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Development of underground communication system for data transmission using Wi-Fi direct and power line communication

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ABSTRACT

Safety and productivity are of utmost concern to companies in the underground mining industry. To improve safety and productivity, it is important to understand the underground environment using sensing methods. Such sensors obtain important measurement factors such as temperature, humidity, and gas concentration that assist with accurate decision making. However, it still remains challenging to develop a communication system that can transmit data obtained by the sensors from the underground to the surface. In addition to that, the cost of maintaining a wireline communication system in an ever-expanding underground mine is high and there is a high risk of wire breakage. Hence, the introduction and use of wireless communication networks (WSNs) in underground communication systems. This study proposes a data transmission system for an underground communication system in which Wi-Fi Direct and power line communications (PLC) are selected as part of the system. The purpose is to conduct a demonstration experiment and analyze the performance of the system based on the conditions of the mine.

In this study, it was developed a data transfer system with minimum cost by using PLC and Wi-Fi Direct as a means of communication as well as Wi-Fi Ad hoc. The result of the Wi-Fi Direct system was that the distance from a data logger to a smartphone was 140 m in a straight line. At this time, the communication speed was 9.1MB/s, which means that the miner could recover 230MB of data before the data loggers pass the data to the miner's smartphone. The distance between smartphones was 130 m in a straight line, and they were able to communicate at 5.7MB/s. By the time the data is shared from one smartphone to another, 72MB of data can be shared. The necessary monitoring data in the underground mine can be transmitted reliably as text and image files.

Moreover, based on the results of performance analysis, a design of a data transfer system for the underground mine is demonstrated. The costs of the proposed system are estimated and compared with the most common communication system (leaky feeder). The proposed system can achieve communication for only 3% of its cost and 2% of the maintenance cost. The proposed data transfer system can be installed in a complex underground mine including a dwarf space with low cost and can be easily expanded. This data transfer system can be diverted to other mines with the installation of equipment, making it the data transfer system that underground mining companies are looking for.

1. Introduction

Deep underground environments are often considered hazardous due to poor lighting, confined spaces, falling rocks, poor ventilation, wetting, communication constraints, and structural complexity. These place safety, side-by-side with productivity, as a major objective for companies in the deep underground mining industry. Efficient communication and sensing are key to making underground environments safer, with several communication and sensing methods proposed to understand the environment. Many sensors are installed in the underground mine to measure factors such as temperature, humidity and gas concentration, the records which are processed at the edge and

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also transmitted to control room locations for monitoring and alert management. However, transmitting the data obtained by the sensors from the underground to the surface where critical decisions are made remains challenging.

Wired communication systems are highly reliable for such long distance but come at a high cost of maintenance. Mine tunnels tend to have space constraints, leaving insufficient room for efficient cabling. As a consequence, wired links suffer breakages due to the activities of heavy duty machines in the working areas, which is expensive to replace and causes long communication downtime. In addition, underground mines are continuously expanding to fulfill their primary purpose of mineral extraction. Such expansion also requires communication links to follow because newly dredged areas are of high-priority interest for operations, adding to the cost of installation and maintenance of wired communication links. Therefore, wireless sensor networks (WSNs) are attractive (Minhas et al., 2017), especially in sections of the mine where direct line-of-sight (LOS) exists. WSNs have a flexible network configuration that helps in environmental monitoring and locating miners (Bai, 2017; Bhattacharjee et al., 2012). Moreover, WSNs reduce the number of access points and allow sensors to communicate in a peer to peer (P2P) topology. There are differences in the number of connected terminals and communication performance among them, and it is necessary to select one according to the size of the desired data and the frequency of request. In particular, it can be adapted to the expansion of underground mines by using communication standards that do not require the installation of access points, such as ZigBee and Wi-Fi Ad hoc. However, wireless signal strength depends on the nature of the walls in confined spaces and are commonly known to attenuate significantly at nodes that are not at the line-of-sight of the transmitting node. This is common in underground mines as tunnels consists of corners and irregular wall designs. In order to overcome these limitations, hybrid communication of wired and wireless can be used such that each link is deployed where they can optimally operate. An integration is created between the different communication links in order to ensure adequate handover that continues the communication process.

In this work, an experimental WSN based on Wi-Fi ad-hoc technology in an underground mine site is deployed. An evaluation of a deterministic WSN node deployment scenario is carried out by testing the system via a series of experiments, measuring its performance parameters, and analyzing the results. Additionally, the performance of a hybrid decode-and-forward (DF) powerline and Wi-Fi link for underground communication is evaluated. Wi-Fi Direct, which enables communication between smartphones is used to transfer data from a data logger to the miner's smartphone. Due to the fast attenuation of wireless signals in underground mines with obstacles and corners, the Wi-Fi module is linked to a power line communication (PLC) system in order to navigate corners and obstacles with reduced signal attenuation. This proposed hybrid design is tested in the Osarizawa mine, a closed underground mine located at the Akita prefecture, Japan. The hybrid system is evaluated by measuring the received signal strength (RSSI) and communication speed at the Osarizawa mine. In addition, the costs of the proposed system are estimated and compared with the most common communication system (leaky feeder). Results show the proposed system can achieve communication for only 3% of the installation cost of its system and 2% of the maintenance cost.

2. Background and related work

2.1. Underground mine communication systems

Underground mines present unique challenges when it comes to communication systems. Unlike surface mines which can rely on wireless and satellite technology, underground mines require specialized communication systems that can function in the dark, cramped, and often hazardous conditions found underground. These systems must be reliable, robust, and able to withstand extreme conditions in mines.

There are several factors to consider when designing an industrial communication system for an underground mine. It is vital that the system functions reliably in rugged conditions and exhibit redundancy. This can be achieved through a two-way communication architecture and high-quality hardware. A communication system typically consists of transceivers and a network for transmitting audio, data, and tracking assets. Wired systems are typically used for stationary units, while wireless systems are used for mobile units. Modern mines often use a single network for both voice and data communication, which simplifies deployment and operations and can help reduce costs. In the event of a fault in the network, a redundant architecture such as a ring type or a mesh type can allow for continued communication by looping signals at the location of the fault. It is important to also consider long-term requirements of the ongoing mine development and accordingly mention them in the design of the communication system.

Although there is no unified guideline on the exploitation of the communication and data transfer management systems worldwide, some countries, e.g. Australia, have platforms that define underground mine communications infrastructure. In the case of Australia, an organization called GMG (Global Mining Guidelines Group) published recommendations in 2018, with the intentions of another review in 2024.

Only the 2.4 GHz Wi-Fi protocols (IEEE 802.11) are considered in this work due to worldwide ubiquity and compatibility with almost any device supporting wireless connection (Ikeda et al., 2019). Several researchers considered other types of wireless data transfer methods such as Zigbee (Moridi et al., 2014b), vibrational wireless communication (Zhong and Tao, 2022), and low-frequency radio waves (Roberts, 2007), which have deficiencies in one or multiple areas when compared to Wi-Fi Ad-Hoc systems. However, Wi-Fi Ad-hoc wireless networks are disadvantageous in terms of security management. As the network operates without a central managing unit, each node functions autonomously thus making it easier to hack the network. However, this disadvantage can be neglected due to the limited access to the underground mines where only limited personnel and equipment have access.

