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PAPER Special Section on Integration Technologies of Ambient Intelligence and Sensor Networks

Measurement of Wireless LAN Characteristics in Sewer Pipes for Sewer Inspection Systems Using Drifting Wireless Sensor Nodes*

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SUMMARY Deterioration of sewer pipes is one of very important problems in Japan. Sewer inspections have been carried out mainly by visual check or wired remote robots with a camera. However, such inspection schemes involve high labor and/or monetary cost. Sewer inspection with boat-type video cameras or unwired robots takes a long time to check the result of the inspection because video data are obtained after the equipment is retrieved from the pipe. To realize low cost, safe and quick inspection of sewer pipes, we have proposed a sewer inspection system using drifting wireless sensor nodes. Water, soil, and the narrow space in the pipe make the long-range and high throughput wireless radio communication difficult. Therefore, we have to identify suitable radio frequency and antenna configuration based on wireless communication characteristics in sewer pipes. If the frequency is higher, the Fresnel zone, the needed space for the line of sight is small, but the path loss in free space is large. On the other hand, if the frequency is lower, the size of the Fresnel zone is large, but the path loss in free space is small. We conducted wireless communication experiments using 920 MHz, 2.4 GHz, and 5 GHz band off-the-shelf devices in an experimental underground pipe. The measurement results show that the wireless communication range of 5 GHz (IEEE 802.11a) is over 8m in a 200 mm-diameter pipe and is longer than 920 MHz (ARIB STD-T108), 2.4 GHz (IEEE 802.11g, IEEE 802.15.4) band at their maximum transmission power. In addition, we confirmed that devices that use IEEE 802.11a and 54 Mbps bit rate can transmit about 43 MB data while they are in the communication range of an AP and drift at 1 m/s in a 200 mm-diameter pipe, and it is bigger than one of devices that use other bit rate.

key words: *sensor network, sewer inspection, drifting sensor node, wireless communication quality measurement*

1. Introduction

Maintenance of old city infrastructure has become one of very important problems. Strength of 50-year old polyvinyl chloride (PVC) sewer pipes becomes 20–35% of their original strength [1]. Therefore, old sewer pipes are major causes of sewer pipe accidents. In Japan, 30 years or more have already passed since a quarter of all sewer pipes were laid down. 4,700 road subsidence accidents happened due to such old sewer pipes in 2007. Therefore, inspection and maintenance of them are urgently needed [2].

Today's popular sewer inspection methods are visual check, manhole camera, fiberscope and wired robot-based inspection. Since toxic gas is generated in sewer pipes, visual check is dangerous for operators [3]. A manhole camera, e.g. [4], is a stick with a camera at its tip. In the manhole camera-based video inspection method, operators can receive the video taken at around manholes in real time via a cable. This inspection method does not require that operators enter into the sewer pipe. However, operators cannot receive video taken at a location away from manholes in this method. The inspection range of fiberscope-based inspection is larger than one of the manhole camera-based inspection method [5]. However, the inspection range of fiberscopes depends on the length of the fiber. In addition, if there is any dirt in the sewer pipe, this inspection requires to wash the sewer pipe beforehand. The inspection range of wired robot-based inspection is larger than fiberscope-based inspection [6]. Just like with manhole camera and fiberscope-based inspection methods, the wired robot-based video inspection method does not require that operators enter into the sewer pipe, but it requires cleaning the inside of the pipe and stopping water to put the robot into the pipe. Therefore, sewer inspection time using a wired robot is generally long. Also, the monetary cost of a wired robot is very high. Thus, the total cost is very high. In addition, cables attached to the wired robots make it difficult to handle the robots.

To solve these problems, sewer inspection schemes using unwired robots or boat-type cameras have been developed in recent years [7]. In sewer inspections using such equipment, the equipment records the movie of the inside of a pipe while they drift downstream. Operators can receive the video data from the equipment after retrieving the equipment from the pipe. Especially, boat-type camera equipment is very simple because it does not have actuators, thus the cost is cheap. Though this equipment does not have mobile functions, it can move in the sewer pipe with the flow of the sewer. Therefore, the cost of sewer inspection using boat-type cameras is less than that of schemes using wired robots. However, since operators cannot receive video data during sewer inspection using such unwired equipment, operators cannot know the progress of the inspection in real time. Thus, they cannot respond quickly to problems that have occurred during sewer inspection. For example, if a camera is broken in the pipe, operators cannot obtain the video data and cannot know the incident before retrieving the equipment. Therefore, inexpensive, safe and quick sewer inspection is strongly needed.

Wireless video transmission in sewer pipes makes it easy to confirm the sewer inspection process. In addition, it makes sewer inspection quicker than existing sewer inspection methods. We have proposed an architecture of a drifting

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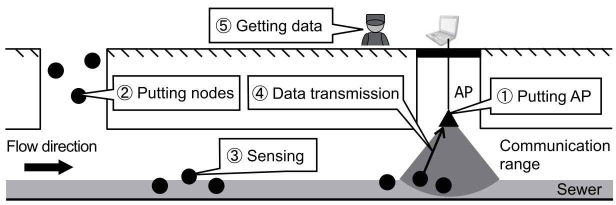


Fig. 1 Sewer Inspection System with Drifting Sensor Nodes. This system consists of multiple drifting sensor nodes and access points placed at manholes.

sensor network for sewer inspections (Fig. 1) [8]. This system provides sensor data to operators using drifting sensor nodes and access points.

