The Effect of Density and Placement of BLE Beacons on Indoor Location and Motion Direction Estimation Accuracy

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***Abstract*-- We investigated a method for simultaneously estimating the position and direction of a pedestrian walking indoors. The estimation is achieved using RSSIs (Received Signal Strength Indicators) from Bluetooth Low Energy (BLE) beacons detected by smartphones carried by pedestrians moving in one of eight directions. We investigated a method to estimate the position and moving direction of pedestrians using multiple time instances of RSSIs from multiple BLE beacons detected. The method was based on DNN (Deep Neural Network), which were trained to estimate the position and moving direction from a set of measured RSSIs.**

We fixed the size of the room to be estimated and compared the estimation accuracy by varying the number of beacons and their placement patterns. We also attempted to reduce the estimation error by treating the direction of movement as a continuous value. As a result, the estimation accuracy improved as the number of beacons increased, and a difference of 60.9% in the position estimation error and 61.2% in the moving direction estimation error was seen when 4 and 8 beacons were used. Regarding the difference in the installation interval of beacons, we found that it is important to install them sparsely and evenly in the room.

I. Introduction

Most people now own a smartphone. One of the most popular functions among the applications in these smartphones is related to positioning and navigation. Location detection in many mapping and navigation applications uses GPS signals received from satellites. Therefore, it is said that accurate location estimation is difficult indoors because signals from GPS cannot be received there. Therefore, various methods for indoor positioning are currently being researched [1], but all the methods leave many challenges. In this study, we focused on BLE beacons, which are superior in terms of ease of installation, battery consumption, device variation, and cost [2].

Our ultimate goal is a navigation system that combines an indoor positioning system with augmented reality (AR). In this system, a stereophonic audio signal is localized towards the target as an auditory sign signal for navigation, which provides a clue to the direction in which the user should move. Localization of the audio signal is done by convolution of the head transfer function (HRTF) of the direction to be localized into the monaural signal. Since this direction is relative to the user's orientation, it is necessary to detect what direction the user is facing at the same time as positioning.

In our previous indoor positioning experiments using BLE [3, 4], we found that the interpolation process applied to the time-series BLE signal strength (RSSI) collected in a real environment was sufficient for an indoor positioning system. Also in previous experiments, the number of beacons installed was fixed to eight at 2-meter intervals. In this study, we investigated how the accuracy of indoor position and direction of movement estimation changes depending on the number of beacons installed and their placement pattern when the size of the room is fixed. In addition, this study attempted to reduce the estimation error of the direction of movement by treating the direction of movement as a continuous value instead of a categorical value and by giving meaning to the magnitude of the value.

II. PROPOSED ESTIMATION METHOD

We proposed an indoor position and movement direction estimation system using DNNs, which are trained with RSSI fingerprints of rooms in advance [3, 4]. The training configuration of the DNN is shown in Figure I. To estimate the user's location, the RSSI from all available BLE beacons is fed to the trained DNN. In addition, multiple time instances (limited to two in this research) of the RSSI set are needed to estimate the user's movement direction.

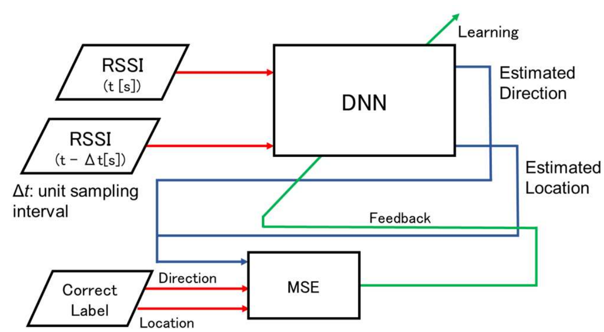


Fig. I. Overview of DNN

The parameters of the DNN are shown in Table I. The DNN is used to estimate the position information and the movement direction. The input layer units are fed RSSIs of multiple beacons for 2 consecutive time instances in the training data. In the output layer, 2 units are used for the x- and y-coordinates of the estimated position and 2 units for the movement direction estimation. When the eight movement directions are treated as categorical values, an estimation error of at least 45° was seen [3]. On the other hand, treating the movement directions as continuous values has the advantage that the numerical differences in the estimated and the true values have meaning, the angles can be expressed freely, and the DNN can learn from the magnitude of the estimation error. The estimation of the direction of movement, the angle θ, is calculated using sin θ and cos θ, estimated as continuous values, according to Eq. (1).

$$\theta = \tan^{-1}\frac{\sin\theta_{estimate}}{\cos\theta_{estimate}}\ [\ ^{\circ}\ ] \qquad (1)$$

Since this system assumes navigation in one of eight directions, the calculated angle θ is classified into eight directions and the estimation accuracy is calculated. To train the DNN, we used RSSI measurements when the receiver moves at a constant walking speed in any of the eight directions. These data were labeled with the correct location and direction. For training, 11,336 sets were used, of which 20% were used as validation data. For test data, 2,434 sets were used.

