Wireless Relay Technologies for Monitoring Underground Infrastructures

Yosuke Fujino, Hiroyuki Fukumoto, Hajime Katsuda, and Kazunori Akabane

Abstract

With the progress made in Internet of Things (IoT) technology, expectations have been raised for IoT services in areas outside the bounds of network coverage such as underground, underwater, and sky environments. We have been developing wireless communications systems aimed at achieving monitoring capabilities of aging underground infrastructures. Our systems make use of wireless relay terminals installed on vehicles or utility poles to efficiently collect data from sensors installed in underground infrastructures. In this article, we introduce two recently developed technologies for radio relay systems that are designed to reduce the costs of installation and operation of the system. One extends the coverage area, and the other reduces power consumption.

Keywords: underground infrastructures, radio relay system, transmitter diversity

1. Introduction

The growth of the Internet of Things (IoT) has been progressing rapidly, and expectations have been raised for IoT services to be provided in areas outside the bounds of network coverage. These include environments underground, under water, and in the sky. Monitoring of aging underground infrastructures such as water pipes is one potential use case. Most water pipes in Japan laid in the era of high economic growth are aging rapidly, and the proportion of deteriorated water pipes is expected to exceed 40% in 2020 [1].

Investigations of water leakage from water pipes as well as maintenance of these pipes currently require skilled engineers, who conduct inspections manually. However, such inspections relying on skilled personnel will become harder to carry out in the future because of a manpower shortage due to the declining birthrate and the aging population. Therefore, the inspection of underground infrastructure making use of IoT combined with various kinds of sensors and wireless communications technologies have been strongly expected for efficient operations.

2. Wireless relay systems for monitoring underground infrastructures

An underground environment such as a water pipe is an enclosed space where the radio propagation path is extremely limited. Thus, radio waves do not travel very far even when compared with indoor environments such as inside buildings. Penetration loss from outdoors to indoors is known to be about 10–30 dB at frequency bands around 1 GHz, which are frequently used in IoT systems [2].

In contrast, the penetration loss from the ground to the valve box of water pipes installed underground is about 50 dB [3]. Hence, it is difficult to accommodate all sensors installed underground by using 4G (fourth-generation wireless systems) and LTE (Long-Term Evolution), which is assumed to be used in outdoor and indoor environments.

