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Review

Reliability of LoRaWAN Communications in Mining Environments: A Survey on Challenges and Design Requirements

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Abstract: While a robust and reliable communication network for monitoring the mining environment in a timely manner to take care of people, the planet Earth and profits is key, the mining environment is very challenging in terms of achieving reliable wireless transmission. This survey therefore investigates the reliability of LoRaWAN communication in the mining environment, identifying the challenges and design requirements. Bearing in mind that LoRaWAN is an IoT communication technology that has not yet been fully deployed in mining, the survey incorporates an investigation of LoRaWAN and other mining IoT communication technologies to determine their records of reliability, strengths and weaknesses and applications in mining. This aspect of the survey gives insight into the requirements of future mining IoT communication technologies and where LoRaWAN can be deployed in both underground and surface mining. Specific questions that the survey addresses are: (1) What is the record of reliability of LoRaWAN in mining environments? (2) What contributions have been made with regard to LoRa/LoRaWAN communication in general towards improving reliability? (3) What are the challenges and design requirements of LoRaWAN reliability in mining environments? (4) What research opportunities exist for achieving LoRaWAN communication in mining environments? In addition to recommending open research opportunities, the lessons learnt from the survey are also outlined.

Keywords: reliability; LoRaWAN; mining environment; Internet of Things (IoT) communication; mission-critical; telemetry and alarms

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1. Introduction

More than ever, the goal of the mining sector is to make mining sustainable, which entails maintaining a certain level of resources for current and future needs, as well as protection of human health and the environment. This is in tandem with the Sustainable Development Goals (SDGs), which aim to achieve, among other things, responsible consumption and production; sustainable industry, innovation and infrastructure; good health and well-being; clean water and sanitation; climate action; and protection of life below water and on land [1]. To make mining sustainable, Internet of Things (IoT) technologies will play a critical role in providing mine monitoring techniques to help avoid accidents, reduce loss of ore resources, maintain and preserve water and soil quality and preserve human life and health. Mining companies require data harvesting technologies that are more effective, work within the field and are faster and more robust. This includes wireless communication solutions that are not disruptive to mining operations and are less costly, as well as novel wireless underground communication techniques for the IoT to support real-time collection of data for decision making [2].

Sensing, monitoring and communications technologies are needed in areas such as exploration, mining and metal processing so as to improve productivity, safety and health. Mine monitoring techniques help to establish a proper environment to avoid accidents, destruction of equipment, loss of ore resources and closure of mines with the greatest effectiveness. This is in line with sustainable mining where human safety and environmental protection are the main priority, thus requiring novel surface and underground IoT techniques to enable real-time collection of data for decision making [3].

Mining environments are mission-critical, requiring reliable communications to address incidents and escalate rescue operations. Accurate monitoring and locating of miners and explosives is crucial to ensure quick response to fatal accidents. This calls for a robust and reliable communication network, which is essential to monitor the mine environment in a timely manner [4]. This environment is also very challenging in terms of achieving reliable wireless transmission (TX) due to a number of factors that work against electromagnetic wave propagation, such as the presence of heavy machinery and extreme humidity, temperature and vibration. In addition, wireless surface technologies fail underground due to signal attenuation, path loss and shadow fading as a result of signal propagation through tunnels characterised by irregular, confined shapes and rough environments. In some mines, high-energy transmission is not allowed due to the presence of methane and carbon monoxide, a typical example being inside coal mines where transmission energy should be below 25 mJ [5].

The smart mining infrastructure uses a large number of sensors to regularly monitor the mining environment for temperature, humidity, the presence of poisonous gases and to track miners and equipment, as well as to detect events and alarms to ensure safety in the workplace. This entails that different types of traffic with varying quality of service are generated that can be broadly classified into two categories: telemetry and alarm messages. The former are regular, non-emergency traffic generated from constant monitoring and measurements, tracking miners and equipment, while the latter are emergency traffic that occur occasionally as a result of sudden and drastic changes in mine conditions or a safety alarm sent by one of the miners. Regular, non-emergency traffic is not delay-sensitive or reliability-constrained, while emergency traffic requires high reliability, low latency and high throughput [2,4].

Long-range (LoRa) technology is promising for mining environments due to characteristics such as long range, ultra-low power consumption, deep penetration capabilities and adaptive rate and chirp spread spectrum modulation [4]. Additionally, it works best for underground scenarios due to the use of an unlicensed frequency band and the unique characteristics of the physical layer, such as −150 dBm receiver sensitivity [5]. This paper therefore surveys the reliability of Long Range Wide Area Network (LoRaWAN) communication in mining environments and discusses the challenges and design requirements of LoRaWAN reliability in the mining environment.

1.1. Summary of Contributions

Recently, the reliability of LoRaWAN communication has been studied from different perspectives by researchers. Some have covered the strengths and weaknesses of LoRaWAN communication [6,7], while others have considered the design goals of various use cases and analysed LoRaWAN's suitability [8]. Some of the research work has focused on its optimisation for urban environments [7], while other work has hinted at its reliability for industrial setups in general [9–11] and yet other researchers have considered specific industrial setups, such as farming [12] and health [13].

We thus identified a gap with regard to research on LoRaWAN communication reliability in mining that takes into consideration the traffic characteristics of the mining environment, as a thorough investigation of the reliability of LoRa/LoRaWAN communication that would enable practical deployment of the technology for mining IoT (MIoT) systems has not been conducted. Additionally, realising that each technology has strengths and weaknesses, the record of reliability of LoRaWAN communication in mining was investigated together with other MIoT technologies. MIoT technologies comprise advanced sensing and communication solutions and information systems and are used for real-time data collection and decision making in mining. In this work, we also cover what communication reliability means in mining and focus in on LoRaWAN techniques for communication reliability in mining.

In summary, the specific contributions of this paper are:

1. It provides an update on mining IoT technologies, highlighting their strengths, weaknesses and record of reliability in order to determine the IoT technologies that are promising for future mining;
2. It provides a solid definition of the reliability of communication systems. In all the publications reviewed by the authors of this paper, only the authors of [14] defined reliability, which was while discussing private 5G networks; thus, it is imperative that we add to this definition to cover communication reliability conclusively;
3. It stipulates what reliability means in the mining environment and outlines the challenges and design requirements of LoRaWAN reliability in mining environments;
4. It highlights the lesson learnt from the survey and unveils the open research challenges related to achieving LoRaWAN communication reliability in mining environments.

1.2. Structure of the Paper

The rest of the paper is structured as follows: Section 2 outlines the works related to this study and Section 3 brings to the fore IoT communication systems in mining environments, discussing their record of reliability. Section 4 focuses on the reliability of LoRaWAN communication for mining, highlighting four aspects of reliable IoT communications in mining, as well as LoRaWAN techniques for reliability. Challenges and design requirements of LoRaWAN reliability in the mining environment are discussed in Section 5, while Section 6 states the lesson learnt from this study and open research challenges. Finally, Section 7 concludes the work. Figure 1 shows the overall structure of the paper.

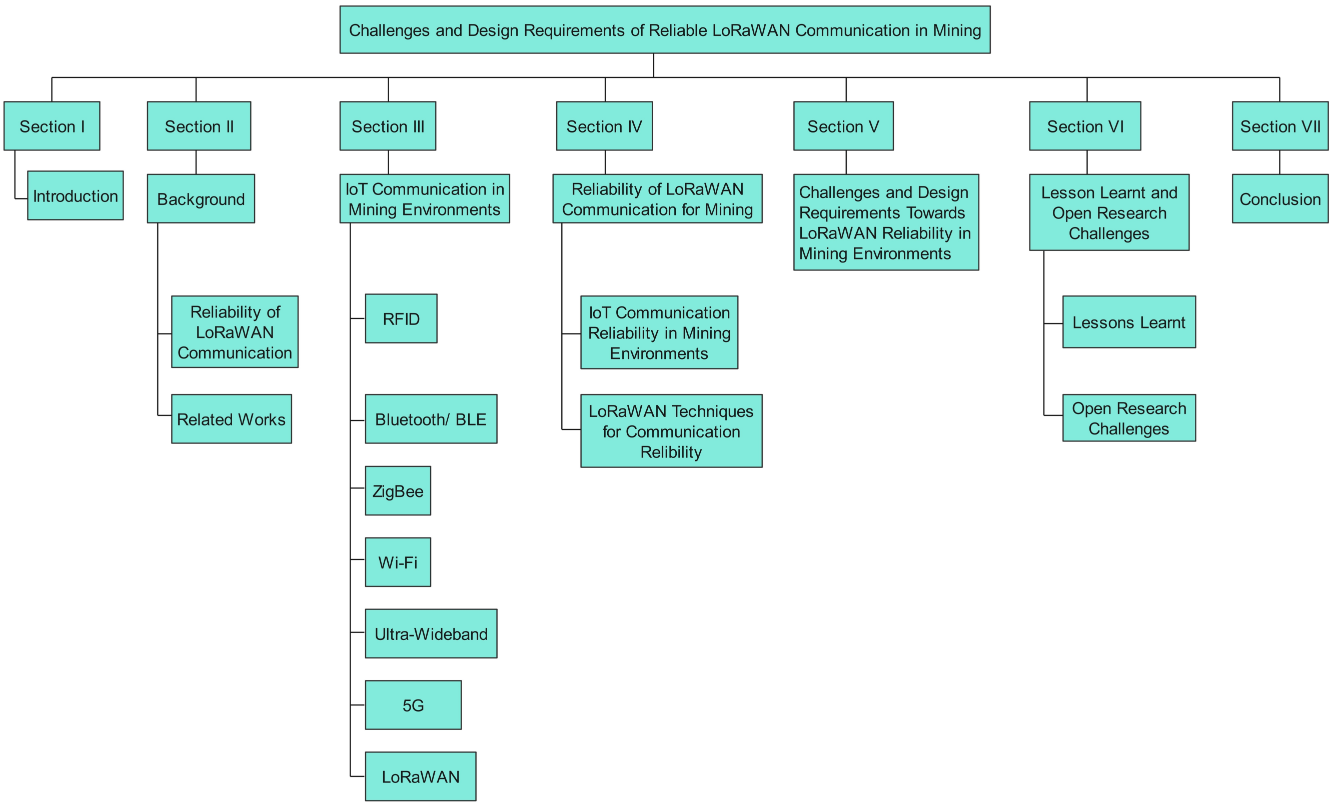

Figure 1. Structure of the paper.

2. Background

2.1. Reliability of LoRaWAN Communication in Mining Environments

LoRaWAN provides a low-power, wide-area network (LPWAN) that can be used to support the IoT for both indoor and outdoor applications. It also allows set up of autonomous LPWANs without any third-party infrastructure, which makes it suitable for industry. It has been deployed for a wide range of applications, such as smart buildings, smart agriculture, smart meters, water quality management, wildlife management, smart transportation and logistics, smart lighting, smart parking and smart bins. In particular, it has been deployed in waste management in North Korea, solar power plant management in the United States of America, power usage monitoring in France, smart meters in Germany, a smart golf course in Canada and smart islands in Spain [6]. However, as observed by Filho et al. [2] and Buurman et al. [8], it has yet to be deployed in mining, deep underground, deep underwater and in space. Also noteworthy is what the investigation by Sundaram et al. [6] brings out, which is that the technology still has challenges in four areas; namely, link coordination, resource allocation, reliable transmission and security.

Some proposals have been made to improve LoRaWAN communication reliability in general [15,16], in industrial applications [2,17] and in mining [4,5,9]. The nature of the mining environment and the unique nature of the traffic generated therein raise the need for more investigation into the reliability of LoRaWAN technology in this environment. Our aim, therefore, is to bring together work on not only IoT communication for LoRaWAN but also other mining IoT communication technologies so as to arrive at the challenges and design requirements of reliable LoRaWAN communication in mining, as well as to gain insights into suitable mining use cases to enable practical deployment.

2.2. Related Work

Sundaram et al. [6] provide a taxonomy of research problems for LoRa technology and, based on this, challenges, current research solutions and open issues are discussed generally without any attachment to a specific industrial environment. Considering the challenge of interference caused by concurrent transmission on the same channel when LoRaWAN is deployed in urban areas, the authors of [7] present a systematic review of state-of-the-art work on LoRaWAN optimisation solutions for IoT networking operations focusing on five aspects that directly affect the performance of LoRaWAN. Additionally, key research challenges and open issues relating to LoRaWAN optimisations for IoT networking operations are identified for further study in the future. In [18], the survey focuses on the need for integration of different low-power, wide-area (LPWA) technologies and recommends the appropriate LPWA solutions for a wide range of applications and service use cases. Opportunities created by these technologies in the market are analysed, and the paper also compares and analyses the latest research efforts to investigate and improve the operation of LPWA networks. Finally, challenges facing LPWA are identified, together with directions for future research. Assessing a technology's ability to meet design goals is essential in determining suitable technologies for a given application; thus, the authors of [8] include a systematic analysis of the design goals and design decisions adopted in various commercially available and emerging LPWAN technologies. System architecture and specifications are also presented for the identified LPWAN solutions, and their ability to meet each design goal is evaluated. Also outlined are 17 use cases with design goals prioritised as low, moderate or high. It is worth noting, however, that among the wide range of applications and service use cases considered in [18] and [8], mining is not covered.

Other related works cover industrial environments in general. In [9], the concepts of the IoT, the industrial IoT (IIoT) and Industry 4.0 are clarified, together with the opportunities brought by the paradigm shift and the challenges for its realisation, such as energy efficiency, real-time performance, coexistence, interoperability, security and privacy. The paper also provides a systematic overview of the state-of-the-art research efforts and potential research directions to solve IIoT challenges. Vitturi et al. [10] provide a comprehensive overview of networks used in factory automation and process control, an analysis of the market status and trends and an assessment of future perspectives, covering next-generation Ethernet, 5G telecommunications, the IIoT, software-defined networking and networks for automotive applications. Finally, the author of [11] analyses the existing media access control (MAC) protocols that are suitable for the IIoT.

