SRT-based cooperative video transmission protocol for inspection of small diameter sewer pipes using multiple drifting wireless cameras

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***Abstract*—It is difficult to inspect the inside of small-diameter sewer pipes safely, quickly, and at low cost using existing inspection methods such as human visual inspection and wired robots. We have proposed a sewer pipe inspection system that uses multiple drifting wireless cameras (drifting nodes) to realize safe, quick, and low-cost sewer inspection. In this system, drifting nodes are put into the pipes, and the video recorded inside the pipe is transmitted to relay servers (Access Points, APs) temporarily deployed in utility holes via wireless communication. To realize this system, we have developed a cooperative video transmission protocol, Sewer Video Transmission Protocol (SVTP), in which multiple drifting nodes that move in the same pipe send the video of different parts of the pipe. The recent implementation of SVTP (SVTP 2022) uses SRT (Secure Reliable Transport) as the transport protocol in order to handle the rapidly changing quality of wireless links between a drifting node and an AP. However, SVTP 2022 has several implementation issues; a drifting node needs a long time to detect that it is out of the communication range of an AP, and packets are frequently retransmitted in the early stage of an SRT session between an AP and a drifting node. In addition, the performance of video transmission using multiple drifting nodes with SVTP 2022's implementation had not been evaluated. In this paper, we present the design and implementation of an improved version of SVTP, SVTP 2023, which solves the implementation issues of SVTP 2022, and show the results of video transmission experiments using multiple drifting nodes.**

***Index Terms*—Sewer inspection, Reliable data transmission, SRT, Intermittent connectivity, Wireless communication**

I. Introduction

Maintenance of old sewer pipes is one of Japan's most severe problems. 40% of all sewer pipes were installed more than 30 years ago, and approximately 2,700 road subsidence accidents occur annually due to old sewer pipes [1]. When repairing or replacing sewer pipes, it is necessary to identify deteriorated areas promptly. Today's popular sewer pipe inspection methods are human visual inspection [2] and the use of wired-connected self-propelled robots [3]. The former, however, requires inspectors to enter a sewer pipe and has high risks of accidents, such as exposure to toxic gases, drowning, injury, etc. The latter is expensive in terms of equipment cost and requires a long inspection time. Therefore, it is not realistic

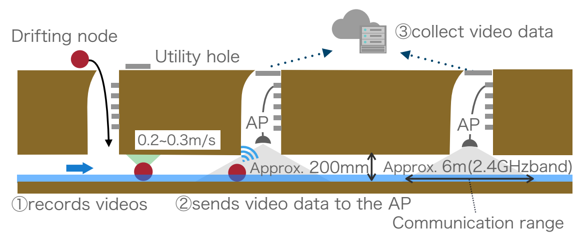


Fig. 1. Sewer inspection system using drifting wireless cameras.

to inspect all sewer pipes that are about to reach the end of their durable period using only existing inspection methods.

We have proposed an inspection system that uses drifting wireless cameras (drifting nodes) to realize safe, quick, and low-cost sewer pipe inspections [4]. In this system, each drifting node inserted into a sewer pipe records videos of the inside of the pipe, and when entering the communication range of one of relay servers (access points, APs) temporarily deployed in utility holes, it transmits the video data to a centralized server via a wireless LAN link to the AP. This system enables inspectors outside the pipe to view the videos of the inside of the sewer pipe even while the drifting nodes are in the pipe, reducing the number of times that inspectors have to enter the sewer pipe. Thus, this system reduces the risk of accidents. Unlike the sewer pipe inspection method using wired-connected self-propelled robots, the inspection area of our system is not limited by the cable length and workers do not need to handle a heavy long wire. Therefore, this method reduces the inspection cost compared to conventional inspection methods and enables safe inspection in a short time.

