

Can Be Applied for Bluetooth Low Energy to i-construction? : Characterization of BLE on Excavator

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Abstract

The Government of Japan has declared that construction sites must implement *i-construction*, in which information communication technology (ICT) is used to improve construction site productivity and throughput. Examples of *i-construction* include remote and automatic control systems for construction machinery, for which wireless communication is generally required; however, the wireless characteristics that must be considered in *i-construction* remain unclear. To clarify these characteristics, Bluetooth Low Energy (BLE) beacon module is implemented for construction machines, and we investigate its communication characteristics. We focussed on two evaluations: characterisation of the BLE unit module and its feasibility in *i-construction*. Experimental results were used to characterise BLE communication in a residential area and construction site. In the latter, BLE beacon module communication was possible between a sender located in an excavator attachment and a receiver in its cabin.

Keywords: Excavator, *i-construction*, Bluetooth, Wireless communication, Internet of Things

Received on 03 August 2020, accepted on 03 October 2020, published on 16 October 2020

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doi: 10.4108/eai.16-10-2020.166662

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1. Introduction

An earlier version of this paper was presented at the 12th International Workshop on Autonomous Self-Organizing Networks (ASON 2019) [1]. Please read the additional evaluations reported in the body of this paper.

How can the efficiency of labourers at a construction site be increased? To solve this issue, Japan is promoting work style reforms. In 2015, the Ministry of Land, Infrastructure, Transport, and Tourism of Japan declared that construction sites must drastically introduce information and communications technology (ICT) to improve productivity and throughput throughout the construction site [2]. This approach is called *i-construction*. In *i-construction*, many ICT technologies are applied to the operation of a construction site. Remote

[3] or automatic [4] control of construction machinery such as excavators, cranes, and other vehicles has been widely discussed. Automatic measurement of construction sites using drones is also another popular approach. Other *i-construction* applications include preventive maintenance [5] for construction machinery. In prevention maintenance, data gathered by various sensors installed on the construction machines are sent to servers via cellular or satellite networks. Each communication solution in *i-construction* is based on an *Internet of Things* (IoT) system. In IoT systems, networks comprise numerous data-gathering IoT devices (such as sensor devices), with each device sending data through wireless communication. Therefore, specific requirements specific to IT devices such as desktop PCs and servers must be met in order to implement these kinds of networks. For example, because IoT devices can be directly accessed by anyone at any time, additional security solutions must be

introduced. Furthermore, maintenance methods of IoT devices are required for their effective operation.

Because IoT devices operate using battery power, one of their important requirements is power saving. If the batteries of several IoT devices are not charged, they cannot communicate to the network and preventing the IoT system to function properly. In order to meet this requirement, the use of a low-power-consumption communication protocol is crucial. To date, numerous low-power-consumption communication protocols for IoT systems have been proposed by many researchers and vendors. For example, LPWA (sigfox, LoRa, etc.) is a well-known communication protocol for IoT devices. Moreover, ZigBee and Wi-SAN have been also considered for application in IoT systems.

One of the standard wireless communication protocols for IoT systems is Bluetooth Low Energy (BLE) [6]. Because BLE is known for its low power consumption and its large communication range, a typical i-construction implementation might include BLE communication modules. Various studies have evaluated the characteristics of BLE communication, but the required wireless communication characteristics for i-construction are still unclear. In order to clarify this point, this paper examines the communication characteristics of BLE in consideration of the working area for different construction machines. In the evaluations, we used a BLE beacon module as the communication device. To develop the evaluation system, we used waterfall model. Experimental results that clarify the characteristics of communication in public roads and construction sites are provided. Moreover, assessments of a BLE beacon module in an excavator revealed that it was able to communicate between the sender in the excavator's attachment and the receiver in the cabin. Even if the size of the excavator was changed, communication could be established by adjusting the communication distance (Tx power). Finally, the results showed that wireless communication systems can be potentially applied for construction machinery.

Contribution

The contributions of this study are summarised as follows:

- (i) The characteristics of BLE communication in public roads and construction sites were examined.
- (ii) The communication characteristics of the beacon module in 13-, 20-, and 45-ton class excavators were assessed.
- (iii) The relationship between the Received Signal Strength Indicator (RSSI) and communication availability using real machines was analysed.

Organisation

The rest of this paper is organised as follows. Section 2 describes the works related to this study. The experimental evaluation of BLE using a beacon module is

explained and the results are discussed in Section 3. Section 4 describes the characteristics evaluation of BLE communication in construction excavators. Finally, Section 5 concludes this paper and explains future work.