LoRaWAN technology has also been explored as a solution for underground communication systems. LoRa provides long range, deep penetration, ultra-low power consumption, and single hop wireless communication, making it a reliable choice for harsh environments like mines. A study by Emmanuel et al. (2019) demonstrated that LoRa technology offers effective connectivity in mining areas with strong multipath conditions, providing reliable performance for different spread factors (SF).

2.2. Wireless sensor networks

Wireless sensor networks (WSNs) consist of numerous nodes, including sensors, controllers, data transmission antennas, and energy sources, deployed throughout underground mines to collect and transmit data (Akyildiz et al., 2002). Sensor nodes collect data for self-organized sensing networks, while sink nodes, positioned closer to decision-making areas, store and forward larger amounts of data and possess more powerful processing capabilities.

Traditional Wi-Fi infrastructure mode, based on the IEEE 802.11 standard, faces challenges in underground mines due to the need for additional infrastructure. Wi-Fi Direct, a peer-to-peer wireless network, offers compatibility with various devices and requires no additional hardware, making it a convenient option for underground mine applications.

Wi-Fi ad hoc networks, on the other hand, use multi-hop peer-to-peer connections managed by protocols to reduce power consumption and connection interruptions and to properly manage the connection topology. Unlike regular Wi-Fi infrastructure mode, the ad hoc mode does not follow any specific topology pattern and connects to any other available node. Wi-Fi ad hoc-based WSNs offer several advantages:

- **No need for infrastructure:** Wi-Fi ad hoc networks do not require any infrastructure, such as a router or access point, making them easy to set up and maintain. This makes them suitable for use in areas where it is difficult or impossible to install traditional network infrastructure.
- **Cost-effective:** Because they do not require additional hardware or infrastructure, Wi-Fi ad hoc networks can be more cost-effective than other networks.
- **Easy to configure:** Wi-Fi ad hoc networks are relatively easy to configure, making them a good choice for users who are not familiar with networking concepts.
- **Flexibility:** Wi-Fi ad hoc networks offer a high degree of flexibility, as they can be set up quickly and easily to meet the changing needs of users.
- **Good for temporary or emergency situations:** Due to their easy installation, Wi-Fi ad hoc networks are well-suited for temporary or emergency situations, such as disaster recovery or one-time events (e.g., rock burst, blasting).

Moridi et al. (2014a) explored the use of ZigBee WSN systems in underground mines, comparing their performance to Wi-Fi and UWB. ZigBee, based on the IEEE 802.15.4 protocol, offers low energy consumption and long-distance coverage, making it suitable for mine environments. However, it has limited bandwidth. Ikeda et al. (2019) evaluated Wi-Fi Direct in a real mine environment, finding it to have better bandwidth and signal strength than ZigBee, but less efficient in energy consumption and signal propagation distance.

Underground mines present challenges for wireless communication due to obstacles, moisture, and rock walls (Yarkan et al., 2009). Radio communications should address propagation challenges and meet three goals: operate in emergencies, cover the entire work area, and assist in monitoring and warning within the mine. Monitoring can be divided into environmental and operational monitoring, both of which can improve productivity and safety (He et al., 2012; Krithika and Seethalakshmi, 2014; He et al., 2009; Minhas et al., 2017; Prasant et al., 2010). However, the high cost of efficient underground communication technologies hinders rapid digitization.

Previous studies focused on ZigBee and Wi-Fi ad hoc systems (Ikeda et al., 2018, 2019, 2022, 2021; Kawamura et al., 2014; Moridi et al., 2014b, 2015, 2018a,b). The ZigBee-based system was found suitable for underground mines, accommodating environmental data sensing, ventilation fan control, and emergency messaging (Moridi et al., 2015). Wi-Fi ad hoc enables the use of smartphones for relaying, allowing sensor data to be sent beyond the normal communication range.

2.3. Hybrid PLC-WiFi

Additional to the reliability, as well as minimal deviation from above-ground performance of wired communication, is the advantage of PLC's capability to use existing power infrastructure. PLC enables the co-existence of communication signals with power signals in a powerline connection (Zimmermann and Dostert, 2002; Middleton, 1977, 1999; Kolade et al., 2021). In legacy underground mines, PLC can provide the advantage of reducing the cost and space required to upgrade the mine with sophisticated communication links.

PLC is matured in above-ground applications such as smart homes (Han et al., 2014), smart grids and smart cities for providing connectivity between utilities and consumers. However, little is yet known in its performance in underground mines. In Zhang et al. (2014), PLC is evaluated and proposed for monitoring in underground coal mines. Debita et al. (2019) performs a measurement-based evaluation of medium voltage PLC in a real underground mine in order to determine its suitability for useful applications such as voice communication. Further, Kolade and Cheng (2021a,b) performs an evaluation of the noise distribution in underground PLC by assuming the channel as a memory channel.

Table 1
Previous and current studies description.

Research	Standards	Features
Previous	ZigBee	• Multi-hop • Many concurrent nodes
	Wi-Fi Ad Hoc	• Multi-hop • Miner's movements used
This	Wi-Fi Direct	• Continuing Wi-Fi Ad hoc • Simplified config • Improved security • Enhanced communication
	PLC	• Uses existing power lines • Bypasses obstacles

Several efforts have integrated hybrid PLC with WiFi in order to optimize the performance of smart grid applications (Zhang et al., 2020). A major motivation is to extend the coverage of WiFi using PLC, such as in indoor environments (Apicharttrisorn et al., 2017). Smart metering using PLC WiFi is proposed by Rafiei and Eftekhari (2012), harnessing the strengths of both technologies in order to enhance the smart meter for both the utility and the consumer. Mengi et al. (2016) presents a broader view in the network layer, by using the IEEE 1905.1 standard to integrate Ethernet technology with PLC and wireless LAN (see Table 1).

3. Underground mine data transmission communication system design

3.1. Experimental principles

The data transfer system proposed in this study is based on Wi-Fi Direct as the main communication system. In addition, PLC is used to expand the range of transmission in semi-real time. To get data to the surface, the communication system must be able to handle the complexity and ever-expanding underground mines. The selected Wi-Fi Direct is considered to be a communication standard that inherits the advantages of Wi-Fi Ad hoc (Ikeda et al., 2018, 2019) and improves on the cumbersome configuration and security aspects that have been considered problematic.

Besides, PLC can make use of the power lines originally installed in the mine to provide power for lighting, heavy equipment, sensors and dataloggers. While Wi-Fi direct enables data hops between a wireless node to a mobile device, the PLC line used to charge the datalogger can be used to send the data to the wireless node inaccessible by Wi-Fi due to distance, corners and walls. In reverse, data can be sent from surface to an underground wireless node which then hops the information to a mobile device. If the combined PLC-Wi-Fi is used to send data from an underground location to a surface location such as a control room, such data can be further analyzed at the mine site office or a remote location via the cloud. The overall flow of the proposed communication system is shown in Fig. 1 where the input data is adjusted to meet the requirements of each underground mine.

In this study, environmental data such as temperature, humidity, and smoke detection, which are generally considered to be important, and the movement trajectory of miners are used as input data. The input data will be sent to the surface via the proposed communication system which can be further available in the cloud. The proposed data transfer system design is shown in Fig. 2. As shown in Fig. 2, a data logger installed inside the underground mine senses environmental data and accumulates the data, enabling it to be transferred to a smartphone owned by a neighboring miner. The dataloggers connected to the powerline automatically creates a network with any wireless node on the same network, hence allowing data to be shared with the wireless node. Such data can then be sent to a miner's mobile phone using Wi-Fi Direct. This extends data logger's communication range beyond obstacles in the mine without the installation of additional communication infrastructure.