In order to realize this system, a large amount of video data needs to be transmitted from a drifting node to an AP while they are connected. However, since most of the first Fresnel zone between an AP and a drifting node's antenna is blocked in small-diameter sewer pipes, the communication range of the wireless LAN is shorter than that on the ground. Nagashima et al. [5] investigated the communication range of 2.4 GHz and 5 GHz band IEEE 802.11 radios in a 250 mm diameter reinforced concrete sewer pipe (Hume pipe) and a 200 mm diameter PVC pipe. Their measurement results have shown that the maximum wireless communication range in the pipes using 5 GHz band IEEE 802.11n wireless LAN is about 8 m and that using 2.4 GHz band IEEE 802.11n wireless LAN is about 3 m. These distances are much smaller than those on the ground. The wireless link condition quickly changes while a drifting node is moving in the short communication range of an AP. Since the modulation and coding scheme (MCS) in a wireless LAN is dynamically adapted to the link condition and parameters used in the transport layer protocol are changed according to the occurrence of packet losses, it is essential to develop a way that maximizes the size of reliably transmitted data.

Tanaka et al. [6] designed a cooperative video transmission protocol, Sewer Video Transmission Protocol (SVTP), which reduces the data size that a single drifting node needs to send to an AP by using multiple drifting nodes. Each drifting node sends the video of a different part in a section between two APs. For example, if two drifting nodes are used, the first one sends the video of the first half of the section between APs, and the second one sends the video of the rest of the section.

However, SVTP has some problems. First, SVTP in early implementations uses TCP as a transport layer protocol, and loss-based congestion control algorithm used in TCP, such as CUBIC [7], tends to reduce the congestion window size excessively due to packet loss. In addition, dynamic adaptation of MCS is performed over the wireless LAN. In an environment with frequent packet losses, such as in a small-diameter sewer pipe, it is difficult to keep the congestion window size sufficiently large and configure the MCS appropriately. Second, a drifting node moving in small-diameter sewer pipes has difficulty in immediately and correctly detecting events that the node has entered or left an AP's communication range.

Tachibana et al. [8] implemented an extended version of SVTP, SVTP 2022, which used a UDP-based reliable transport protocol, SRT (Secure Reliable Transport) [9], in the video transmission part of SVTP in order to increase the amount of video data that can be sent from a drifting node to an AP. It was confirmed that SVTP 2022 improves the amount of data that a single drifting node can transmit to an AP. However, the performance of functions of SVTP 2022 related to cooperative data transmission using multiple drifting nodes has not been evaluated. In addition, SVTP 2022 has several implementation issues; a drifting node needs a long time to detect that it is out of the AP's communication range, and packets are frequently retransmitted in the early stage of video data transmission.

Therefore, we have implemented an improved version of SVTP, SVTP 2023, that solves the implementation issues of SVTP 2022. The contributions of this paper are summarized as follows.

1) We designed and implemented an improved version of SVTP 2022, SVTP 2023, in which a drifting node can (i) quickly detect that it is out of the AP's communication range and (ii) reduce the number of data retransmissions in the early stage of an SRT session with an AP.
2) We confirmed the performance of SVTP 2023 when multiple drifting nodes are used through experiments using an experimental underground pipe.

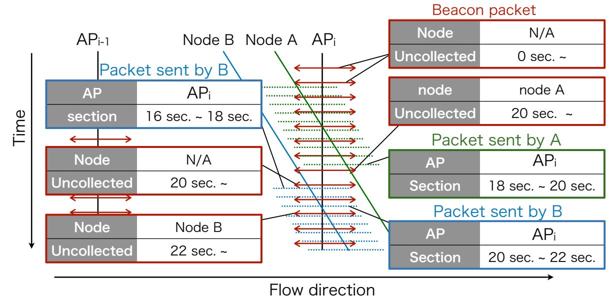


Fig. 2. Example of video data transmission from multiple nodes with SVTP.

The rest of this paper is organized as follows. Section II gives an overview of the previous versions of SVTP. Section III explains the new functions introduced to SVTP 2023. In Section IV, we explain the video transmission experiments conducted in an experimental underground pipe, present the performance of SVTP 2023 and discuss the remaining performance issues. Finally, Section V summarizes this paper.

