Development of a Wireless Communication System for Reliable Acoustic Data Collection Toward Anomaly Detection in Mechanical Equipment

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***Abstract*—With the recent proliferation of Internet of Things (IoT) devices that can send and receive data via wireless communication, we are able to monitor and operate these devices remotely. An example of an IoT system using wireless communication is a system for anomaly detection in mechanical equipment using acoustic data. In order to detect anomalies using acoustic data, continuous recording is essential, thereby increasing the data size. Although Wi-Fi networks provide high-capacity data transfer, performance degradation cannot be avoided due to reasons such as packet losses caused by collisions with data from other devices using the same frequency and the increase in distance between two communicating devices. In the present study, we developed a wireless communication system for reliable acoustic data collection for anomaly detection in mechanical equipment. First, as preliminary experiments, we investigated the communication characteristics for the transmission of large-size data by Wi-Fi in indoor and outdoor environments. The results indicated the communication performance was insufficient for transferring all recorded data handled by this system. Therefore, we developed a simple heuristic transmission timing control method and a method that can reduce the amount of transmission data in order to realize a stable acoustic data collection system. Finally, through demonstration experiments using mechanical equipment in the field, we verified the feasibility of the acoustic data collection system.**

***Index Terms*—Anomaly detection system, acoustic data, Wi-Fi, wireless communication, IoT.**

I. Introduction

With the development of Internet of Things (IoT) technologies, the number of IoT devices has been increasing [1]. Since the IoT devices send and receive data via the Internet, we are able to monitor and operate remote devices. Although IoT devices typically use wireless communications, it is necessary to consider communication performance degradation. In particular, wireless communication technologies that use unlicensed bands, such as Wi-Fi and LPWA, may be heavily used in the same space [2]. Furthermore, the appropriate wireless technology change for different applications due to the combination of parameters for not only the network (transmission rate and coverage) but also the application (sending rate and acceptable delay).

An example of an IoT system using wireless communication is a system for efficient agriculture [3]. This system acquires information on the moisture content of the soil, humidity, and air temperature using sensors. Since the data collected by this system can exchange information in a text file, the amount of data is small. As shown in this example, a system can easily collect a small amount of data through wireless communication, even through LPWA.

Furthermore, by implementing an IoT system that can collect a large amount of data, we can make a more valuable contribution. Anomaly detection in equipment by acoustic data is one example. Anomalies in machines, such as pumps and motors, often appear in operating noise. Therefore, there are many studies that detect anomalies in equipment by using acoustic data [4] [5]. However, in order to detect anomalies using acoustic data, the sound must be recorded continuously. Although Wi-Fi provides us with high-capacity data transfer, performance degradation cannot be avoided for reasons such as packet losses caused by collisions with data from other devices using the same frequency and the increase in distance between two communicating devices.

In the present paper, we develop a wireless communication system for reliable acoustic data collection for anomaly detection in mechanical equipment. The proposed system collects acoustic data from multiple sensors simultaneously using Wi-Fi. The communication performance of Wi-Fi may deteriorate due to channel collisions or performance anomalies [6]. Therefore, as preliminary experiments, we investigated the communication characteristics for transmission of large-size data by Wi-Fi in indoor and outdoor environments. The results indicated that the communication performance was insufficient for transferring all recorded data handled by this system. Therefore, we developed a simple heuristic transmission timing control method and a method that can reduce the amount of transmission data for realizing a stable acoustic data collection system. Finally, through demonstration experiments using mechanical equipment in the field, we verified the feasibility of the acoustic data collection system.

II. Assumed system

In the present paper, we adopt sets of pumps for large mechanical equipment to be monitored. There are several pumps lined up in the measurement area, and each pump is not always running, but instead runs periodically for a short time. The interval between the operation of each pump is approximately 1 hour, but that interval is different for each

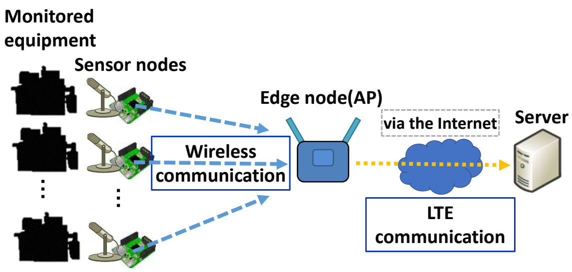

Fig. 1. Overview of the assumed system.

pump. The duration of pump operation is approximately 1 minute, but is not the same each time. In general, we can say that the change in the running period and/or the inactive interval is a sign of anomalies in mechanical equipment. Therefore, by collecting and analyzing data on the operating interval and operating duration of the pumps, we can expect to detect signs of anomalies.