In the area of mining, related works cover current MIoT technologies, indoor positioning techniques and wireless communication. Kim et al. [19] analyse IoT and open-source-hardware technology use cases in the mining industry. The IoT technologies considered are Bluetooth, radio-frequency identification (RFID) and wireless sensor networks (Zigbee). The hardware technologies they focus on are Arduino and Raspberry Pi as IoT platforms that can connect wireless sensors. The authors of [20] provide a review of indoor localisation techniques and technologies, beginning with current localisation systems and a summary of comparisons between these systems in terms of accuracy, cost, advantages and disadvantages. Different detection techniques are also studied and compared in terms of accuracy and cost. Additionally, localisation methods and algorithms, including angle of arrival (AOA), time of arrival (TOA) and received signal strength (RSS), are introduced. The study thus contains concepts, requirements and specifications for each category of methods; discusses pros and cons for the investigated methods; and presents comparisons between them. A systematic survey involving the Internet of Underground Things [21] finds that the harsh underground propagation environment, including sand, rock, and watersheds, does not allow the use of a single communication technology for information transfer between the surface and underground things. Therefore, various wireless and wired communication technologies must be used for underground communication. In this paper, state-of-the-art communication technologies are surveyed, and the respective networking and localisation techniques for The Internet of Underground Things (IoUT) are presented together with the advances in and applications of the IoUT. Additionally, new research challenges for the design and implementation of the IoUT are identified. Liu et al. [22] provide a comprehensive comparison and analysis of wireless fidelity (Wi-Fi)-based indoor positioning techniques from the perspective of passive and active positioning, also outlining the requirements and challenges of the two techniques in practice. In addition, they introduce the Wi-Fi-based positioning system combined with other positioning technologies and analyse the applicability, advantages and disadvantages of these systems. As a response to the challenges, open research issues concerning Wi-Fi positioning are also covered.

Lastly, some of the related works involve industrial environments, such as farming and health. Islam et al. [12] outline some major applications of the IoT and unmanned aerial vehicles (UAVs) in smart farming and explore the communication technologies, network functionalities and connectivity requirements for smart farming. The connectivity limitations of smart agriculture and their solutions are analysed with two case studies. In case study one, the authors propose and evaluate meshed LoRaWAN gateways to address the connectivity limitations of smart farming. In case study two, they explore the use of satellite communication systems to provide connectivity to smart farms in remote areas of Australia. Finally, they identify future research challenges related to this topic, outlining directions to address those challenges. In [13], a survey of emerging healthcare applications, including detailed technical aspects required for the realisation of a complete end-to-end solution for each application, is presented. The paper explores the key application-specific requirements from the perspective of communication technologies, as well as providing a detailed exploration of the existing and emerging technologies and standards that would enable such applications, highlighting the critical consideration of short-range and long-range communications. The survey also highlights important open research challenges and issues specifically related to future IoT-based healthcare systems.

In the existing literature, there is a lack of specific studies on LoRa/LoRaWAN in mining. This survey thus addresses the reliability of LoRaWAN communication in the mining environment, highlighting the communication challenges and design requirements of LoRaWAN in this environment. In addition to LoRaWAN, it considers other MIoT technologies, such as Zigbee, Bluetooth, RFID, Wi-Fi, fifth-generation cellular technology

(5G) and ultra-wideband (UWB), specifying their strengths, weaknesses and records of reliability. Further, lessons learnt from the survey and open research challenges for future studies are presented. To the best of the knowledge of the authors, such a survey has not been undertaken before.

A summary comparison of the related work discussed in this section and our work is presented in Table 1.

Table 1. A comparison of related articles on reliability of LoRaWAN communication in mining environments (✓ indicates an aspect has been covered, ✗ indicates an aspect has not been covered and ∗ indicates that an aspect is partially covered or not directly connected to mining).

		Reliability of LoRaWAN Communication				
Reference	**Focus Area**	**Strengths and Weaknesses**	**Record of Reliability**	**Design Requirements and Challenges in Mining**	**IoT Communication Reliability in Mining Environments**	**LoRaWAN Techniques for Communication Reliability**
Sundaram et al. [6]	LoRa technology problems and solutions in general	✓	✗	✗	✗	∗
Silva et al. [7]	LoRaWAN challenges in urban areas	∗	✗	✗	✗	∗
Qadir et al. [18]	LoRaWAN and LPWA technologies in general	✓	✗	✗	✗	∗
Buurman et al. [8]	LoRaWAN and LPWAN technologies in general	✓	✗	✗	✗	∗
Sisinni et al. [9]	LoRaWAN and IIoT technologies	∗	✗	∗	✗	∗
Vitturi et al. [10]	Industrial communication systems	✗	✗	∗	✗	✗
Chehri et al. [11]	MAC protocols for the IIoT	∗	✗	✗	✗	✗
Kim et al. [19]	RFID, Zigbee and Bluetooth for the mining IoT	✓	∗	∗	∗	✗
Obeidat et al. [20]	Indoor localisation technologies in mining	✓	∗	∗	∗	✗
Saeed et al. [21]	Internet of Underground Things	✓	∗	∗	∗	✗
Liu et al. [22]	Wi-Fi positioning techniques	✓	∗	∗	∗	✗
Islam et al. [12]	LoRaWAN and UAVs in farming	✓	∗	✗	✗	✗
Alam et al. [13]	LoRaWAN and other technologies in healthcare	✓	✗	✗	✗	∗
This survey	LoRaWAN communication in mining	✓	✓	✓	✓	✓

3. IoT Communication in Mining Environments

IoT-based monitoring systems employing advanced sensing, communication systems and information systems are needed in mining to specifically deal with health and safety, environmental issues, earth crust monitoring, transportation management, gas detection, fire prevention and detection, conveyor belt monitoring, water hazards and quality and miner tracking [3]. There is particularly a need for reliable wireless underground communication techniques for the IoT to address incidents and escalate rescue operations [3,4]. However, wireless communication is very difficult in underground mines because of irregular, confined shapes and rough environments. This section looks at technologies being implemented for the IoT in mines and their applications, strengths, weaknesses and records of reliability. The technologies covered are classified as licensed and unlicensed; long-range, medium-range and short-range; and cellular and non-cellular, as shown in Figure 2.

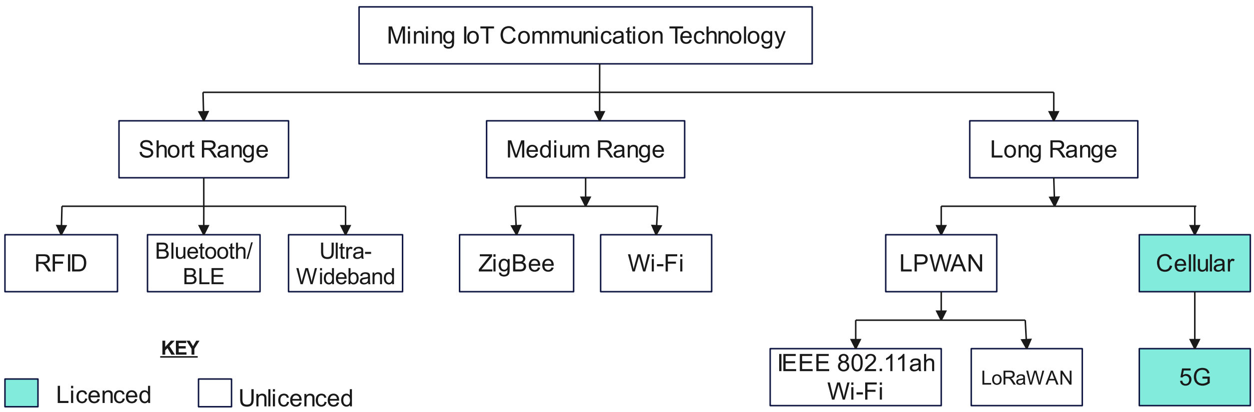

Figure 2. Classification of mining IoT technologies.

3.1. *Radio-Frequency Identification (RFID)*

RFID, also known as wireless identification, uses radio frequencies (RFs) to read data stored in a contactless tag, making it useful for identifying items. It is an improvement of barcode technology meant to address its limitations; thus, it has a high recognition rate, is not affected by the direction of access and can read or modify multiple pieces of information simultaneously. RFID is classified according to the frequency band used: low-frequency RFID (30–500 kHz), high-frequency RFID (10–15 MHz) and ultra-high-frequency (UHF)/microwave RFID (850–950 MHz, 2.4–3.5 GHz and 5.8 GHz) [19,23]. It has different strengths and weaknesses depending on the band used.

3.1.1. Application in Mining

RFID is actively used in mines for localisation and tracking applications [4]. Specific applications include efficient equipment operation and worker safety, where receivers are placed at mine entrances and major workshops and RFID tags are installed on mine equipment and workers' hard hats. RFID is also used to manage logistics in mines, vehicle operations and worker time and attendance. For applications that involve the location of workers, RFID tags are embedded in lamp batteries. RFID is also used in reduction furnaces to automate the process and establish a systematic quality control system. Figure 3 illustrates an RFID mining system for tracking dump trucks. From a survey of the Zambian copper mining industry, it shows how RFID is applied underground for location tracking of dump trucks.

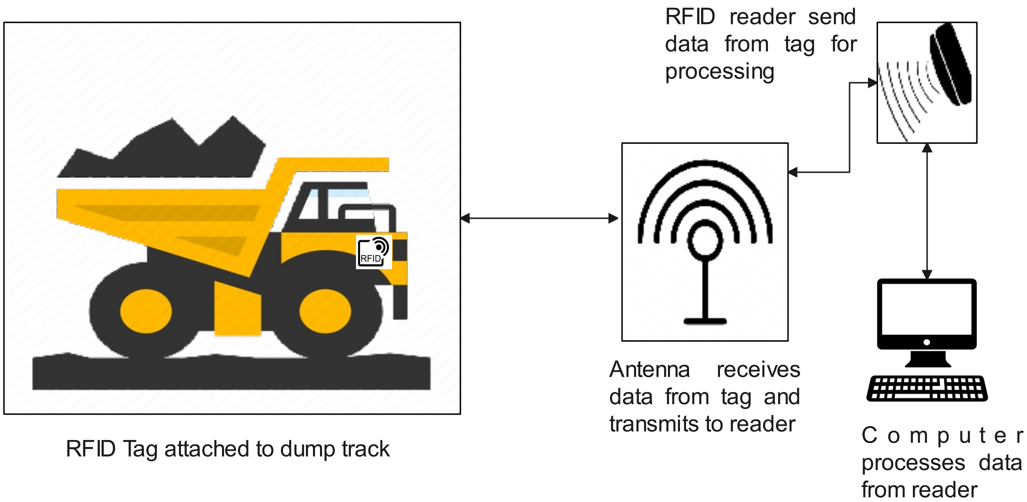

Figure 3. Schematic diagram of RFID tracking system—adapted from [24].

3.1.2. Strengths and Weaknesses

Low-frequency RFID has the advantages of short recognition distance, relatively slow recognition speed, low performance degradation and low price. High-frequency RFID can recognise multiple tags, while microwave RFID has an excellent recognition rate even at long distances. Data on tags are more secure because they are hidden from plain sight and are represented by digital signals. Data can also be encrypted such that only specialised equipment can read the data. It is also important to note that there are three types of RFID tags in terms of power supply: passive, semi-passive and active. Passive tags do not have an internal power source but rely on the power provided by the RFID reader. Passive tags thus have the advantage of an unlimited lifespan due to not being dependant on an internal power source.

On the other hand, interception is still possible since data are transmitted as digital signals. Additionally, microwave RFID in particular is greatly affected by environmental conditions, such as moisture and physical obstructions, which can limit the system as readers can have problems scanning through metallic and conductive objects. Compared to other wireless technologies and standards, such as ultra-wideband, Bluetooth and Zigbee, RFID is considerably inferior due to technological limitations [25].

3.1.3. Record of Reliability

With regard to the record of reliability of RFID, high-frequency RFID has high reliability for transmitted data, and ultra-high-frequency RFID in particular is reliable for capturing data with fast-moving objects, such as dump trucks. In addition, tags can be read away from the line of sight and can also track items in real time to provide important information about their location and status. The advantage of the passive tags stated above adds to the reliability of the system in terms of both unlimited lifespan and security because the tag can only be read if powered by a related reader. Studies and systems implemented in mining indicate that RFID is both accurate and reliable [23]. In relation to the IoT, however, RFID is used for data perception; therefore, it is equivalent to a sensor or end node. This places a limitation on it in that it depends entirely on other network technologies to transmit the data read to servers or cloud databases, as well as monitoring devices. The required distance between the RFID tag and reader is short: practically, 10 m for UHF RFID [23] and 100 m for microwave RFID [19].

3.2. Bluetooth/Bluetooth Low Energy (BLE)

Bluetooth is a short-range wireless technology standard that connects mobile devices for information exchange. It wirelessly exchanges data using ultra-high-frequency radio waves in an unlicensed (free-to-use) industrial, scientific and medical (ISM) frequency band specifically from 2.4 GHz to 2.485 GHz. Recently, measures have been introduced to improve transmission speed from the typical 720 kbps and to reduce energy consumption. For instance, version 4 of the standard enables periodic transmission of Bluetooth signals with a low-energy protocol. In addition, Bluetooth beacons can be used to identify indoor locations and detect environmental changes in various fields. Version 4.2, released in 2014, improves the ability to respond to the IoT due to the addition of an Internet protocol support profile (IPSP) to the standard. The latest version (5.0) improves the slow transmission speed of the low-energy protocol and adds the slot availability mask (SAM) function to block interference between IoT devices in advance, while versions 3.0 and 4.0 support 25 Mbps [19,26]. BLE (version 4 and higher) consumes less energy than standard Bluetooth (versions 1 to 3) because it was developed for applications that require only periodic data and not continuous streaming of data; thus, it remains in sleep constantly except when a connection is initiated [27].

3.2.1. Application in Mining

In mining, Bluetooth is used for localisation and tracking [4]. Investigational tests have also been undertaken to enable application of Bluetooth in underground intra-mine location-tracking systems, measuring the travel time of transport trucks using smartphones by means of Bluetooth beacon signals and employing a smartphone application that uses Bluetooth beacons to track and visualise objects in three dimensions (3D). Figure 4 is a block diagram of a Bluetooth position-sensing device and alert system to help miners move away from dangerous zones. It is worth noting that Bluetooth was less useful in the mining field in the past due to communication distance and transmission speed limitations, but due to continuous improvements, it is expected to have effective future applications in mining [19].

