Smart Structures and Systems, *Vol. 30, No. 5 (2022) 433-446*
https://doi.org/10.12989/sss.2022.30.5.433

Wireless safety monitoring of a water pipeline construction site using LoRa communication

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(*Received August 31, 2021, Revised July 18, 2022, Accepted August 4, 2022*)

Abstract. Despite efforts to reduce unexpected accidents at confined construction sites, choking accidents continue to occur. Because of the poorly ventilated atmosphere, particularly in long, confined underground spaces, workers are subject to dangerous working conditions despite the use of artificial ventilation. Moreover, the traditional monitoring methods of using portable gas detectors place safety inspectors in direct contact with hazardous conditions. In this study, a long-range (LoRa)-based wireless safety monitoring system that features the network organization, fault-tolerant, power management, and a graphical user interface (GUI) was developed for underground construction sites. The LoRa wireless data communication system was adopted to detect hazardous gases and oxygen deficiency within a confined underground space with adjustable communication range and low power consumption. Fault tolerance based on the mapping information of the entire wireless sensor network was particularly implemented to ensure the reliable operation of the monitoring system. Moreover, a sleep mode was implemented for the efficient power management. The GUI was also developed to control the entire safety-monitoring system and to manage the measured data. The developed safety-monitoring system was validated in an indoor testing and at two full-scale water pipeline construction sites.

Keywords: confined underground space; fault tolerance; LoRa communication; mapping information; underground construction site; wireless safety monitoring

1. Introduction

Health and safety protocols to reduce disasters at construction sites are widely implemented. However, given the complex and dynamic nature of these working environments, accidents continue to occur (Carbonari *et al.* 2011, Pinto *et al.* 2011, Sakhakarmi *et al.* 2021, Lee *et al.* 2009). According to the Occupational Safety and Health Administration (OSHA) of the USA, worker fatalities in the construction industry accounted for 20.7% of total worker fatalities in private industries in 2017 (OSHA 2019). In South Korea, accidents at construction sites account for 49.9% and 29.2% of the total fatal and non-fatal industrial accidents, respectively (KOSHA, Korea Occupational Safety & Health Agency 2018). In 2018, accidents at construction sites accounted for one-quarter of the total number of accidents in all Korean industries. Therefore, construction is considered one of the most dangerous industrial fields.

Accidents related to confined construction sites account for a relatively high proportion of all accidents, despite continuous efforts to reduce them (Burlet-Vienney *et al.* 2014, 2015, Selman *et al.* 2018). In particular, asphyxiation, which occurs because of a deficiency in the supply of oxygen and occurrence of hazardous gases, remains the main cause of the high fatality rates in confined spaces, accounting for 73% of all choking accidents (Lee *et al.* 2016) and 42.6% of deaths in the construction field (KOSHA 2017). Although artificial ventilators are used to prevent accidents, workers are still subject to dangerous conditions because of site factors, such as limited or restricted entrances and exits and small spaces over long distances that create poorly ventilated environments. The KOSHA has suggested monitoring the oxygen and hazardous gas concentrations in confined spaces before and during construction in these areas (KOSHA 2017). Nevertheless, current monitoring systems rarely reflect the real-time conditions of confined spaces. These systems rely on traditional monitoring methods in which a safety manager proceeds to the site and performs periodic measurements using a portable gas detector. Therefore, to prevent accidents caused by oxygen deficiency and hazardous gases, an efficient monitoring method must be developed.

For the safety monitoring of confined underground spaces, which usually encompass long distances, such as

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http://www.techno-press.org/?journal=sss&subpage=7
ISSN: 1738-1584 (Print), 1738-1991 (Online)

water pipelines and metro tunnels, the use of the wireless sensor network (WSN) technique has considerable advantages over traditional monitoring methods. WSNs are composed of several independent sensors that enable wireless communication; therefore, data acquisition from different locations throughout a structure can be conducted without wire installation (Aliyu and Sheltami 2016, Abdulkarem *et al.* 2020, Noel *et al.* 2017, Sofi *et al.* 2022). In addition, the scale of a WSN system, such as the number of integrated sensors and complexity of the network topology, can be adjusted according to the environmental conditions of a confined space. Furthermore, wireless sensors are versatile and can be designed to acquire different measurements; the detection of hazardous gases is one of the important applications of wireless sensors (Chraim *et al.* 2015, Deshmukh *et al.* 2018, Ramya and Palaniappan 2012). Hence, it is efficient to apply the WSN technique when monitoring confined underground spaces, especially in terms of the data acquisition and scale flexibility. However, as confined underground spaces generally create harsh environments for wireless communication sensing and thus hinder the usefulness of the WSN technique, the network configuration should be adequately considered.

To monitor confined underground spaces using the WSN technique, a site-specific configuration of the system is required. For example, the WSN technique integrated with building information modeling (BIM) has been utilized for the safety management of underground construction sites (Cheung *et al.* 2018). The developed WSN system enables remote monitoring of multiple locations inside a tunnel using a Zigbee network, providing a real-time safety status and spatial information through site BIM. Moreover, the WSN technique has been implemented for ambient environment monitoring in underground mines using the Zigbee network (Moridi *et al.* 2018, Pramanik *et al.* 2021, Ranjan *et al.* 2020). Effective parameters, such as the arrangement and localization of nodes and maximum distances between nodes, were investigated for a reliable Zigbee network in an underground mine. However, because each sensor node using the Zigbee network has a short transmission distance, a dense network with sensor nodes and routers must be deployed to achieve stable wireless communication. Indeed, a large-scale WSN system can be burdensome to manage because underground confined structures have restricted access to entrances and exits. Moreover, geometrical characteristics, such as curvature and bends along the structures, cause non-line-of-sight between nodes and consequently impair reliable wireless communication. Thus, because the nodes in a WSN should be properly placed according to the conditions of the underground confined space, short- or long-range communication and a combination of both are required to establish reliable wireless communication. In addition, fault-tolerant functions that prepare for any possible network failure caused by harsh sensing environments should be implemented for reliable operation of the WSN system.

In this study, a framework was developed for a long-range (LoRa)-based wireless safety monitoring system for confined construction sites that are threatened by hazardous gases. Therefore, the network organization, fault-tolerant features, power management, and graphical user interface (GUI) were outlined. The safety monitoring system was designed to transmit real-time gas concentration data and instructions for remote monitoring and control. For stable and reliable operation of the proposed system, fault-tolerant features with mapping information and a sleep mode were implemented for power management. Additionally, the GUI was presented to collect the received data and to control the platform for the safety manager on the ground. The designed safety-monitoring system was implemented for indoor testing to investigate its reliability with fault-tolerant features. Full-scale field testing using two replacement construction sites for water pipelines in South Korea was conducted to demonstrate the potential for real-world applications.

2. Design requirements

To develop a safety monitoring system for confined underground spaces, several design requirements that consider the environmental conditions, limitations, and practical problems of construction sites should be defined. KOSHA (2017) and OSHA (2015) standards regulate oxygen and hazardous gas concentrations because atmospheric hazards, including insufficient oxygen and toxic or flammable gases, are the main causes of accidents in confined spaces (Table 1). To ensure a safe atmosphere within a confined space, a safety monitoring system is required to measure real-time gas concentrations and transmit measured data to the main computer at the construction office. Then, a safety monitoring system is required to automatically evaluate and display the safety conditions of the working environment based on real-time measured data compared to those with standard concentrations. In addition, these were visualized as a GUI on the main computer to inform the safety manager of the real-time situations.

