Recent Advancements in IoT Implementation for Environmental, Safety, and Production Monitoring in Underground Mines

Huili Zhang, Binghao Li, *Senior Member, IEEE*, Mahmoud Karimi, Serkan Saydam, and Mahbub Hassan, *Senior Member, IEEE*

***Abstract*—Internet of Things (IoT) technology has been widely used for real-time monitoring of the environment, safety, and production in underground mines. This article presents the basic structure of a Mine IoT (MIoT) system based on a widely used three-layer IoT architecture, classifies types of sensors commonly used in underground mines by specific application, and introduces available wired and wireless communication technologies and network topologies that can be applied in underground mines. This article provides a comprehensive review of recent developments in IoT applications in underground mines to monitor various environmental parameters, including mine gas and dust concentrations, temperature, humidity and airflow, groundwater, ground support, and seismic activity. MIoT applications for fire and hazard detection, personnel and equipment positioning, and production safety management have also been investigated. This article highlights key challenges for the broad application of IoT technology in underground mines, such as operation disruption, additional investment, limited battery life, poor quality of underground communication, and difficulty in data management. Further research on novel advanced techniques, such as self-powered sensors, MIoT standardization, and underground wireless communication technologies, is essential to improve the applicability and effectiveness of IoT applications in underground mines.**

***Index Terms*—Mine Internet of Things (MIoT), underground communications, underground mine management, wireless sensor network (WSN).**

I. Introduction

MINING is critical for global socio-economic growth as almost every industry value chain has a high demand for mineral resources. However, the global mining industry is facing economic concerns, such as high initial investment [1] and fluctuating commodity prices [2], extreme mining conditions, such as deeper and steeper deposits [3], severe geotechnical and geological challenges [4], such as lower ore grade [5], and a range of social and environmental issues, such as safety and diverse community responses to mining activities [6]. To address these problems, the mining industry has implemented numerous emerging technologies to improve mining efficiency and safety and reduce environmental hazards. Like many other industries, the mining industry is implementing digital transformation to achieve automation. To achieve efficient and safe mineral exploitation and extraction in underground mines, intelligent mining has become a trend in operations by increasing the autonomy of machines and by real-time monitoring of the environment, equipment, and crew [7].

The complicated and extreme working environment in underground mines is one of the main constraints to productivity and safety in the mining industry. Underground mines have long and sometimes relatively narrow tunnels [8], unstable geological structures [9], hazardous atmospheres [10], and equipment failures [11]. Considering these environmental and operational challenges, monitoring of relevant environmental and structural parameters, positioning of personnel and equipment, and supervision of mine personnel can effectively enhance the productivity, efficiency, and safety of underground mining. Traditionally, wired sensors monitor working conditions at underground mines. However, a wired system can fail easily once the network has faults [12], significantly increasing the complexity of cable deployment and maintenance and reducing system scalability and capability [13]. With the development of sensor and communication technologies, wireless sensor networks (WSNs) have gained popularity and have been widely used in the mining industry. Small, light, and energy-efficient wireless sensor nodes can overcome the limitations of wired systems due to the advantages of convenient deployment, cost effectiveness, high reliability, scalability, capability, mobility, and flexibility [14]. To maintain safe and efficient underground mining operations, the demand for various types of sensors will continue to grow. Internet of Things (IoT) technology has great potential to achieve real-time monitoring of the underground mining process without blind areas by using a large number of sensors.

Mine IoT (MIoT) is a technological paradigm that originates from IoT. IoT is a global network that enables connectivity and interaction between devices or machines [15]. Industrial

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Huili Zhang, Binghao Li, and Serkan Saydam are with the School of Minerals and Energy Resources Engineering, University of New South Wales, Sydney, NSW 2052, Australia (e-mail: huili.zhang@unsw.edu.au; binghao.li@unsw.edu.au; s.saydam@unsw.edu.au).

Mahmoud Karimi is with the Centre for Audio, Acoustics and Vibration, University of Technology Sydney, Sydney, NSW 2007, Australia (e-mail: mahmoud.karimi@uts.edu.au).

Mahbub Hassan is with the School of Computer Science and Engineering, University of New South Wales, Sydney, NSW 2052, Australia (e-mail: mahbub.hassan@unsw.edu.au).

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TABLE I
COMPARISON OF RELATED WORKS AND THIS SURVEY

Reference	Topic	Key contributions	Limitations
[21]	Underground mine communication	A survey on wired, radio frequency, hybrid and emergency underground mine communication systems.	IoT applications in underground mine systems have not been presented.
[22]	Underground mine wireless communication and propagation modelling	A survey on wireless communication technologies, typical applications, and signal propagation modelling techniques in underground mines.	IoT applications in underground mines have not been discussed.
[23]	IoT based underground mine communication	A survey on the establishment of robust IoT based communication systems in underground mines, with a discussion of security challenges and open issues.	This survey only focused on adopting IoT for underground mine support systems.
[9]	Underground coal mine environmental monitoring	A survey on wireless communication networks and applications for environmental monitoring in underground coal mines.	This survey only focused on wireless communication techniques used in underground coal mine IoT applications.
[11]	WSN based underground coal mine monitoring	A systematic review on WSN based monitoring systems in underground coal mines, with a discussion of smart mine incorporating IoT.	The challenges of adopting IoT in underground mines have not been discussed.
[17]	Underground coal mine IoT	A survey on feasibility, potential applications and challenges of bringing IoT to coal mining industry.	Only one practical example of IoT applications in underground mines has been discussed.
[24]	Mine IoT	A survey on adaptability, current developments and challenges of adopting IoT in the mining industry.	The analysis of IoT applications in the mining industry is limited.
This survey	Underground mine IoT	A comprehensive survey on underground mine IoT from a mining perspective, particularly • The introduction of an adapted three-layer MIoT architecture and key components of underground mine IoT systems. • A detailed review of current developments of IoT applications for underground mine monitoring. • Insights into key challenges and further directions for IoT research in underground mines.	

IoT (IIoT) is the industrial application of IoT. IIoT is a network of interconnected smart industrial objects embedded with electronics, sensors, and/or actuators, and these interconnected things can communicate with each other [16]. MIoT is an important branch of IIoT, mainly referring to a network that comprises a group of interconnected sensors and actuators at mine sites. Sensors are used for data collection, and actuators are responsible for system adjustment and warning of abnormal conditions when the obtained value exceeds the prelimited value. In other words, MIoT can help real-time monitoring of mines, predicting potential accidents, optimizing the mining process, and managing personnel and equipment [17], [18], [19].

In contrast to underground IoT in other industries (e.g., oil and agriculture) where sensors are buried and communicate through the soil, IoT systems designed for underground mines enable IoT devices to be placed in open underground spaces and communicate through the air. Although MIoT devices are located deep underground, communication methods in surface and underground mines are similar, mainly achieved through cable-based or radio frequency (RF) communication technologies [20]. However, due to the signal attenuation caused by tunnel walls, the deployment and operation of IoT devices in underground mines is much more challenging and complicated than in surface mines.

There are several representative reviews on communication technologies and IoT-based environmental monitoring applications in underground mines. The review by Yarkan et al. [21] focused on existing wired, RF, hybrid, and emergency communication systems in underground mines. The survey by Forooshani et al. [22] investigated wireless communication technologies and signal propagation modeling techniques in underground mines. Singh et al. [23] provided an overview of information and communication systems in underground mines based on IoT technologies. The related security challenges and open issues of IoT systems in underground mines have also been discussed. Dohare et al. [9] reviewed the recent technological development of wireless communication networks and environmental monitoring systems in underground coal mines. Muduli et al. [11] proposed a systematic review on WSN-based applications for the monitoring of environmental and other parameters in underground coal mines. Zhou et al. [17] discussed the feasibility, potential applications, and challenges of bringing IoT to the coal mining industry based on the current infrastructure in underground coal mines. Molaei et al. [24] focused on the adaptability, current developments, and challenges of adopting IoT in the mining industry based on data collection, communication, and management. Key contributions and the main limitations of the review works mentioned above are summarized in Table I.

From a mining perspective, the mining industry is focused on deploying robust, reliable, and cost-effective MIoT systems in underground mines by placing sensors and communication hardware at appropriate locations and is less concerned with tasks that can be completed outside the mine site. Only the end users in the mining sector, such as workers, know exactly what parameters should be monitored in underground mines, and decide what type of sensors are required and where to deploy them. However, the above-mentioned reviews primarily focused on protocols and algorithms applied in MIoT applications for data communication and processing. They have not investigated the applicability of wireless communication systems for underground mines based on technical characteristics and application scenarios. They also have not systematically summarized design parameters for MIoT applications, such as sensor types, deployment of sensor nodes, and the threshold value of monitored environmental parameters. Potential further directions for IoT research in underground mining have not been discussed. Therefore, this article provides a comprehensive and state-of-the-art review of IoT

