Journal of Mining and Environment (JME) Vol. 15, No. 3, 2024, 923-942

Shahrood University of Technology

Journal of Mining and Environment (JME)

Journal homepage: www.jme.shahroodut.ac.ir

Iranian Society of Mining Engineering (IRSME)

Applications of IoT Framework for Underground Mine Safety: Limitations and Solutions

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Article Info

Received 27 November 2023

Received in Revised form 15 January 2023

Accepted 23 January 2024

Published online 23 January 2024

DOI: 10.22044/jme.2024.13868.2584

Keywords

Wireless sensor network

Wireless communication

Underground communication

Safe mining

Ambiance monitoring

Abstract

The environmental conditions present in underground (UG) mines working site significantly impacts the productivity, efficiency, effectiveness as well as threatened security levels. Consequently, maintaining safety in mineral excavation process requires continuous monitoring of the intricate and perilous operating conditions within the mining work site. At this juncture of time, in this information age, when all walks of life are undergoing continuous modernization, with today's workplace being no exception, Internet of Things (IoT) technology is playing a key role in acquiring relevant information to support monitoring vital operational man and machine safety parameters such as temperature, pressure, humidity, luminance and noise levels, and miner's location in subterranean mining operations. This study has attempted to exhaustively explore state of current research on the use of IoT in underground mining applications. This paper examines the utilization of IoT applications for monitoring several environmental parameters, including obnoxious mine gases and dust concentrations, temperature, humidity, groundwater levels, and strata behaviour to facilitate ground support activities. This paper attempts exploitation of possible scopes of IoT integration from the implementation perspective to monitor and control the various aspects that contribute towards various types and incidents of mine accidents. This research elucidates the primary obstacles that impede the widespread implementation of IoT-enabled systems in underground mining applications.

1. Introduction

The extraction of minerals plays a pivotal role in advancing global societies since these valuable resources are extensively utilized across the value chains of many sectors. The global mining industry encounters numerous challenges including extreme mining conditions characterized by more profound and steeper deposits, a diverse spectrum of environmental issues encompassing safety concerns and various neighborhood responses to mining activities, and significant geotechnical and geological obstacles [1]. By considering these environmental and operational considerations, along with monitoring pertinent environmental and structural factors, the placement of personnel and equipment, and the oversight of mining personnel, it is possible to effectively enhance the productivity, efficiency, and safety of underground (UG) mining operations. In response to these challenges, the mining sector has used a range of advanced technical interventions that have yielded enhanced efficiency and safety outcomes, alongside a reduction in environmental apprehensions. Like numerous other industries, the mining sector is adopting digital transformation to achieve heightened degrees of automation. Most current electronic mine automation and monitoring instrumentation systems are built utilizing discrete, non-wireless components. Implementing wired network systems for establishing connectivity in UG mines may not be suitable in certain places due to the potential risk of connection failure. Numerous evaluations have demonstrated that unintentional connection

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damage is the prevailing factor contributing to monitoring equipment failure. When an operator is required to approach or transport the monitoring equipment to obtain data manually, there is an increased likelihood of human error, a potential threat to personal physical safety during operation, and challenges related to occupational health.

In contrast, a wired connection is characterized by higher costs, susceptibility to damage, and frequent malfunctions. A dependable and efficient communication system is necessary to conduct operations without potential risks [2-4]. Utilizing a vast array of sensors facilitated by IoT technology holds significant promise in enabling real-time monitoring of UG mining operations. The mining industry has witnessed extensive use of IoT due to advancements in communication and sensor technology. The compact dimensions, lightweight construction, and energy-efficient operation of IoT nodes enable them to surpass the constraints imposed by wired systems effectively.

Furthermore, wireless solutions offer a high degree of flexibility in implementation, allowing for easy setup and dismantling processes. In an IoT-based system, data acquisition is done by sensors, while actuators are responsible for system calibration and alerts in anomalous circumstances. The IoT presents potential solutions to enhance real-time monitoring of mining activities, predict accidents, optimize processes, and effectively manage personnel and equipment.

Several comprehensive reviews have previously been conducted, with a specific emphasis on the utilization of IoT technology for communication and environmental monitoring within UG mining operations. The merits and limitations of the reviews discussed above are summarized in Table 1.

Table 1. Abstract of related works.

Ref.	Subject matter	Significance	Shortcomings
[5]	Environment monitoring of UG coal mine	Insights to WSN application for mine environmental monitoring.	The scope of this study was limited to wireless communication methods deployed in IoT applications in mines.
[6]	Application of WSN for UG coal mine environment monitoring	Explores the concept of intelligent mines that leverage the capabilities of the Internet of Things (IoT) with a comprehensive overview of the application of WSN.	The difficulties of implementing the IoT have not been explored.
[2]	UG mine communication systems	Study examines UG mine communication systems.	UG mine IoT applications have not been presented.
[7]	UG mine communication and propagation modeling	Overview of wireless communication systems, common uses, and methods for modeling signal propagation	UG mine IoT applications have not been presented.
[8]	IIoT in the mining industry	Analyzes the current state of information technology and presents an IIoT architecture suitable for the mining industry.	Limited review of IoT applications in mining.
[9]	TTA communication in UG mines	Investigated the influence of tunnel shape and antenna characteristics on the performance of TTA communication systems.	IoT application in UG mine is not discussed.
[10]	UG mine communication systems	Investigated resiliency of IoT connectivity in UG mining environments and their security issues.	Highly centered around the usage of IoT in UG mines.

The studies mentioned above primarily focused on using the system's communication and data processing protocols. The investigation did not consider technical aspects and potential use cases for wireless networks in UG mines. The exploration of possible future avenues for study in IoT within the context of UG mining has yet to be thoroughly examined. This report presents a state-of-the-art review of the development of IoT-enabled wireless systems for use in mining environments. It centers on the impact of automation and information technology on enhancing worker safety and productivity within the mining industry. This study aims to elucidate the potential of digital advancements in improving communication and data-gathering methods within the mining industry. The primary objective of this work is to provide a comprehensive understanding of integrating IoT applications into UG mining safety for scholars and practitioners. This article provides an in-depth examination of the application of IoT technology and its potential utilization to monitor and manage the diverse factors contributing to accidents and injuries within the mining industry. It also investigates the adaptability of the mining industry to Internet-based systems, identifying the key challenges and further research directions.

