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LETTER

Performance Evaluation Considering Real Usage in Positioning and Direction Finding System Using Radio Signals

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SUMMARY This study evaluates the Bluetooth low-energy (BLE) positioning and direction-finding system. The evaluation conditions are set closer to real usage; considering the number of devices, type of devices, and time interval between measurements of the database and measurements of evaluation. Subsequently, positioning and direction-finding performance evaluation experiments are performed in a real environment. The results of the comparison with a previous method show that the hybrid method including both positioning and direction-finding performs better under the conditions considering real usage. The analysis using confusion matrices reveals the trends of the direction errors. Furthermore, the hybrid method maintains the positioning and direction-finding performance and reduces the number of BLE beacon installations. Consequently, the effectiveness of the hybrid method under the evaluation conditions considering real usage is demonstrated and the importance of performance evaluation closer to real usage is shown.
key words: *hybrid algorithm, positioning, direction finding, real usage*

1. Introduction

In recent years, the use of location-based services (LBS) using smartphones has increased (e.g., [1]). The quality of location information is crucial in LBS. Therefore, a high-performance positioning method is required to provide high-quality LBS. It has been reported that 90% of human behavior occurs indoor (e.g., [2]). Owing to the complexity of indoor environments, indoor LBS often require directional information in addition to location information. For example, maps and navigation systems use directional information.

Location and direction information are obtained using various methods. Sensors (e.g., [3]) and radio signals (e.g., [4], [5]) are primarily used in positioning methods. Geomagnetism is used in direction-finding methods (e.g., [3]). The method can be used indoors and outdoors. However, the performance of the geomagnetic direction determination is decreased by the influence of the surrounding environment. This is particularly evident in indoor environments. It was also necessary to calibrate the sensors for each device. Radio signals are also used in direction finding methods. Examples include Bluetooth Direction Finding [6] and fingerprinting using Wi-Fi (e.g., [7]). However, the received signal strength indicator (RSSI) from Bluetooth Low-Energy (BLE) is affected by obstacles. Therefore, it may be possible to find directions based on RSSI using BLE.

The BLE hybrid algorithm is a two dimensional (2D) positioning method (e.g., [8]–[10]). The method combines proximity, which refers to the location of the transmitter with the strongest RSSI, and fingerprinting positioning by comparing the evaluation data and database. First, we extracted the area with the strongest RSSI from the BLE beacon using proximity. Second, the search area for the fingerprinting database and positioning are limited. This method prevents large positioning errors by limiting the database search area. Therefore, the hybrid algorithm exhibits high positioning performance and robustness. However, the direction-finding performance of the hybrid algorithm has not shown yet. In this study, we evaluate the positioning and direction-finding performance of the hybrid algorithm under conditions considering real usage.

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2. Related work

Fingerprinting is a positioning method that uses radio signals and exhibits a higher performance than other positioning methods [11]. Bi et al. [12] improved the positioning performance of fingerprinting using data measured from multiple directions. However, these methods do not estimate direction. Bluetooth direction finding [6] is a direction-finding method based on radio signals and is included in Bluetooth version 5.1. The previous studies, e.g., [13], [14], use antenna arrays. Therefore, Bluetooth direction finding cannot use only commercially available smartphones.

There are direction-finding methods using Wi-Fi fingerprinting estimating directions based on positioning results. In the previous study [7], the high accuracy was achieved, i.e., two-way direction estimation was 88% and four-way direction estimation was 77%, but only a laptop was used to perform measurements. Many such devices have been used in practical applications. However, the evaluation conditions of the previous study were insufficient to account for real usage. Thus, this study sets evaluation conditions closer to real usage than in [7].

3. Positioning and direction finding algorithm targeted in this paper

The BLE hybrid algorithm combines proximity and fingerprinting for positioning. First, we extract the area with the strongest RSSI from the BLE beacons. Subsequently, the search area of the fingerprinting database was limited to the reference points in the extracted area to calculate similarity. The reference point with the highest similarity is the position-

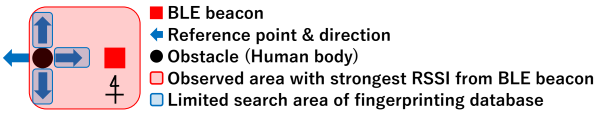


Fig. 1 Image of the limiting search area.