A few additional requirements, such as battery and network topology, should be considered to ensure efficient

Table 1 Standard concentrations of oxygen and hazardous gas at a confined space for work safety

Measured gas	Standard concentration	
	KOSHA*	OSHA*
Oxygen (O_2)	18–23.5%	19.5–23.5%
Carbon monoxide (CO)	Less than 50 ppm	Less than 35 ppm
Hydrogen sulfide (H_2S)	Less than 10 ppm	Less than 10 ppm
Methane and combustible gas	Less than 10%/LEL*	Less than 10 %/LEL

*KOSHA: Korea Occupational Safety & Health Agency; OSHA: Occupational Safety and Health Administration; LEL: Lower Explosive Limit

Table 2 Hardware specifications

Hardware	Specification
Core board	Version: 1.5 Dimensions: 73.5 × 51 × 13 mm; Weight: 20 g Microcontroller: ATmega1281 Frequency: 14.74 MHz SRAM/EEPROM/FLASH: 8 kB/4 kB/128 kB Power consumption (on/sleep): 17 mA/30 μA
Gas sensor board	Version: 3 Dimensions: 73.5 × 51 × 22 mm; Weight: 20 g Supports 16 different gas sensors
Gateway	USB-PC interface Dimensions: 71 × 28 × 6 mm
Gas sensor	Oxygen: 0–30% (calibrated ± 0.1%) Carbon monoxide: 0–25 ppm (calibrated ± 0.1 ppm) Hydrogen sulfide: 0–100 ppm (calibrated ± 10 ppm) Methane and combustible gas: 0–100%/LEL (calibrated ± 0.15%/LEL)
Communication module	Model: Semtech SX1272 Frequency: 900 MHz ISM bands Antenna: 4.5 dBi Range: 21 km (line-of-sight and Fresnel zone clearance), 2 km (non-line-of-sight going through buildings, urban environment)
Battery	6,600 mAh Li-ion, rechargeable

management of the safety monitoring system. The battery of the safety-monitoring system should last for a long time after installation. Furthermore, short- or long-range communication can be adjusted depending on the purpose of monitoring or the environment of the confined space. To satisfy these requirements, a LoRa wireless communication system that can reach up to 21 km with a low power consumption was adopted in the designed safety-monitoring system. Although the LoRa wireless communication system can reach long distances, the available communication range could be substantially reduced depending on the environmental conditions of the confined construction site. Moreover, a small number of nodes allows for a more efficient management in a confined space than a large number of nodes. Therefore, the line network topology in which the nodes are positioned along the length of the distance is considered the optimal network topology for monitoring a confined space. Because simple installation and extension of nodes are available in a line network, the distances between nodes and number of nodes can be controlled according to the network environment.

The design requirements of a safety monitoring system for confined underground spaces can be summarized as follows: (1) near real-time data acquisition and transmission, (2) automatic identification and visualization of safety conditions, (3) proper network topology tailored to monitoring the confined underground space, and (4) robust and efficient hardware/software systems for long-term operation. The detailed development of a safety-monitoring system that satisfies these design requirements is described in the following sections.

3. Hardware module configuration

To satisfy the design requirements described in the previous section, the sensor platform needs to be capable of implementing a LoRa communication module and required gas sensors with measurable ranges that cover the required standard concentrations (Table 1). Libelium Waspmote is a sensor platform that satisfies the aforementioned requirements and was, thus, used to develop the safety-monitoring system. This sensor platform includes a core board, gas sensor board, gas sensors, communication module, gateway, and battery. The detailed hardware specifications are listed in Table 2. The gas sensor board can implement the required gas sensors (i.e., oxygen, carbon monoxide, hydrogen sulfide, methane, and combustible gas sensors) with a measurable range that meets the safety standards described in Table 1. The communication module was LoRa with an antenna for the radio frequency band of 900 MHz and a 4.5 dBi gain, which can transmit data for up to 21 km, depending on the communication environment.

The line network employed in this study had three types of nodes—sensor, gateway, and relay nodes. The hardware configurations for each node are summarized in Fig. 1. The relay node allows stable communication because it improves the network connectivity between the gateway and sensor nodes or both sensor nodes. Thus, proper use of relay nodes in the line network helps with the robust transmission of data from each node without packet loss, even in long-distance monitoring. The sensor node measures gas concentrations periodically and then transmits the measured data to the gateway node. It should be noted that the sensor node incorporates the sensing and data

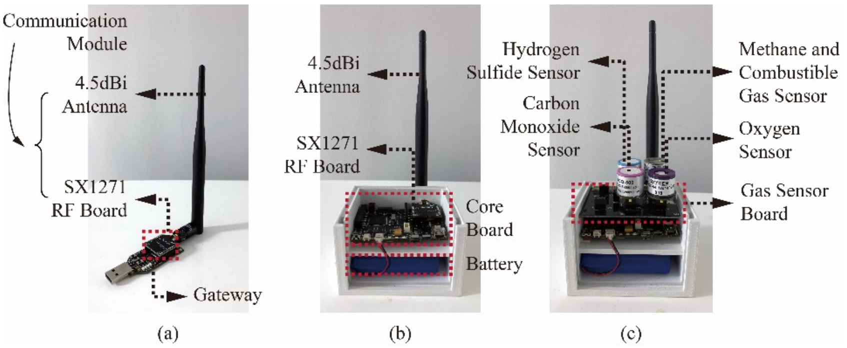


Fig. 1 Hardware configuration: (a) gateway node; (b) relay node; and (c) sensor node

processing added to the functions of the relay node. The gateway node is connected to the computer that enables control of the entire safety monitoring system and receives data, including gas concentrations and the current status of the relay and sensor nodes (e.g., battery level and network availability). The node status information can be used to maintain the gas monitoring system.

For the reliable operation of the developed safety monitoring system in the confined underground space, the number of relay and sensor nodes and the distances between the nodes should be properly configured in the line network topology. The system, including all relay, sensor, and gateway nodes, should be installed at the start of construction so that hazardous gases can be continuously monitored. Herein, only one gateway node is required to control the entire safety monitoring system and for the reception of data from the sensor and relay nodes. According to the purpose of monitoring, the sensor node should be installed inside the pipeline where monitoring of the oxygen and hazardous gas concentrations is required. Thereafter, the relay node should be placed to improve the network connectivity between the gateway and sensor nodes or both sensor nodes in the various environments of the confined underground space that causes non-line-of-sight between the nodes. Herein, the proper location of the relay node can be determined by changing its position between the nodes during on-site testing while the distances between the nodes does not exceed 2 km. In particular, because the sensor node includes the function of the relay node, the two can be installed interchangeably.

4. Operation and control system development

4.1 Overview

This section describes the software of the proposed safety-monitoring system in detail. The developed software consists of (1) network operating software embedded in each node, including the gateway, relay, and sensor nodes, and (2) a GUI running on a computer, which allows a human operator to interact with the safety monitoring system (Fig. 2). The network operating software mainly measures and collects gas concentrations. In addition, it features fault tolerance and sleep mode for stable and efficient monitoring. The first process of the safety monitoring system is network initialization, which boots the system and disseminates the network mapping information and operation schedule. Once the system is ready for operation, the sensor nodes start measuring the gas concentrations, and the measured data are delivered to the gateway node through the network. To effectively handle unexpected network failures during monitoring, fault tolerance is implemented to ensure the reliable operation of the monitoring system. Furthermore, the sleep mode, which turns off the sensor and relay nodes, is introduced into the software to avoid unnecessary battery consumption during off-work hours. The network operating software was developed in Waspmote Pro IDE, which was provided by Libelium for the development of the Waspmote software (Libelium Official Website).