Therefore, we have been developing novel radio

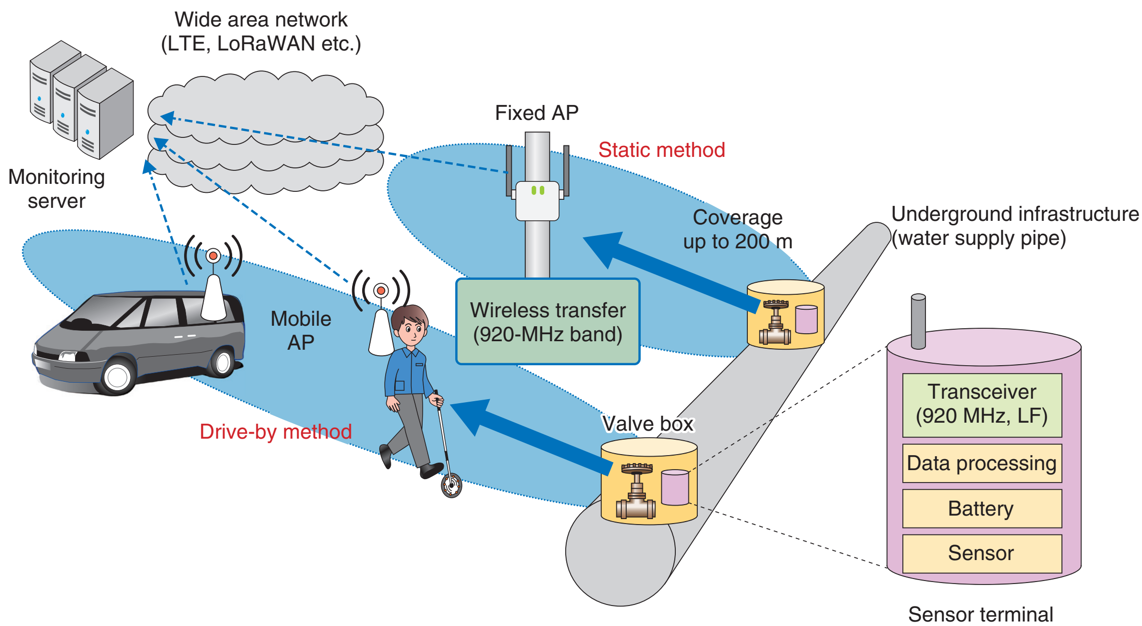


Fig. 1. Concept of wireless relay system for monitoring underground infrastructure.

relay systems that efficiently collect data from sensors under ground-level structures by using relay stations installed on cars and on utility poles [4]. A schematic drawing of our proposed system is shown in **Fig. 1**. In radio relay systems, efficient installation and operation of repeaters is important. Hence, we have developed two techniques to achieve this. One technique extends the coverage area of the relay system, which enables the repeaters to accommodate a large number of sensors over a wide area. Consequently, we can reduce the number of relay units installed. The other technique saves power. It enables relay terminals to operate on batteries, which makes it possible to install them anywhere, even in locations without a power supply.

3. Technique for extending coverage area

In wireless communications, the strength of radio waves gradually weakens as the communication distance increases. There are two simple methods to extend coverage areas. One is to improve receiver sensitivity by sacrificing transmission speed. In recently introduced wide area communication systems such as LoRa [5] and Sigfox [6], an ultrahigh sensitivity of –130 dBm or more has been achieved by limiting the speed by up to several hundred bits per second. However, since the required air time, or the running time of a transceiver, becomes longer as the transmission speed becomes slower, the power consumption increases.

The other method is to increase the transmission power. However, this also leads to an increase in power consumption at the transmitter. Therefore, other technologies for extending coverage areas are necessary for battery-powered long-life communication systems such as monitoring systems for underground infrastructures.

We are working to extend the coverage area by focusing on a phenomenon referred to as multi-path fading, which has a peculiar effect on radio communications. Radio waves in general propagate through multiple paths due to diffraction and reflection. Hence, the received signal is the sum of multiple waves, each of which traveled along a different path. With multi-path fading, the reception power level varies drastically depending on the receiving position due to differences in the phase relationship between each path (**Fig. 2(a)**). For example, at receiving positions where two waves with the same phase are combined, the strength of the received signal is 3 dB higher than the signal of a single path. On the other

