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- Title
Wireless communication for environmental monitoring at waste landfills using low-frequency electromagnetic waves

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Abstract: Wireless sensor networks (WSNs) have become indispensable for environmental monitoring, especially in infrastructures like waste landfills. This research probed the feasibility of underground WSNs employing low-frequency electromagnetic waves (LFEMW) for transmitting data from sensors embedded within landfill waste layers to surface-based receivers. A conceptual WSN system was designed wherein data from these underground sensors was relayed via LFEMW to a surface receiver. This receiver subsequently forwarded the data to a cloud server. We investigated various factors that might influence LFEMW communication performance, including equipment installation conditions and the specific characteristics of landfill waste. Experiments conducted with incineration ash showcased the potential of LFEMW for underground communication. Furthermore, the research delved into how waste attributes like density, moisture, and metal content can impact communication, thereby reinforcing the practicality of using LFEMWs in landfill contexts. Conclusively, the study affirmed successful wireless communication within a simulated waste landfill over a span of 1 year, highlighting the promise of LFEMWs for consistent, real-time monitoring in landfill scenarios.

Keywords: wireless communication, low-frequency electromagnetic waves (LFEMW), waste

landfills, environmental monitoring

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Introduction

In recent times, both private and public sector organizations are compelled to explore cutting-edge technologies and their potential applications for the purpose of digital transformation (DX). DX can be divided into three distinct categories: technology readiness, technology exploration, and technology exploitation [1]. Information and communication technology (ICT), encompassing wireless communication, diverse sensors, and big data analysis, is advancing rapidly and stands as a pivotal technology for DX. The concept of smart cities, where ICT merges with the existing urban infrastructure, which is then harmonized and managed using digital tools, is progressively transitioning from concept to reality [2]. To ensure the sustainability of these smart cities, it becomes crucial to monitor the environmental safety of critical infrastructures, including waste treatment facilities such as landfill sites.

Environmental monitoring is imperative at waste landfills to comprehend various factors such as waste properties, temperature, water quality, composition of generated gases, and other parameters. Within the layers of landfill waste, heterogeneous physical, chemical, and biological reactions occur based on their specific locations. Consequently, in order to facilitate effective environmental monitoring across extensive and diverse landfill waste layers, a monitoring system capable of prolonged, automated observations across multiple points within the landfill becomes indispensable. To realize such multi-point automated observation, the utilization of sensor networks employing wireless communication proves invaluable [3], often referred to as wireless sensor networks (WSNs).

For efficient environmental monitoring at landfills, the establishment of subterranean WSNs is essential to transmit data collected by sensors positioned within underground landfill waste layers to the surface level. In recent years, the application of underground WSNs utilizing electromagnetic waves has garnered significant attention for various purposes and applications [4]. The advantages of underground WSN technology have been highlighted as follows [5] [6]:

1.Real-time information dissemination from underground without the need for cabling.

2. Easy installation of sensors and related equipment.

3. Prevention of potential collisions between sensors, cables, and machinery like trucks and bulldozers.

In the realm of subterranean wireless communication through electromagnetic waves, soil moisture content notably influences communication range and overall network performance. In many practical scenarios, wireless communication techniques employing high-frequency electromagnetic waves, such as Wi-Fi and Bluetooth, are only viable for exceedingly short transmission distances due to substantial path loss and susceptibility to variations in soil moisture [7]. Conversely, wireless communication technology grounded in low-frequency electromagnetic waves (LFEMW) can be employed in conductive media, including soil and water, in addition to air [8][9]. However, scant research has evaluated the applicability of

LFEMW within waste landfills. Thus, this study endeavors to investigate the attributes of LFEMW with the intention of establishing a WSN system tailored to waste landfill environments.

Wireless communication system for waste landfills

Figure 1 shows a conceptual image of a WSN based monitoring system for landfills. In this communication system, the data measured by sensors installed in landfill waste layers or on geomembrane sheets are transmitted to a receiver on the ground through LFEMW. The receiver on the ground transmits the data to a cloud server or a receiving device through a Wi-Fi or other method. Factors that could potentially affect the communication performance of LFEMW equipment installed within a landfill include: 1) those related to the installation conditions for both the transmitter and receiver, and 2) those associated with the characteristics of the landfill waste that serves as the communication medium. For the former, it's believed that the distance between the transmitter and receiver, and their installation angle are significant. Regarding the latter, characteristics of the landfill waste that acts as the communication medium (in this study, incineration residues which are the primary materials in municipal solid waste landfills in Japan) such as density, moisture content, and the degree of contamination with metals that can impact communication, like iron scrap, are notable. Consequently, this study individually assessed the effects of these factors on LFEMW communication. Other potential factors include, for the former, the naturally occurring geomagnetic strength of the installation location, and potential radio wave interference when strong power sources or devices emitting radio waves (e.g., high-voltage power lines) are nearby. For the latter, while it's recognized that the temperature and salinity of the communication medium can influence communication, it was deemed that within the temperature range and salinity range of the landfilled waste and leachate in the targeted landfill site, the impact isn't significant, hence it was not examined in this study. In addition, we verified whether long-term data communication is possible based on a simulated waste landfill.