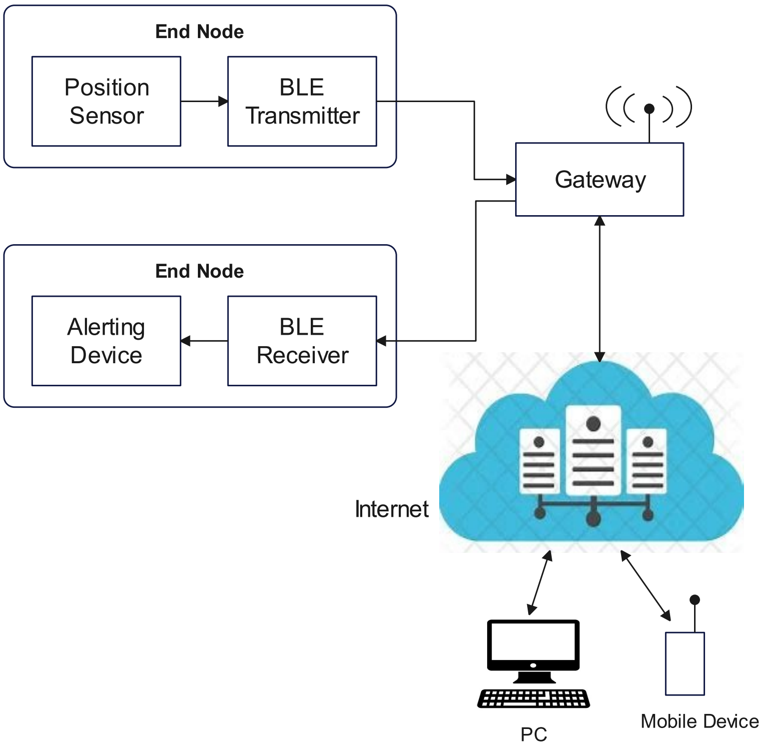

Figure 4. Block diagram of Bluetooth miner alert system.

3.2.2. Strengths and Weaknesses

Bluetooth makes it possible to wirelessly connect or pair devices to create a WPAN, enable wireless Internet connectivity and wireless synchronisation and conveniently exchange files without the trouble of using cables or hardware interfacing technology. The technology has extensive availability and accessibility in that most laptops and mobile devices (smartphones and tablet computers) have inbuilt Bluetooth hardware, and personal computers (PCs) that do not have the required hardware component can communicate with Bluetooth-enabled devices using a Bluetooth adapter. Additionally, the technology has seemingly become a standard feature of modern computers (laptops and mobile devices) as these include wireless speakers and headphones, and such devices, together with microphones, mice, etc., can be obtained at a reasonable cost. It is also considerably easy and convenient to use, since devices with built-in Bluetooth radios can easily be paired, and there is no need to install additional software or drivers to establish communication between devices enabled with the technology and no rigorous setup process. In addition, it is relatively energy-efficient, particularly for the BLE standard, the ultra-low-power requirement of which makes it ideal for small devices and wearable technologies that need minimal battery lifespan and a small form factor [26,28]. Standard Bluetooth can consume up to a maximum of 1 watt of power, while BLE consumes between 0.01 and 0.5 watts; thus, some BLE devises use 100 times less power [29].

Despite the outlined strengths, Bluetooth/BLE has limited operational range. The range depends on the class of radio used; thus, enabled devices can only establish and maintain communication as long as they are within the range limit. Class-one radios range from 20 to 30 m for commercial use and up to 100 m for industrial use cases, while class-two radios have a more limited range of up to 10 m and class three less than 10 m. With regard to energy consumption, however, Bluetooth can be energy-inefficient in real-world applications as it can significantly drain the battery life of a device, particularly if it remains turned on. In addition, for mobile devices that use their battery for different software processes and keep the hardware components running, a Bluetooth radio increases the power requirement of the device. Energy efficiency is also dependent on the specific class of the radio, with class-one radios being more power-intensive and requiring 100 milliwatts (mW) due to their comparatively longer range relative to classes two and three, which transmit at 2.5 mW and 1 mW [30]. Bluetooth has a slower data transmission rate compared to other hardware interfacing technologies, such as Wi-Fi Direct at 250 Mbps, USB 3.0 (wired) at 5 Gbps and at 40 Gbps. There are also security vulnerabilities as Bluetooth can be susceptible to denial-of-service attacks, eavesdropping, man-in-the-middle attacks, message modification and resource misappropriation. Although a standard has been implemented, there are still compatibility and functionality issues as a result of factors such as the version of Bluetooth used, drivers and profiles, etc. It is noteworthy that the low-energy (LE) technology of Bluetooth 4.0 is not compatible with other classic versions; hence, devices equipped with Bluetooth 4.0 that only have the LE technology component will not work with devices equipped with Bluetooth 2.0, and BLE will not work with classic Bluetooth. Upgradability is also a challenge for devices such as headsets or smartphones. Lastly, it has limited connection in the latest version (5.0), only supporting up to seven devices [26,28]. However, mesh topology can be used to expand the network, although the challenge with using this topology is that it may not be suitable for real-time communication due to connection establishment procedures that introduce delay [9].

3.2.3. Record of Reliability

Although a Bluetooth network supports fewer devices, the network forms a piconet and groups of piconets can be interconnected to form a scatternet [28], thus making it possible to considerably expand the network. However, a larger mesh network cannot be created to support long-distance communication [31]. Bluetooth can easily be updated and does not have interoperability issues as devices from different vendors can connect [28]. BLE is often viewed as the optimal technology for IoT applications because of two main reasons: low power consumption and the type of data exchanged [32]. BLE is optimised to transmit a small amount of data. This works well for IoT devices like sensors that just need to transfer state data. It is also accurate for indoor location-tracking applications [27]. Standard Bluetooth can transfer data in different formats, such as text, videos, pictures, etc., and the latest version (5.0) offers better speed than older versions [28]; thus, it could be suitable for future IoT applications. The latest Bluetooth technology uses the frequency-hopping spread spectrum (FH-SS), which protects data. FH-SS provides superior resistance to interference and multipath effects and also performs well in harsh environments. Additionally, spread spectrum modulation has high spectral efficiency and is heavily resistant to noise and malicious jamming [8]. Bluetooth technology is also reliable due to its long battery lifespan of about 5–10 years resulting from low power consumption, with the latest version using only a tenth of the power of the classic version. BLE has lower latency than classic Bluetooth, typically 6 milliseconds (ms) while that of the classic (standard) version is 100 ms [29]. Version 5.0 has greater reliability than the previous versions [28].

3.3. Zigbee

Zigbee is defined by the Institute of Electrical and Electronics Engineers (IEEE) 802.15.4 standard and is used to configure wireless personal area networks (WPANs) using small, low-power digital radios. It is relatively simpler and cheaper compared to Bluetooth or Wi-Fi and can be used to deploy a large number of devices in a wide area. It enables a wide range of communication using a mesh network and is suitable for applications requiring low transfer speeds, long battery life and security [19]. It operates in the 2.4 GHz band in most jurisdictions worldwide, though some devices use 784 MHz in China, 868 MHz in Europe and 915 MHz in the United States of America and Australia. It is a short-range wireless technology with typical transmission ranges of 10 to 100 m depending on power output and environmental characteristics. It supports low data rates ranging from 20 kbps (868 MHz) to 250 kbps (2.4 GHz), making it suitable for intermittent data transmission from a sensor or input device. It also relies on the carrier sense multiple access with collision avoidance protocol [18,33]. It is worth noting that the IEEE 802.15.4e standard has been released to enhance the original standard by introducing five different MAC behaviour modes, among which are time-slotted channel hopping (TSCH), deterministic and synchronous multichannel extension (DSME) and low-latency deterministic networks (LLDNs). These modes have features that improve the performance of Zigbee and its suitability for industrial communications [10].

3.3.1. Application in Mining

Zigbee is applied in conjunction with various sensors underground. For instance, it is used to detect environmental information related to gas concentrations, temperature and humidity in underground coal mines. A robot based on network communication using Zigbee can be employed to achieve this. Zigbee technology is also used to sound safety alarms. Gas-concentration, temperature and humidity sensors are placed on helmets, and Zigbee is used to transmit sensed data to systems on the ground so as to manage workers' conditions. Sensors mounted on UAVs are also used to sense the underground mine environment and acquire location information with network communication performed using Zigbee [19]. It is also used for localisation and tracking [4].

3.3.2. Strengths and Weaknesses

Zigbee technology has strong node support and can support 6500 nodes. The nodes also act as intermediary devices, which helps in increasing the range and makes it easier to expand the network. It is suitable for devices with low power since it does not require much bandwidth; thus, devices such as object tags and sensors can be battery-operated. It is an alternative to Wi-Fi and Bluetooth, with the advantages of being a simpler and less expensive technology [34]. Although Zigbee is a short-range technology with typical ranges of 10 to 100 m, this can be extended by arranging the devices to form a mesh network. The structure of the technology is very flexible, and it has an easy installation process. The network is easy to maintain as this can even be achieved with the help of a remote control. In addition, the technology can be monitored and controlled easily. Across the network, loads are evenly distributed [34,35]. Figure 5 shows elements of a Zigbee mesh network.

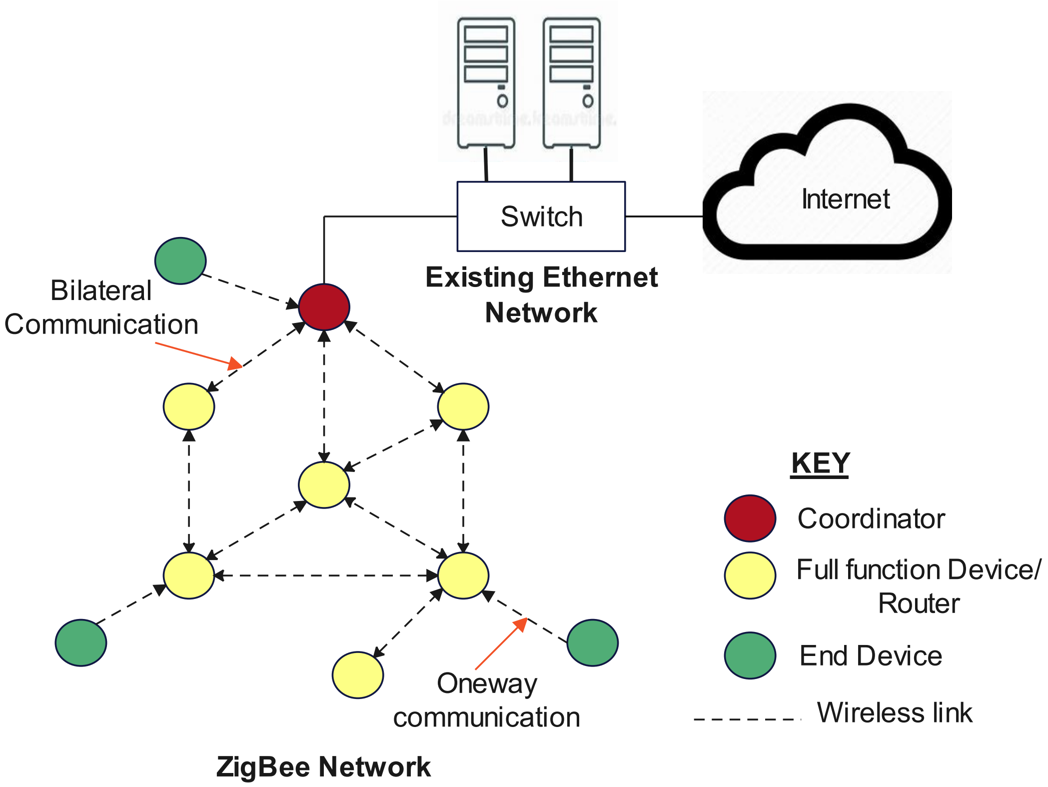

Figure 5. Elements of a Zigbee mesh network.

Zigbee technology is, however, only suitable for indoor applications and cannot be used for outdoor wireless communication systems due to its short coverage range. In instances where sensed data in an underground mine environment have to be monitored from the surface control room or remotely, Zigbee has range limitations; therefore, it has been integrated with cellular technologies to enable it to cover long distances [31,36]. The technology is prone to network interference due to overcrowding and channel noise since it uses the 2.4 GHz band, which is also used by Bluetooth, cordless phones, microwave ovens and other wireless devices. Another notable weakness is that it has a low transmission rate, lower than Bluetooth and Wi-Fi, and as such is not suitable for transmitting data at high speed. It still has compatibility issues with mainstream devices like smartphones, tablets, computers and laptops. It is not as secure as Wi-Fi, and its susceptibility to interference presents a security issue in that interference can cause loss of network service, theft of data from nodes and theft of entire nodes. Implementation of the technology can be expensive due to the size and range of the network being determined by the number of nodes, which entails that more nodes are required to cover a greater range. Other factors affecting cost are the availability of compatible products and devices and, depending on the use case, the level of complexity of the network. Lastly, better alternatives to standard wireless technologies are available, such as Z-Wave, which has a more extended range and better reliability and stability as it operates in the 908 MHz band [34,35].

3.3.3. Record of Reliability

The mesh topology used in Zigbee networks enhances the reliability of the network in that it forms a peer-to-peer network of nodes that allows a sensor (source) node to be out of range in relation to the collection (sink) node as long as other sensor nodes are in close proximity that can relay the data [31]. Additionally, mesh topology makes the network reliable because it improves the throughput, packet delivery rate (PDR) and security, thus enabling Zigbee nodes to create an underground wireless network that is more secure and delivers higher quality of service [37]. This also enables the network to expand and considerably increases its range. The transmitted signals are able to penetrate walls, making the technology not only useful for indoor but also mining environments. End nodes in this network do not just sense the environment but also have the capability to serve as coordinators and perform routing functions, and this provides better stability compared to using a single router, as is the case with Wi-Fi or Bluetooth [36,37]. The strengths listed above—namely, long battery life, low power consumption, ease of maintenance and even distribution of load—also make the technology reliable. The Zigbee network is an autonomous wireless sensor network (WSN); thus, to enable IoT and cloud services, it can be integrated with other communication technologies, such as Wi-Fi, Ethernet and the Global System for Mobile Communications (GSM). This adds positive notes to the technology in terms of reliability in that it can be IoT-based and it is possible to integrate other communication technologies, thus further increasing its range. However, this also brings a challenge because riding on GSM, for instance, to transmit data to remote locations or to enable IoT attracts charges from the cellular operators, thus increasing the cost. In addition, communication reliability is compromised since both quality of service and network availability depend on the prevailing conditions of the GSM network [31]. In terms of network capacity, there is also a limitation because Zigbee can connect up to 255 devices within a maximum of 100 m [18]. Zigbee networks do not support mobility, hence presenting a challenge when using them for miner safety in that if the miner moves out of range, there is no communication [36]. Added to this, as noted in relation to the weaknesses, is that it is prone to interference, hence compromising its communication reliability.

