Implementation of a Multi-UV System for Sewer Inspection Using Bi-Directional Intermittent Multi-hop Video and Command Transmission

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***Abstract*—Video-based inspection using multiple wireless unmanned vehicles (UVs) with camera is a promising approach for small-diameter sewer pipes, where conventional wired or floating cameras face operational and cost limitations. However, the limited wireless communication range within narrow pipes necessitates a multi-hop video data transmission. Operating on a single wireless channel, this network suffers from intra-flow interference issues, necessitating transmission scheduling methods to avoid interference. Furthermore, maintaining network connectivity requires dynamic, coordinated positioning of the UV's movement. This paper proposes a design and implementation of a multi-UV system that addresses these challenges. This system includes "MUCViS", a Bi-IPT-based packet transmission scheduling protocol, and a position control method that manages the UVs' locations and transmission path. The system's performance is evaluated in an indoor pipe environment and an experimental underground pipe.**

***Index Terms*—sewer pipe, wireless LAN, video streaming, multi-hop wireless network, robotics**

I. Introduction

In the management of urban infrastructure, the inspection and repair of aging sewer pipes are critical challenges. For example, in Japan, the total length of sewer conduits nationwide is approximately 490,000 km, and as of the end of March 2023, the length of sewer pipes that have exceeded their standard service life of 50 years is approximately 30,000 km (about 7% of the total length). The length of these aging pipes is projected to increase rapidly, reaching 90,000 km (about 19%) in 10 years and 200,000 km (about 40%) in 20 years [1] . Furthermore, due to the deterioration of sewer pipes, there are approximately 2,600 road subsidence incidents caused by conduit facilities annually.

Current sewer pipe inspection methods, such as visual observation and self-propelled wired unmanned vehicles (UVs), have problems including time-consuming, safety risks, and high costs. Moreover, inspections using boat-type UVs or drifting wireless cameras require sufficient water flow within the sewer pipes to allow the camera to float, and they do not allow for real-time video confirmation.

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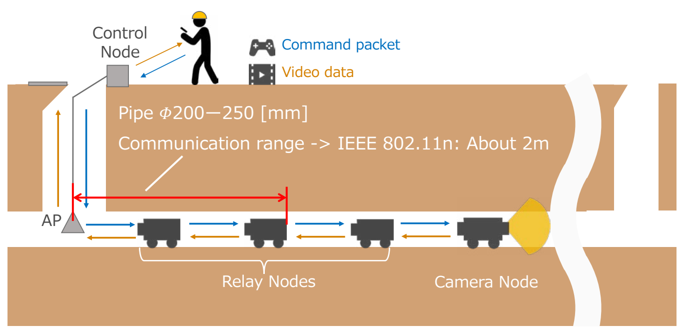


Fig. 1. Sewer pipe inspection system using multiple UVs.

To overcome these limitations, we have developed a sewer pipe inspection system that uses multiple wirelessly controlled UVs. It has become clear that the communication range of wireless LAN is extremely short inside the small-diameter sewer pipes (e.g., about 2 meters for 2.4 GHz band Wi-Fi and less than 10 meters with 5 GHz band Wi-Fi in a 200 mm diameter PVC pipe [2].) To solve this problem, as shown in Fig. 1, we use multiple UVs to form a multi-hop network inside the sewer pipe, thereby extending the inspection range. In this system, video data captured by the leading UV equipped with a camera is transmitted to a control node on the ground via a multi-hop wireless LAN, relayed through intermediate UVs and an access point (AP) placed inside a sewer pipe. An inspector uses the control node to send control commands to each UV. To achieve stable UV control and wireless communication, two key requirements must be met: (i) The distance between two adjacent UVs is maintained to ensure communication connectivity between them at all times, (ii) In multi-hop communication, the reliability of control command is ensured, and sufficient throughput for video data transmission is guaranteed.

Regarding (i), we proposed a position control method, named *Partial expanding method*, in which only one pair of neighboring UVs is changed to avoid occurrence of simultaneous multiple link failures and to minimize the communication overhead associated with route updates [3]. We implemented a combination of the *Partial expanding method* and a simple video and control command transmission mechanism, in which video and control commands are immediately forwarded to their destination without any special scheduling to avoid interference in a multi-hop wireless network. Due to the lack of such scheduling, video transmission problems, such as stalls and noise, frequently occurred.