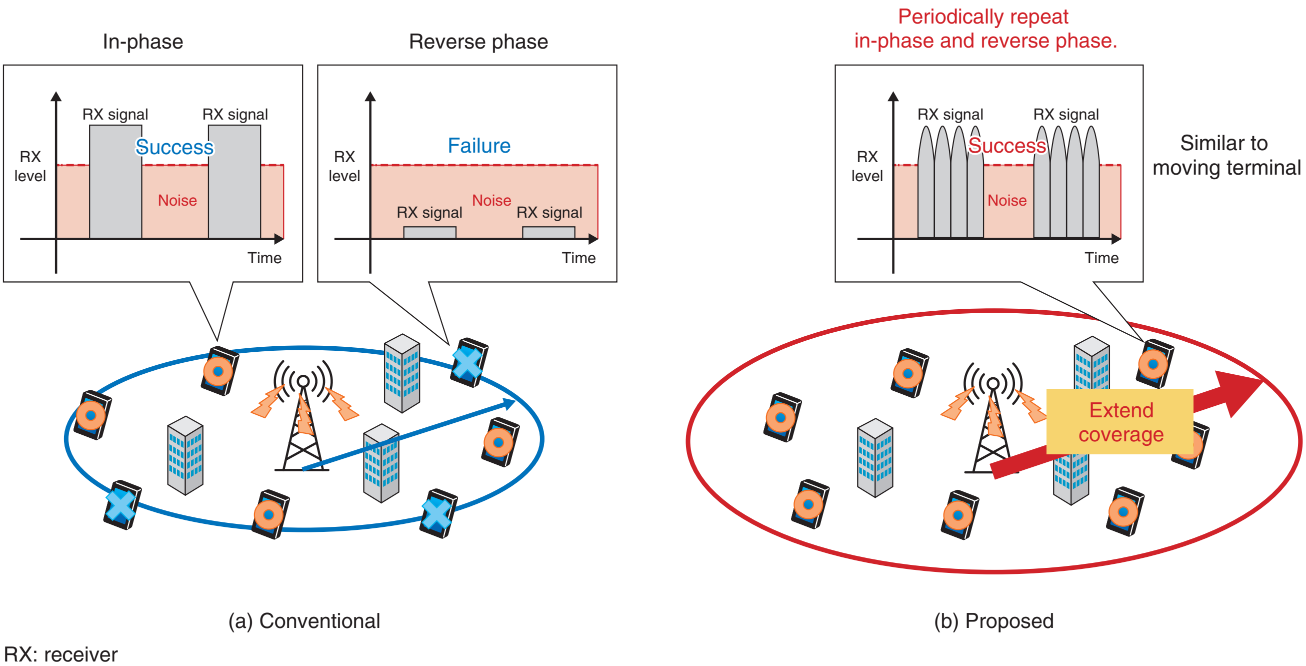


Fig. 2. Technology to extend coverage.

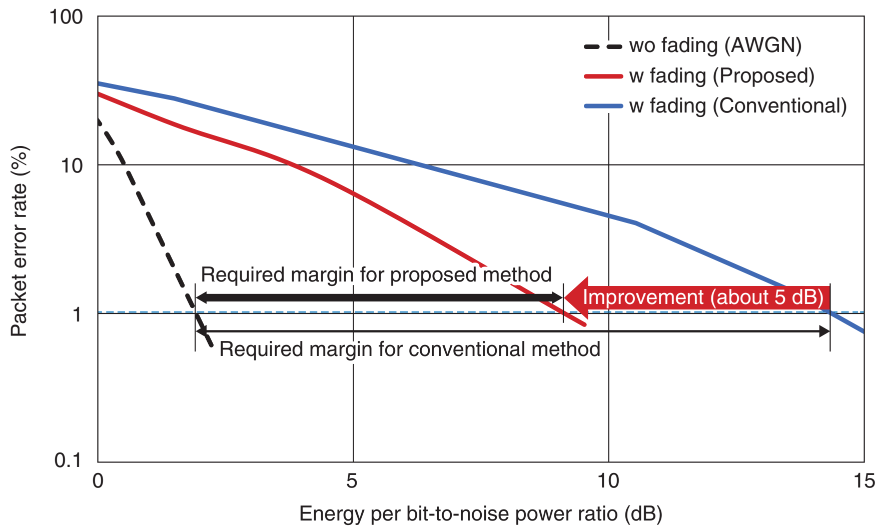
hand, the strength of the received signal significantly weakens at positions where two waves with reverse phase, or a 180-degree difference from one another, are combined. To cope with such fluctuations in strength, wireless communications systems are generally designed with a level margin according to the required quality.

Multi-path fading can cause a level fluctuation at a cycle of one wavelength or less. For instance, in a 1-GHz frequency band, it occurs at a cycle of 15 cm or less. In mobile communication systems where users typically use cell phones holding them in their hand, the terminal moves around naturally by about several centimeters. Moreover, it is possible for a person to autonomously move the terminal when it is not connected with a base station. Therefore, the link level margin that takes into account the effect of multi-path fading can be reduced more than in other communication systems.