As the second part of the operating software, a GUI was developed in MATLAB for efficient management of the measured data and to control the sensor network for users. The operation of the safety-monitoring system can be conveniently controlled using the GUI. For example, users can start and pause monitoring by pressing the start and stop buttons on the GUI. Moreover, users can provide orders, such as network initialization and scheduling. The GUI includes a function for displaying the measured gas concentrations from the sensor nodes as graphs and safety status bars. Furthermore, the remaining battery levels of all nodes in the WSN were collected in near real-time, enabling the effective management of the monitoring system.

For a stable WSN, the communication protocol of the designed safety monitoring system is based on an automatic repeat request. Every node transmits a packet using cyclic redundancy check codes to detect errors. When the packet is sent without errors, the receiver replies with positive acknowledgement (ACK). However, when an error is

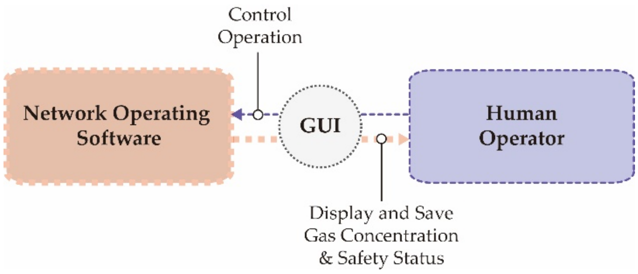


Fig. 2 Software composition

detected, the receiver sends a negative acknowledgement and requests retransmission. Herein, the maximum retransmission number was set to three to prevent packet collisions when the sensor node was trying to transmit the next sensing data during retransmission between relay nodes.

4.2 Network initialization

The arrangement of nodes in the network can be a useful guide for wireless communication. All nodes in the network are assigned unique node addresses as values contained in non-volatile memory (i.e., EEPROM). As the node address of each node does not change after designation, the arrangement of all nodes inside the confined space can be considered as the mapping of the WSN for communication (Fig. 3). Based on the mapping, each node can transmit measured data and its status, such as the remaining battery level and communication possibility, to its correct destination. For example, according to the mapping shown in Fig. 3 (i.e., 1-2-3-4), the relay node with address 2 transmits instructions from the gateway node to the relay node with address 3. In the case of the measured sensing data from the sensor node with address 4, the relay node with address 2 transmits data to the gateway node with address 1. Thus, as mapping provides useful information for wireless communication, once all nodes are installed in the designated locations, the gateway node is programed to start providing mapping to all nodes, thereby automatically enabling the nodes in the WSN to identify their destinations.

Network initialization involves two steps: (1) system reset and (2) assignment of the operational schedule. Before monitoring, the system resets all nodes in the WSN to initialize all variables in the flash memory. For stable initialization, when the gateway node sends the initialization command with mapping information, the nodes that are placed far away from the gateway node are sequentially reset. After a successful reset, the node transmits a confirmation signal with its node address to the gateway node. In the case of mapping, all information is saved in the EEPROM to continue communication even after the reset. However, if a node is unavailable for receiving the initialization command, the neighboring node sends information regarding the unresponsive node to the gateway node to verify the status of the node. It should be noted that the neighboring node uses the mapping table of the network to identify the address of the unavailable node. Once the unresponsive node is discovered, all remaining nodes are placed on standby until the gateway node sends another command. Thus, from the first step of the network initialization process, the condition of the WSN in the confined space can be identified.

The second step of network initialization is to send the operation schedule of the safety monitoring system, including the present time and duration of monitoring and sleeping. The gateway node transmits the schedule with a command that causes all nodes in the network to start monitoring. The sensor and relay nodes set the time and date on an internal real-time clock (RTC), which manages the alarms for sleep mode. For the sensor nodes, the sleep and operation durations, which were calculated from the GUI, were saved in the EEPROM. Based on the sleep and operation durations, the sensor nodes set an alarm to automatically wake up. In contrast to the first step, the settings are sequentially conducted from the nearest node to the gateway node to prevent the initiation of monitoring before all nodes are ready. After network initialization, the relay and gateway nodes wait for the sensor nodes to start measuring the gas concentrations.

4.3 Monitoring with fault tolerance

When the sensor node transmits measured data, the relay node gathers the data from the other nodes and sends the data with its remaining battery level to the neighboring relay node until the packet reaches the gateway node. However, because the failure of one node can affect the entire network system in the line network topology, fault tolerance is essential to prevent failure of the entire network and loss of measured data. In particular, the relay nodes are a main component of the stable network of the entire platform as they connect the gateway and sensor nodes or both sensor nodes. Therefore, fault tolerance is mainly developed to prevent the malfunction of relay nodes that have the following three functions.

The relay nodes are programmed to automatically determine the network directions depending on the received packets. Because the relay nodes receive various packets from other nodes before or during monitoring, the network directions should be changed according to the content of the packets for stable communication. For example, the relay nodes should deliver commands from the gateway node to the sensor nodes. By contrast, the relay nodes are required