Regarding (ii), we proposed a bi-directional multi-hop packet transmission method for video data and control commands named *Multi-hop UV Control and Video Streaming (MUCViS)* [4] based on Bi-directional Intermittent Periodic Transmission (Bi-IPT) protocol [5] [6]. When performing multi-hop communication over a single-channel, interference occurs when different nodes simultaneously transmit packets from the same flow. This problem becomes more significant in video streaming, where video data packets are periodically transmitted in bursts from the camera node, causing interference between relay nodes. MUCViS performs video streaming while periodically sending control commands based on a packet delivery schedule designed to prevent interference. Furthermore, to enable implementation on the protocol at the application level, MUCViS introduces a unicast-based notification of packet transmission at the downstream node to the upstream node while the original Bi-IPT uses overhearing for the same purpose. It also incorporates a mechanism to compensate for packet timing jitter.

We implemented MUCViS protocol on Raspberry Pi devices and conducted experiments of video and UV control commands transmission using a simulated wireless environment using fixed nodes and coaxial cables in [7] . Compared with other transmission methods, MUCViS achieved lower packet loss and higher video throughput. However, (i) UV motion control using the Partial expanding method and (ii) video transmission using MUCViS were implemented on separate devices and verified independently. They were not integrated into a single system, and their performance in a real environment has not been evaluated.

This paper proposes design and implementation of a system that integrates the UV motion control and the MUCViS protocol on multiple UVs. Through experiments using the system to validate the effectiveness of MUCViS,we confirmed correctness of the movement of UVs according to the proposed motion control by experiments using a transparent pipe placed indoors. Additionally, we conducted a multi-hop video transmission evaluation using MUCViS on experimental underground pipe. UV control was not performed, and the distance between nodes was fixed shorter than the maximum communication range.

The remainder of this paper is organized as follows. Section 2 describes technologies and issues related to multi-hop UV video transmission and UV control in small-diameter sewer pipes. Section 3 describes the system overview and core technologies. Section 4 describes implementation of the integrated system of UV motion control and the MUCViS protocol. Section 5 presents the experimental results and discussion. Finally, Section 6 concludes the paper.

II. Operational Environment and System Requirement

Achieving long distance wireless communication in small-diameter sewer pipes is a significant challenge. Our study in [2] revealed that the communication range of 2.4 GHz and 5 GHz IEEE 802.11n wireless LAN in a 200 mm-diameter sewer pipe is less than 10 m. Alternative methods such as optical wireless communications (including infrared and visible light) and acoustic communications (including ultrasonic waves) are hard to use for wireless UV systems due to the difficulty of handling highly directional optical signals, weight of optical communication interface, and low-speed bit rates of acoustic communication for video data transmission. Therefore, we use a multi-hop network using multiple UVs connected via wireless LAN to expand the inspection range and enable real-time inspection. However, two distinct yet interdependent challenges exist for the practical operation of such multi-UV systems.

The first challenge is maintaining network connectivity. In the narrow sewer pipe environment, the limited communication range means that UVs' movement frequently leads to the change of the network topology. Consequently, packet delivery routes must be dynamically updated. The critical issue in this process is the potential for the simultaneous disconnection of multiple links. Such events trigger complex route updates, resulting in significant communication overhead and potential network instability. Therefore, an advanced positioning control strategy that can manage UVs formation while strategically minimizing the routing overhead is required.

The second challenge is ensuring communication quality. When performing multi-hop communication over a single-channel, interference occurs when different nodes simultaneously transmit packets from the same flow. This problem becomes more significant in video streaming, where video data packets are periodically transmitted in bursts from the camera node, causing interference between relay nodes. Furthermore, the system must satisfy conflicting bidirectional communication requirements: the transmission of low-latency, high-reliability control commands from the control node to each UV and the transmission of video data with high throughput from the camera UVs to the control node. Therefore, to support these bidirectional communications while avoiding interference, an advanced network protocol capable of managing packet transmission timing is essential. The following sections detail the system we have designed and the core technologies implemented to address these challenges.