In contrast, when the terminal is installed in a fixed position and does not autonomously move, as in a sensing system for underground infrastructures, a large level margin is required since the phase relationship of arrival waves is unchanged. This margin is a factor that limits the communication distance for IoT wireless systems.

To address this problem, we have developed a technology that suppresses the fluctuation of the reception level by transmitting radio waves from multiple antennas simultaneously with slightly different frequencies [7]. This makes it possible to forcibly change the phase relationship of arrival waves at the fixed reception point. This is analogous to generating a slight movement of the terminal. As a result, the arrival waves are not combined in reverse phases. Hence, the required level margin can be reduced, and the coverage area can be extended, as shown in **Fig. 2(b)**. Although the reception level fluctuates greatly within a packet by applying this technique, such distortion can be recovered by a receiver equipped with compensation functions for movement if an appropriate frequency offset is set.

This technology can be applied to various wireless systems. As an example, we experimentally evaluated the effectiveness of this technology when applied to a LoRa system. The relationship between Eb/No (signal energy versus noise power density ratio per bit) and packet error rate (PER) under the multi-path fading environment is shown in **Fig. 3**. The graph shows that the proposed method reduces the required Eb/No at the 1% point of PER by about 5 dB compared to the conventional method. This means that the level margin can be reduced by about 5 dB when designing a coverage area with a 1% dead zone (the ratio of



AWGN: additive white Gaussian noise

Fig. 3. Performance of packet error rate.

terminals that cannot communicate) allowed. In non-line-of-sight communications, the signal strength is mostly inversely proportional to the third power of the distance. Hence, the proposed method can extend the reachable distance by about 1.5 times longer than the conventional method by reducing the level margin of 5 dB.

4. Technology for reducing power consumption

IoT radio devices have achieved a battery life of several years by saving power consumption using the sleep state. However, power saving using sleep modes cannot easily be applied with relay stations since they are always waiting for data to arrive from sensor terminals and must remain in a receive mode. Therefore, another means of reducing power consumption is necessary to extend the battery life of relay terminals.

A method referred to as preamble sampling has been proposed to achieve a way for receivers to wait for data reception with low power consumption [8]. In preamble sampling, the receiver performs preamble detection at regular intervals as it waits for the arrival of data. Meanwhile, before the transmitter sends data, it transmits preambles with longer lengths than the period of receiver detection intervals. This makes it possible for the receiver to receive signals without fail, as shown in **Fig. 4(a)**. With preamble detection, reliable signal detection can be achieved in a short time even in environments where large environmental noise exists, or when the noise power is greater than the signal power. CSL (coordinated sampled listening), which is a kind of preamble sampling, is adopted as the power saving technology in IEEE* 802.15.4e.

However, in an unlicensed band shared by various wireless systems, it is impossible to send a long preamble with a length that is longer than a certain length because the air time of a radio signal at one time is limited by the radio laws of each country. For example, in Japan's 920-MHz band, the continuous transmission time at one instance is limited to 400 ms (4 s). For this reason, an intermittent standby with intervals longer than a certain length cannot be achieved. Hence, reducing the power consumption of repeaters is difficult.

To address this issue, we have developed a technique to activate a relay terminal using multiple transmission of divided preambles. This involves appropriately controlling the transmission length and the transmission interval of divided preambles, making it possible to reliably activate the relay terminals with the shortest time and minimum power while waiting for the arrival of data at an arbitrary reception interval, as shown in **Fig. 4(b)**. The method enables relay terminals to set a long intermittent reception interval that does not depend on the continuous transmission

