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Underground Infrastructure Management System using Internet of Things Wireless Transmission Technology

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SUMMARY This paper presents a water leakage monitoring system that gathers acoustic data of water pipes using wireless communication technology and identifies the sound of water leakage using machine leaning technology. To collect acoustic data effectively, this system combines three types of data-collection methods: drive-by, walk-by, and static. To design this system, it is important to ascertain the wireless communication distance that can be achieved with sensors installed in a basement. This paper also reports on radio propagation from underground manholes made from reinforced concrete and resin concrete in residential and commercial areas using the 920 MHz band. We reveal that it is possible to design a practical system that uses radio communication from underground sensors.
key words: *IoT wireless access networks, 920 MHz Band, Propagation from underground manholes, IoT services*

1. Introduction

The number of sensors and terminals connected to public networks has been rapidly increasing and will increase to 20.8 billion units by 2020 [1] as shown in Fig. 1. The research and development of Internet-of-Things (IoT) related technology has also become active [2]–[5]. Because wireless communication technologies have very important roles in IoT systems, various wireless systems for connecting IoT terminals to a network have been proposed such as IEEE 802.15.4g [6], ARIB STD-T108 [7], SIGFOX [8], LoRa WAN [9], and NB-IoT [10]. Some use the 920 MHz band, which is preferred for wireless data communication.

One of the leading applications of IoT related technology is logistics systems. Hundreds of pallets, which are boards for transporting goods, are carried by trucks every day. A typical pallet-rental company stores over 10,000 pallets. Conventionally, passive radio frequency identification (RFID) tags have been used for pallet management [11], [12]. However, the readers must be very close to the pallets to read passive RFID tags and large gates are needed for reading the tags attached to the pallets. In addition, passive tag readers often fail to read tags, resulting in the loss of a large number of pallets annually. Research on active RFID tags, which is one solution to the above problem, has been conducted. For example, active RFID tags using the ultra-high frequency (UHF) band have been studied regarding child protection [13] and health management using pedometers [14].

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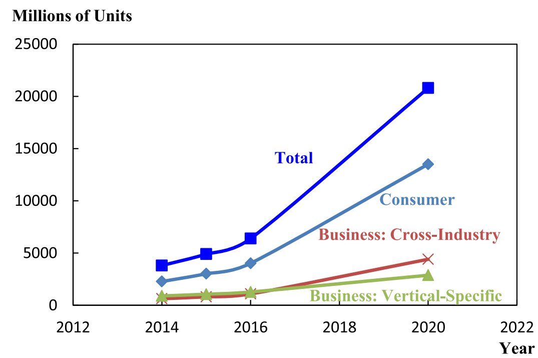

Fig. 1 Predicted number of IoT terminals.

One of the leading applications of IoT related technology is the smart meter system. Smart meter systems that automate monthly meter readings and visualize electricity consumption in a household energy management system (HEMS) have been introduced by various power companies [15], [16]. For example, TEPCO has a plan to switch wattmeters to smart meters by 2020 [17]; automation of gas meters and visualization of gas consumption are also being addressed. The U bus air system has been standardized by the Japan Utility Telemetering Association, which is aiming to build a network of connected gas meters [18], [19].

To expand the application potentiality of IoT services, it is necessary for sensors to have extremely long battery life and for system cost to be low. Therefore, NTT has been researching and developing high-capacity protocols that can accommodate many terminals and technologies to extend the battery lifetime of terminals [20]–[22]. These protocols, one for a physical distribution pallet management system and one for a wide-area and high-capacity radio relay system for smart metering service, have the following advantages.

- A wide area ubiquitous network, which is a star type wireless system having a single access point supporting a large number of wireless terminals over a wide spatial domain
- A wide area, large capacity wireless relay system using a multi-layer star wireless system
- A new high capacity protocol supporting more than 10,000 terminals

NTT has also been developing a system to monitor underground infrastructures [23]. To design this system, radio propagation data from underground manholes is necessary. Although there have been reports on radio wave propagation from underground manholes using the 430 MHz band [24]–[26], there are not enough examples of propagation at the 920 MHz band.