II. Sewer Video Transmission Protocol

This chapter outlines the design and implementation of SVTP developed in our previous work. SVTP is a protocol for transmitting video data recorded in sewer pipes to several APs temporarily deployed in utility holes using multiple drifting nodes. The previous version of SVTP, SVTP 2022, has the following features.

- Each drifting node selects a part of video data that it has recorded while it moved between two neighboring APs according to information sent from an AP so that video data sent from multiple drifting nodes can finally cover the entire inspection section of the pipe.
- By observing data transmission between other drifting nodes and an AP, each drifting node defers starting the next data transmission section between itself and the closest AP to avoid simultaneous transmissions and packet collisions.
- SRT is used as a transport layer protocol to improve the amount of data that can be sent from a drifting node to an AP over a short-lifetime wireless link.

A. Selection of the part of video data sent from a drifting node

In SVTP, drifting nodes in a pipe receive UDP beacon packets periodically broadcast by APs. When a drifting node detects that it enters the AP's communication range and that no video data recorded in a section between the AP and its direct upstream AP are received by the (downstream) AP, it transmits video taken in the section. Fig. 2 shows how two drifting nodes cooperate in sending video data. A drifting node sends only the video data captured in section S_i (from AP_{i-1} to AP_i) to the AP_i. Each drifting node stores the video chunk (two seconds long in our implementation) taken in the pipe with the timestamp of the start and end time. Assuming that the movement speed of drifting nodes in sewer pipes is constant, the drifting nodes can estimate their video-recorded position from the difference between the time when it first received a beacon from each AP and the start and end time of the chunk from that point. Before sending a video chunk, drifting nodes send meta information (e.g., their node ID, video data size, and start and end time stamps) for the video chunk they are sending. Using this information, the video receiver (i.e., an AP) can realize which part of the pipe is covered by the received video data. Each AP includes this information in its beacon to inform approaching drifting nodes of the part of the pipe not covered by received video data.

B. Prevention of simultaneous transmissions from multiple drifting nodes

When multiple drifting nodes are ready to communicate with the same AP at the same time, if they are in a hidden terminal relationship with each other, their signals may collide and the AP is not able to receive packets correctly. Therefore, SVTP prevents multiple drifting nodes from simultaneously sending packets to the same AP by including the IDs of the nodes currently communicating with the AP in its beacons.

When a drifting node enters an AP's communication range and receives a beacon packet, it checks a node ID in the beacon packet. If it does not match its node ID, the drifting node judges that the AP is currently communicating with another drifting node and does not start sending video data to the AP. When the AP judges that the currently communicating drifting node has left its AP's communication range, it closes the session with that drifting node and stops including the node ID in its beacon.

C. Use of SRT as a transport layer protocol

The SVTP 2022 uses the Secure Reliable Transport (SRT) [9] protocol in the transport layer to ensure stable data transmission following changes in link conditions between devices. SRT is an open-source transport protocol developed for stable streaming of high-quality video with minimal delay in networks where the link conditions change rapidly due to the movement of devices, such as mobile communications, and where changes in network bandwidth, delay, jitter, etc., are unpredictable. SRT is based on UDT, a UDP-based protocol with guaranteed communication reliability developed by Yunhong Gu et al. in response to the emergence of high-speed networks. UDT combines UDP data transmission with the function of fast packet retransmission and congestion control to enable reliable and low-latency communications regardless of link conditions. In the following sections, we will describe the UDT's retransmission control and congestion control mechanisms, followed by a description of the SRT protocol.

1) Retransmission control: In TCP, retransmission control is based on ACK (Acknowledgement). That is, each time a segment is received, a receiver sends an ACK for that segment to a sender. The sender retransmits based on an ACK timeout or receipt of a duplicate ACK. In UDT, on the other hand, a receiver periodically sends control packets and retransmits based on NAK (Negative ACK). As shown in Fig. 3, a receiver

