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Development of Digital Device Using ZigBee for Environmental Monitoring in Underground Mines

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Abstract: In underground mines, various mining activities may generate dust or vibrations, affecting workers' health and safety. Therefore, for worker safety, we must monitor the environment and identify possible risks. However, it is difficult to install multiple sensors and acquire data simultaneously because of the difficulties of connecting to an external network in underground mines. This study developed a digital device to share acquired data by combining ZigBee communication technology with an accelerometer and dust sensor. In total, 29 vibration modules, 14 dust modules, and 2 coordinator modules were installed at Taeyoung EMC's Samdo Mine in Samcheok, Republic of Korea. Because of its application, we could detect changes in vibration and dust before and after blasting. The dust density of the devices close to the blasting point increases rapidly up to about 230 μg/m^3 and then decreases to about 180 μg/m^3, and the dust density of the devices further increases over time. The dust density was usually maintained at a value of about 100 to 150 μg/m^3 before blasting. The spatial distribution of the dust density of multiple devices was visualized using ArcGIS Pro. Although the wireless sensor network is well-established, some modules were temporarily disconnected from the network. In order to solve the problem of unstable network connection in some modules, change of network settings and line of sight analysis are required. Improvements in the technology developed in this study may help prevent potential hazards in underground mines.

Keywords: ZigBee; wireless sensor network; accelerometer; dust sensor; underground mine

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1. Introduction

In underground mines, vibrations and dust are generated from heavy equipment, excavation, and blasting operations. Ground vibrations generated during excavation and blasting can cause cracks in the surrounding rock and structures, leading to severe risks, such as collapse accidents or ground subsidence [1]. To prevent geohazards in underground mines, numerous studies have been conducted to predict the impact of blasting or detect the destruction of rock structures in advance by measuring microseismic vibrations [2,3]. However, maintaining a microseismic monitoring system in underground mines is challenging because mining is conducted at multiple points [4]. In addition, dust generated from mining activities floats in the atmosphere, worsening the mining environment and causing various diseases in workers [5,6]. In particular, toxic NOx and Diesel Particulate Matter (DPM) are also emitted in significant amounts due to the excessive use of large diesel equipment in underground mines [7]. The large amount of dust generated during blasting may obstruct the view of workers and cause vehicle accidents. Various aspects should be considered to prevent such vibrations and atmospheric problems in underground mines. In particular, we must understand the current status through monitoring. Vibration monitoring can help prevent rock collapse by reinforcing structurally unstable areas, and monitoring the amount of dust can help establish a ventilation system by installing a fan in an area where a large amount of dust is concentrated. However, compared to open-pit mines, which have a good connection to existing networks, underground mines have difficulty connecting to networks outside the mine [8]. Recently, with the development of Internet of Things (IoT) technology, attempts to combine various sensors and IoT to monitor the environment in mines have been increasing. Sun et al. [9] combined IoT and cloud computing with various sensors that can measure the water level, deformation, and pressure of tailings dams to prevent collapse accidents that may occur in tailings dams. Prashanth and Nimaje [10] observed vibrations caused by blasting in open-pit mines using an accelerometer and radio frequency (RF) module. Gangwar et al. [11] provided a miniaturized antenna system that uses a global system for mobile communication (GSM) to enable communication between miners in an underground mine. In addition, numerous studies have been conducted on air monitoring in mines using IoT technologies such as Bluetooth, Wi-Fi, and ZigBee [12–16]. IoT technologies, including Bluetooth, near-field communication (NFC), Wi-Fi, and ZigBee, can be utilized for wireless communication depending on the environment and application. Bluetooth is a short-range wireless communication technology with a range of approximately 10 m that consumes barely any power. For the recently developed Bluetooth 5.0, the transmission distance was approximately 40 m, and the transmission speed was increased to 2 Mbps. However, it is not suitable for real-time monitoring because the communication distance is extremely short for use in mines, and the maximum number of devices that can be connected is relatively small. NFC is also a short-distance wireless communication technology that can exchange data at a short distance of within 10 cm, and because it uses a one-to-one tagging method, it is not suitable for the real-time monitoring of multiple points. Wi-Fi is useful for monitoring because of its wide communication range and fast data transmission speed, but it is power- and cost-extensive for routers to build Wi-Fi networks. In contrast, ZigBee has the advantage that one node is connected to 255 devices, which can be extended to up to 65,000 devices [17] and consumes little enough power to operate for several years with a low-capacity battery depending on the settings [18]. Representative technologies used for wireless communication are listed in Table 1, and the features, advantages, and disadvantages of each are also summarized. Considering the advantages and disadvantages of the ZigBee technology, which can construct a relatively wide area network at low power and cost, it was used in this study to measure the amount of vibration and dust over a wide area within an underground mine. Recently, some studies [19,20] have used ZigBee to build wireless sensor networks (WSNs) in underground mines or tunnels. However, most studies are limited to conceptual design or communication between a few devices; moreover, there are only limited number of practically applicable systems that continuously collect data from multiple nodes while considering the battery life and data load. This study deals with practical concerns in applying ZigBee technology and discusses the problems and solutions for implementing a low-power and -cost system applicable to relatively small and poor underground mines. Digital devices capable of measuring vibration and dust were developed by combining a ZigBee module, accelerometer, and dust sensor. In addition, these devices could construct a WSN to exchange measured data. By applying the developed technology to Taeyoung EMC's Samdo Mine, we could confirm the spatial distribution and the change in vibration and dust density at multiple points in the underground mine when blasting was performed. This paper is organized into six sections. Section 1 introduces the main concepts of this study. Section 2 describes the study area in which the developed technology is applied. Sections 3 and 4 describe the Zigbee-based vibration and dust monitoring methods and application results in the study area, respectively. Section 5 discusses the challenges and methods used to solve them. Finally, conclusions are summarized in Section 6.

Table 1. Comparison of wireless communication technologies (modified from Duan and Chen [21]).

Wireless Technical Standards	ZigBee/802.15.4	Bluetooth	Wi-Fi	GSM [1]/GPRS [2]
System resource requirements	4 KB–32 KB	>250 KB	>1 MB	>16 MB
Power waste	Low	Common	Common	High
Battery life (days)	100–1000+	1–7	1–5	1–7
Number of nodes in local network	65,000+	7	30	1000+
Data rate (Kbps)	20–250	1000	11,000+	64–128
Communication distance	1–3200	1–10+	1–100	1000+
Advantage	Reliability, low cost, low power consumption	Low cost and easy to operate	High speed and adaptability	Good transmission quality and large coverage range
Applications	Wireless detection and control	Short-distance data transmission	A lot of data transmissions such as Web access and video.	Voice and data transmission

[1] GSM: global system for mobile communications. [2] GPRS: general packet radio service.

2. Study Area

Taeyoung EMC's Samdo Mine, located in Dogye-eup, Samcheok-si, Gangwon-do, was selected as the study area (Figure 1). The Samdo Mine was established in April 1993 by registering six mining rights. It is an underground mine that produces high-quality limestone for iron and steel production, and the board-and-pillar method with modernized facilities was applied. At the Samdo Mine, the main mining target is the Pungchon Formation limestone, where white to grayish-white microcrystalline calcite-type high-grade limestone deposits form along the homogeneous limestone zone. It was formed by the alteration action of tidal water (100–200 °C) during the Jurassic period (189–205 Ma) [22]. About 1.5 million tons of limestone annually are continuously mined at the Samdo Mine. Particularly, because the equipment operation is repeated and blasting operations are performed several times daily, we must monitor the amount of vibration and dust in the mine. Currently, the Samdo Mine operates a ventilation system that uses both a method using fans and a natural ventilation shaft. This study applied the developed technology to the area around the blasting site, which is approximately 2 km from the mine adit.