In this paper, we introduce a water leakage monitoring system that we are developing and report on radio wave propagation from underground manholes using the 920 MHz band. Section 2 of this paper introduces this system. Section 3 explains the experiment method of propagation from manholes. The experimental results are presented in Sect. 4.

2. Water Leakage Monitoring System

Generally, it is said that the useful lifetime of a water pipe is 40 years. However, under severe financial conditions, the annual pipeline renewal rate has remained at only 0.7% [27]. Therefore, the percentage of water pipes over the age of 40 continues to increase. In 2015, the length and percentage of water pipes over 40 years old in Japan are about 90,000 km and 14% as shown in Fig. 2 [28]. As the deterioration of the pipes progresses, the risk of water leakage increases. Figure 3 shows a water pipe that has a hole due to aging.

Some leakage accidents cause great economic loss, with recovery costs amounting to more than several hundred million yen [29]. Human injury may also occur. Understanding the damage situation of water pipes is necessary in order to restore them. Because water pipes are usually located underground and difficult to directly observe, special skills are required to understand the situation of buried water pipes. However, the number of skilled engineers is expected to decrease greatly over the next ten years in the water industry because the percentage of staff in their 50s is about 40% [30]. For this reason, social infrastructure maintenance and management using IoT technology and AI technology is necessary. A system that collects data efficiently from low-power sensors installed in basements and contributes to the maintenance and management of conduits is currently being investigated [22].

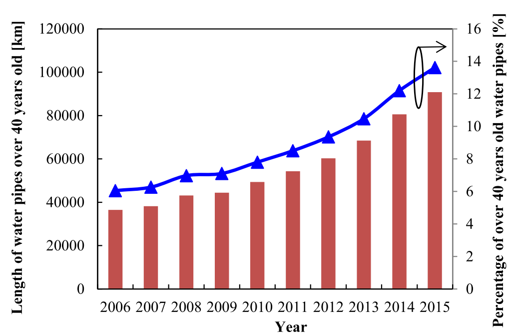

Fig. 2 Length and percentage of water pipes that are over 40 years old in Japan.

Fig. 3 Water pipe over 40 years old.

Figure 4 shows a schematic diagram of our developing water leak monitoring system. In Japan's water supply pipeline, a stopcock and fire hydrant are usually installed every several tens of meters. The current method of investigating water leakage involves opening the lid of a manhole (valve box) in which the stopcock or the like is installed, after which a skilled technician listens to the sound and judges the presence or absence of water leakage. In our system, a sensor terminal driven by a battery is installed in the valve box. To prolong the battery life for about 5 to 10 years, the sensor is normally in a sleep state and activated periodically to sense the sound from the water pipe. Saved data need to be gathered periodically, but in a big city the water supply pipeline will be several thousand kilometers long and monitored at one- to two-year periods, so an efficient collection method is required. Therefore, in this system, three types of data-collection methods are being studied.

One is a drive-by data-collection method. The data are collected through wireless communication when an automobile that has an access point passes by a valve box installed with a sensor terminal (see Fig. 5). In this method, it is important to send the data from each sensor during the short time the car is passing by the valve box.

The second method is a walk-by data-collection method that uses portable access points to cover environments where it is difficult to use cars (see Fig. 6). In this method, it is important to send the data from each sensor quickly to collect data from many valve boxes.

The third is a static data-collection method that permits

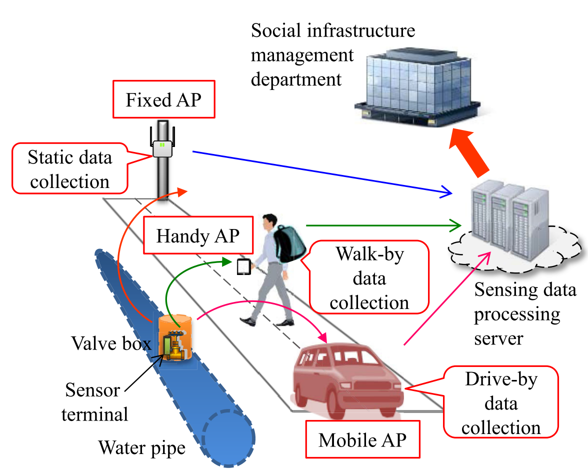

Fig. 4 Proposed system configuration.

