Implementation of A Bi-Directional Intermittent Wireless Multi-Hop Transmission Method for Multiple UAVs Control and Video Streaming

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***Abstract*—Maintenance of sewer pipe infrastructure is costly and time-consuming. To tackle this problem, we have been developing a sewer pipe inspection system using multiple UAVs (unmanned aerial vehicles). In the inspection system, multiple UAVs form a multi-hop network to extend the communication range of Wi-Fi in small-diameter pipes. The leading UAV, which is equipped with a camera, transmits the recorded video data to a control node on the ground via relay UAVs while the control node sends control commands to the UAVs to manage their positions. For this multi-hop transmission of UAV control commands and video data, our previous work has proposed a packet transmission scheduling method based on the Bi-IPT (Bidirectional Intermittent Periodic Transmit) protocol. In this paper, we report on the implementation of the proposed scheduling method and evaluate its performance through experiments in a communication environment using coaxial cables. Specifically, we conducted experiments over a multi-hop network having four nodes, transmitting dummy data to simulate video data. Experimental results confirmed that the proposed method achieves a significantly lower packet loss rate and higher throughput than conventional transmission methods that do not control transmission timing.**

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

I. Introduction

Maintaining sewer systems is one of the most important tasks of local governments. Aged sewer pipes are at risk of corrosion, cracking, and breakage. In addition, soil and sand from the damaged areas can infiltrate sewer pipes, creating cavities in the surrounding underground soil, often leading to road collapses (about 3,000 road collapses occur annually in Japan). Currently, in Japan, sewer pipes that have exceeded their standard service life account for about 7 % of the total length of sewage pipes, and this figure will rapidly increase to about 19 % after 10 years and about 40 % after 20 years [1]. Therefore, inspection, repair, and replacement are necessary to address the issues with aging sewer pipes.

Current sewer pipe inspection methods such as visual observation, pipe periscopes, fiberscopes, and wired self-propelled robots with cameras on boats are time-consuming, expensive, and dangerous. To address these issues, Ishihara *et al.* proposed a sewer pipe inspection system using drifting wireless cameras [2]. However, the proposed system requires sufficient water flowing inside the sewer pipe for the cameras to drift. In the case that there is not sufficient (or no) flowing water, we have proposed and investigated an inspection system using multiple wireless-controlled UAVs (Unmanned Aerial Vehicles) [3], [4]. It has been verified in [5] that the communication ranges of wireless LAN in small-diameter sewer pipes are considerably short (e.g., less than 10 meters with 5GHz Wi-Fi in a 200mm-diameter pipe), resulting in a limited inspection range. To resolve this problem, as shown in Fig. 1, the proposed system uses multiple UAVs to form a multi-hop network in a sewer pipe, thus expanding the inspection range. In this system, the leading UAV, equipped with a camera, transmits the recorded video data to a control node on the ground through the multi-hop wireless LAN formed by relay UAVs. An operator controls the UAVs using the control node, which transmits control commands to the UAVs. Each relay UAV transmits video data while maintaining connectivity with the UAVs in front and behind. Note that the term *control* referred to here does not mean to perform detailed posture control but to instruct the camera UAV to move back and forth or change the camera's direction. Since video data and control commands are transmitted via wireless links, fast and low-cost inspections can be performed.

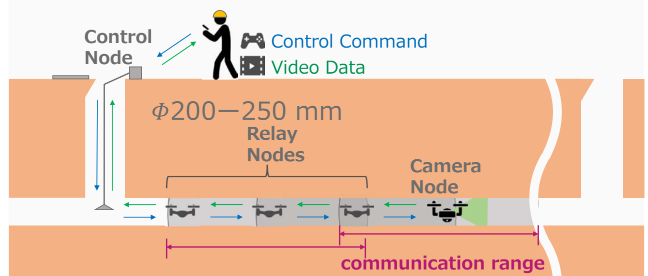

Fig. 1: A sewer pipe inspection system using multiple UAVs.

Nonetheless, there are two problems in realizing this inspection method. One problem is automatically adjusting the po-

This work is partly supported by the Amano Institute of Technology and JST CREST JPMJCR21D2.

sition of relay UAVs to maintain communication connectivity. Another problem is how to achieve both UAV maneuvering and real-time video transmission. For the first problem, we have proposed a method for automatically adjusting the UAV positions in [6]. We also proposed a video/control command transmission method for the system in [3], assuming a single-channel multi-hop wireless network where interference caused by hidden terminals is a serious problem. While this issue can be effectively resolved using multi-channel networks [7]–[11], a single-channel network is preferable for our proposed system since the UAVs need to be lightweight to prolong its flying time and do not need additional hardware for supporting multiple channels.