Since the space inside a sewer pipe is narrow and there are many radio attenuation factors, it is difficult to ensure the line of sight (LOS) for wireless communication in sewer pipes. To achieve sufficiently long wireless communication range and high transmission rate for delivering sensor/video data, suitable radio frequency should be used. However, there is a trade-off between the path loss of radio waves and the size of the Fresnel zone. The path loss of low frequency radio wave is smaller than that of high frequency radio. In contrast, the Fresnel zone of high frequency radio is smaller than that of low frequency. It means that the LOS is easily achieved when the high frequency band radio is used. In this paper, we present the results of wireless communication experiments in a 200 mm diameter-experimental pipe to obtain the guideline to select suitable radio configuration of off-the-shelf devices for wireless communication in trunk lines of sewer systems.

The remainder of the paper is organized as follows. Section 2 describes related work on sewer inspection system using sensor network. In Sect. 3, we explain our proposed sewer inspection system and problems of the system. Section 4 describes a trade-off between the path loss of radio waves and the Fresnel zone radius. We present measurement result using 920 MHz, 2.4 GHz and 5 GHz band off-the-shelf devices in an experimental underground pipe in Sect. 5. Concluding remarks are included in Sect. 6.

2. Related Work

So far, several literature related to sewer inspection using sensor networks has been published. Stoianoy et al. propose PIPENET, a system for monitoring large diameter bulk-water transmission pipelines [9]. This system is composed of stationary sound sensors and stationary vibration sensors. This system collects the sensor data and detects leeks. This system can be applied to sewer pipe monitoring. In this case, the system monitors water level using stationary ultrasonic sensor and stationary pressure sensor. However, the system requires to place a number of stationary sensors. Thus, the cost of operating this system is high.

Kim et al. propose SPAMMS, a pipeline inspection system [10]. This system is composed of stationary sensors, mobile sensors and an inspection robot. Each stationary sensor has an RFIDs and the mobile sensor equips an RFID writers, and the inspection robot equips an RFID readers. The mobile sensors drift on the sewer and observe inside of the sewer pipe, and write the observational data and time stamps to the RFIDs of the stationary sensors. The stationary sensors identify the damaged points of the sewer pipe using the received data. The inspection robot reads coordinates of the damaged points from RFIDs of stationary sensors and inspects the points.

Kim et al. propose Sewer Snort, a system for detecting concentration of gas and estimates the position of drifting sensor nodes using the received signal strength from beacon nodes at manholes [11]. In their system, the drifting sensor nodes and the beacon nodes were Crossbow MicaZ working on 2.4 GHz band. The wireless communication standard of the sensor node and the beacon node was IEEE 802.15.4, and the transmission power was set to their maximum transmission power of 0dBm. To prevent drifting sensor nodes from sinking and breaking down, they have tube-like outer shell. This study does not aim that delivery of large-size data such as video. To understand the damage level of sewer pipes, image information is useful and such data that are taken by wired robots and/or fiber scopes have been used in sewer inspections. In this paper, we consider delivering not only small data like gas concentration but also large-size data from drifting sensor nodes to APs.

So far, several studies have reported wireless communication experiments of systems using underground sensor network. In [12], the authors measured the characteristics of wireless communication between an underground sensor node and a sensor node on the ground for agriculture, security, and infrastructure monitoring sensor networks. The underground sensor was buried into moderately wet soil at the depth of 0–13 cm. Another sensor was placed at a height of 1m from the ground or on the ground. Sensor nodes were Crossbow MicaZ, which use Zigbee-compliant Chipcon CC2420 radio working on 2.4 GHz band and a quarter-wavelength whip antenna. The wireless communication standard of the sensor node was IEEE 802.15.4, and the transmission power was set to their maximum transmission power of 0 dBm. The wireless communication between an underground sensor nodes and a sensor node on the ground succeeded in all cases, but communication between two underground sensor nodes failed in all cases. Note that the underground sensor nodes in this experiment were buried completely into the soil. On the other hand, in our system, sensor nodes and access points are placed in a pipe with 200 mm diameter.

In [13], the authors measured the path loss of wireless communication between a portable spectrum analyzer (SA) (Anritsu MS2721A) on the ground and a transmitter placed in a fire hydrant that was placed at contact points with an underground water distribution pipe network. Fire hydrants were buried in the soil and was made of concrete and iron and is closed. There were gaps between the fire hydrant lid and the rim. The transmitter had a dipole antenna and used 868 MHz and 2.4 GHz band for wireless communication. The transmission power of the transmitter was set to their maximum transmission power of 19 dBm. The signal strength was measured using a SA with a dipole antenna. The result showed that the path loss at 2.4 GHz band was small and that of 868 MHz band was big. The authors consider that the short wavelength is easier to propagate from gaps than the long wavelength.