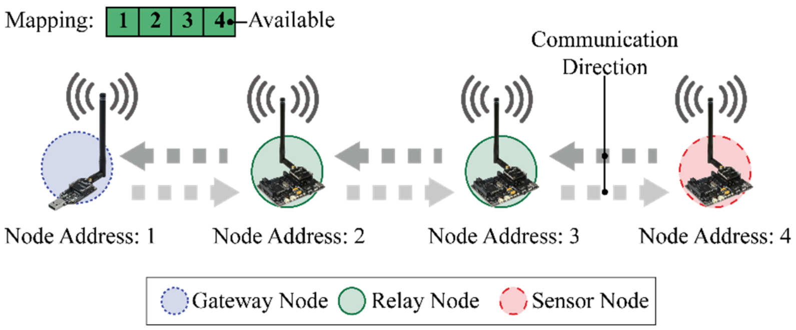


Fig. 3 Mapping of wireless sensor network in line topology

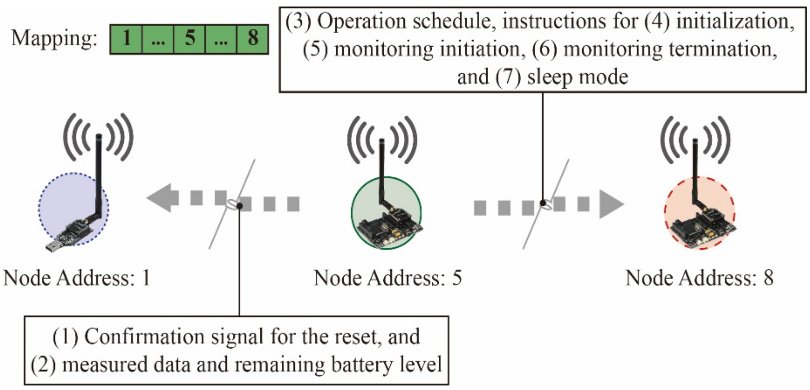


Fig. 4 Automatic decision of network direction according to packets

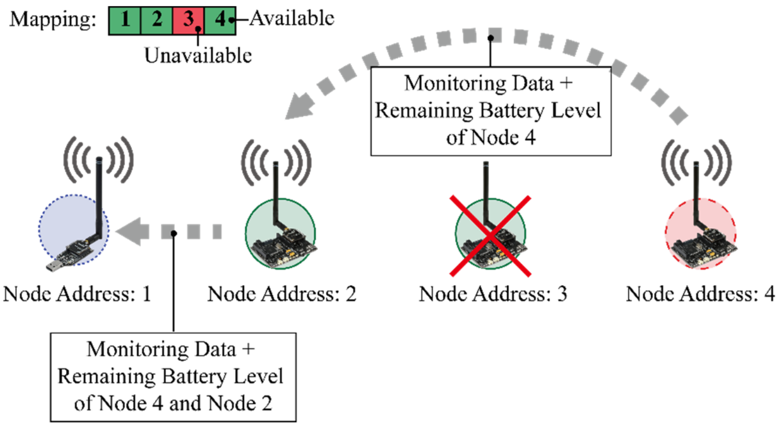


Fig. 5 Automatic transmission to possible neighboring nodes (i.e., fault tolerance)

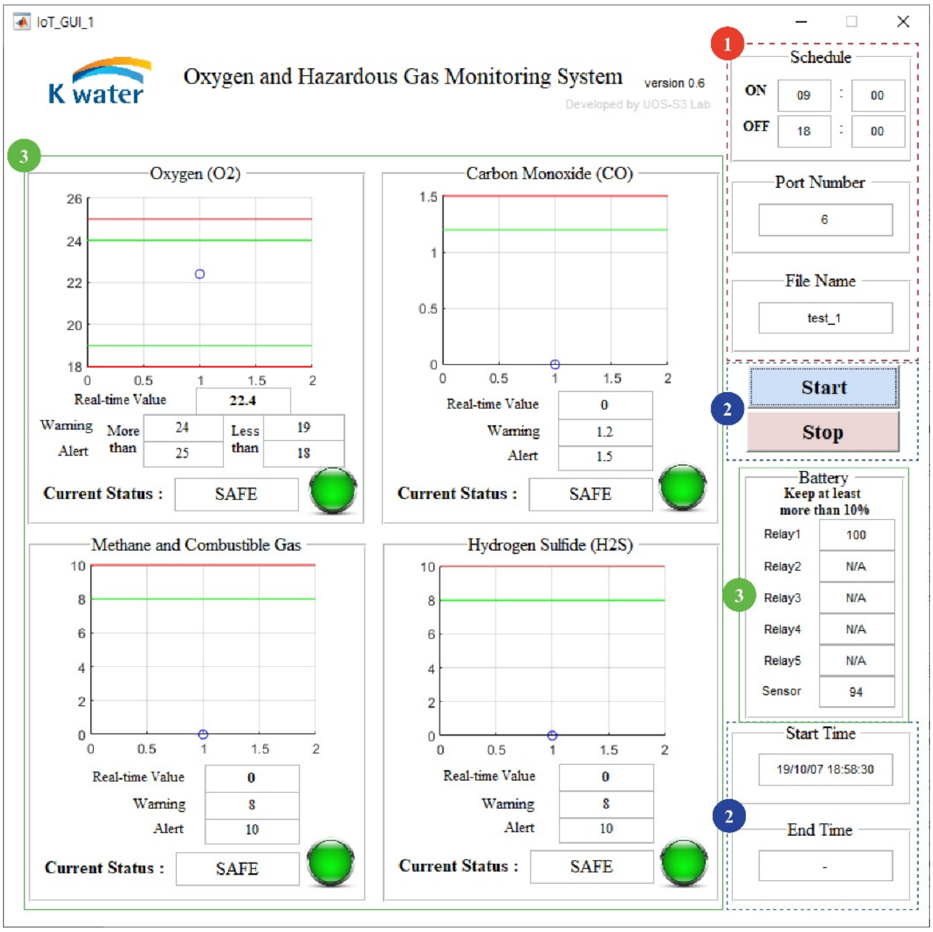
to convey the measured data from the sensor nodes to the gateway node. In this study, a fault-tolerance feature for the relay nodes was implemented to allow the network to operate the wireless communication robustly. The system was designed to work even when the relay nodes were unexpectedly reset during communication, which could cause all volatile information to be lost. It can take the necessary actions upon receiving a data packet. Seven cases for the packets that the relay nodes could potentially receive were considered when deciding on the network directions: (1) confirmation signal for the reset, (2) measured data and remaining battery level, (3) operation schedule, and the following instructions: (4) initialization, (5) monitoring initiation, (6) monitoring termination, and (7) sleep mode. According to the cases of the received packets, the relay nodes automatically decide on the network directions and send them to their destination based on the mapping information (Fig. 4).

To reduce packet loss during wireless communication, the relay and sensor nodes transmit packets to another possible node when neighboring nodes are unavailable for communication. The failure of a node in a line-type network can result in complete network failure unless properly handled. The operating systems of the relay and sensor nodes are designed to identify other responsive nodes when data transmission fails (Fig. 5). Because all nodes have the mapping information of the WSN, the operating system on each node can establish the route on which the data is delivered. It should be noted that redundancy of the relay nodes is necessary for a robust network operation.

For stable network communication, a relay node will reboot regularly if it does not receive any packets within a predefined duration. The relay nodes are set to be in the waiting status for the packets to be received. However, temporary hardware or software malfunctions may occur, resulting in a long lag in a relay node; rebooting on a regular basis can reduce such network errors. As the mapping and operation schedule are saved in the EEPROM of each relay node, the network operation can continue despite system rebooting.

4.4 Sleep mode

For efficient power management, a sleep mode that deactivates all sensor and relay nodes is implemented. The network operating system is designed to monitor for a fixed amount of time defined by the users at the initialization step. Once the operation time ends, a sleep command is disseminated to all the nodes in the network, allowing them to sleep until the wake-up time. In the designed safety-monitoring system, the relay nodes sleep only after the neighboring sensor nodes are deactivated. Finally, the sensor and relay nodes are reactivated at the appointed wake-up time. Unless the gateway node provides instructions, the sensor nodes continue measuring gas concentrations.



Schedule: ON 09 : 00, OFF 18 : 00
Port Number: 6
File Name: test_1
Oxygen (O2): Real-time Value 22.4; Warning More than 24, Less than 19; Alert More than 25, Less than 18; Current Status: SAFE
Carbon Monoxide (CO): Real-time Value 0; Warning 1.2; Alert 1.5; Current Status: SAFE
Methane and Combustible Gas: Real-time Value 0; Warning 8; Alert 10; Current Status: SAFE
Hydrogen Sulfide (H2S): Real-time Value 0; Warning 8; Alert 10; Current Status: SAFE
Battery (Keep at least more than 10%): Relay1 100; Relay2 N/A; Relay3 N/A; Relay4 N/A; Relay5 N/A; Sensor 94
Start Time: 19/10/07 18:58:30
End Time: -

Fig. 6 GUI of a safety monitoring system

To effectively manage the deactivation time of all nodes in the network, the monitoring end time of each node in the network can be formulated as follows

$$t_2^i = t_1^i + (t_2 - t_1) \tag{1}$$

where t_1^i and t_2^i are the monitoring start and end times of the i^{th} node in the network and t_1 and t_2 are the user-defined monitoring start and end times, respectively. As the safety monitoring system consists of several independent nodes in the network, each node starts monitoring at a different time, at approximately t_1. All sensor nodes in the network are programmed to conduct monitoring during time $(t_2 - t_1)$ so that the monitoring end time of each node can be estimated from Eq. (1).

