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Characterization of IEEE802.11 WLAN Implementing on Excavator: Can We Use IEEE802.11 for i-construction?

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Abstract

As network systems become more sophisticated, through network systems, the automatic/remote-automatic/remote-control technology is spreading to construction machinery. These technologies are supported by wireless communication. Currently, IEEE802.11 is a widely used wireless communication standard. This IEEE802.11 standard is expected to improve the usability of construction machinery, similar to other mobilities, such as vehicles. However, its communication characteristics are unknown. Here, we evaluate the performance of a wireless local area network (WLAN) comprising wireless communication modules implemented in an excavator. In particular, we focus on the throughput when sender and receiver positions are changed. Experimental results were used to characterise the WLAN device communication between a PC and a communication controller. We found that the IEEE802.11 WLAN has been confirmed as having applicability to i-construction.

Keywords: construction machinery, excavator, IEEE802.11, communication characteristics, i-construction

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1. Introduction

What can be done to improve productivity and safety at construction sites? One solution is to use information communication technology. In fact, in Japan, the Ministry of Land, Infrastructure, Transport, and Tourism promotes *i-construction* [1]. i-construction aims to improve productivity and safety at construction sites by using numerous Internet of Things (IoT) [2] devices such as drones, sensors, and cameras. Wireless communication is used to connect the devices to construction machinery, such as excavators and cranes. In such situations, the IEEE802.11 standard [3] is used as a wireless communication technology. However, the performance of IEEE802.11 communication when used with construction machinery is unclear.

Here, to clarify this performance, we evaluate the communication characteristics of an IEEE802.11 wireless local area network (WLAN) implemented on construction machinery. In particular, we focus on the packet reception success rate, throughput, and jitter when the sender and receiver positions are changed.

Contribution

From the experimental evaluations using a seven-ton class excavator, we obtained the following results:

(i) The characteristics of the packet reception success rate considering the communication distance and location are clarified.
(ii) The characteristics of the TCP and UDP throughput and the UDP jitter considering the communication distance and location are shown.

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(iii) The communication characteristics in seven-ton class excavator are assessed.

Organization

The remainder of this paper is organised as follows. Section 2 describes the work related to this study. Section 3 explains the experimental evaluation of the IEEE802.11WLAN considering the use of the excavator. Section 4 discusses the experimental results. Finally, Section 5 summarises the conclusions and future work.

2. Related works

This section explains the existing studies related to this study. In particular, this section provides an overview of IEEE802.11 WLAN and some existing studies.

2.1. Overview of IEEE802.11 WLAN

IEEE802.11 standard WLAN is a widely used wireless LAN standard. IEEE802.11b [4] and IEEE802.11g [5], which were standardised in 1999, are representative examples of IEEE802.11 WLAN. These standards use radio waves in the 2.4 GHz band, and the maximum nominal transmission rates are 11 Mbps and 54 Mbps, respectively. There is also IEEE802.11a [6], which uses the 5 GHz frequency band and has a maximum nominal transmission rate of 54 Mbps, and IEEE802.11n [7] and IEEE802.11ac [8], which use MIMO technology to achieve faster and stable communications. Recently, IEEE802.11ax (Wi-Fi6) [9] has been proposed to improve multi-user performance metrics, such as delay, latency, and throughput. All these standards aim to increase the speed and stability of communications.

To communicate with devices in IEEE802.11 WLANs, carrier sense multiple access with collision avoidance (CSMA/CA) is used as the media access control (MAC) method and devices autonomously send data frames [10]. Therefore, each device decides the timing of the data transmission. In CSMA/CA, the channel becomes idle when a data frame arrives in the transmission queue, it defers to the DCF inter-frame space (DIFS) time. Then, when the channel remains idle after DIFS, CSMA/CA waits for the back-off time, which is randomly calculated using a contention window (CW). The device sends a data frame when the channel remains idle after the back-off time. The back-off time of the i-th device at t is calculated using Eq. (1).

$$\mathrm{Backoff}_i(t) = \mathrm{Random}() \times \mathrm{SlotTime} \tag{1}$$

In Eq. (1), random () and slot time represent a random integer derived from a discrete uniform distribution [0, CW] and a SlotTime interval specified in IEEE802.11, respectively. CW satisfies $CW_{min} \leq CW \leq CW_{max}$. Here, the initial CW was set to CW_{min}. When a frame collision occurred (terminals failed to send the frames), the terminal set the back-off time using Eq. (1) again. In this case, the CW became twice as large as the previous value, and the upper bound was CW_{max} (= 1023). When the retransmission exceeded the maximum retry limit (normally seven), the device discarded the frame.

2.2. Existing studies of IEEE802.11WLAN

In the IEEE802.11 WLAN environment, there are many existing studies.

Reference [11] shows the throughput performance, jitter, and packet loss rate in an IEEE802.11a/g environment using real machines. Moreover, [12] evaluated TCP throughput performance in IEEE802.11b WLAN and showed TCP throughput unfairness in a WLAN environment. In [13], the throughput performance of the IEEE802.11ac WLAN multi-rate environment was shown. Further, [13] showed that the impact of performance anomalies [14] was quantitatively demonstrated using real machines. These studies focused on communication performance.