III. System Overview and Core Technologies

The system proposed in this paper is a linear multi-hop network composed of two or more nodes, as shown in Fig. 2. It consists of three functionally distinct types of nodes: a Control Node (CtlN), which serves as the base station for operator control and real-time video monitoring; a Camera Node (CamN), which moves at the front, capturing video footage inside the pipe using its onboard camera; and Relay Nodes (RNs), which are positioned between the CtlN and

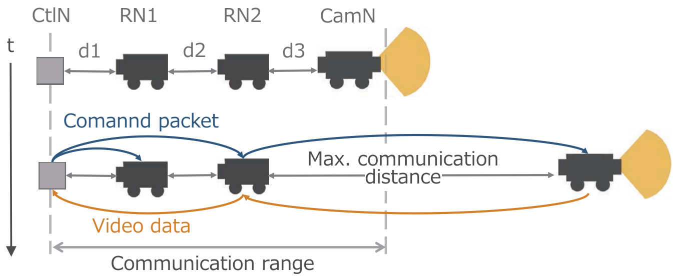
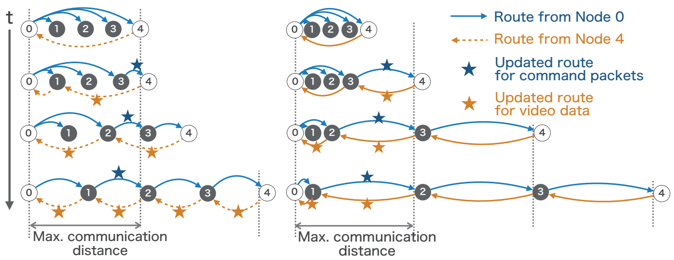


Fig. 2. System Overview



(a) Uniform expanding method (b) Partial expanding method

Fig. 3. UV motion control method

CamN to relay communication data. In this network, video data captured by CamN is transmitted sequentially through the RNs to the CtlN. Conversely, control commands (such as forward/reverse) sent from CtlN are forwarded to each UV. Thus, within the severely limited communication range of sewer pipes, multiple UVs collaborate to construct communication paths, enabling an extended inspection range. To realize this system, two core technologies were implemented to address the key challenges of "maintaining network connectivity" and "ensuring communication quality," which are detailed in the following subsections.

A. Multiple UV's Position Control Methods

Among the UV position control methods for moving CamN while maintaining connectivity between CtlN and CamN, the straightforward approach involves simultaneously and uniformly increasing or decreasing the distance between all adjacent UVs. We refer to this method as *Uniform expanding method* as shown in Fig. 3 (a). With this approach, wireless link connectivity between UVs is lost simultaneously at distinct locations while extending the distance between CtlN and CamN. This triggers complex route updates, resulting in large overhead that can destabilize the network. To address this issue, we propose *Partial expanding method*, in which the distance between only one neighboring UVs' pair is changed as shown in Fig. 3 (b). Each UV has a sensor that measures the distance to the rear adjacent UV. In this method, the UVs are controlled so that the distance of only one neighboring pair is changed at a time. This sequential approach ensures that any link disconnections and topology changes are localized and predictable. By limiting the occurrence of link disconnections to a single, specific part of the UV's platoon, the associated route update overhead becomes small. This minimizes communication overhead and significantly reduces the risk of communication disruption, thereby achieving stable control throughout the entire system.

B. Multi-Hop Transmission Protocol for Video Data and UV Control Commands (MUCViS)

In [4], we proposed a bi-directional multi-hop packet transmission method for video data and control commands, named *Multi-hop UV Control and Video Streaming (MUCViS)*, based on the Bi-directional Intermittent Periodic Transmission (Bi-IPT) protocol designed for single channel wireless multi-hop networks [5] [6]. MUCViS performs video streaming while periodically sending control commands according to a packet delivery schedule designed to prevent interference. Furthermore, to enable implementation at the application layer, MUCViS introduces a unicast-based notification of packet transmission from the downstream node to the upstream node. This replaces the overhearing mechanism used in the original Bi-IPT, which makes its implementation difficult with off-the-shelf Wi-Fi devices. It also incorporates a mechanism to compensate for packet timing jitter, which ensures stable packet intervals under fluctuating processing delays. This scheduling design ensures that packet transmissions are triggered only by reception events, preventing simultaneous transmissions among neighboring nodes.

Fig. 4 shows the basic operation of MUCViS. The protocol defines three node types (CamN, RN, and CtlN) and three UDP packet types (control command, video data, and dummy packets). The direction from the CtlN to the CamN is defined as upstream, and the direction from CamN to CtlN as downstream. Each type of nodes operates as follows.