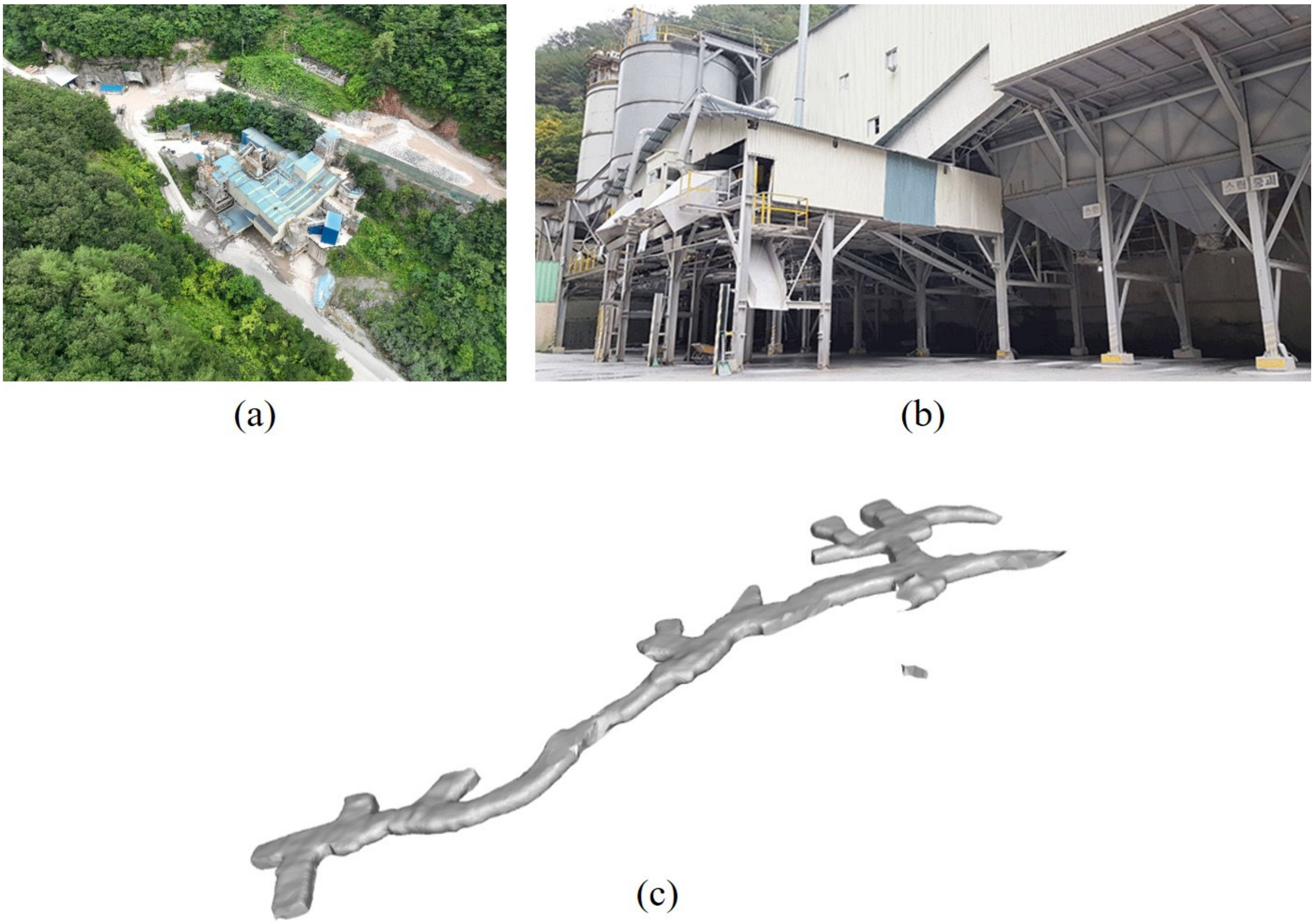

Figure 1. Taeyoung EMC Samdo Mine. (**a**) Panoramic view, (**b**) mineral processing facility, and (**c**) 3D map of underground mine.

3. Methods

Because the sensor installed in an underground mine cannot be directly connected to an external network, we had to use a separate storage device or transmit data to the external network through routers to transfer the data acquired inside the mine. This study used an accelerometer to measure vibration, and a dust sensor was used to measure dust density. The WSN was built such that the data acquired by these sensors could be transmitted to the destination through the ZigBee network. If the coordinator module where the data are collected is located outside the mine, the data can be transmitted to a separate server through an external network, and when located inside the mine, the data can be stored on laptop storage or memory card.

3.1. ZigBee Module for Communication

ZigBee communication technology transmits measurement data even in underground mines, where it is difficult to connect to an external communication network. It is a low-power wireless communication protocol used for local-area wireless networking. As Bluetooth is a standardized communication method, ZigBee is also a standard communication method. Therefore, if the standard is followed, various products from different companies can communicate with each other using the ZigBee protocol. ZigBee communication has three major characteristics: First, it has a routing function that allows packet data to be passed through another module while it travels to its final destination. Second, an ad hoc network function can automatically instantly create an entire wireless network.

Third, it has its mesh recovery capability that can automatically detect and reconfigure the network if one or more modules are missing [23].

Based on these characteristics, each module in the ZigBee network can be assigned three roles: coordinator, router, and end device. Only one coordinator can exist in one network, performing administrative tasks, such as network formation, address assignment, security setting, and network maintenance. A router accesses the network to exchange information and performs routing tasks between distant devices. We must maintain power at all times because it acts as a channel for the network. The end device can access the network and send information; however, because it does not have a routing role, energy can be saved through the power-saving mode [24]. Depending on the purpose, different network methods can be applied between these modules, and they can be classified into star, tree, and mesh networks. The star network is a method in which the end device is directly connected to the coordinator, and there is no router; therefore, the network cannot be expanded widely. The tree network is branch-shaped, the routers are connected by a single line, and the end device is connected to the nearest router to transmit data to the coordinator. Finally, the mesh network allows multiple connections between the routers. This study performed ZigBee protocol-based wireless communication using Digi International's XBee 3 Pro product (Figure 2a). The XBee 3 Pro product has a communication range of approximately 3200 m outdoors and 90 m indoors.