The present paper assumes a wireless communication system for the collection of acoustic data from eleven pumps, as shown in Fig. 1. The pumps are in an outdoor facility in Fukuoka Prefecture, Japan. Thus, the recorded acoustic data includes not only noise based on the natural environment, such as that produced by birds and insects, but also noise due to artifacts, such as that produced by aircraft and vehicles. In order to collect clearer acoustic data, we attach a sensor with a microphone to each pump.

Since it is possible to detect anomalies in the pump not only based on the interval and duration of the sound during operation, but also the sound quality, the acoustic data obtained by the microphone should be collected to the greatest degree possible using the original sounds. However, if the recording time per file is long, the data size increases, and the transfer time per file also increases. On the other hand, if the recording time is short, one operating sound is saved across multiple files. The recording time per file was set to three minutes in this system, and the codec was PCM 44.1 kHz, 16 bit, monaural (approximately 15 MB per file).

As shown in Fig. 1, the acoustic data collected by the sensor is aggregated once to the edge node. Since the system is installed outdoors, for wireless communication between the sensor and the edge node, we adopted Wi-Fi 5 (IEEE 802.11ac), which uses the 2.4-GHz band. Note that we did not assume Wi-Fi 6, which uses the 5-GHz band, because Wi-Fi 6 is limited with respect to the available frequency channel and may stop due to the dynamic frequency selection (DFS) function when a satellite radar signal is detected. In particular, Wi-Fi using the 2.4-GHz band may not be able to achieve satisfactory performance because it competes with various commensurations and other Wi-Fi signals. In addition, the Wi-Fi transmission rate varies depending on the distance between the sensor and the Wi-Fi access point (AP), so the transmission rate for each sensor will fluctuate [8]. If sensors with different transmission rates communicate simultaneously using the same AP, then performance anomaly problems inevitably occur. As a result, the communication performance of all sensors may be degraded.

When collecting data from multiple sensors, we consider the transfer time and the amount of data transfer [9]. In order to achieve efficient acoustic data transfer from 11 sensors to one edge node without the problems described above, it is necessary to introduce a transfer control method, such as shifting the transfer timing for each sensor. If the transmission rate for eleven sensors is lowered due to contention, the data transfer time per file inevitably increases and untransferable data accumulates in the node, which may result in not only a shortage of storage for sensor devices, but also stalling of the entire system. Therefore, a new wireless communication system is required.

III. Preliminary Experiment

In order to design a system for reliable acoustic data collection, we conducted experiments to measure the continuous file transfer characteristics by Wi-Fi in indoor and outdoor environments. A Raspberry Pi 4 Model B was used as the sensor node (hereinafter, referred to simply as a node). Each node recorded acoustic data using a custom-made board equipped with a MEMS microphone. In order to measure Wi-Fi communication, we used a wireless capture node created using a Raspberry Pi 4 Model B. A JETSON TX2 module (NVIDIA) was used for the edge node. The node has a Wi-Fi 5 (11ac) interface that operates in the 2.4-GHz band with a channel width of 20 MHz and two streams of MIMO.

First, as shown in Fig. 2, the edge node was installed at the end of a long indoor corridor. Nodes for data transmission were installed at intervals of five meters, and the nodes transmitted 50 consecutive 15 MB files at each point independently. We measured the transmission rate for each packet and the throughput. Figure 3 shows the dependence of the transmission rate and the throughput on the communication distance. The blue line in the graph indicates the throughput, and the red line indicates the maximum, minimum, and mode of the transmission rate for each distance. These results show that both the transmission rate and the throughput decrease as the distance increases. Moreover, the difference between the maximum and minimum values of the transmission rate also increases, and the transmission rate is not stable. The above results show that the performance was significantly dependent on the communication distance, even in an indoor environment, where radio wave propagation is relatively good. The communication performance may deteriorate further in an outdoor environment [10].

