IIoT framework, comprising sensors, communication modules, gateways, switches, repeaters, and electronic components to create a wireless network within the mine, enabling data transfer from the underground to the surface. UMIoT alerts personnel to abnormal conditions or changes in environmental parameters when measured values surpass predetermined thresholds. The deployment of UMIoT is beneficial for continuous environmental monitoring and hazard prevention [13].

This paper outlines the framework for implementing IoT in underground mining and provides a systematic review of the existing interdisciplinary research on the application of WSN and IoT, utilizing ZigBee or LoRa for real-time environmental monitoring in underground mines. The move towards automation within the mining sector minimizes accidents and enhances efficiency. The review emphasizes the effects of harmful gases in mines on the health of workers, the potential disasters resulting from gas-related incidents, and the importance of wireless communication technologies such as ZigBee and LoRa transceivers for monitoring environmental conditions underground. Additionally, it puts forward a design for an industrial system aimed at the real-time monitoring of environmental parameters in underground mines.

2. The Architecture of Underground Mine IoT (UMIoT)

The structure of UMIoT outlines the process of gathering and transmitting environmental data from the underground mine to the surface. This structure comprises three layers: perception and input, network, and application, as illustrated in Fig. 1. This three-layer framework serves as a blueprint for designing and developing standard industrial IoT systems in underground mining. The perception and input layer is responsible for gathering data from various sensors and relaying it to the network layer. The network layer then transmits the sensor data received to the application layer via a communication medium that may be either wireless or wired, or a combination of both. The application layer functions as the interface between users and applications. The analysis of data collected from underground mining locations and the forecasting of environmental parameters are managed locally at the surface.

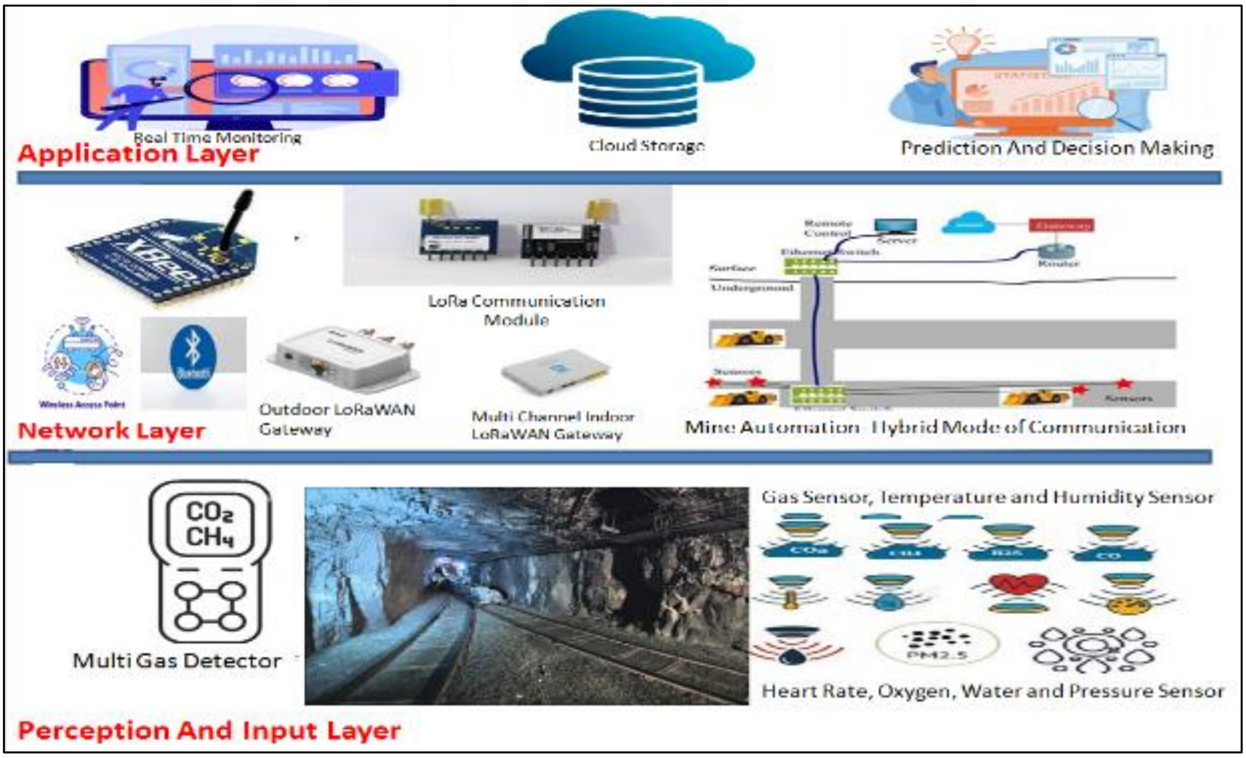

Figure 1 Architecture of UMIoT (Underground Mine IoT) System

Sensors utilized in underground mines are classified into two categories: those that measure environmental physical quantities and convert them to electrical signals for further processing to be sent to the upper layer, and those that integrate with a microcontroller unit for processing. A typical representation of sensor placements in the walls of underground mine tunnels, as well as some sensors attached to mine workers and equipment, is depicted in Fig. 2. To track environmental parameters in underground mines, sensors such as those for gas, dust, temperature, humidity, health, position, and proximity detection are installed to ensure the safety of workers at the site. Different industries employ various techniques for measuring these parameters in underground mining environments, including multi-gas detectors, hybrid communication methods (both wired and wireless), and entirely wireless communication.