2. Related works

This section summarises the works related to this study. In the area of Bluetooth communication, there have been many fundamental studies. For example, previous work [7] provides an overview of the communication and architecture of the Bluetooth framework. In addition, some protocols for operating Bluetooth are also summarised in this study. More recently, BLE has been proposed and evaluated for inter-vehicular communication [8]. From this work, BLE can be used to form the infrastructure of Vehicle-to-everything (V2X) systems. BLE can be used to construct not only a single-hop network (in which the sender and receiver communicate directly) but also multi-hop networks (in which the sender and receiver communicate via multiple terminals). The performance of Bluetooth-based multi-hop networks was evaluated in [9]. From the findings of this study, Bluetooth-using terminals were found to be able to communicate over long distances via relay terminals. The studies discussed above demonstrated that Bluetooth is a very useful communication protocol. In addition, the impact of Bluetooth communication broadcast has also been investigated [10]. This study shows that careful network design is necessary. Some studies have evaluated the Bluetooth communication characteristics considering an IEEE 802.11 and a ZigBee coexistence environment [11, 12]. However, previous studies do not focus the communication characteristics considering construction machines such as excavators. This study evaluates it using real machines. The results of this paper are useful to design the application for construction machines using BLE.

Applications of Bluetooth communications have been described in many papers. For example, [13] describes a position prediction method using BLE. In [14], a system for multiple device control was implemented using Bluetooth. Actuator control using Bluetooth communication is evaluated in [15] and a manufacturing network application using Bluetooth is discussed in [16]. Although much research effort has focussed on the topic of Bluetooth, the literature on the detailed evaluation of Bluetooth communication characteristics is still insufficient. In particular, there have been fewer experimental evaluations of the use of Bluetooth in construction machinery than on the use of Wi-Fi or WiMAX [17]. Thus, the evaluation results described in this paper can be utilised as implementation guidelines in i-construction. In the next section, experimental evaluations of BLE communication in two specific environments are presented. The characterisation was conducted using a BLE communication module installed in different excavators. Note that this paper is not



Figure 1. Experimental environment 1: Public road.

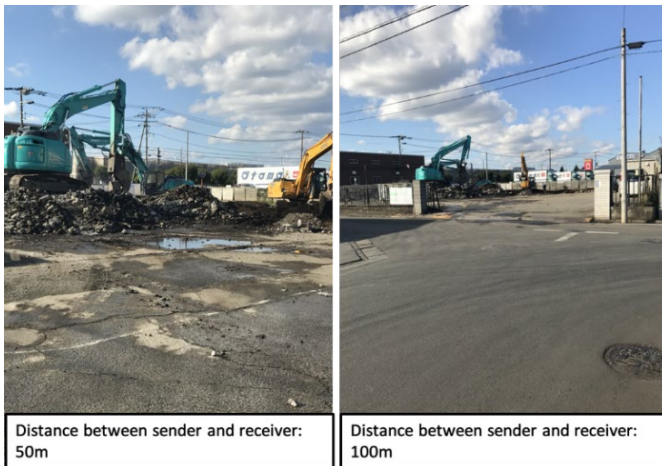


Figure 2. Experimental environment 2: Construction site.

proposing the application using BLE considering construction machines. In future, we will propose some applications based on this paper’s results.

3. Evaluation of Bluetooth Low Energy in Various Situations

This section shows the experimental evaluation using a Bluetooth Low Energy beacon module. Specifically, we focused on two environments: a public road and a construction site. Note that, because this section reports on a basic version of the study described in the following section, we describe a simple experimental set up. Moreover, we used black box test for testing approach.

3.1 Experimental Settings for Unit Test

The sender was a beacon module using BLE 4.2 with a communication distance (Tx power) of 100 m. The receiver was an iPad mini. Two points were evaluated:



Figure 3. Sender and receiver.

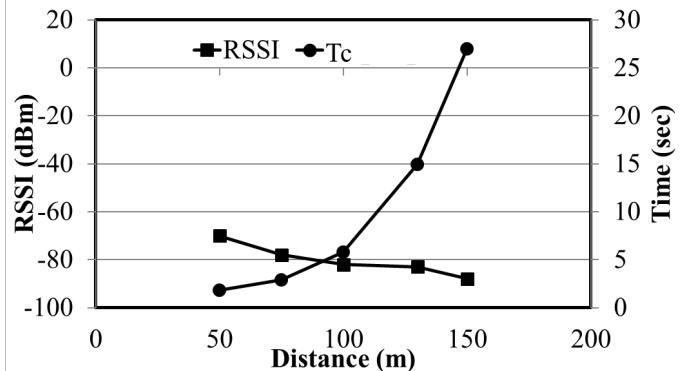


Figure 4. Relationship among RSSI, T_c , and communication distance at experimental environment 1.