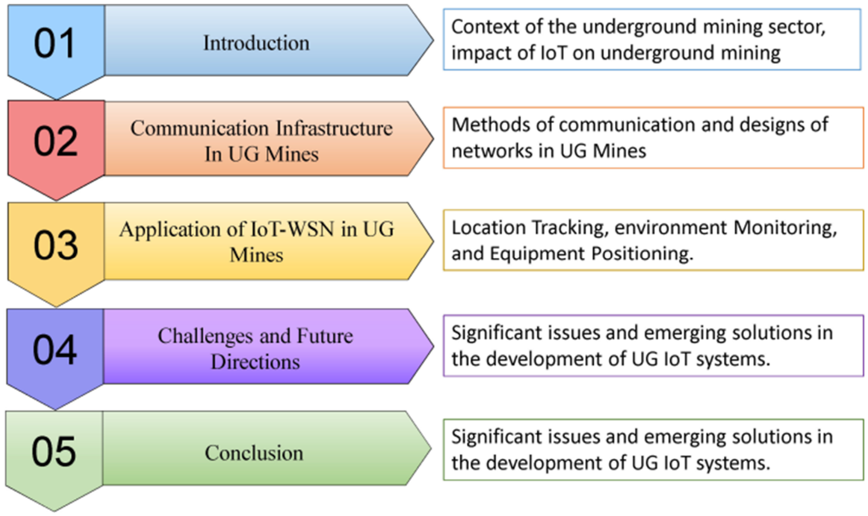


Figure 1. Graphical presentation of the organization of the paper.

2. Communication Infrastructures in UG Mines

Communication must be solid and practical in underground mining operations, just as in other industrial business types. In the mining sector, communication is the most critical aspect in guaranteeing the health and safety of the workers required to perform their jobs underground. A solid information technology communication system in underground mining will boost security and give real-time information, allowing for a quicker response to potentially deadly events [4]. Communication technologies capable of withstanding the rugged terrain and extreme environment within a mine and between the surface and underground workstations are essential to remotely monitoring the various underground mining operations. Different approaches exist to break down the underground mine's communication infrastructure (see Figure 2).

2.1. Wired communication

Fiber optics transmission is one of the most prevalent forms of wired communication in mining. Data transfer in a communication system that uses fiber optics is accomplished by converting electrical signals to light signals. Initially, an optical transmitter undertakes the conversion of electrical signals into light signals. Then, the optical receiver receives optical signals across a visual fiber line. In conclusion, an optical receiver is necessary because it reestablishes the connection between optical impulses and electrical signals [12]. Fiber optics are easy to transport, reliable, have short latency, are intrinsically safe, and prevent interference [13]. It provides the highest degree of adaptability for use in the communication systems of UG mines compared to other cables. Within an underground mine's communication system, optical fibers are permanently employed as the backbone network to join the various networks [14]. In deep mines, one of the communication methods that combine wired and wireless connections is the leaky feeder. This is one of the methods that are used the most frequently. Radio signals are transmitted and received through the tunnel by a leaky feeder system that uses a coaxial radiating wire [15]. Along the length of the leaky feeder, amplifiers have been placed at predetermined intervals ranging from 350 to 500 meters to compensate for the loss of signal [7]. Table 2 depicts a comparison of the properties of several wired systems.

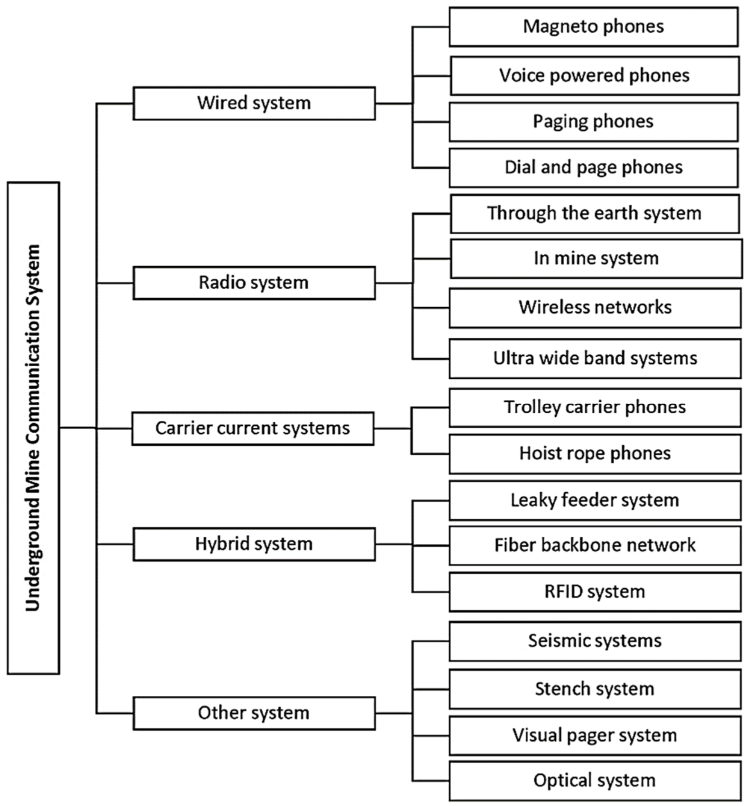


Figure 2. A taxonomy of underground mine communication infrastructures [11].

Table 2. Wired communication system characteristics comparison.

Characteristics	Wired Infrastructure Technology				
	Telephone	**Paging**	**LAN**	**Optical**	**Leaky feeder**
Media	Copper cabling	Mixed type	Coaxial	Fiber optic	Radiating cable
Investment	Low	Low	Low	High	Moderate
Complexity	Simple	Simple	Moderate	High	High
Latency	Low	-	Low	Low	
Safety	Yes	-	Yes	Yes	High
Resiliency	Good	-	Good	Good	Good
Free from interference	Electrical	RF	Possibility of electrical disruption	Yes	No

2.2. Wireless communication

Connectivity issues make it more challenging for underground miners to join external networks than open-pit mines. The wireless network system uses WiFi (IEEE802.11), Bluetooth (IEEE802.15), and WiMAX. Data transmission using Ultra-Wide Band, IEEE 802.15.4 guides ZigBee, a new wireless technology. It replaces non-standard technology for broad control applications. The IoT-WSN-based system has the potential to play a significant role in mining operations, contributing significantly to the improvement of worker safety while also boosting overall production. Underground mine communication mainly relies on wireless communication, an IoT-WSN infrastructure component. In recent years, there has been a rise in the number of initiatives to combine a variety of sensors with IoT to monitor the environment in mines.