4.5 GUI

The GUI running on the base station computer was developed to ensure that users could manage the data and control the safety monitoring system efficiently. The configuration of the developed GUI is illustrated in Fig. 6. As the gateway node and computer exchange data using serial communication, the GUI enables the management of measured data and controls the entire safety monitoring system. The GUI has three main purposes: (1) providing information before monitoring, (2) controlling the safety-monitoring system, and (3) displaying the measured data and safety status.

Before monitoring, information, such as the operation schedule, port number, and file name, should be provided. In the schedule section, the user must enter the operation schedule, which shows the start and end of the operation. Thereafter, the port number of the gateway node is required to allow a serial connection with the computer. The third part is to save the data in an Excel file with the specified name. The oxygen and gas concentrations, remaining battery level of each node, and received time were saved in real-time.

After entering all the information, the safety monitoring system is ready to start monitoring. Once the user presses the start button, the computer calculates the operation and sleep duration based on the input schedule and sends the calculated time with the present time to the gateway node using serial communication. The gateway node finally starts to send the initialization order with the mapping information to the relay node, and monitoring is performed. In addition, the stop button in the GUI terminates monitoring, and all nodes in the WSN are in the wait-status until another order from the gateway node is sent. At the initial and final time sections in the GUI, the time at which the user presses the start and stop buttons is presented.

During monitoring, the measured data delivered to the gateway node from each sensor node are displayed as graphs in the GUI. For the sensor node placed at the end of the WSN, the measured data are presented as the values under each graph. Based on the comparative analysis between the measured gas concentrations and the safety standards, the safety status of each gas, which has three states: safe, cautious, and dangerous, is denoted using letters and colors. In addition, as the green and red lines, which show the ranges of safety and danger, respectively, are described in the graphs, the user can evaluate the safety conditions of the locations where the sensor nodes are installed. Moreover, the remaining battery level of each relay and sensor node is shown as the value for efficient management of the safety monitoring system. As such, by using the GUI, the user enables control of the safety monitoring system and monitors the water pipeline, even without specialized knowledge and skills.

5. Experimental validation

The developed safety monitoring system was implemented in an indoor testing and at two full-scale underground water pipelines during rehabilitation construction. Indoor testing was conducted to investigate the reliability of the developed wireless safety-monitoring system with fault-tolerant features. Subsequently, the developed safety-monitoring system was tested at two full-scale underground construction sites with different testing environments: the first site, a pipeline that was 2 m in diameter and 1.7 km in length, was in Seoul, and the second site, a pipeline that was 1.3 m in diameter and 500 m in length, was in Gumi. The main purpose of the experimental validation was to investigate the reliability of the proposed safety-monitoring system. The accuracy of the measured gas concentrations was not evaluated because the gas sensors used were already calibrated, as described in Table 2.

5.1 Indoor testing for reliable system operation

Indoor testing was conducted to verify the reliability of the developed wireless safety-monitoring system with fault-tolerant features. The safety-monitoring system was composed of one gateway, three sensor nodes, and two computers. It should be noted that one computer is connected to node address 2 only for debugging purposes; it is not an essential component for network operations. Moreover, as the sensor node includes the function of the relay node, only the sensor nodes were placed so that all nodes communicate under the same conditions during the indoor testing. The corridor of the building was selected to form a line network of the developed wireless safety-monitoring system, and the nodes were placed 50 m apart (Fig. 7). To effectively test the fault-tolerance features implemented in the system, an artificial sensor failure was introduced (Fig. 7). During monitoring, the sensor node with address 1 was turned off to create a failure status.

The LoRa parameters were selected for wireless communication. The frequency channel was assigned as channel number 4, with a central frequency of 911.72 MHz. In addition, the first LoRa mode, which was a combination of three LoRa parameters, namely, bandwidth, coding rate, and spreading factor, was used. The parameters used are listed in Table 3.

Fig. 8 Shows the debug messages of the gateway and sensor nodes with address 2. All nodes in the WSN sent their data to the neighboring node with an automatic decision on the network direction based on the mapping information. As such, the sensor node with address 2 gathered the data from the sensor node with address 3 and sent the data to the sensor node with address 1. The debug message from the gateway node confirms that all the sensor nodes successfully transmitted the measured data to the gateway node (Fig. 8(a)). However, when the sensor node