For other motivations, there have been studies that focus on modelling communication in the IEEE802.11 WLAN. For example, in [15], a throughput modelling method based on a viscoelastic material model was proposed. Further, [16] proposed a throughput model of the IEEE802.11 multi-rate WLAN environment considering the cycle time. Using these methods, the throughput performance of the IEEE802.11 WLAN was estimated. Furthermore, [17] showed a model of rate adaptation using the Markov property. Some studies have evaluated IEEE802.11 considering vehicles [18, 19, 20]; however, there has been no detailed characterisation of IEEE802.11 in excavator equipment.

The next section describes the experimental evaluation of the IEEE802.11 WLAN performance considering the excavator.

3. Experimental evaluations and results

This section explains the experimental evaluations of the IEEE802.11 WLAN performance, which was implemented on the excavator, and presents the results.

3.1. Evaluation settings

Table 1 shows the experiment for the communication. In the evaluation, we used a communication controller (see Fig. 1) and a Windows PC. In the communication controller, Sitara™ AM3358 Cortex-A8 [21] was implemented as a CPU, and the RAM size was 256 MB.

Table 1. Experimental environment for communication: Device specification and protocol.

CPU	Communication controller: Sitara™ AM3356 Cortex-A8 [21] PC: Intel® Core™ i5
RAM	Communication controller: 256 MB PC: 8 GB
Operating system	Communication controller: Yocto Linux® (Agaro Project) PC: Windows 10
Linux kernel of the communication controller	Version 4.19.94-gbe5389fd85
Physical protocol	IEEE802.11n (2.4-GHz band) with rate adaptation
MAC protocol	CSMA/CA
Internet protocol	IPv4
Transport protocol	CUBIC TCP [24] / UDP [22]
Application protocol	Iperf3: Throughput and jitter [26] TI calibrator tool: Packet reception success rate [25]

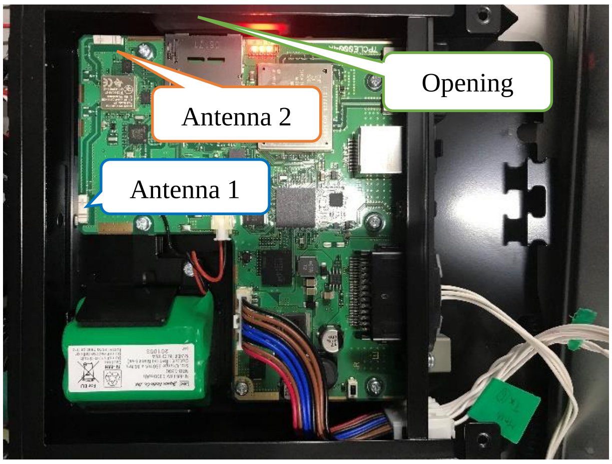

Figure 1. Communication device: It is implementing on the cabin of the excavator.

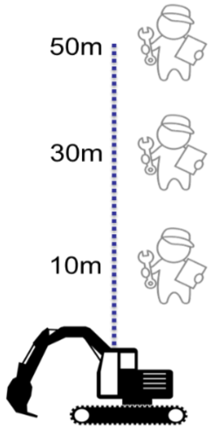

Figure 2. Test pattern 1: when the distance between the PC and the communication controller in the excavator was changed in 10 m, 30 m, and 50 m.

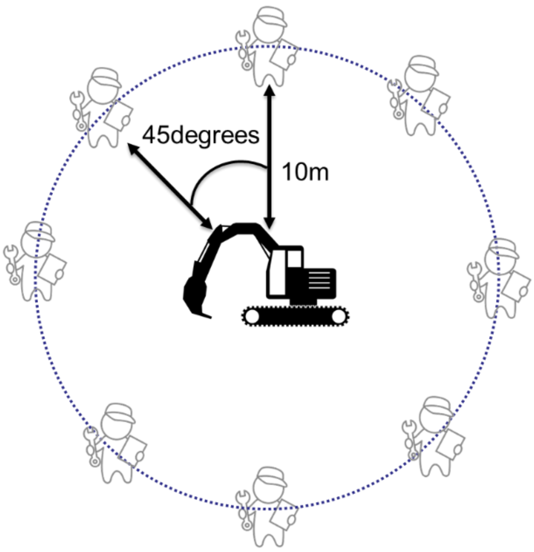

Figure 3. Test pattern 2: when the PC's position is fixed at 10 m away from the centre of the communication controller and the construction machine is rotated in increments of 45 degrees.