CamN: The CamN periodically transmits video data packets downstream at a fixed Intermittent Periodic Transmission (IPT) interval, which is designed to be longer than the time required for packet forwarding over three hops. This prevents nodes from transmitting simultaneously with nodes within two hops, thereby avoiding intra-flow interference. If no video data is available, the CamN sends dummy packets to maintain the transmission schedule. When a control command packet is received in the upstream direction, the CamN extracts and applies the command.

RN: Each RN forwards packets by using the reception of a downstream packet as a trigger for its own transmission. Upon this trigger, the RN applies a prioritization rule: it first checks its control command queue. If a high-priority command is present, the RN transmits it upstream. If the command queue is empty, it forwards the received video or dummy packet downstream. This trigger-based forwarding mechanism ensures that critical control commands can propagate upstream immediately while preserving the interference-free schedule for downstream video transmission. As a result, simultaneous transmissions among neighboring nodes are avoided.

CtlN: The CtlN does not initiate an independent packet transmission schedule but instead reacts to the downstream packet flow. It uses the reception of any downstream packet as a trigger to transmit. Upon this trigger, the CtlN checks its command queue and, if a command is available, transmits the corresponding control packet upstream. This trigger-synchronized scheduling maintains temporal separation be-

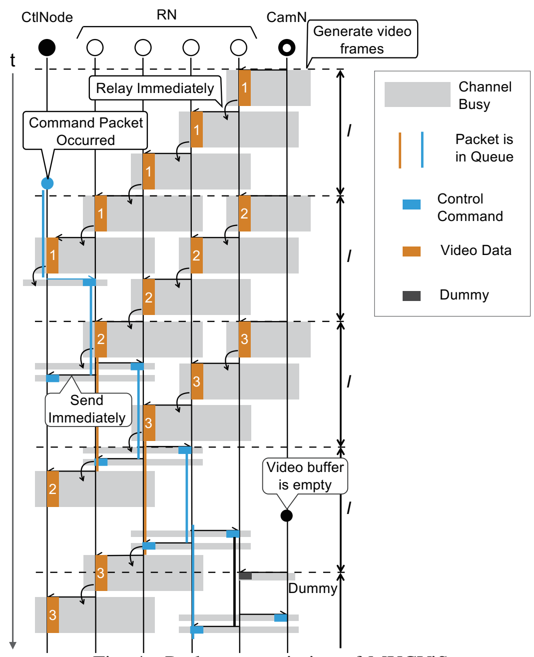


Fig. 4. Packet transmission of MUCViS.

tween upstream and downstream transmissions, achieving collision-free bidirectional communication. Upon receiving video data packets, the CtlN extracts the payload and displays it in real time. As a result, it achieves collision-free bidirectional communication. For a detailed algorithmic description and evaluation, refer to our previous work [4].

IV. Implementation

We designed and implemented a system that integrates the UV motion control method, *Partial expanding method* and the packet transfer method, *MUCViS* on multiple UVs.

A. UV Control

This subsection describes how *Partial expanding method* is implemented as a cooperative position control scheme among multiple UVs. The objective of this control logic is to move the leading CamN to the operator-specified target position L while maintaining network connectivity. As shown in Figure 2, We define d_1, d_2, and d_3 as the real-time distances between CtlN-RN1, RN1-RN2, and RN2-CamN, respectively. Let $d_{\max}$ be the maximum wireless communication distance, and l_{body} be the length of each UV. To maintain these inter-node distances, each node (RN1, RN2, CamN) utilizes a rear-facing optical distance sensor. We used a 1D-LiDAR sensor that can measure distances up to approximately 40 m. In our implementation of the system, each UV measures the distance to the trailing node at 0.2-second intervals. Real-time distance data from this sensor is fed into a PID control loop that controls the UV's drive motor. This enables each UV to autonomously maintain the given distance from the node positioned behind it.

The system operation begins from an initial state where all UVs are proximate to CtlN ($d_1, d_2, d_3 \approx 0$). In this state, CtlN and CamN are within 1-hop communication range, enabling direct data transmission without RNs.