Table 1 provides an overview of the communication equipment used in this study. A transmitter consisted of a temperature sensor, a data logger, a transmission circuit, a transmission coil (antenna), and a battery. Measurement data were sent by LFEMW to the receiver consisted of a receiving coil (antenna) and receiver body which is connected to a computer, and measurement data were recovered.

Effect of installation conditions for both transmitter and receiver on LFMEW communication performance

As illustrated in Figure 2, wooden tanks filled with incineration ash were connected, and the receiving-end voltage was measured at communication distances of 1.8 m, 3.6 m, 5.4 m,

7.2 m, and 9.0 m. The incineration ash used, from which iron had been removed through magnetic separation, served as the landfilled waste. During measurements, the transmitter was embedded at one edge of the tank, while the receiver was placed at the opposite edge. To ensure that only electromagnetic waves passing through the incineration ash were measured, the receiver was encased in a shield against external electromagnetic interference.

The relationship between the receiving-end voltage and the communication distance is depicted in Figure 3. This figure illustrates instances where the receiving-end voltage was measured using incineration ash as the communication medium. For comparison, it also shows cases where the receiving voltage was measured in open air. As the communication distance increased, the receiving-end voltage decreased due to distance attenuation. For the equipment utilized in this study, the minimum receiving-end voltage necessary for communication was 1.5 mVrms. This value is three times the background noise level of 0.5 mVrms observed during the experiment. Therefore, communication was feasible at any communication distance through the tanks filled with incineration ash. The receiving-end voltage at a communication distance of 1.8 m remained consistent at 5,000 mVrms in both air and incineration ash. At a distance of 9.0 m, the receiving-end voltages were 70 mVrms in the air (an attenuation rate of 98.6%) and 55 mVrms in the incineration ash (an attenuation rate of 98.9%). The attenuation rate difference at a communication distance of 9.0m between air and incineration ash was a mere 0.3%. Given that the incineration ash is presumed to have higher magnetic permeability (μ) and conductivity (σ) than air, the receiving-end voltages through the ash were lower than those in the air.

The strength of the magnetic field H (A/m), is given by Equation (1) which incorporates variables such as I (A), surface area of the antenna S (m^2), communication distance D (m), frequencies ω (rad/s), magnetic permeability μ (H/m), and conductivity σ (S/m).

$$H = \frac{IS}{2\pi D^3} e^{-\sqrt{\frac{\omega\mu\sigma}{2}}D} \text{ (A/m)} \quad \cdots\cdots (1)$$

For short-range communications, the magnetic field strength H (A/m) exhibits a linear relationship with the receiving-end voltage Vr (mVrms). Referring to the correlation between the receiving-end voltage Vr(mVrms) and distance D (m) illustrated in Figure 3, Equation (2) can be formulated without considering individual factors such as I (A), S (m^2), ω (rad/s), μ (H/m), and σ (S/m):

$$Vr = \frac{29333}{D^3} e^{-0.0035D} \text{ (mVrms)} \quad \cdots (2)$$

Inserting the minimum receiving-end voltage of 1.5 mVrms required for communication into this equation yields a maximum communication distance of 26 m through incinerated ash

for the LFEMW transmitter used in this study. This distance significantly surpasses the average landfill depth of 11 m, derived from data spanning 1,698 Japanese landfills [10]. Considering the landfill depth, underground communication using LFEMW is feasible in landfills.