Prashanth et al. [16] detected vibrations in open-pit mines with the help of an accelerometer and a radio frequency (RF) module. These vibrations were caused by blasting. To make it possible for miners to communicate with one another while they are working in an underground mine, Gangwar et al. [17] designed a miniaturized antenna system that could be used in conjunction with a global mobile communication (GSM) network. Much research has been carried out on air monitoring in mines using IoT technologies such as Bluetooth, Wi-Fi, and ZigBee [18–22]. These studies range in number from three to nineteen. Several Internet of Things (IoT) technologies are capable of wireless communication. Some examples of these technologies are Bluetooth, near-field communication (NFC), Wi-Fi, and ZigBee. The specific context and reason for the connection will determine which of these technologies is utilized. In recent research [23, 24], ZigBee has been employed to construct WSNs in tunnels and mines. However, most research focuses on conceptual design or communication between a small number of devices, and even fewer systems are available that can be used in the real world to continually collect data from a large number of nodes while also taking their battery life and data load into account. Table 3 depicts the comparison of wireless technologies.

The mining industry extensively uses radiofrequency identification (RFID) and other forms of radiofrequency technology. Asset tracking and security access control are two common uses for passive RFID tags [25, 26]. Active RFID devices allow for the precise tracking of mobile assets and workers in real-time since their communication range is much greater than passive RFID tags' 5–10 meters [26]. This is compared to passive RFID tags, which only have a range of up to 100 meters in open regions [27]. The utilization of RFID systems in the mining industry is broken down and summarized in Table 4, which is organized according to the frequency of operation.

Table 3. Comparison of wireless communication technologies [28].

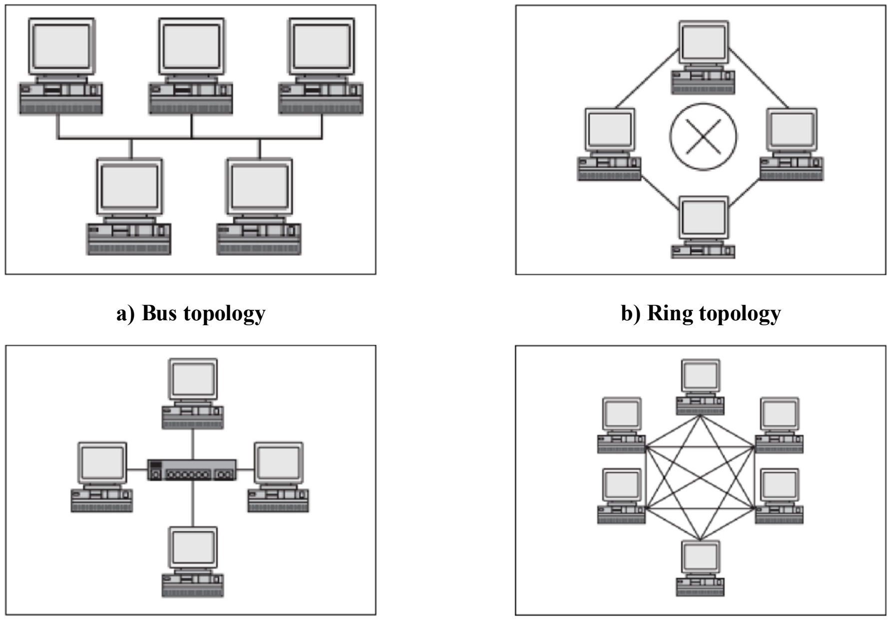
Wireless technical standards	GSM/GPRS	Wi-Fi	ZigBee	Bluetooth	LoRa
System resource requirement	> 16 MB	> 1 MB	4 KB-32 KB	>250 KB	> 300 KB
Data rate (Kbps)	64-128	1-100	20-250	1000	0.5-50
Power waste	High	Moderate	Low	Moderate	Low
Applications	Data and voice transmission	Web access and video	Wireless detection and control	Short distance transmission	Data communication
Frequency	800-2100 MHz	2.4 GHz	868/ 915/ 2.4 GHz	2.45 GHz	863-928 MHz
Coverage	> 5 Km	450 m (802.11n)	100 m	10m	Up to 15 Km
Deployment	Cellular	Independent	Independent	Independent	Independent

Table 4. RFID application in mining industry [27].

Frequency	RFID type	Application areas
131 KHz	Active	Asset detection in flood condition
13.56 MHz	Passive	Access control
433 MHz	Active	Environmental monitoring and communication
900 MHz	Passive	Resource localization
2.4 GHz	Active	Mobile personnel and equipment localization

2.3. Network topology

The communication system's network topology of a UG mine refers to the layout of the devices used for communication and the path the data takes as it travels from one device to another (whether wired or wirelessly) [29]. Underground communications in locations with complicated topographies can be made highly dependable and robust with the help of a proper network topology design. Figure 3 presents several examples of network topologies frequently implemented in underground mines.



a) Bus topology **b) Ring topology**

c) Star topology **d) Mesh topology**

Figure 3. Network topologies used in underground mines [30, 31].

Each node in a bus topology as shown in Figure 3(a) is connected to the bus directly. As a result, all of the data is sent down the bus and is accessible by all of the nodes that are linked to it. Bus topology's transmission capacity limitation causes network traffic despite its ease of wiring and scalability. This is despite bus topology's straightforward wiring. In the meantime, determining where the problem lies can be difficult with such a straightforward framework. CAN, also known as the controller area network bus, and RS485, also known as the serial 485 bus, are two examples of conventional bus topologies. All communication devices are connected in a ring topology, as shown in Figure 3(b), which is an enclosed and around structure. Data packets make their way across the ring layout when using it, stopping at each node before arriving at the node that will serve as their final destination. This layout is more straightforward and conveys information across great distances.

However, because the failure of a single node might fail the network as a whole, this structure has subpar efficiency in terms of both reliability and problem diagnostics. A ring topology is always utilized for underground mines' optical fiber backbone networks. As seen in Figure 3, a central hub organizes and transmits messages to each network node. This construction can tolerate failure at joint points and can diagnose problems. However, the effectiveness of the network is mainly dependent on its hub. This is because a malfunction in the central hub might result in the malfunction of the entire network. The star topology as shown in Figure 3(c) may be used for the network in the control center of an underground mine. Figure 3(d) shows a complete mesh architecture, where each device in the network can establish direct communication with different devices over a point-to-point link and share data. Implementing partial mesh topologies is done to cut costs and simplify the system. In this topology, most nodes are connected, whereas only a select few are connected to a small group of other nodes. Due to their endurance and reliability, sensors prefer mesh topologies for underground mine interactive communications. Data transport requires routing algorithms and flow control measures.