In [14], the authors measured the received signal power of wireless communication between a receiver on the ground and a sensor node in an underground plastic pipe for wireless mobile monitoring network inside water distribution conduits. The thickness of the plastic pipes was 1 cm. The diameter of plastic pipes was 10–20 cm. The depth of the plastic pipes was 5–250cm. The plastic pipe was filled with water. Sensor nodes were Ubiquity radios model XR7 with an RF carrier at 750 MHz band, bandwidth of 5/10/20/40 MHz, sensibility of −83 dBm for a data link with the maximum speed of 24 Mbps bit rate. The sensor nodes used a proprietary protocol based on IEEE 802.11g OFDM. The transmission power of them was 28 dBm. The sensor node in the plastic pipe had a loop antenna and was closed in a box of dimensions 1.5 × 6 × 10 cm. The receiver on the ground had a broadside antenna with 12 dBi antenna gain and was placed at 1.5 m above the ground. In all scenarios, the communication between the sensor nodes in the underground pipe and the receiver on the ground succeeded.

3. Drifting Sensor Network

Figure 1 shows the overview of a drifting sensor network for sewer inspection that we have proposed in [8]. To use the system, the operator firstly places access points (APs) in manholes in the inspection range of the pipe. Secondly, the operator puts sensor nodes into the sewer pipe. Nodes record a video and/or sense gas concentration data while they drift downstream, and transmit the data to access points while they are in the communication range of one of APs. Finally, the operator obtains the data forwarded by APs. Ideally, sensor nodes should be disposable. Thus, the operator does not have to remove sensor nodes after the inspection. Among many types of sewer pipes, we focus on PVC pipes of 200 mm diameter, which are mainly used to constitute trunk lines of sewer systems.

This system reduces the labor cost of sewer inspection. Operators do not have to enter the pipe, stop the sewer stream, and pick up dirty equipment. Therefore, inspection work will be safe and quick. Since operators can receive sensor data during sewer inspection, they can know the progress of the inspection and quickly respond to the failures of nodes. In addition, even if nodes stop in the middle inspection range of the pipe, operators can obtain the data from the lastly visited AP because the data observed until the nodes reached the AP have been forwarded to the AP. By reducing the cost and/or the number of nodes used in this system, the total cost of the inspection can be reduced.

At least, there are four problems for realizing such a system.

The first problem is battery capacity of the nodes. Sensor nodes are required to be small and light so that sewer pipes are not clogged with the nodes. Therefore, battery capacity of the sensor nodes is limited. Thus, the energy effective design of the system is important. The second problem is malfunction of nodes due to collisions to pipe walls, other nodes, and other obstacles. To solve these problems, we have proposed a system that uses multiple sensor nodes that adaptively schedule their sleep/active modes. Nodes can switch to sleep mode to save their battery consumption and back up data each other. In addition, the system is designed so that a group of sensor nodes does not lose the opportunities to communicate with APs [15].

The third and fourth problems are short wireless communication range and low throughput in sewer pipes. Inside of sewer pipes is a narrow closed space, and there are many obstacles such as water, soil, tree roots, and garbages. Therefore, these make difficult to ensure the LOS in sewer pipes. Since drifting rate of sewer is from 1 m to 2 m per second, the moving speed of sensor nodes is also 1–2 m per second. It means that if the wireless communication range is short, the duration of the period that sensor nodes can successfully send data to APs is short and it is difficult to transmit large data. Therefore, we need sufficient wireless communication range and throughput for transmitting video data.

4. Radio Frequency for Wireless Communication in Sewer Pipes

To achieve sufficient wireless communication range and transmission rate, we have to use a suitable radio frequency. There is a trade-off between the path loss of radio waves and the Fresnel zone radius. The Fresnel zone influences the space required for assuring the LOS. The path loss of low frequency radio is smaller than that of high frequency radio. In contrast, the Fresnel zone of high frequency radio is smaller than that with low frequency radio.

The received signal power of radio communication can be given by the Friis transmission equation,

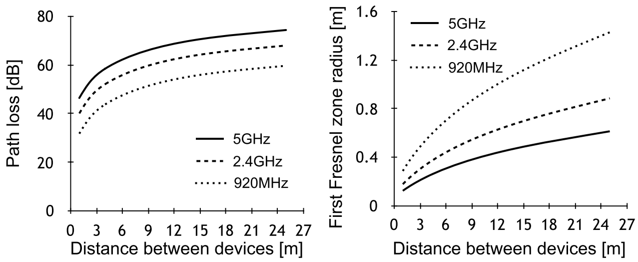
$$P_r = \frac{G_t G_r P_t}{L}. \tag{1}$$

P_t and P_r are the transmission power and the reception power respectively. G_r and G_t are the antenna gain of the sender and the receiver, respectively. L means the path loss. We can see that it is necessary to increase the transmission power or the antenna gain, or decrease the path loss in order to extend the reception power. We consider decreasing the path loss in this paper.