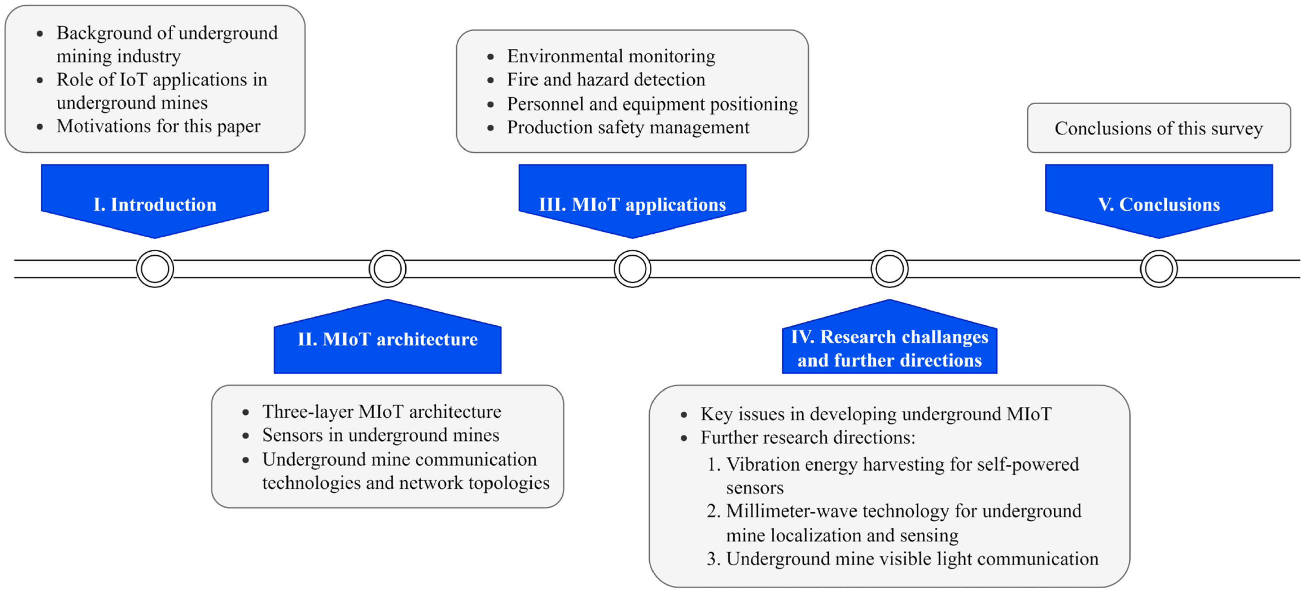

Fig. 1. Organization of this survey.

applications for environmental, safety, and production monitoring in underground mines from a mining perspective and identifies key challenges and further research directions for developing underground MIoT.

This article is organized as follows (shown in Fig. 1). Section II presents a three-layer MIoT architecture adapted from [25] and key components of underground MIoT systems. Section III provides a review of IoT applications in underground mines for environmental monitoring, fire detection, personnel and equipment positioning, and production safety management. Section IV discusses key challenges and further directions for IoT research in underground mines. Finally, Section V provides the conclusion of this survey.

II. MIoT Architecture

Due to the harsh environmental conditions and poor communications in confined spaces, it is difficult to collect and transmit data from underground mines. To successfully deploy reliable IoT systems at mine sites, it is crucial to have a clear understanding of sensors required for underground mine monitoring and communication technologies suitable for underground mine communications. On the one hand, common sensors and communication hardware may need to be redesigned to withstand hostile environments, such as extreme temperatures and depth. On the other hand, the problem of limited communication connectivity and coverage must be addressed to achieve ultralow latency underground communication up to hundreds of kilometers. Thus, the architecture of MIoT should emphasize the importance of data acquisition and data transmission at mine sites. The MIoT architecture must also be flexible and scalable to meet the demands of continuous dynamic mining operations.

In our study, the widely used three-layer architecture [25] is applied to represent the basic structure of the MIoT system, which consists of the perception and control layer, network layer, and application layer (as shown in Fig. 2). Such an architecture can provide more practical guidance for designing IoT systems in hostile and confined underground mining environments due to its simplicity and ease of implementation. It is also familiar to other disciplines, therefore increasing cross-discipline collaboration. Other MIoT architectures can be customized based on the three-layer architecture by adding additional layers to meet specific operational requirements and environmental conditions.

The perception and control layer is the lowest layer of the MIoT architecture. This layer is responsible for collecting data and information from the environment and “things” through sensors, transmitting collected information to the upper layer, and executing feedback commands using actuators. The network layer acts as a bridge between the perception layer and the application layer. It carries and transmits the information collected from the physical objects through sensors and interconnects machines embedded with sensors, actuators, communication devices, and networks. The medium for the data transmission can be wired, wireless, or hybrid based. Communication technology and network topology are two main factors that determine the stability and timeliness of underground mine communication.

The application layer is the top layer of the MIoT architecture, the interface between the users and applications. This layer is designed to analyze the data and information collected by the perception layer using appropriate data processing tools. After data analytics, decisions are made locally or remotely, and relevant commands are sent to the control layer to perform specific control functions. Currently, the required actions are mostly carried out by humans due to insufficient collaboration with artificial intelligence (AI) in the mining industry.

In terms of data processing, cloud computing deals with big data analysis and storage, where all computing services from MIoT are delivered to remote cloud computing platforms

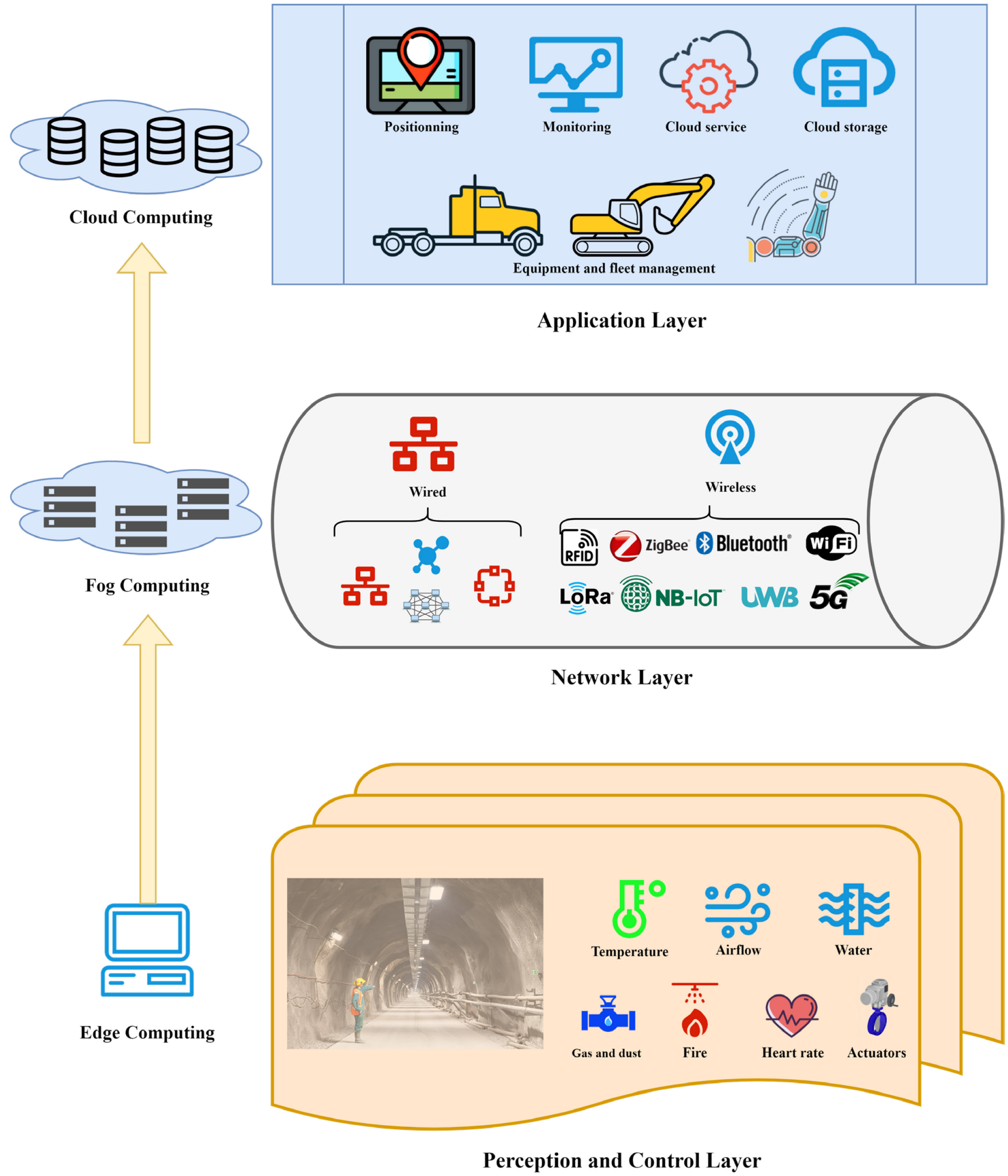

Fig. 2. Three-layer architecture of MIoT.

provided by Internet enterprises (e.g., Google and Microsoft) on demand through the Internet [26]. To reduce network congestion and service latency of MIoT systems, distributed computing approaches (e.g., edge computing and fog computing) are introduced to store and compute the collected data locally rather than directly delivering all the information to the cloud server [27]. Edge computing is capable of raw data analysis and processing using limited computing resources (e.g., embedded microcontroller unit and gateway) at each isolated edge node within the proximity of sensors. Fog computing can be regarded as an extension of cloud computing, which provides data integration and computation at interconnected fog nodes located between edge nodes and cloud data centers [26].