Based on the Bi-IPT (Bidirectional Intermittent Periodic Transmit) protocol [12] [13], the proposed transmission method in [3] ensures sufficient throughput for video data transfer and reliable control command transmission while reducing delay. The Bi-IPT protocol schedules packet transmission timing to avoid interference caused by hidden terminals and supports bi-directional transmission, assuming TCP data and ACKs. Specifically, the source node (e.g., a camera UAV) intermittently transmits packets at a fixed interval (IPT transmission interval I). The protocol schedules packet transmission so that relay nodes and another source node (e.g., a control node) can forward a buffered packet immediately after receiving a packet. To avoid interference from hidden terminals, it synchronizes the transmission timing of all nodes. Our proposed method modifies the packet size and packet transmission timing of the Bi-IPT protocol so that they can be suitable for UAV control and video streaming. It also defines the packet composition and the behavior of each node. In our previous work [4], extensive computer simulations using real videos have confirmed that compared with other methods, (1) the proposed transmission method achieves sufficiently low end-to-end (E2E) packet delay and loss, and (2) video streaming is possible at higher video bit rates.

To validate the practical feasibility of the proposed transmission method, this paper reports its implementation on Raspberry Pi single-board computers. We conduct experiments over a simulated wireless network environment using coaxial cables and evaluate the performance of the system. The remainder of this paper is structured as follows. Section 2 describes technologies and issues related to multi-hop UAV video transmission in small-diameter sewer pipes. Section 3 briefly illustrates our proposed video/control command transmission method in [3]. Section 4 describes the implementation of the proposed method and its performance evaluation based on experiments in a simulated wireless network environment. Finally, we conclude the paper in Section 5.

II. Transmission of Video Data and UAV Control Commands in Small-Diameter Sewage Pipes

Achieving long transmission distances and sufficient data rates for video streaming is challenging in small-diameter sewer pipe environments. Our study in [5] revealed that the transmission distance of the $2.4\,\mathrm{GHz}$ and $5\,\mathrm{GHz}$ IEEE 802.11n wireless LAN in a $200\,\mathrm{mm}$-diameter sewer pipe is about $5\,\mathrm{m}$ to $10\,\mathrm{m}$. Also, the communication distance of the $920\,\mathrm{MHz}$ ARIB STD T-108 wireless communication is only about $3\,\mathrm{m}$. Alternative methods such as optical wireless communications (including infrared and visible light) and acoustic communications (including ultrasonic waves) are unrealistic for wireless UAV systems due to the optical signal's high directivity, UAV weight limitations, and insufficient bit rates for video transmission. Therefore, we employ a multi-hop network of multiple UAVs connecting via wireless LAN to expand the inspection range and enable real-time inspection.

In our proposed system, the network needs to reliably transfer control commands (about a few tens of bytes in size) at the interval of about $0.1\,\mathrm{s}$ with sufficiently short delays from the control node to the camera UAV. On the other hand, video data transmission for the camera UAV requires a sufficient data rate for real-time streaming at a minimum acceptable quality. Some packet losses are tolerable as long as they do not significantly degrade the video quality and an operator can still monitor the progress of the inspection.

However, in signal channel multi-hop networks, interference caused by the hidden node problem can be a major impairment factor that degrades the system performance. This problem arises when transmitting nodes cannot detect each other's transmissions directly. It causes packet transmissions within the same communication path to interfere with each other, resulting in reduced throughput. The IEEE 802.11 standard includes an RTS/CTS (Request to Send/Clear to Send) mechanism that helps avoid the hidden terminal problem. When a node wants to transmit a data packet, it broadcasts an RTS before the transaction of the packet. When the destination node receives the RTS, it responds with a CTS packet. By doing so, packet collisions due to hidden terminals can be detected and avoided. However, the RTS/CTS packets can increase the transmission overhead. By synchronizing the transmission timings of nodes with 3 hops intervals, the Bi-IPT protocol can avoid collisions in single-channel multi-hop wireless networks without the use of RTS/CTS [12] [13]. Our previous study in [3] then proposed an improved transmission method for sewer inspection systems based on the Bi-IPT protocol.