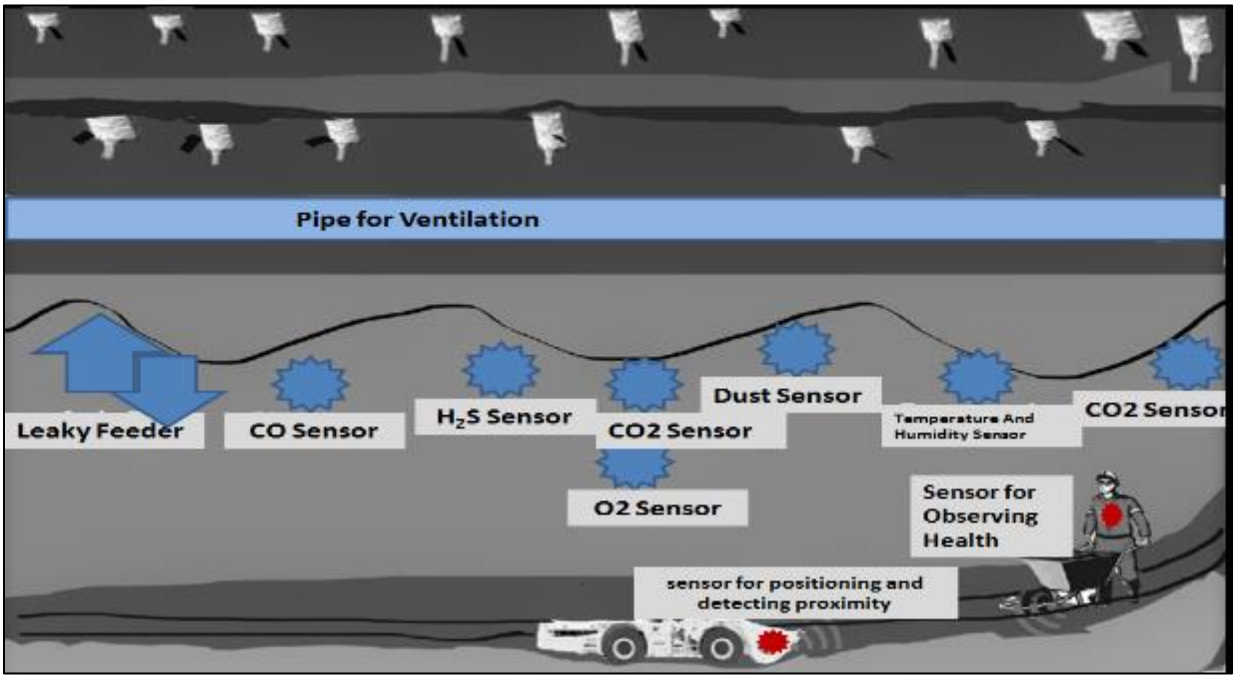

Figure 2 Common perspective of the setup of sensors within an underground mine passage

- Handheld portable multi-gas detectors: These are devices used by mine supervisors to monitor environmental parameters once per shift. It is costly to supply these devices to all mine workers, and they do not conduct any analysis on the collected data [14].
- Hybrid communication: In advanced automated mines, there exists a wireless real-time monitoring system that gathers environmental parameter data from underground mines. These systems utilize both wired and wireless communication methods, relying on complete cable installations or portable devices used on-site. The ever-changing working conditions underground can lead to cable damage, increased fault rates, and challenges related to system maintenance, among other issues [15, 16].
- Wireless communication technology: Technologies such as Wi-Fi, ZigBee, or LoRa-based Wireless Sensor Networks (WSNs), alongside IoT-enabled Low-power Wide Area Network (LoRaWAN) real-time systems, are implemented to monitor environmental parameters in underground mines, enhancing safety, efficiency, and productivity [17–21].

To continuously assess environmental factors, there is a need for a dependable and cost-effective real-time monitoring system in underground mines. This necessity arises because underground mining operations present greater hazards to the health and safety of workers, particularly as these mines often employ diesel machinery and extend to greater depths. Ensuring worker safety in mining is a critical issue, as exposure to harmful gases, dust, carbon dioxide, and nitrogen can lead to chronic health conditions. Additionally, contact with diesel-powered vehicles heightens the risk of cancer and cardiopulmonary illnesses [22]. To enhance safety protocols, it is essential to monitor toxic gas concentrations and maintain them within safe ranges in real-time, necessitating low-power wireless communication technologies [23]. Given that the layout of underground mines is inconsistent, communication can be difficult due to their ever-changing nature, curves, and junctions. An effective communication system is crucial for sharing information regarding environmental conditions, monitoring worker locations, and signaling safe and hazardous areas. Implementing automation can enhance worker health and safety by establishing a reliable and resilient communication infrastructure.

3. Underground Mine Disasters

In the mining sector, underground operations are among the most dangerous work environments when compared to other fields, leading to a higher number of fatalities. The key factors contributing to mining accidents include rock falls, gas explosions, dust, fires, and the buildup of harmful gases like carbon monoxide (CO), nitrogen oxides (NOx, NO), and hydrogen sulfide (H2S). The major reasons for mining accidents and the suggestions put forth by researchers are outlined below. The review of existing literature explores the causes and effects of gas explosions in underground mines, emphasizing the risk assessment associated with events that have taken place in such environments. A selection of gas explosion incidents that have occurred in underground mines in India is presented in Table 2.

Table 2 Incidents of gas explosions in underground mines across India.