The experiments conducted above were based on the premise that a transmitter, located within an underground waste layer in a landfill, would transmit data vertically to a receiver on the surface. However, during the actual deployment of this system in waste landfills, the placement of transmitters and factors from daily landfill operations can alter the orientation of transmitters relative to the receiver. Consequently, this study also investigated the effects of varying the orientation of the transmitter with respect to the receiver on the receiving-end voltage. As illustrated in Figure 4, the transmitter was oriented both vertically and horizontally relative to the ground surface, at angles denoted as θ and ϕ, respectively. These angles were adjusted to -90°, -45°, 0°, 45°, and 90°. At θ and ϕ values of 0°, the coils of the transmitter and receiver were aligned parallel to their axial directions. Figure 5 depicts the relation between the receiving-end voltage and these installation angles. The receiving-end voltage peaked when the transmitter and receiver coils were aligned parallel to their axes. As the transmitter's angle deviated from this alignment, the receiving-end voltage diminished. The attenuation rates for angles θ and ϕ between 0° and 90° amounted to 75% and 83%, respectively. Applying Equation (2), the maximum communication distance at a θ of 90° was deduced to be 16 m, and at a ϕ of 90°, it was 14 m. These distances are still greater than the average landfill depth of 11 m in Japan. It's worth noting that these calculations were made under the assumption that the rate of voltage attenuation for each angle remains consistent, independent of communication distance.

Effect of landfill waste characteristics on LFMEW communication performance

Using the two tanks depicted in Figure 2, the receiving-end voltage at a 3.6m communication distance was evaluated under varying wet packing densities: 1.0 t/m^3, 1.25 t/m^3, 1.5 t/m^3, and 1.75 t/m^3. These densities were chosen based on data from boring surveys at a landfill site predominantly composed of incineration ash [11]. In every scenario, the receiving-end voltage was a consistent 580 mVrms, showcasing no dependency on packing density. Given the set experimental conditions, which spanned the potential range of packing densities for incineration ash, density appeared to have no significant impact on wireless communication via LFEMW.

Following this, the effect of water content in the incineration ash on the receiving-end voltage was explored. Water was introduced to the wooden tanks (depicted in Figure 2). The water content in the incineration ash increased from 24% pre-watering to 35% post-watering. Figure 6 illustrates the relationship between the receiving-end voltage and communication distance under each condition. For a communication distance of 9.0 m, the receiving-end

voltages were 55 mVrms for the ash before watering and 50 mVrms after watering.

Furthermore, to examine the impact of iron scraps in the incinerated ash, rebars (deformed iron rebars: Φ13 mm × 400 mm) were embedded in the ash, as displayed in Figure 7. The receiving-end voltage at a 1.8m communication distance was recorded. Given that the mass ratio of iron in incineration ash before magnetic sorting was around 5%, we set the mass ratio of rebars to 0%, 1%, 2%, 5%, and 10% (see Table 2). Figure 8 demonstrates the correlation between the receiving-end voltage and the rebar mass ratio. With a rebar ratio from 0 to 5%, the receiving-end voltage remained steady at 4,000 mVrms. However, at 10%, it dropped marginally to 3,750 mVrms.

To delve deeper, another experiment was carried out, focusing on the arrangement of rebars and its potential effect on the receiving-end voltage (detailed in Table 3). As Figure 9 suggests, when rebars encircled the transmitter (Condition 5), the receiving-end voltage diminished the most, reaching 3,000 mVrms with the S/N ratio dropping to 75 dB. The S/N ratio was determined using the formula S/N = (dB), incorporating the receiving-end voltage VS (mVrms) and noise level VN (mVrms). This decline in receiving-end voltage might be attributed to the formation of eddy currents on the nearby rebars, which results in voltage loss as heat. Alternatively, the rebars around the transmitter might act as coils, inducing an electromagnetic field opposing the original field created by the transmission coil [12].

One-year LFEMW communication experiment in a simulated landfill

A simulated waste landfill was constructed, comprising five layers of solidified incineration residue topped with a soil cover layer. To evaluate the feasibility of data communication using LFEMW within this simulated landfill, two transmitters equipped with temperature sensors were positioned between the first and second layers as well as between the fourth and fifth layers, as illustrated in Figure 10. A prefabricated building was situated 12 meters away from the simulated landfill, housing a receiver, computer, and other essential equipment.

Figure 11 presents the measurement results of internal temperatures within the landfill as recorded by the temperature sensors connected to the LFEMW transmitters and by wired thermocouples. From November 2021 to October 2022, a period of approximately 1 year, temporary data reception interruptions occurred in April to July 2022 due to issues with the PC connected to the receiver; however, excluding that period, temperature data was continuously received. Furthermore, we confirmed that the measured data matched the temperature data measured using wired methods.