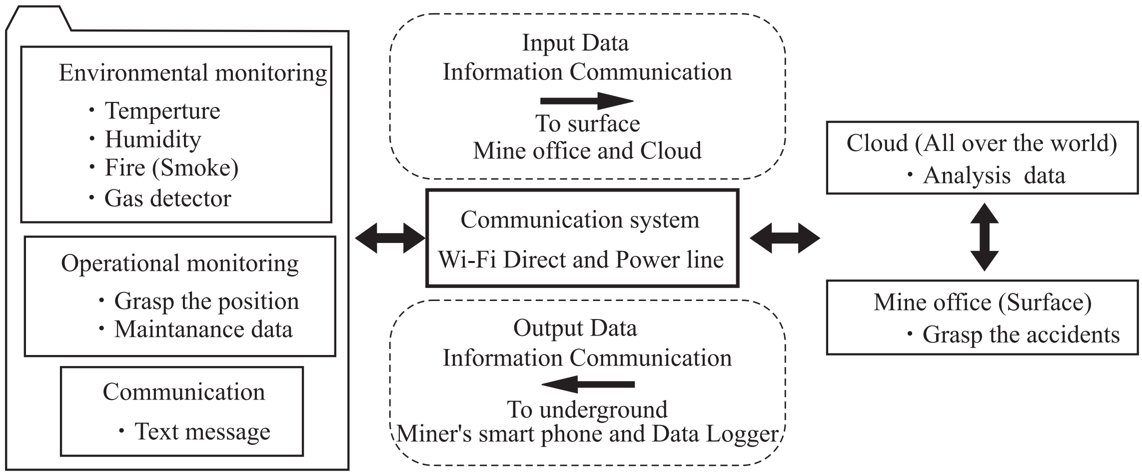


Fig. 1. Overview of a mine communication system.

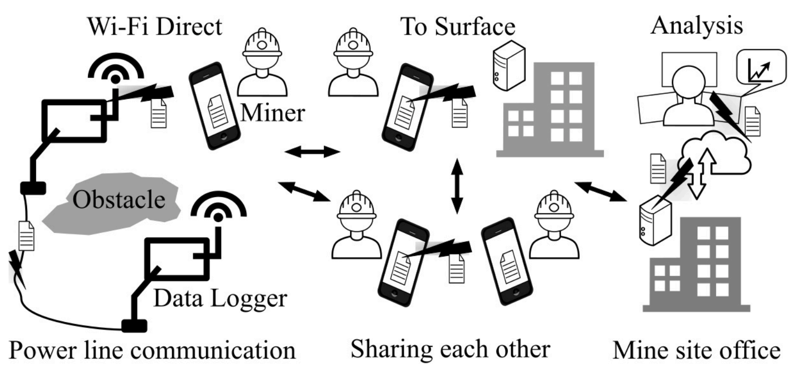


Fig. 2. Schematic representation of the hybrid underground communication system for data transmission.

3.2. Powerline communication

The PLC channel is generally highly impure for communication signals. Signal contamination is not only due to the Gaussian nature of the channel, but also affected by impulse noise which occurs as short spikes of low-to-high peaked signals. These impulses are invariably linked to the devices connected to and powered by the channel. Hence, the frequency of occurrence of the impulses and disturbances in the channel is linked to them. In addition, signals transmitted over the PLC channel may suffer from path loss when the powerline has multiple branches. This is common because powerlines are originally designed to connect multiple rooms and spaces in the environments where they are installed.

As observed from PLC channel models, the noise occurs in bursts, transitioning the channel from the long period of error-free states to short successive error states or alternate between an error-free state and an error state. The successive error states can be attributed to the impulsive nature of the channel, while the alternating states can be attributed to the Gaussian behavior in the channel. Therefore, the Middleton Class A noise model is commonly used to evaluate the occurrence of Gaussian noise, with zero mean and variance σ_G^2 or impulse noise, also with zero-mean but variance σ_I^2 and Gaussian noise in PLC. This is based on fair assumption that impulse noise is not persistent over the duration of the transmitted signal. Therefore, a Middleton Class A model with two states, for illustration, will model that channel as either in a purely Gaussian noise state or a Gaussian and impulse noise state. Depending on how busy the channel is in terms of the number of devices connected, the channel can be simplified to be mildly, medium or heavily disturbed scenarios. The scenarios mainly differ due to the length of the noise duration and inter arrival time. At the instant when

Table 2
RSSI's strength scale according to strength of connect.

RSSI (dBm)	>−39	−49∼−40	−59∼−50	−79∼−60	<−80
Connection	Very strong	Strong	Normal	Weak	Bad

impulse noise occurs, the size of the Gaussian noise is negligible as it is assumed the impulse noise dominates due to its high-pitched nature. As a result, the impulse noise is modeled as zero-mean but with a variance $\sigma_I^2 = \frac{\sigma_G^2}{A}$, $(A < 1)$, where A represents the factor of the magnitude of the impulse noise with respect to the Gaussian noise.

The PLC channel is not devoid from multipath attenuation. Such is common over distance, and is a factor of how many lines branch off the main line. Given that U paths exist between the transmitter and the receiver, at time t, each signal a_u, each along the path u, will sum up to produce an impulse response $I(t)$

$$I(t) = \sum_{u=1}^{U} a_u \delta(t - \hat{t}_u), \tag{1}$$

where $\tilde{t}_p$ is the time the transmitted signal arrives in each path.

3.3. Radio wave communication

To propose a communication system using Wi-Fi Direct and power line communication, it is necessary to investigate the radio attenuation trends in underground mines. Conducting such experiments is critical because of the different characteristics of the subsurface environment and the impact of ongoing mining on the complexity of radio communication distances. Indicators to evaluate the communication performance are Received Signal Strength Indication (RSSI), communication speed, and communication distance. Communication performance also varies greatly depending on environmental conditions and wireless communication standards. This will cause communication errors, so the surrounding situation should be considered. It is important to make sure that the radio waves are stable when communicating wirelessly. Even in a wireless LAN, the strength of the signal becomes weaker as the distance increases, hence, the communication speed will be slower. RSSI is an indicator of the strength of signals received by wireless communication devices which, is mainly used to control the transmission range in wireless communications such as wireless LAN and Bluetooth. This is because if the radio wave is too strong, it will cover an area unnecessarily far away, causing a waste of power and the danger of eavesdropping. Table 2 shows the general RSSI and connection strength as a guide where the communication speed is the amount of data transferred per unit of time. Stable radio communication is established when the RSSI is above −80 dBm. Also, the theoretical maximum communication speed may differ from the actual measured communication speed then, RSSI and communication speed are decayed by distance. Therefore, it is necessary to measure the RSSI and communication speed for each distance in the communication test between two points. Since the attenuation varies depending on the surrounding environment, it is also necessary to make a distinction based on the nature of the surroundings and the shielding, and whether it is a straight line or a turn. The presence or absence of moisture, the physical properties of rock walls, and the presence or absence of heavy machinery are representative of the conditions that can be a major factor of radio wave attenuation in an underground mine. Another major factor is the uniformity of the size of the tunnels. In free space, the amount of radio attenuation is proportional to the square of the distance and the square of the wavelength. The free space fundamental propagation loss, which measures the radiation attenuation from the antenna to a certain distance, is expressed as