The structure of our proposed indoor position and movement direction estimation system is shown in Fig. II. This system is a client-server type system. First, the user's smartphone collects RSSI transmitted from multiple beacons at regular intervals. Next, the smartphone sends the collected RSSI to the PC server via UDP packets. The server processes the received RSSI and estimates the position and direction of movement using a DNN that has been trained in advance, then sends the estimated positions and directions back to the smartphone in a UDP packet. By repeating the above operation, continuous estimation becomes possible.

In previous work [3, 4], we have shown that it is indeed possible to estimate the indoor location and motion direction at high accuracy, provided we place enough BLE beacons evenly inside the room being tested. In the experiments in the next section, we will investigate how the number of beacons, as well as their placement, affects the estimation accuracy.

Table I. DNN Configuration

Item		Condition	
Number of units		16-600-1200-900-450-4	
Epochs		1000	
Batch size		256	
Activation function	Hidden layers	ReLU	
	Output layers	X, Y	Output layers
		sin θ, cos θ	tanh
Loss function		Mean Squared Error	
Optimization method		Adam	
Learning rate		0.001	
Dropout rate		0.5	

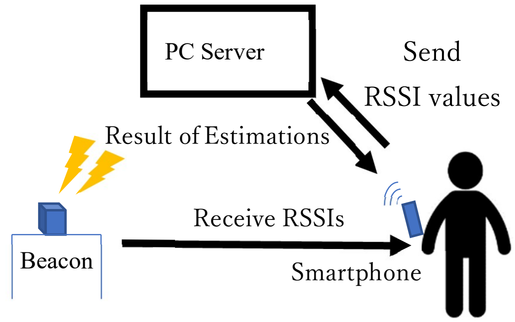


Fig. II. Client-server BLE indoor location and motion direction estimation system

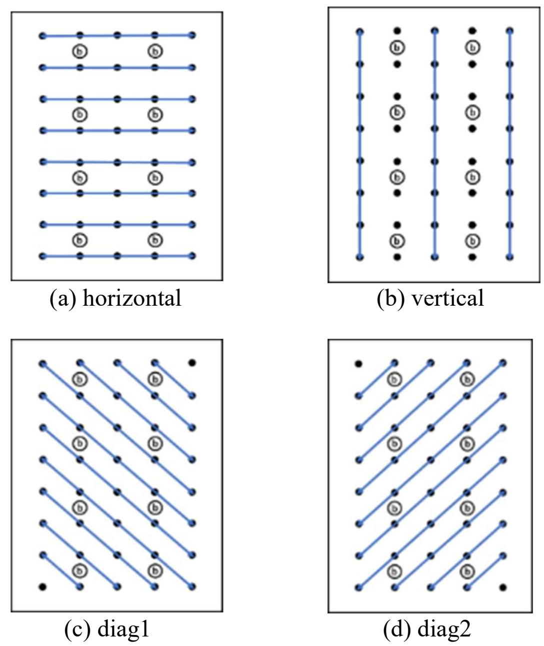


Fig. III. Experimental environment and configuration of routes

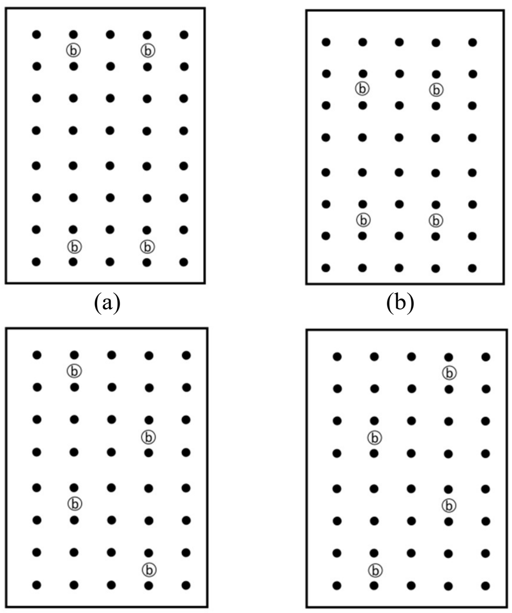
III. EXPERIMENTAL CONDITIONS

A. *Effect of beacon placement on estimation accuracy*

In this experiment, the size of the room and the number of beacons to be installed are fixed, and the results of the estimation of position and direction of movement by different patterns of beacon placement are compared. The routes of the movements are shown in Fig. III. We assumed 8 horizontal routes, 3 vertical routes, and 20 diagonal routes, for a total of 31 routes, as shown.