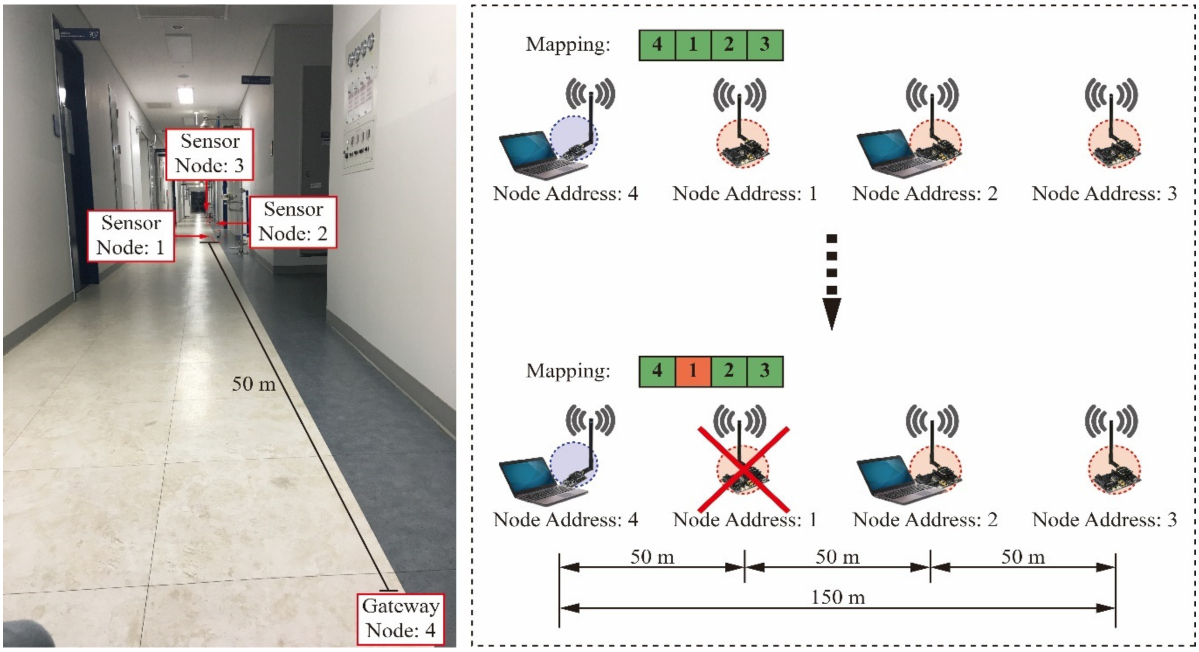
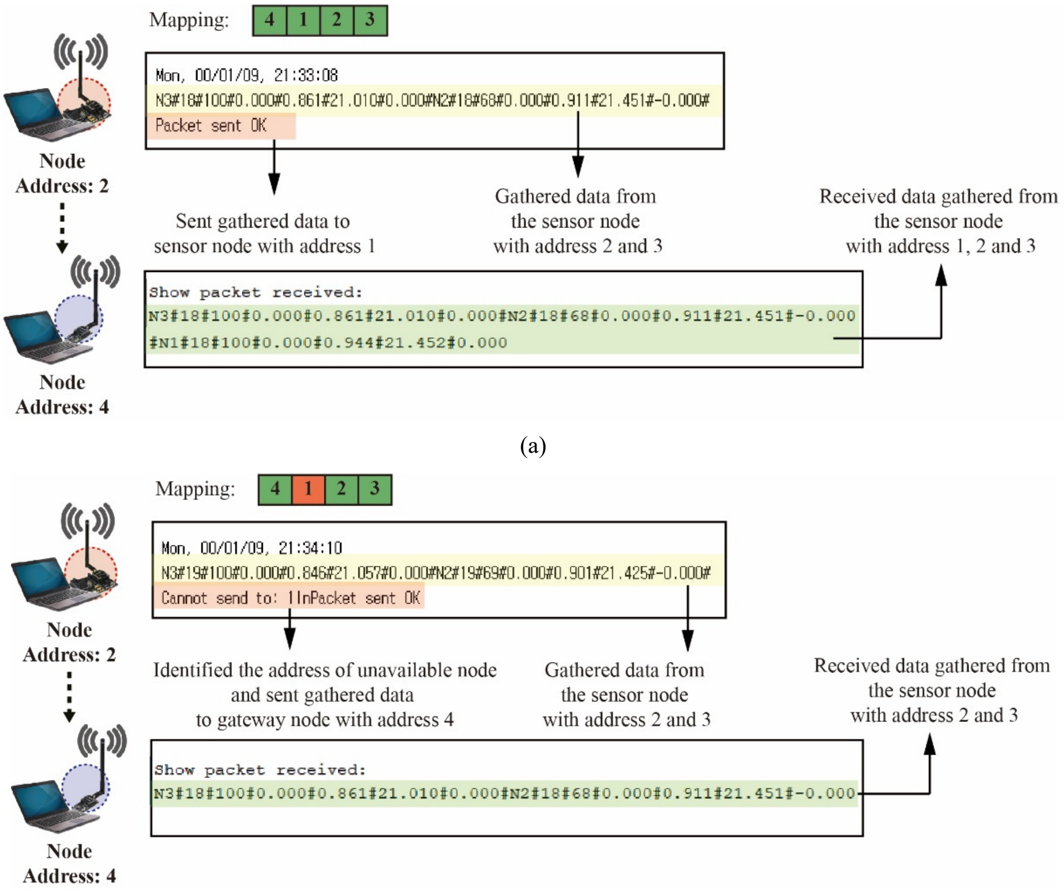


Fig. 7 Schematic configuration of experimental setup

Table 3 LoRa parameters of the first mode (Libelium Official Website)

Bandwidth	Coding rate	Spreading factor	Sensitivity (dB)	Transmission time (ms) for a 100-byte packet sent	Transmission time (ms) for a 100-byte packet sent and ACK received	Comments
125	4/5	12	−134	4245	5781	Max range, slow data rate



```
Mon, 00/01/09, 21:33:08
N3#18#100#0.000#0.861#21.010#0.000#N2#18#68#0.000#0.911#21.451#-0.000#
Packet sent OK
```

```
Show packet received:
N3#18#100#0.000#0.861#21.010#0.000#N2#18#68#0.000#0.911#21.451#-0.000
#N1#18#100#0.000#0.944#21.452#0.000
```

(a)

```
Mon, 00/01/09, 21:34:10
N3#19#100#0.000#0.846#21.057#0.000#N2#19#69#0.000#0.901#21.425#-0.000#
Cannot send to: 1InPacket sent OK
```

```
Show packet received:
N3#18#100#0.000#0.861#21.010#0.000#N2#18#68#0.000#0.911#21.451#-0.000
```

(b)

Fig. 8 Debug messages of gateway and sensor nodes with address 2: (a) when all nodes were available; and (b) when an artificial sensor failure was introduced

with address 1 was turned off, the sensor node with address 2 successfully identified the availability of the sensor node with address 1 by repeating the communication three times, and then automatically located another responsive neighboring node, which was the gateway node in this example (Fig. 8(b)). The results showed that the developed safety-monitoring system can handle sensor failures.

5.2 Field testing in the water pipeline (diameter: 2 m)

Fig. 9 illustrates the schematic configuration of the first construction site of the underground water pipeline in Seoul. The first underground water pipeline was a round steel pipe with a diameter of 2 m. The total length of the rehabilitation section was 1.7 km; however, the accessible section was only 1 km because the remaining section was under construction. Along the water pipeline, straight and curved sections and height differences, which cause non-line-of-sight between the nodes, existed. Air ventilators and gas sensors were installed at both ends of the water pipeline to manage the indoor air quality. The entrance was a steel box that was mainly closed during testing.

Because the location that required monitoring of oxygen and hazardous gas concentrations in the underground water pipeline was around the accessible section, the safety monitoring system was composed of one gateway node, two relay nodes, one sensor node, and a computer (Fig. 10). The gateway node was connected to a computer placed on the ground of the construction office. Two relay nodes were installed at the entrance of the underground water pipeline and 400 m from the entrance. Although the LoRa system can communicate within a range of 2 km in an environment with obstacles, two relay nodes were used and installed within a few hundred meters because several factors, such as non-line-of-sight between the gateway and sensor nodes

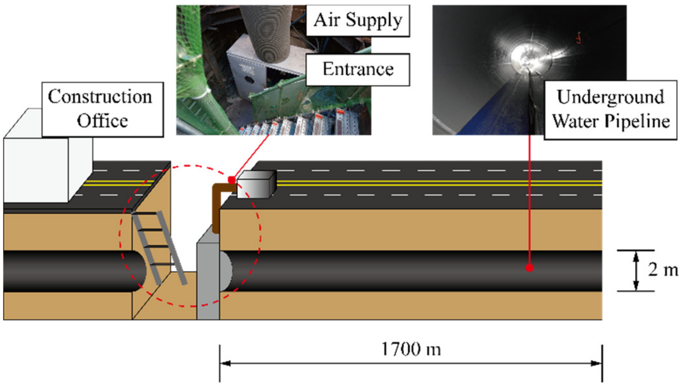


Fig. 9 Schematic configuration of first construction site of underground water pipeline