$$L = 10 \log \frac{4\pi d}{\lambda}, \tag{2}$$

where L is the free space fundamental propagation loss, λ and d are the wavelength and distance in meters (m) and f is the frequency (MHz), respectively. However, in the real environment, reflected waves from the earth cause interference, and other factors related to propagation loss appear. Therefore, it is not possible to calculate losses simply as expressed in Eq. (2) within an underground mine. However, it is possible to estimate the actual values using the trends obtained from the measurements. As shown in Eq. (2), the propagation loss increases with distance. It is also necessary to conduct communication tests in straight and curved lines, considering that the surrounding environment contributes to propagation losses. Assuming the transmitter and receiver have a gain of unity, the path loss between a point r meters from a reference point r_0 is given as

$$\mathrm{PL}_{\mathrm{dB}}(r) = \bar{\mathrm{PL}}_{\mathrm{dB}}(r_0) + 10\gamma \log_{10}\left(\frac{r}{r_0}\right) + N, \tag{3}$$

in decibels (dB). $\bar{\mathrm{PL}}_{\mathrm{dB}}(r_0)$ is the average path loss at r_0, the path loss exponent γ is a constant and N follows the Gaussian distribution with zero-mean and variance of σ^2_{PL}.

4. Experimental setup

The PLC and Wi-Fi Ad Hoc and Wi-Fi Direct experiments are carried out at Osarizawa mine, a closed underground copper mine located in Akita Prefecture, north of Japan (see Fig. 3). The mine was once a flourishing copper mine but has now been recommissioned for tourism, educational, and research purposes. The layout of the tunnels in the mine is shown in Fig. 4, and the inset shows the respective positions of the PLC and Wi-Fi links.

The choice of Osarizawa mine for the experiments was based on several key factors. Firstly, the logistics and existing collaborative agreements with local authorities and institutions facilitated the use of this site for research. The Osarizawa mine offers convenient access and logistical support for conducting the experiments.

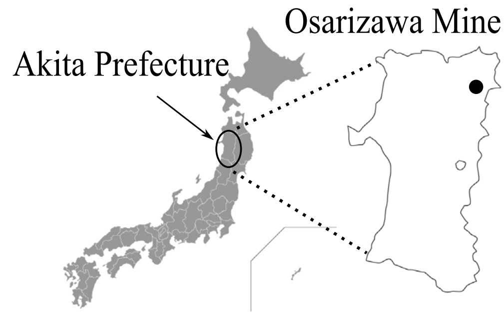


Fig. 3. Geographic location of Osarizawa mine.

Table 3
The three communication scenarios and the devices used to conduct the measurements.

Communication system	Device
Wi-Fi Ad hoc, Wi-Fi Direct	Data loggers to smartphone
Wi-Fi Direct	Smartphone to smartphone
Power line communication	Data logger to data logger

Secondly, although the mine has been recommissioned for non-mining purposes, it closely simulates the conditions of an operational underground mining environment. This includes similar tunnel layouts, geological formations, and environmental conditions, making it a suitable testbed for the communication system.

Lastly, the mine's active use for educational and research purposes provides a controlled yet realistic environment for testing and validating the communication system.

To ensure the robustness and applicability of the communication system across diverse mining environments, plans for future testing have been outlined. Experiments will be extended to larger mining countries such as the United States, South Africa, and China. These locations will provide a wider range of geological conditions and mine structures to validate the performance of the system. Future tests will be conducted in mines with varying geological conditions, including different types of rock formations, moisture levels, and tunnel layouts, helping to understand how these factors influence the performance of the communication system. Additionally, the system will be tested in mines with different structural characteristics, such as open-pit mines, deep shaft mines, and room-and-pillar mines, to ensure that the communication system can adapt to and perform reliably in a wide range of mining environments.

By addressing these points, a comprehensive validation of the communication system is aimed for, ensuring its effectiveness and reliability across various underground mining scenarios.

The tunnel in the mine is about 2 m high and 2 m wide (Fig. 5(a)), with an arched ceiling that exposes the surrounding bedrock with 90% humidity in the mine. Since the mine is closed with no mining equipment in active use, equipment powered by the powerline are those used for exhibition such as sound, lighting and mechanical figures.

The PLC transmitter, as shown in Fig. 5(b) is connected to the data logger in order to transfer the sensor data over the PLC channel. The transmitter used is a home plug which allows transmission control protocol/internet protocol (TCP/IP) protocol. The home plug is a D-Link DHP 208 AV/B (d-link, 2024) that can transmit up to 100 Mbps over a distance of 300 m. The PLC receiver is identical and also uses the same protocol and is placed away from the transmitter in increments of 5 m at each experiment as shown in Fig. 5. This distance is however not a straight line, as it has corners and bends as can be seen in Fig. 4. The list of communication standards in this study is shown in Table 3.

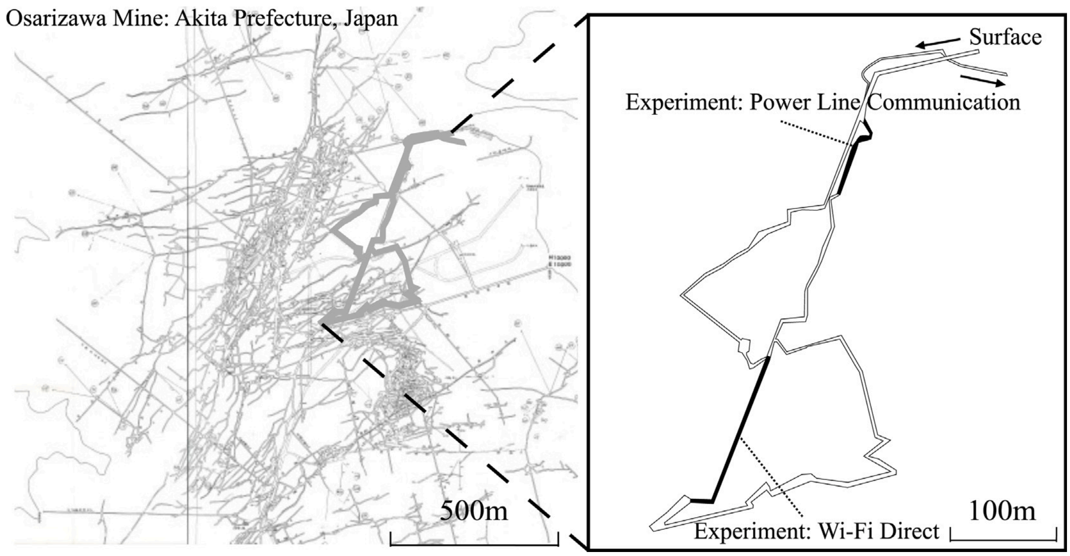
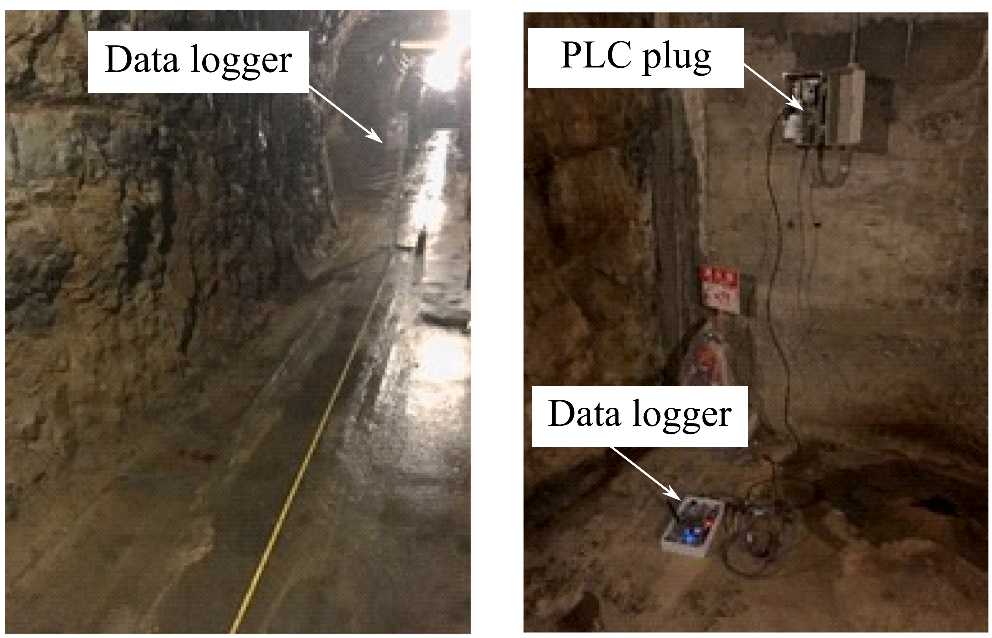