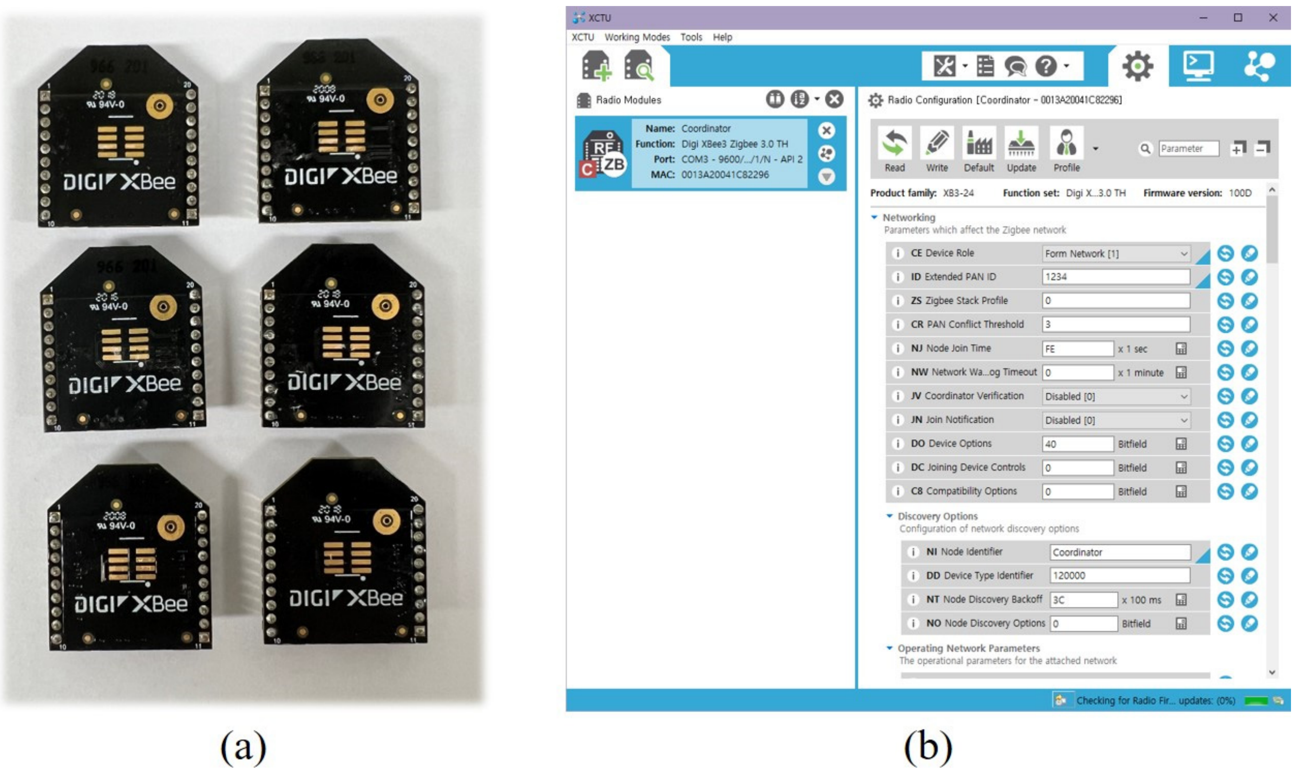

Figure 2. (**a**) XBee 3 Pro modules and (**b**) XCTU application for XBee settings.

In the XCTU program (Figure 2b) provided by Digi International, various settings for the XBee 3 Pro network, such as the role of each module, network type, and power saving mode, are possible. The XBee module can be used in conjunction with a microcontroller, such as an Arduino or Raspberry, and because it has a total of 20 pins, it can be used independently in combination with various sensors.

3.2. Development of Vibration Measurement Module

This study used a low-cost accelerometer (ADXL335) to measure vibration values. The ADXL335 is a micro-electromechanical system (MEMS) accelerometer, and when an acceleration force is applied to a specific axis, the microstructure supported by the polysilicon spring is deflected to change the capacitance. These variations are designed to be proportional to the acceleration of the corresponding axis. The static acceleration due to gravity and dynamic acceleration due to impact or vibration can be measured in the range of ± 3 g for the X-, Y-, and Z-axes, respectively. The sensor operates from a power supply of 1.8 to 3.6 V and typically consumes only 350 µA of current, making it suitable for this study, which requires low power. The ADXL335 sensor sends out voltage through three analog output pins according to the acceleration values of the X-, Y-, and Z-axes. The sensor was powered by the VCC pin and grounded through the GND pin (Figure 3a). The relationship between the output analog value and the acceleration is the same as that in Equation (1). Here, the ADC value is an analog value, Vref is the reference voltage, 1.65 V is the voltage at 0 g, and 0.330 V is the sensitivity scale factor.

$$\text{Acceleration value} = ((\text{ADC value} \times \text{Vref})/1024) - 1.65)/0.330, \quad (1)$$

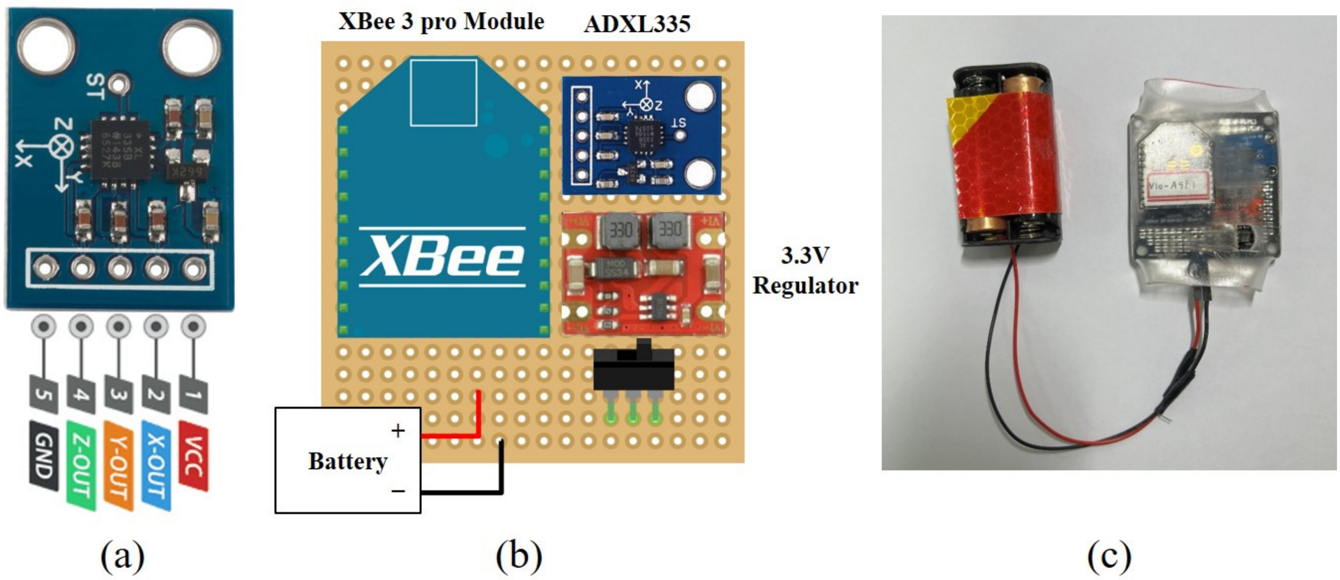

Figure 3. (**a**) ADXL335 accelerometer, (**b**) schematic, and (**c**) product of vibration measurement module.