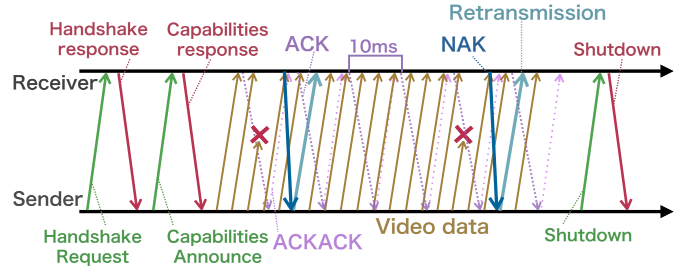


Fig. 3. Data transmission with UDT.

sends a control packet every 10 msec. This control packet contains information such as the sequence number of the last received packet, the receive buffer size, and the RTT (Round Trip Time), and is called an ACK in UDT protocol. The sender also sends an acknowledgment to the ACK control packet, which is called an ACKACK. The RTT is calculated by a receiver upon receipt of the ACKACK. When a packet loss occurs, the sender can quickly detect the packet loss by receiving a NAK (Negative ACK), which enables immediate retransmissions.

2) Congestion Control: Congestion control in UDT is performed by controlling the transmission rate and adjusting the congestion window calculated at the receiver side. The algorithm for updating the congestion window is a partial modification of the AIMD (Additive Increase Multiple Decrease) based algorithm which is widely used in TCP congestion control.

The AIMD-based algorithm in TCP gradually increases the congestion window until a packet loss occurs. The algorithm in UDT, if no NAK is received, increases the number of packets to be sent by the number of inc by the next ACK received. inc is calculated every 10 ms by Equation 1.

$$inc = \max\left(10^{\lceil \log_{10} B - 9 \rceil}, 1/1500\right) \times 1500/MSS, \quad (1)$$

where MSS is the Maximum Segment Size and B is the estimated available bandwidth of the network.

When a packet loss occurs in TCP, the window size is reduced by two factors: duplicate ACK detection and retransmission timeout. On the other hand, in the UDT's algorithm, each time a NAK is received, the sender decreases the window size according to Equation 2.

$$R_{i+1} = R_i \times \frac{8}{9}. \quad (2)$$

3) Unique Features of SRT: SRT is a protocol that adds timestamp-based packet delivery and packet encryption to UDT so that UDT, which is not intended to be used for video streaming, can be used for video streaming [9]. SRT adds the transmitted NAK packets to the compressed list (NAK reports) and sends this list to the sender every RTT/2 in case the NAK packets implemented in UDT are lost. This ensures the reliability of data transmission even if the NAK packets sent by the receiver are lost. Furthermore, SRT supports AES128/256 for encryption of communication. This ensures data security even if the data itself is intercepted. In addition, most of the flow control, congestion control, etc., rely on the UDT mechanism.

III. Design of SVTP 2023

We designed SVTP 2023 to solve the implementation issues of SVTP 2022. The main features of SVTP 2023 are i) early disconnection when a drifting node leaves an AP's communication range and ii) a short timeout when establishing an SRT session to avoid data transmission in poor link conditions.

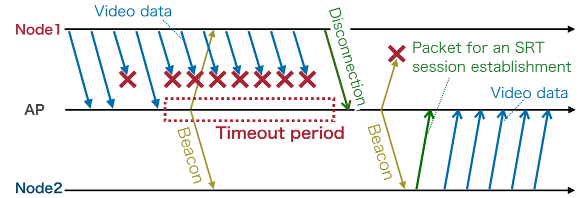
A. Early disconnection when a drifting node leaves an AP's communication range

Drifting nodes with SVTP 2022 often continue to retransmit packets even if they have left an AP's communication range because the protocol does not have a function for a drifting node to detect that it has left the AP. However, in the sewer inspection using multiple nodes, a drifting node should close a session as soon as it has left an AP's communication range so that the AP can quickly start communication with the following drifting node that is approaching the AP and has a better link condition. For example, as shown in Fig. 4 (a), since an AP does not have a function to detect the drifting node has left, even after node #1 has left the AP's communication range, the AP judges that the link condition is not bad and continues to request packet retransmissions from the drifting node. This operation delays closing the session with the drifting node. Then, even if a following node #2 enters the AP's communication range, it cannot start a session with the AP because the AP is still trying to communicate with node #1.