The communication controller had two antennas (Fig. 1 shows each position). The operating system (OS) was Yocto Linux® (Agaro project), and the kernel version was 4.19.94. However, the Windows PC had an Intel® Core™ i5 the CPU with a RAM size of 8 GB. The OS version used was the Windows 10. WLAN was IEEE802.11n (2.4-GHz), and CSMA/CA was used for the MAC. In the WLAN, the rate adaptation was ON (not fixed baud rate). The internet protocol was IPv4, and the transport protocol was UDP [22] and TCP [23]. The TCP congestion control algorithm was CUBIC-TCP [24] for each device. The application was the TI calibrator tool [25] for packet error rate evaluation and Iperf3 [26] for other evaluations, and the sender generated the flow for 30 s (segment size: 1000 B). There were three trials, and the results were averaged. The communication controller was implemented in the cabin of SK-75SR [27], which is a seven-ton class excavator.

In the evaluation, (1) the communication characteristics when the distance between the PC and the communication controller was changed to 10 m, 30 m, and 50 m (see Fig. 2), and (2) the communication characteristics when the PC's position was fixed at 10 m away from the centre of the communication controller and the construction machine was rotated in increments of 45° (see Fig. 3) were evaluated. In both evaluations, there was one sender and one receiver (PC or communication controller).

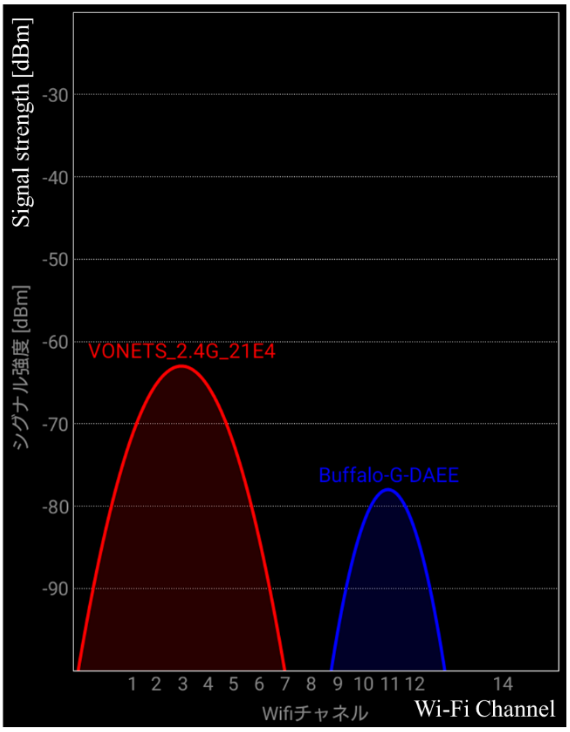

Figure 4. Utilisation of the 2.4-GHz band: Horizontal axis and vertical axis are Wi-Fi channel and signal strength, respectively.

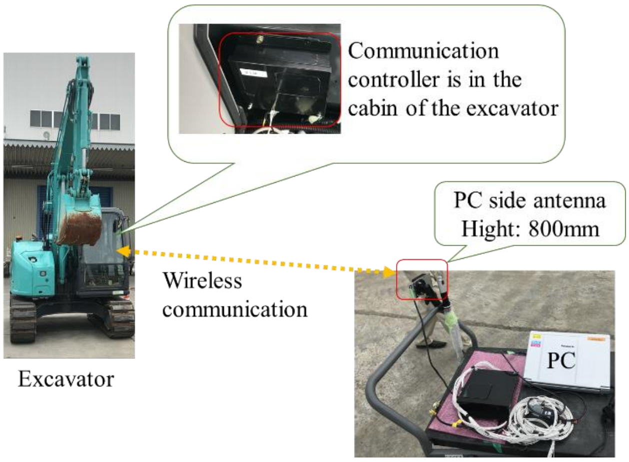

Figure 5. Experimental environment. The PC and the communication controller communicate using IEEE802.11 WLAN.

Fig. 4 shows the utilisation of the 2.4-GHz band. The horizontal and vertical axes represent the channel and signal strengths, respectively. From Fig. 4, some access points were used in 2.4-GHz band. Fig. 5 shows the test field image. In the field, some excavators existed around the communication controller equipped with an excavator and a PC.

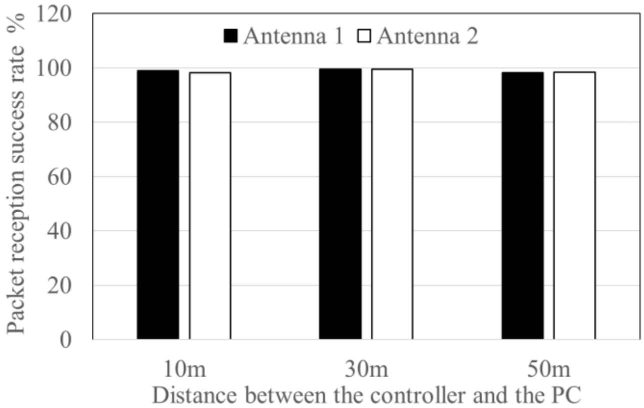

Figure 6. Average packet reception success rate in each communication distance: The black bar is the antenna 1's results, and the white bar is the antenna 2's results, respectively.