AI can be leveraged at edge and fog nodes for real-time data processing and analysis, enabling more efficient and more accurate decision making or predictions. Muduli et al. [28] applied a supervised learning method based on the Naive Bayes classification algorithm to analyze collected environmental data sets of an underground coal mine at the base station for early fire predictions. The simulation results indicated that the proposed machine learning algorithm could improve the accuracy and responsiveness of the environmental monitoring system. Zhang et al. [29] developed a distributed gas concentration prediction model for underground coal mines based on a single hidden layer random weights neural network (SRWNN) and a nondominated sorting genetic algorithm II (NSGA-II) for interval prediction. This model was trained in a distributed manner using intelligent edge devices, which could reduce training time and achieve load balancing. Sanyal and Chattopadhyay [30] proposed a methane prediction

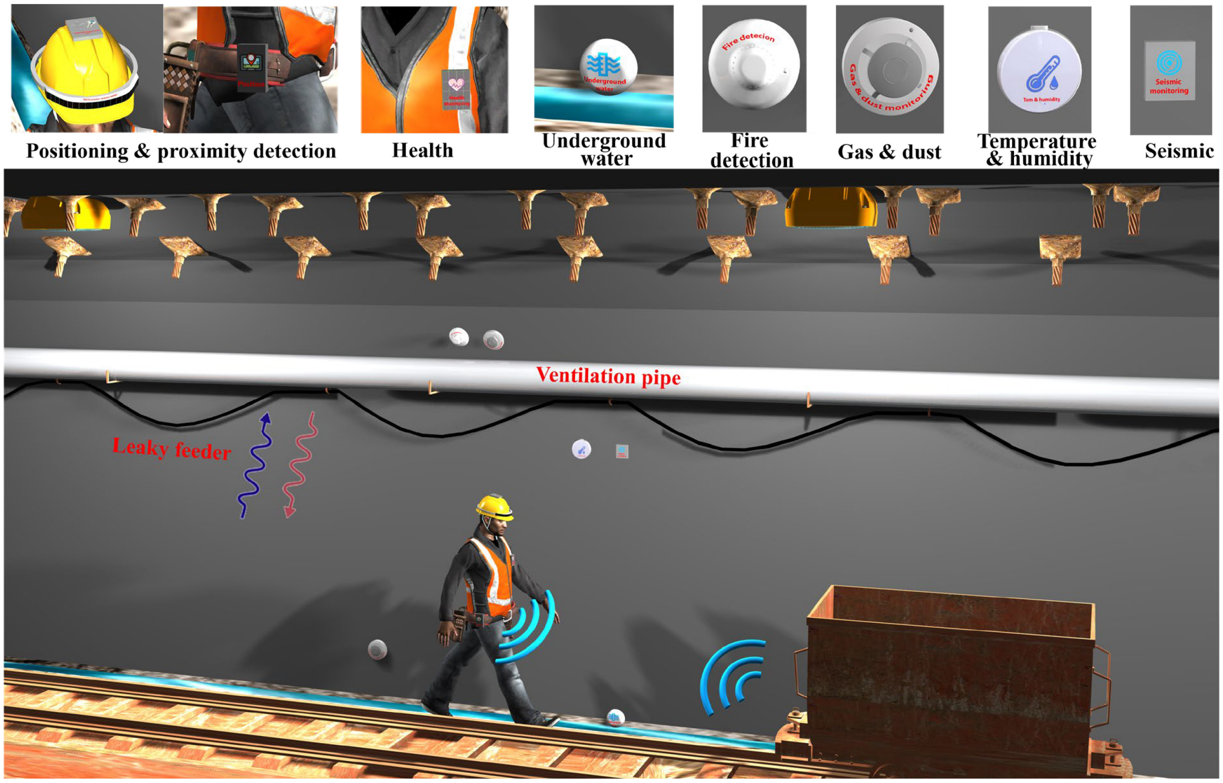

Fig. 3. Sensors used in underground mines for environmental, safety, and production monitoring.

platform for underground mines, where data was aggregated in the fog layer and processed using long short-term memory (LSTM) networks. This system achieved a forecast accuracy of 94.23%. Zhang et al. [31] used the Vision Swin Transformer-YOLOv5 algorithm to develop an object detection model that was capable of handling data captured by underground mine surveillance cameras. The proposed model improved the average detection accuracy by 25% and was designed to operate at the edge due to its low memory and computational requirements. The integration of AI and IoT in underground mining is expected to realize proactive and predictive maintenance of operating machines, while also facilitating the development of fully automated systems [3], [32]. Currently, the application of AI in underground mines is still in its early stages due to challenges, such as limited data availability and power constraints.

A. Sensors in Underground Mines

There are two types of sensors. Common sensors convert measured physical quantities into electrical signals suitable for further processing and interpretation in the upper layer, while a smart sensor is embedded with a microprocessor unit for the initial data processing [33]. Actuators operate in an opposite working principle of a sensor, which converts a source of energy, such as electrical input into a physical–mechanical motion [34]. In MIoT applications, different types of sensors are introduced to collect useful data and information, where sensors are installed on tunnel walls, attached to operating machines, and worn by underground miners (as shown in Fig. 3). Taking the environmental monitoring system in underground mines as an example, numerous sensors (e.g., gas sensors, smoke and dust sensors, temperature sensors, humidity sensors, airflow sensors, water quality sensors, level sensors, etc.) are required to monitor environmental parameters to ensure mine safety. Table II summarizes sensors that are commonly used in underground mining.

B. Communication in Underground Mines

Because of the complex, dynamic, and harsh operational environment in underground mines, it is highly challenging to deploy a reliable and robust communication system for data collection and information exchange for MIoT applications. To provide efficient and cost-effective communication in underground mines, both wired and wireless communication technologies are used for underground communication.

1) Wired Communication: Fiber-optic communication is a commonly used wired communication method in the mining industry. A fiber-optic communication system realizes data transmission through conversion between electrical and optical signals. First, an optical transmitter converts electrical input signals into optical signals. Then, optical signals are transmitted to the optical receiver along an optical fiber cable. Finally, an optical receiver reconverts optical signals back to the electrical signals [43]. The fiber-optic system has the advantage of being lightweight, flexible, reliable, low latency, intrinsically safe, and interference proof [44]. Therefore, compared with other cables, optical fibers are the most suitable for underground mine communications. Currently, optical fibers are always used as a backbone network in an underground mine communication system to interconnect different networks [45].

TABLE II
SENSORS COMMONLY USED IN UNDERGROUND MINING OPERATIONS [11], [35], [36], [37], [38], [39], [40], [41], [42]

MIoT applications	Monitored parameters	Sensor types
Environmental monitoring	Gas concentration (O_2, CO_2, SO_2, NO_x, CO, H_2S, CH_4, C_2H_2, H_2, etc.), temperature, smoke and dust concentrations, humidity, airflow, water quality, water quantity, seismicity, etc.	Gas sensors, temperature sensors, smoke detectors, dust sensors, humidity sensors, airflow sensors, water quality sensors, level sensors, pressure sensors, accelerometers, gyroscope sensors, strain sensors, geophones, etc.
Fire detection	Gas concentration (CO, CH_4, C_2H_4, etc.), smoke concentration, temperature, presence of fires, etc.	Gas sensors, smoke detectors, temperature/heat sensors, infrared sensors, etc.
Personnel and equipment management	Real-time location of personnel and equipment, Personnel health status (body temperature, heart rate, respiration, and posture), equipment status, presence of nearby objects, etc.	Fixed reference nodes and mobile sensor nodes, RFID devices, Fiber Bragg Grating (FBG) sensors, accelerometers, temperature sensors, proximity sensors, etc.

TABLE III
APPLICATION OF RFID SYSTEMS IN THE MINING INDUSTRY [50]

Frequency range	Type of RFID	Typical mining application
Low frequency: 131 kHz	Active (RuBee: IEEE standard 1902.1)	Detection of assets buried in coal slurry or an inundated mine
High frequency: 13.56 MHz	Passive (similar to near-field communication)	Access control
Ultra-high frequency: 433 MHz	Active (Dash7: ISO/IEC 18000-7)	Long-range communication and environmental monitoring
Ultra-high frequency: 900 MHz	Passive or semi-passive	Asset tracking
Microwave: 2.4 GHz	Active	Real-time localization of mobile personnel and equipment

The leaky feeder is one of the most commonly used communication approaches in underground mines that combines wired and wireless communication methods. A leaky feeder system emits and receives radio signals along the tunnel by using a coaxial radiating cable [21]. Moreover, amplifiers are deployed at fixed intervals (typically 350–500 m) along the leaky feeder cable to compensate for signal loss [22]. Therefore, the leaky feeder cable can significantly extend the communication range of radio waves and is suitable for underground mine environments. Leaky feeder systems can be used for ventilation control [36] and rescue communication in mines [46].

2) Wireless Communication: RF and identification (RFID) is widely used in the mining industry. An RFID system mainly consists of tags and readers. The reader is continuously sending radio waves. Once the tag attached to the object is within range of the reader, the tag can transmit data to the reader. RFID tag devices can be passive, semi-passive, or active. An RFID system with a passive tag only works when the tag is in proximity to the reader because received radio waves are used to power the internal circuit of a tag. Then, the tag takes advantage of backscattering to send the data back to the reader. A semi-passive tag uses the battery to power its circuit but relies on backscattering for data transmission. In contrast, an active tag is embedded with a transmitter to transmit data and is fully powered by an onboard power supply [47]. RFID systems with passive tags are used for access control [48] and asset tracking [49] due to the advantages of low cost, small size, long lifetime, and easy maintenance. Active RFID systems are commonly used for real-time localization of mobile personnel and equipment because they provide a more accurate and wider communication range of up to 100 m in open areas [50] compared to passive tags with a coverage range of 5–10 m [49]. Table III summarizes the application of RFID systems in the mining industry according to the operating frequency.

Apart from RFID, many other noncable-based wireless communication technologies have also been developed for underground mine communication systems, including Wi-Fi, ultra-wideband (UWB), ZigBee, 3G, LTE/4G, Bluetooth low energy (BLE), long-range (LoRa), narrowband-IoT (NB-IoT), and 5G. Although MIoT applications based on RFID, ZigBee, BLE, and Wi-Fi are most used in underground mining operations in recent years, Mekki et al. [51] expected that low-power wide-area networks (LPWANs) technologies, such as LoRa and NB-IoT, would dominate the communication of MIoT applications in the near future because of their low-power, LoRa, and low-cost network communication. Moreover, cellular mobile communications (3G, LTE/4G, and 5G) are developing rapidly. 5G may provide a new era for MIoT because 5G networks have high data rates and low latency. It means that 5G has the potential to realize fully digital management of the mining area and real-time remote control of mining operations with minimal manual intervention [52]. Among the above-mentioned wireless communication technologies, Wi-Fi and cellular mobile communications are not suitable for battery-powered IoT applications due to their high energy consumption. Table IV summarizes the technical features and the typical IoT applications of wireless communication technologies in underground mines.