Fig. 4. Osarizawa mine map showing the sections of the PLC and Wi-Fi setups.



(a) Wi-Fi Ad hoc and Wi-Fi Direct.

(b) PLC transmitter connected to the data logger inside the mine.

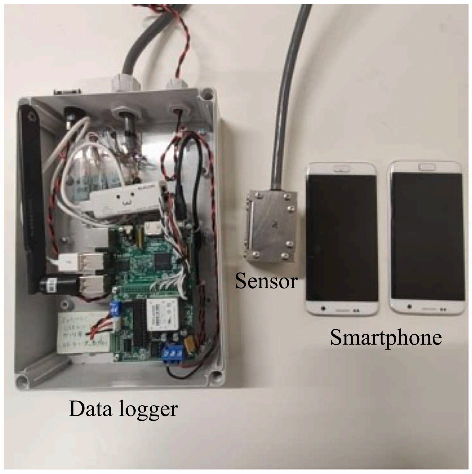
Fig. 5. Experiments setup inside the Osarizawa mine, showing the placements of the data logger and PLC plug.

Table 4
Devices used for conducting the experiments.

Device	Name
Data logger (Including sensor)	Raspberry Pi 3
Wi-Fi dongle	GW-300S
Smartphone (Android 4.0~)	Galaxy S7 Edge
PLC plug	DHP-208AV

The data logger utilized in this study is a Raspberry Pi 3 computer (Fig. 6(a)), which supports the IEEE 802.11a/ac/b/g/n standard through the GW-300S KATANA module, as shown in Table 4. Specifically, the IEEE 802.11n standard was employed in the experiment to maximize the output voltage of the module. The two smartphones used in the experiment were Galaxy S7 Edge devices, which are compatible with the IEEE 802.11a/ac/b/g/n standard and run on Android 4.0 or higher. Additionally, the DHP-208AV PLC plug was used for power line communication (Fig. 6(b)). A summary of the devices used in the experiment is provided in Table 4.

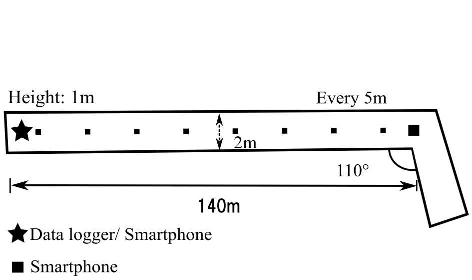
The choice of Galaxy S7 Edge for this experiment was influenced by several factors. Firstly, the availability and budget constraints played a significant role, as these devices were readily accessible and within the budget. Additionally, the performance of the Galaxy S7 Edge was considered adequate for the requirements of the experiment, providing compatibility with the necessary IEEE 802.11 standards. While newer devices offer potential benefits such as improved battery life, better processing power, and enhanced communication capabilities, the Galaxy S7 Edge was selected based on the aforementioned practical considerations.



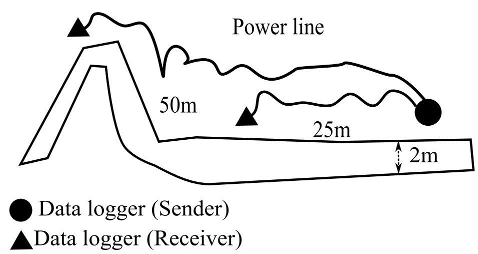
(a) Data logger, sensor and Smartphones.

(b) Indoor testbed setup of the PLC transmitter-receiver pair.

Fig. 6. Equipment used for the experiment.



(a) Data logger, sensor and Smartphones.



(b) Indoor testbed setup of the PLC transmitter-receiver pair.

Fig. 7. Datalogger and receiver positions for Wi-Fi and PLC links.

Future experiments will aim to utilize more current smartphones to take advantage of these improvements. Newer devices are expected to provide enhanced performance, greater reliability, and potentially lower energy consumption, which will be critical for long-term deployments in underground environments.

To address power consumption concerns, several power management strategies were implemented and discussed in the revised manuscript. These include optimizing the transmission intervals to reduce unnecessary energy use, utilizing low-power modes to conserve battery life, and ensuring that devices are adequately charged before deployment. The use of power banks or external battery packs was also suggested for extended operations, providing a reliable source of additional power.

Furthermore, considering advancements in battery technology and hardware capabilities since the initial experiments, it is also proposed to implement background operation modes. This would allow the devices to perform necessary communication tasks while minimizing power consumption, ensuring efficient and sustainable operation throughout the deployment period.

By incorporating these considerations, the revised experimental setup aims to enhance the reliability, efficiency, and practicality of the communication system in various underground mining scenarios (see Fig. 7).