III. Multi-hop Transmission Protocol for Video Data and UAV Control Commands

This section describes Multi-hop UAV Control and Video Streaming (MUCViS), a bi-directional multi-hop packet transmission method for control commands and video data [3].

A. Packets Used in MUCViS

Firstly, we define the direction from the control node (CN) to the camera node (CamN) as *upstream*. Conversely, we define the direction from CamN to CN as *downstream*. We assume that control command packets are smaller in size and transmitted less frequently than video data packets. Since control command packets should be delivered quickly and reliably, MUCViS aims to ensure low latency and reliability in the upstream. In contrast, video data packets are large in size and are transmitted frequently. Therefore, it is reasonable that the system can tolerate some packet loss in the video data as long as it does not significantly affect the quality of the video or the inspector's ability to detect damages.

MUCViS uses three types of packets: Control command packets, Video data packets, and Dummy packets. These are stored as the payload of UDP packets. The Packet Type (Type) field is present in all packets and contains the same value for each packet type. The Sequence Number (Seq) field is used for control command packets and video data packets and stores the serial number of each packet. The Acknowledgement (Ack) field stores the maximum sequence number of control command packets reaching CamN. The Ack field is shared by video data packets and dummy packets. The Control Command (Ctl.) field stores control commands for adjusting the UAV's position and camera direction. The Video Data (Data) field stores the video data captured by CamN in segments to restore the video according to the sequence number.

B. Basic Operation of MUCViS

Fig. 2 shows the packet transmissions of MUCViS. MUCViS has the following modifications and improvements over the Bi-IPT protocol to accommodate the differences in the nature of video data and control commands.

- CamN sends video data to CN.
- CN sends UAV control commands to CamN.
- CamN sends dummy packets when there is no video data to transmit. These packets allow relay nodes (RN) and CN to send packets, triggering the packet transmission.
- RN sends control command packets via unicast to its neighbors in both upstream and downstream directions. RN and CN that receive control commands as downstream packets use this reception as an opportunity to send their packets.
- RN prioritizes sending control commands over video packets.

C. Camera node (CamN) operation

CamN has a video data queue and periodically stores the captured video data in the queue. CamN intermittently sends one packet to the CN-side node according to the IPT transfer interval I. When the video data queue is empty, CamN sents a dummy packet CamN receives a control command packet and executes the command.

CamN performs the following operations according to the IPT transfer interval.

1) If video data exist in the queue, CamN retrieves and transmits them in the downstream direction.
2) If the video data queue is empty, CamN sends dummy packets in the downstream direction. However, an upper limit is set on the number of consecutive dummy packet transmissions. This is to restore the original IPT transfer interval if the CamN packet transfer interval is disturbed by retransmissions.

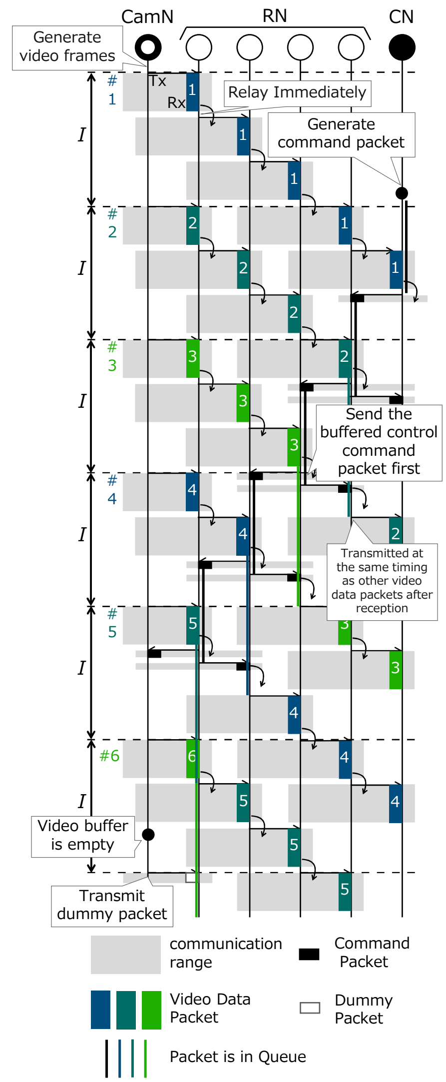

Fig. 2: The proposed method for transmission of UAV video data and control commands (MUCViS).