3. Application of IoT-WSN in Underground Mines

WSNs are currently being implemented in underground mines, a research field still in its infancy [6]. Figures 4 and 5 illustrate the required elements of the IoT-WSN system and its application in different areas. The voluminous corpus of research on wireless communication and environmental monitoring in underground coal mines is condensed into a comprehensible format [5]. Recent work at the Shangwan Coal Mine in Erdos, China [32] resulted in the installation of a highly dependable and cutting-edge intelligent system. They enhanced a cable environmental monitoring system constructed into a WSN earlier in the project. This system can undertake environmental monitoring, in addition to having the capacity to be examined regularly and having the ability to be shut down. In a bord-and-pillar mine, a technique for early fire detection that uses alarms was deployed as part of a wireless sensor network (WSN) [33, 34]. The feature of this technology that has the most promise is its capability to detect flames early and pinpoint their position within an underground mine. This is the aspect that holds the most promise. Several studies have used WSNs in real-world underground situations to improve safety and productivity [35, 36]. Emergency and non-emergency communication in deep coal mines use the minimal delay maximum longevity (MDML) routing approach [37]. MDML is its name. This method was developed specifically for wireless routing. Jin-ling et al. [38] used virtual multiple-input multiple-output (V-MIMO) and orthogonal frequency division multiplexing to solve diffraction, attenuation, and scattering in deep mine wireless sensor networks.

Compared to a straightforward single-input and single-output (SISO) system, the simulation results demonstrated an improvement in the dependability of wireless transmission and a decrease in the bit error rate in deep mines. To find miners, Li and Liu [39] created a Structure-Aware Self-Adaptive (SASA) Wireless Sensor Network (WSN) based on stationary mesh nodes. In deep coal mines, this system employs a conventional beacon technique for detecting falling roofs, and it also does some environmental parameter monitoring on a more limited scale. WSNs with a variety of indoor localization algorithms have seen widespread implementation. Some of these algorithms include RSS, time-of-arrival (ToA), time difference of arrival (TDoA) [40], and angle of arrival (AoA) [41]. RSS-based indoor localization has recently seen a surge in popularity due to the ease with which it can perform calculations and the fact that it can accurately predict the position of a mobile node (MN) without any additional hardware [42]. An RSSI strategy for indoor localization utilizing Bluetooth nodes was suggested by Akeila et al. [43], who claimed that their method had a lower accuracy error. A sensing platform developed by Qandour et al. [44] and was based on the Wasmote that Meshlium gateway was presented. With the installation of the data-forwarding strategy, this platform made it possible to have improved wireless (ZigBee/802.15.4) communication between the sensing platform and the routing nodes (RNs). Cloud services were introduced by Bychkov et al. [45] for mining informatics and information management. This was in addition to everything else. In a nutshell, the localization of miners, tracking of miners, monitoring of gas levels, and identification of events, all based on online cloud services, may be efficiently integrated into a single platform to improve underground coal mine safety further.

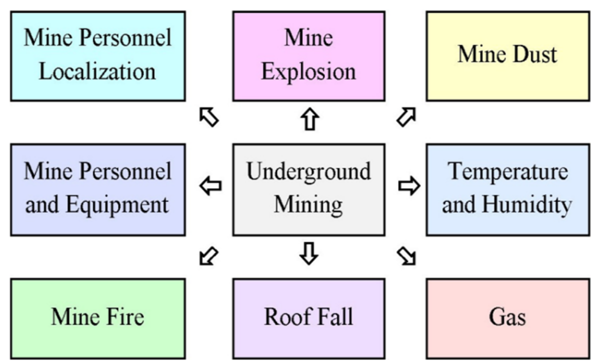


Figure 4. IoT enabled WSN framework for monitoring environmental parameters of an underground mine.

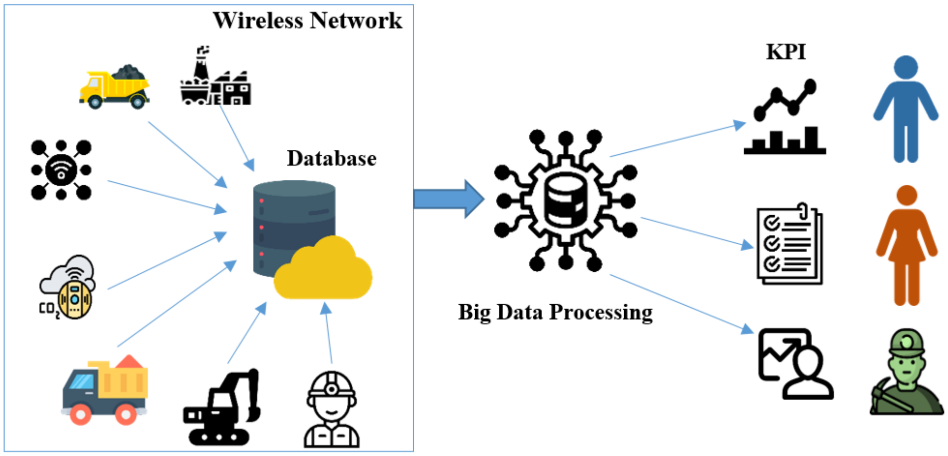


Figure 5. Components of IoT-WSN-based systems in the mining industry.

3.1. Location monitoring in UG mines

One of the challenging tasks for mine management is to locate the trapped miners effectively with exact numbers in case of disasters. Location monitoring data becomes vital in assessing the damage and initiating an immediate rescue. Any delay in rescue operations significantly decreases its success rate. Most mines use a manual tracking system to watch over the mining personnel, which has several limitations. The safety management system of a UG mine will receive a massive boost with the incorporation of wireless system-based real-time monitoring and tracking of miners and mining gadgets. It will help to restrict the illegitimate access of the work party to a risk zone [46, 47], and facilitate rescue operations during an emergency.