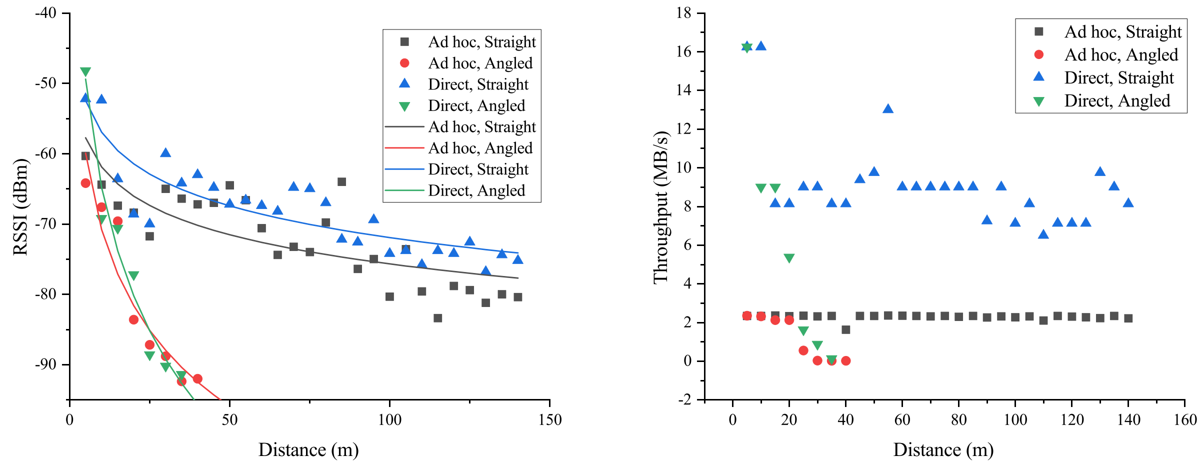
5. Results

5.1. From data loggers to smartphones

Fig. 8(a) compares the RSSI results between a datalogger and smartphone set up in the straight and winding tunnels in the Osarizawa mine using Wi-Fi Ad hoc and direct. An RSSI value is defined as -80 dBm as a minimum value for a stable connection (Kawamura et al., 2014). In this figure, the RSSI value is −75.2 dBm at the furthest 140 m point from the data obtained in a straight line, which is greater than the standard for stable communication (−80 dBm). There is a declining trend as the distance increases, but there are also upward fluctuations at some points. Each data point represents the median value from 100 measurements taken at that location, ensuring the reliability of the plotted RSSI values.

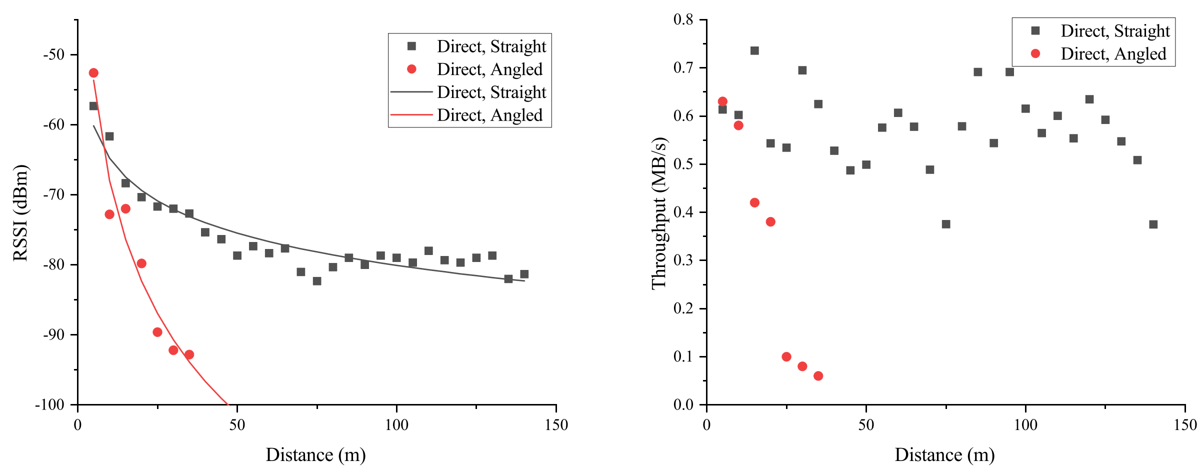
This variability could be attributed to the nature of the underground mine, and the fact that the unevenness of the rock walls may have affected the wave reflection. Therefore, free space propagation losses may not be an adequate estimate in such a situation. From Fig. 8(a), we conclude that the communication range of this system is 140 m for a linear path. This result shows that the communication distance is greater than the result of Wi-Fi Ad hoc, which is a straight line 110 m. As shown in Fig. 8(a), the RSSI at 25 m is −88.6 dBm in the experiment at the turn, and it decreases further beyond that. From the figure, we can conclude that the communication range at the turn is 20 m. This results in a larger range of communication compared to the Wi-Fi Ad hoc result of 15 m.

Fig. 8(b) shows the results of the communication speed, which can be summarized as follows. On the straight line connection, fast communication speeds averaging 9.1 MB/s were observed. At the turn, the average communication speed was 5.0 MB/s, but between 25 and 35 m, where communication was still possible below −80 dBm, it was found to be between 0.1 and 1.6 MB/s. The results show a similar trend to previous research results on Wi-Fi Ad hoc communications conducted at the same location. The discrepancy on communication speed and RSSI



(a) RSSI vs distance in the tunnel (b) Throughput vs distance in the tunnel

Fig. 8. RSSI and throughput measurements of a datalogger to smartphone connection, showing Wi-Fi Direct in the tunnel.



(a) Plot of the RSSI over distance. (b) Plot of the throughput over distance.

Fig. 9. RSSI and throughput measurements of a smartphone to smartphone connection, Wi-Fi Direct techniques in the tunnel.

can be attributed to the nature of the underground mine, where uneven rock walls could have affected the wave reflection (Ikeda et al., 2019). This also shows that the communication was not stable.

5.2. Smartphone to smartphone

Fig. 9(a) shows the RSSI results for straight lines and turns in the Osarizawa mine conducted between smartphones. In this figure, in a straight line, the RSSI value at 130 m is −82.0 dBm, which is less than the standard for stable communication (−80 dBm). There is a declining trend as distance increases, but there are also upward variations at some points. The communication range of the system was set to 130 m in a straight line. The experiment at the turn shows that the RSSI value is −89.6 dBm at 25 m and decreases further beyond that. From the figure, it can be concluded that the communication range at the turn is 20 m. In addition, using Eq. (3), the path loss exponent is in the Osarizawa mine is found to be 1.4983.

Fig. 9(b) shows the results of the communication speed, which can be summarized as follows. On the straight line, a high speed of 5.7 MB/s was observed on average. At the turn, the average communication speed was 5.5 MB/s, but between 25 and 35 m, communication was still possible below −80 dB.

5.3. Path loss modeling

The parameters of the approximation equations displayed in Figs. 8(a) and 9(a) are summarized in Table 5. In Table 5, we present the radio wave attenuation constants for data loggers and smartphones in both Ad hoc and Direct modes, obtained through linear regression on logarithmically transformed distances. The adjusted R-squared values for all the experiment cases are equal to 1, indicating a strong fit. This implies that the approximation equations accurately describe the relationship between the RSSI values and the logarithm of the distances in each scenario. This analysis provides valuable insights into the radio wave propagation characteristics in different communication modes and device types, with the application of logarithmic distance transformation in linear regression.

In this study, we investigated the Radio Wave Attenuation Constants for Data Loggers and Smartphones in Ad hoc and Direct Modes. To achieve this, we conducted experiments to measure the Received Signal Strength Indicator (RSSI) values at various communication distances. We employed linear regression on logarithmically transformed distances to approximate the relationship between the communication distance and the measured RSSI values. This approach allowed us to estimate the path loss exponent (γ) and the zero-mean Gaussian noise (N) for the path loss model, as described by Eq. (3).

Table 5
Radio wave attenuation constants for data loggers and smartphone in ad hoc and direct modes.

Experiment cases			Intercept(N)		Slope(10γ)		Statistics
			Value	Standard error	Value	Standard error	Adj. R-Square
Data loggers	Ad hoc	Straight	−48.1	1.15E−14	−13.79	6.41E−15	1
		Angled	−34.7	1.74E−14	−36.07	9.71E−15	1
	Direct	Straight	−41.96	6.25E−15	−14.98	3.49E−15	1
		Angled	−13.62	3.98E−14	−51.20	2.22E−14	1
Smartphone	Direct	Straight	−49.47	1.07E−14	−15.30	5.99E−15	1
		Angled	−20.40	1.69E−14	−47.58	9.45E−15	1

Table 6
Path loss exponent and noise values for data loggers and smartphones in ad hoc and direct modes.