Figure 3b is a schematic figure, and Figure 3c shows the actual product of the vibration measurement module developed in this study. Two AA-size batteries were built to supply a voltage of approximately 3 V, and a 3.3 V regulator was connected to supply a constant voltage. Because both the XBee module and ADXL335 were optimized for an input voltage of 3.3 V, a constant voltage output from the regulator was supplied to each. XBee's analog pin measures the voltage from 0 to 3.3 as a digital number of 0 to 1023 (10 bit); therefore, when a voltage of 1.65 V corresponding to 0 acceleration is input, a value of approximately 511 is measured. The value data obtained are sent to another XBee module that acts as a router and are finally transmitted to the coordinator.

3.3. Development of Dust Measurement Module

To measure the dust density in the mine, PMSA003A, a sensor that optically detects dust using a laser, was used. The sensor uses the laser-scattering principle. After irradiating a laser with suspended particles in the air, a certain amount of scattered light was collected, and fine dust was measured with scattered light that varied according to the diameter per unit volume of the suspended particles. In Figure 4a, the shape and pin arrangement of the sensor can be confirmed, the Vcc pin supplies power to the dust sensor itself, and the GND pin is used to ground the current. The Rx and Tx pins were connected to the microcontroller and transmitted the measured value of the dust sensor. This sensor can measure up to approximately 1 mg/m^3 of particulate matter (PM) 2.5 and PM 10. However, it is difficult to obtain high accuracy owing to the limitations of low-cost sensors; therefore, this study aimed to understand the overall dust density change and distribution in the mine rather than obtaining accurate dust density.

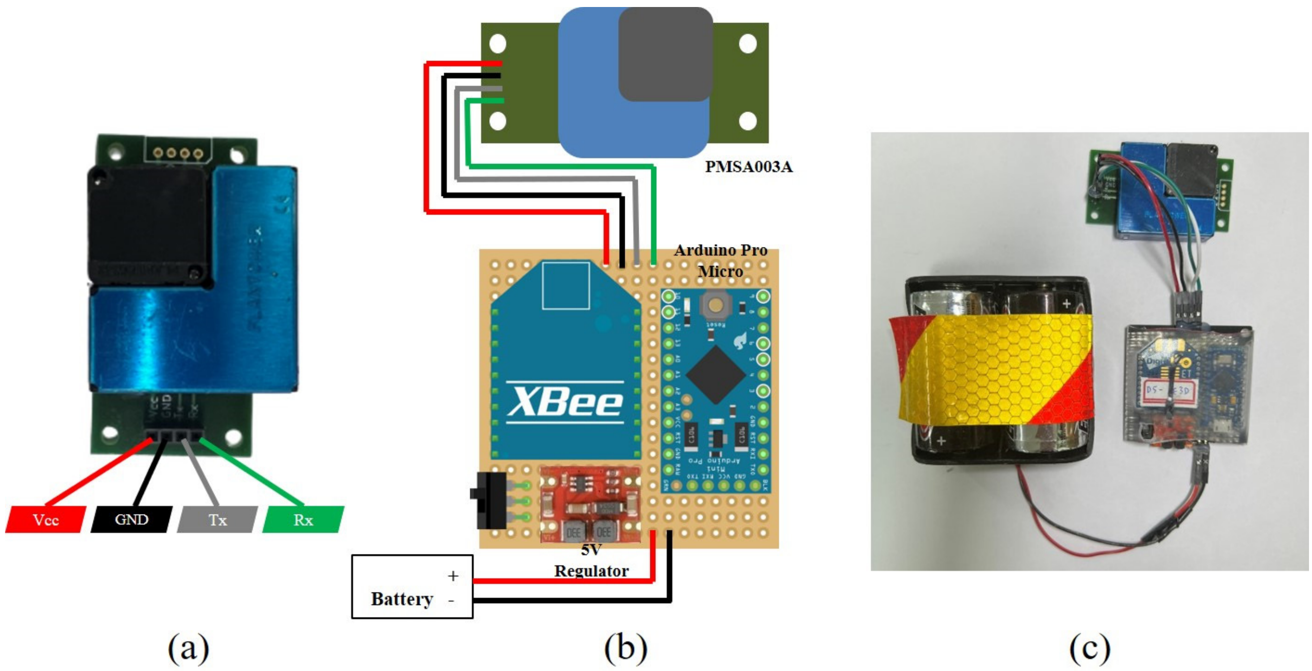

Figure 4. (**a**) PMSA003A dust sensor, (**b**) schematic, and (**c**) product of dust measurement module.

To measure the dust density in an underground mine and transmit data, we developed a portable dust measurement module. Figure 4b shows the schematic of the developed module. Figure 4c shows the actual developed module. To read data from the PMSA003A sensor, software serial communication was used for programming and connecting the Arduino Pro Micro microcontroller. As the dust sensor was optimized for a voltage of 5 V, the power supplied from the battery was boosted to 5 V using a regulator. Because the dust measurement module uses more power than the vibration measurement module, we connected D-type batteries with relatively large capacities. The measured dust density value was input to the Arduino through the Rx and Tx pins of the Arduino Pro Micro, and the result was transmitted to other modules through Xbee. The dust measurement module must continuously measure and transmit dust values and act as a router for connecting the Xbee modules.

3.4. Module Installation and Data Acquisition in Underground Mine

The vibration and dust measurement modules developed in this study were applied to the Taeyoung EMC Samdo Mine, an underground mine. The experiments were conducted in part of the main drift, where blasting was performed periodically several times a day. The vibration measurement modules were set as routers to continuously acquire data, and 29 modules were installed. To obtain dust values, 14 dust measuring modules were installed as routers, and the line of sight (LOS) was secured for smooth communication between modules. The modules were arranged at intervals of ~20 m. The experiment was conducted for blasting work at approximately 4:40 pm, and the blasting spot is shown in Figure 5.