In [48], WSN-based video transmission was reported to monitor mine tunnels remotely. The braided cooperative, reliable transport (BCRT) algorithm ensures end-to-end transmission reliability. With the help of forwarding neighbors, the data rate is adjusted, thereby improving the sensing reliability. In a UG, mine sensor nodes are placed at critical junctures for monitoring and early system. In positioning zones, the central ground station can get updates on subterranean workers' locations. However, in the subsurface system, their global positions within the blind areas must be approximated numerically. With the help of this, the risk of accidents can be easily minimized. [49] reported the use of WSN based personnel positioning scheme to cover the blind areas in the tunnel network. It gathers the real-time location of the miners via the sensor positioned at the critical locations, which are further transmitted to the surface to a central computer system. Upon correcting, the error involved in the sensing data numerical computation is used to estimate the 3D location of miners. The authors [50] proposed an improved DV-Hop localization algorithm based on WSN for the tracking of industrial personnel. It was reported that the DV-Hop positioning algorithm effectively estimated the miners' location, thereby improving the localization of the distributed WSN. In [51], the authors established an IoT framework-based safety system with safety diagnosis, inspection, and emergency rescue systems. The developed method could monitor and record production systems along with location information of underground equipment and miners. It also incorporates cloud-based big data analytics for quick analysis. The platform was said to enhance the safety of coal mines through precise danger-spotting and decision-making capabilities. [52] presented the design of a WSN system equipped with Self-organization. As UG mine conditions are very harsh, a WSN equipped to construct network topology without human intervention becomes highly effective, as onsite technical service could be more workable. The paper's authors [53] constructed a local personnel placement approach in deep mines using sensor nodes based on Wi-Fi. Dynamic sensor nodes have been built with a mode that allows them to enter a deep sleep state and is powered by batteries that have a high capacity. The researchers [54] showed that it is possible to track the location of dump trucks working within an underground mine (limestone) by installing Bluetooth beacons supplied by rechargeable batteries along the haul routes. Additionally, [55] discussed a LoRa-based crisis locating system. In this system, a linear wireless sensor network transmits the location of underground mining workers and equipment if the communications infrastructure fails. The paper's authors built an underground limestone mining helmet [56]. BLE-based proximity detection and warning were in this helmet. The intelligent helmet's Bluetooth low energy (BLE) module may receive signals from dangerous machinery and regions on mine sites' Bluetooth beacons. An innovative RFID design for performing proximity detection was introduced [57]. This system came out with a new piece of hardware known as the "Sense-a-Tag," designed to passively receive and decode signals sent by standard RFID tags in the surrounding area. Researchers [58] created a two-way-ranging UWB module for precise tracking and proximity detection in underground mines. According to the field test, the UWB module can alert miners to approaching locomotives.

Table 5. Summary of technologies used in UG positioning/localization [59, 60].

Technology	Algorithm	Accuracy	Coverage	Application
RFID	RSS	Medium	3 – 300 m	Miner/Resource Tracking
WiFi	RSS	Medium	50-150 m	Miner/Resource Tracking
ZigBee	RSS	Medium	20-30 m	Miner/Resource Tracking
BLE	ToA, AoA	Medium	30 m	Miner/Resource Tracking
LoRa	RSS	Low	5 km	Emergency localization
UWB	TDoA	High	10 m	Proximity detection

3.2. Ambience monitoring in mines

Safe mining in an underground setting presents a unique set of issues. Toxic gases, roof integrity, flames, and explosions all fall within this category. Continuous environmental monitoring is required to ensure that employees can do their jobs in a safe atmosphere free of harmful substances (see Figure 6). The contemporary mining industry has greatly improved worker safety by instituting various safety standards and processes and training mine workers on safety measures. Nevertheless, underground mining is a dangerous industry with harsh working conditions that will only improve once serious action is taken.

Many studies reported the development of prototypes capable of collecting environmental data by employing gas, temperature, humidity, and noise and dust sensors. These parameters significantly influence the safety and well-being of UG miners. [61] reported the development of a ZigBee WSN-based real-time monitoring system for coal mines. The system can record and transfer temperature, humidity, and gas variations to the surface computer. It triggers a warning as the monitored parameters go beyond the specific group. [62] proposed ambient environment system for UG mines. The deployed nodes collect humidity, temperature, and gas data and send it to the collector node via ZigBee protocol. A GUI/ computer is used to visualize the measured parameters for a particular zone of the mine. [63] reported the application of GSM and ZigBee for monitoring unsafe conditions. The system continuously gathers vital environmental parameters and sends them to the surface station through ZigBee technology. The surface station can send an emergency message to the safety department when the monitored parameters exceed the critical value.

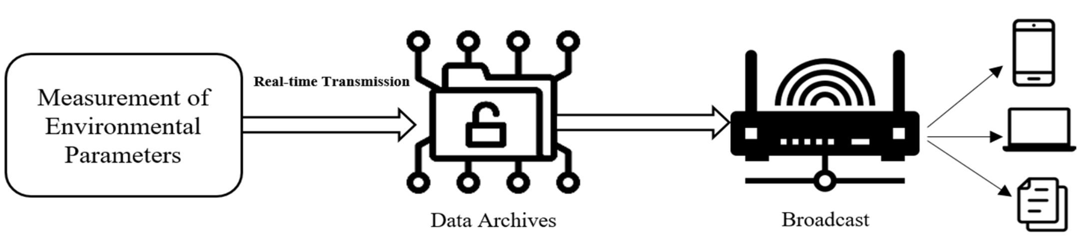


Figure 6. An automatic framework for environment monitoring system for mining industry.

Table 6. Abstract of literature reviewed to study and assess the industry practices of implementation.

Ref.	Communication technology	Application Area	Remark
[61]	ZigBee Radio-based WSN	Noise level measurement	Field experimentation study
[64]	Wireless sensor network	Roof fall detection	Field experimentation study
[65]	Numerical modelling	Detecting the collapsed hole	Simulation work-based study
[66]	Wireless sensor network	Total incombustible content measurement	Field experimentation study
[67]	ZigBee radio based WSN	Indoor CO_2 monitoring	Lab experimentation and simulation study
[68]	ZigBee radio-based WSN	Underground coal mine environment monitoring	Lab experimentation and simulation study

3.3. Groundwater monitoring

The process of underground mining is regularly interrupted by water inrush. It poses a significant risk to the health and safety of mine workers, and the direct discharge of untreated groundwater can damage the surrounding ecosystem [69]. To address these issues, the Internet of Things has offered the technical support necessary for precise and real-time groundwater monitoring in underground mines. An overview of leveraging the Internet of Things to improve mine water management was provided in reference [70]. The amount of water, temperature, pH value, electrical conductivity, and dissolved oxygen are some physicochemical parameters of on-site mine water that are monitored using wireless sensor networks. Other qualities being monitored include electrical conductivity. RFID tags were affixed to the water sample bottles used in the mining operation to track and record the most basic sampling information.

An Internet of Things-based online mine water monitoring tool was developed by Bo et al. [71] to characterize the quantity and quality of mine water in real-time. The system in question used a connected multisensory network to accomplish the task of data collecting. This network comprised level sensors, pH sensors, suspended particle sensors, water oil sensors, and conductivity sensors. An Internet of Things platform was developed by Yan et al. [72] with the intention of real-time monitoring of the water level, temperature, flow, and quality (i.e., salinity and specific ions) of the water supply for the coal mine. After that, the data that had been acquired was sent over wired and wireless networks to the cloud service platform to undergo additional data management and analytics. RFID technology and quantum computing were presented [73] as the foundation for a mine water management system. This system would manage mine water in all forms, including precipitation and groundwater. Pumps and sensors with RFID tags would monitor water circulation in the mine shaft in real-time. Furthermore, quantum computing allows for rapidly analyzing massive amounts of collected data.