Table 1 Evaluation conditions

	This paper	Previous study [7]
Exp. dev.	Smartphones (5 models × 2 sets)	Laptop (1 model × 1 set)
Dev. for DB & eval.	Different	Same
Time intvl. btwn. DB & eval.	Enough time	Unknown

ing result. This method prevented large positioning errors and exhibits high positioning performance and showed the robustness [8]–[10]. On the other hand, the RSSI of the radio signals, e.g., Wi-Fi and BLE, changes with the direction of measurement. In other words, the RSSI will be changed the user of the device himself/herself shielding the radio waves from a specific direction (the opposite of the user's direction of travel, i.e., from the user's back, since the device is usually operated while looking at the screen). In this paper, we use the BLE hybrid algorithm added the direction-finding for providing location- and direction-information. Considering the effects of human-body occlusion, the hybrid algorithm limits the search area of the fingerprinting database to include its direction. This process prevents large directional errors. An image that limits the search area of a fingerprinting database by the hybrid algorithm is shown in Fig. 1. In Fig. 1, when the user is facing west, the RSSI observed by the user's device is smaller than in other directions because the radio waves from the BLE beacon are blocked by the user's body. In the following evaluations, we compare the hybrid method with a previous method [7] that includes direction estimation using the divergence of the RSS distribution.

4. Performance evaluation of positioning and direction finding

4.1 Evaluation conditions to be considered for real usage

The number of devices, type of devices, and time interval between measurements of database data and evaluation data are crucial for evaluations that consider real usage. Thus, the definition in this paper of an evaluation considering real-usage is an evaluation that satisfies all of the following: Multiple devices should be used, the devices used for data collection should be separated for training and evaluation, and data for training and evaluation should be collected with a sufficient time interval. The evaluation conditions in the previous study [7] only used a laptop for measurements. Various smartphone models have been used for indoor LBS. Measurements of the database and evaluation data were performed using the same device. Different models are used for each measurement. The time interval between the measurement of the database data and that of the evaluation data is not shown; however, it requires sufficient time. Considering the aforementioned problems, we set evaluation conditions closer to real usage than a previous study [7]. The evaluation conditions are listed in Table 1. Two sets of five models are used as the measurement devices. Different sets of devices are used for the measurements of the database data and evaluation data. This is because, in the situation where LBS is actually used, it is extremely rare that the user's device and the device used to create the database are the same. The time interval between the measurement of the database data and evaluation data was sufficient. This is because, in the situation where LBS is actually used, the database is created and then used in LBS after some time has passed.

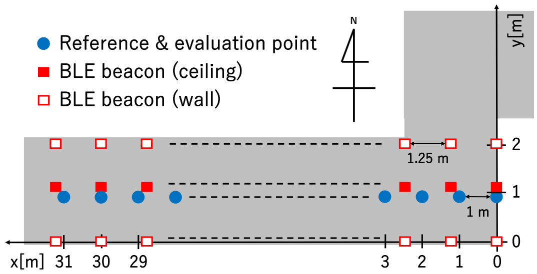
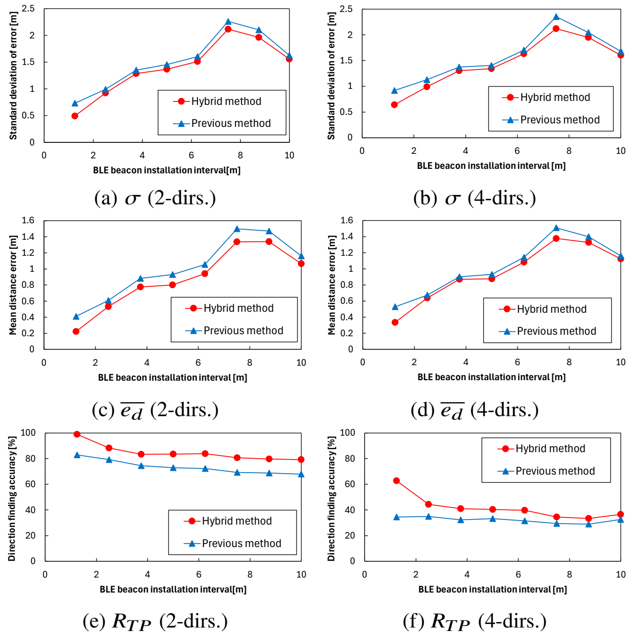