3.4. Wireless Fidelity (Wi-Fi)

Wi-Fi is a family of technologies defined by the IEEE 802.11 standard for short- to long-range wireless communication and is commonly used for closed or indoor environments. It uses 2.4 GHz and 5 GHz in the ISM band. In addition to IEEE 802.11, there are also the 802.11a/b/e/g/h/i/k/n/p/r/s/ac/ad/ax and 802.11be standards, which cover short- to medium-range communication. IEEE 802.11ac has additional features that make it possible to improve performance and speed and better manage interference by means of channel bonding, multiple-input and multiple-output (MIMO) and denser modulation. New generations of Wi-Fi allow nodes to operate at very high data rates of up to 7 Gbps for 802.11ad and 9.6 Gbps for 802.11ax. IEEE 802.11ax is enhanced further to include features that improve network capacity and delay, while IEEE 802.11ah Wi-Fi, which operates in the 900 MHz license-exempt band, is a low-data-rate and low-energy solution designed for IoT applications that can cover up to 1 km with 200 mW default power transmission at a minimum data rate of 100 kbps [12,18,38]. IEEE 802.11p, which provides 10 MHz bandwidth and a data transmission rate of up to 27 Mbps, supports intelligent transport systems for vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communication within a range of 1000 m. IEEE 802.11s is a mesh local area networking standard meant to increase Wi-Fi coverage through the use of a master AP to provide wireless backhaul to extenders, while 802.11be, also known as Wi-Fi 7, takes advantage of the large bandwidth available in the 6 GHz band to significantly reduce latency and enhance reliability. Wi-Fi 7 provides the standard with which the next generation Wi-Fi will be built [39,40].

3.4.1. Application in Mining

Wi-Fi—particularly the IEEE 802.11ax standard, also known as Wi-Fi 6—is used for underground mine coverage involving long distance roadways. It is also used for multi-function communication systems, dispatch communication and safety monitoring in coal mine tunnels. Additional applications include location tracking in underground mines to accurately locate mining personnel and determine their distribution and operating conditions in real time. Of course, in this case Wi-Fi acts as the core network for the sensors in the network. In open-pit mines, Wi-Fi technology is used for automated ticketing and tracking systems for monitoring surface-mine hauling operations [38,41–44]. The situation on the ground in the copper mining industry in Zambia is that Wi-Fi has been deployed in some underground mines to support sensing and monitoring, voice communication and surveillance systems.

3.4.2. Strengths and Weaknesses

Wi-Fi can be used in complex terrain in underground mines where optical fibre cannot reach easily and has the additional advantage that it does not depend on line-of-sight communication. It can also easily reach the blind spots in existing mobile network coverage. For underground communication, Wi-Fi 6 is better than 5G because it covers longer distances, thus providing wide network coverage, and has lower power consumption. It also has fast communication speed, with a typical downlink speed being 9.6 Gbps. For underground coal mines in particular, it meets the requirements of full wireless coverage. It is possible to cover a distance of 1.4 km through wireless signal stretching with four access points in the most difficult parts of the coal mine (i.e., the mining roadway, return air roadway and long-distance transportation roadway) [38,42]. This technology can be implemented underground using different topologies, such as linear (with redundancy appropriately provided), ring and mesh topologies, as illustrated in Figures 6 and 7. IEEE 802.11p, released in 2010, is able to support high mobility requirements, has a longer range of up to 1 km and uses the less interference-prone ISM band of 5.9 GHz. Compared to Zigbee and Bluetooth, Wi-Fi has much lower latency and longer range.

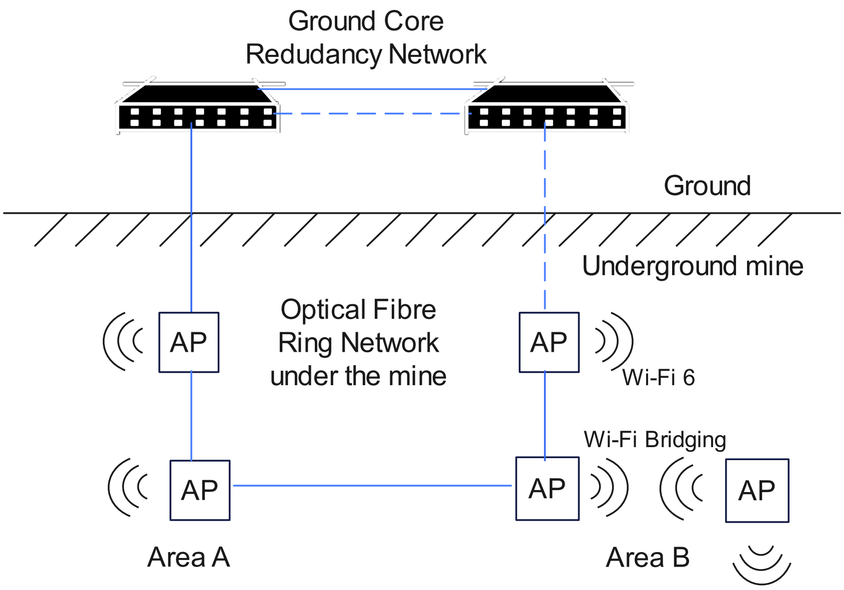

Figure 6. Wi-Fi ring network for underground communication [38].

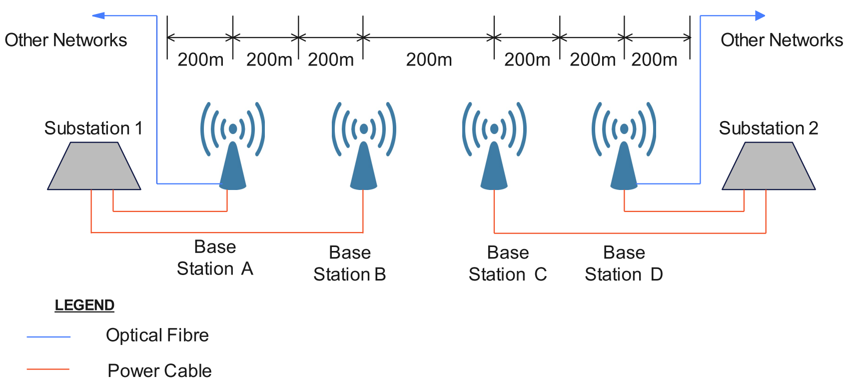

Figure 7. Wi-Fi linear network for long-distance underground roadway [38].

One of the notable challenges with Wi-Fi is that it cannot stand alone as a network since it does not have its own backbone but has to "lean on" a wired network, such as Ethernet. Wi-Fi 6 is still classified as a short-range technology because practically, with one access point at 2.4 GHz, it is only possible to cover 200–300 m [38]. Although mesh networking can be adopted for underground communication, multi-hop transmission throughputs decline while average delays increase with increased hops [43]. Despite the range being extended and delay decreased for Wi-Fi, power consumption is still high and the number of devices supported is still low (typically 250), except for 802.11ah, which is able to provide connectivity to thousands of devices within a radius of 1 km [12,18].

3.4.3. Record of Reliability

Wi-Fi 6 uses orthogonal frequency-division multiple access (OFDMA), which helps improve network delay and communication efficiency: communication delay is typically 10 ms. It uses transmit beam-forming technology to improve network capacity. It also has a dual-frequency signal output of 2.4 GHz and 5 GHz and the base station automatically adjusts the user frequency band through an internal control circuit to ensure communication quality and reliability. The 2.4 GHz signal has strong signal diffraction, anti-interference properties and a long transmission distance [38]. The wireless routers for Wi-Fi 6 consume 9 to 12 watts and depend on an external power source [38]; this does not meet the power requirements of the IoT. Additionally, according to the advantages stated above, Wi-Fi is reliable because it can be integrated with technologies such as Zigbee and Bluetooth. Applying a Wi-Fi mesh underground gives the technology higher flexibility and greater reliability in applications than WLAN and WSN, and it may be a preferred mine emergency communication system in the future. However, reliability factors such as throughput and delay are affected with increased hops [43]. With regard to the IoT, IEEE 802.11ah Wi-Fi is suitable for outdoor environments but unsuitable for remote and underground environments, and it has been highlighted as the most reliable long-range communication technology alongside LoRa/LoRaWAN in farming, where the IIoT is applied outdoors [12]. Thus, 802.11ah may be a suitable candidate for long-range surface IoT mining technologies. It also has features that enhance its communication reliability similarly to 802.11ac, such as OFDMA, downlink multi-user multiple-input and multiple-output (DL-MU-MIMO) and efficient modulation and coding schemes [18]. It is worth noting that one of the current IoT requirements is low data rates, and Wi-Fi notably supports high data rates, which makes it a promising technology for future IoT systems.

3.5. Ultra-Wideband (UWB)

UWB entails transmitting across a wide range of radio bandwidths from 500 MHz to several GHz. It is a short-range radio technology enabling high-bandwidth communication at very low energy levels and covers a large portion of the radio spectrum. The technology, previously known as "pulse radio", has been with us since 1901 and has mostly been used in military communication applications. Currently, it is defined by IEEE 802.15.4a/z. The transmitter sends billions of pulses over a wide-spectrum frequency range while the receiver converts the pulses into data by identifying a recognisable pulse sequence delivered by the transmitter [45]. Therefore, UWB wireless communication technology is a carrier-free communication technology that does not use carriers but short energy pulse sequences, expanding the pulses to a frequency range through orthogonal frequency modulation or direct sequencing [46]. The frequency range for UWB is 3.1 to 10.5 GHz in the unlicensed band with a bandwidth of 500 MHz or more and data rate of up to 27 Mbps. In trials undertaken in an underground coal mine, the communication range between the transmitter and receiver was 28 m [45]. UWB has an added portion in the physical layer used to send and receive data packets specified as IEEE 802.15.4z. This serves as a critical extension not available in other technologies that allows for security techniques, such as cryptography and random number generation, to deter attackers from accessing the UWB communication [47]. Two modes of transmission are supported: ultra-short pulses in the picosecond range, which are also known as impulse radios, and subdividing the total UWB bandwidth into a set of broadband orthogonal frequency-division multiplexed channels. The first mode is cost-effective at the expense of degrading the signal-to-noise ratio and does not need the use of carriers, which makes the transmission less complex with simpler transceivers. The second mode uses the spectrum more efficiently and has better performance and data throughput at the expense of increased complexity and power consumption. The choice between the two modes of transmission depends on the application.

3.5.1. Application in Mining

UWB technology is used to estimate and track position in underground mines. Recently, new UWB modules for positioning and collision avoidance for human safety in non-explosive areas have been developed for use in underground mining operations. UWB technology is as an excellent and cost-effective technology that can be used for tracking and tracing people and machines in underground situations. To be specific, it is widely used in underground equipment positioning and information transmission in coal mines. In the future, UWB technology may be applied in self-driving vehicles underground or autonomous robots where line of sight is a necessary component for safe implementation [45,46,48].

3.5.2. Strengths and Weaknesses

UWB technology provides a high data rate and robust communication in dense multipath environments, as well as high performance and good positioning effects in non-visual environments [46,49]. Tests conducted in underground mine environments have shown that UWB communication does not experience signal interference from other networks, such as local WLAN or radio communication systems. It is also used concurrently in smartphones along with other technologies, such as Bluetooth, WLAN and the Global Positioning System (GPS), without any interference problems. Compared with Wi-Fi, Bluetooth, Zigbee and RFID, UWB has the advantages of low power consumption, high measurement accuracy and strong robustness in relation to multipath effects and non-line-of-sight environments [45,46,48]. An additional useful property of UWB is that it is permitted to use low carrier frequencies, where signals can easily pass through obstacles.

UWB depends on line of sight for accuracy, and the best range can experience loss of signal where there is no direct line of sight. Tests described in [45] for communication with sensors on moving targets show that UWB is only accurate for single-sensor location and tracking. Results obtained in multiple moving scenarios were not precise due to mutual shielding (shadowing) of sensors in the observed area.

3.5.3. Record of Reliability

As far as the record of reliability is concerned, UWB has the ability to transmit pulses at a rate of one per two nanoseconds, which contributes to its real-time precision. It is accurate and reliable for data transfer, positioning and tracking of employees. It also enables fast and reliable data transmission across small distances between 10 and 200 m. With regard to energy consumption, UWB can carry a huge amount of data using very little power: between 9 and 22 milliwatts [45,48]. When UWB employs time-of-flight techniques for positioning, reliability is enhanced and the performance is better because the signal can cover a large bandwidth, which provides a high resolution, hence resolving multipath effects and giving robust performance in indoor environments [48]. While ultrasonic and optical cameras fail to collect data in underground roadways of coal mines characterised by dust, water mist, significant impacts from noise and low light illumination, UWB has good positioning effects and works in these environments. Also noteworthy is that UWB is immune to interference since it has a significantly different spectrum [20,46]. Additionally, the low spectral density of UWB signals makes it less susceptible to the in-band interference of narrowband signals, as well as making it very secure since signals are difficult to detect [50]. The location accuracy of UWB is 10 cm and this is better than that of Bluetooth and Wi-Fi, which is around 150 cm. Therefore, UWB is preferred for applications requiring lower latency, better energy efficiency and accurate positioning, while Wi-Fi is preferred for high-data-rate communications. In addition, in the future, UWB could prove more successful than Bluetooth because of its superior speed, low cost, low power requirements, more secure transmission, superior location discovery and device ranging [47]. In the IoT, UWB is used for perception and, partly, transmission. UWB end nodes are used as sensors and actuators. Sensed data are transmitted wirelessly over short distances to a UWB receiver, which relies on other wireless or wired technologies to enable Internet connection and cloud services. This places a limitation on the UWB network but at the same time implies that it can be integrated with other technologies to increase its communication range and enable use with the IoT as illustrated in Figure 8.

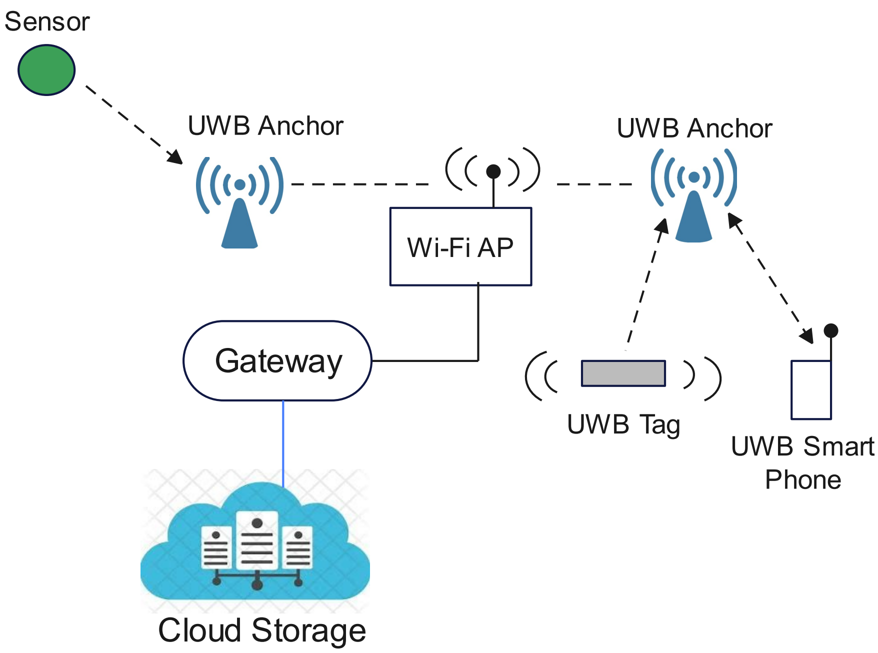

Figure 8. Enabling use of the IoT with an ultra-wideband network.