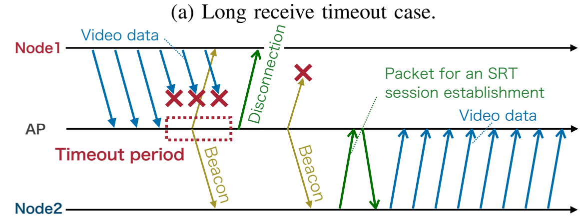
Therefore, in the SVTP 2023, the timeout period to close an SRT session with an AP is set to be much shorter than the default value in an implementation of SRT by Haivision [10], which we used in previous implementation SVTP 2022. When an AP does not receive any packets of video data from a drifting node for a receive timeout period, it judges that the drifting node has left its communication range and closes the session. In Fig. 4 (b), as soon as the AP fails to receive a packet from node #1 for the entire receive timeout period, it closes the session with node #1. In this way, the AP can communicate with the following node #2 as soon as it enters the AP's communication range. We set the receive timeout value to 0.6 seconds after experiments in a real underground pipe. 0.6 seconds corresponds to a distance of about 12 cm, assuming the drifting speed is 0.2 m/s.

B. Short timeout when establishing an SRT session to avoid data transmission in poor link conditions

We have added a function to SVTP 2023 to avoid data transmission when a link condition is poor in the early stage of an SRT session by setting a short timeout period for an SRT session establishment. The reason for adding the function is described below. In small-diameter sewer pipes, even when the distance between an AP and a drifting node is long and the link condition is poor, the received signal strength temporarily becomes high, then the drifting node may receive some beacon packets from the AP. Then, a drifting node may accidentally receive a beacon packet from an AP and initiate an SRT session establishment even though the link condition is poor. If the timeout period for an SRT session establishment is long, packet retransmissions for establishing a session occur frequently. In such a case, the rate adaptation process of the MCS in the physical layer of IEEE 802.11 wireless LAN reduces the transmission rate. Then, the transmission rate during the SRT session is low, resulting in a low throughput during the session. Even if the session is successfully established under this condition, it is difficult for the drifting node to increase the transmission rate after the link condition becomes better. If the timeout period for an SRT session establishment is set to be short, the drifting node quickly gives up on establishing an SRT session when the link condition is poor. Then, the node can start an SRT session after the link condition becomes good, keep a faster MCS configuration, and send a large amount of data during the session.



(a) Long receive timeout case.



(b) Short receive timeout case.

Fig. 4. Difference in data transmission with different lengths of receive timeout period.

For example, as shown in Fig. 5's *Problem case*, due to the long timeout period for an SRT session establishment, when a beacon packet is received during poor link conditions, it takes a long time to establish a session, and the data transmission rate of the drifting node becomes lower. However, as shown in *Ideal case*, using a shorter timeout period, the drifting node gives up on establishing a session initiated by receiving a beacon packet under a poor link condition. When the link condition improves, the drifting node will receive a beacon packet again and establish another session.

IV. Experiment of cooperative transmission using SVTP 2023

A. Experiment setup

We conducted experiments to measure the performance of video transmission from multiple drifting nodes equipped with the SVTP 2023 to an AP in a small-diameter underground pipe using 2.4 GHz band IEEE 802.11n links. The experiments were conducted in a 22 m long ϕ200 mm PVC pipe installed underground in a university campus. The PVC pipe had utility holes every 1 m for working purposes, and during the

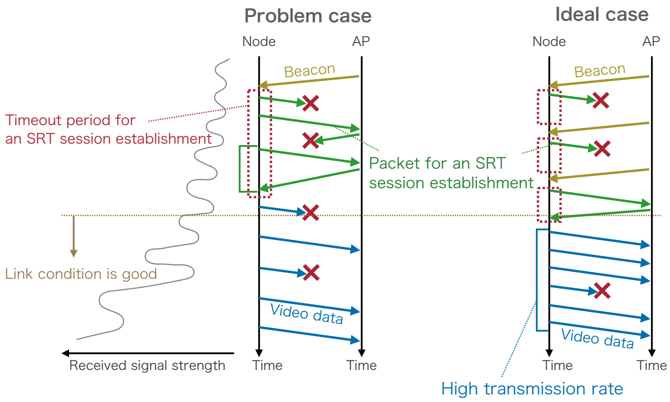


Fig. 5. Difference in data transmission due to different lengths of timeout for SRT session establishment.