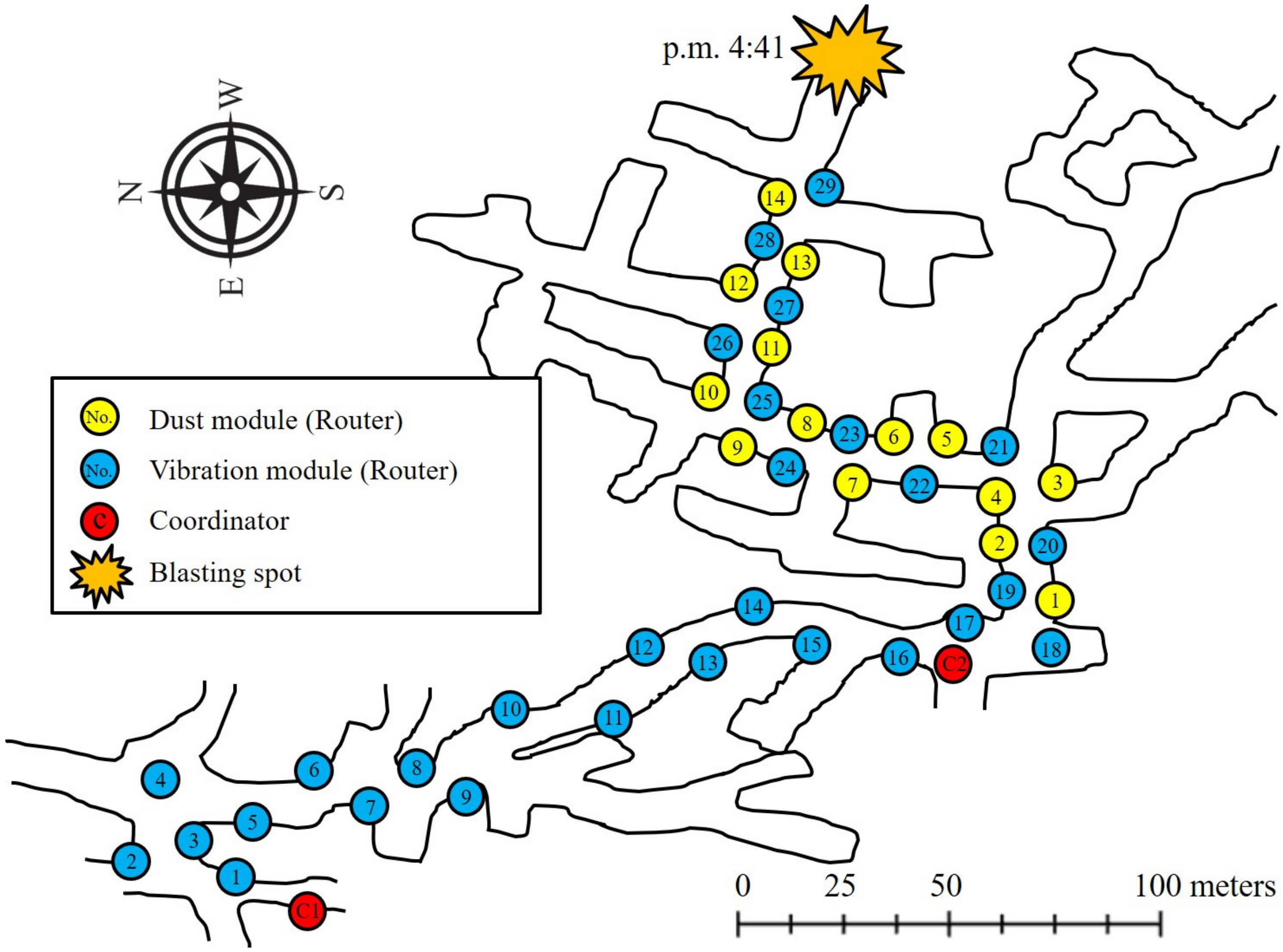

Figure 5. Drift map of Samdo Mine showing installed modules and blasting spot.

One coordinator must be present in the ZigBee network. In this study, 29 vibration and 14 dust modules were arranged along the mine drift, and we could connect all of these modules with one coordinator. However, because the vibration module has a high sampling rate that can acquire multiple data points per second, data loss may occur in one coordinator if excessively many modules are connected. Therefore, in this study, two networks are constructed by installing two coordinators. Coordinator 1 manages the vibration modules from V1 to V15, and Coordinator 2 manages the V16 to V29 vibration modules and dust modules. The coordinator module was constructed by connecting the XBee and Arduino Uno with the XBee shield, and it was programmed to monitor all data acquired from the measurement module and connected to the laptop. The packet data acquired from the module have a unique code defining each module and analog value data, and the Arduino connected to the coordinator transmits these data to the laptop through time-to-live serial communication. Figure 6 shows a technology roadmap of the overall flow from the device hardware and software development to data acquisition and utilization. Because the acquired data are recorded in real-time in a comma-separated values format, the monitoring status can be easily checked even in the field.

The Technology Roadmap	Device Hardware	Device Software	Communications	Applications
Vibration Measurement	• Add Xbee3 Pro • Add accelerometer (ADXL335) • Add 3.3V Regulator • Add AA batteries	• Set sampling rate • Read acceleration for 3 axes	• Transfer data to the coordinator module through the router modules • Store data	• Remove gravitational acceleration using low-pass filter • Calculate vibration • Display vibration graph
Dust Measurement	• Add Xbee3 Pro • Add Arduino Pro Micro • Add dust sensor (PMSA003A) • Add 5V Regulator • Add D batteries	• Set Arduino code • Read dust density	• Transfer data to the coordinator module through the router modules • Store data	• Display dust density graph • Display dust density distribution and risk area on the map (ArcGIS)

Figure 6. Technology roadmap of vibration and dust measurement modules.

4. Results

4.1. Vibration Measurement Result

A total of 29 vibration measurement modules were installed. Because of installing the coordinator module at the farthest point from the blasting point, the observed values of all vibration measurement modules were monitored by the coordinator. Modules near the blasting point are over 400 m away from Coordinator 1, and each XBee 3 Pro communication module has a communication range of approximately 90 m in an indoor environment; therefore, direct communication between them is impossible. Particularly, it was confirmed that the router modules performed the relay activity of wireless communication. Although Coordinator 1 can be connected to all modules, two coordinators are installed to reduce data loss. Figure 7 shows the vibration measurement results for blasting obtained from the vibration measurement modules. Because the vibration measurement module is manufactured using an accelerometer, the acceleration due to gravity is measured even in an environment without vibration. Therefore, the gravitational acceleration was removed by applying a low-pass filter to the acquired data. In modules relatively close to the blasting spot, a little vibration was observed at around 4:40 pm, when blasting was made (Figure 7a–e). This is a small vibration, and the impact of the vibration propagation through the ground is not large because of the hard rock of the Samdo Mine. As the coordinator and the vibration measurement module are farther apart, data must be transmitted through routers; therefore, if the connection is lost somewhere in the network, stable data transmission may be difficult. For example, for V2, some data were missing (Figure 7f). In addition, there was a blank period during which data were not acquired. This means that the network connection of the vibration measurement module is momentarily disconnected, owing to the complex structure of the underground mine, which we discuss in detail in the conclusions.