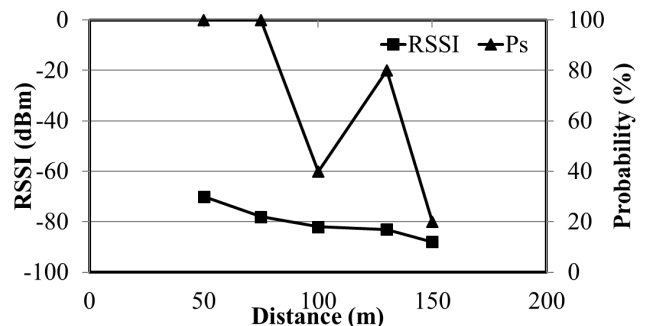


Figure 5. Relationship among RSSI, P_s , and communication distance in experimental environment 1.

- The relationship among the distance between the sender and the receiver, the RSSI, and the communication establishment time (T_c)
- The relationship among the distance between the sender and the receiver, the RSSI, and communication success percentage (P_s)

T_c is the time difference between the start of beacon transmission and the completion of reception. P_s is the percentage of beacon signals received for the trials at each distance. As this study represented the first step in assessing the applicability of BLE for i-construction, we used a simple evaluation item. In the future, we will carry out evaluations for BLE using more detailed and complex

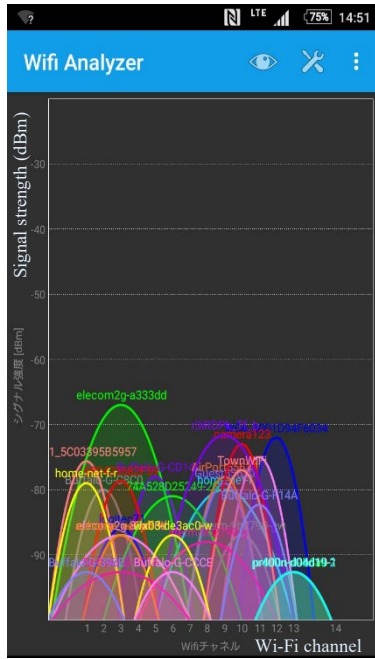


Figure 6. Utilisation of the 2.4-GHz band when the distance is 100 m (public road). Horizontal axis and vertical axis mean Wi-Fi channel and signal strength, respectively.

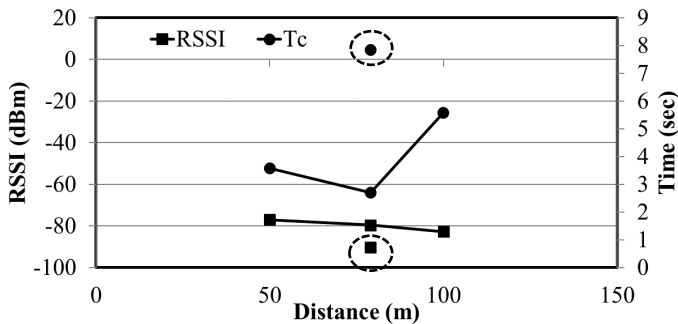


Figure 7. Relationship among RSSI, T_c , and communication distance in experimental environment 2.

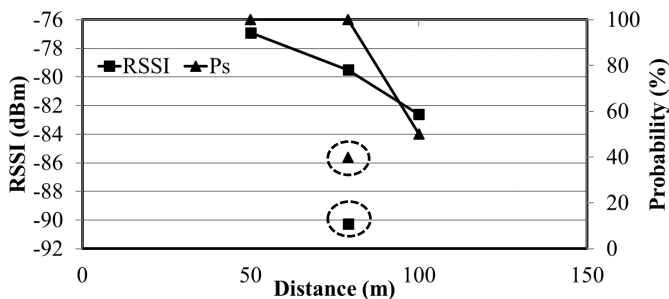


Figure 8. Relationship among RSSI, P_s , and communication distance in experimental environment 2.

characteristics. The evaluations were carried out at a

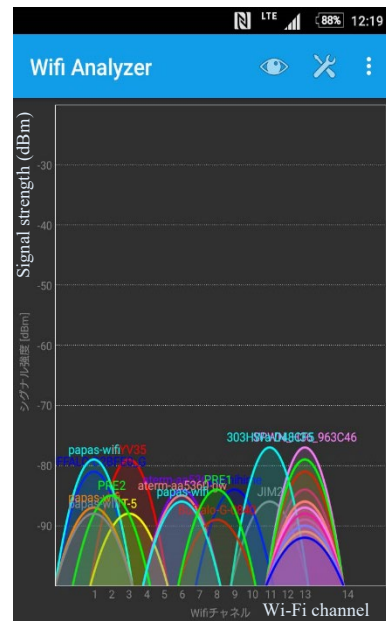


Figure 9. Utilisation of the 2.4-GHz band when the distance is 80 m (construction site). Horizontal axis and vertical axis mean Wi-Fi channel and signal strength, respectively.