* IEEE: Institute of Electrical and Electronics Engineers

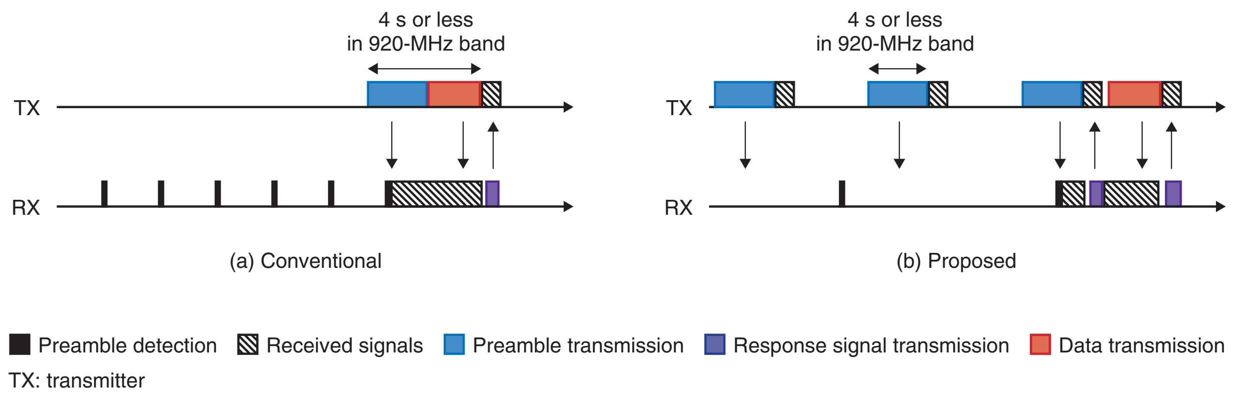


Fig. 4. Power saving standby operations.

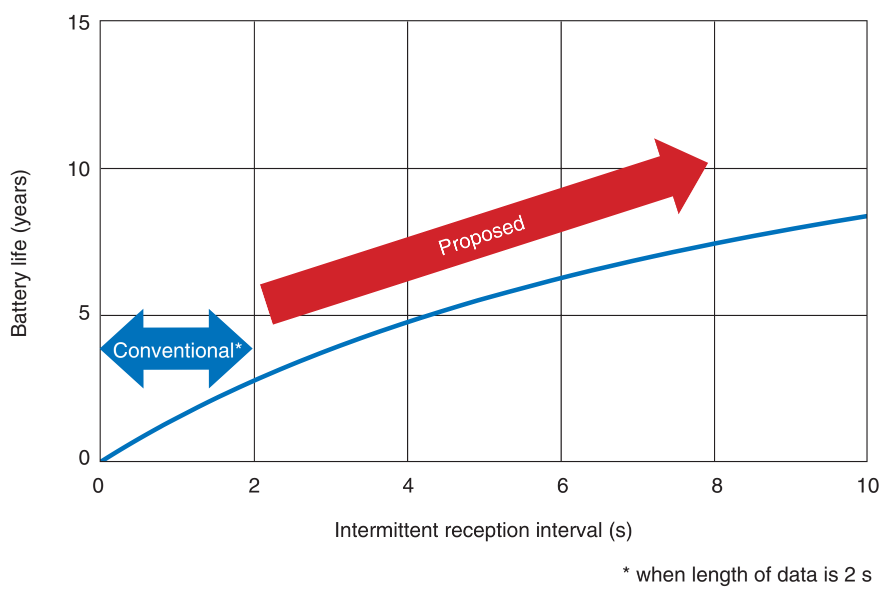


Fig. 5. Performance of power saving technology.

time that is restricted by radio laws. Hence, the repeater can be driven by the battery for several years.

As an example, we conducted an experiment to evaluate the effectiveness of our proposed method for wireless systems using Japan's 920-MHz band. The relationship between an intermittent reception interval and battery life is shown in **Fig. 5**. In the experiment, the battery capacity was 3000 mAh, the current consumption for data transmission and measurement was 0.5 mAh per day, and the current consumption at reception was 20 mA. The period of intermittent reception time was 10 ms. This technique enables repeaters to set a long intermittent reception interval regardless of the transmission time limit. Moreover, a battery life of five years or more can be achieved by setting the intermittent reception interval to 5 s or more.