3) Network Topology: The network topology of an underground mine communication system refers to the architecture of the communication devices and data transmission medium (wired or wireless) within the communication network [65]. An appropriate network topology design ensures highly reliable and robust underground communication for MIoT in complex geographical environments. As shown in Fig. 4, the communication hardware in the network can be regarded as a point, while the transmission medium can be regarded as a line to interconnect the communication devices. Four network topologies are commonly used for underground mine communications: bus, star, ring, and mesh topologies [66], [67].

In a bus topology [Fig. 4(a)], each node is directly connected to the bus. Thus, all data is transmitted along the bus

TABLE IV
SUMMARY OF WIRELESS COMMUNICATION TECHNOLOGIES IN UNDERGROUND MINES [36], [42], [46], [50], [52], [53], [54], [55], [56], [57], [58], [59], [60], [61], [62], [63], [64]

Technologies	Year launched	Network deployment	Frequency band (Hz)	Data rate (bps)	Range	Capacity	Operation cycle	Battery life	Typical underground mining application
Leaky feeder	1970	Base stations + coaxial cable + amplifiers	VHF or UHF band (30 M – 3000 M)	Capable of simultaneous voice, video, and data communication	500 m, can be relayed	Broadcast	On request	Days to weeks	Ventilation control and rescue communication
RFID	1983	Peer to peer/ card emulation	125 k – 134 k/ 131 k/13.56 M /433 M/900 M /2.4 G	Up to 500 k	0.1 m – 5 m	Peer to peer/peer to multi-peer	On request	3–5 years	Access control and positioning
Wi-Fi	1997	Individual network	2.4 G/5 G	Up to 1300 M (802.11ac)/450 M (802.11n)	50 m – 100 m	16–250	Stand by	Not for low power application	Environmental monitoring and positioning
3G	2001	Cellular network	800 M – 2100 M (3GPP protocol)	Up to 7 M	Up to 8 km	Depends on the bandwidth	Stand by	Not for low energy application	Multi-media surveillance
UWB	2002	Peer to peer	3.1 G – 10.6 G	Up to 1.6 G	10 m	8	1 Hz – 10 Hz	3–5 years	High accurate positioning
Zigbee	2004	Individual network	868 M/ 915 M/ 2.4 G	Up to 250 k	10 m – 100 m	Star network, 254 per router/mesh network	0.01 Hz – 1 Hz	3–5 years	Environmental monitoring and positioning
LTE/4G	2010	Cellular network	700 M – 2100 M (3GPP protocol)	Up to 100 M	Up to 5 km	Depends on the bandwidth	Stand by	Not for low power application	Multi-media surveillance
BLE	2012	Individual network	2.4 G	Up to 1 M	30 m – 100 m	P2P/mesh network	1 Hz – 10 Hz	3–5 years	Environmental monitoring and positioning
LoRa	2013	Individual network	150 M – 1 G	0.3 k – 50 k	Up to 15 km	20 k – 300 k per hub	Once per day	3–10 years	Detonation of explosives and rescue communication
NB-IoT	2015	Based on cellular network	800–900 M/ 1700–1800 M	Up to 220 k	Up to 15 km	50 k per cell	Once per day	3–10 years	Environmental monitoring
5G	2019	Cellular network	600 M–4700 M (3GPP protocol)	Up to 20 G	Up to 1 km	Depends on the bandwidth	Stand by	Not for low power application	Positioning, unmanned driving, and remote control

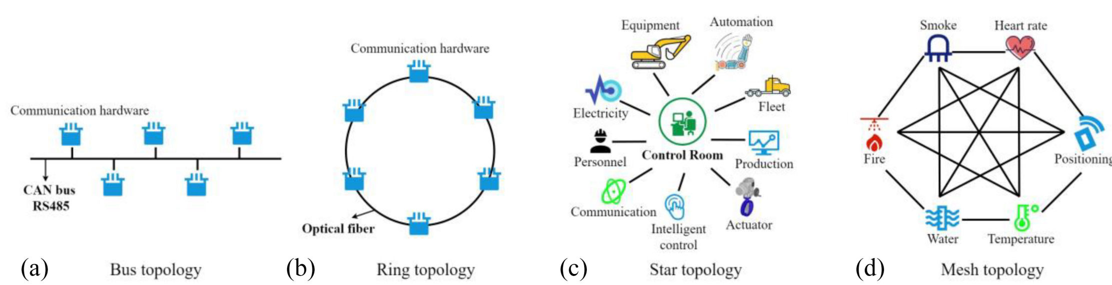

Fig. 4. Commonly used network topologies for underground mines. (a) Bus topology. (b) Ring topology. (c) Star topology. (d) Mesh topology.

and is visible to all connected nodes. Although bus topology has the advantages of easy wiring and high scalability, network traffic frequently occurs due to the bottleneck of the bus transmission capacity. Meanwhile, fault diagnosis can be challenging in such a simple structure. The controller area network (CAN) bus and RS485 are two typical examples of bus topology.

In a ring topology [Fig. 4(b)], all communication devices are interconnected in a closed circular structure. In this topology, data jackets pass through all nodes in the ring layout

TABLE V
COMPARISON OF NETWORK TOPOLOGIES FOR UNDERGROUND MINES [66], [67]

Parameter	Bus topology	Ring topology	Star topology	Mesh topology
Robustness	Low	Low	Medium	High
Reliability	Medium	Medium	High	High
Scalability	High	Medium	High	Low
Flexibility	High	Low	High	Low
Fault diagnosis	No	No	Yes	Yes
Cost	Low	Medium	Medium	High

until they reach the destination node. This structure is relatively simple and suitable for long-distance communication. However, this structure has poor performance in reliability and fault diagnosis because a single node failure can lead to network failure. The optical fiber backbone network in underground mines always adopts a ring topology.

In a star topology [Fig. 4(c)], each node in the network is connected to a central hub that can organize and transmit messages. This structure can withstand joint point failure and is capable of fault diagnosis. However, the network performance mainly depends on the central node because the failure of the central hub can lead to the failure of the entire network. The network of a control room in an underground mine may use the star topology.

In a full mesh topology [Fig. 4(d)], every device can directly communicate with other devices in the network through a point-to-point connection, and data can be simultaneously shared among all nodes. To reduce the cost and system complexity, partial mesh topologies are introduced. In this topology, most nodes are interconnected, while a few nodes are only linked to several other nodes. Mesh topologies are widely used for underground mine interactive communications among sensors due to their high robustness and reliability. However, routing algorithms and flow control methods are required to enable accurate and efficient data transmission. Table V compares network topologies commonly used for communication in underground mines.

III. MIOT APPLICATIONS IN UNDERGROUND MINING

This section reviews MIoT applications for environmental monitoring, fire detection, personnel and equipment positioning, and production safety management in underground mines.

A. Environmental Monitoring

To ensure the safety of underground mining operations, environmental parameters should be monitored in real time, including gas and dust concentrations, variations of temperature, humidity and airflow, groundwater level and quality, and the locations of seismic activities and roof collapses.

1) Gas and Dust Monitoring: Underground mining can generate hazardous gases as well as explosive and respirable mine dust. Therefore, gas monitoring systems can provide early warning for potential hazards and achieve safe mining. To ensure that miners can survive in underground mines, atmospheric gases (O_2 and CO_2), typical toxic gases (e.g., SO_2, NO_x, CO, and H_2S) and respirable concentration of mine dust should be continuously monitored. Concentrations of explosive gases (e.g., CH_4, C_2H_2, and H_2) and total incombustible content (TIC) of mine dust also need to be maintained at a relatively low level to prevent fatal explosions and fire incidents [11]. Sensors should be deployed at places where hazardous gases are prone to accumulate or release. Table VI summarizes the properties and primary sources of commonly identified gases and dust in underground mines. The concentration of each type of hazardous gas in underground mines should always be below the 8-h shift time-weighted average (TWA) concentration to avoid any adverse health effects and should never exceed the ceiling limit (CL) concentration.

Qin et al. [73] proposed a wireless gas monitoring system in coal mines based on ZigBee to monitor methane concentration. In this system, methane in the coal mine laneway was detected by fixed and mobile sensor nodes. A large number of catalytic combustion methane sensors were placed along the laneway as fixed detection nodes. Hand-held nondispersive infrared methane sensors and catalytic combustion methane sensors attached to the miner's helmet and mobile car were regarded as mobile detection nodes. Once the detected gas concentration exceeds the prescribed limit, the sound and light alarm will be triggered, and the location of abnormal methane concentration can be determined based on the address code. Osunmakinde [74] developed an autonomous toxic gas remote monitoring framework based on real-time gas detection, which also introduced mobile robot sensing nodes to expand the detection area. This design adopted an integrated network, where optical fiber was the backbone network along the shaft and ZigBee-based WSNs were used for gas monitoring. The proposed system simultaneously monitored five types of hazardous gases (i.e., CO_2, CO, H_2, CH_4, and NO_2) through static and mobile robot sensing nodes. A ZigBee-based gas monitoring platform with an Internet protocol (IP)-enabled Wi-Fi gateway was designed by Mishra et al. [13]. It continuously detected and recorded gases in underground mines, including O_2, CO_2, CH_4, CO, H_2S, and H_2. In this design, sensor nodes could be more power efficient by discarding redundant data before transmitting information to the IP gateway for further communication. A dashboard installed between the perception layer and application layer visualized sensed data to check data validity. Useful data was transmitted to the server through the Wi-Fi gateway, where the server was used for data processing and generated audio–visual alarms whenever recorded data exceeded the threshold. In addition, an Android application was developed for data management and visualization, which enabled professionals to access information remotely by entering a specific IP address. Jo and Khan [35] proposed an early-warning safety system using BLE communication protocol for a coal mine. Stationary sensor nodes were installed on the side walls of the main roadway and galleries to monitor a wide range of gases, including CO_2, NH_3, smoke, CO, CH_4, and other combustible gases. A term called *Mine Warning Index*, which combined the effect of temperature, humidity,