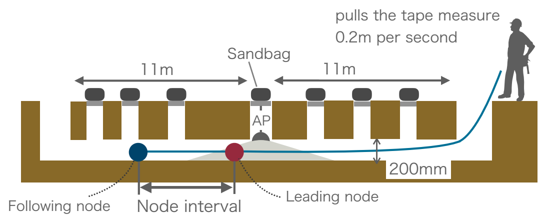


Fig. 6. Overview of the testbed.

TABLE I
PARAMETERS IN THE EXPERIMENT.

Parameter	Value
Receive timeout at AP	0.6 sec.
SRT session establishment timeout	3 sec. [Haivision's Default]
Beacon packet transmission interval	300 ms
Overlap time of video data transmitted by following nodes	2 sec.

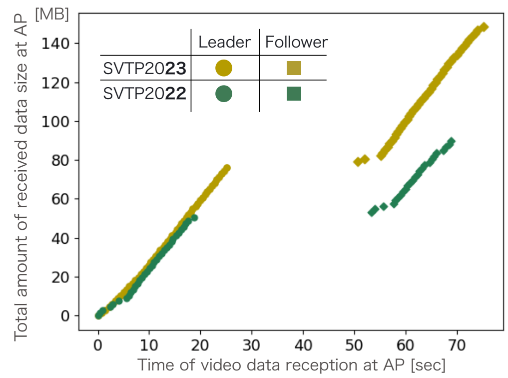


Fig. 7. Changes in the amount of video data received from each node when the node interval was 10 m.

experiment, the holes were covered with sandbags to prevent radio waves from leaking out of the pipe.

In this experiment, a small Linux computer (Raspberry Pi Model 3B+) was used for drifting nodes and an AP. For data transmission, a 2.4 GHz band IEEE 802.11n wireless LAN chip built into the Raspberry Pi was used. The drifting nodes and the AP were connected in ad-hoc mode. The MCS setting was set to auto. The video data was recorded using *raspivid* command with a variable bit rate, frame size of 1280×1080, 30 fps, and H.264 format. In the experiment, two drifting nodes were provided with dummy data prepared in advance. The drifting nodes were fixed to a tape measure as shown in Fig. 6, and a worker pulled the tape measure at a constant speed so that the distance between the two nodes could be kept during their move.

We conducted the following three experiments.

1) We measured the total amount of video data received by the AP when the distance between the two drifting nodes was sufficiently large.
2) We measured the amount of video data received in the early stage of data transmission when the timeout period for an SRT session establishment was set to be short.
3) We measured the total amount of video data received by the AP when the distance between two drifting nodes was shorter than the distance that the drifting node could communicate with the AP to confirm that the AP quickly closed the session with a leaving node.

B. Results and Discussion

1) The total amount of transmitted video data when the node interval was sufficiently long: We measured the total amount of video data correctly received by the AP from the two drifting nodes. We conducted the same experiment five times. The distance between the two nodes was 10 m, which was sufficiently longer than the distance that a drifting node could communicate with an AP in a sewer pipe using a 2.4 GHz band IEEE 802.11n wireless LAN. The timeout period for an SRT session establishment was set to the default value of Haivision's SRT implementation, 3 seconds. Other parameter values are shown in Table I.

Fig. 7 shows the change in the total amount of video data correctly received by the AP from each drifting node with the reception time of the video data chunk. The reception time values are relative to the time when the AP received the first video data chunk from the first drifting node. The average total amount of received data for the five experiments was about 95.75 MB. The results of experiments conducted under similar conditions using SVTP 2022 showed that the average total amount of received data was about 88.7 MB. The gain in the total amount of received data by the new implementation is 7.05 MB. Note that the timeout for an SRT session establishment was set to the default value of Haivision, 3 seconds, in this experiment. Thus, the amount of data received from each node in the early stage of data transmission was low, as shown in Fig. 7.