5. Future work

We will continue to carry out research and development while working in cooperation with water enterprises and leakage research organizations to further advance the technology described here. In addition, because the extension technology and power saving technology introduced in this article are general-purpose technologies independent of the radio system, we plan to promote horizontal deployment to various uses other than underground infrastructure monitoring.

Acknowledgment

Part of this work was supported by the Council for Science, Technology and Innovation project called "Cross-ministerial Strategic Innovation Promotion Program (SIP), Infrastructure Maintenance, Renovation, and Management" (Funding agency: JST).

References

[1] Japan Water Works Association, "Water Statistics," No. 97, 2014.
[2] Recommendation ITU-R P.2109-0: "Prediction of Building Entry Loss," 2017.
[3] S. Teruhi, Y. Yamaguchi, and J. Akahani, "Water Leakage Detection System for Underground Pipes by Using Wireless Sensors and Machine Learning," Journal of Disaster Research, Vol. 12, No. 3, pp. 557–568, 2017.
[4] S. Yoshino, "R&D on Technologies for Collecting, Transmitting, and Processing Sensing Data of Civil Infrastructures (Underground Structures)," Booklet of the Cross-ministerial Strategic Innovation Promotion Program (SIP) Infrastructure Maintenance, Renovation and Management, pp. 88–89, 2017.
https://www.jst.go.jp/sip/dl/k07/booklet_2017_A4_en.pdf
[5] LoRa Alliance, https://www.lora-alliance.org/
[6] Website of Sigfox, https://www.sigfox.com/
[7] Y. Fujino, S. Kuwano, S. Ohmori, T. Fujita, and S. Yoshino, "Cell Range Extension Techniques for Wide-area Ubiquitous Network," Proc. of the 10th International Symposium on Autonomous Decentralized Systems (ISADS 2011), Kobe, Japan, June 2011.
[8] A. El-Hoiydi, "Aloha with Preamble Sampling for Sporadic Traffic in Ad Hoc Wireless Sensor Networks," Proc. of the 2002 IEEE International Conference on Communications (ICC 2002), New York, USA, Apr. 2002.

Trademark notes

Yosuke Fujino

Research Engineer, Wireless Systems Innovation Laboratory, NTT Network Innovation Laboratories.

He received a B.E. and M.E. in electrical and electronic engineering from Shizuoka University in 2002 and 2004. He joined NTT Network Innovation Laboratories in 2004 and engaged in research on multi-user detection for a multi-antenna, multi-user wireless system. He is currently researching a low-latency and low-power media access control (MAC) protocol and transmitter diversity for IoT wireless systems. He is a member of the Institute of Electronics, Information and Communication Engineers (IEICE).

Hiroyuki Fukumoto

Researcher, Wireless Systems Innovation Laboratory, NTT Network Innovation Laboratories.

He received a B.E. in engineering from Kobe University in 2013, and an M.E. in informatics from Kyoto University in 2015. He has been with NTT Network Innovation Laboratories since 2015. His research interests include digital signal processing and information theory in communication systems. He received the Best Paper Award from IEICE SmartCom 2016 and the Best Paper Award and Special Technical Award in Smart Radio from IEICE Smart Radio in 2017.

Hajime Katsuda

Researcher, Wireless Systems Innovation Laboratory, NTT Network Innovation Laboratories.

He received a B.E. and M.E. from Tohoku University, Miyagi, in 2011 and 2013. Since joining NTT Network Innovation Laboratories in 2013, he has been engaged in research and development (R&D) of wireless technology for IoT wireless access systems. He received the Young Researcher's Award from IEICE in 2016. He is a member of IEICE.

Kazunori Akabane

Senior Research Engineer, Supervisor, Wireless Systems Innovation Laboratory, NTT Network Innovation Laboratories.

He received a B.E. and M.E. from Keio University, Kanagawa, in 1994 and 1996. He joined NTT Wireless Systems Laboratories in 1996, where he has been involved in the R&D of wireless personal communication systems and software-defined radio systems. He is currently engaged in R&D of IoT/M2M (machine-to-machine) wireless access systems.