TABLE VI
PROPERTIES OF COMMONLY IDENTIFIED GASES AND DUST IN UNDERGROUND MINES [68], [69], [70], [71], [72]

Gas	Primary sources in mines	Characteristics	Hazards	Threshold limit value
O_2	Atmosphere (21%), ventilation system	Colorless, odorless, tasteless, non-explosive, support combustion, easily displaced by other gases	N/A	Minimum required concentration for human breathing ~ 19.5%
CO_2	Atmosphere (0.04%), oxidation of carbon-based materials, explosion, fire, diesel exhaust	Colorless, odorless, tasteless at low concentration	Difficulty breathing and increased heartbeat (stimulate breathing at 5%; unconsciousness after several minutes of exposure at 7%–10%)	TWA concentration ~ 0.5%; CL concentration ~ 5%
CO	Blasting, fire, explosion, incomplete combustion of carbon-based material, diesel exhaust	Colorless, odorless, tasteless, flammable	Highly toxic, explosive	TWA concentration ~ 50 ppm; CL concentration ~ 200 ppm; Explosive range: 12.5%–74.5%
SO_2	Blasting, oxidation of sulphides, diesel exhaust	Colorless, strong odor, acidic taste, non-flammable	Extremely toxic, severe irritant to eyes and respiratory system (lungs)	TWA concentration ~ 2 ppm; CL concentration ~ 10 ppm
NO_2	Blasting, welding, diesel exhaust, stagnant pond	Reddish-brown color, acrid odour, non-flammable	Extremely toxic, severe irritant to respiratory system (lungs)	TWA concentration ~ 3 ppm; CL concentration ~ 5 ppm
H_2S	Decomposition of sulphur strata, stagnant pond	Colorless, rotten egg odor, extremely flammable, highly soluble	Extremely toxic, severe irritant to respiratory system and eyes, explosive	TWA concentration ~ 10 ppm; CL concentration ~ 15 ppm; Explosive range: 4.3%–45.5%
CH_4	Coal seam, sewage	Colorless, odorless, tasteless, flammable	Difficulty breathing (displacement of oxygen), explosive with high frequency	Explosive range: 5%–15%
H_2	Battery charging station, incomplete combustion of mine fire	Colorless, odorless, tasteless, flammable	Extremely explosive	Explosive range: 4%–74.2% Violent explosive range: > 7%
Mine dust	Drilling, blasting, loading, crushing, transportation	Inhalable dust (< 100 μm); respirable dust (<10 μm)	Explosive, toxic, severe irritant to respiratory system (lungs)	TWA concentration of diesel Particulate matter (DPM) ~ 160 ppm

and hazardous gas concentrations, was defined to evaluate mine safety.

A helmet embedded with sensors can also be used for gas monitoring. Hazarika [75] designed a battery-powered smart helmet to detect CH_4 and CO gas concentrations. The collected data was transmitted to the control room using Digi XBee RF modules for continuous monitoring. XBee modules may go into cyclic sleep mode when idle to save power. An alarm would be generated in the control room once the gas concentration was beyond the threshold value. The helmet developed by Sharma and Maity [76] was equipped with a microcontroller for data analytics followed by indicating devices (a speaker and a light-emitting diode (LED) light) to achieve real-time alerts of excessive CH_4 and CO gases in underground mines. Helmet prototypes with a gas monitoring function were also presented in [77] and [78]. A low-cost portable gas monitoring system was proposed by Ziętek et al. [79] to alert miners of gas hazards in underground mines. This system integrated portable sensors, a microcontroller, and a smartphone. Portable gas sensors were used to detect CO and H_2S gases, and the microcontroller calculated the corresponding gas concentrations of the collected data. Then, data was transmitted to a smartphone via a Bluetooth connection for storage, computing, and visualization. In an emergency, the smartphone could vibrate along with the background flashing red to remind miners of increasing hazardous gas concentration.

For dust monitoring, Mahdavipour et al. [80] presented a dust sensing system in underground coal mines to continuously monitor the variation of TIC of deposited coal dust. This system consists of three types of wireless sensors, including an optical dust deposition sensor for measuring TIC with moisture, a dielectrometry moisture sensor for eliminating the effect of moisture, and a capacitive mass sensor for evaluating the dust accumulation level. XBee RF modules were also used in this design to achieve low-power network communication. Lebecki et al. [81] developed a dust monitoring system to monitor dust concentration in underground coal mine headings. In this design, gravimetric dust samplers CIP-10-R and CIP-10-I were introduced to measure the mean concentration of respirable dust and total dust, respectively, while optical dust samplers PL-2 were introduced to record instantaneous dust concentration. Table VII summarizes the MIoT applications for gas and dust monitoring.

2) Temperature, Humidity, and Airflow Monitoring: The variations in temperature, humidity, and air velocity exert a significant impact on the physical comfort and working efficiency of underground miners [82]. Therefore, temperature, humidity, and air velocity in underground mines should be maintained within the human thermal comfort zone [83], [84], [85], as shown in Table VIII. However, the temperature level in underground mines mainly depends on the depth and location of the mine site and can range from −40 °C in Mongolia [86] to 50 °C in Western Australia [87]. To mitigate the adverse impact of high temperature, ventilation is an effective approach. The function of a ventilation system in an underground mine is to ensure that the values of critical environmental parameters (i.e., hazardous gas concentration, dust concentration, temperature, and humidity) are maintained at acceptable levels. Since real-time monitoring of relevant environmental parameters can provide a reference for mine ventilation, ventilation on demand can be realized

TABLE VII
SUMMARY OF MIoT APPLICATIONS FOR GAS AND DUST MONITORING

Reference	Year	Sensor deployment	Communication approach	Measured parameters	Sensors	Limitations
[77]	2009	Sensors embedded in helmet	Zigbee	CH_4, temperature, humidity	CH_4 sensor (TP-I1A), temperature and humidity sensor (SHT11)	Lack of performance analysis and experimental validation
[73]	2011	Fixed and mobile sensor nodes	Zigbee	CH_4	Catalytic combustion/ non-dispersive infrared methane sensors	Lack of performance analysis and experimental validation
[74]	2013	Static and mobile robot sensing nodes	Zigbee and optical fiber backbone	CO_2, CO, H_2, CH_4, NO_2, temperature	N/A	Lack of optimization of sensor placement and energy management
[80]	2015	Fixed sensor nodes	Digi XBee 2.4 GHz RF	TIC, humidity, dust mass	Optical dust deposition sensor, dielectrometry moisture sensor, and capacitive mass sensor	Lack of feasibility validation in underground mines
[75]	2016	Sensors embedded in helmet	Digi XBee RF	CH_4, CO	CH_4 sensor (MQ2), CO sensor (MQ7)	Lack of real-time alarm for hazardous gases
[81]	2016	Fixed sensor nodes	N/A	Respirable and total dust concentration	Gravimetric dust samplers (CIP-10-R and CIP-10-I), optical dust sampler (PL-2)	Lack of real-time monitoring and alarm
[35]	2017	Fixed sensor nodes	BLE	CO_2, NH_3, smoke, CO, CH_4, combustible gases, temperature, humidity	CO and combustible gas sensor (MQ9), CH_4 sensor (MQ4), CO_2, NH_3, smoke sensor (MQ135), temperature and humidity sensor (DHT11)	Lack of optimization of energy management for sensor nodes
[76]	2018	Sensors embedded in helmet	Zigbee	CH_4, CO, temperature, humidity	CH_4 sensor (MQ4), CO sensor (MQ7), temperature and humidity sensor (DHT11)	Lack of feasibility validation in underground mines
[78]	2018	Sensors embedded in helmet	2.4 GHz RF	CH_4, temperature, humidity	CH_4 sensor (MQ4), temperature and humidity sensor (DHT11)	Lack of performance analysis and experimental validation
[13]	2019	N/A	Zigbee and IP enabled Wi-Fi gateway	O_2, CO_2, CH_4, CO, H_2S, H_2, temperature, humidity	N/A	Lack of feasibility validation in underground mines
[79]	2020	Portable sensors	Bluetooth	CO, H_2S, temperature, humidity	CO sensor (MQ9), H_2S sensor (MQ136, ZE03), temperature and humidity sensor (DHT22)	Lack of sensor calibration when detecting gas mixtures

in underground mines. The ventilation system can provide the required volume of fresh air for a specific underground area based on the balance between intake air supply and demand [88]. According to Table VII, MIoT applications for gas monitoring always record variations of temperature and humidity as auxiliary parameters to evaluate the safety of the working environment in underground mines.

The airflow monitoring system can provide accurate information on air distribution in each branch of an underground mine [89] and reflect the working performance of a ventilation system [90]. Most mines prefer to use handheld vane anemometers to measure the airflow and determine air velocity along the tunnel due to their high flexibility [36]. In recent years, airflow sensors are increasingly deployed at key locations (e.g., main fans and regulators) for real-time monitoring of airflow and assistance of ventilation control integrated with data analysis tools and ventilation simulation platforms [90]. Zhou et al. [17] also noted that ventilation-related sensors could be added to the MIoT network to develop a comprehensive monitoring system.

3) Groundwater Monitoring: Water inrush occurs frequently during underground mining. It poses a serious threat to mine safety, and direct discharge of untreated groundwater can pollute the environment [91]. To address these problems, IoT has provided technical support for accurate and real-time monitoring of groundwater in underground mines [39], [63], [92], [93]. More et al. [63] presented an overview of using IoT to optimize mine water management. WSNs were introduced to monitor physicochemical characteristics of on-site mine water, including water level, temperature, pH value, electrical conductivity, and dissolved oxygen. RFID tags were attached to mine water sample bottles to track and store basic sampling information.