References	Date of accident	Name of Mine	Fatalities	Brief cause of accident
[24]	25.01.2024	'Rat-hole' coal mine in Nagaland's Wokha district., India	Death of 06 mine workers	Fire and subsequent Methane gas explosion.
[24]	16.02.2022	Coal mine in Shallang area of West Khasi Hills, Meghalaya, India	Death of 02 mine workers	Due to asphyxiation
[24]	23.06.2020	Kurasia Underground Mine, South Eastern Coalfields Limited, India	Death of 1 mine worker	Explosives
[24]	18.04.2015	Ankleshwar project oil mine of oil & natural gas corporation ltd, India	Death of 2 mine workers	Dust and gas explosion
[24]	06.09. 2006	Bhatdih colliery coal mine of Jharia Coalfeld, India	Death of 50 mine workers	Methane gas explosion
[24]	27.12.1975	Chasnala coal mine of the Indian Iron and Steel Company (now SAIL) near Dhanbad, India	Death of 372 mine workers	Explosion
[25]	19.02.1958	Chinakuri colliery of Raniganj Coalfeld, India	Death of 183 mine workers	An outburst of methane gas

Prominent researchers have documented gas explosions that took place in underground mines globally, also. Mandal et al. [26] conducted an examination of incidents that transpired in an Indian coal mine from April 1989 to March 1998. The findings indicate that there were nine gas explosion incidents in underground mines, four in open-cast mining, and two at the surface. The authors noted that Indian mines exhibit higher rates of accidents and fatalities compared to those in the USA and South Africa. Tripathy et al. [27] identified various safety hazards present in Indian coal mines and highlighted techniques for risk assessment and control in the workplace. The primary reasons for gas-related incidents in underground mining areas are sealed-off sections and older work sites within the mines. Mishra et al. [28] concentrated their investigation on geo-mining factors, such as air velocity, methane emission rates, gallery width, surface roughness, and slope, to evaluate the dispersion and layering of methane gas at the Moonidih Colliery in India.

Maximilien et al. [22] explored the exposure of mine workers to diesel engines in an underground gold mine located in Canada. This exposure adversely impacts the health of mine workers, resulting in a rise in cancer and cardiopulmonary diseases. Khodabandeh-Shahraki et al. [3] utilized a random sampling technique to study the effect of carbon dioxide gas (CO2) on the health of coal mine workers, interacting with 161 individuals in Iran. The authors emphasized the importance of regulating gas exposure levels and stressed the need for adequate medical care and support within the mining sector. Mahdevari et al. [29] examined the impacts of exposure to dust, particulates, naturally occurring gases (O2 and CO2), engine emissions, and chemical vapors in the Kerman Coalfield of Iran. The findings highlighted the negative health effects of toxic gases on coal miners, contributing to lung diseases and pneumoconiosis. Yuan et al. [30] conducted a study to model the dispersion of CO gas in a safety research coal mine in the USA by employing fire dynamics simulation and MFIRE programs. The authors reported that a fire incident in an underground mine, resulting from CO gas released during the combustion of a conveyor belt, led to the fatalities of two mine workers. Tong et al. [31] assessed the risks and unsafe human behaviors in the mining workplace by analyzing data from 3,695 gas explosions that occurred in Chinese coal mines. They developed a risk assessment model for gas explosions and detailed the unsafe practices observed during these events. Deng et al. [32] documented incidents triggered by an abnormal rise in H2S gas in coal mines in China and proposed strategies to mitigate and control H2S gas levels in underground tunnels. Zhanga et al. [33] investigated the causes of gas explosions and reported a higher death toll compared to other types of accidents in coal mines across China. Fan et al. [34] created a deep learning algorithm and mathematical model to evaluate health risks associated with occupational exposure to toxic substances in various working environments of four distinct coal mining areas in China. The authors identified high-risk factors such as H2S, NO, NO2, and CO, along with medium-risk factors like sulfur dioxide (SO2). Bonetti et al. [35] evaluated gas concentrations within the ventilation systems of two coal mines in Southern Brazil, recommending ongoing monitoring of methane emission areas and enhancements to ventilation within mines. Stemn et al. [36] examined accidents linked to artisanal and small-scale gold mining, based on

22 reports from a public database. Among these, eight accidents resulted in 67 fatalities due to blast fumes or gases in Ghana's underground mines, leading the authors to advocate for the adoption of technology to ensure safety and sustainability. Banasiewicz [37] identified and described sources of NO and NO2 gases produced by diesel engine-powered heavy machinery operating in underground mines in Poland, recommending the implementation of innovative methods and techniques to eliminate nitrogen compounds from the mining atmosphere. Panhwar et al. [38] assessed safety and health concerns, including the inhalation of toxic gases among workers in Lakhra Coal Mines, finding that miners were largely unaware of health and safety regulations and confirming that health issues arise from an unhealthy working environment.Shah et al. [39] examined the factors contributing to accidents in an underground mine located in the Cherat Coalfield of Pakistan, identifying risk hazards such as inexperienced workers, roof collapses, and gas explosions stemming from inadequate maintenance at the coal mine's working face. Ayaz et al. [40] focused on the economic analysis and assessed the health-related costs faced by underground coal mine employees in Balochistan (Pakistan). The authors concluded that coal mine employees suffer from more health problems, and the financial burden of these illnesses is greater compared to workers in other sectors.

These studies offer important insights for enhancing the safety and health conditions of mining personnel and advancing safety protocols within the industry. Research highlighting gas explosions, dust, and hazardous gases in coal mines has illustrated their contribution to injuries and fatalities among miners. The researchers outlined the accident causes and proposed preventative strategies to improve safety and manage production in underground sites. The identified factors leading to gas explosions include the improper installation of gas extraction and ventilation systems, illegal blasting activities, gas outbursts from geologically unstable regions, and the absence of real-time monitoring within underground environments. The study highlights the necessity for controlling gas parameters in underground mines and providing essential medical care for the well-being of mine workers. Suggested measures to prevent the formation of dangerous gases and regulate environmental conditions through continuous real-time monitoring can significantly improve safety in underground mines.

4. The Role of Wireless Communication Technology in Monitoring Environmental Factors

The mining sector is implementing wireless communication technologies to enable real-time tracking of environmental conditions and notify mine workers. This shift entails substituting traditional approaches to measuring environmental factors and setting up communication systems at the mining site to ensure the safety of personnel.