Table 4 presents data on the receiving-end voltage, noise level, and S/N both inside and outside the prefabricated building at a communication distance of 12 meters. Notably, the S/N decreased within the prefabricated structure. This phenomenon can be attributed to two primary factors:1)The metal structure of the prefabricated building encompassing the receiver likely attenuated the receiving-end voltage. 2)Within the building, electromagnetic

interference, termed as artificial noise, emanated from electronic devices such as the computer, elevating the surrounding noise level.

Conclusions

In this study, the potential of LFEMW for environmental monitoring in waste landfills was evaluated. Key findings from the investigation can be summarized as follows:

1. Communication through incineration ash: LFEMW demonstrated a promising capability to communicate through layers of incineration ash, with only marginal differences in attenuation rates when compared to communication through air.
2. Orientation and distance: The orientation of the transmitter relative to the receiver did affect the receiving-end voltage. However, even with these angle deviations, the maximum communication distance using LFEMW was determined to be greater than the average landfill depth in Japan, making it feasible for practical applications.
3. Waste characteristics: Variations in the packing density of incineration ash had negligible effects on LFEMW communication. Water content had only a slight impact on the receiving-end voltage. The presence of rebars did influence the communication, especially when they surrounded the transmitter, but the effect was manageable and understood.
4. Simulated landfill experiment: The successful implementation of a wireless sensor network in a simulated waste landfill using LFEMW was demonstrated over a four-month period. This not only provided proof of concept but also showcased the robustness of the LFEMW communication method in realistic scenarios.
5. S/N ratios: The signal-to-noise (S/N) ratio is crucial for ensuring reliable communication. Since S/N decreased when the receiver and other electronics were installed in the building, it would be desirable to remove the receiving coil (antenna) from the body of the receiver and install it outside.

In conclusion, the application of LFEMW offers a promising avenue for the environmental monitoring of waste landfills. This wireless communication method can potentially provide real-time, multi-point observations within landfill layers, paving the way for more efficient and comprehensive environmental monitoring systems in the future. As digital transformation continues to reshape our urban infrastructures, leveraging such advanced technologies will be pivotal for achieving sustainable smart cities. Future research should focus on optimizing the system, addressing potential interferences, and conducting long-term field trials in diverse landfill conditions to further validate and improve upon these findings.

To enhance the efficiency and applicability of LFEMW technology, several improvement suggestions have emerged from the study. Firstly, while the research primarily focuses on

incineration residues typical of Japanese waste landfills, broadening the spectrum of materials studied would pave the way for its global application. Another promising enhancement is the introduction of an automated system to adjust the transmitter-receiver angle, especially useful when landfill operations inadvertently move the sensors. Lastly, as we advocate for the deployment of LFEMW in landfills, it's also crucial to probe into any potential long-term environmental repercussions.

Acknowledgements

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Figure and Table Captions

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Figure 3. Relationship between the receiving-end voltage and communication distance
Figure 4. Relationship between the receiving-end voltage and packing density
Figure 5. Relationship between the receiving-end voltage and communication distance before and after spraying with water
Figure 6. The experiment schematics with rebar insertion
Figure 7. Relationship between the receiving-end voltage and the rebar mass ratio
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Table 1. Communication equipment used in this study
Table 2. Rebar arrangement
Table 3. Rebar arrangement patterns

Table 4. Receiving-end voltage and noise level at inside and outside of the prefabricated building