Fig. 2 Experimental environment.

4.2 Experimental method

The experiment was conducted in a corridor on the fourth floor of the Department Building of Electrical Engineering, Electronics, and Applied Physics at the Saitama University. The BLE beacons were MyBeacon Pro MB004 series by Aplix Corporation. The BLE beacon installation positions and data collection points in the evaluation environment are depicted in Fig. 2. The BLE beacons were installed at 1.25 m intervals along the x-axis and 1 m intervals along the y-axis of the corridor. They were installed on the walls ($y = 0$, 2 m, $h = 1.2$ m), and ceiling ($y = 1$ m, $h = 2.5$ m). Data collection points were set at 1 m intervals along the x-axis ($y = 1$ m). We used five different devices for the measurements as follows: Google Pixel 6, Essential Phone PH-1, Huawei nove lite 3, TESPRO Mayumi world smartphone U1, and ASUS ZenFone Max M2. Two sets are available, one for each model. The experiment was performed under the evaluation conditions described in Sect. 4.1. Data were collected from four directions at each data collection point. The data collection time was 60 s. The devices were mounted on a tripod at a fixed height of 1.2 m above the floor to simulate use by a standing human. The reason for fixing the device on a tripod is that it is difficult to keep the device completely still for 60 seconds to prevent its position from moving in a hand-held experiment[†]. The measurer (i.e., the user himself/herself), who is a shield for the device from radio waves from a specific direction, was measured standing 0.2 m away

[†]Preliminary experiments have confirmed that there is no effect on the RSSI frequency distribution when the device is fixed on a tripod and when it is hand-held.



(a) σ (2-dirs.) (b) σ (4-dirs.)
(c) $\overline{e_d}$ (2-dirs.) (d) $\overline{e_d}$ (4-dirs.)
(e) R_{TP} (2-dirs.) (f) R_{TP} (4-dirs.)

Fig. 3 Performance evaluation results.

from the device. Data were collected twice. This is the first database to be constructed. A second evaluation was then conducted. Between the first and second iterations, sufficient time elapsed and different sets of devices were used.

Evaluation indices of positioning performance are mean error $\overline{e}$, standard deviation of error σ, and mean distance error $\overline{e_d}$. Moreover, the evaluation index of the direction-finding performance is the direction-finding accuracy R_{TP}. The evaluation indices are as follows:

$$\overline{e} = \frac{1}{N_{ALL}} \sum_{i=1}^{N_{ALL}} (x_i - X_i),\ \sigma = \sqrt{\frac{1}{N_{ALL}} \sum_{i=1}^{N_{ALL}} (x_i - X_i)^2},$$

$$\overline{e_d} = \frac{1}{N_{ALL}} \sum_{i=1}^{N_{ALL}} |x_i - X_i|,\ R_{TP} = \frac{N_{TP}}{N_{ALL}} \times 100,$$