D. Relay node (RN) operation

Each RN has a control command packet queue and a video data packet queue. When an RN receives a downstream packet, it forwards one packet. When an RN receives an upstream packet, it stores that packet in the queue. The detailed operation is described below.

- When the RN receives a packet in the downstream direction, it performs the following tasks.
  1) The RN checks the type of the received packet. If it is a video data packet, the RN places it in the video data packet queue. When the maximum length of the queue is reached, the RN removes the video data packet from the queue and discards it.
  2) The RN checks the control command packet queue. If a control command packet is in the queue, the RN retrieves it and sends it to the adjacent nodes in both upstream and downstream directions. This

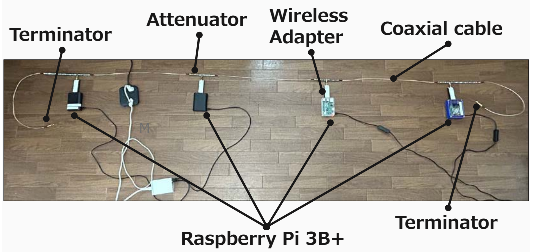

Fig. 3: Simulated radio communication environment.

downstream packet triggers the downstream neighbors (RN and CN) to send packets. If the queue is empty, the RN retrieves video data packets from the video data packet queue and transmits them only in the downstream direction. If all queues are empty, the RN creates dummy packets and sends them only in the downstream direction.

- When the RN receives a packet in the upstream direction, it checks the type of the received packet. If the type is a control command packet, the RN places the packet in the control command packet queue.

E. Control node (CN) operation

CN has a control command queue, which stores control commands generated by the CN. When the CN receives a packet in the downstream direction, it sends one packet containing commands. The details are described below.

1) When the CN receives a downstream packet, it checks the type of the packet. If it is a video data packet, the CN extracts the video data from that packet. If it is a control command packet, the CN discards it.
2) The CN sends a control command packet in the upstream direction. If the queue is empty, nothing is done.

IV. Evaluation of communication performance in a simulated environment

In this paper, we evaluate the performance of MUCViS implemented on Raspberry Pi single-board computers over a simulated communication environment using wireless LAN adapters and coaxial cables. We also compare the performance of MUCViS with other transmission methods in terms of E2E delay and packet loss rate through extensive experiments.

A. Experimental Environment

We construct a simulated communication environment using Raspberry Pi devices, a wireless LAN adapter, and a coaxial cable as pictured in Fig. 3. The simulated communication environment and parameters for wireless communication are shown in Table I. We use four Raspberry Pis where the two end devices act as the CamN node and the CN node, while the two in the middle are the RN nodes. The main unit model is Raspberry Pi 3 Model B+, and the OS is Raspberry Pi OS 11 (Kernel Ver. 6.1.21–v8+).

An Ad-hoc network is formed between Raspberry Pis via IEEE 802.11n. The chipset used for the wireless LAN adapter is RT2870/RT3070. We remove the antenna of the wireless LAN adapter and connect it to the coaxial cable. Attenuators are used to attenuate the radio waves so that only adjacent nodes can communicate. This simulates the hidden terminal problem. However, this ad hoc network periodically interrupted communication for approximately $10\,\mathrm{s}$. In the following, we show the results when communication was not interrupted. Iperf3's TCP mode [14] measured the throughput between adjacent nodes, which was approximately 40 Mbps when communication was not interrupted. We also confirmed that each node could not communicate with more than two adjacent nodes.

TABLE I: Coaxial cable environment and wireless communication-related parameters.

Parameter Name	Value
Number of nodes	4
Power attenuation between adjacent nodes	$60\,\mathrm{dB}$
Coaxial cable impedance	$50\,\Omega$
Wireless comm. Std.	IEEE 802.11n Ad-hoc
Central frequency	$2.412\,\mathrm{GHz}$
MCS	Automatic
Transmission rate	$13.0\,\mathrm{Mbps}$–$72.2\,\mathrm{Mbps}$
Channel width	$20\,\mathrm{MHz}$
GI	$0.4\,\mu\mathrm{s}$
Transmission power	$20\,\mathrm{dBm}$
Maximum AMSDU length	$3839\,\mathrm{bytes}$
Maximum AMPDU length	$32\,767\,\mathrm{bytes}$

B. Implementation of MUCViS

This section describes the detailed implementation of the CamN, RN, and CN nodes. The details of the parameters are shown in Table II.