3.6. Fifth-Generation Cellular Technology (5G)

5G was set up by the industry consortium known as the 3GPP and is a new global wireless standard following the 1G, 2G, 3G and 4G networks. The 1G mobile network was for analogue voice signals, 2G was for digital voice signals, 3G combines digital voice signals and mobile data and 4G supports broadband mobile data; all of these have brought into 5G, which is designed to provide more connectivity and faster connection speeds. Like its predecessors, service area is divided into small geographical areas called cells but 5G uses higher frequency bands. The air interface defined by the 3GPP for 5G is known as New Radio (NR) and the specification is divided into two frequency bands: frequency range (FR) 1 (below 6 GHz) and FR 2 (24–54 GHz). FR 1 is also known as sub-6: it has a maximum channel of 100 MHz and the band widely used is 3.3–4.2 GHz. FR 2 has a minimum channel bandwidth of 50 MHz and maximum of 400 MHz, with two-channel aggregation supported in 3GPP release 15. Signals in this frequency range with wavelengths between 4 and 12 mm are called millimetre waves (mmwaves). 5G is much faster than 4G and 3G; for instance, the average speeds of 5G, 4G+ and 3G are 130–240 Mbps, 42 Mbps and 8 Mbps, respectively, while the maximum speeds are 1–10 Gbps (theoretical) for 5G and 300 Mbps in the case of 4G+. 5G utilises MIMO antennae to boost signals and capacity across the wireless network, supporting 1000 more devices per metre than 4G [51,52].

3.6.1. Application in Mining

Demonstration mines in China have successfully deployed 5G systems, and 5G-based mine IoT applications, such as unmanned driving, intelligent video, unmanned work surfaces, industrial control and intelligent robot inspection, have been or should soon be successfully implemented [53]. Despite the fact that the private 5G network is still in its infancy, China Mobile, Yangquan Coal Group and Huawei successfully built China's lowest underground network at Xinyuan Coal Mine in Shanxi province. This private 5G network is located deep underground at 534 m and has an upload speed greater than 1 Gbps. It has enabled the launch of a 5G smart coal mine and three 5G-enabled unmanned applications involving the inspection of electromechanical chambers, operations on the coal face and comprehensive mechanised coal mine operations. This has benefited the mine in that it is possible to lower labour intensity and improve the security of workers [40]. Figure 9 shows the 5G deployment architectural diagram for an underground coal mine.

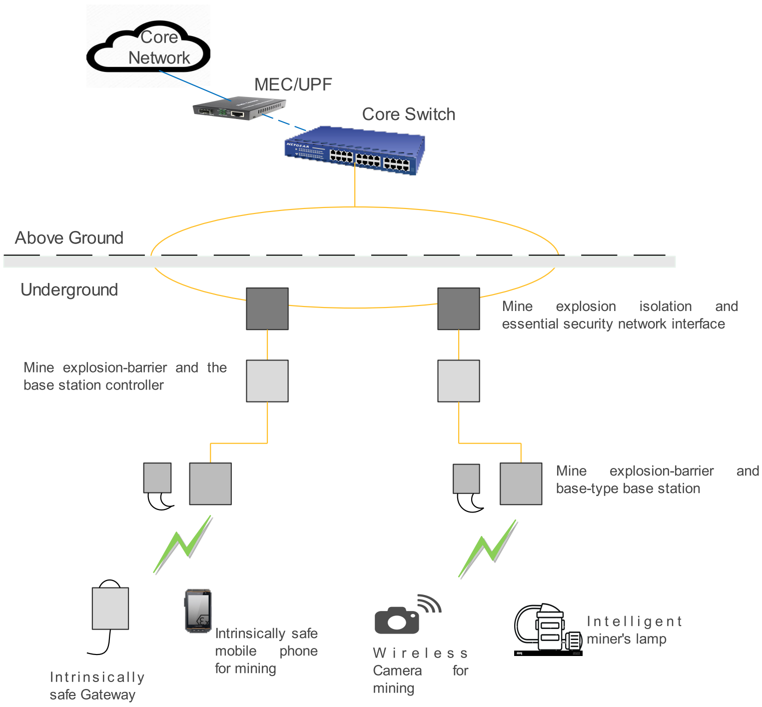

Figure 9. 5G deployment architectural diagram for an underground coal mine [14].

3.6.2. Strengths and Weaknesses

5G technology operates on a higher frequency band, which means that it has a wide channel bandwidth and supports a high number of devices per square kilometre and high speed. Compared with older techniques, 5G communication provides higher speed, greater capacity and lower latency, and when employed for the IoT, it allows the interconnection of diversified sensors in one framework. On the ground or surface, 5G has a superior communication range, offering multi-channel data return over long distances of up to 100 km [12,54]. Compared with 4G communication, the working power and RF energy of the 5G base station greatly improves its application underground, as the general requirement for transmission equipment underground is that the RF threshold power is less than or equal to 6 watts, thus making 5G safe underground. 5G supports ultra-reliable low-latency communication (URLLC) and massive machine-type communication (mMTC), making it suitable for safe production business scenarios involving the IoT in mines. It is also worth mentioning that, for industrial applications such as mining, it is possible to deploy private 5G networks exclusively designed for a single organisation. These share the advantages of public 5G networks and also simplify challenges such as interference management, as well as further reducing transmission delay, since the core network can be deployed locally [40,53].

The drawback of 5G is that it is not economically viable to deploy public 5G networks in remote locations; thus, it is unavailable in these locations where most mines exist. It also has high power consumption and requires complex devices (that is, base stations and end devices) since it is designed to process complex waveforms, such as voice and high-data services. In addition, it is not suitable for energy-constrained IoT devices and relies on long-term evolution machine-type communication (LTE-M) and narrowband IoT (NB-IoT) to support mMTC [12]. In coal mines, to be specific, there are challenges in achieving full wireless coverage with 5G because its wireless signal distance underground is short due to the signal being high-frequency with high diffraction loss; hence, it fails to meet the transmission demands of irregular roadways and to provide network coverage for the whole roadway [38]. Mine 5G suffers from multifactorial interference; for instance, in the mining roadway, the strong electrical equipment induces an alternating magnetic field at turn on and turn off that disrupts the normal operation of the base station and terminal of the mine 5G systems. Additionally, signal propagation is blocked by large-scale mechanical equipment, such as trains, scrapers and shearers, resulting in reflection scattering, phase mismatch and waveform distortion, which weakens the 5G signal. Underground substation equipment with coupling circuits, such as high-voltage distribution boxes, power boxes and relays, generates electromagnetic interference that interferes with 5G signals and affects the accuracy of signal transmission [53]. It also has an insufficient uplink rate; hence, studies are being conducted to improve its rate and communication reliability in underground mines [14,55].

3.6.3. Record of Reliability

5G is most suitable and reliable where precision is required and large amounts of real-time data need to be transmitted and processed [12]. 5G URLLC in particular has specific features in both the radio interface and the network architecture to enable shorter latency and high reliability. The strengths highlighted above—namely, high speed, high capacity and low latency—enable the technology to satisfy the requirements of IoT communications; specifically, high-quality data transmission with real-time monitoring. It is also suitable for surveillance systems with high-definition cameras, as these require high bandwidth. This makes 5G good for future IoT systems as it is a potential technology that can realise the interconnection of all "things". In addition, private 5G, Wi-Fi 6 and Wi-Fi 7 networks are expected to coexist and complement each other, hence adding to the reliability of 5G [54]. Existing 5G anti-interference schemes follow the 3D model of the overground environment and are mainly based on MIMO technology and smart antennae, with MIMO technology improving system performance and increasing processing flexibility. MIMO technology has two basic elements: multiplexing and diversity. Multiplexing increases the system's capacity by transmitting data along multiple independent paths, while diversity involves transmitting the same data along multiple independent paths to resist channel fading and improve transmission reliability. Smart antennae improve mobile communication quality by directing the wireless electromagnetic wave signals in the effective direction to reach the user and also solve problems in the mobile communication environment such as Rayleigh fading, multi-user interference and delay spread. To meet the radio frequency power specification in mines of less than or equal to 6 W, plate-shaped directional antennae with gain of 8 dBi are generally used in mine 5G base stations, which seriously restricts the application of massive MIMO and smart antenna technology in underground explosive environments. Two objectives for 5G that would make it possible to leverage URLLC are mMTC and critical machine-type communication (cMTC), with mMTC having been developed for the IoT. However, mMTC in 5G is fulfilled using LTE-M and NB-IoT, and there are no other dedicated solutions specified for 5G IoT. Although 5G meets the power requirements in underground mines, the expected performance for underground application scenarios has not been fully achieved due to the waste of bandwidth and resources [12,14]. In addition, spurs and crosstalk in the frequency domain are considered to be the greatest culprits leading to instability and inaccuracy, which in their effects influence the reliability of 5G signals [53].

3.7. LoRa and LoRaWAN

LoRaWAN is a wireless LPWAN technology and an open standard managed by the LoRa Alliance that defines the datalink layer of a wireless communication solution based on LoRa radios in the physical layer. LoRa is a modulation technology created by SemTech to standardise LPWANs based on the chirp spread spectrum technique and enables long-range datalinks, thus providing long-range communication at up to 5 km (urban) and 15 km (rural). In simpler terms, LoRaWAN is a wide-area network (WAN) based on LoRa, which is deployed in a star topology (star of stars) and is suitable for applications that require long-range or in-building communication among a large number of devices that have low power requirements and collect small amounts of data. LoRaWAN has two tiers, as shown in Figure 10, wireless links for connecting end nodes and a base station (gateway) and backend servers where network management and user applications are executed [17,56]. It operates in the unlicensed ISM band and uses fixed bandwidths of 125, 250 or 500 kHz. The ISM bands used for LoRa transmission are 863 to 870 MHz (Europe), 902 to 928 MHz (North America) and 470 to 510 MHz (China). It uses six orthogonal spreading factors (SFs) from 7 to 12, which enable adaptive optimisation of an end node's power level and data rate. End nodes closer to the gateway use low spreading factors while those far away use high spreading factors to transmit data. The high spreading factor provides increased gain and higher reception sensitivity at the expense of data rate.

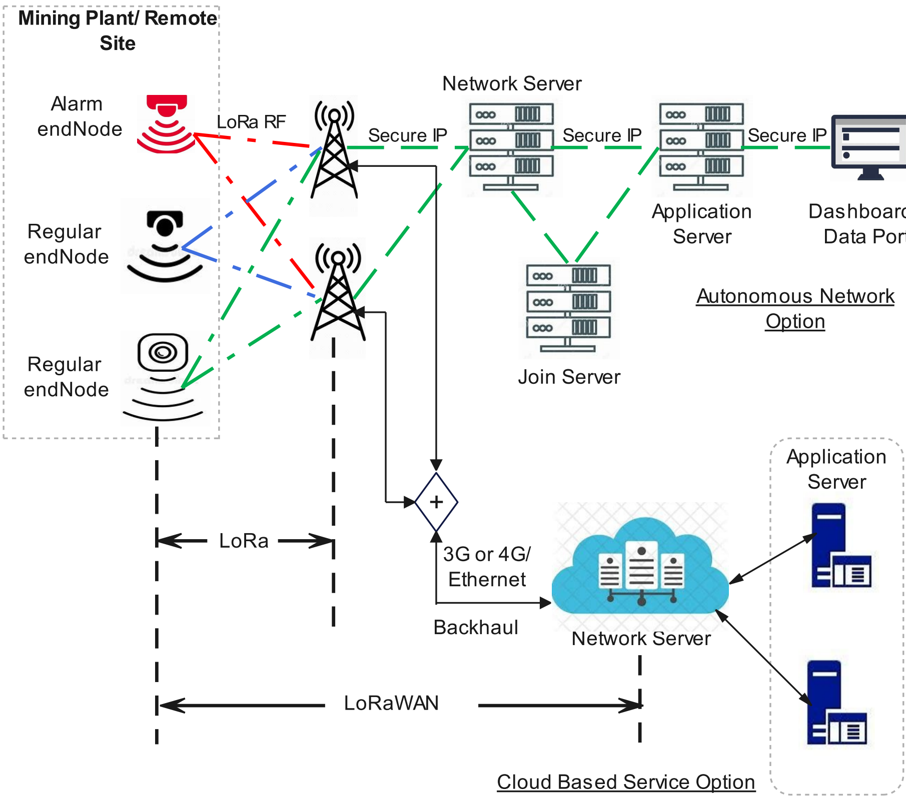

Figure 10. LoRa wide-area network setup—adapted from [2,56].

3.7.1. Application in Mining

LoRaWAN is yet to be deployed in mining. A few studies have been conducted to determine how it can best be implemented in the harsh mining environment. Some of the applications that have been attempted are smart monitoring of workers and machinery in the underground mine environment and smart data transmission of underground localisation traffic to an above-the-surface control room. Furthermore, at the EGAT Mae

Mao coal mine in Lampang, Thailand, a prototype was tested that integrated LoRa with NB-IoT as an alternative communication channel for the IoT [4,5,57].

3.7.2. Strengths and Weaknesses

LoRaWAN has excellent characteristics, such as ultra-low power consumption, an extensive communication range, deep penetration capabilities, an adaptive rate of data transmission and high immunity to interference due to chirp spread spectrum modulation, which makes the technology promising for mine environments [4,56]. The extensive communication range makes it possible to achieve deep indoor coverage in multi-floor buildings and also entails a reduction in the number of gateways deployed on the field for covering wide areas, which lowers both the initial and maintenance costs. LoRa end nodes have a long battery life of up to 10 years, and LoRa also supports geolocation and firmware updates over-the-air for applications and LoRaWAN stacks. The other positive aspect of LoRaWAN is that it is unlicensed and non-cellular but also available from mobile network service providers around the world.

The main drawback is the Aloha MAC protocol used, which may not meet the needs of some of the mission-critical communications that are present in mining environments, especially when a large number of devices use the same channel frequently to transfer data [4]. Additionally, it requires subscription with a single vendor (SemTech), is not suitable for video surveillance due to low data rates and has no handover mechanism for mobile devices. Although the adaptive data rate (ADR) mechanism can save power in LoRaWAN end nodes, distant nodes use more battery power since the spreading factor is high and time on air is longer [56].