public road (Fig. 1) in Chofu, Tokyo and at a construction site (Fig. 2) in Sagami-hara, Kanagawa. Heavy vehicular traffic was observed in the public road and some excavators were working at the construction site, indicating that the network environments of both areas changed dynamically. However, the trends were nearly the same at the two sites. The beacon module was fixed and the iPad (Fig. 3) was mobile. The RSSI, T_c , and P_s were measured over a distance from 50 to 150 m. At each distance, 10 trials were conducted and the average was recorded as the result. The payload size was 70 bytes. The BLE communication mode was set as connection. The total measurement time was 60 s. The evaluation system's algorithm is summarized in the Appendix A (see Algorithm 1 and Algorithm 2).

3.2 Experimental results and discussion in each situation

First, we show the results obtained at the public road. Fig. 4 shows the relationship among communication distance, RSSI, and T_c . Additionally, Fig. 5 plots the relationship among communication distance, RSSI, and P_s . As shown in Fig. 4, T_c increased when the distance increased. Furthermore, RSSI decreased when the distance increased. As shown in Fig. 5, as the distance increased, P_s showed a decreasing trend. These results indicate that a decrease in radio field intensity affects the communication establishment time and hence the success rate of the communication. The maximum difference of T_c was 25 s. In Fig. 5, the percentage appears to decrease significantly

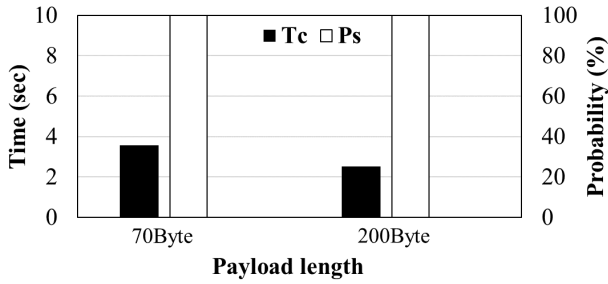


Figure 10. Relationship among payload size, T_c , and P_s when communication distance equals to 50 m (communication in prospect).



Figure 11. Position of the sender (in SK-470-10). The others machine set the sender in the same position.

(40%) when the distance reaches 100 m. The reason for this is the interference of other radio waves. Fig. 6 shows the utilisation of the 2.4-GHz band at a distance of 100 m (by Wi-Fi analyser [18]). It is seen from the results that many radio wave generators were present. In this experimental location, there were many residences near the area that probably have Wi-Fi access points, a factor that appears to have adversely affected the results.

Second, we show the results obtained at the construction site. Fig. 7 describes the relationship among the communication distance, the RSSI, and T_c ; Fig. 8 shows the relationship among the communication distance, the RSSI, and P_s . In this evaluation, results were measured at distances of 50, 80, and 100 m. In Figs. 7 and 8, the dotted black circles indicate the results of communication outside prospect, in which the excavator serves as an obstruction. As shown in Fig. 7, the difference between the in- and out-of-prospect T_c is 7 s, indicating that the communication establishment time is strongly affected by the obstruction. The reason for this is the decrease in RSSI introduced by the obstruction. It is difficult to implement stable communication at this RSSI (approximately -90 dBm). As shown in Fig. 8, the outside prospect communication results differ significantly from

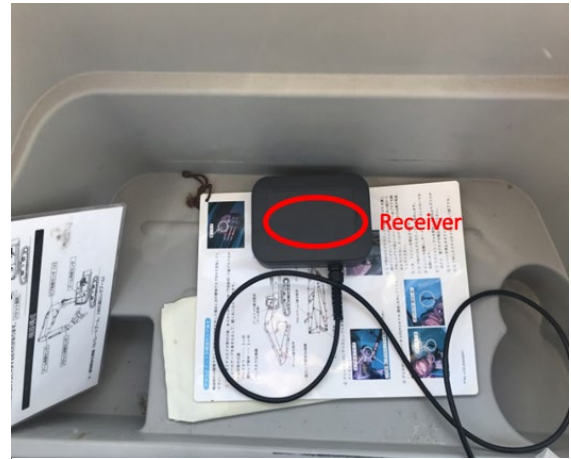


Figure 12. Position of the receiver in the excavator Cabin.