4. Discussions on Scopes, Challenges, and Mitigations

The IoT-WSN has excellent potential in the mining industry, especially for optimizing the administration of facilities and equipment (see Figure 7). Connectivity in real time and analytics of collected data hold significant promise for enhancing the operational effectiveness of mines, both now and in the future [74]. However, even though the Internet of Things technology can significantly improve underground mining operations, the industry must catch up to other sectors adopting these technologies. This section highlights potential future approaches and addresses the crucial issues that need to be overcome when developing and implementing technologies in underground mines based on an Internet of Things foundation.

4.1 Challenges unique to the mining sector

In the beginning stages of mining, a very high investment is required. In most cases, there is only a possibility of making a profit once continuous mining operations are initiated. It is reasonable to anticipate that a mine will continue operating for several decades. During this period, there was a general trend of price instability in the market for minerals. Mining firms are hesitant to make extensive modifications that affect their operations and break the flow of continuous production because doing so could maximize the value of the mine throughout its lifetime. As a result, the mining industry has a well-deserved reputation for being not known for innovation but rather for being a quick follower.

4.2 IoT architecture standardization

The Internet of Things (IoT) is experiencing slow growth due to the industry's inability to agree upon architectural standards. Internet of Things (IoT) systems that could be better conceived and deployed, involving devices and protocols from various manufacturers, add a layer of complexity. It still needs to be possible to select and construct the Internet of Things architecture most appropriate for underground mining while addressing the issues influencing each Internet of Things component (shown in Figure 8) [75]. This remains an unresolved question.

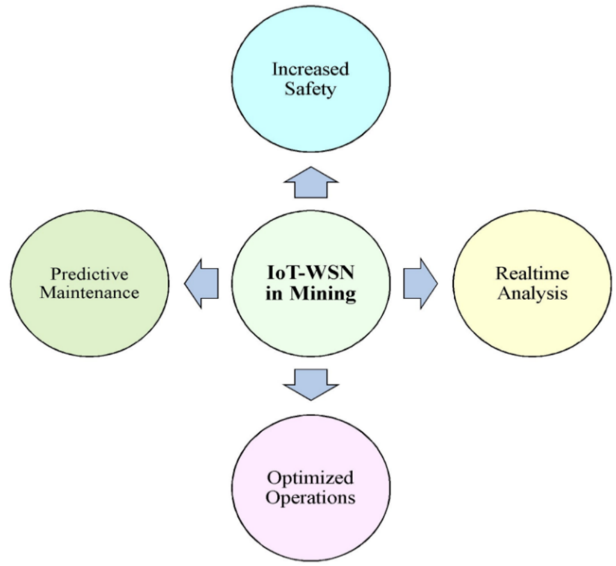


Figure 7. Positive effects of IoT on the mining sector.

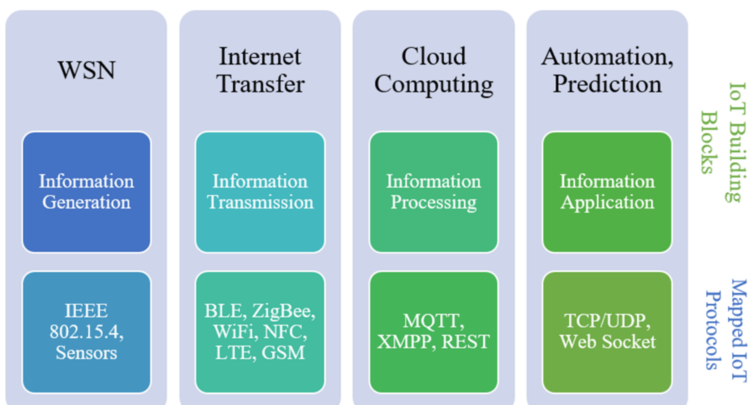


Figure 8. IoT building Blocks and mapped protocols.

4.3 Impact of mine condition on communication system

Underground mines can vary significantly from one another in terms of both their layout and their current mining status (see Table 7). Standardization may be challenging and come at a high financial cost if the Internet of Things applications used in underground mines must be designed according to the mine's operating conditions. Despite all the possible challenges involved in developing, implementing, and maintaining wireless communication systems, it is essential to provide consistent and trouble-free connectivity to ensure the safety of the workforce. Research has already been done to forecast and examine the signal behavior in an underground mine's tunnel space. In addition, many study results only apply to test or experimental mines. Therefore, the real-time propagation environment of active mine workings is not recorded.

Table 7. Environmental features of underground mines [76].

Characteristics	Remarks
Structure	Unevenness and roughness of the walls/ceilings cause drastic attenuation of the radio signal
Limited LOS	Presence of structures of different shapes and sizes
Waveguide effect	Operational at certain frequencies only
Ionized air	Impact on signal attenuation
Temp and humidity	As the depth increases, the rise becomes more noticeable, altering the propagation characteristics.
Gases	In the presence of explosive gases and fumes produced by fuel-powered engines, an explosion is possible.

An explosion is possible due to explosive gases and fumes produced by fuel-powered engines. Temperature increases with depth are common in mine shafts due to the geothermal gradient characteristics [77]. These adjustments to the working depth shall inspire researchers to look into how depth affects the properties of radio signals and how far apart sensor nodes may communicate. To expand upon this, investigators shall consider straight mining tunnels and galleries with varying cross-sectional dimensions and sharp turns and curves. These two analyses of the propagation environment could help isolate the factors that led to low signal strength and additional losses. The effects of humidity and temperature on wireless sensor network connections were also studied and reported in [78]. In addition, Mottola et al. [79] performed an in-depth study on the influence of environmental elements on WSN in connection to different kinds of road and rail tunnels. Research claims that the physical layer is not significantly impacted by changes in temperature or humidity below a particular threshold, whereas performance suffers beyond.

The route loss of a signal is a significant problem in underground mines. Communication systems in the hazardous environment of mines have characteristics that make reliable functioning difficult. As the signal moves away from the transmitter, the route length in a mine's gallery is drastically reduced due to unbalanced geometric factors. Attenuation factors are proportional to link distance and inversely related to transmitted signal power [80]. Because temperature and humidity change the dielectric medium in deep mines, signals are absorbed by it [81]. Underground mines and the mining equipment required to collect minerals can have reflective surfaces, which can interfere with the propagation of signals. The reflection of the signal of these obstacles results in multipath propagation, which produces signal fading and oscillations [9]. Delay spread is an effect of the dispersive nature of the channel and occurs when a signal must traverse multiple channels before it reaches a receiver.