Assuming free space, path loss is given by the following equation (2).

$$L = \left(\frac{4\pi d}{\lambda}\right)^2 . \tag{2}$$

d is the distance between sender and receiver, and λ is wavelength of radio signals. As shown in this equation, the path



(a) Path loss (b) First Fresnel zone radius

Fig. 2 The path loss in free space and the first Fresnel zone radius. If the distance between devices is longer, the path loss is bigger and the first Fresnel zone radius is longer.

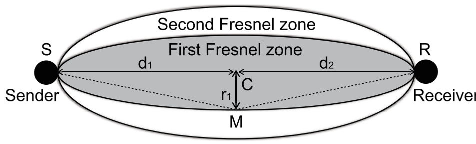


Fig. 3 The Fresnel zone between two devices. If the first Fresnel zone includes obstacles, the received signal strength becomes severely worse.

Table 1 Parameters of FDTD simulation.

	Relative permittivity	Electric Conductivity [S/m]	Relative Permeability
Inside of the pipe	1.0	0	1.0
Pipe wall	3.0	1.0×10^{-4}	1.0
Soil	3.0	1.0×10^{-12}	1.0

loss of low frequency radio is lower than that of high frequency. Fig. 2(a) shows path losses of 920 MHz, 2.4 GHz and 5 GHz band calculated by Equation (2).

Radio frequency influences not only path loss but also the Fresnel zone radius. Fig. 3 illustrates the Fresnel zone. S and R are the point that the sending and receiving antenna are placed respectively. Segment MC is a straight line perpendicular to segment SR. The area of the Fresnel zone is given by the following equation,

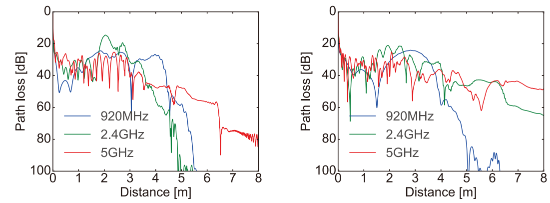
$$SM + MR - SR = \frac{n\lambda}{2} \qquad (n = 1, 2, \ldots). \tag{3}$$

Segment MC is called the n-th Fresnel zone radius r_n, and is given by

$$r_n = \sqrt{n\lambda \frac{d_1\, d_2}{d_1 + d_2}}, \tag{4}$$

where d_1 is the length of segment SC, and d_2 is the length of the segment RC. The first Fresnel zone contributes to the energy transmission. To ensure the LOS for wireless communication, 60% of the first Fresnel zone radius should be free from obstacles. Fig. 2(b) shows the maximum first Fresnel zone radiuses of 920 MHz, 2.4 GHz and 5 GHz band calculated with equation (4). To include a 200 mm-diameter pipe inside 60% of the first Fresnel zone, 1 m, 3 m, and 7 m are the maximum distance between the sender and the receiver with 920 MHz, 2.4 GHz, and 5 GHz radio, respectively.

Figure 4 shows simulation results of radio propagation in narrow pipes with 200 mm and 400 mm-diameters obtained with the FDTD method using open FDTD [16].



(a) Diameter=200mm (b) Diameter=400mm

Fig. 4 FDTD simulation results of radio propagation in a pipe without water surrounded by soil with 5 mm × 5 mm × 5 mm-mesh.

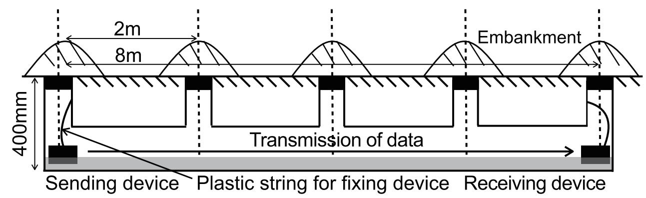


Fig. 5 Experimental underground pipe.

Fig. 6 The experimental pipe before buried in the ground.

We assume there is a half-wave dipole antenna at the center of pipe and plotted the path loss at the center of the cross section of the pipe. The pipe is surrounded by box-shaped soil. The minimum distance between the pipe and the external surface of the soil is 400mm. The thickness of the pipe is 6.5 mm. Other simulation parameters are summarized in Table 1. The results clearly show the diameter of the pipe strongly affects the path loss and the path loss of 5 GHz frequency is smaller than that of lower frequencies.

5. Wireless Communication Experiment with a Real Underground Pipe

To understand the radio characteristics in sewer pipes, we measured the data reception ratio, the throughput, and the RSSI of wireless standards that use 920 MHz, 2.4 GHz, and 5 GHz band using off-the-shelf devices and an experimental underground pipe.

5.1 Measurement Set Up

5.1.1 Experimental Pipe

Figures 5 and 6 show the experimental underground pipe we

Table 2 Data transmission setting of devices.