Device type	Mode	Alignment	Gaussian noise (N)	Path loss exponent (γ)
Data loggers	Ad hoc	Straight	−48.10	−1.38
		Angled	−34.70	−3.61
	Direct	Straight	−41.96	−1.50
		Angled	−13.62	−5.12
Smartphone	Direct	Straight	−49.47	−1.53
		Angled	−20.40	−4.76

Table 6 presents the values of γ and N, along with their standard errors and the adjusted R-squared values obtained from our experiments with data loggers and smartphones in both Ad hoc and Direct modes. These values are essential components of the path loss model described by Eq. (3), which helps us understand the radio wave attenuation characteristics in underground communication systems. In Eq. (3), $\bar{\mathrm{PL}}_{\mathrm{dB}}(r_0)$ represents the average path loss at distance r_0, while γ and N are the path loss exponent and the Gaussian noise, respectively. The results of our experiments are detailed in Table 5.

The results show that for data loggers in Ad hoc mode with a straight alignment, the intercept value is −48.10 with a standard error of 1.15E−2, and the slope value is −13.79 with a standard error of 6.41E−2. In the angled alignment, the intercept value is −34.70 with a standard error of 1.74E−2, and the slope value is −36.07 with a standard error of 9.71E−2. For data loggers in Direct mode with a straight alignment, the intercept value is −41.96 with a standard error of 6.25E−2, and the slope value is −14.98 with a standard error of 3.49E−2. In the angled alignment, the intercept value is −13.62 with a standard error of 3.98E−2, and the slope value is −51.20 with a standard error of 2.22E−2. For smartphones in Direct mode with a straight alignment, the intercept value is −49.47 with a standard error of 1.07E−2, and the slope value is −15.30 with a standard error of 5.99E−2. In the angled alignment, the intercept value is −20.40 with a standard error of 1.69E−2, and the slope value is −47.58 with a standard error of 9.45E−2.

The adjusted R-squared values for all the experiment cases are equal to 1, indicating a strong fit. This finding suggests that the approximation equations accurately describe the relationship between the RSSI values and the logarithm of the distances in each scenario. Our analysis provides valuable insights into the radio wave propagation characteristics in different communication modes and device types, highlighting the effectiveness of using logarithmic distance transformation in linear regression.

5.4. PLC performance

Fig. 10 shows the results of the communication speed of PLC using an existing power installation in the mine. This setup models the scenario wherein a 220 V, 50 Hz powerline used for lighting the tunnel and powering compatible equipment, is also used for communication. As expected, the longer the distance, the lower the communication speed for most measurements. The figure shows multiple speed test trials over approximately 25 m and 50 m distance between the transmitter and receiver positions in the mine. The mean value for 25 m is 7.4 MB/s, which is higher than the 50 m average of 6.2 MB/s. The high variations in the speed can be attributed to the multipath of the channel and switching transients of the devices connected to the powerline link, hence requiring re-transmission when the channel experiences low signal-to-noise ratio.

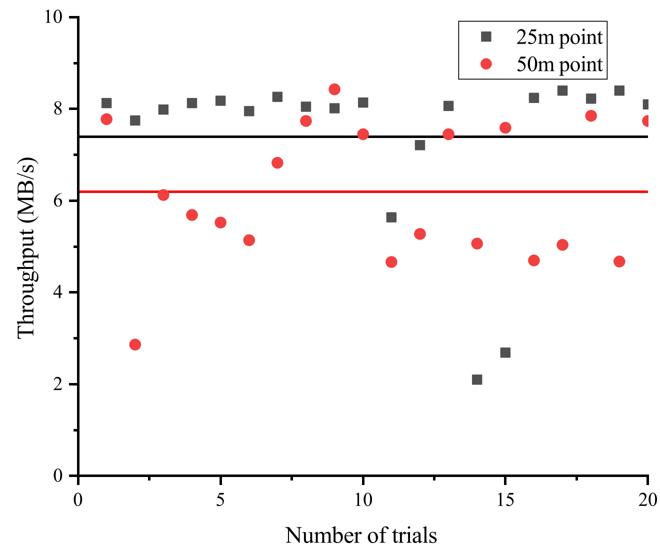


Fig. 10. Throughput measurements over a PLC link.

5.5. Discussion

From the findings of the experiments which consider communication from the data loggers to the smartphone, it is suggested to install a base station at each corner or each 140 m in a straight-line path. This configuration would be suitable for building a stable Wi-Fi Ad hoc network in an underground mine. In addition, if the RSSI is above −80 dBm, it is possible to communicate at speeds of 9.1 MB/s in most places. This is sufficient for transferring image files and sensing data (text files) as small as 1MB quickly and consistently within an underground mine. The communication time was calculated by dividing the vehicle speed by the communication range, and the amount of transferred data was obtained by multiplying the communication time by the throughput:

$$\mathrm{CT}(s) = \frac{\mathrm{CR} \times \frac{3600\ \mathrm{s/h}}{1000\ \mathrm{m/km}}}{\mathrm{VS}}, \tag{4}$$

where CT is the communication time, CR is the communication distance in meters, VS is the vehicle speed in kilometers per hour, and T is the throughput in megabytes per second.

According to the Haul road inspection handbook, speed limits should be established based on the layout, condition, and the capabilities of the equipment using the roads. Depending on road curvature and vehicle size, the speed limit ranges between 32 km/h and 48 km/h for surface mines. Contrary to this, underground mine sites have a speed limit of less than 32 km/h since roads are narrow and allow for far more restricted maneuvers, hence this limit. For this study, we set the maximum speed of moving equipment and people is 20 km/h. For workers carrying smartphones, the slower the speed, the greater the amount of communication possible. As soon as the data loggers and the miner's smartphone come within range of each other, the data transfer begins. Whether only one of the miners is on the move or communicating between the moving smartphone and a fixed data logger, the data transferable time is 25.2 s with a maximum transfer of 230 MB; if two miners are moving towards each other, the relative speed of the mining equipment is 40 km/h, the communication time frame is reduced to 12.6 s with a maximum transfer of 115 MB of data. To summarize, the slower the relative speed between devices, the more data that can be transferred. The communication speed between smartphones is 5.7 MB/s, which is transferred between each other. The communication time was calculated by dividing the vehicle speed by the communication range and multiplying the communication time by the throughput to obtain the amount of data transferred. From the above theoretical situation and calculation results, it was found that the maximum data transfer capacity of 72 MB can be expected, and the necessary monitoring data in the underground mine can be transmitted reliably as text and image files.

The layout of the data communication system proposed in this study is shown in Fig. 11. The power lines used for the PLC are the same as those originally installed in the underground mine. The power line wiring in the Osarizawa mine is divided into six regions, A–F, as shown in Fig. 11. Within each region, data can be shared via a PLC plug. It is also possible to share data via Wi-Fi Direct with data loggers installed in different areas. From the results, a throughput of 8 Mbps over the PLC line at the 25 m and 50 m distances is able to match the Wi-Fi Direct and Ad Hoc throughputs at over 100 m. This is important in integrating PLC with Wi-Fi. In a PLC to Wi-Fi direction, the received and decoded data at the PLC receiver can be re-transmitted over the Wi-Fi link without creating a bottleneck. This is also applicable to the reverse Wi-Fi to PLC link. The PLC transceivers are capable of higher throughputs. However, multipath and busyness of the link, in terms of the devices connected to the line, affect the data quality and consequently, the throughput. Therefore, a mine design that implements PLC-Wi-Fi integration would consider the use of PLC to navigate corners in the mine, while Wi-Fi is deployed in areas with less obstacles, straight tunnels with direct line-of-sight.