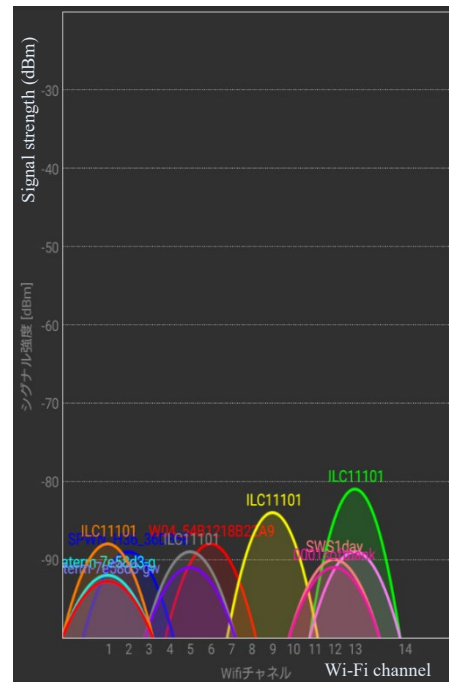


Figure 13. Utilisation of the 2.4-GHz band in the evaluation field. Horizontal axis and vertical axis mean Wi-Fi channel and signal strength, respectively.

the in-prospect results; in terms of P_s , the results differ by 60%. From these results, we can conclude that obstructions must be considered when implementing a BLE network. Fig. 9 shows the utilisation of the 2.4-GHz band at a distance of 80 m. It is seen that, although the utilisation trend is the same as in the public road (Fig. 6), the number of radio wave generators is reduced. The reason for this is that the experimental area was surrounded by an industrial park; as a result, there were few Wi-Fi access points and the distances between the radio wave generator and beacon module or iPad were

smaller than in the public road case. Finally, we evaluated the effect of the payload size of the T_c and P_s . Fig. 10 shows the relationship among payload size, T_c , and P_s at a distance of 50 m in construction site. The results show the communication in the prospect case. As shown in the figure, the difference in T_c is approximately 1 s and P_s is 100% at each payload size. Therefore, in this evaluation the payload size did not have a significant impact on the BLE communication performance.

4. Evaluation of Bluetooth Low Energy using Excavators

This section describes an experimental evaluation using a BLE beacon module installed in several excavators. We used three different excavator classes. Note that, the testing approach is same as Section 3. Same as Section 3, furthermore, the evaluation system's algorithm is summarized in the Appendix A (see Algorithm 1 and Algorithm 3).

4.1 Experimental Settings for Unit Test

In the evaluations, a beacon module using BLE 4.2 was

used as a sender (communication distances: 10 and 30 m) and an in-vehicle computer housing an Intel Atom E3950 (Apollo Lake) processor made by Interface [19] was used as a receiver. We evaluated the relationships among distance between sender and receiver, RSSI, and communication establishment time (T_c). Note that the evaluations described in this section focused only on T_c because the communication success percentage was either 0 or 100%. When P_s was 0%, the result of T_c was NG. In the evaluation, we used an application program to receive

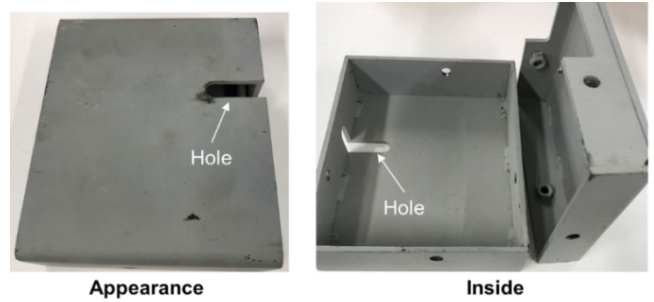


Figure 14. Bracket for beacon. The BLE module was encased in this bracket. The distance between the hole and BLE antenna changed according to the orientation of the BLE module.



Figure 15. Postures of excavator (SK470-10).

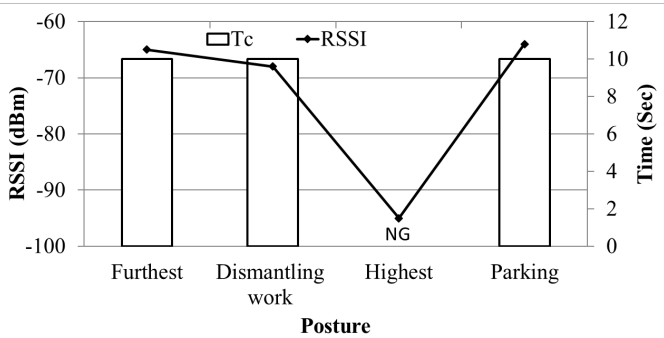


Figure 16. T_c and RSSI result for SK470-10 (Beacon communication distance of 10 m; installation was correct).