Band & center frequency	Standard & bit rate & bandwidth	PHY/MAC device	Controller	Tx-power	Receive Sensitivity	Protocol	Antenna & antenna gain	Position	Mobility
920 MHz (925.2 MHz)	ARIB STD T-108 (9600 bps) [200 kHz/ch]	Toho technology, TMJ0914 (Low power wireless module)	Arduino Uno	10 dBm	−100 dBm	Proprietary protocol	Map electronics, GHX-463XSAXX-350 (Rubber duck O antenna, 3 dBi)	W	Fixed
								C	Fixed
2.4 GHz (2.44 GHz, 2.437 GHz)	IEEE 802.15.4 (256 kbps) [2 MHz/ch]	Digi, Xbee Pro (Wire antenna)	Arduino Uno	10 dBm/MHz	−100 dBm	UDP	Supplied wire antenna (O antenna, 1.65 dBi)	W	Fixed
								C	Fixed
							Joymax electronics, ICF-6010RSX8 (Openable stand D antenna, 8 dBi)	W	Fixed
								C	Fixed
	IEEE 802.11g (6–54 Mbps) [20 MHz/ch]	Planex, GW-450D (USB dongle)	Raspberry Pi	10 dBm/MHz	−83 dBm	UDP	Built-in dongle (O antenna, 3 dBi)	W	Fixed
								C	Fixed
5 GHz (5.7 GHz)	IEEE 802.11a (6–54 Mbps) [20 MHz/ch]	Planex, GW-450D (USB dongle)	Raspberry Pi	10 dBm/MHz	−83 dBm	UDP	Built-in dongle (O antenna, 3 dBi)	W	Fixed
									1m/s
								C	Fixed

O: Omnidirectional, D: Directional, W: On the water, C: Center of the pipe's cross section.

(a) TMJ0914 + Arduino Uno (b) Xbee Pro + Arduino Uno (c) GW-450D + Raspberry pi

Fig. 7 Devices used for the measurement. For waterproof, all devices are sealed with a sealed box.

used. The material of the pipe is PVC. The length of the pipe is 8 m, the diameter is 200 mm, and the thickness is 6.5 mm. The depth from the surface on the ground to the bottom of the experimental pipe is 400 mm. 40 mm-deep water was put into the pipe. We covere the rid of the pit at the both ends and the center of the pipe with soil to prevent emission of radio waves from the pits.

5.1.2 Communication Devices

Table 2 and Fig. 7 show off-the-shelf wireless LAN/PAN devices that we used for measurements. For 920 MHz band, we used ARIB STD T-108 standard devices. They use an omnidirectional antenna with 3 dBi gain and a proprietary wireless communication protocol. The protocol performs wireless serial communication at 9600 bps. For 2.4 GHz band, we used IEEE 802.15.4 and 11g standard devices. IEEE 802.15.4 standard devices use an omnidirectional antenna with 1.65 dBi and UDP protocol. In addition, we also used directional antennas with 8 dBi gain. Each device and each directional antenna is connected with an 300 mm-cable with a reverse SMA plug. The half power beam widths of the antennas are 50 degrees at E-plane and 100 degrees at H-plane. Each antenna was installed in a sealed box so that the strongest beam direction faced to another antenna. It was laid in the box so that the E-plane paralleled with the bottom of the pipe and the box. The IEEE 802.11g standard devices used an omnidirectional antenna with 3 dBi gain and UDP protocol. We used different bit rate from 6 to 54 Mbps on these devices. For 5 GHz band, we used IEEE 802.11a standard devices. They use an omnidirectional antenna with 3 dBi gain, UDP protocol, and bit rates from 6 to 54 Mbps.

The transmission power of ARIB STD T-108 devices was set to 10 dBm and that of IEEE 802.15.4, 11g and 11a devices was set to 10 dBm/MHz, the maximum transmission power of IEEE 802.11g and 11a devices allowed in Japan. The number of retransmissions was set to zero.

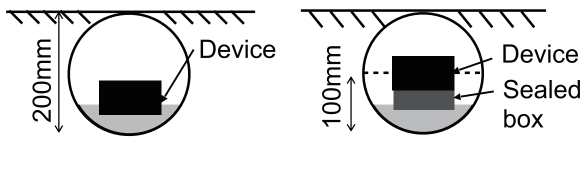
5.1.3 Measurement Methods

To compare the radio communication characteristics of 920 MHz and 2.4 GHz, we measured packet delivery ratio and RSSI with ARIB STD-T108 and IEEE 802.15.4 devices. In the experiment, the sending device transmitted 180 packets of 100 bytes to the receiving device at 1-second intervals and the receiving device measured the data reception ratio and the RSSI.

To compare the characteristics of 2.4 GHz and 5 GHz radio communication especially focusing on large data transmission, we measured the throughput and RSSI using IEEE802.11g and 11a devices. In the experiment, the sending device continuously transmitted packets of 1870 bytes using Iperf [17] and the receiving device measured the throughput and the RSSI.