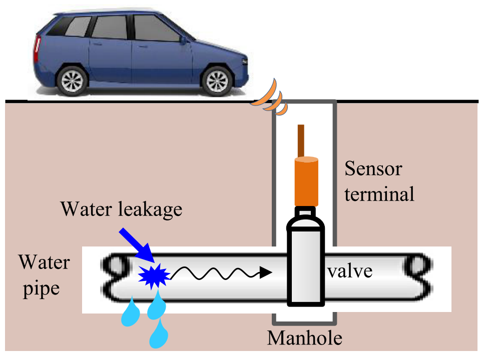

Fig. 5 Drive-by data collection method.

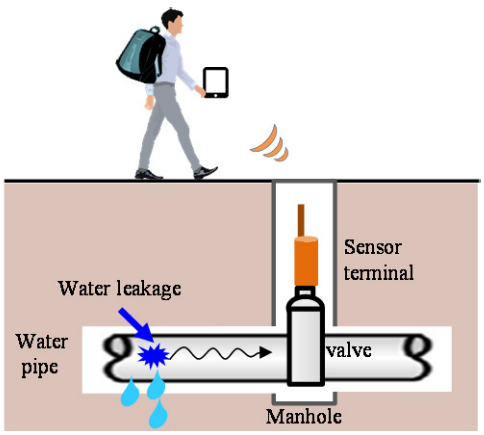

Fig. 6 Walk-by data collection method.

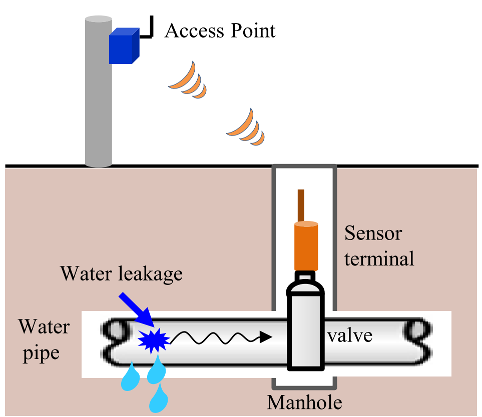

Fig. 7 Static data collection method.

continuous monitoring using a pillar type access point installed in a telegraph pole or the like for important pipelines (see Fig. 7). In this method, it is important to make the communication distance as long as possible to reduce the number of necessary access points. Figure 8 shows a prototype sensor that can be used with an extension antenna of the type shown in Fig. 9.

The acoustic data captured by the sensor are transmitted to a cloud for analysis [23]. This analysis can be replaced by a two-class problem of whether or not leakage occurs.

Fig. 8 Prototype sensor.

Fig. 9 Antenna with extension cable.

Therefore, we applied Support Vector Machine (SVM) technology, which is one of the machine learning methods using teacher data [31]. The specific method we used was as follows. In advance, we acquire the sounds of water pipes with and without leakage at many places. Using the acquired sounds as teacher data, a detection algorithm is created by SVM. A Gaussian kernel function introduces it to extend its applicability to nonlinear problems [32]. After such preparation, the algorithm is applied to the data acquired by the sensors to judge the presence or absence of water leakage.

The data to be wirelessly transmitted are on the order of several kilobytes because the algorithm requires data of such size data to make correct judgments. Since it is necessary to transmit these data quickly time at drive-by time, a 920 MHz band self-service radio based on IEEE 802.15.4g is used for radio communication. The devices based on it send signals on the order of several tens kbps in the 920 MHz band. To design the system, it is important to determine the wireless communication distance that can be achieved with sensors installed in a basement. Therefore, we measured radio propagation from underground manholes using the 920 MHz band.

3. Measurement Methods

Radio propagation from underground manholes was measured in three areas. Area A was a residential area. The measurements were carried out in daytime. We used two types of valve boxes (manholes) made from reinforced concrete and resin concrete. Both paths were line of sight as shown in Fig. 10.