Figure 19. Postures of excavator (SK135-5).

on the excavator’s magnetic attachment (Fig. 11); in all three cases, the receiver’s antenna was placed in the cabin (Fig. 12). The utilisation of the 2.4-GHz band in the evaluation area was measured by a Wi-Fi analyser and is shown in Fig. 13. As shown in the figure, the signal strengths of other wireless communications sources were not large. The sender was placed in a bracket (Fig. 14) with an opening for transmission of radio waves. The hole was set near the BLE antenna. If the module were mounted upside down, the antenna would be further from the radiation hole; therefore, we evaluated the two installation cases. We changed the posture of the excavator (Fig. 15) several times during each evaluation. The different postures were (1) Parking, (2) Highest, (3) Furthest, and (4) Dismantling work. In each posture, the distance between the sender and receiver changed, and we measured the RSSI and T_c for each posture over 10 trials and averaged the results. The payload size was 70 bytes and the BLE communication mode was set to connection.

4.2 Experimental results and discussion by situation

4.2.1 Results for SK470-10

Fig. 16 shows the results when the beacon module’s communication distance was set to 10 m. As shown in the figure, the receiver was able to receive the beacon signal in the Parking, Furthest, and Dismantling work postures. Therefore, the T_c of each case was 10 s. Moreover, RSSI was approximately -65 dBm. In the Highest posture, however, the beacon signal was too weak and could not be received. The RSSI was approximately -95 dBm. From these results, when the excavator was in the Highest posture, communication could not be established at a beacon module communication distance of 10 m., Fig. 17 shows the results at a communication distance of 30 m. As shown in the figure, unlike the previous

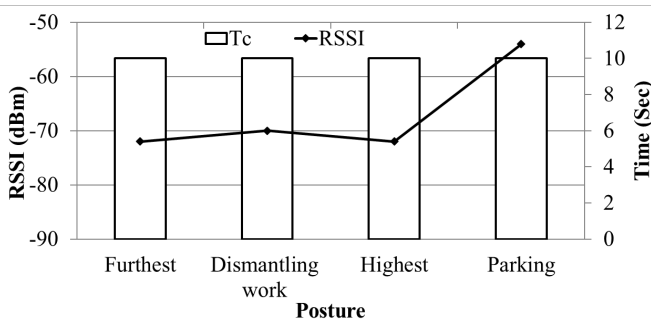


Figure 17. T_c and RSSI results for SK470-10 (Beacon communication distance of 30 m; installation was correct).

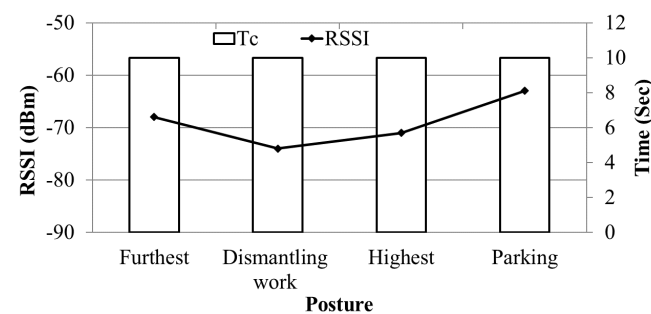


Figure 18. Results of T_c and RSSI for SK470-10 (Beacon’s communication distance was 30 m, installation is upside down).

the signal produced by a beacon module. Unlike the system used in Section 3.1, the application of the receiver took approximately 10 s to display results; therefore, when a signal was successfully received, the T_c used as the evaluation time was considered to be 10 s. That means that the results were the same when the connection was established in the first attempt (10 s). The total measurement time was 60 s.

In the evaluations, we attached the beacon module to several excavators. Specifically, we used an SK135-5 [20], an SK470-10 [21], and an SK210DLC-10 [22], which are examples of 13-, 45-, and 20-ton class excavator, respectively. The latter is used for metal recycling. In the evaluation, the module was attached to both the SK135-5 and SK470-10 via a nibbler used for building demolition. For the SK210DLC-10, the sender module was positioned

communication distance setting, the receiver and sender modules were able to establish communication in all postures. Additionally, the measured RSSI was approximately -55 dBm in the Parking posture as a result of the short distance between the sender and the receiver. From the results displayed in Figs. 16 and 17, it was established that a 30-m communication distance setting of the beacon module was required to establish communication in all postures.

Figs. 16 and 17 show the results obtained when the beacon module was correctly installed in the bracket. Fig. 18 plots the results when the beacon module was installed upside down in the bracket with the communication distance of the beacon set to 30 m. It is seen from Fig. 18 that communication could still be established even with an upside down installation configuration. In all postures, the RSSI was at least -75 dBm. A comparison of Figs. 17 and 18 shows that the RSSI was nearly the same under both installation conditions. Thus, if the module's communication distance was set to 30 m, the installation orientation of the beacon module did not significantly affect the BLE communication performance.