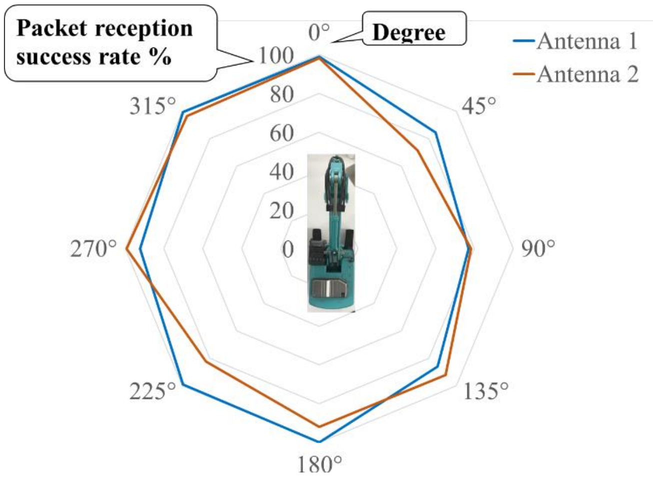

Figure 7. Average packet reception success rate in each direction: The blue line is the antenna 1's results, and the orange line is the antenna 2's results, respectively. The communication distance is 10 m.

3.2. Packet reception success rate results

This section presents the results of packet reception success rate. In the evaluation, we communicate with the PC using one antenna each for antennas 1 and 2. Note that the PC was set up in front of the excavator, and the packet flow direction was from the controller to the PC.

First, Fig. 6 shows the average packet reception success rate for each communication distance. In Fig. 6, the horizontal axis represents the distance between the controller and PC. The vertical axis represents the packet reception success rate. As Fig. 6 shows, the packet reception success rate does not change regardless of the antenna used for communication. Moreover, Fig. 6 shows that the success rate of packet reception was approximately 99%.

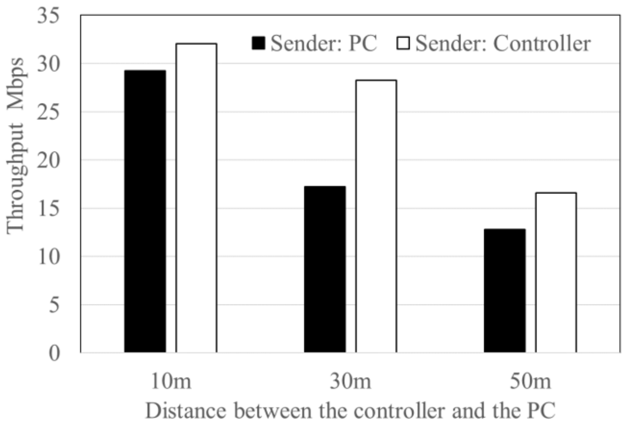

Figure 8. Average TCP throughput in each communication distance: The black bar is the results when the PC is the sender, and the white bar is results when the communication controller is the sender, respectively.

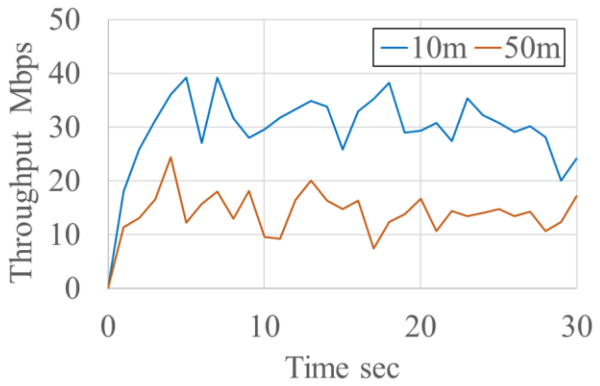

Figure 9. Temporal evolution of TCP throughput in each communication distance (the sender is PC): The blue line is the 10 m results, and the orange line is the 50 m results.

Second, Fig. 7 plots the average packet reception success rate in each direction around the excavator. The communication distance was 10 m. As Fig. 7 shows, the packet reception success rate was more than 70% regardless of the location. When antenna 1 was used, the minimum packet reception success rate was 77% (90°). Moreover, when antenna 2 was used, the minimum packet reception success rate was 71% (45°). From these results, location had a greater influence on the success rate of packet reception than the distance. Note that in the direction of 270° to 315°, the packet reception rate is good because there is an opening in the structure of the enclosure. On the contrary, the packet reception in the direction of 45° to 90° is worse because there is not the opening in the structure of the enclosure.