Figure 11 shows a valve box on a street. A prototype sensor with an extension antenna was installed in a valve box as shown in Fig. 12, and transmitted 920 MHz band signals. A measuring instrument (radio frequency (RF)-capture) on a car recorded the received power level while the car moved at 10 km/h. The receiving antenna was mounted

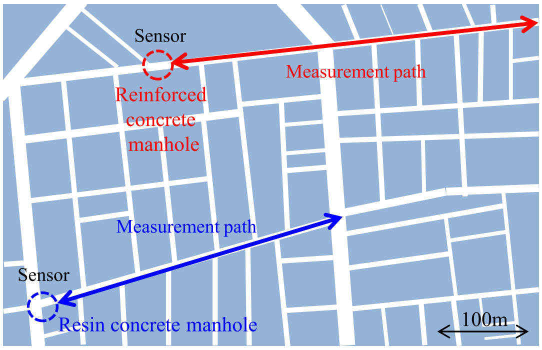

Fig. 10 Experimental area (area A).

Fig. 11 External appearance of valve box.

Fig. 12 Sensor terminal and internal appearance of valve box

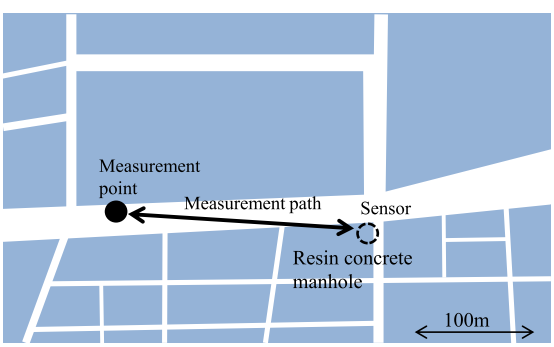

Fig. 13 Experimental area (area B).

on its roof at a height of 1.9 m above the ground.

Figures 13 and 14 show maps of the other areas (Areas B and C) used. Area B was a commercial area around a major road. Measurements simulating the static data-collection method were carried out at midnight. A sensor terminal was installed in a valve box made of resin concrete. An RF-capture on a car recorded the received power level while the car remained at a point 200 m from the valve box. The height of the antenna, which was mounted on the car roof, was the same as that of a fixed access point on a pole (3.8 m above the ground). Like Area A, Area C was a residential area. The measurements for this area were carried out using the same scheme as for Area B to compare the propagation of commercial and residential areas.

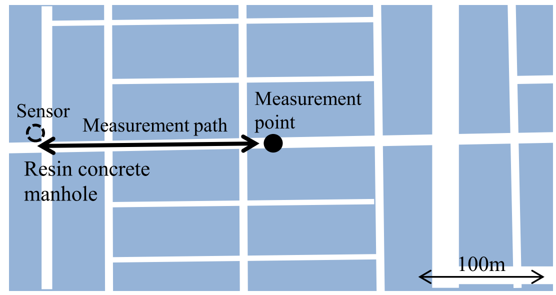

Fig. 14 Experimental area (area C).

4. Results

Figure 15 shows the measurement results from Area A when the transmitted power of the sensor terminal was 19 dBm and both transmitting and receiving antennas are half-wavelength dipole antennas (2.14 dBi). Because our access point for the drive-by data-collection method requires a received power of −107 dBm, the communication distance was estimated as 100 m or more from valve boxes made from both reinforced concrete and resin concrete. Because our access point for the static data-collection method requires a received power of −124 dBm, the communication distance was estimated as 200 m or more for valve boxes made from both reinforced concrete and resin concrete.

Figure 15 also indicates that received power sometimes dropped 10 dB or more. The measurements were carried out in daytime, when vehicles sometimes passed by the measurement area. Shielding by passing vehicles is thought to have caused this drop. To confirm this, the measurement results from Areas B and C were compared. Because Area B is a commercial area around a major road, vehicles often use the road even at midnight. On the other hand, no vehicles and few people use the roads at midnight around Area C, which is a residential area.