From these results, we can conclude that BLE

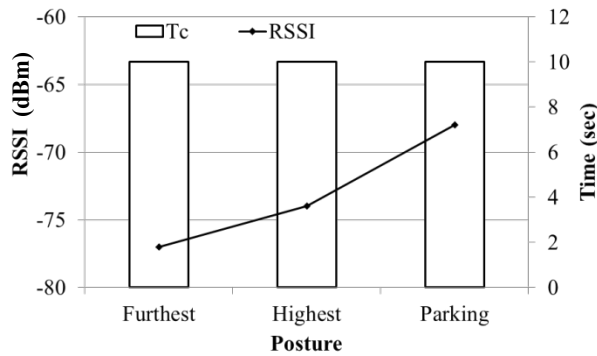


Figure 20. Results of T_c and RSSI for SK135-5 (Beacon's communication distance was 10 m, installation was correct).

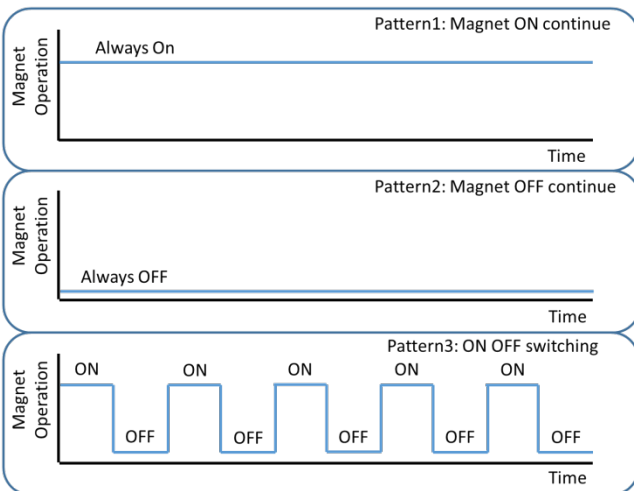


Figure 21. Magnet operational patterns.

communication can be used for internal and external communication by 45-ton class excavators. The following subsection shows the results for the smaller excavators.

4.2.2 Results for SK135-5

This subsection shows the results obtained using the SK135-5, a 13-ton class excavator. This machine is used in urban construction areas because of its relatively compact size.

The same items used to evaluate the SK470-10 were used to evaluate the SK135-5. Note that the utilisation trend for the 2.4-GHz band in the evaluation field was the same as that shown in Fig. 13. Fig. 19 shows the postures of the SK130-5. We evaluated only three postures—Furthest, Highest, and Parking—as the results for the Dismantling posture were nearly the same as those for Highest. Fig. 20 shows the relationships among posture, RSSI, and T_c . In this case, the distance under the Furthest posture was larger than that under Highest, which in turn was larger than that under Parking. From these results, the distance between the sender and receiver increased when the RSSI decreased, a trend seen in the evaluation results. The minimum RSSI (obtained in the Furthest case) was approximately -77 dBm. Even at the minimum RSSI,



Figure 22. Posture of excavator (SK210DLC-10).

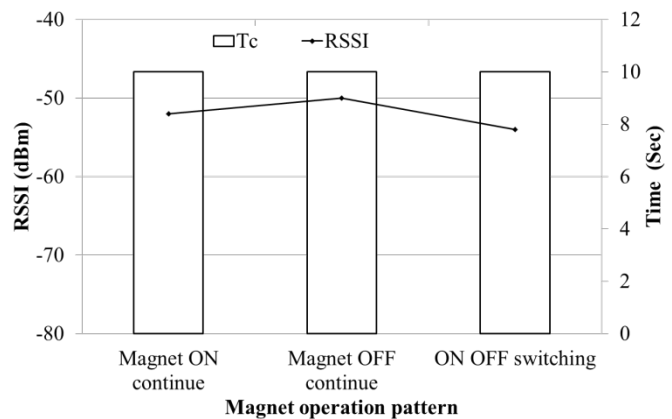


Figure 23. T_c and RSSI results for SK210DLC-10 (Beacon communication distance was 10 m; installation was correct).

however, communication could be established between the sender and receiver. Thus, we can conclude that BLE communication can be applied in the use of 13-ton class excavators.

4.2.3 Results for SK-210DLC-10

This subsection shows the results obtained for the SK210DLC-10, a 20-ton class excavator. Excavators of this class can be equipped with a magnetic attachment for gathering metal and scrap, making them useful in metal recycling factories. In these analyses, therefore, we evaluated the BLE communication characteristics with the magnetic field effect taken into consideration under three magnet operational patterns (Fig. 21):

- Magnet ON continuously;
- Magnet OFF continuously;
- ON/OFF switching (changing every 3 s).