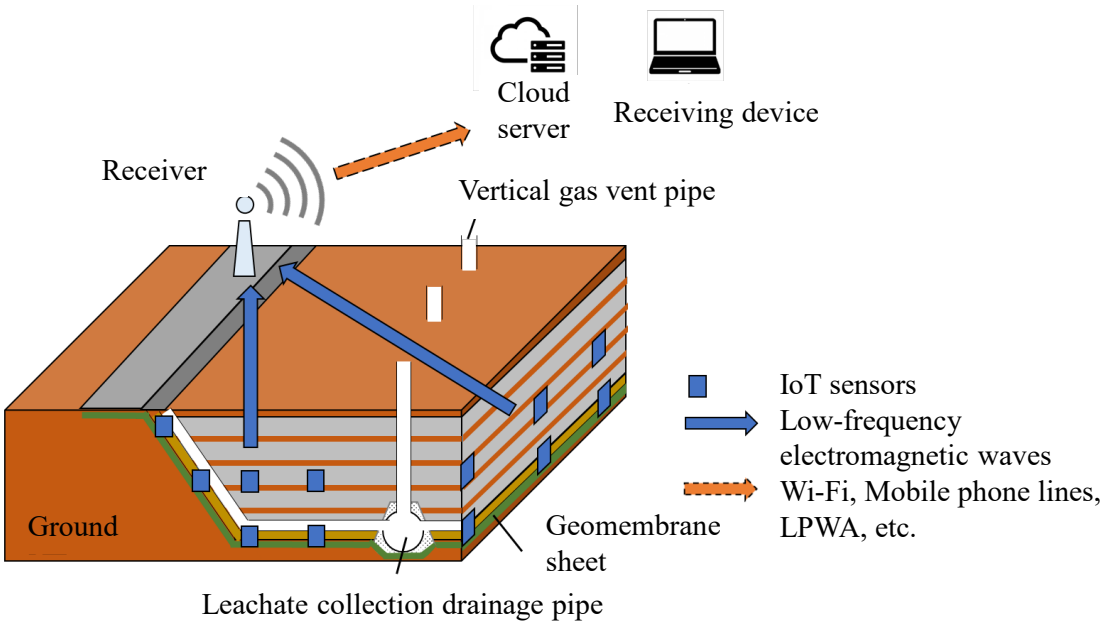


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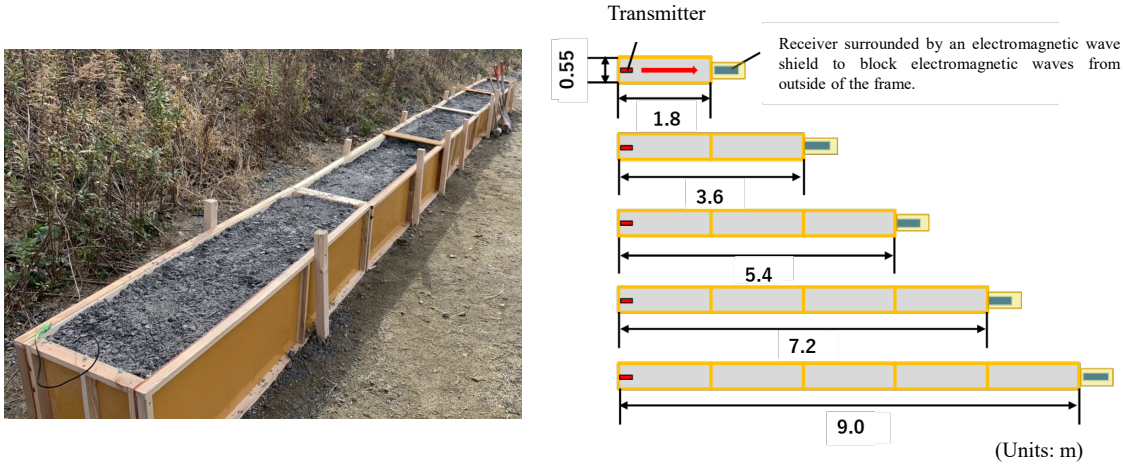


Figure 2. Wooden tanks filled with incineration ash(left) and position of the transmitter and receiver installation along with the tanks (right)

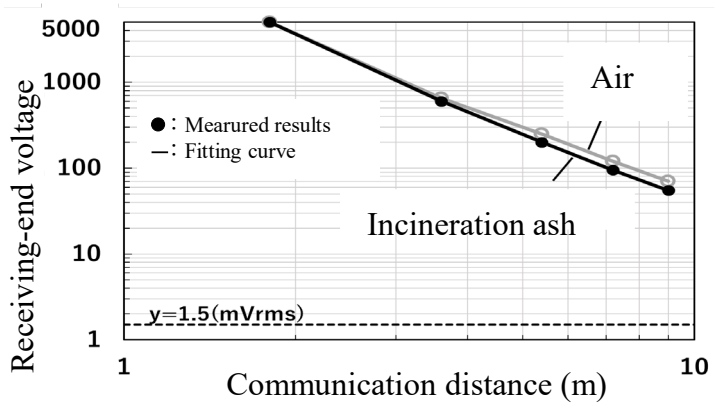


Figure 3. Relationship between the receiving-end voltage and communication distance