Figure 16 shows the measurement results from Area B. As in Area A, the received power sometimes dropped 10 dB or more, but only for a very short time in each case. On the other hand, the received power of Area C rarely dropped and when it did the dropping was small as shown in Fig. 17). This indicates the drops shown in Fig. 15 were caused by shielding from passing vehicles. This can be avoided by retransmission. The mean of the received power in Areas B and C is −101 dBm. The calculated received power at 200 m away in free space is −54 dBm when the antenna gain in both areas is 2.14 dBi and transmitted power is 19 dBm at 920 MHz. Therefore, the propagation loss from the man-

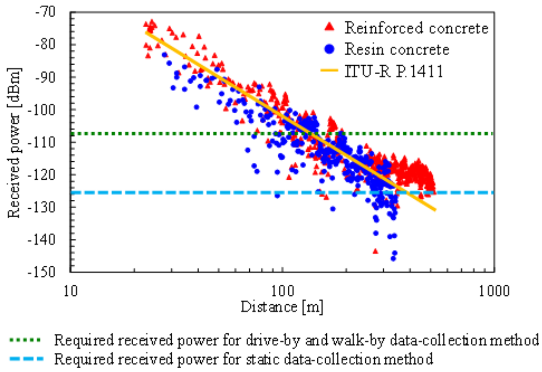

Fig. 15 Measurement results (Area A).

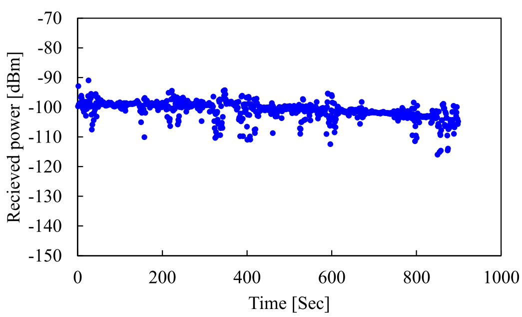

Fig. 16 Measurement results (Area B).

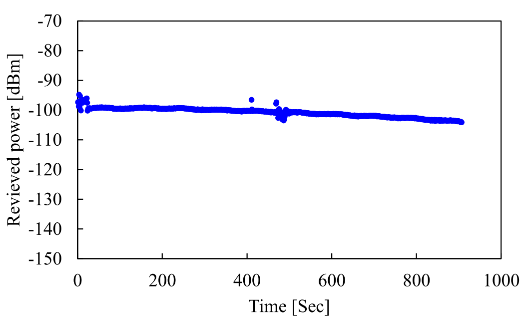

Fig. 17 Measurement results (Area C).

holes in both areas is 47 dB larger than that in free space.

It is well known that received power, P_r, is given by:

$$P_r = P_t + G_t + G_r + L_{path} \quad (1)$$

where P_t, G_t and G_r are respectively transmitted power, transmit antenna gain and receive antenna gain. L_{path} is transmission loss and is calculated according to the ITU-R P.1411 standard, which is applied for short-range outdoor radio communication systems and local area networks [33]. The calculation is as follows:

$$L_{path} = L_{bp} + 6 + 40\log(d/R_{bp}) \quad (2)$$

where d is distance between transmit and receive antennas. R_{bp} is given by:

$$R_{bp} = 4h_t \cdot h_r/\lambda \quad (3)$$

where h_t and h_r are heights of transmit and receive antennas and λ is wavelength. L_{bp} is given by:

$$L_{bp} = 20\log(\lambda^2/(8\pi \cdot h_t \cdot h_r)) \quad (4)$$

Calculated received power using Eq. (1) is also shown in Fig. 15. In this case, h_t is a negative value because the transmit antenna is underground. This means it is out of the application range of Eq. (2). Therefore, with h_t set to 2 m, we reduced P_t by 47 dB (the difference from P_t in the free space with 2 m antenna height) and applied Eq. (2). The calculated received power well matches the measured received power.

5. Conclusions

We presented a water leakage monitoring system we are developing. It gathers acoustic data of water pipes from underground manholes using wireless communication technology to detect water leakage sound using machine learning. To collect data effectively, our system uses three methods to effectively collect acoustic data: drive-by, walk-by, and static. Radio propagation from underground manholes using the 920 MHz band was also investigated. It was revealed that radio communication from manholes made from resin concrete and reinforced concrete was possible in the range of 100 m or more. It was also revealed that the received power sometimes dropped 10 dB or more due to shielding by passing vehicles, even at midnight around a major road. Since in each instance the power dropped for only a very short time, retransmission can suppress adverse effect of the power drops.

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