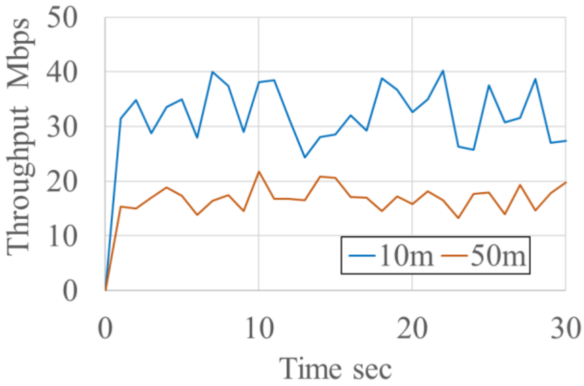

Figure 10. Temporal evolution of TCP throughput in each communication distance (the sender is controller): The blue line is the 10 m results, and the orange line is the 50 m results.

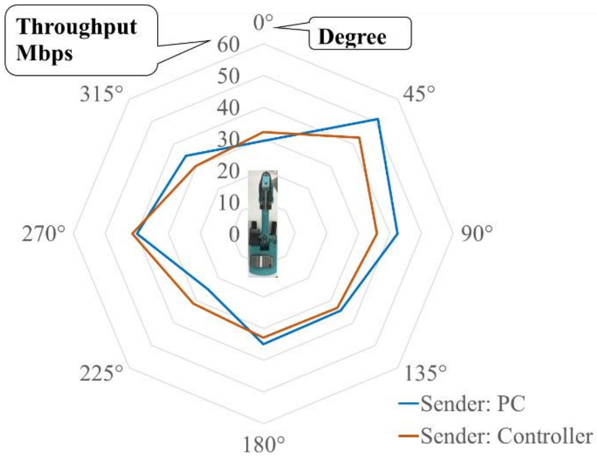

Figure 11. Average TCP throughput in each direction: The blue line is the results when the PC is the sender, and the orange line is the results when the controller is the sender. The communication distance is 10 m.

3.3. Throughput results

This section describes the results of the throughput evaluation. In the evaluation, we evaluated two communication directions, from the PC to the communication controller, and from the communication controller to the PC. We evaluated the characteristics of the throughput by considering the communication distance and location. The controller used both antennas to communicate with the PC.

3.3.1 TCP performance results

Fig. 8 shows the average TCP throughput for each communication distance, the black bar represents the results when the PC was the sender, and the white bar shows the results when the communication controller was

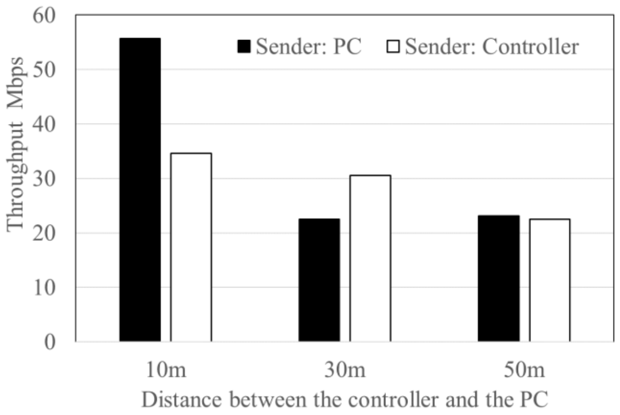

Figure 12. Average UDP throughput in each communication distance: The black bar is the results when the PC is the sender, and the white bar is results when the communication controller is the sender.

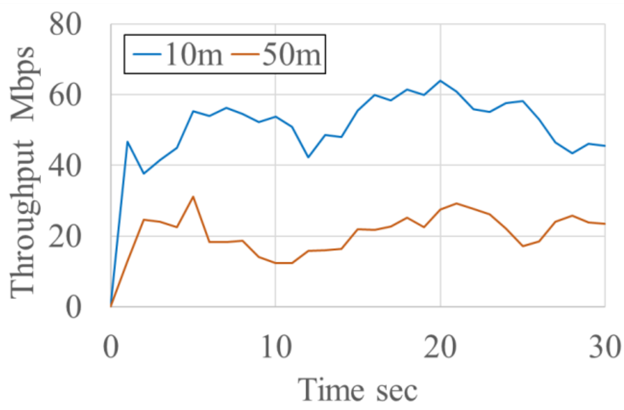

Figure 13. Temporal evolution of UDP throughput in each communication distance (the sender is PC): The blue line is the 10 m results, and the orange line is the 50 m results.

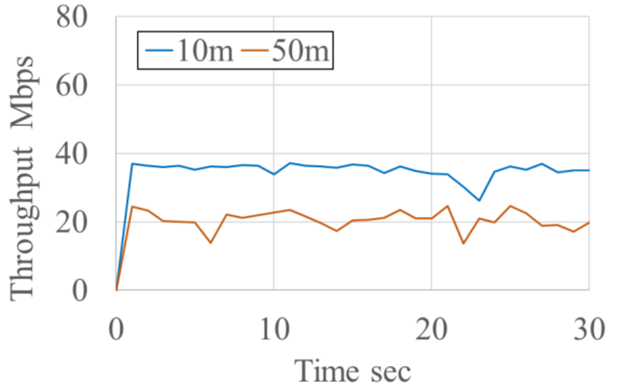

Figure 14. Temporal evolution of UDP throughput in each communication distance (Sender is controller): The blue line is the 10 m results, and the orange line is the 50 m results.