4.1. Characteristics of Wireless Communication Technology

A wireless sensor network (WSN) is comprised of various sensor nodes along with a central sink node or base station to observe environmental parameters. The sensor node relays the data it collects through other sensor nodes (intermediate nodes) to a base station or sink node, as depicted in Fig. 3. The structure of the Internet of Things (IoT), which is founded on the WSN framework, demonstrates how data is transmitted from the source node to the end user via a multi-hop route and gateway, allowing data access at any time and from any location. Sensor nodes are limited in terms of resources, specifically concerning power usage, processing capabilities, and memory for data computation. The radio frequency bands for sensor nodes are unlicensed and utilize ISM bands for communication. Most WSNs are structured to connect a source node to a base station/sink within the networking model. The base station possesses greater processing power and links to a broader network. To address the challenges posed by resource limitations, researchers have created wireless communication protocols like ZigBee, LoRa, SigFox (a global network), and NarrowBand Internet of Things (NB-IoT) for establishing wireless connections. The details of these wireless communication technologies are outlined in Table 4. ZigBee and LoRa are wireless communication technologies applicable in IoT contexts. Wireless communication modules differ in their network architecture, communication range, energy usage, and specific application. ZigBee employs three types of network topologies and utilizes a mesh topology to broaden network coverage, with ZigBee devices functioning as routers to relay data packets or messages to other ZigBee devices, as shown in Fig. 4. Applications utilizing ZigBee include home automation, energy management systems, and industrial control processes. LoRa serves as a wireless communication module that facilitates long-distance wireless communication while maintaining low power consumption. The LoRa network is based on a point-to-point or star network topology, illustrated in Fig. 5. The architecture of the LoRa network consists of LoRa end devices, LoRa gateways, and a LoRa network server. LoRa end devices, which are powered by batteries, have limited processing abilities and transmit data over the LoRa network by employing the LoRa modulation method to send data packets to LoRa gateways. These gateways collect data packets from LoRa end devices and relay information to the network server using either Ethernet or cellular network IP-based connections. They function as a connection point between the LoRa end devices and the network server. The LoRa network server receives data packets from the gateways and is in charge of directing those packets to cloud platforms or application servers.

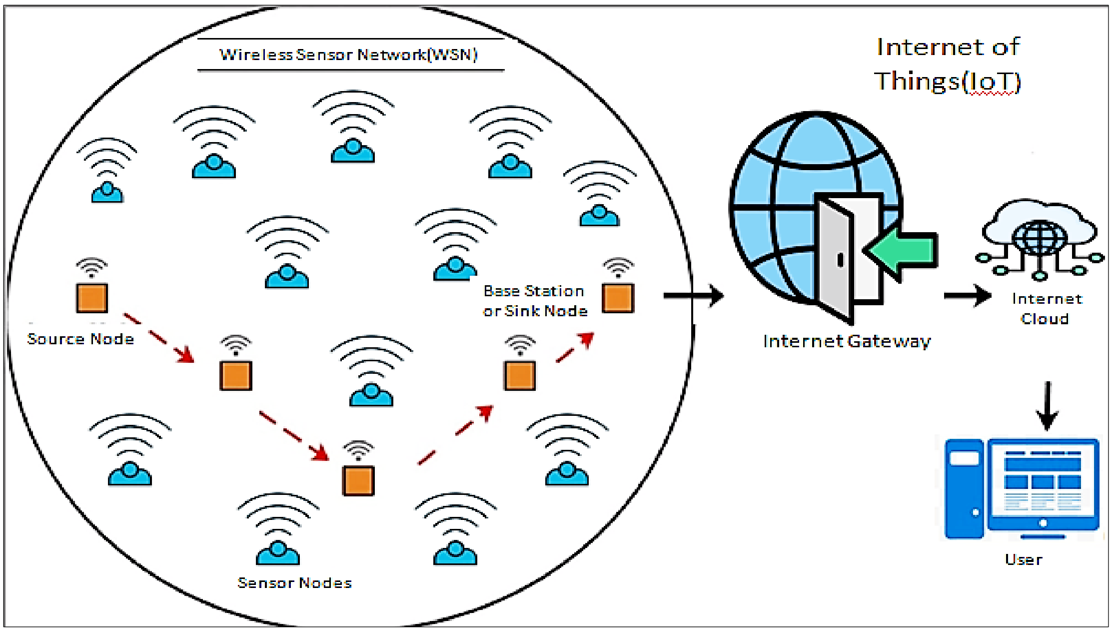

Figure 3 Combined Architecture of Wireless Sensor Networks and the Internet of Things

Table 3 Comparative study: Bluetooth, Wi-Fi, ZigBee, and LoRaWAN

References	Parameters	Bluetooth	Wireless fidelity (Wi-Fi)	ZigBee	Long Range Wide Area Network (LoRaWAN)
[41, 42]	IEEE standard	802.15.1	802.11	802.15.4	802.15.4 g
[41,43-47]	Operating frequency Band	2.4 GHz	2.4 GHz and 5 GHz	2.4 GHz and 850-930 MHz	902.3 to 914.9 MHz
[41, 45]	Data rate	1-3 Mbps	10-100 Mbps	20-250 Kbps	30–50 Kbps
[42, 44, 47]	Transmission Range	10–100 m	Upto 100 m	50–500 m	10 km approximately
[41,48, 49]	Transmission power	0–10 dBm	15–20 dBm	(− 25) − 0 dBm	7–20 dBm
[50]	Network Topology	Ad hoc, point to point, star topology	Ad hoc, point to hub topology	Mesh, star, tree, ad hoc topology	point-to-point, Star topology
[50]	Power consumption	Very low	high	low	Very low
[41, 44]	Data protection	16 bit cyclic redundancy check	32 bit cyclic redundancy check	16 bit cyclic redundancy check	128 bit AES
[41, 44]	Modulation	Gaussian frequency-shift keying (FSK)	Direct Sequence Spread Spectrum (DSSS), complementary code keying, and orthogonal frequency division multiplexing (OFDM)	Direct sequence spread spectrum (DSSS)	Chirp spread spectrum