Next, we measured the performance of Wi-Fi communications in an outdoor experimental environment, as shown in Fig. 2. Since eleven pumps are deployed in a straight line, the edge node is installed between pumps 6 and 7. The distance from pump 1 to the edge node is 17 meters, and the distance from pump 11 to the edge node is 26 meters. In this environment, the dependence of the transmission rate and the throughput on the distance between each node and the edge node are

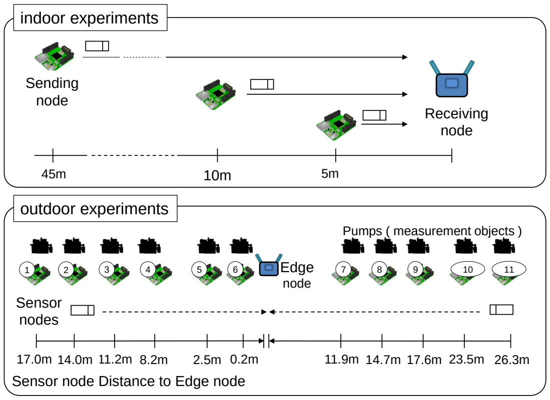

Fig. 2. Network topology (top: indoor, bottom: outdoor).

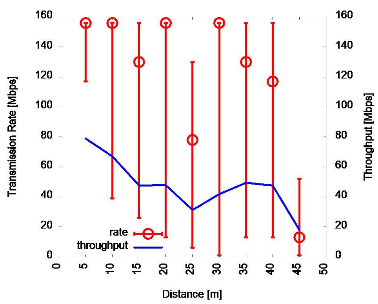

Fig. 3. Distance vs. transmission rate (indoor).

shown in Fig. 4. The transmission rate and the throughput for the node at pump 6, which is installed adjacent to the edge node, are 156 Mbps and 80 Mbps[1], respectively. As the distance between the node and the edge node increases, both the throughput and the transmission rate decrease significantly. The communication performance in the outdoor environment was lower than that in the indoor environment. The indoor communication performance increases due to the effect of rake reception of multipath propagation. On the other hand, the outdoor communication performance decreases due to contention from other communications using the same frequency band and the small benefits of multipath propagation.

From the above results, in order to realize stable acoustic data collection in an outdoor environment, it is necessary to introduce a method for controlling data transmission for a node based on the transmission rate, and to reduce the amount of data transmission without affecting anomaly detection using acoustic data.

IV. Proposed method

Based on the results of our preliminary experiments, we propose a simple heuristic transmission timing control method and a method that can reduce the amount of data transmission for realizing a stable acoustic data collection system.

In the transmission timing control method, an offset time for data transmission is set for each node so that communication

[1]Since the wireless communication is half-duplex, the throughput for data transfer using TCP in this system is approximately 80 Mbps, which is close to the maximum performance.

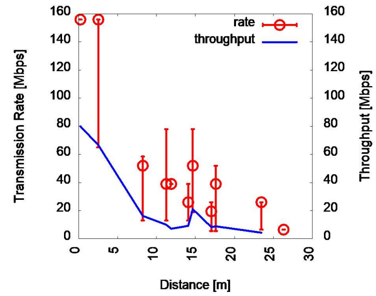

Fig. 4. Distance vs. transmission rate (outdoor).

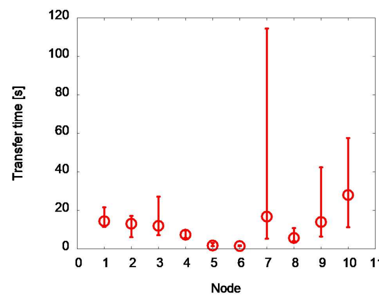

Fig. 5. File transfer time for each node in outdoor experiments.

by each node is possible. Here, we assume that all nodes can synchronize their timing using the network time protocol (NTP) service provided by the edge node. All nodes are required to complete the transfer of their recorded acoustic data once within the transmission interval. For example, if each node generates approximately 15 MB of acoustic data every three minutes, then all nodes must send the data to the edge node within three minutes. In order to determine the offset time for the transmission timing, we focused on the file transfer time in the outdoor experiment and then determined the time t required for data transmission by each node.