As one of the most widespread radio technologies, Zigbee may be used to create a wireless sensor network. Recent projects implementing Zigbee technology in underground mines are presented in [82-86]. Nevertheless, the specifics of underground mines dictate the necessity of diverse communication technologies. Uneven ground, high humidity, and water seepage all play a role in determining the optimal mode of underground and underground-to-surface communication. [87]. Javaid et al. [88] investigated the effects of several degrading variables on wireless networks operating in the 2.4 GHz to 5 GHz frequency spectrum, commonly used in underground coal mines. Complex mine segments' electromagnetic signal transmission qualities were investigated using line-of-sight (LOS) links. In addition, a multimode waveguide model and a geometrical optic (GO) model hybrid channel modeling technique were proposed for use in coal mine communications. The study also evaluates the received power at the receiving point, discovering that the attenuating factor has less impact at lower frequencies of the UHF band in mines, leading to higher received power. Using usage examples, Theissen et al. [89] examined wireless communication alternatives for complex underground mining operations. It discussed the challenges of working in harsh mines. It developed a taxonomy for classifying mining technologies according to their intended applications, such as automation, tracking, and long-distance subsurface monitoring. For dependable and efficient communication networks in the face of limited line-of-sight concerns and subterranean gaseous threats, the authors proposed a multimode channel model as an analytical channel model. The delay spread increases when the same signal is sent over different distances. This is because as the transmission distance rises, the propagation delays between the modes and frequency elements become more and more dissimilar. Kumer et al. [90] looked at radio wave propagation in the ISM band while passing through tunnels and buildings that mimic tunnels. It proves that both real-world and artificial PDPs have wave-guiding properties in the form of tunnels. Information about radio wave propagation in different tunnel environments is provided, and the study also investigates how tunnel diameters affect the mechanics of radio wave propagation. The study found tunnel dimensions significantly impacted wireless channel models for tunnel environments, and tunnel-specific wireless channel models had to be built to predict received signal strength along the tunnel. Combustible petrol emissions are a significant cause of communication signal disruption. The potential for a gas explosion increases whenever their concentration rises above a certain threshold. Therefore, it is always necessary to limit disaster risk by evacuating. Nath et al. [91] proved the feasibility of real-time data transmission from a mine to an IoT platform by developing a gas sensor with high selectivity and sensitivity. To provide immunity to WiFi connectivity, the requested task can be accomplished using through-the-Earth (TTE) communication, which links deep layers of rocks and earth using low-frequency radio waves.

Similarly, Chehri et al. [92] disclosed the experimental results of characterizing the UWB channel in deep mines, focusing on the importance of the communication channel in these settings. The primary objective of the research was to provide a realistic description of UWB propagation to lessen the effects of multipath fading in transmitter and receiver systems. It must be understood that an explosion or other calamity may also alter the EM signal's transmission properties, breaking the connection. In challenging environments, LOS links improve wireless communication quality because waves can propagate directly toward the receiver instead of being deflected by barriers or reflected by corners, which cause significant attenuation. Tunnels and room-and-pillar structures make long-distance communication difficult in subterranean mines.

Mineral exploration techniques, geological settings, ore body orientations, and mining practices can all vary widely between subterranean mines. It is vital to know how mining methods influence signal propagation while developing the wireless infrastructure. Conducting such a study would shed light on the issues that affect wireless signal propagation and explain why wireless signals vary from mine to mine. It is important to note that while cut-and-fill or sublevel stopping procedures are commonly used in metal mines in India, room-and-pillar and longwall mining are the most common methods of coal extraction. Ranjan et al. [76] gave three separate scenarios with varying deployment parameters to illustrate the impact of the mining strategy on signal transmission. The link was characterized by indicators of received signal strength and packet reception rate.

Table 8. Wireless measurement context [76].

Straight mine zones	Frequently used for access to adjacent minefields and for transit
Near face zone	The site of the current mining activity, where numerous miners work together in an environment characterized by close quarters, high humidity, poor illumination, and erratic dimensions.
Curved mine zones	Regions with asymmetrical dimensions

Philip et al. [93] investigated the performance of LoRa in a UG gold mine. In both extraction and access tunnels, measurements were taken for LoS and Non-LoS scenarios. The author created different measurement scenarios by placing nodes at different positions. Radio signal behavior was understood by measuring the received signal strength indicator and signal-to-noise between transmitter and receiver nodes at different spreading factors. Shahid et al. [94] conducted experiments to analyze the radio link concept of an underground mine sensor network. The model takes into account power efficiency, range, and radio wave propagation for applications with modest data rates. Tight tunnels, non-line-of-sight, and metallic conditions hamper wireless signal propagation. Data congestion and delays may occur due to limited network coverage and low data rates. A lack of bandwidth can cause both. As a result, LoRa and 5G must be researched further to enable cost-effective, real-time subsurface connectivity. Another wireless solution for underground mine communication is visible light communication (VLC), which is especially useful in radio frequency-hazardous environments [95, 96]. When radio frequency communications fail, a VLC system can locate personnel.

4.4. Need of alternate energy source

Underground mine communication systems are only sometimes capable of tracking and finding. The accuracy of positioning individuals and equipment in underground mines is influenced by the design and arrangement of the communication network, as signal metrics are used to predict their locations. However, signal multipath effects and unpredictable propagation in dynamic subsurface environments can make precise localization difficult. The enhancement of positioning accuracy and range necessitates a substantial amount of energy for signal transmission and processing.

Because most renewable energy sources cannot be reached underground, power cables are the primary source of electricity used in underground mining activities today. Therefore, underground mine IoT and WSN devices must be powered by power lines or batteries. Owing to the constrained duration of battery performance, the IoT system's compact and energy-efficient wireless sensor modules would still need to be updated often. Underground mine replacement can be difficult and dangerous. By acquiring a limited quantity of the energy lost by working machinery in underground mines, energy harvesting methods can be used to replenish energy charge the batteries of low-power electronics. These methods can also be used to test the batteries in small electronic devices. These methods might help in this situation if they are used. Most methods use piezoelectricity, electromagnetic fields, and electrostatic forces to get energy from movements. Using piezoelectric materials and energy harvesting methods, it has been shown that it is possible to make the amount of power needed to energize a sensor node.