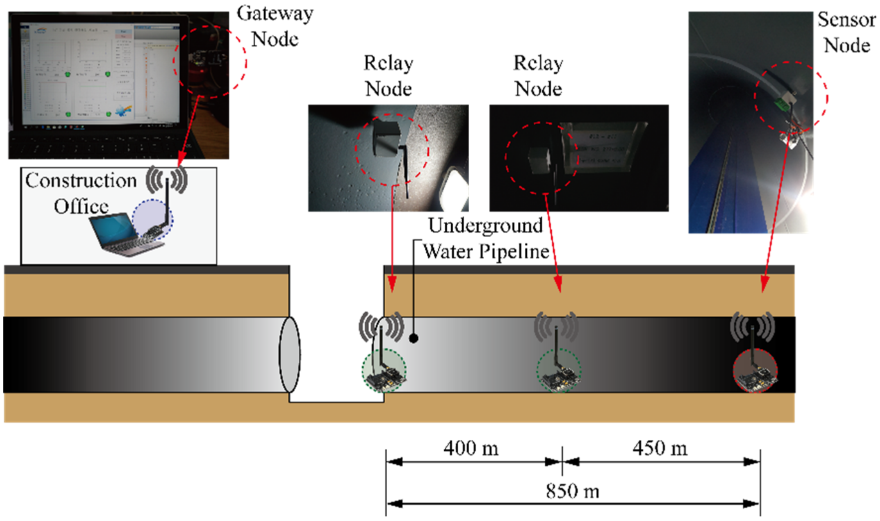
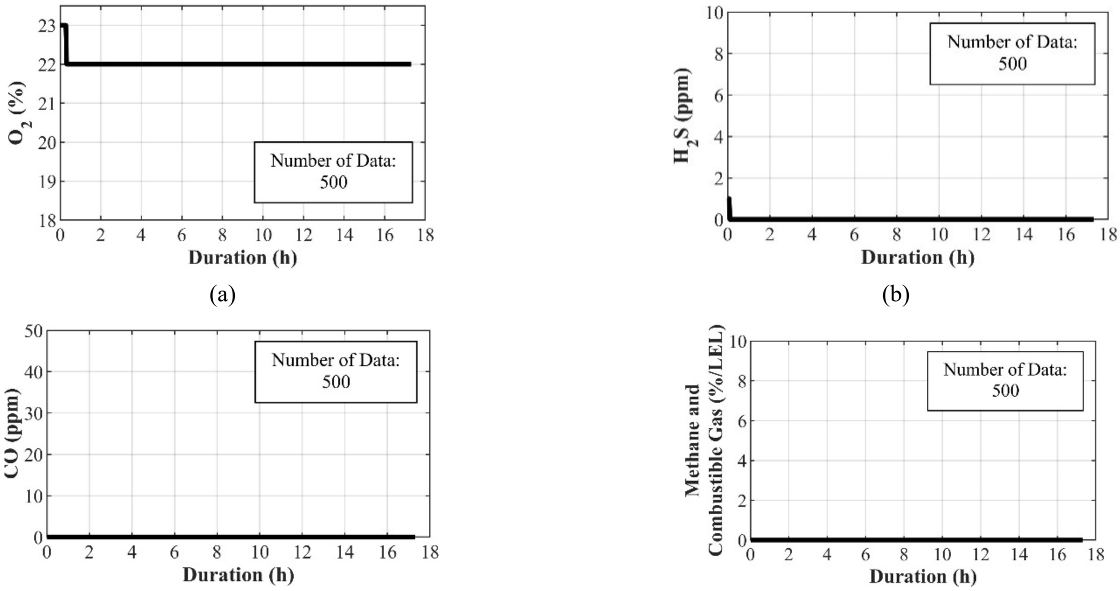


Fig. 10 Test set-up for monitoring underground water pipeline



(a) (b)

(c) (d)

Fig. 11 Oxygen and hazardous gas concentrations and number of data: (a) oxygen; (b) hydrogen sulfide; (c) carbon monoxide; and (d) methane and combustible gas

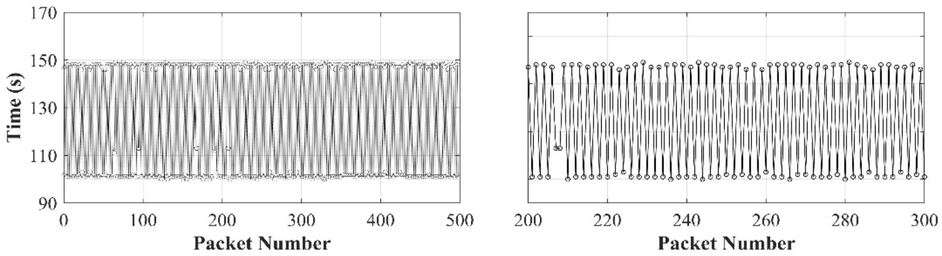


Fig. 12 Time between consecutively received data

and the shielding performance of the steel structure, can cause network jamming. The sensor node, which was placed 850 m from the entrance, was programmed to measure the oxygen and hazardous gas concentrations every 2 min for 500 times. Each node was installed inside waterproof enclosures and held on the side of the pipe with magnets to minimize operational interruptions and prevent any contact with water. The frequency channel and mode for the LoRa communication were the same as those in the first experimental case.

The developed safety monitoring system for the safety monitoring of underground water pipelines was validated based on the total number of measured data delivered to the gateway node and the time between consecutively received data. The delivered monitoring data and time between consecutive data points are described in Figs. 11 and 12. Although the water pipeline had curved sections and height differences, all measured 500 data were successively transferred to the gateway node without any packet loss (Fig. 11). Herein, a time delay of 10 s was observed, as the time between each received data tended to repeat between approximately 148 and 102 s (Fig. 12). Time delay can be caused by several environmental factors that cause wireless network jamming. It should be noted that the time periods between the received packets were approximately 110 s in a few cases because the packets were delivered on time, despite a time delay of 10 s during the previous data retransmission. Nevertheless, the developed wireless safety monitoring system successfully monitored the oxygen and gas concentrations and delivered the measured data to the gateway node without any packet loss, even with a relatively small number of nodes.

Fig. 13 shows the remaining battery level of the sensor node. The initial remaining battery level of the sensor node was 78% and showed a steadily decreasing rate during monitoring. It should be noted that the proposed system operated reliably, regardless of the remaining battery level as shown in Figs. 12 and 13. Because the battery consumption of the sensor node at approximately 17 h was 29%, the battery consumption during the operation time (i.e., approximately 12 h from 9 a.m. to 6 p.m.) was expected to be approximately 20%, which is available for four or five days without recharging the battery. Therefore, the developed safety monitoring system demonstrated the ability to monitor at a low battery consumption. Moreover, as the remaining battery level of each relay and sensor node can be monitored on the GUI, battery management is possible for an efficient performance of the developed safety monitoring system. This is suitable for monitoring locations that are unfavorable for wireless communication and real-time measurements.

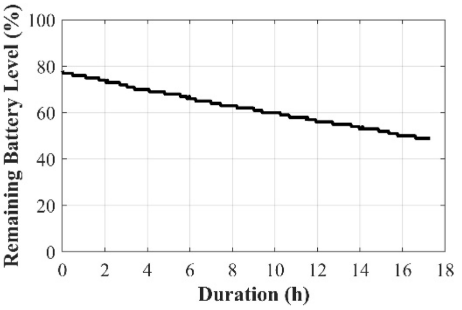


Fig. 13 Remining battery level of sensor node during the monitoring

5.3 Field testing in the water pipeline (diameter: 1.3 m)

The second construction site in Gumi is shown in Fig. 14. The second underground water pipeline was a round steel pipe with a diameter of 1.3 m and length of 500 m. In this case, the accessible section of the pipe was 100 m because the remaining sections were under construction. Along the 100 m water pipeline, only straight sections existed. An air ventilator was installed at one end of the pipe. There were no construction offices in this case.