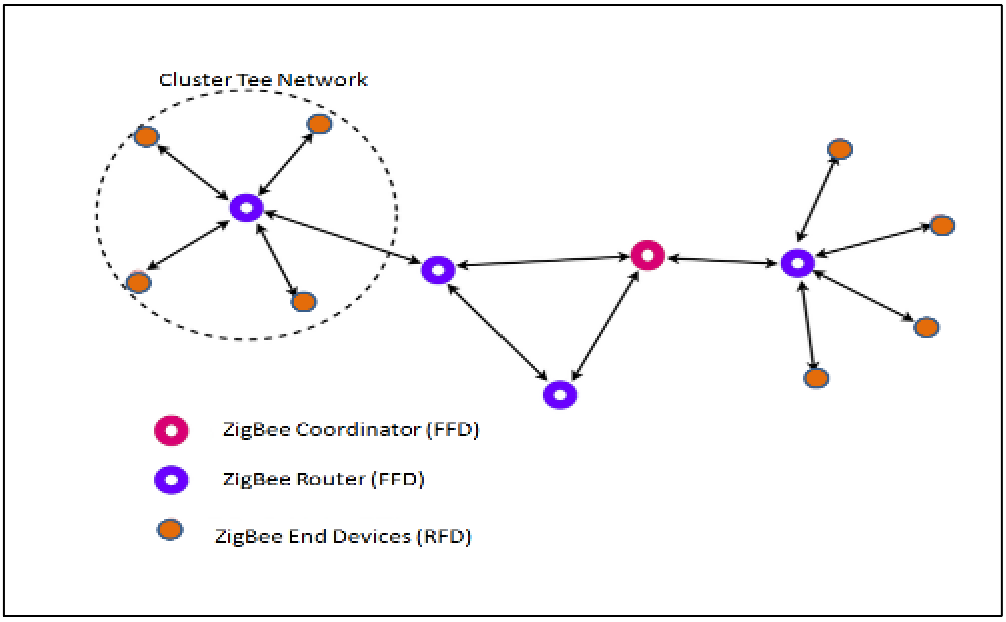

Figure 4 ZigBee Architecture

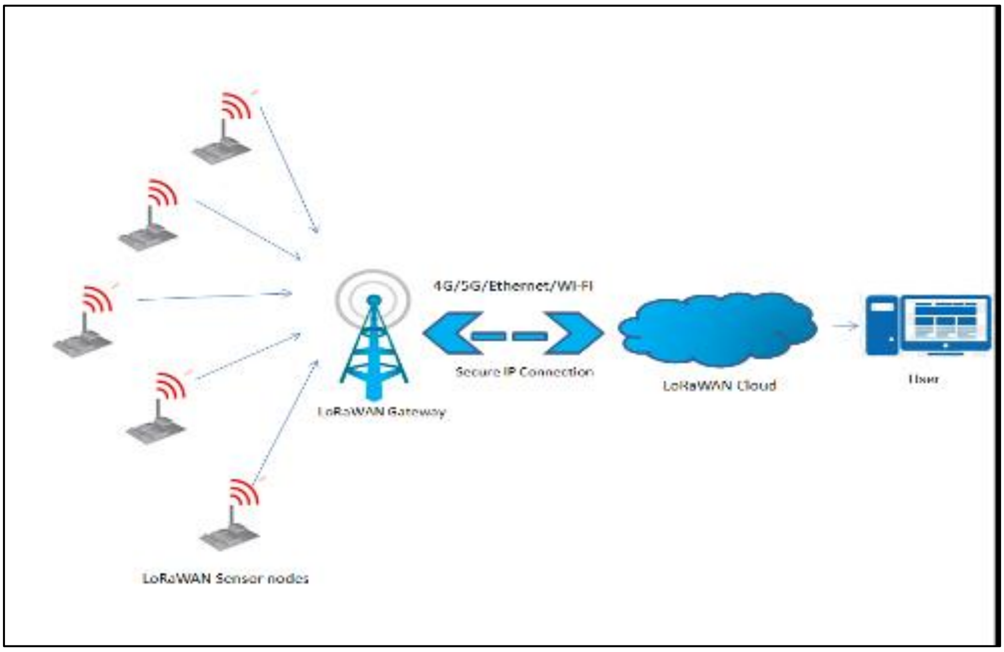

Figure 5 LoRa Architecture

4.2. WSN with ZigBee and LoRa Communication Modules

A proof of concept (POC) system utilizing ZigBee and LoRa for monitoring environmental conditions in underground mines, alongside laboratory experiments conducted by different researchers, is outlined. Researchers have suggested a method for transmitting data from the lower levels of the underground mine to the surface. Tables 5 and 6 present an overview of current solutions regarding experimentally evaluated results, simulation outcomes, proposed methodologies, and the proof of concept (POC).

The investigation and assessment of ZigBee wireless communication technology in underground mining have been addressed through several studies. These studies found that path loss occurs in both branched routes and curved tunnels within the mine, and non-line-of-sight conditions affect communication effectiveness. ZigBee-based wireless systems have been created to sense and relay environmental parameters between locations in underground mines. Mesh topology has emerged as the optimal design choice in wireless sensor networks (WSNs) for monitoring and data communication networks. Nonetheless, some studies do not provide detailed implementations, while results indicate that ZigBee-based wireless monitoring systems can be effectively utilized in underground mining settings. LoRa is a small, low-cost, and low-power reliable wireless communication module used in outdoor environments at the surface for monitoring environmental parameters.