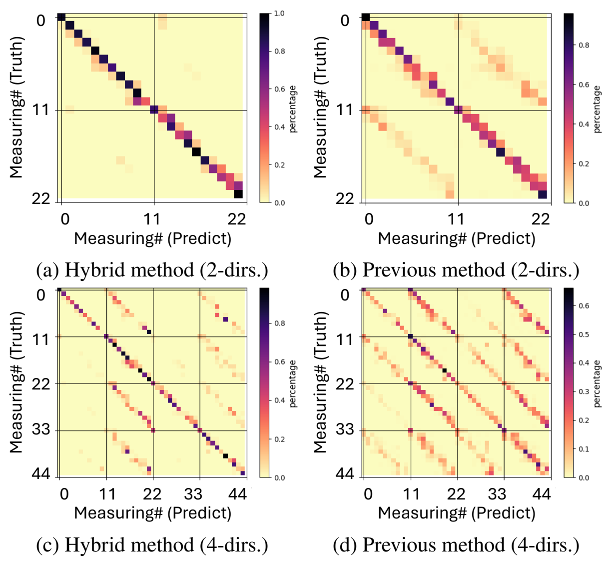
where x_i denotes i-th positioning result, X_i denotes i-th true position, N_{ALL} denotes the total number of evaluations, and N_{TP} denotes the number of true directions obtained.

4.3 Experimental result

The evaluation results of the hybrid method and a previous method [7] are presented in Fig. 3. The evaluation results for the two directions, that used east and west data, are shown in Fig. 3(a)(c)(e). $\overline{e}$ was almost 0 m for both methods. Moreover, R_{TP} of the hybrid method is 10–15 percentage points higher than that of the previous method. R_{TP} of the previous method was worse than the performance, i.e., 88%, shown in [7]. This performance degradation was caused by differences in evaluation conditions. The evaluation results for the four directions are shown, that used all the direction data, in Fig. 3(b)(d)(f). $\overline{e}$ was almost 0 m for both methods. Moreover, the direction finding performance of the hybrid method is 30 percentage points higher than that of the previous method in the 1.25 m BLE beacon installation interval and 10 percentage points higher than that of the previous method in the above 2.5 m BLE beacon installation interval. R_{TP} of the previous method was worse than the performance, i.e., 77%, shown in [7]. This performance degradation was caused by differences in evaluation conditions. On the other hand, the positioning and direction-finding performance of the hybrid method is shown to be higher than that of the previous method under the evaluation conditions considering real usage.

Table 2 Correspondence between the number of measurements and the reference points

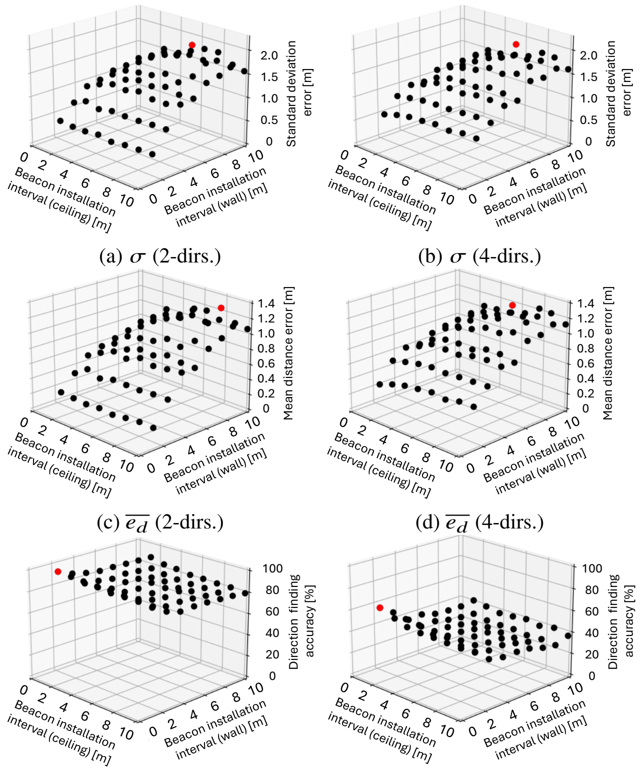
Measurement	Two directions		Four directions	
number	Location#	Dirction	Location#	Dirction
#0–#10	#a–#k	East	#a–#k	East
#11–#21	#a–#k	West	#a–#k	South
#22–#32	—	—	#a–#k	West
#33–#43	—	—	#a–#k	North



(a) Hybrid method (2-dirs.) (b) Previous method (2-dirs.)
(c) Hybrid method (4-dirs.) (d) Previous method (4-dirs.)

Fig. 4 Analysis result using confusion matrix.