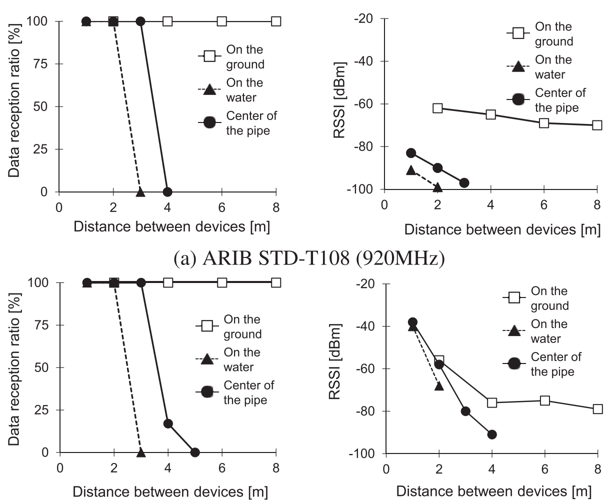
To investigate the relationship between obstacles such as water and soil in the first Fresnel zone and the wireless communication range, we changed the height of the device position by placing polypropylene-made sealed boxes under the devices. Figure 8 shows the two positions of the devices, (a) on the water and (b) at the center of the pipe's cross section.

In addition to experiment with fixed devices, we conducted experiment with moving devices. We placed the sending and the receiving device on the water at the both ends of the pipe, and manually moved the sending device to the position of the receiving device at 1 m/s by pulling a



(a) On the water (b) Center of the pipe's cross section

Fig. 8 Device positions in an experimental underground pipe. In (a), the device floats on the water. In (b), the device is placed on the top of the sealed box floating on the water.



(a) ARIB STD-T108 (920MHz)

(b) IEEE 802.15.4 (2.4GHz)

Fig. 9 Data reception ratio and RSSI when omnidirectional antennas were used.

plastic string attached the sending device.

5.2 Measurement Results

5.2.1 Wireless Communication Range

Figure 9 shows the data reception ratio and the RSSI of ARIB STD-T108 and IEEE 802.15.4. Figure 10 shows the throughput and the RSSI of IEEE 802.11g and 11a. We used omnidirectional antennas for obtaining these results. Firstly, we confirm that the wireless communication range in the underground pipe is shorter than on the ground. Figure 9 presents that the data reception ratio and the RSSI in the pipe are clearly smaller than these on the ground. If antennas are on the ground, soil exists only below the antennas. On the other hand, in the pipe, soil is surrounding the pipe. In addition, the pipe contains water. Since more radio attenuation factors exist in the first Fresnel zone than on the ground, the wireless communication quality in the pipe is worse.

Next, we confirm that the wireless communication range between two devices that placed at the center of the pipe's cross section is longer than one between devices that placed on the water. Figure 9 and Fig. 10 reveal that the data reception ratio, the throughput and the RSSI are improved by placing devices at the center of the pipe's cross section. In the case that devices are placed on the water, the center of the first Fresnel zone is at the bottom of the pipe, thus, large portion of the first Fresnel zone obstructed by soil and water. On the other hand, if they are placed at the center of the pipe's cross section, the center of the first Fresnel zone is also at the center of the cross section and the ratio of the obstructed first Fresnel zone is small.

We can see that the wireless communication range of IEEE 802.11a is longer than one of ARIB STD-T108, IEEE 802.15.4 and 11g. Focusing only in the case of placing devices at the center of the pipe's cross section, the maximum throughput of IEEE 802.11a at 8 m point is about 18.7 Mbps of 36 Mbps bit rate as shown in Fig. 10(b). Thus the maximum wireless communication range of IEEE 802.11a is over 8 m. Similarly, Fig. 10(a) shows that the maximum wireless communication range of IEEE 802.11g is 3 m. The data reception ratio of ARIB STD-T108 at 3 m point is 100% and that at 4 m point is 0% as shown in Fig. 9(a). Thus, the maximum wireless communication range of ARIB STD-T108 at 10 dBm is 3 m. Similarly, Fig. 9(b) shows that the wireless communication range of IEEE 802.15.4 is 3 m. Thus, wireless communication range of IEEE 802.11a is longer than ARIB STD-T108, IEEE 802.15.4, and 11g.

To discuss the relationship between the first Fresnel zone and the wireless communication range, let us examine the maximum first Fresnel zone radiuses at the maximum wireless communication range of each frequency. Figure 2(b) shows that the maximum first Fresnel zone radiuses of 920 MHz (ARIB STD-T108) band is 50 cm at the maximum wireless communication range, that of 2.4 GHz (IEEE 802.15.4 and 11g) band is 30cm, and that of 5 GHz (IEEE 802.11a) band is 27 cm. Most of the first Fresnel zone of 920 MHz band at the maximum wireless communication range is obstructed in the 200 mm diameter underground pipe. On the other hand, in 5 GHz band, the first Fresnel zone is narrow and the ratio of obstructed first Fresnel zone is small. As shown in Fig. 2(a), the path loss of low frequency band is smaller than the high frequency one. The first Fresnel zone radius of 920 MHz band at the maximum wireless communication range of 920 MHz band is more than twice as long as radius of the experimental underground pipe. However, we succeeded in wireless communication at this point. The path loss of 920 MHz band case is smaller than 2.4 GHz and 5GHz band, and the transmission power per MHz is five times of 2.4 and 5 GHz cases (IEEE 802.15.4 and 802.11). These differences contributed that communication using ARIB STD-T108 at 920 MHz succeeded even if large portion of the first Fresnel zone of 920 MHz band is obstructed by soil and water.