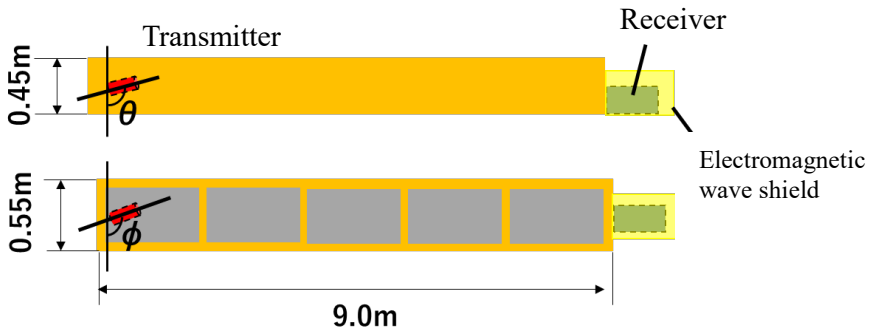


Figure 4. Transmitter installation angles θ and ϕ relative to the receiver

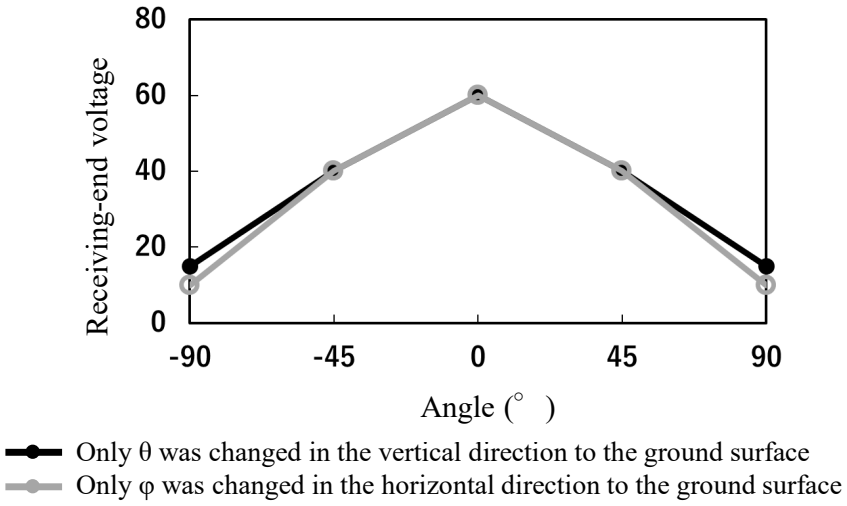


Figure 5. Relationship between the receiving-end voltage and the installation angle

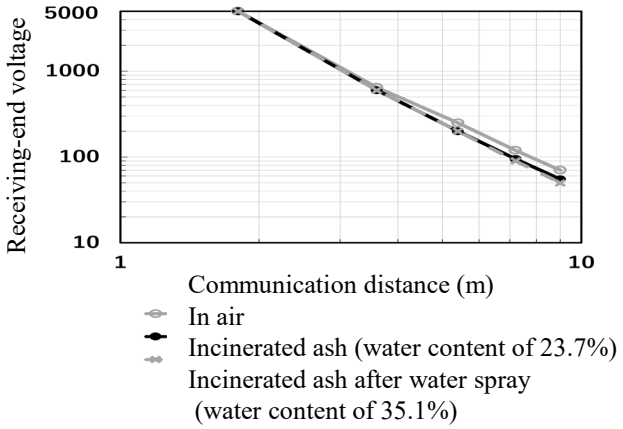


Figure 6. Relationship between the receiving-end voltage and communication distance before and after spraying with water