Numerous studies have explored both wired and wireless sensor networks (WSNs) to monitor environmental factors in underground mining sites [69]. The application of WSNs combined with a Geographic Information System and a probabilistic event detection algorithm has been recommended to maximize coverage and connectivity [18, 70]. The impact of tunnel structures, antenna specifications, and radio wave propagation factors on signal strength has been examined [16, 71], and a graphical user interface (GUI) dashboard based on WSNs has been developed to track environmental parameters and other variables [72]. However, some studies lack implementation specifics or fail to address certain elements, such as radio signal loss in tunnels and vertical shafts. In summary, this research has advanced the creation of dependable systems for gathering and transmitting various environmental parameters in underground mines. There is potential for developing cost-effective, customized designs with specific architectures for real-time monitoring of environmental parameters using WSNs with ZigBee or LoRa communication modules. Moreover, the deployment of IoT-enabled gateway technology combined with industrial-grade gas sensors in underground mines could facilitate the collection and real-time transmission of data to the surface, enhancing the reliability and accuracy of hazard prevention in underground mining operations around the clock.

Table 4 The main researches on wireless sensor networks (WSNs) focusing on the establishment of communication using ZigBee and LoRa, as well as monitoring environmental parameter

References	Technology Used	Methodology and Addressed Problem	Restrictions
[17]	WSN and ZigBee	The performance of ZigBee-based wireless communication is explored and assessed in a straight tunnel of an underground mine, achieving a communication range of 100 meters, and in a curved tunnel, where a communication range of 70 meters was reached.	Information loss in a curved passage of an underground mine.
[51]	WSN and ZigBee	Examined a ZigBee-based proof of concept system to assess reliable communication between ZigBee transmitter and receiver nodes in straight and curved tunnels of an underground mine.	The shape and bends of the underground tunnel influence the attenuation of packets or the propagation of radio waves.
[52]	WSN and ZigBee	Studying the propagation of radio waves to assess the path loss in various locations within underground mine tunnels aids in improving signal reception, localizing sensor nodes, and finding miners.	Outcomes can differ based on the configuration of the mine site.
[53]	WSN and ZigBee	ZigBee technology is utilized to track gas concentration levels in coal mining operations.	Absence of execution specifics
[54]	WSN and ZigBee	A smart helmet equipped with ZigBee technology to monitor dangerous gases and an infrared sensor to identify objects if mine workers take off their helmets.	execution and evaluation at the laboratory stage
[55]	ZigBee, Proteus	Zigbee communication module along with Proteus simulation software is used to observe variations in environmental parameters.	The discussion focuses solely on simulation results; the hardware implementation is still at the laboratory stage.
[56]	WSN and ZigBee	Explored and evaluated different configurations of sensor nodes with scenarios consisting of 12, 20, 30, 40, and 50 nodes within the ZigBee network. A wireless sensor network designed with a mesh topology proves to be dependable for creating the communication network.	A conceptual framework is suggested, and based on simulation findings, a suitable network structure is identified for underground mining.
[57]	WSN and ZigBee	Suggested a real-time wireless communication system for transmitting data from the underground mining location to the surface.	Proposed model
[58]	ZigBee	Established a system to monitor the temperature levels in an underground mining location.	Insufficient details regarding implementation at the mining location.
[59]	WSN and ZigBee	Zigbee-driven IoT integrated with an IP-capable gateway for immediate environmental monitoring of subterranean conditions. A wireless sensor network (WSN) system has been developed for both laboratory settings and mining locations. A power management strategy	Insufficient details regarding implementation at the mining location.

		has been applied, successfully extending the distance coverage to 140 meters between two routers.	
[60]	ZigBee	Suggested an automated system using ZigBee technology that identifies hazardous gases by attaching it to the miner's helmet. The system was designed for real-time monitoring to relay data continuously to the control room.	Evaluated and applied at the foundational level.
[61]	ZigBee	Creation of a ZigBee system for the surveillance of environmental conditions in underground mines.	Evaluated in subterranean mines, but the communication distance is limited, and signal intensity decreases in winding tunnels.
[62]	LoRa	Developed an air quality monitoring system that utilizes LoRa modules integrated with a cloud platform for use in rural settings. A wireless communication link was successfully established between the transmitter and receiver over a distance of 800 meters, experiencing a packet loss of 20%.	executed at the surface level
[63]	LoRa	A simulation analysis was conducted to evaluate the performance of LoRa wireless communication in a mining environment under various frequency spread factors and multipath scenarios. The simulation utilized a Rayleigh multipath channel along with an Additive White Gaussian Noise (AWGN) multipath channel.	Study of simulations
[64]	LoRa	Examined the communication signal strength of the LoRa module by utilizing the Received Signal Strength Indicator (RSSI) value.	Deployment of a LoRa-based system in an open environment.
[65]	LoRa	Developed a positioning system leveraging LoRa RSSI fingerprinting. Conducted tests in both line-of-sight and non-line-of-sight settings to establish dependable communication between the transmitter and receiver.	Executed in an outdoor setting at ground level and assessed the path loss between the transmitter and receiver.
[21]	WSN and LoRa	Suggested wireless sensor network utilizing a LoRa-based system to oversee temperature, humidity, and gas metrics of an underground mining location from a surface control center.	Suggested framework
[66]	IoT and LoRa	A prototype based on IoT is suggested for monitoring data from underground mining sites within a cloud platform. This system actively regulates the ventilation system and minimizes energy usage.	A strong system is necessary to meet safety requirements in underground mining operations.
[67]	LoRa	A linear sensor network utilizing LoRa technology, equipped with relays and tags, is implemented for the purpose of conveying the locations of mine workers and information regarding their equipment in an underground mining environment.	A trial system of limited scale featuring two relays.
[68]	LoRaWAN	Created a resilient, low-complexity control system for underground detonations using a LoRa relay-based mesh network approach. Developed a LoRaWAN network designed specifically for managing underground explosions.	Signal strength decreases because of the lack of line of sight in subterranean mines.