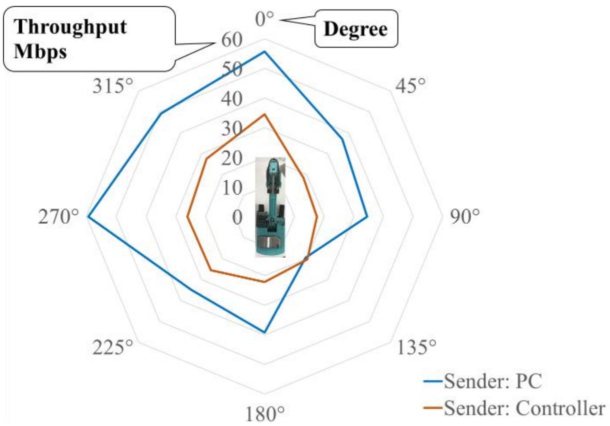

Figure 15. Average UDP throughput in each direction: The blue line is the results when the PC is the sender, and the orange line is the results when the controller is the sender.

the sender. The position of the PC was at the front of the excavator. As Fig. 8 shows, the throughput decreased as the communication distance increased. Furthermore, when the sender was the PC, the maximum throughput was 29 Mbps at 10 m. However, when the sender was the controller, the maximum throughput was 32 Mbps at 10 m. In 50 m, the minimum throughput results were obtained. When the sender was a PC, the minimum throughput was 13 Mbps; when the sender was the controller, the minimum throughput was 17 Mbps.

Figs. 9 and 10 show the temporal evolution of TCP throughput for each communication distance. The horizontal and vertical axes show the time and throughput, respectively. Note that this result was not an average but an example of a single temporal evolution. Fig. 9 shows the result when the sender was a PC, and Fig. 10 shows the result when the sender was the controller. From Figs. 9 and 10, the throughput at 10 m was higher than the one at 50 m.

Next, Fig. 11 shows the average TCP throughput results in each direction around the excavator. The communication distance was 10 m. From Fig. 11, when the PC was the sender, the maximum throughput was 51 Mbps (45°). Moreover, when the controller was the sender, the maximum throughput was 43 Mbps (45°). Furthermore, the minimum throughput was 25 Mbps (225°) when the PC was the sender and 30 Mbps (315°) when the controller was the sender. Therefore, we saw that the TCP throughput was affected by both the distance and location.

3.3.2 UDP performance results

Fig. 12 shows the average UDP throughput for each communication distance. The black bar represents the results when the PC was the sender, and the white bar indicates the results when the communication controller was the sender. The PC was positioned at the front of the excavator. As Fig. 12 shows, the throughput trend decreased as the communication distance increased. In contrast to the TCP results, when the sender was the PC,

Figure 16. Experimental environment of excavator: The position of the excavator's bucket is different. Left side is line-of-sight communication between the PC and the controller, and right side is non-line-of-sight communication (the distance between the PC and the controller is 10 m).

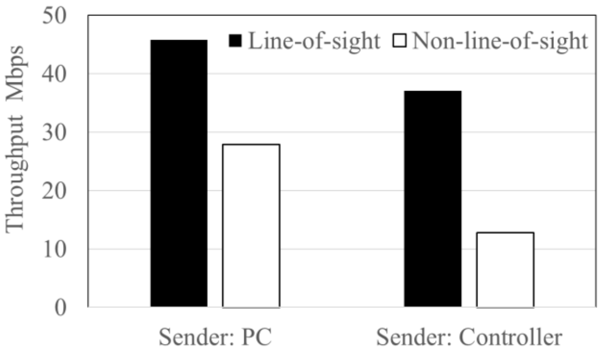

Figure 17. Average TCP throughput results considering position for excavator's bucket (the distance between the PC and the controller is 10 m). The black bar is the results of line-of-sight communication, and the white bar is results of non-line-of-sight communication, respectively.

the minimum throughput (23 Mbps) was obtained at 30 m. However, almost the same value was obtained at 50 m when the sender was a PC. When the sender was the controller, the minimum throughput was 23 Mbps at 50 m. The maximum throughput was 56 Mbps at 10 m when the sender was the PC. However, when the sender was the controller, the maximum throughput was 35 Mbps at 10 m.

Next, Figs. 13 and 14 show the temporal evolution of the UDP throughput for each communication distance. The meaning of each axis was the same as in Figs. 9 and 10. Similar to the TCP results, this was not an average, an example of a single temporal evolution. Fig. 13 shows the result when the sender was a PC, and Fig. 14 shows the result when the sender was the controller. From Figs. 13 and 14, the throughput at 10 m was higher than the one at 50 m.