3.7.3. Record of Reliability

LoRa end nodes are stand-alone or autonomous since they are battery-powered and devices are manufactured in such a way that they can ensure safe transport of packets over a private or public network and deliver encrypted data to the cloud. Additionally, LoRa end nodes can send data to multiple gateways within range as there is no fixed association, which reduces the packet error rate and the probability of reception is high. The LoRa modulation based on the chirp spread spectrum (CSS) adds to the reliability of the technology in that the timing and frequency offsets between the transmitter and receiver are the same, which reduces the complexity of the receiver, and also the frequency bandwidth of the chirp is the same as the spectral bandwidth of the data signal. In addition, since spreading factors are orthogonal, signals modulated with different spreading factors can be transmitted on the same frequency channel at the same time without interfering with each other. LoRa signals are thus robust and resistant to in-band and out-of-band interference and immune to multipath effects and fading. LoRaWAN is also capable of supporting data communications from devices that are mobile since there is no need for a tight-tolerance reference clock [56]. The ADR mechanism makes it possible for each node's SF to be adjusted to select the highest practical data rate while maintaining an acceptable signal-to-noise ratio (SNR) and at the same time enables the gateways to be capable of serving over one million nodes; otherwise, only 120 nodes per gateway would be supported without ADR [8]. The beauty of a LoRa network is that it is possible to set up an autonomous, private and locally administered network. A mining company, for instance, can deploy LoRa end nodes for monitoring various parameters, which will then transmit to gateways that may be connected via Wi-Fi or hardwired Ethernet to the local area network where the network server, join server and application server can be placed. This makes the network more secure as there is no need to go through public infrastructure to connect to the servers. On the other hand, the servers can be housed in the 'cloud' and traffic from the gateways can be transmitted using Wi-Fi, Ethernet or cellular connection to the Internet, hence enabling IoT for LoRaWAN [56]. The authors of [8] demonstrate LPWAN's suitability for use cases such as meter reading, SCADA/infrastructure control, transport, logistics, retail, environmental monitoring, wildlife monitoring, smart buildings, agriculture, smart street lighting and health, defence and military applications and bring out the fact that in practice LoRaWAN is often used as it is not restricted by regional availability, which adds to its reliability. In addition, they also state that, among other LPWANs, LoRaWAN has a sufficiently high data rate for real-time communication and it is also suitable for signal-hostile or hazardous environments. LoRaWAN is only capable of carrying low-data-rate sensor data; however, its future reliability can still be guaranteed by the strength highlighted above that it is available from mobile service providers around the world and may be complemented by the high-bit-rate mobile networks.

Table 2 presents a comparative summary of the properties of mining IoT technologies, while Table 3 gives a summary of their main strengths, weaknesses and records of reliability.

Table 2. A comparative summary of the main properties of the mining IoT communication systems.

Technology	TX Power	Range	TX Speed	Frequency Bands	Sensitivity	Power Consumption	Applications
RFID	30–33 dB	10–100 m	10–640 kbps	30–500 kHz, 10–15 MHz, 850–950 MHz, 2.4–3.5 GHz, 5.8 GHz	Reader: −84 to −92 dBm, tag: −30 to −92 dBm	Typically: 13–26 mW, maximum: 1 W	Localisation and tracking systems, plant automation, quality control
Bluetooth/BLE	−20 to +20 dBm	0–100 m	Typically: 720 kbps, versions 3 and 4: 25 Mbps	2.4–2.485 GHz	−70 to −82 dBm	Classic: 100 mW, 2.5 mW and 1 mW, BLE: 0.01–0.5 W	Localisation and tracking for transport trucks, miner sensing and alerting
Zigbee	12.3 dBm	10–100 m	20–250 kbps	784 MHz, 868 MHz, 915 MHz, 2.4 GHz	−97 to −101 dBm	Classic: 10–100 mW	Environmental sensing, monitoring and alerting
Wi-Fi	23–36 dBm	0–1000 m	160 kbps, 27 Mbps, 7 Gbps, 9.6 Gbps	900 MHz, 2.4 GHz, 5 GHz, 6 GHz	−40 to −80 dBm	9–12 W	Long-distance underground roadway communication, safety monitoring, location tracking, automatic ticketing and tracking, voice and surveillance communication
UWB	Emitter power spectral density: −41.3 to −75 dBm/MHz	10–200 m	Up to 27 Mbps	3.1–10.5 GHz	−73 to −80.8 dBm	9–22 mW	Position tracking and estimation, information transmission
5G	Up to 6 W (mining)	Up to 100 km	-	3.3–4.2 GHz, 24–54 GHz	-	1000 W to 20 KW (dependant on number of bands used)	Unmanned driving and work surfaces, industrial control, intelligent robot inspection
LoRa/LoRaWAN	10–30 dBm	Urban: 5 km, rural: 15 km	0.3–50 kbps	470–510 MHz, 863–870 MHz, 902–928 MHz	25 mW	−137 to −150 dBm	Yet to be deployed

Table 3. Summary of strengths, weaknesses and records of reliability of mining IoT communication systems.

Mining IoT Technology	Strengths	Weaknesses	Record of Reliability
RFID	Short recognition distance, low performance degradation and low price, data secure and hidden from plain sight, long lifespan of passive tags	Affected by environmental conditions (i.e., moisture and physical obstructions), inferior due to technological limitations	Capturing data for fast-moving objects, non-line-of-sight data reading, real-time tracking, data perception only, short-range technology
Bluetooth/BLE	Convenient wireless data sharing between paired devices, technology extensively available and accessible, cost of devices reasonable, easy and convenient to use, BLE relatively energy-efficient	Range of up to 100 m, energy-inefficient in real-time applications and drains battery if left on, slower data transmission rate, security vulnerabilities, BLE not compatible with other classic versions, low node capacity	No interoperability issues and optimal for IoT, accurate for indoor location tracking, resistant to interference and multipath effects when using FH-SS, good performance for harsh environments (i.e., mining), low power consumption results in long battery lifespan of 5–10 years, BLE has low latency
Zigbee	High node support at 6500 nodes, network easily expandable—end nodes can play intermediary roles, simple and less expensive than Wi-Fi and Bluetooth, flexible structure, easy installation process and easy maintenance, load evenly distributed across network	Suitable for indoor applications only, short range—depends on cellular coverage for off-site monitoring; prone to network interference and channel noise and not very secure, lower transmission rate than Bluetooth and Wi-Fi, compatibility issues with computers, laptops and smartphones	Mesh topology enhances reliability of network access, range, throughput, packet delivery rate and security; high signal penetration ability, thus suitable for mining; better stability than Wi-Fi since end nodes also act as coordinators and perform routing functions; reliable due to long battery life, low power consumption, ease of maintenance and even distribution of load; prone to interference and does not support mobility; relies on Wi-Fi, Ethernet or cellular technologies to support IoT; connecting to cellular increases cost and compromises quality and network availability
Wi-Fi	Suitable for complex terrain underground, not dependant on line of sight, Wi-Fi 6 better than 5G underground, fast communication speed of 9.6 Gbps, implemented with different topologies underground (i.e., ring, linear and mesh), lower latency and longer range than Bluetooth and Zigbee	Relies on Ethernet as backbone; high power consumption and low capacity in terms of number of devices supported; practically, with one access point at 2.4 GHz, the range is short, within 200–300 m	OFDM used improves network delay and communication efficiency, dual-frequency adjustment between 2.4 GHz and 5 GHz for communication quality and reliability, integrable with Zigbee and Bluetooth, IEEE802.11ah suitable for outdoor environments and as reliable as LoRaWAN but with shorter range

Table 3. *Cont.*

Mining IoT Technology	Strengths	Weaknesses	Record of Reliability
Ultra-wide band	High data rates and robust communication; high performance and good positioning in non-visual environments; not interfered with by other wireless networks; low power consumption, high measurement accuracy and strong robustness to multipath effects and non-line-of-sight environments compared to RFID, Bluetooth, Zigbee and Wi-Fi; use of low carrier frequency enables penetration through obstacles	For better accuracy, relies on line of sight; accurate for single sensor locating and tracking where mobility is demanded	Excellent real-time precision; accurate and reliable for data transfer, positioning and tracking of employees; fast and reliable data transmission up to 200 m; low power consumption even with huge amounts of data (9–22 mW); TOF technique enhances reliability and performance in multipath environments and indoors; can collect data in dusty, misty, noisy and low-illumination environments; uses pulse transmission and hence immune to interference and very secure; location accuracy better than Bluetooth and Wi-Fi; IoT applications require other wired and wireless technologies for Internet and cloud services
5G	High channel bandwidth, higher capacity in terms of devices per square kilometre, high-speed and ultra-low latency communication, long range of up to 100 km on the ground and safe for underground communication, private 5G network deployment exclusively for single organisations	Unavailable in remote locations where mines exist, high power consumption, devices are more complex, not suitable for energy-constrained IoT devices, coverage distance is short underground, accuracy of signal transmission is affected by multifactorial interference underground	Reliable where precision is required and large amounts of real-time data are transmitted, URLLC enables low latency and high reliability, satisfies requirements for IoT communications involving high-quality data transmission monitored in real time, suitable for surveillance systems, can coexist with Wi-Fi 6 and Wi-Fi 7, transmission reliability and channel capacity enhanced by MIMO and smart antenna technology, communication reliability is affected in underground explosive environments, still relies on LTE-M and NB-IoT to support IoT
LoRaWAN	Unlicensed and non-cellular but available from mobile network providers, end-node battery life of up to 10 years, uses fewer gateways, ultra-low power consumption, long range, adaptive rate of data transmission, strong immunity to interference spectrum	Aloha MAC protocol can cause data collisions and increase delay, requires subscription with a single vendor, unsuitable for video surveillance due to low data rates, distant nodes using high SFs may use more battery power and time on air	Encrypts data to the cloud and hence secure; diversity in transmission reduces packet error rate and increases probability of reception; robust against interference, multipath effects and fading due to CSS; ADR enables support for high capacity; autonomous networks supported; among the most reliable LPWANs; not restricted by regional availability; sufficient data rate for real-time communications, thus promising for mines

4. Reliability of LoRaWAN Communication for Mining

Reliability is a synonym for assurance; thus, communication reliability is when messages sent are guaranteed to reach their destination complete, uncorrupted and in the order in which they were sent and includes the ability to recover from infrastructure or service disruptions by dynamically acquiring alternative paths and mitigating disruptions quickly. Additionally, communication reliability involves communication protocols notifying the sender whether or not the delivery of data to the intended recipients is successful. There are a considerable number of use cases where LoRaWAN communication has proved reliable, as already highlighted in the record of reliability. However, from the literature surveyed, it is clear that it has not yet been deployed deep underground, underwater, in space [8] or even in mining. It is therefore important to consider the reliability of LoRaWAN communication in mining. This section addresses important factors for IoT communication reliability in mining environments and techniques that contribute to LoRaWAN communication reliability.

4.1. IoT Communication Reliability in Mining Environments

The authors in [37] give five quality-of-service metrics that can be used to gauge reliability in industrial and, in particular, mining environments: throughput, packet delivery ratio, end-to-end delay (latency), energy consumption and network security. They recommend the first four as primary. For this survey, we identified four metrics for IoT communication reliability in mining environments: latency, packet delivery, energy consumption and range. From the literature reviewed, the first three were identified as primary, while range came up as a result of studies on VLC and LoRa [5], 5G [12,54], Wi-Fi [38] and Zigbee [31,36]. A survey was also undertaken to determine the situation on the ground in the Zambian copper-mining environment, where there is both underground and open-pit mining. Thus, some of the facts and specifications outlined are derived from there.

4.1.1. Latency

Latency is also known as delay. Delay in wireless networks is the time taken by the packets to propagate from the source to the destination. In the copper-mining industry, for instance, measures are taken to ensure copper production is not compromised and human life and equipment are protected from incidents that could lead to loss or damage. Generally, the acceptable delay in sensor systems in terms of communication for such necessary actions or measures is 100 ms. In copper smelting—particularly for the oxygen plant, which converts atmospheric air to the pure oxygen (at 94%) that serves as a key input to the copper smelter in addition to the copper concentrate—the acceptable delay is 50 ms; otherwise, for the other processes in the smelter, it is, as already mentioned, 100 ms. In a study on LoRaWAN in industrial applications [2], the delay achieved was between 80 ms and 275 ms, while in [4], in an underground mine, the delay achieved was less than 500 ms. From these studies, it can be stated that LoRaWAN is promising for mining environments with a delay of less than 500 ms in underground conditions, while at the surface, the performance in terms of delay could be better. Therefore, more studies can be undertaken to reduce the delay further to enable practical deployment.

4.1.2. Packet Delivery

Packet delivery is normally evaluated as a ratio of the number of packets transmitted to the number of packets received, which is commonly known as the PDR. It helps provide insight into the data or packet loss. In a study where a redundant retransmission-aided adaptive latency reduction protocol was proposed for LoRaWAN to improve the transmission reliability of mission-critical communications in an underground mine [4], the benchmark for the data extraction ratio set was 95%. Data extraction is closely related to packet delivery, although it takes into account the time aspect and concerns primarily the actual packets received from among the total that are transmitted. Another study on LoRaWAN also set a 95% packet delivery ratio as acceptable in an industrial environment for reliable transmission of telemetry and alarms [2]. Additionally, a study that involved integration of LoRaWAN with NB-IoT as an alternative communication channel for the IoT in a surface mine achieved a PDR of between 92 and 98% for 75% of the total transmissions [57]. It can thus be deduced from these studies that an acceptable PDR for reliable IoT communication in mining should be above 90%.