In the evaluations, we focused on the results for T_c and RSSI according to under different magnet operational patterns. Fig. 22 shows the posture of the SK210DLC-10, which in this case remained constant for all tests. In the evaluations, the sender was fixed to the magnet attachment and the receiver was located in the cabin. Note that the trend of utilisation for the 2.4-GHz band in the evaluation field was the same as that shown in Fig. 13.

Fig. 23 plots the relationship among RSSI, T_c , and the magnet operational pattern. As shown in the figure, the operational did not have a significant effect on the RSSI. Thus, communication could be established normally. Note that communication could be carried out continuously for periods of 60 s. From these results, we can conclude that BLE communication can be applied to a wide range of construction machinery, thus verifying the applicability of BLE to i-construction.

4.3 Limitations and constraints

This study includes some limitations and constraints as follows:

- Evaluation system
In this study, we used simple evaluation system. Communication module is only sending/receiving the BLE signal, and we do not implement any applications that considering communication QoS/QoE, and control of construction machines. Therefore, the functions of the system are simple, only sending the signal by BLE beacon and showing the result by tablet PC (monitor). Our evaluation showed the results with the above assumptions.
- Evaluation metrics
In the evaluation, we showed the characteristics of BLE considering construction machines using RSSI, the communication establishment time, and communication success percentage. This study is the

first step for wireless communication characteristics considering construction machines. Therefore, we use simple metric. In future, we will evaluate the communication characteristics using other metric. After implementing applications such as i-construction systems, especially, we will evaluate the usability of it using the metrics proposed by [23]. Also, we will show the analysis of i-construction systems using Use Cases Tool such as UML diagram.

5. Conclusion

In this study, BLE communication was characterised and demonstrated using several real pieces of construction machinery. Specifically, we focused on the applicability of BLE for i-construction. In the evaluation, a beacon module that can communicate using BLE 4.2 was used. From the experimental evaluations, we confirmed the following results:

- We demonstrated the characteristics of communication in both a residential area and at a construction site.
- We quantitatively clarified the relationship among the communication distance, RSSI, and the time to establish device communication.
- We quantitatively demonstrated the effect of length of payload on communication.
- We confirmed the communication characteristics of the beacon module using 45-, 13-, and 20-ton class excavators.

The results of this study confirmed the applicability of BLE for i-construction. We recommend BLE for i-construction applications because of the payload size that can be communicated and the communication connectivity that does not so affect the size of the construction machines and the type of attachments for construction machines.

Future work will include more detailed evaluations carried out in environments with multiple senders to obtain a better understanding of loss rate and communication delay. We will also propose specific applications/systems of i-construction using BLE. After proposing i-construction systems, we will evaluate the usability of it. Moreover, we will analyze the systems using Use Cases tools.

Acknowledgements.

We thank anonymous reviewers for carefully reading our paper. Moreover, we would like to thank Editage (www.editage.jp) for English language editing.

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Appendix A. Pseudocode of the evaluation system

This section shows the algorithms of our evaluation system by the pseudocode.

Algorithm 1. Pseudocode of the BLE signal sender for Section 3 and Section 4.

```

REQUIRE: TSEND > 0 //TSND is sending interval

BEGIN
timer = 0
LOOP
  IF timer == TSEND THEN
    send beacon signal for receiver
    timer = 0
  ENDIF
  IF want to close the communication THEN
    send disconnect request
  EXIT LOOP
  ENDIF
  increment timer
ENDLOOP
END

```

Algorithm 2. Pseudocode of the BLE signal receiver for Section 3.

```

REQUIRE: TWAIT > 0 //TWAIT is waiting time
//for timeout to receive
//the signal

BEGIN
timer = 0
LOOP

```

```
IF signal is received THEN
  notify the receive
  timer = 0
ENDIF
IF timer == TWAIT THEN
  notify the timeout
  timer = 0
ENDIF
IF disconnect request is received THEN
  EXIT LOOP
ENDIF
increment timer
ENDLOOP
END
```

Algorithm 3. Pseudocode of the BLE signal receiver for Section 4.

```
REQUIRE: TDEC > 0 //TDEC is decision interval time

BEGIN
timer = 0
LOOP
  IF timer == TDEC
    IF signal is received THEN
      notify the receive
      timer = 0
    ENDIF
    IF signal is not received THEN
      notify the timeout
      timer = 0
    ENDIF
  ENDIF
  IF disconnect request is received THEN
    EXIT LOOP
  ENDIF
  increment timer
ENDLOOP
END
```

In Section 3, we focused the relationship between the connection and the distance between the sender and the receiver. Thus, we do not set the decision interval. On the other hand, in Section 4, we focused the maximum time to reach the signal. In other words, the motivation of the evaluation of Section 4 was to check that the signal (data) is received within the prescribed time. Therefore, we changed the receiver's algorithm in each evaluation.