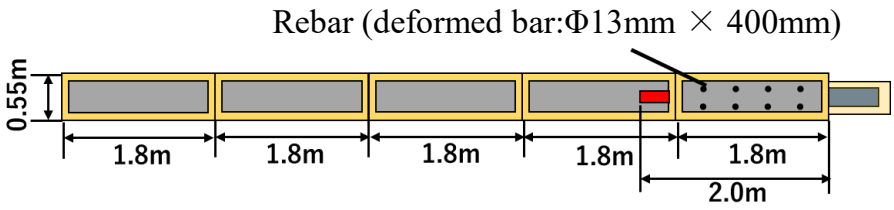


Figure 7. The experiment schematics with rebar insertion

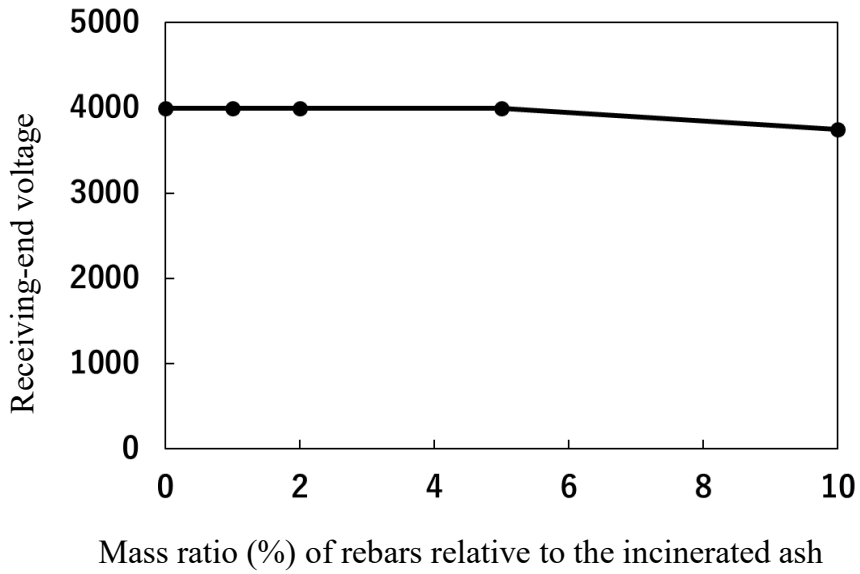


Figure 8. Relationship between the receiving-end voltage and the rebar mass ratio

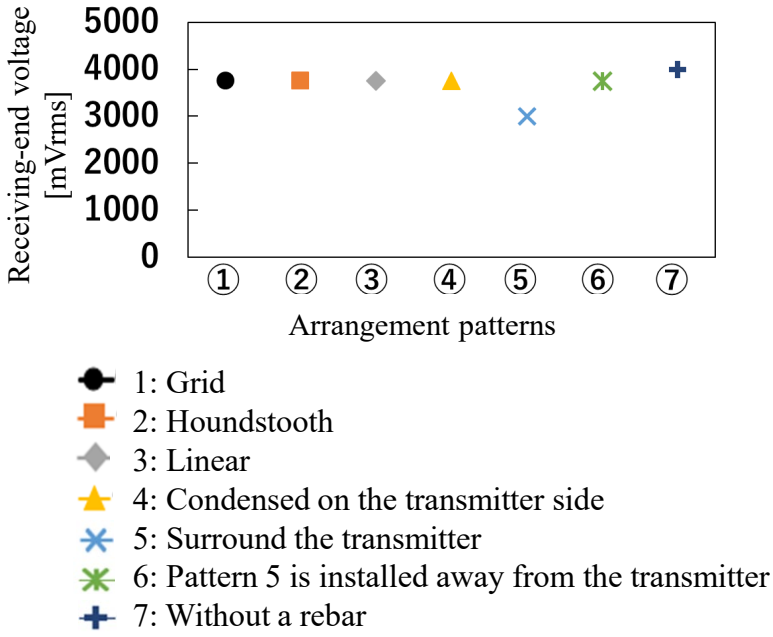


Figure 9. Receiving-end voltage for each arrangement pattern

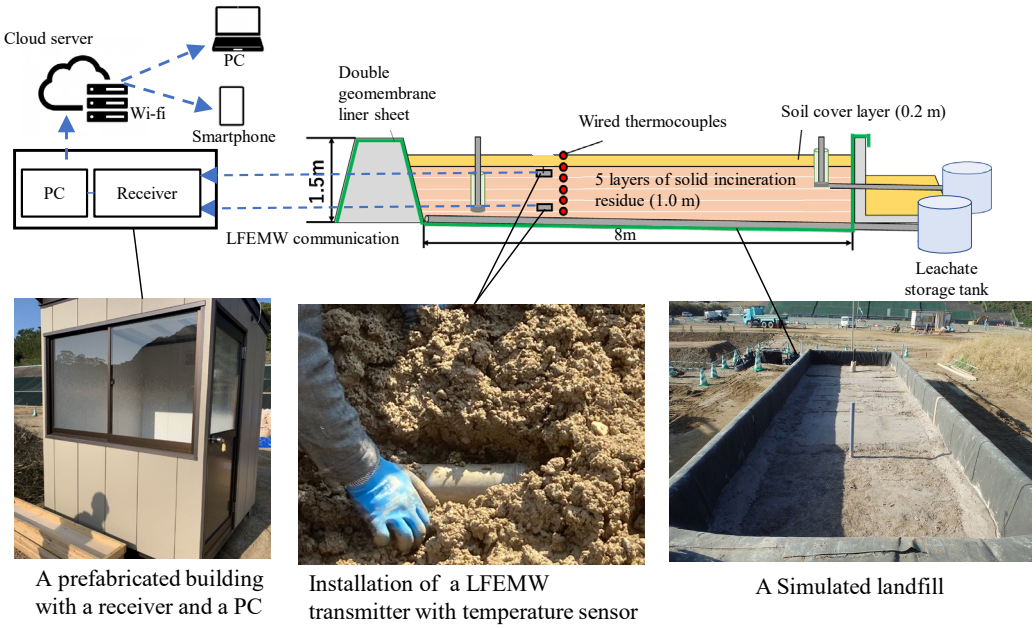


Figure 10. A side view of a simulated landfill and photos of installation of LFEMW communication devices