1) Camera node (CamN): Video traffic is simulated by generating a fixed-size byte sequence at regular intervals and placing it in the video data queue as video data. Dummy packets are set to $4\,\mathrm{bytes}$ for only the packet type field and acknowledgment field. This is to avoid interference caused by sending extra packets and to conserve transmission resources. The IPT transmission interval I, which is CamN's packet transmission interval, is set to $1\,\mathrm{ms}$ based on trial-and-error results, considering the packet size and measured average transmission rate of $40\,\mathrm{Mbps}$.

2) Relay node (RN): The video data packet queue length is capped at 10 packets. This is to prevent the video data packets from increasing the queuing delay. When an RN receives a control command packet or dummy packet as a downstream packet, it waits for a certain period of time before sending a packet. In the implementation in this paper, the waiting time is set to $0.3\,\mathrm{ms}$, which is about one-third of the IPT transmission interval. We set the IPT transmission interval I to at least three times the transmission time of the video data packet. Therefore, if a packet is sent after waiting for $I/3$ after receiving it, the next packet will be sent at approximately the same time as if it were receiving a video data packet. However, in reality, it will be slightly delayed due to the processing time of the shorter packet.

TABLE II: Parameters related to MUCViS

Parameter Name	Value
IPT transfer interval	1 ms
Generation rate of control command	10 Hz
Generation rate of video data	9 Mbps – 12 Mbps
Video data generation time	30 s
Control command packet length	64 bytes
Maximum data length of video data packets	1464 bytes
Dummy packet length	4 bytes
Maximum number of dummy packets sent consecutively	3
RN video data packet queue size	10 packets

3) Control node (CN): CN node generates dummy control commands to simulate actual command transmission. The generation of control commands begins upon receiving the first video data packet.

C. Implementation of Transmission Methods for Comparison

We implement two transmission methods for comparison with the proposed MUCViS. In these methods, packets are sent as soon as they are generated without adjusting the timing of packet transmission (hereafter referred to as *UDP* and *UDP+RTS/CTS*). All packets sent are UDP packets. The operation of each node in *UDP* is described below.

- CamN sends the video data to the CN side node as soon as it is generated.
- As soon as an RN receives a packet, the RN forwards it. The video data packets are sent to the node on the CN side, and the control command packets are sent to the node on the CamN side.
- CN sends control commands to the node on the CamN side as soon as they are generated.
- RTS/CTS of the IEEE 802.11 standard is disabled in *UDP*.

UDP+RTS/CTS is a RTS/CTS enabled method in *UDP*. The middleware used in the *UDP+RTS/CTS* method is the same as in the *UDP* method, but the RTS/CTS threshold for the wireless LAN interface is set to $1000\,\mathrm{bytes}$. Therefore, RTS/CTS is not used for sending control command packets. Note that RTS/CTS is disabled in MUCViS since it is not needed to avoid packet collisions.

D. Experiment Results

We conduct five experiments for each MUCViS, *UDP*, and *UDP+RTS/CTS* transmission method with different video data generation rates ranging from $9\,\mathrm{Mbps}$ to $12\,\mathrm{Mbps}$.

1) End-to-end (E2E) delay: We examined each experiment's maximum end-to-end (E2E) delay of the video data packet and control command packet. Fig. 4 shows the average results of the five experiments. For command packets, all transmission methods achieve low delay. For video data, all transmission methods achieve a delay of less than $1\,\mathrm{s}$. Among them, MUCViS achieves lower delay than the other transmission methods.

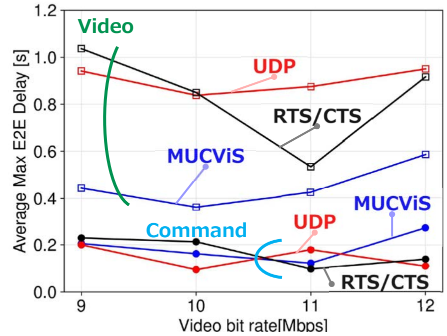

Fig. 4: End-to-end (E2E) delay for each transfer method at each video data generation rate.

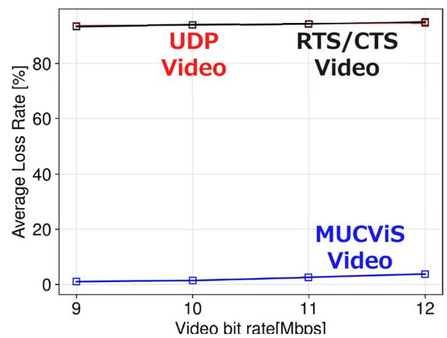

Fig. 5: Average loss ratio of video data packets for each transmission method at each video data generation rate.