More specifically, Bo et al. [39] designed an IoT-based online mine water monitoring platform to characterize mine water quantity and quality in real time. Data acquisition in this design was realized via a wired multisensor network which comprised level sensors, pH sensors, suspended solids sensors, water oil sensors, and conductivity sensors. A wireless communication network based on the LoRa protocol was introduced for data transmission. Yan et al. [92] introduced an IoT platform to monitor the water level, temperature, flow, and quality (i.e., salinity and characteristic ions) of the water source for the coal mine in real time. Then, the collected data

TABLE VIII
HUMAN THERMAL COMFORT ZONE [83], [84], [85]

Parameters	Temperature	Relative humidity	Air velocity
Human thermal comfort zone	20 °C – 23 °C in summer 23 °C – 26 °C in winter	40% – 65%	1 m/s – 2 m/s

was transmitted to the cloud service platform through wired and wireless networks for further data management and analytics. After a series of analyses and modeling, water inrush sources could be identified rapidly, and relevant water disasters could be prevented. Samuel and Christian [93] proposed a mine water (precipitation and groundwater) management system based on RFID technology and quantum computing. In this system, RFID-tagged pumps and sensors could track the volume and direction of water flow throughout the mine shaft in real time, while quantum computing enabled fast processing of large volumes of collected data.

4) Structural and Geotechnical Monitoring: Structural changes in underground mines are mainly due to unstable geological structures and sudden seismic events. The resulting tunnel collapses and rock bursts can lead to fatal accidents and/or huge damage to operations. Therefore, rapid and accurate detection of collapse zones and real-time monitoring can effectively prevent unexpected geotechnical hazards and provide timely early warning for underground mine workers. The collapse detection system is developed to identify structural variations due to roof or wall falls and provide the collapse location for underground workers. Li and Liu [94] designed a structure-aware self-adaptive monitoring system based on the wireless mesh sensor network to detect collapse areas in underground mines and report their locations. In this design, sensor nodes were fixed on ceilings and walls of underground tunnels at a certain distance to form a regular mesh network. A beacon mechanism was proposed to identify the collapse hole outline and location by neighbor nodes broadcasting. This system could discover and reconfigure displaced sensor nodes after the collapse to maintain system integrity and validity. Hu et al. [95] presented a connectivity-based mine collapse detection system using WSN. After simplifying the actual 3-D layout of sensor nodes into an unfolded 2-D representation, collapse hole regions were detected according to connectivity measurements of the neighboring sensor nodes.

To prevent rock bursts caused by rock mass instabilities, a copper mine introduced a wired seismic monitoring system to quantify the seismicity activities of underground mine tunnels by detecting changes in seismic parameters of rock mass in spatial–temporal dimensions using tri-axial geophones [38]. However, Chaamwe et al. [38] recommended that the existing seismic monitoring system at Mufulira mine should be replaced by a WSN with a multihop transmission scheme to form an easy-wiring, reliable, and flexible communication network. Meanwhile, fiber Bragg grating (FBG)-based systems were proposed to monitor the structural health of the underground coal mine roof due to the high accuracy and reliability of FBG sensors. Jo et al. [96] designed an IoT-based structural monitoring platform for damage detection and real-time remote information sharing in a coal mine. In this design, sensing arrays consisted of FBG strain sensors and FBG temperature sensors, where FBG temperature sensors were installed in the vicinity of FBG strain sensors to provide temperature compensation for strain measurements. These FBG arrays were placed at the axial center of the tunnel roof to measure tensile strain and reflected the effect of dynamic mining operations on roof stability. After data acquisition, the collected information was transmitted to a Web 2.0 main server via optic fiber for further data analytics and visualization along with online real-time information sharing. In addition to strain monitoring, the roof safety monitoring system presented by Zhao et al. [97] also introduced FBG roof separation sensors to detect roof strata separation and indicate potential roof collapses. Horizontally mounted FBG accelerometer sensors could also locate seismic events in underground mines by recording micro-seismic signals [40].

B. Fire and Hazard Detection

Mine fires are one of the major concerns in coal mines and can result in catastrophic accidents, with safety and environmental consequences. Although coal fires can be attributed to various external factors (e.g., open flame and electrical sparking), coal spontaneous combustion is responsible for most coal fire incidents [98]. Coal spontaneous combustion is caused by coal oxidation which is a complicated exothermic process along with the generation of a large amount of heat and various gases. In the process of coal oxidation, heat is continuously generated and accumulates in underground coal mines until it reaches the coal ignition temperature [99].

Spontaneous combustion in coal can be judged by the coal temperature and concentration changes of the indicator gases [100]. As shown in Table IX, the coal spontaneous combustion process can be divided into four oxidation stages, and each stage corresponds to different coal temperature and indicator gases. CO is the main indicator gas as it accumulates throughout the entire coal spontaneous combustion process, while the other five gases can be regarded as auxiliary indicator gases to indicate the emergence of different oxidation stages. Since the spontaneous combustion becomes more intense with the increase of coal temperature, the gas sampling interval is shortened to reflect the coal spontaneous combustion status in real time.

IoT-based fire detection systems are widely used to monitor the status of mine fires in underground coal mines to prevent fire accidents. Bhattacharjee et al. [101] developed a fire detection and prevention system based on WSNs for bord and pillar coal mines to prevent the spread of coal fires at the early stage. In this design, gas sensor nodes were deployed at the inlet and outlet of a panel to detect CO and O_2 gas concentrations. Once the measured gas concentration exceeded the threshold value, the temperature sensor node at

TABLE IX
COAL TEMPERATURE AND INDICATOR GASES IN COAL SPONTANEOUS COMBUSTION PROCESS [100]

Oxidation stage	Coal temperature (°C)	CO concentration (ppm)	Auxiliary indicator gases	Gas sampling interval (hours)
Normal temperature self-heating oxidation	40	50–100	N/A	24
Accumulating heat oxidation	70	500	C_2H_6	12
Accelerated oxidation	100	1000	C_2H_6, C_2H_4	6
Fierce oxidation	130	1500	C_2H_6, C_2H_4, C_3H_8, C_3H_6, C_4H_{10}	2

the junction of each pillar was activated and measured temperature. In this case, whenever the measured temperature was above the threshold value, it indicated the possible presence of fire. Therefore, continuous temperature monitoring could effectively indicate the exact fire location and fire spread direction. Moreover, they [101] also proposed a fire prevention system (i.e., water pipes with automatically controlled electronic valves) to keep the coal mine safe from fire. The fire monitoring system proposed by Muduli et al. [98] detected temperature and concentrations of CO, CO_2, and O_2 gases by deploying sensor nodes in underground coal mines and introduced a fuzzy-logic approach to improve system reliability. Liu et al. [40] noted that coal mine goaf combustion in longwall mines could be monitored using a laser multigas sensor array and a fiber-optic distributed temperature sensor. The laser multigas sensor array measured concentrations of CH_4, CO, O_2, and C_2H_4 gases, and the distributed temperature sensor recorded the temperature distribution along the ventilation tunnels.

C. Personnel and Equipment Positioning

Global navigation satellite systems are not suitable for underground positioning because the satellite signal is not capable of penetrating ground and metals [102]. To deal with this problem, WSN-based IoT applications can be widely used for the real-time localization of personnel and vehicles in underground mines. A positioning system includes two types of sensor nodes (i.e., fixed and mobile sensor nodes), where anchors are fixed sensor nodes with known locations, while tags are mobile sensor nodes attached to personnel or equipment. The location of a tag can be determined according to the location information of reference anchors [42]. Range-based techniques [e.g., received signal strength (RSS), Time of Arrival (ToA), Time Difference of Arrival (TDoA), and Angle of Arrival (AoA)] are commonly used for positioning in underground mines because of their high accuracy. Range-based methods directly determine the distance between anchors and tags based on signal geometrical parameters, including signal strength, distance, and angle [103], [104].

Positioning systems in underground mines are mainly used for personnel tracking and proximity detection. Moschevikin et al. [105] discussed the possibility of real-time localization in underground linear mine tunnel environments by using leak feeders. Fink and Beikirch [106] proposed a personnel tracking system for longwall coal mines based on RFID technology and RSS measurements. In this system, anchors were attached to ground support at fixed intervals along the mine galleries, and tags were carried by miners. Mohapatra et al. [54] developed a local personnel positioning scheme in underground mines using Wi-Fi-based sensor nodes. To achieve long battery life, dynamic sensor nodes were configured with deep sleep mode and powered by high-capacity batteries. Liu et al. [107] designed a ZigBee-based positioning system with noncomplete coverage of underground mine tunnels. The entire mine tunnel was divided into several districts, and each district was covered by a separate WSN. They also noted that the previous location of a miner in a blind area was estimated using a linear interpolation approach, while the present and future locations of the miner in a blind area were predicted according to the previous movement using forecasting models [10]. Baek et al. [108] demonstrated that the real-time location of dump trucks in an underground limestone mine can be tracked by installing battery-powered Bluetooth beacons along the haul roads. Furthermore, a LoRa-based positioning system designed for emergencies was presented in [61], where a linear WSN was introduced to transmit the location information of personnel and equipment in underground mines when existing communications infrastructure has broken or failed.