The network configuration and the distances between the nodes were adjusted according to the environment of the water pipeline: as the location that required monitoring of oxygen and hazardous gas concentrations in the underground water pipeline was at the end of the accessible section, the safety monitoring system was composed of one gateway node, one relay node, one sensor node, and a computer (Fig. 15); the gateway node connected to the computer was placed on the ground; the relay and sensor nodes were installed at the entrance of the opposite pipe and 100 m away from the entrance. Herein, although the distance between the gateway and sensor node was short, as the accessible section was only 100 m, the relay node was placed to establish reliable wireless communication owing to the non-line-of-sight between the two nodes. Monitoring was programmed to start at 12:30 p.m. on July 4, 2018, and to enter sleep mode at 8:15 a.m. on July 5, 2018 (i.e., about 20 h of monitoring). The frequency channel and mode for the LoRa communication and monitoring interval were the same as those in the first case.

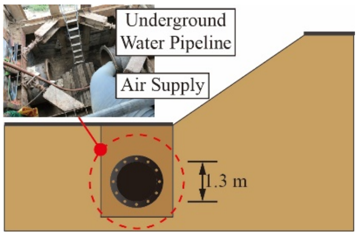


Fig. 14 Schematic configuration of second construction site of underground water pipeline

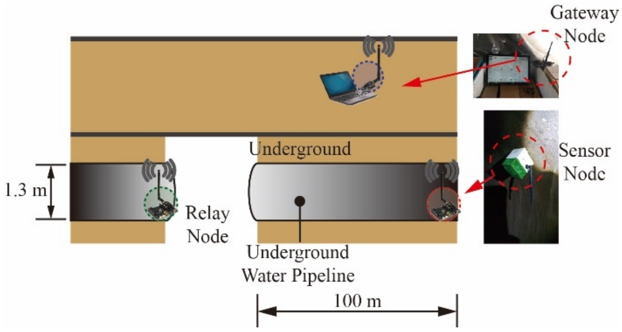


Fig. 15 Test set-up for monitoring of underground water pipeline

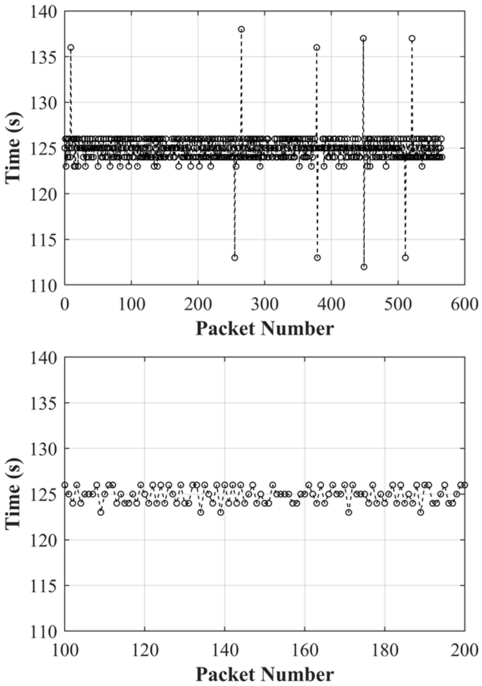


Fig. 16 Time between consecutively received data

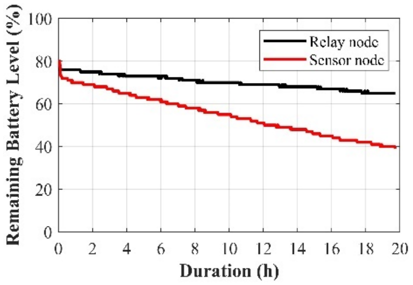


Fig. 17 Remaining battery level of sensor and relay nodes during the monitoring

The developed safety monitoring system was evaluated based on the number of measured data successfully transferred to the gateway node and the time between each received data point. The real-time data were reliably transferred to the gateway node without packet loss, although there was a time delay of approximately 10 s (Fig. 16). Moreover, the relay and sensor nodes in the proposed safety-monitoring system showed reliable functioning regardless of the remaining battery level (Figs. 16 and 17). As the battery consumption of the sensor node at approximately 20 h was 39%, the battery consumption during the operation time was expected to be approximately 24%, which was similar to the first case. For the relay node, the battery consumption at 20 h was approximately 11% and the expected battery consumption during the operation time was 6.6%. It should be noted that the battery consumption of the sensor node was approximately four times that of the relay node owing to the gas sensors, but the rate of decrease was at an acceptable level for monitoring the underground water pipelines.

Although the developed wireless safety monitoring system was shown to successfully operate in underground construction sites, site-specific configuration of the system is still required to establish a reliable wireless network in confined spaces with different diameters, curvatures, bends, and heights. During on-site configuration, the proper distances between the nodes can be determined by gradually increasing the distances between the two nodes at certain intervals until communication is possible. Moreover, if there are environmental factors that cause non-line-of-sight between two nodes, a relay node can be placed to improve the network connectivity between them. Herein, the relay node can be replaced by the sensor node as it incorporated the sensing and data processing added to the functions of the relay node according to the purpose of monitoring. Thereafter, the appropriate number of integrated nodes in the system is determined. Moreover, the number of retransmissions should be appropriately adjusted depending on the network environment so that packet collisions do not occur between the measurement intervals of each sensor node.

6. Conclusions

In this study, a safety-monitoring system for underground water pipelines was developed. To monitor the oxygen and hazardous gases inside the water pipeline using wireless technology, hardware modules that supported LoRa communication and required gas sensors were adopted, and gateway, relay, and sensor nodes were constructed. A line network topology was used to adjust the distances between the nodes according to environmental conditions. The operation and control systems of the safety-monitoring system were developed and divided into two parts: the main operator and the GUI. Network initialization, monitoring, and sleep mode functions were used for the main operator. During network initialization, the mapping information of the WSN was first provided with an initialization order to prepare for monitoring. The operation schedule, present time, and date were set based on the internal RTC of each node. During monitoring, fault tolerances were considered to minimize packet loss using the mapping information in the line network topology. In addition, for efficient power management, the sleep mode was used to deactivate all switches and modules during off-work hours. Finally, the GUI was developed to simplify the control of the safety monitoring system and management of the measured data for the users.

The developed-safety monitoring system was validated through indoor testing and two field testing. Indoor testing was conducted to investigate the reliability of the developed safety-monitoring system with fault-tolerant features, and the results demonstrated the successful handling of sensor failure. Thereafter, the developed safety-monitoring system was implemented at two full-scale underground water pipelines with different diameters and lengths during rehabilitation construction. Herein, the network configuration and distance between the nodes were properly adjusted according to the environment of the water pipeline. Although several environmental conditions can cause wireless network jamming, the measured data from the sensor node were successfully transferred to the gateway node without packet loss, even with a small number of nodes and low battery consumption. Moreover, the GUI allowed the efficient control of entire developed safety-monitoring system and management of measured data. Therefore, the developed safety-monitoring system can monitor the concentrations of oxygen and hazardous gases in the confined underground spaces, which are unfavorable environments for wireless communication and real-time measurements.

Acknowledgments

This research was supported by a research project (Development of Internet of Things (IoT) platform for improving the safety management of construction sites, project manager: Mr. Sung-Hoon Yoon) of the Korea Water Resources Corporation (K-water) and National Research Foundation of Korea (NRF) grant funded by the Korean government (MSIT) (NRF-2020R1A2C2014797).

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