TABLE I
Rules for Transmission Path Updates

Target Position (L)	Path Type	Active Node(s)
$L \leq d_{\max} + 3l_{\text{body}}$	1-Hop Path	CamN
$d_{\max} + 3l_{\text{body}} < L \leq 2d_{\max} + 3l_{\text{body}}$	2-Hop Path	RN2, CamN
$L > 2d_{\max} + 3l_{\text{body}}$	3-Hop Path	RN1, RN2, CamN

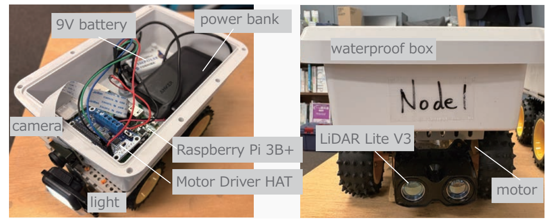


Fig. 5. Wireless Controlled UV

Once the operator gives a new target position of CamN, L, via CtlN, the system follows the transmission path updates method detailed in Table I. Based on the given target position L, CtlN determines the required path configuration. Each UV that becomes active as part of this transmission path then begins to move, using its PID control to achieve the target inter-node distances d_i derived from the specified L. If $L = 0$, all UVs return to their initial positions.

Control commands specifying a new value of L are initiated at CtlN and relayed upstream through the active RNs to CamN. As this command propagates, each UV updates its target distance between itself and its trailing UV according to the new value of L. A key operational constraint is that the difference between a new target L and its previous value is assumed to be less than $d_{\max}$. This constraint ensures that the system expands sequentially, transitioning in order (1-Hop $\rightarrow$ 2-Hop $\rightarrow$ 3-Hop) as the target distance L increases. This gradual expansion prevents multiple link breaks during the UVs' movement for the new L's value and maintains continuous network connectivity.

B. Communication Packets

Control command packets are $64\,\text{bytes}$ long and deliver commands including L's value from the CtlN to the UV's in the system. Video data packets are up to $1472\,\text{bytes}$ long and deliver video data from CamN to CtlN. Dummy packets are $4\,\text{bytes}$ long and are sent up to three times consecutively when no video data are present in the transmission buffer of camN. The maximum video data packet queue size for RNs is 10 packets.

C. UV Hardware and Software

We designed and implemented wirelessly controlled UVs capable of moving in sewer pipes, shown in Fig. 5.

They use IEEE 802.11n wireless interface of the Raspberry Pi 3B+, which employs the Cypress CYW43455 Wi-Fi chipset. The system operates on a $20\,\text{MHz}$-channel in the $2.4\,\text{GHz}$ band.

The operating system is Raspberry Pi OS 12 (Kernel Ver. 6.12.47-v8). The UV's total length is $20\,\text{cm}$. Each UV (RN1, RN2, CamN) is equipped with an optical ranging module

TABLE II
EXPERIMENT SYSTEM CONFIGURATION

Parameter	Value
Wireless Communication interface / mode	IEEE 802.11n 2.4GHz Ad-hoc
Maximum transmission rate	72.2 Mbps
MCS	auto-adjustment (MCS0-MCS7)
Video data	H.264, 24fps, 1280×720p
Video data rate	1, 3, . . . , 15 Mbps
Video packet buffer queue size of RNs	10 packets
Maximum data length of video data packets	1472 bytes
Control command packet length	64 bytes
Dummy packet length	4 bytes
Dummy packet upper limit	3 times
MUCViS Interval I	0.5 ms
Time interval for distance measurement	0.2 s
d_i measurement / control frequency	5 Hz
l_{body}	0.2 m
$d_{\max}$	0.6 m

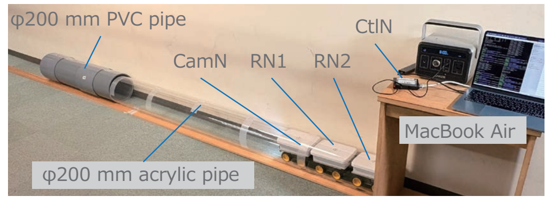


Fig. 6. Indoor testbed using a transparent pipe.

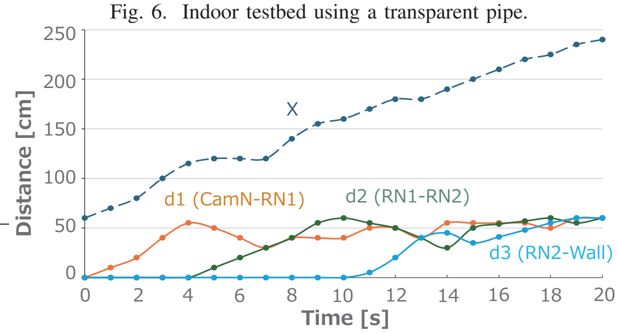


Fig. 7. Changes in CamN's position and inter-node distances.