Fig. 15 plots the average UDP throughput result in each direction around the excavator. The communication distance was 10 m. From Fig. 15, when the PC was the

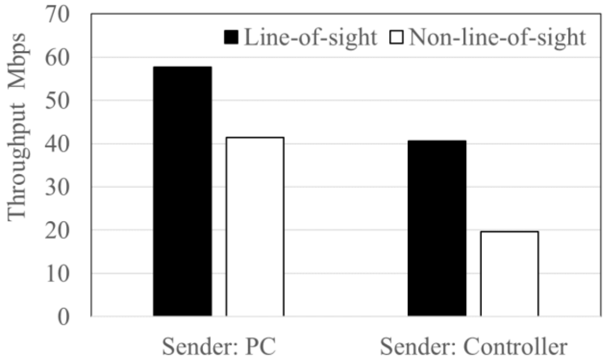

Figure 18. Average UDP throughput results considering position for excavator's bucket (the distance between the PC and the controller is 10 m). The black bar is the results of line-of-sight communication, and the white bar is results of non-line-of-sight communication.

sender, the maximum throughput was 59 Mbps (270°). Moreover, when the controller was the sender, the maximum throughput was 35 Mbps (0°). However, the minimum throughput was 20 Mbps (135°) when the PC was the sender, and 18 Mbps (90°) when the controller was the sender. Therefore, we saw that UDP throughput was also affected by both distance and location same as TCP case.

3.3.3 Considering attachment of excavator

Excavators were fitted with attachments made of metals. Therefore, attachments might become obstacles, which might affect communication characteristics. Therefore, in this section, we changed the position of the backet, which was the attachment to digging the ground and evaluated the TCP/UDP throughput. Fig. 16 shows the position of the bucket. The distance between the PC and the controller was 10 m, and the position of the PC was at the front of the excavator. In Fig. 16, the left-side position achieves line-of-sight communication between the PC and controller. right side position; however, the PC and controller were non-line-of-sight communications.

Figs. 17 and 18 show the average throughput results for TCP and UDP, respectively. The horizontal axis represents the sender, and the vertical axis the throughput. The black bar represents the results of line-of-sight communication, and the white bar the result of non-line-of-sight communication. As Figs. 17 and 18 show, the throughput of line-of-sight communication was larger than the non-line-of-sight communication. In particular, in Fig. 17, when the sender was a PC, the difference between the line-of-sight and non-line-of-sight results was 18 Mbps. However, when the sender was the controller, the difference between the line-of-sight and non-line-of-sight results was 24 Mbps. Furthermore, in Fig. 18, when the sender was a PC, the difference between the line-of-sight and non-line-of-sight results was 16 Mbps. However, when the sender was the controller, the difference between the line-of-sight and non-line-of-sight results was 21 Mbps. Therefore, the

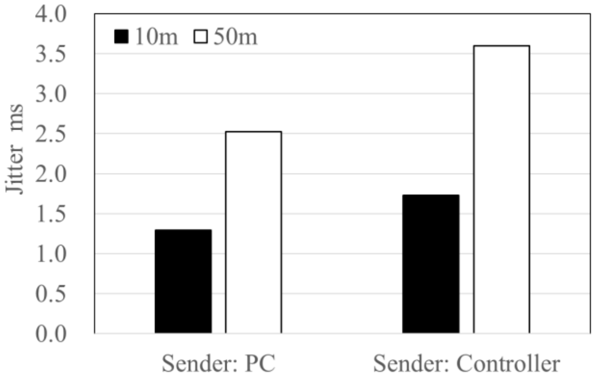

Figure 19. Average UDP jitter results when the distance between the PC and the controller is 10 m and 50 m. Black bar is 10 m results, and white bar is 50 m results.

position of the attachment was important for the throughput.

3.4. UDP jitter results

The number of applications with real-time capabilities is increasing and might be used in excavators. Communication jitter is a performance evaluation measure for services with real-time characteristics. Jitter is a variable value of communication delay and is specified in RFC3550 [28]. In this section, we evaluate the jitter characteristics by considering the communication distance. Herein, we evaluate jitter against communication distance as an example, but we plan to conduct a detailed QoS/QoE evaluation in the future. We evaluated the jitter of UDP communication, which was easy to analyse. The other evaluation conditions were the same as those in Section 3.3.2.

Fig. 19 shows the average UDP jitter results when the distance between the PC and the controller was 10 m and 50 m. The black bar represents the 10 m results, and the white bar the 50 m results. In Fig. 19, the horizontal and vertical axes represent the sender device and jitter, respectively. As Fig. 19 shows, the distance between the PC and controller increased, and the jitter also increased. Especially, in 10 m, the result of the PC sender case was 1.3 ms, and the one of the controller sender case was 1.7 ms. However, in 50 m, the result of the PC sender case was 2.5 ms, and the one of the controller sender case was 3.6 ms. the difference between the 10 m results and the 50 m result was from 1.2 ms to 1.8 ms.