Subsequently, we analyze the positioning and direction-finding results of the hybrid method and the previous method using a confusion matrix. The analysis uses the results of the 1.25 m BLE beacon installation interval. The results are tallied to each reference point and divided by the number of evaluations at each reference point for normalization. The tally results are visualized as heat maps. The correspondence between the number of measurements and reference points (position and direction) is indicated in Table 2. The heat map shows the measured numbers of Predict and Truth. If the letter of the position matches, the positioning result is true; if the letter of the direction matches, the direction finding result is true. The analysis results for the two directions are shown in Fig. 4(a)(b). Both the hybrid method and the previous method have almost no positioning errors. The direction finding using the previous method has opposite direction errors. However, direction-finding using hybrid method has



(a) σ (2-dirs.) (b) σ (4-dirs.)

(c) $\overline{e_d}$ (2-dirs.) (d) $\overline{e_d}$ (4-dirs.)

(e) R_{TP} (2-dirs.) (f) R_{TP} (4-dirs.)

Fig. 5 Results by changing installation interval.

almost no opposite-direction errors. The analysis results for the four directions are shown in Fig. 4(c)(d). Both the hybrid method and the previous methods have almost no positioning errors. Direction finding using the previous method has all direction errors. Direction finding using hybrid method has almost no east and west direction errors, but errors exist in the south and north directions. The rate of south and north direction errors is lower than those of the previous method. The analysis results show that the hybrid method reduces the errors in the opposite direction. The trend of the direction errors is shown in the heat maps. The performance in the four directions can be improved by reducing the errors in the south and north directions.

The hybrid method, which exhibits the highest positioning and direction-finding performance, is evaluated by changing each BLE beacon installation interval on the ceiling and wall. The evaluation results are shown in the three-axis figures. Each axis represents the BLE beacon installation interval on the wall, BLE beacon installation interval on the ceiling, and evaluation indexes. The red dots indicate the best performance. The positioning and direction-finding results for the two directions are shown in Fig. 5(a)(c)(e). The positioning and direction-finding performances decrease as the BLE beacon installation interval increases. It is affected in almost the same manner by the BLE beacons on the ceiling and wall. If the BLE beacon installation interval is 10 m, the performance maintains a mean distance error of 1 m and a direction-finding accuracy of 80%, and the number of BLE beacon installations is reduced by 85%. The positioning and direction-finding results for the four directions are shown in Fig. 5(b)(d)(f). Even in the four directions, the positioning and direction-finding performances decrease by increasing the BLE beacon installation interval. The positioning performance is affected in almost the same manner by the BLE beacons on the ceiling and wall. However, the direction-finding performance is more strongly affected by BLE beacons on the wall than those on the ceiling. If the BLE beacon installation interval is 10 m on the ceiling and 1.25 m on the wall, the performance keeps a 1.25 m mean distance error and 60% direction-finding accuracy, and the number of BLE beacon installations is reduced by 25%. These results show that the hybrid method can maintain positioning and direction-finding performance even if the BLE beacon installations are reduced. It also means the evaluation conditions considering real usage is important. Although BLE is the subject of this paper, the same is applicable to other methods using radio signals (e.g., Wi-Fi).

5. Conclusion

In this study, we compaired the hybrid method with a previous fingerprinting method from the viewpoint of both positioning and direction-finding. We set evaluation conditions closer to real usage. Subsequently, positioning and direction-finding performance-evaluation experiments were conducted in a real environment. The evaluation results showed that the hybrid method performed well under the set conditions. The analysis using confusion matrices revealed the trend of direction errors and showed the potential for increasing performance. Moreover, the hybrid method maintains the positioning and direction-finding performance and reduces the number of BLE beacon installations. Consequently, the effectiveness of the hybrid algorithm was demonstrated under the evaluation conditions considering real usage and the importance of the evaluation conditions closer to real usage was shown.

Future work will include improving the four-direction performance by considering the trend of direction errors, evaluating the positioning and direction-finding performance in other environments, and evaluating the method in combination with sensor technologies.

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