Figure 5 shows the results for the transfer time in the outdoor experiment. The bars and circles in the graph indicate the maximum, minimum, and average of each node, respectively. The time t required for acoustic data transmission is calculated from the results of this experiment. As shown in Fig. 5, the file transfer time to nodes located far from the edge node increases. Therefore, in this system, the start timings of these nodes are shifted backward and have a value of t_{th} from that of nodes located close to the edge node. Assuming a variation in the transfer time caused by unstable communication, the weight w is added to t_{th}. In this system, a node located far from the edge will be able to avoid contention by starting data transmission after data transmission by the nodes close to the edge is completed. In addition, in Fig. 5, since the file transfer distance is longer, the fluctuation in transfer time also tends to increase. A node with other nodes between the edge may increase the transfer time when the transfer overlaps with the node. Therefore, it is necessary to set a weight $w_n(n = 1,2,\cdots,11)$ considering the variation in file transfer time for each node. In other words, the time required for acoustic data transmission by each node is represented by

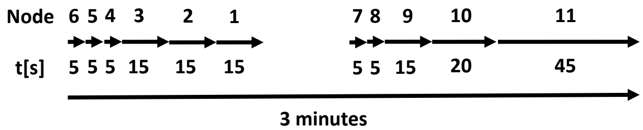

Fig. 6. Transmit node order.

$t = t_{th} + w_n$. Although the values of w_n must be uniquely determined, they are very dependent on the transfer overlap and the experimental environment. Therefore, a method for determining w_n is a future consideration, and in the present paper, we determined the value only by t_{th}. Finally, the offset of the transmission time is set based on the transmission order of the node and the calculated value t.

V. Demonstration Experiment

We verified the effectiveness of the proposed system using 11 pumps as shown in Fig. 2. Each node transfers a recorded file to the edge node using SSH every three minutes. The codec of the audio file is PCM, 44.1 kHz, 16 bit, and monaural, and is therefore approximately 15 MB per file. In this system, the transfer order of nodes is set from node 6 to node 1, and then from node 7 to node 11. Based on the results of Fig. 5, we set t to complete the transfer from all nodes within three minutes, as shown in Fig. 6. The transfer start time for node 7 is set to be later than t. This is because even when unexpected trouble occurs in the transfer from node 6 to node 1 and the data cannot be transferred smoothly, a large margin improves the success probability for data transmission.

First, we compare the continuous working days for the proposed method with those for the method without reduction processing. The method without reduction processing shut down two weeks after system installation, whereas the proposed method was in operation for more than 100 consecutive days. In the method without reduction processing, since communication among nodes competes and communication performance deteriorates, acoustic data cannot be transmitted to the edge node. As a result, acoustic data were accumulated in the nodes, and storage was exhausted. Finally, the system stopped. On the other hand, the proposed method enables nodes to transfer data continuously.

Next, Fig. 7 shows the amount of transmitted data in 24 hours on June 16th, 2021. The red bars indicate the amount of transmitted data per hour, and the purple line indicates the average amount of transmitted data per hour. The actual data volume for the three-minute recording file is 15.7 MB. The number of files acquired by 11 nodes for one day is 5280. Therefore, the amount of data acquired per day is $15.7\,\mathrm{MB} \times 5,280 = 83\,\mathrm{GB}$. The average amount of data acquired per hour is 3.5 GB. Therefore, the average value for the conventional method without the proposed reducing processing method is 3.5 GB, whereas the hourly amount of data transmitted by the proposed method can be compressed to 34 MB. In addition, we can confirm from this graph that the amount of transmitted data differs every hour. This is because the operation time and interval of each pump are not constant every time. From the above results, stable data collection was achieved by accurately extracting the operation sound of the pump for reducing the amount of transmitted data and adjusting the transfer timing.

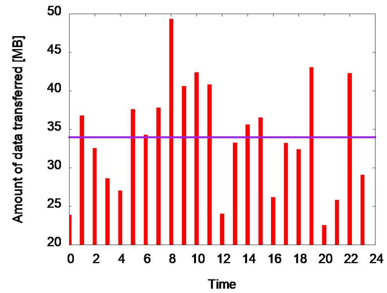

Fig. 7. Amount of data transferred per hour on June 16, 2021.

VI. Conclusion

We conducted preliminary experiments to investigate the communication characteristics for the transmission of large-size data by Wi-Fi in an outdoor environment. The results indicated that the communication performance was insufficient for transferring all recorded data handled by this system. Therefore, we proposed a transmission timing control method for acoustic data and a reduction processing method for transmitted data. Through demonstration experiments using multiple pumps in an outdoor environment, we verified the feasibility of the acoustic data collection system. Future research areas include the realization of a system that can be applied to other devices after determining more accurate transmission timing control and detecting anomalies using acquired data.

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