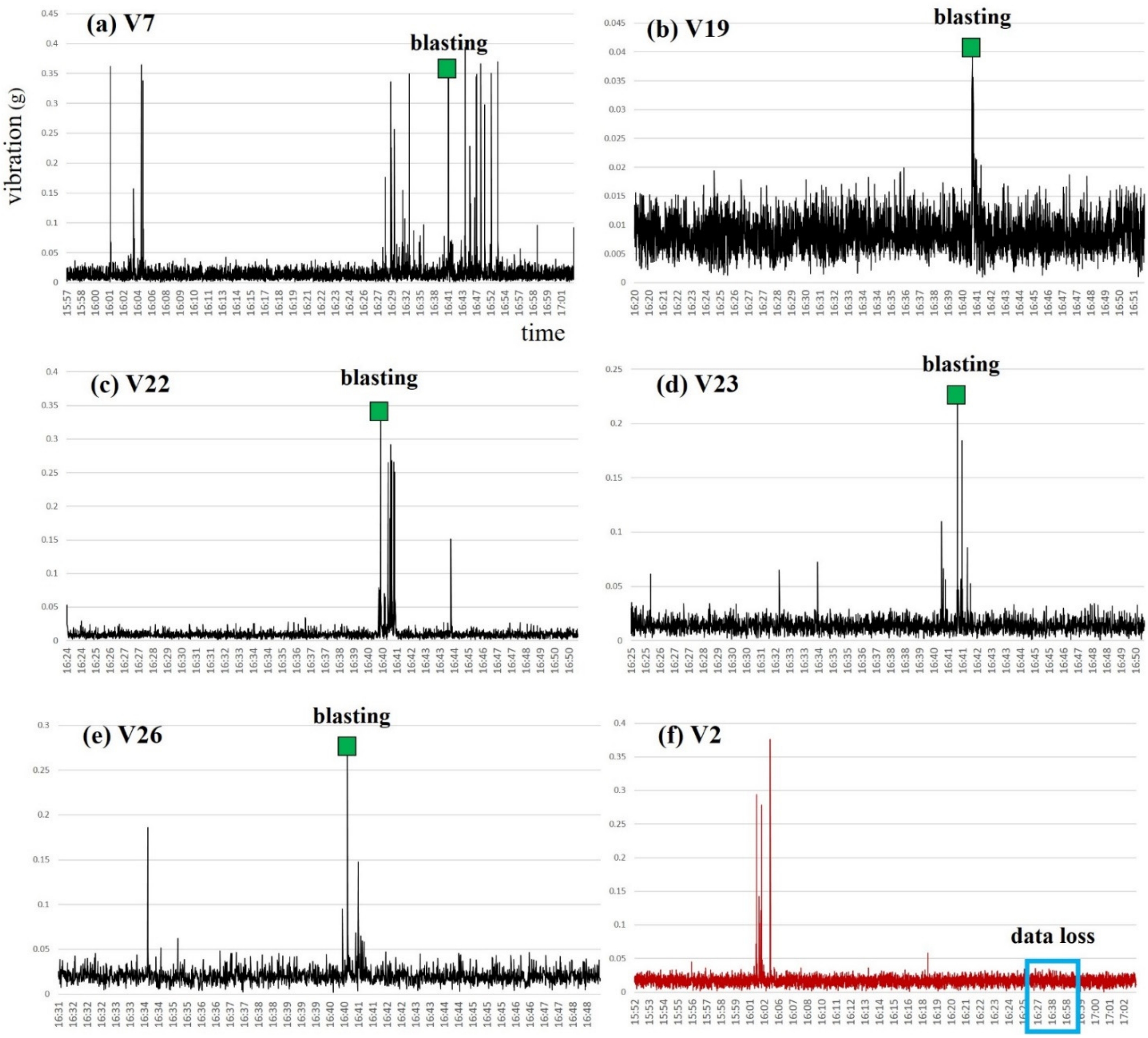

Figure 7. Graph of modules (**a**) V7, (**b**) V19, (**c**) V22, (**d**) V23, and (**e**) V26, where vibration was detected after blasting; and (**f**) graph of module V2 with missing data.

4.2. Dust Measurement Result

Fourteen dust measurement modules were numbered from D1 to D14, and the change in dust density after blasting was observed. Figure 8 shows the 1 min average trend of the measured dust density data for each module. Figure 8a shows the dust density of each module according to its standards. The larger the value, the redder it is, and the smaller the value, the greener it is. The measured value changes significantly in most modules before and after the blasting time. From approximately 4:40 pm, the blasting time, changes were detected from the D14 and D13 modules closest to the blasting point, and the dust density tended to increase sequentially in the direction away from the blasting point. Before the blasting began, the dust density decreased because the equipment was shut down and moved away from the blasting point. Figure 8b displays the dust density of all modules in color with the same standard. Modules farther from the blasting point (such as D1–5) have a low dust density, whereas modules closer to the blasting point (such as D11–14) usually have high values. In addition, the dust density increases earlier in the modules close to the blasting point.

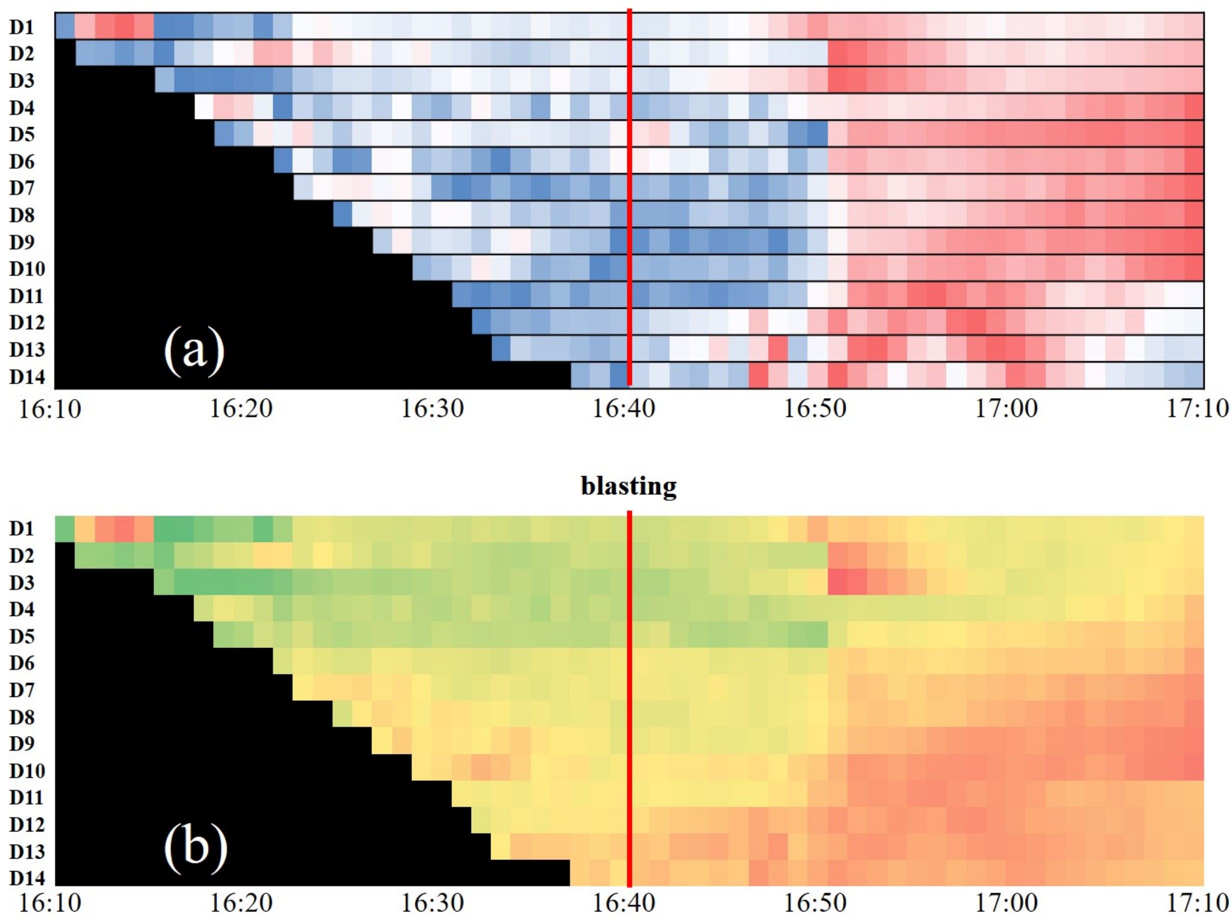

Figure 8. Measurement result of dust density. (**a**) Dust density change of each module and (**b**) distribution of overall dust density.