The comparison of the leaky feeder system costs with the proposed system as actually installed in the range is shown in Fig. 11. As shown in Fig. 11, the tunnel is 1000 m long and it was also decided to have ten miners working in a day, each with one smartphone. The fact that the proposed system is wireless indicates that the costs of installation and maintenance are low.

The proposed system requires approximately 780 USD for data loggers and PLC plug costs and 2000 USD for 10 smartphones. Additionally, the system requires around 500 USD for installation costs and 200 USD per year for maintenance costs. The overall costs for the proposed system are approximately 3280 USD for installation and 200 USD per year for maintenance.

On the other hand, a leaky feeder cable (Msha Slywv-75-10), which has been in use in recent years, costs 95 USD per meter. Installing 1000 meters of leaky feeder cable to enable data communication would cost about 95,000 USD. Furthermore, the leaky feeder system requires around 5000 USD for installation costs and 10,000 USD per year for maintenance costs. The overall costs for the leaky feeder system are approximately 100,000 USD for installation and 10,000 USD per year for maintenance.

Comparing the costs of both systems, the proposed system can achieve communication for only 3% of the cost and 2% of the maintenance cost of the leaky feeder system. This comparison highlights the cost-effectiveness of the proposed communication system.

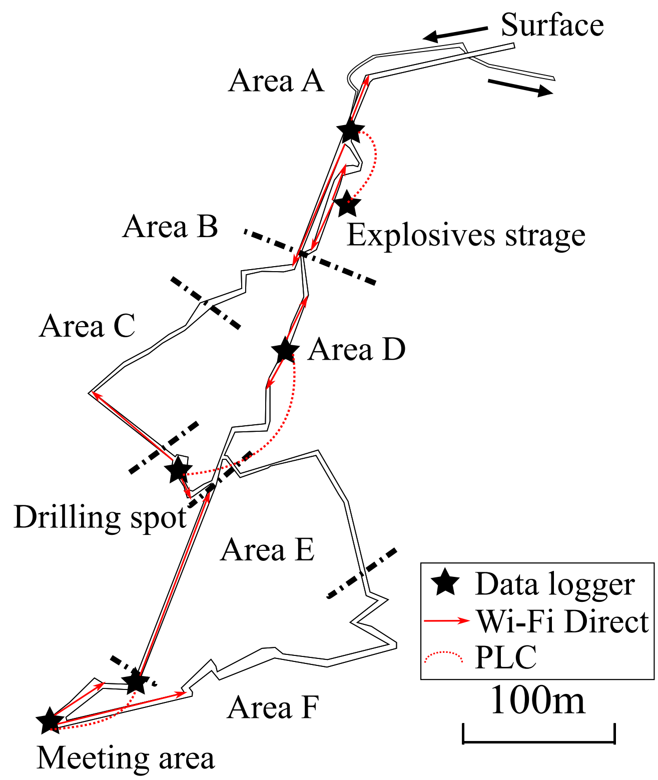


Fig. 11. Layout of the proposed Wi-Fi/PLC system.

Table 7
Investment costs for the proposed communication system.

Device	Costs
Data logger (Including sensor)	100 USD/Item
Smartphone (Android 4.0~)	200 USD/Item
PLC plug	30 USD/Item
Power line	Already installed
Installation costs	500 USD
Maintenance costs (per year)	200 USD

For example, in the explosives storage areas, monitoring of temperature, humidity, and gas concentration is required, and this data is stored as text data. If a data logger is installed on the other side of the wall from the tunnel, it will share data with the data loggers using a PLC. This makes it possible to collect data without having to enter the explosives storage areas when a miner passes through. Since the data transfer distance is about 140 m from Fig. 11, a maximum of 230MB of data can be recovered. This communication capability allows for the daily data storage to be transferred through the mine, enabling data to be verified at the underground site office. Similarly, the environmental data required for drilling spots and meeting areas can be managed with this data transfer system. The cost of this system is low, as shown in Table 7, and it is easy to install because it can utilize existing power lines. In addition to installing a communication system in a newly developed mine, the system can be operated by simply installing data loggers and other equipment in an already operational mine. This makes the system suitable for a wide range of mining operations.

6. Conclusion

In this study, we developed a hybrid, low-cost data transfer system for underground mining using PLC with Wi-Fi Direct and Wi-Fi Ad hoc. In deep underground environments, reliable, cable-based communication links that can easily scale with underground mine expansion, such as PLC, are becoming attractive. These links can assist in transferring critical sensor data from underground locations to the control room or to the next reliable, high-speed link, such as optic fiber. We further integrated the PLC link with a Wi-Fi Direct wireless link to extend the range of the wired link to the last mile users. This integration enables communication over existing power installations in the mine without incurring additional cable installation costs. In earlier studies, ZigBee and Wi-Fi Ad hoc have been proposed for wireless data transfer in underground environments.

Our experiments provided valuable insights into the radio wave propagation characteristics in different communication modes and device types. By employing linear regression on logarithmically transformed distances, we were able to estimate the path loss exponent (γ) and the zero-mean Gaussian noise (N) for the path loss model. This analysis highlights the effectiveness of using logarithmic distance transformation in linear regression when determining the Radio Wave Attenuation Constants for Data Loggers and Smartphones in Ad hoc and Direct Modes.

From the results, the Wi-Fi Direct system achieved a communication speed of 9.1 MB/s between a data logger and mobile phone 140 m apart, tested by transferring 230 MB of data between a wireless node and a miner's smartphone. At 130 m apart, the speed reduced to 5.7 MB/s using a data transfer size of 72 MB. The proposed system's costs were estimated and compared with the Leaky feeder link, showing that the proposed system can achieve communication for only 3% of its cost and 2% of the maintenance cost. An experimental test of the hybrid PLC-Wi-Fi link was carried out at the Osarizawa mine using existing powerline installations in the mine. The communication speed and data throughput over the PLC channel in the existing powerline installation in the mine are presented, with results showing that up to 6.2 MB/s is achievable over a distance of 50 m, hence supporting voice and video streaming data.

In conclusion, this study presents a promising hybrid, low-cost data transfer system for underground mining applications. Our approach integrates PLC with Wi-Fi Direct and Wi-Fi Ad hoc, offering a scalable and cost-effective solution for underground communications. The analysis of radio wave propagation characteristics further demonstrates the effectiveness of logarithmic distance transformation in linear regression, providing a useful reference for future research and practical applications in underground communication systems.

CRediT authorship contribution statement

Hajime Ikeda: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Resources, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Oluwafemi Kolade:** Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Project administration, Data curation, Conceptualization. **Ling Cheng:** Visualization, Validation, Software, Project administration, Investigation. **Frederick Cawood:** Supervision, Project administration, Funding acquisition, Formal analysis, Conceptualization. **Youhei Kawamura:** Supervision, Methodology, Funding acquisition, Formal analysis, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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