To make the wireless communication range longer, it is conceivable using a higher frequency than 5 GHz band. However, since the path loss of high frequency is large, even if the first Fresnel zone is narrow, the larger path loss may make it difficult to communicate using the frequency.

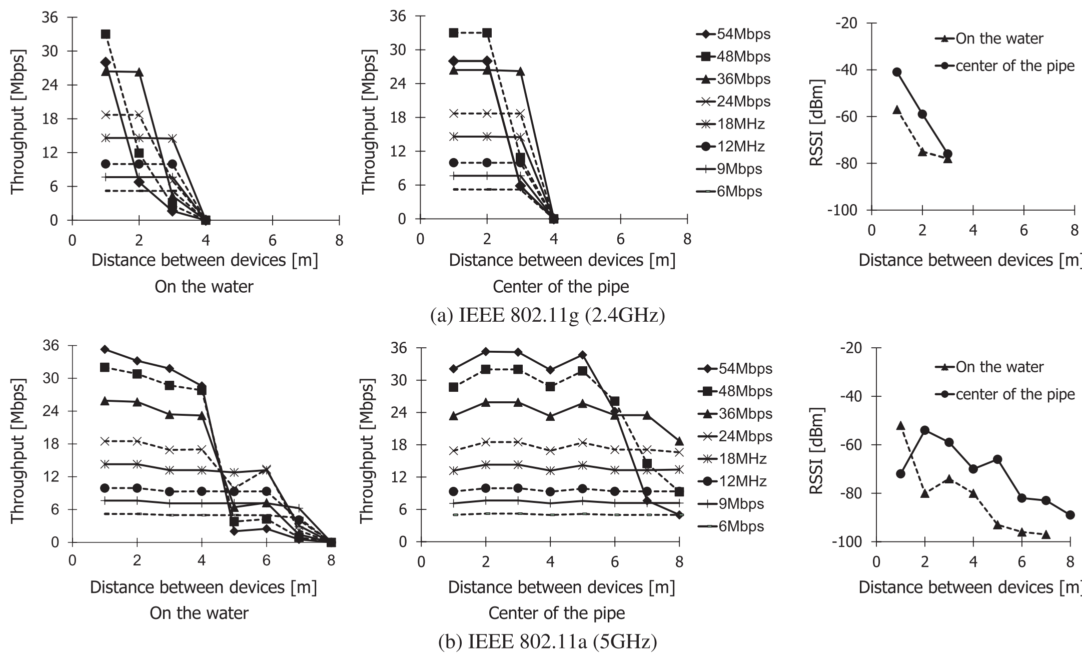


Fig. 10 Throughput and RSSI of IEEE 802.11g and 11a devices.

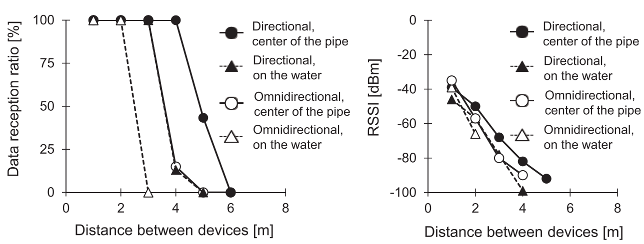


Fig. 11 Data reception ratio and RSSI when directional antennas were used.

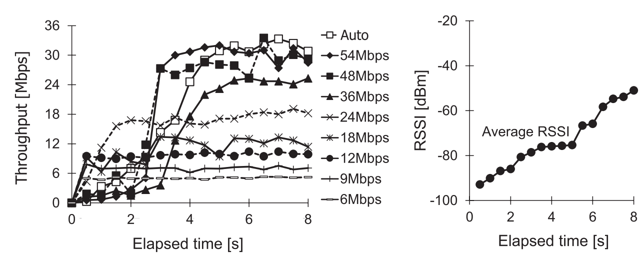


Fig. 12 Throughput and RSSI when moving devices were used.

5.2.2 The Effect of the Directional Antenna

We confirm that wireless communication range between two devices with directional antennas is longer than with omnidirectional antennas. Figure 11 shows the data reception ratio and the RSSI obtained with different types of antennas. We can see that the directional antenna is effective to lengthen the communication range. The data reception ratio with directional antennas when the distance between the sender and the receiver is 4 m and 5 m is 100% and 42%, respectively. Therefore, the maximum wireless communication range with directional antennas in IEEE 802.15.4 is 4 m. On the other hand, the maximum wireless communication range with omnidirectional antennas in 15.4 is 3 m.

Equation (1) indicates that wireless communication range of devices with higher gain antenna becomes longer. Directional antennas with high gain cannot transmit radio waves in all directions at the same time. Since sensor nodes always move, the geographical direction from nodes to APs also changes. Thus, if we use directional antennas, the operation of radio wave radiation direction will be a big problem.