(LiDAR Lite V3), a motor control module (Motor Driver HAT), a mobility battery (9V battery), and a motor. All components except the motor and LiDAR are housed in a waterproof enclosure. CamN additionally features a Raspberry Pi wide-angle camera and a light source.

V. Performance Evaluation

In this section, we describe two experiments conducted to verify the effectiveness of the proposed system. Experiment 1 verified the basic operation of the integrated *Partial expanding method* and *MUCViS* in an indoor pipe environment. Experiment 2 evaluated the video streaming performance in an experimental underground pipe.

A. Experiment 1: Integrated Operation Verification of Partial Expanding Method and Video Transmission

1) Objective: The objective of this experiment is to confirm the following three points: (i) Each UV operates cooperatively based on the target position L given by the operator, following the Partial expanding method described in Section 4. (ii) The communication path between UVs is appropriately updated according to the value of L. (iii) Video captured by CamN is transferred to CtlN according to the MUCViS packet transmission scheduling, enabling real-time video playback.

2) Experimental Conditions: Table II summarizes the experimental configuration. UV position control and path changes follow the *Partial expanding method* described in Section IV. The maximum communication range of 2.4 GHz IEEE 802.11 is expected to be several tens of meters indoors and about 2–3 m in sewer pipes. However, as this experiment was conducted in a limited indoor space to verify the basic operation of the system, the parameter $d_{\max}$, representing the maximum stable communication distance between adjacent nodes, was intentionally set to a small value of $0.6\,\text{m}$.

The communication path for control commands and video data is determined based on the CamN's target position L, as defined in Table I in Section IV. The CamN's current position x is calculated as the sum of the inter-node distances d_i and the length of each UV l_{body}. Updates to L are made by transferring a control command with the new L from CtlN to each UV; as this command is transmitted, each UV updates d_i according to the new L. In this process, to ensure stable system operation, the difference between the new L input by the operator and its previous value was always kept less than $d_{\max}$. The IPT transfer interval I was set to $0.5\,\text{ms}$, which adopts the minimum transmission interval that was confirmed to provide good transmission in a simulated environment using coaxial cables in [7].

3) Experimental Method: The overview of the testbed is shown in Fig. 6. A $3\,\text{m}$ pipe ($2\,\text{m}$ acrylic, $1\,\text{m}$ PVC) with a $200\,\text{mm}$ diameter was placed indoors. RN1, RN2, and CamN were placed inside the pipe, while CtlN was placed outside the pipe. The CtlN was connected to a laptop via a wired LAN for video verification. The input of L was given by an operator who visually confirmed the UV's position through the transparent pipe. Specifically, a new L value was input after confirming that CamN had reached the previously given target position L. Measurements were conducted three times for each video data rate.

4) Results and Discussion: Fig. 7 plots the inter-node distances d_i and the CamN's current position x as a function of time. At approximately 0, 4, and 10 seconds after the start of the experiment, the target position L was input as 1.2, 1.8, and 2.4 m respectively. In response, x and d_i (i=1,2,3) increased, confirming that Partial expanding method operated as designed. Although some oscillation due to PID control is visible in the d_i values, they eventually converged to the target values and stabilize. This oscillation is largely attributed to control parameters and hardware implementation, leaving room for future improvement.

Real-time, uninterrupted video playback was possible at video data rates up to $7\,\text{Mbps}$. CtlN logs confirmed that packets were transferred via the appropriate path (1-Hop, 2-Hop, or 3-Hop) determined based on L. Note that in this testbed, the interference between two hop away nodes was avoided by the IEEE 802.11's MAC (CSMA/CA) because all nodes were in the communication range and no hidden node problem occurred.

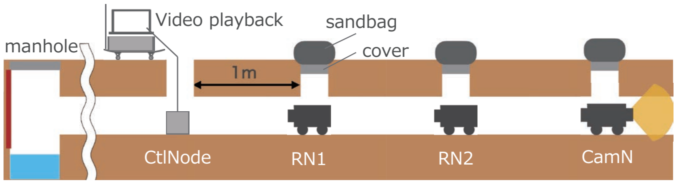


Fig. 8. Experimental environment

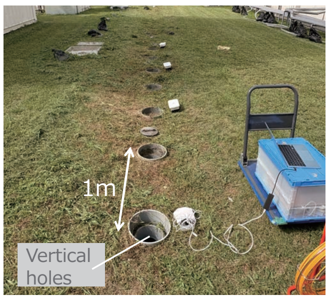


Fig. 9. Outdoor testbed with an underground pipe.