2) Packet loss rate: Fig. 5 shows the average packet loss ratio of the video data packets in CN. It can be observed that MUCViS achieves a very low packet loss ratio compared to other methods. Specifically, MUCViS has an average packet loss rate of approximately $2.2\,\%$, with a minimum of $0.61\,\%$ and a maximum of $4.73\,\%$ at a video data generation rate of $12\,\mathrm{Mbps}$. For command packets, the loss rate was almost $0\,\%$ for all transmission methods.

3) Throughput of video data: Fig. 6 shows the average throughput of video data packets received by CN. The maximum possible reception rate of a CN in MUCViS, $\theta_{\max}$, is about $11.5\,\mathrm{Mbps}$ from the following equation [3].

$$\theta_{\max} = L_v \left(\frac{1}{I} - N_c \right) \tag{1}$$

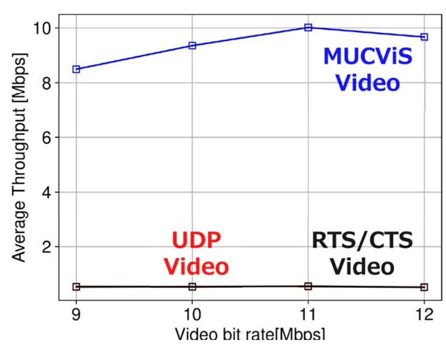

Fig. 6: Throughput of video data received by CN

where L_v is the video data packet length (1464×8 [bit]), the IPT transmission interval I is 0.001 [s], and Nc is the control command packet transmission rate ($= 10$ [Hz]). MUCViS has a very high video data throughput at CN compared to *UDP* and *UDP+RTS/CTS*. MUCViS allows video data packets to be properly spaced for transmission, avoiding interference and minimizing packet loss.

E. Discussion

Experiment results revealed that MUCViS achieves a lower packet loss ratio and higher throughput than the two transmission methods *UDP* and *UDP+RTS/CTS*. However, it could not achieve a packet loss rate of $0\,\%$ since, other than sending packets specified in the implementation, the wireless LAN adapter also transmits Beacon and Probe Request frames by default.

In the experiments, we tested the MUCViS IPT transfer interval I at different values, set to $1\,\text{ms}$. Theoretically, this interval can be made even smaller to improve the throughput. Nevertheless, if the IPT transmission interval is too small, the packet transmission timing may deviate from the intended timing due to frame aggregation in IEEE 802.11n. In addition, in the experiments in this paper, the wireless LAN adapter automatically adjusts the MCS (Modulation Coding Scheme), resulting in changes in the transmission rate. Consequently, setting a fixed transmission interval may lead to varying packet transmission times due to MCS changes. This variation can cause interference with other nodes' transmissions.

The multi-hop network in the simulated communication environment using coaxial cable experienced periodic interruptions of approximately $10\,\text{s}$. Therefore, we mainly present our experimental results when communication is maintained uninterrupted in this paper. Although we checked the logs of the experiments to ensure that communication was not interrupted, it is possible that some of the experimental results presented in this paper were affected.

The experiments in this paper were conducted in a simulated wireless communication environment using coaxial cables. The video data generated by CamN was dummy data created at regular intervals. Therefore, the quality of the received video, when replayed, cannot be evaluated. Furthermore, we have yet to verify how using an actual camera for video capture, instead of generating dummy data, would impact CamN's communication performance.

V. Conclusion

This paper introduced the implementation of MUCViS, a video/UAV control command transmission method proposed for the inspection of small-diameter sewers using multi-UAVs to overcome the short wireless transmission distance. Extensive experiments using a simulated radio communication environment with a coaxial cable were conducted to evaluate the performance of the proposed method. Our goal was to enable the operation and real-time video transmission of a camera-equipped UAV in a single-channel multi-hop wireless network. Experiment results showed that compared with other transmission methods using UDP and RTS/CTS, MUCViS achieved a lower packet loss rate than other transmission methods for both control command packets and video data packets. The E2E delay was within acceptable limits for control command and video data packets. In the future, we plan to conduct experiments in real communication environments inside sewer pipes.

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