4.1.3. Range

Range is also referred to as span. It is the maximum distance between the transmitter and receiver at which data communication can take place. For LoRaWAN, the transmission takes place between the end nodes and the gateway. Depending on whether the network is deployed in an urban or rural/remote location, the range is stipulated as up to 5 km or 15 km, respectively. One study combined visible light communication for estimation of the location of miners underground with LoRa technology for transmitting underground information to an above-the-surface control room [5]. The range test carried out resulted in a better transmission range for LoRa than for a WPAN and wireless local area network (WLAN) for indoors, outdoors, the underground utility tunnel and the underground mine. This indicates the viability of LoRa for communication of sensed data from an underground mine for monitoring at the surface control room. For situations where it is impractical to set up multiple gateways, a LoRaWAN range extender was proposed in [17] to provide a single-hop extension, which was tested in an industrial environment for integration in an IIoT infrastructure. This improved the signal strength for nodes that were far away from the gateway (more than 100 m), an approach that may be adopted in the mining environment when it is not feasible to deploy multiple gateways. Communication of position data collected by LoRa global positioning system end-nodes and sent to a LoRa gateway at ranges of 1 to 5 km was successfully achieved in a study where a single LoRaWAN gateway was integrated with an NB-IoT system as an alternative channel for IoT communication in surface mines. This demonstrates the viability of LoRa for communication in surface mines. The authors of [44], who used Wi-Fi technology to provide an online tracking and ticketing system for mine hauling vehicles in which data obtained were sent to a surface mine monitoring station using GSM, highlighted the need for a cheaper alternative in data-sending technology. This shows the need for alternative, low-cost, long-range technologies; hence, LoRa could be a suitable technology in this scenario. Reverting back to the underground environment, the work considered for Wi-Fi 6 communication in [38], where four access points were connected linearly to cover a distance of 1.4 km, presents a possible scenario for introducing long-range communication using LoRa. LoRa could be a suitable technology in underground mines for monitoring environmental conditions underground and for miner alerts where technologies such as Zigbee and Bluetooth have range limitations and cables cannot be laid to support long-distance communication, as outlined in [58,59]. The industry survey of the situation on the ground in the copper-mining industry indicated that reliable long-range communication to enable real-time monitoring is needed at the dump sites for sensors deployed to sense contaminants in mine water in the reservoir tank before releasing it into the nearby stream. Other areas include plants located 500 m from the monitoring centre, such as the acid plant, and tailing dams and air pollution monitoring sites that need to communicate sensed data at distances varying from 500 m to 7 km from the mine. The above cases indicate that there is a need for long-range wireless transmission to support underground monitoring systems and surface mine communication. Therefore, LoRa technology can be further tested for possible and suitable deployments in mining environments.

4.1.4. Energy Consumption

For communication systems that support sensing and monitoring, interconnection devices, such as gateways, access points, switches, routers and servers, normally depend on grid-connected power. End nodes, however, may need to be battery-powered if they are mobile or if grid power is unavailable in environments where they may be deployed to sense required parameters or initiate required actions, such as alerting, actuation, etc. In such cases, energy efficiency becomes critical and is governed by the amount of energy consumed, which in turn has a bearing on the battery life. Low-power, wide-area networks have been developed to enable the use of battery-powered end devices with batteries that are able to last up to 10 years and end devices that consume low power [6,56]. This is possible because nodes are able to go into sleep mode when not transmitting or receiving data. The energy consumption of a node depends on four factors: the transmit, receive, idle and sleep modes. Therefore, the total energy consumed by a node is the sum of the energy consumed in the four modes in milliwatt-hours [37]. Energy consumption is higher when a node is in transmit mode and lowest when it is in sleep mode [15,37]. A LoRa-based sensor node was evaluated for industrial use in [60] in terms of the energy consumption rate and communication reliability in a harsh environment. The results indicated that the sensor node could operate efficiently with a battery for a long period of time, up to a cut-off voltage of 3.2 V. Despite the harsh environment, the signals received were sufficiently reliable. This shows that a node can be deployed for industrial use with high reliability and lower maintenance costs. In the mining industry survey, it was found that the end nodes used rely on grid-connected power, which has to be converted to the required DC level, and thus we were not able to gain insights into energy consumption. What should not be overlooked for battery-powered devices is the cost of replacing batteries for systems that have high capacity in terms of end nodes. Moreover, in some cases, the lifespan of the devices may be dependent on the battery's lifespan, meaning that once the battery expires, the device's life ends and it has to be replaced [61]. From the foregoing, it can be concluded that LoRa technology that uses a star-of-stars topology could result in better energy consumption, as nodes do not need to be always active to coordinate communications from other end nodes. Each end node transmits data using a single hop to the gateway, which relays it for centralised coordination by the network server; hence, end nodes can go back into sleep mode once communication is achieved. More studies on energy consumption for mining IoT technologies are required to specify what reliability means in this regard.

4.2. LoRaWAN Techniques for Communication Reliability

Some notable contributions have been made towards improving the reliability of LoRa communications. This section outlines these contributions in general and classifies them into five categories: coding, modulation, adaptive techniques, technology integration and communication distance.

4.2.1. Coding

A novel coding scheme called Data Recovery using Application Layer Coding (DaRe) that combines techniques from convolutional and fountain codes at the application layer was designed to solve the problem of frame loss in LoRaWAN due to channel effects when the end nodes are mobile [15]. The performance metrics used were the data recovery ratio (DRR) and latency. DaRe can handle both bursty and non-bursty frame losses equally well and significantly reduces data loss in LoRaWAN. However, it was tested on a newly deployed LoRaWAN system and hence needs to be studied with more realistic scenarios. Forward error correction (FEC) using the inbuilt hamming code with a code rate of 4/8 at the physical layer was employed in [62] to solve the problem of packet error rate (PER) degradation with LoRa in industrial environments. The PER performance improved considerably with SNR gains of 7 to 11 dB.

4.2.2. Modulation

Work on spreading factor (SF) management has been undertaken. To improve LoRaWAN's communication reliability for telemetry and alarms in industrial environments, the authors of [2] proposed an allocation scheme that assigns different SFs to a device depending on whether the event is regular monitoring or an alarm. They considered three scenarios: an indoor industrial environment, an open field with one gateway with retransmission only for alarms and an open field with four gateways without retransmissions for alarms. With this proposal, LoRa was able to handle alarms, delivering them with high reliability, and showed negligible performance loss with the regular (telemetry) messages. Reliability factors, such as throughput, delay and the packet success rate, were used to evaluate performance. To improve the reliability and scalability of LoRaWANs, RS-LoRa was proposed in [16]. This technique specifically solves the capture effect and packet loss due to collisions when high spreading factors are used that increase time on air. RS-LoRa uses a lightweight scheduling that guides nodes to select different SFs to improve reliability and scalability. The performance measures used here were the packet error ratio, throughput and fairness. RS-LoRa resulted in better network performance for nodes and a lower packet error rate (PER) at the edge of the cell than legacy LoRaWAN due to a reduction in the capture effect.

4.2.3. Adaptive Techniques

To enable reliable transmission of mission-critical communications in mining, the authors of [4] proposed a redundant retransmission-aided adaptive latency reduction protocol (RRALRP) for low-latency communication of delay-sensitive emergency traffic, such as alarms. The protocol adjusts the acknowledgement (ACK) time-out based on the time for the previous transmission rather than having it fixed as in LoRaWAN. When retransmitting unacknowledged messages, two packets are sent in the same channel, a retransmission and a redundant packet, without increasing the spreading factor. The proposed protocol significantly improves performance in terms of the data extraction ratio and average transmission delay.

4.2.4. Technology Integration

Work has also been undertaken involving the integration of LoRa with other technologies in order to improve communication reliability underground and at the surface of mines. Chowdhury et al. [5] developed an approach to access real-time data from an underground mine using two technologies (namely, visible light communication (VLC) and LoRa) to overcome the adverse environmental effects of underground mines. VLC was used to estimate the locations of miners inside the mine, while LoRa technology was used for transmitting underground information to the above-the-surface control room. The study was tested indoors, outdoors and in both an underground mine and underground utility tunnel. SNR and range tests were undertaken, with results for both the underground mine and underground utility tunnel tallying. LoRa had a higher transmission range inside the mine for location tracking than existing technologies (namely, WPAN (Zigbee) and WLAN (Wi-Fi)).

For use at the surface of mines, the authors of [57] designed a prototype for an alternative communication channel for the IoT. They used a GPS-enabled LoRa end node to sense position in terms of longitude and latitude and then transmit the data to a single LoRa gateway, which was connected to the AIS NB-IoT for public communication to the cloud. The performance of the system was evaluated using the received signal strength indicator (RSSI), packet success rate and range. The integration enables real-time monitoring online using smartphones and is a suitable low-cost solution for isolated areas with no Wi-Fi or 3G cellular access.

The authors of [62] further improved the FEC scheme by integrating an Infinite Impulsive Response (IIR) or Finite Impulsive Response (FIR) filter into the LoRa architecture, which yielded additional gains in the SNR of 2 to 6 dB. This can make LoRa robust in harsh industrial environments.

4.2.5. Communication Distance

Work on extending the communication distance of LoRaWAN in an industrial environment was described in [17], where the authors proposed a transparent enhanced node (e-node) for range extension to improve coverage for nodes far away from the gateway. The study was conducted in a four-storey building in an industrial indoor environment and the performance metrics were the RSSI, SNR and delay. End nodes in the basement, which were more than 100 m away from the gateway, could not be covered by the standard LoRaWAN infrastructure. However, when the e-node was placed in between the end nodes in the basement and the gateway at a distance of 100 m from the gateway, the data could be relayed to the gateway. For underground environments such as utility tunnels, the authors of [63] compared the radio-wave propagation of LoRaWAN- and Zigbee-based WSNs and performed radio channel analysis that took into account performance measures such as sensitivity and range. LoRaWAN performed better than Zigbee, with a sensitivity of −148 dBm for LoRaWAN compared to −100 dBm for Zigbee with a range of 327 m. Additionally, LoRaWAN presented greater range and better robustness in the presence of humans in the utility tunnels. The studies highlighted in the Technology Integration section also considered range as a performance metric. In [5], LoRa performed better than WPAN and WLAN in terms of range in underground environments, with ranges of 28.8 m, 13 m and 17 m achieved, respectively, for the three technologies in the underground mine. In [57], a range of 5 km was achieved with LoRa communication between the GPS-enabled LoRa end node and the single LoRa gateway. Table 4 summarises and provides a classification of the contributions made towards LoRaWAN communication reliability, giving the advantages and challenges.

Table 4. Classification of LoRaWAN reliability techniques.

Reference	Technique Used	Advantages	Challenges
[15]	Data Recovery using Application Layer Coding (DaRe): convolution and fountain codes	Handles bursty and non-bursty frame losses equally well, significantly reduces data loss in LoRaWAN, recovered 99% data with a code rate of one half and erasure probability of 0.4, reduces energy requirement by up to 42% compared to repetitive coding	Average delay increases for smaller code rates, was tested on newly deployed LoRaWAN, needs to be studied with more realistic scenarios
[2]	SF allocation scheme for telemetry and alarms: SF Basic, SF Shift and SF Reservation	Throughput increased linearly at 37 kbps every 100 nodes for indoor industrial environment (IID); 100% packet success rate with retransmission for all scenarios for alarm nodes for IID; reserving SFs gave the least delay of 80 ms for IID; open field with four gateways (diversity) gave better throughput, 16.6% greater than single gateway; open field with four gateways had best packet success rate, with the waste case for alarms being 98.45%	Reserving SF for alarms resulted in poor packet success rate for regular nodes, SF shift only feasible with small number of alarms (large number increased delay for IID), open field with single gateway increased delay to 275 ms to maintain reliability of alarms through retransmission

Table 4. *Cont.*

Reference	Technique Used	Advantages	Challenges
[16]	RS-LoRa protocol: lightweight scheduling of SFs and transmit power	Increases network throughput and fairness, better network performance for nodes compared to legacy LoRaWAN, better energy efficiency at high traffic loads, lower PER at the edge of the cell than legacy LoRaWAN due to reduction in capture effect, decrease in PER results in increased network reliability and scalability	Fairness decreases when there are few nodes, consumes more energy with less traffic loads, nodes prone to collisions when closer to the gateway
[4]	RRALRP for emergency traffic	Outperforms LoRaWAN in terms of data extraction rate (DER) for emergency traffic for different network sizes, requires fewer transmission attempts than LoRaWAN for successful packet reception, transmission delay is much shorter than LoRaWAN	DERs of localisation and regular sensing data are degraded using this protocol compared to LoRaWAN since they are unconfirmed
[5]	Integration of VLC and LoRa	Novel zone-division method employed for estimation location using VLC completely nullifies interference, LoRa had higher transmission range inside mine for location tracking than existing technologies (WPAN and WLAN)	SNR decreases as the miner moves away from the centre to the edge of the zone, use of single gateway limits the range underground to 28.8 m
[57]	Integration of LoRa with AIS NB-IoT	Suitable low-cost solution for isolated areas with no Wi-Fi or 3G cellular access, enables real-time monitoring online using smartphones	Private LoRa received highest number of incomplete packets when there was no line of sight due to obstruction caused by trees and propagation of signal downhill
[17]	Enhanced node (e-node): range extender	Improves link quality of poorly connected nodes; extends the range of nodes far away from the gateway in the basement; enables nodes far away to operate with the fastest SFs (i.e., SF of seven), producing a gain of up to 16 dB of the signal strength indicator	Processing unit could not efficiently handle longer messages when spreading factor increased to nine, was only implemented with three spreading factors (i.e., seven, eight and nine)
[63]	Three-dimensional (3D) ray launching	Better sensitivity of −148 dBm for LoRaWAN compared to Zigbee with −100 dBm for a range of 327 m, LoRaWAN presented higher range and better robustness in the presence of humans in the utility tunnels, LoRaWAN provided high tolerance against interference in the confined tunnels with the presence of tubes, grids and metal trays	Reduced transfer capacity of LoRaWAN by up to 242 bytes, star network topology of LoRaWAN could not support single-gateway deployment due to morphology of tunnels, need for external communications for gateways to send data from underground to the cloud
[62]	FEC using 4/8 Hamming code and IIR/FIR filter	PER improved to over 90%, FEC yielded gain in SNR of 7 to 11 dB, IIR/FIR filter yielded additional gain in SNR of 2 to 7 dB, robust in harsh industrial environments	Increased complexity, greater resource use and may increase energy consumption, additional latency introduced may be a hindrance to some real-time applications, possible increase in packet size may affect throughput, efficiency of filters may not be universal due to diversity of industrial environments

5. Challenges and Design Requirements concerning LoRaWAN Reliability in Mining Environments

Mining is characterised by three main environments: indoors, outdoors and underground. The most challenging among these for radio propagation is the underground environment. This section first outlines the challenges concerning LoRaWAN reliability in the mining environment and then describes some design requirements to achieve reliable LoRaWAN communication.

5.1. Challenges Concerning LoRaWAN Reliability in Mining Environments

5.1.1. Challenge One—Mine Environment

LoRa communication largely depends on line of sight; thus, the most obvious challenge is signal propagation in the underground mine in places where the mine structure is full of twists and turns [5], as well as the presence of heavy mobile machinery that can cause multipath effects. Additional factors that work against radio-wave propagation might be present, such as extreme humidity, temperature and vibration. At the surface of the mine, the presence of structures, trees [57] and heavy mobile machinery may cause obstruction of signals. It may be difficult to connect gateways to the existing wired Ethernet as it may not be easy to lay cables underground or, due to the confined nature of some underground tunnels, cables may be susceptible to accidental cuts. In an underground coal mine where there are explosives, wireless transmission may not be desired. If it is employed, then there will be strict power limits. In some coal mines, for instance, the maximum transmission energy allowed is 25 mJ [5].