4.3. Role of IoT with Machine Learning in Underground Mines

The creation of IoT-driven communication systems to monitor and predict air quality in underground mines aims to improve safety through timely alerts. The research suggests employing machine learning models, portable gas detectors, and IoT-enabled gas sensors to evaluate environmental conditions and forecast gas concentration levels. Machine learning enhances wireless sensor networks (WSNs) by processing the significant volume of data gathered from the sensors and deriving valuable insights from it. These machine learning algorithms can be trained using sensor data to recognize patterns, forecast outcomes, and identify anomalies, thereby increasing the accuracy and efficiency of WSNs for diverse applications, including environmental monitoring, surveillance, and industrial automation. Furthermore, machine learning can optimize WSN performance by anticipating and preventing malfunctions or enhancing energy efficiency. However, some studies fall short on technical specifics, and additional toxic gas parameters need to be included in the analysis. Moreover, there is a necessity for robust electronic components to ensure the longevity of the sensors in the demanding environment of underground mines. Nevertheless, the suggested IoT-based systems have the capacity to improve safety in these mining settings. ZigBee wireless technology plays a significant role in facilitating wireless communication for transmitting environmental data between nodes and tracking miners' locations in underground mines. Other wireless technologies such as RFID, Bluetooth, and Wi-Fi combined with sensors are utilized to establish dependable communication. Researchers assessed radio wave propagation by positioning ZigBee nodes in straight and tilted/curved tunnels at an underground mine location. The implementation of a wireless network was carried out by integrating several ZigBee-based routers and one coordinator at the mining site. Researchers advocated for ZigBee with a mesh topology for effective underground wireless monitoring and communication systems.

Table 5 The main researches focusing on the integration of IoT and Machine Learning in the setup of communications and the observation of environmental factors in the underground mine sites.

References	Technology Used	Methodology and Addressed Problem	Restrictions
[19]	IoT and Machine Learning	Created an IoT system for monitoring and forecasting air quality to enhance safety in underground mining by providing early alerts. Machine learning models have been developed to forecast air quality.	Insufficient information regarding the monitoring system
[20]	IoT	Real-time environmental monitoring in underground mines utilizing IoT and cloud technology, along with a ventilation management system and an early warning system.	Only the results from the simulations are addressed.
[73]	Smartphone	An Arduino, along with a sensor board and a smartphone-based system, is utilized to track and forecast the concentration of carbon monoxide gas at mining sites in order to provide early alerts to miners.	Suggested a prototype system
[14]	Bluetooth and IOT	The implementation of portable gas detectors and the deployment of IoT technology-driven gas sensors help gather environmental metrics at underground mining locations. These sensors collect environmental information and transmit it to smartphones via Bluetooth. Smartphones serve as a platform for visualizing and monitoring this data. Once a Wi-Fi or internet connection is established, the data gathered on the smartphone is uploaded to the cloud.	Every employee working in the mine must have a personal gas concentration sensor or analyzer. Real-time detection has been established specifically for CO and H2S gases.
[74]	IoT and GIS	Detection of environmental parameters using IoT technology with gas sensors and GIS tools to present information in a laboratory setup.	Execution of the system at the lab level.
[75]	Portable Intelligent Sensors	Portable smart sensors are employed to relay information utilizing a hybrid communication approach in a coal mine. Furthermore, a methodology integrating IoT with a cloud platform is suggested for gathering and transmitting mine	The harsh conditions of an underground mine can lead to damage of sensors. Durable electronic

		data, as well as for monitoring the positions of equipment and miners in an underground coal mining environment.	components are necessary at the mine location.
[76]	UMAP and LSTM deep learning algorithm	Suggested the development of an intelligent real-time system for monitoring gas concentrations in non-operational or sealed-off sections of underground coal mines. A real-time forecasting model to anticipate gas parameters or the free state of the sealed-off areas within an underground mine utilizing deep learning methodologies.	The technical details for the real-time implementation of an IoT-based system are not specified.

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

The system being proposed is intended for use in one of India's underground mines, where ore extraction has reached a depth of about 832 meters from the surface. A typical overview of an underground mine in India and the layout of level 26, showcasing the locations of the LoRaWAN gateway/sensor controller, sensors, repeaters, and surface control room. Implementing an IoT-enabled LoRaWAN gateway smart safety environmental monitoring system in underground mines can enhance safety protocols and operational efficiency in mining activities [77]. A standard industrial monitoring system is employed to track environmental factors in the underground mine using a hybrid approach. Sensors such as those for CO_2, CO, O_2, H_2S, CH_4, alongside temperature and humidity sensors, can be deployed at the mining site to assess the surrounding conditions. The collected data can be sent to an IoT server utilizing either a LoRaWAN gateway or a wireless communication protocol.

The proposed setup is generally categorized into three primary sections:

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

The surface control room oversees the environmental data gathered by various sensors via the LoRaWAN gateway. The programmable IoT-enabled LoRaWAN gateway/sensor controller serves as an underground remote station, providing real-time monitoring of environmental factors and transmitting data to the surface control room using an Ethernet cable and repeater device. Industrial sensors detect environmental conditions and relay the data to the control room in real time through the sensor controller or LoRaWAN gateway, allowing for immediate data display or analysis to avert hazardous situations at the underground site. The smart safety system can also feature an alert mechanism that informs miners and managers instantly in case of any perilous or emergency situation. A LoRaWAN gateway can be programmed to take necessary actions when the sensed parameter values exceed their threshold limits. The environmental data archived on a cloud platform can be accessed by the supervisor or relevant authority from the mining office for analysis to mitigate hazards. This approach can significantly enhance operational efficiency and productivity in mining operations, minimize downtime, and ensure adherence to safety regulations. Furthermore, the system can be improved by offering guidance and support to miners during emergencies, such as suggesting the safest evacuation route. Adopting an IoT-enabled smart safety monitoring system in underground mines can substantially bolster safety measures, boost productivity, and secure compliance with safety requirements.