Proximity detection provides miner-to-vehicle and vehicle-to-vehicle awareness in underground mines to prevent collisions. Bolic et al. [109] presented a novel RFID design to perform proximity detection. This system introduced a new device called "Sense-a-Tag" to passively receive and decode signals emitted by nearby normal RFID tags. Kianfar et al. [110] developed a UWB module for highly accurate tracking and proximity detection in underground mines based on a two-way ranging method. The field test indicated that the proposed UWB module could effectively alert miners of incoming locomotives in their proximity. Kim et al. [111] designed a smart helmet with a personal proximity detection and warning system based on BLE technology in an underground limestone mine. The BLE module at the rear of the smart helmet received signals transmitted from the Bluetooth beacon that was attached to heavy machines and dangerous zones at mine sites. The smart helmet was equipped with LED straps to provide personnel with visual warnings. Ullah et al. [112] noted that the advent of 5G would greatly facilitate vehicle-to-everything communication, which might be ideal for proximity detection in underground mines. Table X summarizes wireless communication technologies for underground mine positioning.

TABLE X
SUMMARY OF WIRELESS COMMUNICATION TECHNOLOGIES FOR UNDERGROUND MINE POSITIONING [22], [42], [102], [113]

Technology	Positioning algorithms	Positioning accuracy	Positioning coverage range	Typical applications
Leaky feeder	RSS, ToA [105] and TDoA [114]	Medium	300–500 m	Personnel/asset tracking
RFID	RSS and TDoA	Medium	100–300 m (active tag) 3–5 m (passive tag)	Proximity detection and personnel/asset tracking
Wi-Fi	RSS	Medium	50–150 m	Personnel/asset tracking
UWB	ToA and TDoA	High	10 m	Proximity detection
Zigbee	RSS	Medium	20–30 m	Personnel/asset tracking
BLE	RSS, ToA and AoA	Medium	30 m	Personnel/asset tracking
LoRa	RSS	Low	5 km	Localization in emergencies
5G	RSS, ToA and TDoA	High	20 m	Proximity detection and personnel/asset tracking

D. Production Safety Management

IoT technology has been introduced to ensure the safety of personnel in underground mines. An IoT-based smart helmet could detect hazardous events suffered by miners in underground mines and send a timely alert to the control room. Ramya et al. [115] designed a smart helmet integrated with four sensors using 2.4-GHz RF technology to detect potential accidents in underground mines. The infrared sensor detected abnormal helmet wearing such as helmet removal. The temperature sensor and the gas sensor were used to monitor the surrounding environment. The force sensor identified collision to the head. To timely alert the responsible person, an alert message was displayed on the graphical user interface and a buzzer was automatically activated in the control room when unexpected accidents occurred. A similar design was also presented by Eldemerdash et al. [116] based on ZigBee technology. However, the proposed system only worked when the infrared sensor reading was abnormal, and the buzzer in the control room was activated only when collision accidents might occur. Three LED lights in different colors were attached to the helmet to visually indicate the abnormal environmental parameters and infrared sensor value. Geetha [117] mentioned that a wireless voice transmission system could be established for the smart helmet based on ZigBee technology for communications between miners, and information exchange between miners and the control center.

Porselvi et al. [118] developed an underground miner health monitoring system based on LoRa technology. Heartbeat and respiratory sensors were used to monitor the health status of mine workers. Whenever the sensed value was beyond the threshold range, a buzzer turned on to alert miners. Meanwhile, the received data was uploaded to an online webpage in real time. Once the abnormal status was detected, the supervisor immediately received a crisis alarm and notified the rescue team if necessary. Zhou [55] designed a 3G-based video surveillance system to timely and accurately visualize the condition of mine workers and equipment in underground mines. If a mine accident occurred, the rescue team could gain a better understanding of the underground mine and take appropriate rescue measures. To ensure the safety of the rescue team in underground mines, Wang [41] designed a wireless emergency rescue system to monitor the vital signs of the rescuers using FBG and three-axis acceleration sensors. FBG sensors were used to detect the heart rate and body temperature of the rescuers, while the three-axis acceleration sensor was used to recognize the posture of the rescuers. Moreover, after the mine accident, mobile rescue equipment, such as radars [119] and rescue robots [120], was widely used to search for trapped miners and provide structural and environmental information about disaster areas for the rescue team as soon as possible.

IV. RESEARCH CHALLENGES AND FURTHER DIRECTIONS

Real-time connectivity and data analytics have great potential to improve the efficiency of mines today and in the future [121]. Although IoT can greatly benefit underground mining production, the industry lags behind other industries in adopting IoT-related technologies. This section discusses the key challenges in developing MIoT technologies in underground mines and highlights some potential future directions for underground MIoT research.

A. Inherent Issues in the Mining Industry

Mining activities require significantly high investment in the initial stage, and generally, no profit is gained until the start of continuous mining operations. The lifespan of a mine is expected to be decades. During this period, the market prices of minerals fluctuate. To maximize the value over the lifespan of a mine, mining companies are reluctant to make significant changes that may affect their operations and interrupt continuous production. Therefore, the mining industry is well known for not being innovative but a fast follower. The layout and mining status of underground mines varies from mine to mine. Every underground mine needs to design IoT applications based on its specific conditions, which means it can be expensive and difficult to develop standardization.

Data availability of MIoT applications is another intractable issue in the mining industry as mining companies rarely share their data with external parties due to concerns about confidentiality and competitive advantage. This is especially true for data sets that contain sensitive information, such as production rates, mineral grades, and exploitation costs. There are only a few open-access data sets relevant to underground MIoT systems. Kozielski et al. [122] presented a data set obtained by 28 sensors installed in different locations in an underground coal mine in Poland. This data set contained environmental data of the mine and status data of an operating longwall shear. The data was collected at 1-s interval between March and July 2014, with a total of 9 199 930 data samples. Using this data set, Ślęzak et al. [123] developed a forecasting model to predict the methane concentration in the coal mine. Similarly, Lyu et al. [124] trained an LSTM-based encoder–decoder model to predict the concentration of CH_4 gas in an underground coal mine working face using a smaller data set. The data set included concentration data of CH_4 gas collected by four sensors (from 2017-10-30 to 2017-11-18) in an underground coal mine working face in China.

B. Hardware Issues

IoT is an emerging technology, which encounters various technical issues in practical applications. Since some underground mines have explosive gases, dust, and humidity, sensors and communication devices should be resilient and intrinsically safe (especially for coal mines). The limited power supply in an underground mine is one of the major constraints for MIoT applications. Currently, the electricity consumed in underground mining operations is mainly provided by power cables because most renewable energy sources (e.g., solar, strong wind, and hydropower) are not available underground. Therefore, IoT-related electronic devices in underground mines need to be connected to power cables or equipped with batteries. Although small-size and low-power smart wireless sensors and communication modules have been developed for the IoT system to reduce power consumption, the battery still needs to be replaced regularly due to the limited battery life. Replacement can be complicated and hazardous at underground mine sites.

Energy harvesting techniques can be a potential solution to charge the batteries of low-power electronic devices by capturing a small amount of dissipated energy (e.g., heat, wind, sound, vibration, and movement) from working machines in underground mines. Vibration is one of the most common energy sources in underground mines because of the continuous operation of various machines. Energy harvesting from vibrations is mainly based on piezoelectric, electromagnetic, and electrostatic methods. Compared to electromagnetic and electrostatic mechanisms, piezoelectric transduction is the most suitable approach for vibration energy harvesting at mine sites because piezoelectric energy harvesters have the advantages of simple structure, miniature size, high energy density, and ease of integration [125], which can minimize interference to mining production.

So far, piezoelectric energy harvesting has demonstrated the ability to generate sufficient energy to power a wireless sensor node. Mouapi et al. [126] designed a cantilevered piezoelectric energy harvester to scavenge the vibration of an operating mining locomotive. The recorded vibration data indicated that the test locomotive produced random vibrations with a dominant acceleration of 0.72 g at a frequency of 21.88 Hz. In this case, the proposed energy harvester could generate a maximum power of 240.3 μW, allowing a commercial wireless ZigBee sensor node (CC2520 of Texas Instruments) to transmit data approximately 1 km every 7 min with appropriate power management. Khazaee et al. [127] developed a method for autonomous condition monitoring of water pumps based on the pulse duration of an RF transmitter. In this design, a cantilevered piezoelectric transducer was attached to the water pump to harvest vibration energy, with a power output of up to 710.45 μW. The harvested energy was then stored in a capacitor and used to provide continuous energy for the microprocessor and RF pulse transmitter. Le Scornec et al. [128] proposed a piezoelectric airflow energy harvester with a maximum power output of 60 μW at a wind speed of 6.3 m/s. Experimental results showed that four generators connected in parallel could fully charge a capacitor (capacitance of 1.2 mF) in 1 h. Once fully charged, the capacitor was capable of powering a wireless sensor node to conduct temperature measurements and RF communications seven times at intervals of 4 min.

According to the measurement conducted by Rodriguez et al. [129], the average power consumption of a BLE board (TI's CC2650) embedded with three sensors was around 255.3 μW with a sleep time of 2.5 s, while the average power consumption of a LoRaWAN end-device (Pervasive Nation) embedded with four sensors can be as low as 9.6 μW when the sleep time is 15 min. Therefore, due to the relatively low energy requirements of wireless sensor nodes, vibration energy harvesting from operating machines and ventilation airflow in underground mines show great potential for developing self-powered sensor nodes. As shown in Table XI, there are numerous potential vibration sources in underground mines. These vibration sources can generate steady vibrations that can be harvested to power sensors in nearby control and monitoring systems. However, to design an efficient vibration energy harvester for underground mines, the total amount, frequencies, and amplitudes of generated vibrations (including air flow for ventilation as it can generate vibration) in underground mines should be investigated.

Another outstanding hardware issue is system interoperability. Interoperability refers to the ability of a system or device to communicate and interoperate with other systems or devices within one department [16]. Various types of sensors are deployed in underground mines, and these sensors may come from different manufacturers. In this case, vertical fragmentation may occur because sensors from different vendors have their own technology stack and data formats. Therefore, sensors could only communicate with sensors of the same brand, which can be a massive hurdle for developing MIoT. To deal with this problem, MIoT standardization is an effective solution, which provides a unified approach for device interoperability and information security regardless of provider and communication technology.