Scornec et al. [97] demonstrated a 60-W piezoelectric airflow energy harvester at 6.3 m/s wind speed. The airflow created by the wind would power this energy harvester. In one hour, four generators that were connected in parallel were able to fully charge a capacitor that had a capacity of 1.2 millifarads (mF), according to the findings of an experiment. After being established, the capacitor might energize a wireless node to measure temperature and communicate through RF. Khazaee et al. [98] developed an autonomous water pump monitoring system using RF transmitter pulse duration. Condition monitoring describes this strategy. This system captured vibration energy using a cantilevered piezoelectric transducer affixed to the water pump. Up to 710.45 microwatts could be generated by this design. After collecting energy, it was stored in a capacitor to power the CPU and RF pulse transmitter. A cantilevered piezoelectric energy harvester was developed as one method of dampening the tremors caused by mining trains [99]. To create a proficient vibration energy harvester for deep mines, it is imperative to get comprehensive knowledge regarding the vibrations generated, encompassing the number, frequencies, and amplitudes thereof. This includes considering vibrations generated by air movement for ventilation, which may contribute to the overall vibrational landscape.

4.5. Data security

The development of today's global economy is increasingly dependent on the availability of natural resources. Cyber espionage is big business, and the mining industry is a prime target because of the volatile and politically sensitive global market for manufactured goods, commodities, and information. Cyber campaigns initiate retaliatory attacks against a country's critical infrastructure or are carefully planned and executed [100]. There are now hundreds of interconnected equipment in mines, which increases the attack surface and the number of exploitable security flaws [101]. Due to the rapid growth of billions of linked nodes, security and privacy have proven to be challenging study issues in Internet of Things (IoT) technology. The nodes' processing, energy, and storage constraints can be exploited thanks to the security flaws in the IoT-WSN nodes, which puts the integrity of the essential infrastructure at risk. For example, despite the low processing capability of IoT nodes, a resource depletion attack may keep the node busy by forcing it to complete tasks or requests. This causes some of the nodes in the network to become unavailable, which brings a general decline in the network's overall quality. In a similar vein, the Sleep deprivation assault [102] can shorten the lifespan of power-constrained nodes by keeping them in a state of constant overwork and preventing them from entering a mode that saves energy. Following the depletion of all available power, this leads to the nodes being rendered inoperable. It causes an interruption in the Internet of Things network, which might have severe repercussions due to the critical safety aspect of specific nodes in the network (for example, the monitoring system for underground mines). As a result of the side effects of the two attacks described above, the constrained nodes' limited available storage might become full, which would put their operational capabilities at risk, which could put the availability of the nodes as a whole at risk. The attacks that have been detailed could have a significant impact on the availability of the nodes that make up the mine's IoT-WSN architecture. However, the utilization of blockchain technology has the potential to improve the data's integrity [10] dramatically. When the nodes' resource limitations are considered, lightweight can be developed to address security concerns.

5. Conclusions

The mining industry bears a substantial duty toward meeting the safety guidelines encompassing both miner and machine safety – per the health and safety standards and the legal and social requirements imposed by the Government's DGMS on the country's people, resources, and economy. The mining industry dramatically benefits from implementing IoT technology to increase worker protection and productivity. The study examines the network architecture employed for deploying an Internet of Things (IoT) enabled wireless sensor network applicable for data transmission in underground mines to comprehend the fundamental aspects of IoT in this context thoroughly. This article focuses on the latest developments in IoT applications within the context of environmental, safety, and production monitoring in UG mines. Currently, mines employ IoT-enabled technology to fulfill specific tasks throughout several phases of mining operations. These tasks encompass gas detection, equipment deployment, worker localization, and real-time fatal and safety conditions monitoring. Several attempts have been made to use IoT applications to keep track of operations in mines below ground, but most of these methods are still in the planning or testing stages. This study has examined the feasibility of creating self-sustaining wireless sensors and communication modules utilizing energy-harvesting techniques with built-in health monitoring systems to increase the effectiveness of IoT systems. Additional investigation is warranted about the standardization of IoT integration guidelines and the advancement of wireless communication technologies specifically tailored for application in subterranean mining operations.

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کاربردهای چارچوب اینترنت اشیا برای ایمنی معادن زیرزمینی: محدودیت‌ها و راه حل‌ها

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ارسال ۲۰۲۳/۱۱/۲۷، پذیرش ۲۰۲۴/۰۱/۲۳

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چکیده:

شرایط محیطی موجود در محل کار معادن زیرزمینی (UG) به طور قابل توجهی بر بهره‌وری، کارایی، اثر بخشی و همچنین سطوح امنیتی تهدید شده تأثیر می‌گذارد. در نتیجه، حفظ ایمنی در فرآیند حفاری معدنی مستلزم نظارت مستمر بر شرایط عملیاتی پیچیده و خطرناک در محل کار معدن است. در این مقطع زمانی، در این عصر اطلاعات، زمانی که همه اقشار جامعه در حال مدرن شدن مستمر هستند، با توجه به اینکه محل کار امروزی از این قاعده مستثنی نیست، فناوری اینترنت اشیا (IoT) نقش کلیدی در کسب اطلاعات مرتبط برای حمایت از نظارت بر انسان عملیاتی حیاتی ایفا می‌کند. و پارامترهای ایمنی ماشین مانند دما، فشار، رطوبت، درخشندگی و سطوح سر و صدا، و موقعیت ماینر در عملیات استخراج زیرزمینی. این مطالعه تلاش کرده است تا وضعیت تحقیقات فعلی در مورد استفاده از اینترنت اشیاء در کاربردهای استخراج زیرزمینی را به طور جامع بررسی کند. این مقاله استفاده از برنامه‌های IoT را برای نظارت بر چندین پارامتر محیطی، از جمله گازهای مضر معدن و غلظت غبار، دما، رطوبت، سطح آب‌های زیرزمینی و رفتار لایه‌ها برای تسهیل فعالیت‌های پشتیبانی زمینی بررسی می‌کند. این مقاله تلاش می‌کند تا از حوزه‌های ممکن یکپارچه‌سازی اینترنت اشیا از منظر پیاده‌سازی برای نظارت و کنترل جنبه‌های مختلفی که به انواع و حوادث مختلف حوادث معدن کمک می‌کند، بهره‌برداری کند. این تحقیق موانع اولیه‌ای را که مانع اجرای گسترده سیستم‌های مجهز به اینترنت اشیا در کاربردهای استخراج زیرزمینی می‌شود، روشن می‌کند.

کلمات کلیدی: شبکه حسگر بی‌سیم، ارتباطات بی سیم، ارتباطات زیرزمینی، استخراج ایمن، نظارت بر محیط.