The dust density variations in each module are shown in Figure 9. They were classified into three groups based on their installation location. After blasting, the dust density increased in all modules; however, over time, the dust density began to decrease in modules such as D11–14 (Figure 9c). In these areas close to the blasting site, the dust density gradually stabilizes over time after blasting. In addition, modules such as D1–3 showed a tendency for dust density to increase and then rapidly decrease (Figure 9a). Because these points are far from the blasting point, they are considered to be less-affected by dust and are well-ventilated areas. However, modules such as D5–9 show an increasing tendency in dust density owing to the slow influence of the blasting point.

Figure 10 shows the results of visualizing the dust density measured in each module using ArcGIS Pro, a geographic information system software. The dust density values before and after blasting were shown at 5 min intervals, and the spatial distribution was predicted using the inverse distance weighting technique, an interpolation method. The dust density gradually increases even at a location away from the blasting point. The dust density increased immediately after blasting but slightly decreased over time. Owing to the short-monitoring time, there was no noticeable reduction in dust density. However, considering that the blasting occurred even before the start of monitoring, it was confirmed that the ventilation system was operating, and the dust density was relatively low.

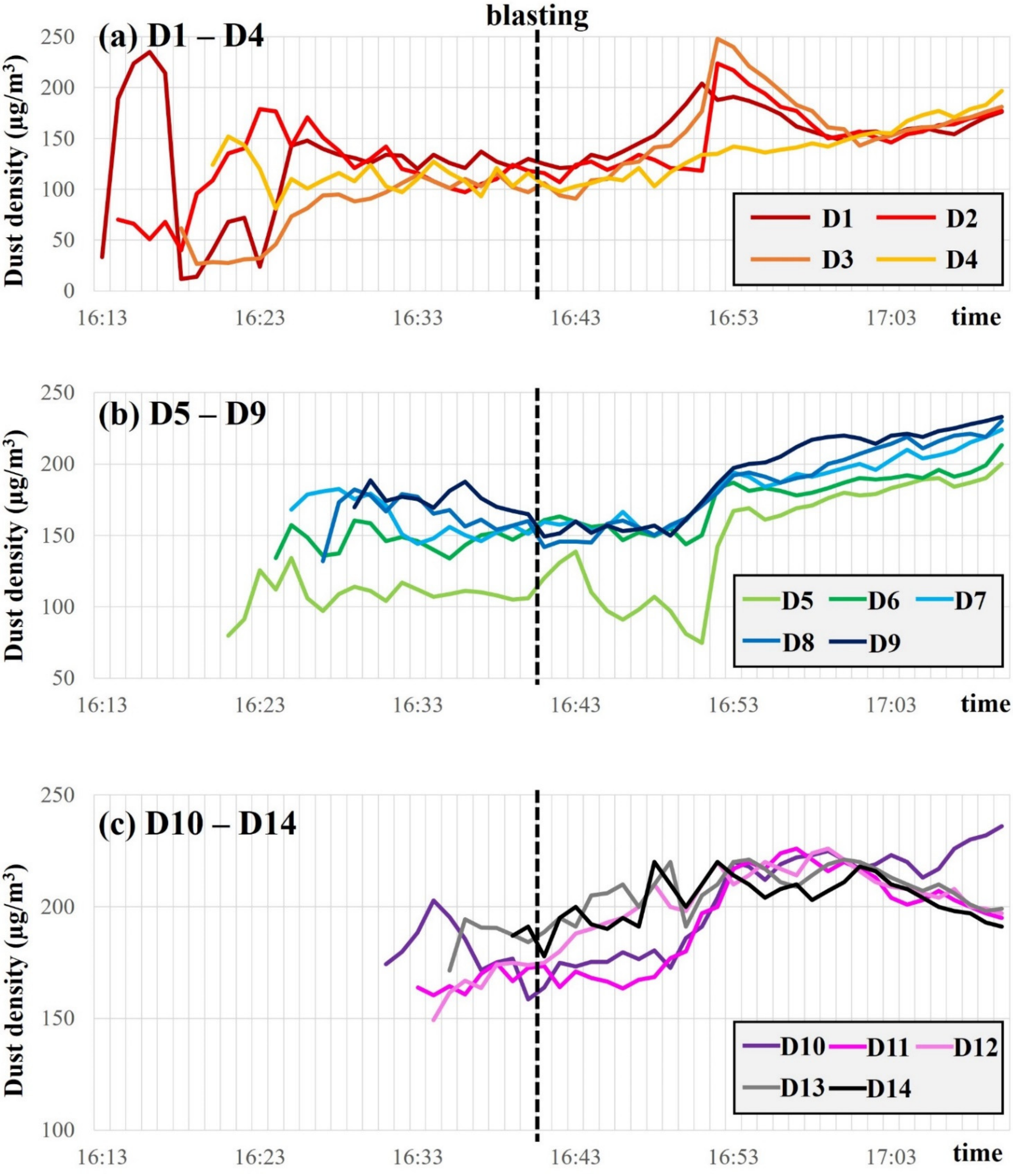

Figure 9. Chart of changes in dust density over time for all the modules. (**a**) D1–4 modules, (**b**) D5–9 modules, and (**c**) D10–14 modules.