2) Measurement of the amount of video data received in the early stage of data transmission: Table II shows the amount of data correctly received during the first 2 seconds of an SRT session when the timeout period was set to the default value (3 seconds) and short one (0.5 seconds). The measurement results showed that a short timeout period for an SRT session establishment improved the amount of received data in the first

TABLE II
AMOUNT OF VIDEO DATA RECEIVED IN THE EARLY STAGE OF AN SRT SESSION (FOR 2 SECONDS AFTER THE SRT SESSION STARTED).

SRT session establishment timeout [sec.]	Received data size [MB]
3 (default)	1.12
0.5	1.56

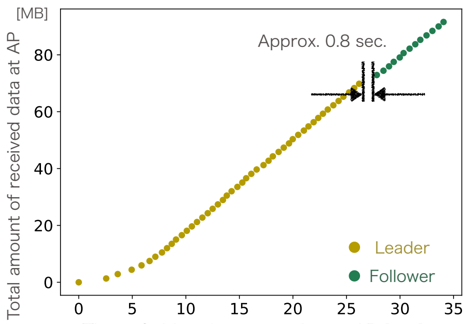


Fig. 8. Video transmission performance when the node interval was 2 m.

two seconds by approximately 0.44 MB.

3) Data transmission performance when the node interval was short: We measured the total amount of video data received by an AP when the distance between two drifting nodes was shorter than the distance that a drifting node could communicate with the AP in the underground pipe to confirm that the AP quickly closed an SRT session with a leaving node. We used two drifting nodes and set the distance between them to 2 m. The other parameters are shown in Table I. We conducted the same experiment five times. Fig. 8 shows the amount of data received from each drifting node with respect to the time when receiving each video data chunk (relative to the first receipt time). We can see that it took 0.8 seconds for the AP to start a session with the following drifting node after the last packet reception from the preceding drifting node.

In some of the five experiments, however, it took more than three seconds to start a session with the following drifting node as shown in Fig. 9. The reason is explained as follows. When the AP wrote the received video data to a file, the file-writing operation stalled due to the low performance of Raspberry Pi in writing data to an SD card. Then the data reading process from the receive buffer stalled, and the data transmission on the SRT session stalled due to the SRT's flow control operation.

V. CONCLUSIONS

We designed and implemented an improved version of SVTP, SVTP 2023, that solves the implementation issues of SVTP 2022 developed in our previous work for our proposed sewer pipe inspection system, which uses multiple drifting wireless cameras (drifting nodes) to compensate for the short radio communication range in narrow sewer pipes. Through experimentations conducted in an underground pipe testbed, we confirmed the performance of SVTP 2023. We introduced the following functions to SVTP 2023. i) By setting a short timeout to close an SRT session, each drifting node and AP

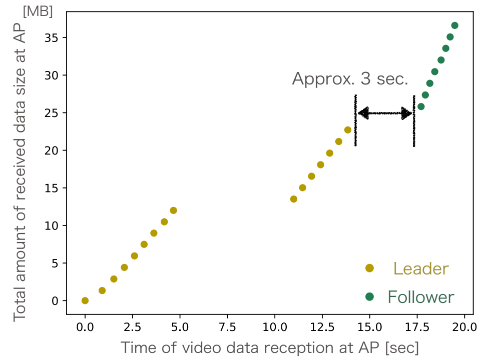


Fig. 9. Example of delay in establishing a connection with the subsequent node.

can immediately close the session between them when the drifting node has left the AP's communication range. ii) The timeout value for an SRT session establishment between a drifting node and an AP is configured to be short to prevent packets from being retransmitted frequently in the early stage of the SRT session. We confirmed that the performance gain in the total amount of video data received by an AP is 7.05 MB and the session between a drifting node and an AP can be closed immediately after the preceding node left the AP's communication range. In the future, we plan to conduct a cooperative video transmission experiment using multiple drifting nodes and multiple APs in an actual sewer pipe using the actual recorded video.

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