5.1.2. Challenge Two—Regulatory Limitations

LoRaWAN operates in the unlicensed band, utilising frequencies like 169 MHz, 433 MHz, 868 MHz (Europe) and 915 MHz (North America). Operating in the unlicensed band means that there are regulatory limitations in terms of the duty cycle and transmission power. It is difficult to achieve the long ranges realisable at the surface in underground scenarios with the stipulated power limit of 14 dB, as already indicated in [5]. The 27 dB power limit is only allowed for the 915 MHz band used in North America. Duty-cycle limitations also limit the media access control mechanisms that can be employed, hence the use of random access mechanisms.

5.1.3. Challenge Three—MAC Protocol

The media access protocol used by LoRaWAN is pure Aloha, a random access protocol whereby a node transmits as soon as data are available to send over the channel. When the number of nodes transmitting on the network increases, packet collisions occur, which affect network performance. The cell edge nodes are normally the most affected by collisions, resulting in a phenomenon referred to as the capture effect [16]. The edge nodes are also susceptible to collisions due to the use of high SFs, which increase channel occupation. Resolving and recovering from collisions may also cause delay, which is not desired with emergency traffic.

5.1.4. Challenge Four—Increasing the Spreading Factor

In order to make communication reliable when packets are unacknowledged, as well as improve robustness for nodes that are far away from the gateway so as to enable long-range transmission, higher spreading factors are employed by LoRaWAN by means of its adaptive rate technique. This, however, presents a challenge in that data rates are reduced with increases in distance and SF. At the same time, channel occupancy increases, which may not be desirable for mission-critical communication, as it will result in transmission delays and also more collisions that may lead to loss of packets [4]. If two end nodes use the same SF to transmit uplink messages, packet loss is possible. To mitigate this, the LoRaWAN specification stipulates the addition of a random delay known as the random ACK_TIMEOUT before retransmission [4]. This is set without taking into account the duration of the previous transmission and thus it affects throughput when larger SFs are used.

5.2. Design Requirements for LoRaWAN Reliability

5.2.1. Integration

In areas underground where it is difficult to achieve line of sight, which LoRa depends on for reliable transmission, we propose integrating with short-range technologies that do not rely on line of sight, such as UWB, Wi-Fi and RFID. LoRaWAN can be employed where it is feasible to achieve line of sight and where there is a need for long-distance transmission, such as in mining roadways and in the relay of underground data to the control room above the mine. It is also a cheaper alternative than riding on cellular infrastructure, as was undertaken in [31], in which the Zigbee network was integrated with GSM for remote mine monitoring above the surface.

5.2.2. Transmission Power

Chowdhury et al. [5] used a single gateway and 14 dBm to transmit underground location-tracking data to the surface mine control room. They proposed that the transmission power to work with longer ranges greater than 29 m should be higher than 50 dBm and multiple industrial gateways should be employed. LoRaWAN is most suitable for underground mines due to its −150 dBm receiver sensitivity. It should be noted, however, that for some underground coal mines with a high presence of methane and carbon monoxide, as well as for areas with explosives, transmission energy may not be allowed to exceed 25 mJ. For surface mining, it is possible to transmit over a range of 5 km with line of sight and 14 dBm transmission power with LoRaWAN, resulting in 98% packet success rate [57]. For good line-of-sight communication, it is proposed that gateway antennae should be placed 30 m above the ground.

5.2.3. Support for Emergency and Non-Emergency Traffic

In addition to voice and surveillance communication, mine traffic includes telemetry and alarms. This includes traffic for monitoring the mine environment and machinery, tracking information for mine personnel and machines, etc., and such traffic is categorised as emergency and non-emergency traffic. This traffic requires high reliability and data rates capable of real-time transmission. The minimum value to support real-time communication is 28.8 kbps [8]. As stated above, to support emergency and non-emergency traffic, the transmission delay should be below 500 ms. In addition, allocation of SFs for LoRaWAN should also be undertaken based on whether the traffic is classified as emergency or non-emergency to support mission-critical communications in mining. Therefore, the techniques developed in [4,5] and [16] can be incorporated in the legacy LoRaWAN to make it reliable for mining environments.

5.2.4. Network Preference

The three studies that included trials underground and in surface mines indicated that LoRaWAN can be implemented in mines as a technology to support IoT communication by employing cloud-based services or localised services, which entail setting up an autonomous network. The survey of the situation on the ground for the Zambian copper-mining industry indicated that mining companies prefer autonomous networks with localised services rather than using web-based services for monitoring and sensor networks due to the sensitive nature of the data collected from mines. A connection to cellular infrastructure is required to enable mobile phone message alerts for personnel responsible for decision making.

A summary of the challenges and design requirements regarding LoRaWAN reliability is presented in Table 5.

Table 5. Challenges concerning LoRaWAN reliability in mining environments and associated design requirements.

LoRaWAN Reliability Challenges	Design Requirements
Signal propagation in mine environments	1. LoRaWAN for transmission of underground data to surface control room [5] 2. Integration with other short-range technologies (i.e., UWB, WiFi, RFID)—based on our analysis of mining IoT communication technologies 3. LoRaWAN for long-distance transmission on mining roadway—based on our analysis of mining IoT communication technologies and mining industry survey
Regulatory limitations for transmit power and duty cycle	1. Increase transmission to 50 dB in non-explosive underground environments [5] 2. Employ multiple industrial gateways [5] 3. Place antennae 30 m above the ground for good line of sight with 14 dB transmit power at the surface [57]
Delay caused by Aloha MAC protocol	1. Incorporate RRALRP for emergency traffic to keep delay below 500 ms [4] 2. Spreading factor (SF) allocation to be undertaken based on traffic classification (i.e., emergency and non-emergency) [2]
Reduced data rates and increased channel occupancy for high SFs	1. Incorporate SF allocation strategies [2] 2. Use lightweight scheduling of SFs and transmit power [16]
Sensitive nature of data collected in the mines	1. Autonomous network with localised services—based on mining industry survey 2. Connection to cellular network provider for short message alerts to mining personnel—based on mining industry survey

6. Lessons Learnt and Open Research Challenges

This section outlines the lessons learnt from this study, which was undertaken by means of both a literature review and a survey of the Zambian mining industry. It also presents open research challenges for further study of LoRaWAN reliability both from the literature and from the authors of this paper.

6.1. Lessons Learnt

1. Increasing the number of gateways is a strategy that can prolong battery life as end nodes are likely to have shorter distances to gateways for transmission.
2. Employing time-slotted channel hopping for MAC to meet the critical demand of timely and reliable communication is better than using pure Aloha.
3. Most short-range communication technologies work best for indoor applications. As such, RFID, Bluetooth and Zigbee have been widely applied in underground mining for sensor networks and positioning and tracking applications. Ultra-wide band is another upcoming communication technology that enables quick and reliable data transmission across small distances and is not affected by other wireless systems present in the same environment where it is deployed.
4. To support IoT systems, LPWAN can be implemented in two ways either using cloud-based services or as an autonomous network using localised services. However, the cost of implementation and the security of the network also need to be taken into account.
5. The literature survey indicates that LoRaWAN, which is a non-cellular and unlicensed technology, is among the best LPWANs and is not restricted by regional availability. As such, it is very popular and is employed in practice in a variety of use cases, such as meter reading, supervisory control and data acquisition (SCADA)/infrastructure control, transport, logistics, retail, environmental monitoring, wildlife monitoring, smart buildings, agriculture, smart street lighting and healthcare, defence and military applications. However, it has not yet been deployed in mining, underwater or deep-space communications. Additionally, the LoRaWAN specification includes an application server intended to facilitate integration with external systems.
6. Cellular IoT technologies require end devices to have periodic synchronisation with the network at constant intervals, which results in increased energy consumption,

unlike technologies such as LoRa, where end devices can sleep for as long as the application requires due to asynchronous Aloha-based protocols.

7. Interference resistance can be achieved in data transmission by employing techniques such as the chirp spread spectrum, the combination of ultra-narrowband modulation and the frequency-hopping spread spectrum. The adaptive data rate technique also makes long-range transmission robust against interference through the use of orthogonal spreading factors.
8. Short-range technologies have been successfully integrated with cellular networks to increase their transmission range and enable long-distance monitoring. This, however, may affect their cost-effectiveness by incurring charges for using these carrier systems. In addition, their reliability becomes dependent on the network reliability of the cellular system.
9. IoT devices can be classified in two ways: those connected through gateways and those connected directly using wireless connections. Connecting them through the gateway helps resolve the limitations relating to batteries, the communication radius and processing and storage capabilities.
10. Communication reliability is determined by factors such as the throughput, packet delivery ratio, end-to-end delay, energy consumption, range and network security.
11. For sensor data communication, Wi-Fi is best suited as a relay technology because Wi-Fi-based sensors require a power supply of 9–12 volts. Thus, it is often integrated with RFID, Bluetooth and Zigbee, which use low-power end nodes.
12. For positioning applications, time-of-flight techniques are the best to use in order to resolve multipath effects, and they are more reliable with better performance compared to other methods.
13. Although it is challenging to use 5G technology in underground mines due to its susceptibility to interference, it is suitable for establishing an efficient remote sensing system for geological disasters and other open-field communications due to its high speed, high capacity and lower latency. When employed for IoT applications, it enables interconnection of diversified sensors in one framework to synthetically analyse and assess a problem.
14. Most short-range protocols are energy-efficient but limited in terms of range, with the exception of Wi-Fi, which, although relatively inexpensive, is not energy-efficient. On the other hand, cellular networks are capable of long-range communication but are expensive and power-consuming and coverage may not be available in some locations.
15. UWB is not meant to replace Wi-Fi, Bluetooth or satellite navigation but can serve as a complementary technology that enhances location identification when used in combination with these technologies.
16. Lastly, future IoT communication systems may need to not only transmit regular monitoring and alarm traffic but also support high-bandwidth applications, such as audio and video.

6.2. Open Research Challenges

6.2.1. From the Literature Review

- LoRaWAN range extender [17]: When a range extender was used, latency was introduced in the network. A study should be undertaken on how to mitigate or reduce the latency.
- Redundant retransmission-aided adaptive latency reduction protocol [4]: The impact of this protocol on energy consumption should be studied.
- SF allocation schemes for telemetry and alarms in industrial environments [2]: The findings of this study should be applied in specific industrial environments, such as farming, solar power plants and mining. There is also a need to devise a detailed sensitivity analysis of design parameters, such as the relative sizes of telemetry and alarm messages or the frequency of regular messages, optimisation of the trade-offs regulated by such parameters and development of adaptive "online" strategies based

on the actual situation of the network. To achieve this, a mathematical model of the packet success probability can be developed to serve as a guide in optimisation. This can involve first modelling the alarm packet arrival process as a Poisson point process and then focusing on the impact of the alarm nodes on the communication system performance. The results obtained from the simulation or mathematical model can also be validated by carrying out small-scale field experiments.

- Data recovery through application layer coding [16]: What needs to be resolved for this study is the derivation of the optimal degree. The authors also suggest developing a protocol that integrates with the ADR scheme for LoRaWAN. Lastly, the impact of DaRe with a higher number of devices should be studied in a realistic scenario since the work was undertaken with a newly deployed network, which was collision-free.
- VLC and LoRa communication [5]: A study should be conducted in an underground mine using multiple industrial gateways and, if possible, the transmission power should be increased to 50 dB. This may be a solution to increasing the range in an underground environment.
- LoRa and NB-IoT [57]: The study was conducted with one LoRa GPS end node and one gateway. It would be good to determine the performance of the network by increasing the number of nodes and also study a scenario employing multiple LoRa gateways.
- RS-LoRa [16]: The network performance and energy consumption of the RS-LoRa network should be optimised.

6.2.2. Input from Authors

- The study of the LoRaWAN range extender, which only considered range tests, can be extended to include a study on frame loss and delay.
- The redundant retransmission-aided adaptive latency protocol was developed to improve the reliability of emergency traffic (alarms). To ensure that telemetry data are also transmitted reliably, we propose applying application layer coding to telemetry data to guarantee quality of service when adaptive latency reduction is applied to alarm messages.
- The SF allocation schemes proposed in [5] focus on prioritising alarms without adversely affecting telemetry through strategies such as SF Basic, SF Shift and SF Reservation in industrial environments. The SF Shift strategy had the limitation of not being able to increase the number of alarms, while the SF Reservation strategy tended to crowd telemetry data in another inappropriate SF, thus affecting its reliability. The SF Reservation strategy yielded a very good delay of 80 ms when applied in the indoor industrial plant setup, while the SF Shift strategy kept the reliability of telemetry data above 98% with a delay of 100 ms. We propose carrying out further studies to mitigate the challenges identified for the SF Shift and SF Reservation strategies.
- The study in [63] focused on rectangular utility tunnels. A similar study can be carried out for cylindrical tunnels in an underground mine environment to (1) analyse the effects of propagation in the presence of machinery, people and an irregular and rough underground environment; (2) assess the performance of LoRaWAN against one of the current wireless technologies being used; and (3) determine the most suitable technology and how the network layout and configuration can be implemented.
- Since LoRa communications depend on line of sight, studies can be undertaken to integrate LoRa with short-range counterparts that do not rely on line of sight, such as RFID, Wi-Fi and UWB, to enhance communication reliability in the underground mine environment.
- VLC and LoRa communication [5]: Future research should consider incorporating the LDPC techniques from [64], which were used to increase transmission speed for VLC. In light of the possibility of future IoT systems that may require high data rates, both VLC and LoRa can be considered.

7. Conclusions

Considering the need for sensing, monitoring and communication technology to help establish a proper environment that promotes the health and safety of workers and productivity and avoids destruction of equipment, we investigated different mining IoT communication technologies to determine their records of reliability, as well as their strengths, weaknesses and use cases in relation to mining. We also focused on the reliability of LoRaWAN technology in mining, describing what reliability means and the factors to be considered for reliable communication. Furthermore, we provided some benchmarks for reliable communication that also enables real-time transmission of sensor data in mining environments in terms of the data rate, latency, packet delivery rate and range. Various techniques developed to enable LoRaWAN communication reliability were also described. Although LoRaWAN is popular and among the best LPWANs, with many use cases, this survey brought to the fore specific challenges and design requirements regarding LoRaWAN reliability in mining environments. Finally, the lessons learnt from the survey were highlighted and open research challenges concerning LoRaWAN communication reliability were identified.

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