C. Underground Communication Issues

Effective and efficient network communication is the key for underground MIoT applications. Although there are various communication technologies, wireless signal propagation is poor in confined and narrow tunnels and can be affected by metal and non-line-of-sight environments. The limited network coverage significantly increases the complexity and

TABLE XI
SUMMARY OF POTENTIAL VIBRATION SOURCES IN UNDERGROUND MINES FOR ENERGY HARVESTING

IoT Application	Hardrock mine	Coal mine (longwall)	Coal mine (room/bord and pillar)	Industrial mineral mine
Blasting control	Jumbo drill	-	-	-
Environmental monitoring	Truck, loader	Plow/shear	Continuous miner, haulage system	Continuous miner, haulage system
Loading weight monitoring	Truck	Stage loader	Continuous miner, feeder breaker/sizer, haulage system	Continuous miner, feeder breaker/sizer, haulage system
Structural health monitoring	Jumbo scaling, bolter	Ground support	Bolter	Bolter
Operating speed monitoring	Underground conveyor system, tunnelling conveyor	Plow/shear, armoured face conveyor, underground conveying system	Continuous miner/entry driver, conveying system	Continuous miner, conveying system
Machine health monitoring	Jumbo drill, jumbo scaling, bolter, tunnelling conveyor, underground conveying system, air compressor	Plow/shear, crusher, tunnelling conveyor, underground conveying system, air compressor	Continuous miner/entry driver, feeder breaker/sizer, bolter, tunnelling conveyor, underground conveying system, air compressor	Continuous miner, feeder breaker/sizer, bolter, tunnelling conveyor, underground conveying system, air compressor
Gas and airflow monitoring	Ventilation system (primary/secondary fan/ventilation airflow)			
Groundwater monitoring	Water management system (slurry/dewatering pump)			

expense of network deployment, while the low data rate can lead to data congestion and time delay. Therefore, further research on emerging RF communication technologies, such as LoRa and 5G, is necessary to provide cost-effective and real-time underground communication. Millimeter-wave technology has also gained widespread attention in recent years. On the one hand, millimeter-wave communication provides IoT applications with high-rate data transmission and massive available bandwidth (30–300 GHz) [120]. On the other hand, although millimeter-wave systems can experience significant signal path loss due to obstacles, they can be used for accurate underground location estimation and environment sensing, especially with the advent of low-cost, small-sized, and light-weighted millimeter-wave radar sensors [131]. For example, millimeter-wave radar systems have been used for indoor human positioning and motion recognition [132], driver health monitoring [133], automotive tracking and localization [134], and proximity detection [135]. With further research, these applications can be adapted to vehicles and miners working in underground mines. To improve the effectiveness of millimeter-wave communication systems in non-line-of-sight scenarios, techniques, such as massive multiple-input–multiple-output [136], beamforming [137], and reflector-assisted communication [138], [139], are introduced to compensate for signal attenuation and scattering caused by obstacles.

Visible light communication (VLC) is another potential wireless solution for underground mine communication, especially in areas that pose risks or other challenges to radio frequencies [140]. For instance, a VLC system can be used for personnel localization when RF signals do not work. In this case, a VLC system mainly consists of LED luminaries as transmitters mounted on the ceilings and walls and photodetectors (PDs) as receivers placed on miners' helmets [141]. Similarly, proximity detection for oncoming vehicles and miners can be achieved using VLC [142].

Due to the uneven and dynamic geographical environment, it is challenging to design a robust and reliable network topology in underground mines. Node failure and damage may occur in the event of roof collapses and mine accidents, and more nodes are required as the working face advances. To cope with these unexpected situations, network topology should be self-adaptable and scalable to maintain the smooth operation of the network and enable network expansion.

A communication system in an underground mine always provides positioning and tracking capabilities. The configuration and deployment of an underground mine communication network have a significant influence on the accuracy of positioning because the locations of personnel and equipment in underground mines are mainly predicted by various signal metrics. However, accurate positioning is challenging because of signal multipath effects and varying propagation characteristics in dynamic underground environments. Additionally, positioning systems consume high energy for signal transmission and processing to improve positioning accuracy and range. Ideally, the communication network can be parallelly used for normal data communication and accurate positioning and tracking in underground mines with robust and energy-efficient localization algorithms.

D. Data Management Issues

It is challenging to integrate data collected by MIoT applications because of the data silos and massive amount of data. Data silos describe the incompatible data distributed across different platforms [63]. Since an underground mine can operate for a long time, data obtained from legacy systems is often in information silos. The existence of data silos leads to inconvenience in data gathering and data management. Meanwhile, the prevalence of underground MIoT applications can lead to an unprecedented increase in data categories and data volumes from various information systems across mining sectors, which may exacerbate data silos and significantly increase the workload of data processing. The use of MIoT applications generates time-series data in the mining lifecycle which plays a crucial role in the monitoring and prediction of mining safety and production (e.g., predicting geological hazards based on the time-series data).

For efficient data management, a unified data structure should be proposed to standardize various collected data and ensure compatibility with the time dimension iteration. Data exchange and processing workflows, such as raw data conversion, data cleaning, analytics data exchange, and multiplatform data exchange, are required for initial data processing. Edge, fog, and cloud computing platforms can be used for massive data analytics and storage based on specific situations.

V. Conclusion

This article has presented recent developments in IoT applications for environmental, safety, and production monitoring in underground mines. To gain a comprehensive understanding of IoT essentials in underground mines, this article discussed a generic three-layer MIoT architecture, the sensors used for data collection, and communication technologies used for data transmission in underground mines. IoT applications have been widely used for environmental monitoring in underground mines, such as mine gas and dust monitoring, temperature, humidity and airflow monitoring, groundwater monitoring, and structural monitoring. Fire detection systems have been developed to effectively prevent coal mine fire accidents by monitoring coal temperature and indicator gases. Real-time and accurate localization of personnel and equipment, and production safety management in underground mines have been realized by using IoT technology based on wireless communication.

Although various IoT applications have been proposed to monitor the operation of underground mines, most designs are still in theoretical and experimental stages. It is challenging to run in-situ tests in underground mines due to the potential disruption to active operations. To enhance the effectiveness and efficiency of IoT-based monitoring systems, this article has discussed the possibility of developing self-powered wireless sensors and communication modules using energy harvesting techniques. MIoT standardization, wireless communication technologies suitable for underground mines, and efficient data management approaches should be further investigated.

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Huili Zhang received the B.Sc. degree in energy and power engineering from the University of Science and Technology Beijing, Beijing, China, in 2019, and the M.Sc. degree in renewable energy engineering from the University of New South Wales, Sydney, NSW, Australia, in 2021, where she is currently pursuing the Ph.D. degree with the School of Minerals and Energy Resources Engineering.

Her research interests mainly focus on vibration energy harvesting and sensing for mine Internet of Things.

Binghao Li (Senior Member, IEEE) received the B.Sc. degree in electrical and mechanical engineering from Beijing Jiaotong University, Beijing, China, in 1994, the M.Sc. degree in civil engineering from Tsinghua University, Beijing, in 2001, and the Ph.D. degree in spatial information systems from the University of New South Wales, Sydney, NSW, Australia, in 2006.

He is currently an Associate Professor and a Leader with the MIoT & IPIN Lab, School of Minerals and Energy Resources Engineering, University of New South Wales. His research interests include indoor positioning, pedestrian navigation, satellite positioning and navigation, and mine Internet of Things.

Mahmoud Karimi received the B.Sc. degree in mechanical engineering from Azad University, Karaj, Iran, in 2006, the M.Sc. degree in mechanical engineering from Iran University of Science and Technology, Tehran, Iran, in 2010, and the Ph.D. degree in mechanical engineering from the University of New South Wales, Sydney, NSW, Australia, in 2016.

He is currently an ARC DECRA Fellow and a Senior Lecturer with the Centre for Audio, Acoustics and Vibration, University of Technology Sydney, Sydney. His research interests include computational vibration and acoustics, flow-induced noise and vibrations, uncertainty quantifications in mechanical systems, and identification of stochastic vibration forces.

Serkan Saydam received the B.Sc., M.Sc., and Ph.D. degrees in mining engineering from Dokuz Eylul University, Izmir, Turkey, in 1992, 1995, and 2000, respectively.

He was a Postdoctoral Fellow with the University of Witwatersrand, Johannesburg, South Africa. He is currently a Professor and a Chair of Mining Engineering with the School of Minerals and Energy Resources Engineering, University of New South Wales, Sydney, NSW, Australia. His research interests include space resources engineering, ground control, mine systems design, mine Internet of Things, and technology integration and management.

Prof. Saydam is currently a Fellow Member of AusIMM; the President of the ISRM Commission on Planetary Rock Mechanics; the Deputy Director of the Australian Centre for Space Engineering Research at UNSW; and the Deputy Secretary-General and a Council Member of The Society of Mining Professors.

Mahbub Hassan (Senior Member, IEEE) received the B.Sc. degree in computer engineering from Middle East Technical University, Ankara, Turkey, in 1989, the M.Sc. degree in computer science from the University of Victoria, Victoria, BC, Canada, in 1991, and the Ph.D. degree in computer science from Monash University, Melbourne, VIC, Australia, in 1998.

He is currently a Professor with the School of Computer Science and Engineering, University of New South Wales, Sydney, NSW, Australia. His research interests include mobile networks, nanoscale wireless sensor network, self-powered and energy-harvesting wireless networks, Internet of Things, and wearable computing.

Prof. Hassan was a Distinguished Lecturer of IEEE (COMSOC) from 2013 to 2016. He is currently an Editor of IEEE COMMUNICATIONS SURVEYS AND TUTORIALS and has previously served as a Guest Editor for IEEE NETWORK and an Associate Technical Editor for the *IEEE Communications Magazine*.