Figs. 20 and 21 show the temporal evolution of the jitter at each distance. Fig. 20 shows the PC sender results, and Fig. 21 shows the controller sender result. In Figs. 20 and 21, the horizontal axis shows the time, and the vertical axis is the jitter. From Figs. 20 and 21, the trend remained the same if the sender device changed. Further, the jitter in the 10 m result was smaller than that in the 50 m result. In Fig. 20, the maximum jitter in 10 m was 1.9 ms, and in 50 m, it

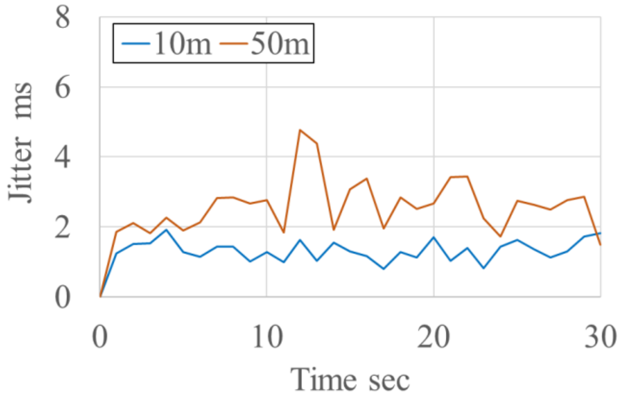

Figure 20. Temporal evolution of UDP jitter in each communication distance (Sender is PC): The blue line is the 10 m results, and the orange line is the 50 m results.

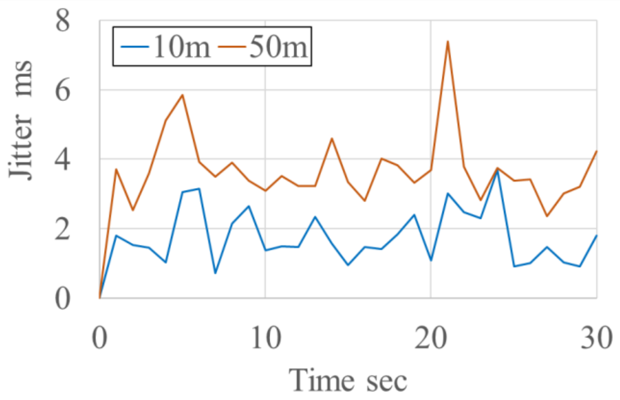

Figure 21. Temporal evolution of UDP jitter in each communication distance (the sender is controller): The blue line is the 10 m results, and the orange line is the 50 m results.

was 4.8 ms. Moreover, in Fig. 21, the maximum jitter at 10 m was 3.7 ms, and that at 50 m was 7.4 ms.

Here, we focus only on the results when the distance between the PC and the controller was changed. From these results, the jitter depended on the distance between the PC and the controller.

4. Discussion

First, we discuss the characteristics related to the distance between the PC and controller. It was found that the packet reception success rate did not depend significantly on the distance, regardless of the antenna used. This was because there was no obstacle between the front of the construction machine and the PC that interfered with the reception of wireless signals, so packet reception was thought to be successful. In contrast, in the case of throughput and jitter evaluation at a higher layer (over transport layer), we found that the transmission characteristics deteriorated when the distance between the

PC and the controller was greater. This was caused the data not to be passed to the higher layers due to some effect such as transmission delay, though the signals were physically received.

Second, we discuss the characteristics related to the location of the PC and controller. In both the case of packet reception success rate and throughput, we found that the results changed significantly when the location relationship changed. It was found that the communication performance degraded when there was a metal plate covering the cabin of the excavator between the controller and PC. This was because the iron plate blocked the radio waves. Further, it was observed that when the attachment (bucket) of the excavator blocked the line of sight between the controller and the PC, the throughput was significantly reduced. This was because the attachment, which was made of metal as well as the steel plate of the cabin, blocked the radio.

From the above, we confirmed that the communication characteristics were affected by the distance and positional relationship between the controller and the PC, so it was necessary to use and design communication devices that took these effects into account.

5. Conclusion

In Japan, the Ministry of Land, Infrastructure, Transport, and Tourism promotes i-construction to improve productivity and safety at construction sites. i-construction is realised using numerous IoT devices such as drones, sensors, and cameras. WLAN based on the IEEE802.11 standard is used to connect the devices to the construction machinery. However, the performance of IEEE802.11 communication considering construction machinery has remained unclear.

To demonstrate the performance, this study evaluated the communication characteristics of IEEE802.11 WLAN implementing on construction machinery. In particular, we evaluated the packet error rate and throughput when the sender and receiver positions were changed. From the experimental evaluations, we obtained the following results using a seven-ton class excavator:

- The characteristics of the packet reception success rate considering the communication distance and location was clarified.
- The characteristics of the TCP and UDP throughput and the UDP jitter considering the communication distance and location was shown.
- The communication characteristics in seven-ton class excavator were assessed.

Future works include an evaluation of the performance when the construction machinery was working, and multiple devices were in the WLAN. Further, it needs to be evaluated in an environment where other radios using the 2.4-GHz band (such as Bluetooth using devices such as BLE beacon devices [29] exist) were present. Finally, applications of i-construction using the IEEE802.11 WLAN will be implemented.

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