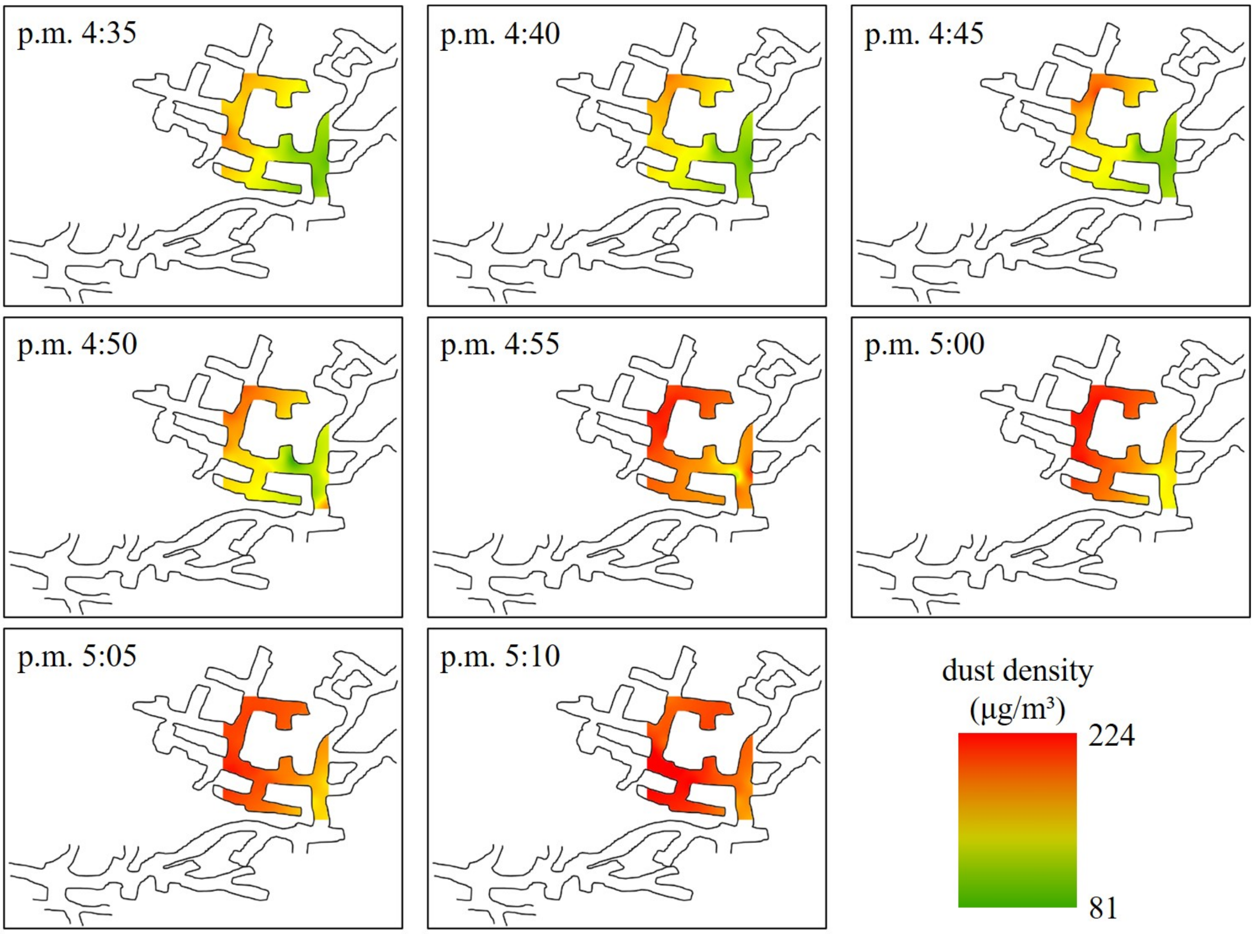

Figure 10. Spatial distribution of dust measurement results at 5 min intervals in the drift of Samdo Mine.

5. Discussion

In this study, data were acquired from all the sensor modules installed in an underground mine by constructing a WSN using ZigBee. After numerous experiments in the laboratory, and trial and error at the underground mining site, the applicability of the developed technology was improved. However, some modules still exhibited low network connection stability, depending on the installation location. To properly install a ZigBee-based sensor at an underground mining site and acquire stable data, we considered and improved on the following issues.

(1) The vibration measurement module was set as an end device to minimize power consumption in the preliminary experiment. Unlike a router, which can send and receive data, the end device can only transmit the acquired data. Therefore, the number of routers was small compared to that of the end device; hence, the network connection was easily disconnected, and data acquisition was unstable in some vibration measurement modules. To address this, in this study, the number of router modules was increased by setting the vibration measurement module as a router, and the communication stability was improved.

(2) In the preliminary experiment, by setting the vibration measurement module as an end device and applying the sleep mode, the battery life was increased, compared to supplying power at all times. However, when the power was turned off and on during the sleep mode, the connection to the WSN was weaker than when the power was constantly supplied. The stability of the network is generally low in underground mines compared to laboratories. Because the underground power supply is a crucial issue, if a permanent power supply is impossible, it is necessary to consider a method

of reducing battery consumption in sleep mode. However, for this, it is a prerequisite to maintain a stable network through the optimal arrangement of modules.

(3) The sensors were arranged as linear or branched, considering the shape of a long mine shaft. Although the arrangement of the sensors appears to be a simple linear arrangement, in reality, multiple sensors can be directly connected to each other because the distance between adjacent modules was approximately 30–50 m. However, it is not possible to form a complex network. Increasing the number of router modules can be a solution to configure a more stable network. Thus, the stability of the network can be maintained even if the intermediate node does not function properly; however, this means that the required capital increases. Moreover, if continuous power supply through wires is difficult, it increases the number of devices to be replaced with batteries. Therefore, we must determine the optimal module arrangement by simultaneously considering the stability of the network, budget, and power supply possibility.

(4) Owing to the nature of ZigBee, only one coordinator module can exist in a network, and the data transmitted from each node is concentrated in the coordinator module. Therefore, because there are many sensor modules in one network, the data load increases and may exceed the limit that can be processed by the coordinator. To solve this problem, there is a method for configuring multiple networks by increasing the number of coordinators, and the data load can be reduced by adjusting the sampling rate. Increasing the number of coordinators can be an effective method, but it requires multiple storage devices to be installed underground. Adjusting the sampling rate is useful when acquiring data at short intervals is unnecessary; however, in the opposite case, it is less useful. Therefore, we must select the optimal number of coordinators and sampling rate according to the purpose of monitoring and the environment of the underground mine.

(5) Regardless of how well the network is configured, communication cannot be fully performed if the power of each device is insufficient. The XBee module operates at a voltage of 3.3V, but the required power increases when a microcontroller, such as an Arduino or other sensors, is connected. Therefore, we must determine whether the battery system supplies sufficient power for communication. In the preliminary experiment, the XBee S2C product was used, but in this study, it was replaced with the XBee 3 Pro product to improve communication performance.

(6) Although electromagnetic waves can be partially transmitted over obstacles, owing to diffraction and reflection, they are emitted along a straight path. Therefore, it is important to secure LOS between devices for smooth communication. Because the underground mine is surrounded by solid rock walls, the LOS must be secured such that there are no obstacles between the modules. However, it was difficult to fully consider the communication range and LOS of the module because the installation work was conducted depending on the paper map and intuition of the installer in a dark and inconvenient environment. Therefore, if 3D modeling and LOS analysis of underground tunnels are performed in advance, a more effective network can be built.

6. Conclusions

This study developed a low-power, low-cost module for monitoring vibration and dust density in an underground mine using an XBee module, accelerometer, and dust sensor. The manufactured module was installed along the drift of Samdo Mine located in Dogye-eup, Samcheok-si, Gangwon-do, and the vibration and dust density were measured before and after blasting. Therefore, we could collect data on changes in vibration and dust density, even at a distance of 400 m or more from the blasting point, and it was confirmed that data from multiple points could be simultaneously acquired even in an underground environment where connecting to an external communication network is difficult. After blasting, the dust density increased in all the modules. However, depending on the location where the module was installed, the dust density trend varied with time. In some modules, the stability of communication deteriorated slightly. To solve this problem, maintaining more-stable power or increasing the number of router modules is required. In addition, increasing the number of coordinators or adjusting the sampling rate may be considered for establishing a stable network. However, because this choice is directly related to the cost, various attempts are required to make the optimal choice. Additionally, we must consider installing a large-capacity battery or improving the battery efficiency of the module. To build a stable network, we must secure an LOS between the modules. Therefore, if 3D modeling and LOS analysis of underground mines are performed in advance, modules can be installed at more-effective points. If light detection and ranging (LiDAR) is used in the field, obstacles can be analyzed in real-time, and appropriate installation points can be identified. In a future study, we intend to analyze the optimal module-installation points for a complete network using LOS analysis. In addition, we aim to visualize the monitoring results in real-time through a dashboard to more intuitively understand the environment in an underground mine. If the acquired data are learned through machine learning technology and dangerous areas are identified in advance, this can help prevent potential risks in underground mines and improve the working environment. Because this study can be constructed with low power and cost, it can be applied to relatively small and poor underground mines and used as basic research for a safe environment.

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Abbreviations and Symbols

The following abbreviations are used in this manuscript:

DPM	diesel particulate matter
GPRS	general packet radio service
GSM	global system for mobile communications
IoT	Internet of Things
LiDAR	light detection and ranging
LOS	line of sight
MEMS	micro-electromechanical system
NFC	near-field communication
RF	radio frequency
WSN	wireless sensor network

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