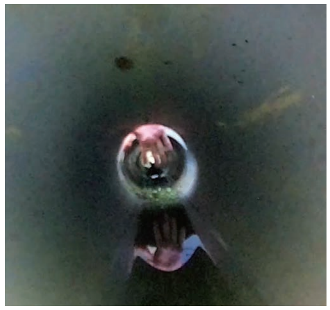


Fig. 10. Video feed from the camera node (CamN).

B. Experiment 2: Video Transmission Evaluation in an Underground Pipe Environment

1) Objective: Using the system verified in Experiment 1, this experiment verifies whether control command transmission and video data streaming can be performed correctly under conditions simulating a more realistic underground pipe.

2) Experimental Conditions: We used an experimental underground pipe with vertical holes at 1 m intervals (Figs. 8, 9). The PVC pipe is 24 m in total length and is buried so that the distance from the pipe bottom to the ground surface is approximately 400 mm. Preliminary experiments had shown that while UVs using 2.4 GHz IEEE 802.11n could reliably communicate at 1 m within this pipe, connectivity was occasionally lost at 2 m. Based on this finding, the inter-node distance for this experiment was set to 1 m, the same as the interval of the vertical holes. Once four nodes were placed, each vertical hole was closed by a cap and covered by a sandbag to simulate that the pipe is fully buried.

In this experiment, UV movement was not performed. Video streaming and control command transmission (continuously sending the same L value) were tested in a static state, assuming the inter-node distance $d_{\max}$=1 m. This configuration resulted in a 3-hop chain path via RN1 and RN2 for all communication between CamN and CtlN. CamN captured video inside the pipe. It is difficult to verify that video is being recorded correctly if there is nothing moving inside the pipe. Therefore, to enable this confirmation, we opened one vertical hole in front of the CamN. By inserting and moving an arm through this hole, we created motion within the camera's view, allowing us to confirm proper video capture.

3) Results and Discussion: As shown in Fig. 10, the hand moving in the forward vertical hole was clearly visible in the video footage received at CtlN. Fig. 11 shows the throughput for video traffic calculated from packet reception logs at CtlN. The achieved throughput matched the video data rate for rates up to $5\,\mathrm{Mbps}$. However, at a data rate of $7\,\mathrm{Mbps}$, throughput dropped significantly, and video could not be transferred correctly. This is likely because signals reached nodes beyond adjacent UVs, causing interference more frequently than assumed in the MUCViS packet scheduling. The primary cause is considered to be that $d_{\max}$ was set too small relative to the actual communication range within the pipe. Improving performance may require a system design that dynamically adjusts $d_{\max}$ based on real-world radio propagation characteristics such as RSSI and packet loss.

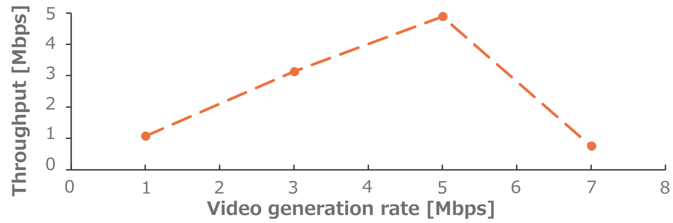


Fig. 11. Throughput of video data.

VI. Conclusion

We designed and implemented a multi-UV system integrating the *Partial expanding method* and the *MUCViS* protocol for sewer pipe inspection. Through an experiment with an indoor testbed, we confirmed the basic operation of the integrated *Partial expanding method* and *MUCViS* in an indoor pipe environment. In addition, through an experiment in a real underground pipe testbed, we confirmed that the implemented system can achieve at least $5\,\mathrm{Mbps}$ data rate video streaming without video quality degradation. These results demonstrate that the system can maintain reliable multi-hop communication in narrow sewer pipes up to 3-hops and $5\,\mathrm{Mbps}$ video bitrate. Future work includes validating the video transfer performance on an underground testbed based on the precise maximum communication range between adjacent nodes, as well as verifying the system's operation under more realistic conditions that incorporate UV movement within the sewer pipe.

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