5.2.3 The Effect of the Movement of the Device and Auto Bit Rate Control

Firstly, we confirm that the throughput and the RSSI at each point of the moving device approach them of the fixing device. Figur 12 shows that the throughput and the RSSI of moving devices. These graphs show the measurement results of devices placed on the water. In addition to 8 different data rates, we used auto data rate control in the experiment. Figure 9(b) and Fig. 12 reveal that the measurement results of the moving device are similar to these of the fixing devices. Therefore, the movement of the device at 1m/s does not have a big impact on the wireless communication quality.

Next, we can see that the throughput of auto bit rate is lower than one of 54 Mbps bit rate. We calculated the data size that nodes that use each bit rate can transmit while in the chance of communication to an AP when a node moves at 1 m/s. As a result, the transmission data size of devices that use auto bit rate is about 41 MB, and is higher than one of 48 Mbps or less bit rate. However, the transmission data size of devices that use 54 Mbps bit rate is about 43 MB, and is higher than one of auto bit rate. The throughput during 1–2.5 s with auto bit rate is higher than one with 54 Mbps bit rate as shown in Fig. 12. However, the throughput during 3–4.5 s with auto bit rate is much lower than one with 54Mbps bit rate. Devices that we used for the experiment use auto bit rate fallback that changes the data rate of devices based on the packet losses. However, since the sending device keeps moving in the experimental pipe, the wireless communication quality and the packet loss probability continuously change. In addition, it takes time to change the bit rate. Therefore, while auto bit rate mechanism changes the data rate, wireless communication quality significantly changes. Thus, auto rate fallback cannot follow the change of wireless communication quality due to the movement of the node in a sewer pipe.

5.2.4 Discussion Regarding the Deployment of Sewer Inspection Systems with Drifting Sensor Nodes

We discuss deployment issues of sewer inspection systems with drifting sensor nodes proposed in [8] using IEEE 802.11a devices. The key issue of the design of the sewer inspection system is that the sensor nodes have to transmit sensor/video data recorded during they move between APs within limited periods that they have connectivity to APs. Thus, considering the size of data that a sensor node records between APs and the maximum data size that it can transmit during it has connectivity to an AP is important. Assuming that the interval of the APs is 100 m, there is one node and it moves at 1 m/s, and it records H.264 video with a resolution of 640 by 480 pixels, the size of video data that have to be transmitted to an AP is about 25 MB. Since the available transmission data size of devices that use 54 Mbps bit rate is about 43 MB as presented in 5.2.3, we can realize the proposed system by using IEEE 802.11a and 54 Mbps bit rate placing the sensor device on the water and using an omnidirectional antenna.

However, if we increase the resolution of the video for more precise sewer inspection or choose other video coding formats, the total amount of video data transmitted while in the chance of communication of an AP becomes bigger and 54 Mbps bit rate may not be enough to transmit all the video data. Changing the data rate of devices in accordance with the communication quality can be a mean for increasing the total data transmission size. If we can select the suitable bit rate at the current position of a node, the transmission data size can be about 50 MB according to the measurement results shown in Fig. 12. However, existing auto bit rate cannot achieve this transmission data size in a sewer pipe. Therefore, a rate adaptation method optimized for the movement of nodes in a sewer pipe would be helpful to increase the transmission data size in sewer pipes.

If we use multiple sensor nodes, we will be able to manage short communication range and relatively longer distance between APs. In this case, each of the multiple sensor nodes sends video data of a different section of a segment of a pipe between APs to an AP at different timing so that it can avoid interference on the radio channel. Thus they have to be put into the pipe with sufficiently long intervals and APs need to give information about the sections of the pipe that each sensor node has to take video.

6. Conclusions

To understand the wireless LAN characteristics in trunk lines of sewer systems for drifting sensor/video network system for sewer inspection, we measured the throughput, the data reception ratio, and RSSI of 920 MHz (ARIB STD-T108), 2.4 GHz (IEEE 802.15.4 and 11g), and 5 GHz (IEEE 802.11a) band using off-the-shelf devices and a 200 mm diameter-experimental underground pipe. Initially, we supposed that the wireless communication range of low frequency is longer than high frequency. In practice, the wireless communication range of 5 GHz band is over 8 m and longer than 920 MHz and 2.4 GHz band. This is due to the narrow Fresnel zone of the higher frequency band. These results backup simulation results with the FDTD method in 200–400 mm pipes. We have also confirmed that the wireless communication range becomes longer by placing devices at the center of the pipe's cross section. If devices are placed at the center of the pipe's cross section, the center of the first Fresnel zone is also at the center of the cross section. Therefore, the ratio of obstructed first Fresnel zone is small and the wireless communication quality are improved. We confirmed that the directional antenna with high antenna gain is effective to lengthen the communication range in sewer pipes. We confirmed that the movement of the device at 1m/s does not have a big impact on the wireless communication quality in sewer pipes. In addition, we confirmed that the throughput of auto bit rate is lower than one of 54 Mbps bit rate in sewer pipes. This is because that auto rate mechanism cannot follow the change of wireless communication quality by the movement of the node in sewer pipes.

In the future, we will develop a prototype of the proposed system using IEEE 802.11a devices and transmit video data. To increase the transmission data size, we are designing rate adaptation mechanisms that quickly follow the change of wireless communication quality due to the movement of nodes in sewer pipes.

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