A hybrid communication method is one of the technologies used to transmit environmental parameters sensed from various levels of the underground mine to the surface control room, as well as to alert mine workers in cases of any irregular situations. Wireless communication technologies like ZigBee or LoRa have some limitations, including inefficiencies in energy consumption, limited communication ranges, challenges in deploying sensor nodes, and potential data packet loss at the mining site. To overcome these limitations, researchers have proposed solutions that include intelligent algorithms for managing power, optimizing data transmission paths, utilizing various topologies, and employing big data technologies along with data analytics techniques for monitoring and predictive analysis of environmental factors.

In order to tackle these issues, a dependable communication technology is essential for establishing an intelligent sensing and warning system within underground mines. Various companies, such as Rajant [78], MST [79], CISCO [80], Carroll Technologies Group [81], and PBE Group [82], offer technological solutions for real-time monitoring systems in underground mines worldwide, with significant variations in cost and reliability. The exact cost and reliability of each solution will hinge on aspects such as the technology used, the mine's size and structure, and the specific needs of mine organizations. Typically, real-time monitoring systems deliver a more comprehensive and advanced solution that integrates a variety of sensors, devices, software applications, and data analytics tools into a cohesive system. These systems also feature more sophisticated capabilities, yet they tend to be pricier and more complex to implement.

6. Future Scope

Implementing automation in underground mining offers numerous advantages through the use of emerging technologies, particularly IoT, which includes improvements in sensor technology, communication and connectivity, robotics integration, artificial intelligence methods, as well as virtual and augmented reality, drones, and unmanned aerial vehicles (UAVs) to boost safety, productivity, and efficiency in mining operations.

Improvements in sensor technology facilitate the real-time collection and monitoring of various conditions within underground mines, focusing on compact, wireless, and more durable sensors capable of functioning in the challenging underground environment. Connectivity and communication systems enhance underground communication to guarantee uninterrupted connectivity and allow for real-time monitoring and management. Underground mining operations can gain from higher levels of automation and the incorporation of robotics. Data analytics along with artificial intelligence methods can evaluate data trends, detect irregularities, and offer insights into predictive maintenance. Virtual and augmented reality technologies can assist in training mine workers, modeling emergency situations, and allowing remote experts to provide assistance and support to on-site staff. Drones and UAVs outfitted with cameras and sensors can be employed to access hard-to-reach areas, conduct infrastructure inspections, and monitor environmental conditions.

The sensor data fusion technique refers to the process of merging information from various sensors to gain a thorough understanding of the environment or a specific phenomenon. By incorporating data fusion techniques with gas sensor data, the precision and dependability of gas detection and monitoring can be improved, considering the following steps.

- Choosing suitable sensors and their placement: Ideal for detecting the gases of interest in subterranean mines.
- Data preprocessing: Processing sensor information to eliminate noise by applying filtering or calibration methods and addressing the effects of temperature and humidity on sensor readings.
- Synchronization and alignment of sensor data: To guarantee precise fusion by utilizing synchronized clocks or common triggers to timestamp the sensor data.
- Feature extraction: Derive pertinent features from the pre-processed sensor data, including gas concentrations, response times, or other characteristics specific to the target gases that simplify data representation and lower dimensionality.
- Association of sensor data: Correlating data from various gas sensors to link measurements that correspond to the same gas event or concentration.
- Selection of fusion algorithms: Choosing algorithms based on specific needs like weighted averaging, fuzzy logic, or artificial intelligence methods, taking into account sensor reliability and gas dispersion characteristics suitable for gas sensor data fusion.
- Sensor data fusion and decision-making: To detect and estimate gas concentration or draw other relevant conclusions.
- Validation of fusion results: Assessment of results by comparing them with reference measurements and evaluating the performance of the fusion system concerning accuracy, false alarms, detection of threshold levels, and response times.

Continuous real-time monitoring of environmental factors and evaluation of the system’s effectiveness to ensure compliance with the safety standards in underground mining operations, as well as the reliability and efficacy of the fusion system in critical conditions.

7. Conclusion

The introduction of environmental monitoring systems in underground mining operations offers multiple advantages, including enhanced safety and health for mine workers, adherence to regulatory requirements concerning environmental monitoring and emission reporting, increased efficiency, and reduced costs by swiftly identifying and resolving environmental challenges. Wireless communication technologies like ZigBee or LoRa provide a more straightforward and specialized approach designed primarily for facilitating wireless communication between devices to track environmental conditions with low power consumption and affordability for small mine operators. The ZigBee system offers a mesh network setup, enabling various devices to communicate with one another and extend the network's reach. In contrast, the LoRa network operates on a star configuration, where all devices interact with a central gateway. The choice between ZigBee and LoRa will be guided by the unique requirements of the application, taking into account aspects like range, power usage, data transmission rate, network structure, and cost. However, the prolonged installation of ZigBee and LoRa wireless communication systems isn't suitable for long-term use in underground mines. The suggested IoT-enabled LoRaWAN gateway environmental monitoring system will provide benefits to underground miners and organizations by addressing safety and productivity issues over an extended period. Additionally, a dashboard located in the surface control room will showcase real-time monitoring data, allowing for a clearer comprehension of the underground mining atmosphere. Moreover, machine learning methods will analyze the gathered data to detect hazardous zones ahead of time, enabling proactive measures to minimize risks and enhance working environments. The adoption of this proposed system will be both cost-effective and efficient for ongoing real-time tracking of environmental factors in underground mines for an extended duration.

Compliance with ethical standards

Disclosure of conflict of interest

There is no conflict of interest.

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