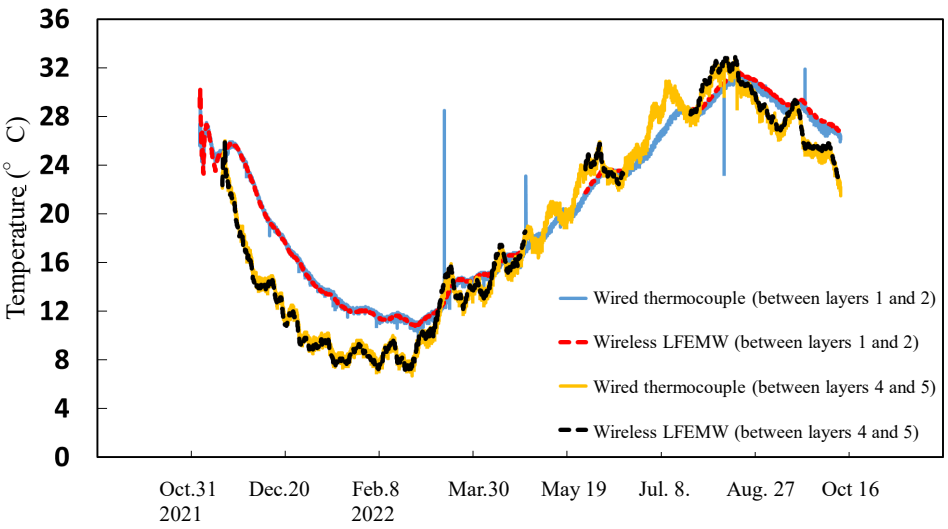


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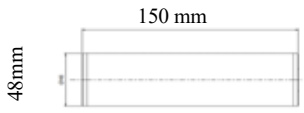
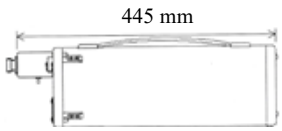
	Transmitter with temperature sensor	Receiver
Size	Φ48 ㎜ × 150 ㎜	140 ㎜ × 140 ㎜ × 445 ㎜
Mass	1 kg	6 kg
Power	Lithium thionyl chloride battery	Lithium-ion battery
Frequency	Low-frequency magnetic field of 8,533 Hz.	
Diagram		

Table 2. Rebar arrangement

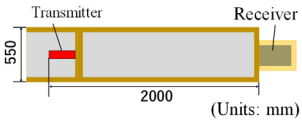
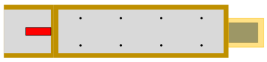
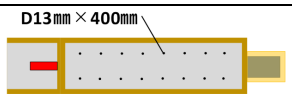
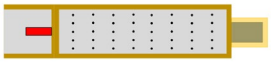
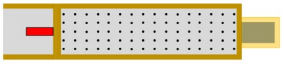
Mass ratio (%) of rebars relative to the incineration ash	Arrangement of rebars	Mass ratio (%) of rebars relative to the incineration ash	Arrangement of rebars
0		1	
2		5	
10			

Table 3. Rebar arrangement patterns

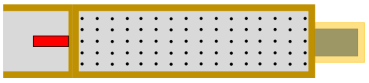
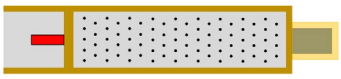
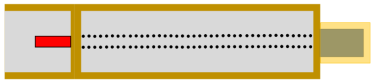
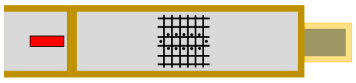
Mass ratio (%) of rebars relative to the incineration ash	Arrangement of rebars	Mass ratio (%) of rebars relative to the incineration ash	Arrangement of rebars
1.Grid		4.Hounds tooth	
2.Linear		5. Condensed on the transmitter	
3.Surrounding the transmitter		6. Pattern 5 is placed away from the transmitter	

Table 4. Receiving-end voltage and noise level at inside and outside of the prefabricated building

	Outside the prefabricated building	Inside the prefabricated building
Receiving-end voltage Vs (mVrms)	30	15
Noise level V_N (mVrms)	0.5	1.5
S/N (dB)	36	20