We placed 4 beacons in 4 different patterns on a table in a conference room. These arrangements are shown in Figure IV. Estimation was done for a single point in a rectangular grid with 5 points in the horizontal direction and 8 points in the vertical direction spaced one meter apart. The user moves at a constant speed along one of 31 fixed routes in the horizontal, vertical, or diagonal directions. Beacons are denoted as b_n (n =1, 2, 3, 4).

The RSSI measurements were collected from the Bluetooth advertisement packets from each beacon. In this experiment, we found that not all requests for these packets were answered on time, i.e., the measurements were non-uniform. Therefore, we applied a preprocessing and interpolation process to the measurements to obtain equally time-spaced measurements. This interpolation process was performed on both the training and test data.



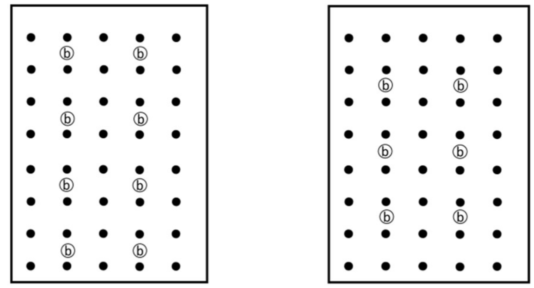
(a) (b) (c) (d)

Fig. IV. Beacon placement and configuration of routes for experiment A

B. Effect of number of beacons

In this experiment, the size of the room and the distance between the installed beacons are fixed, and the results of the estimation of the position and direction of movement indoors by the different number of beacons are compared. Either 8, 6, or 4 beacons were placed on a table in a conference room. Estimation was done for a single point in a rectangular grid with 5 points in the horizontal direction and 8 points in the vertical direction, spaced 1 m apart (Figure V). The user moves at a constant speed along one of 31 fixed routes in the horizontal, vertical, and diagonal directions. The beacons are denoted as b_n (n =1, 2,... 8).

The RSSI measurements were again collected from the Bluetooth advertisement packets from each beacon. As in experiment A, we found that not all requests for these packets were answered on time, i.e., the measurements were unevenly spaced. Therefore, we applied preprocessing and interpolation to the measurements to obtain evenly spaced measurements. The interpolation process was performed on both the training data and the test data. To compare the accuracy when four beacons are installed, we use the results for the beacon placement pattern (b) from experiment A as shown in Fig IV.



(a) 8 beacons (b) 6 beacons

Fig. V. Beacon placement and configuration of routes for experiment B

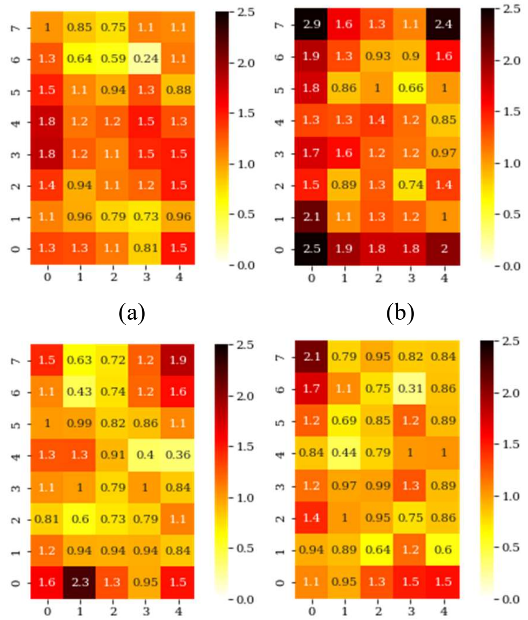
IV. RESULTS AND DISCUSSIONS

A. Experiment of accuracy comparison by beacon placement

Figure VI shows the heat map of the location estimation error when four beacons are placed at locations shown in Fig. IV. The average estimation error at each coordinate was 1.093[m] for placement (a), 2.425[m] for (b), 0.976[m] for (c), and 0.960[m] for (d). These results show that it is desirable to place the beacons sparsely and evenly inside the room, as shown in placements (c) and (d). Table II shows the estimation error of the direction of movement in each placement pattern when four beacons are placed in the four patterns. The bold figures indicate the smallest error for each direction. Table II also shows that placements (c) and (d) are preferable. Overall, both in terms of location estimation and motion direction estimation accuracy, placing beacons sparsely and evenly seems to give the best results, namely patterns (c) and (d) in this case.

Table II. Movement direction estimation error for each placement pattern with 4 beacons in experiment A

Direction	**Average Estimation Error [°]**			
	(a)	**(b)**	**(c)**	**(d)**
All	40.35	48.04	**36.41**	36.89
L	38.62	43.07	**34.17**	35.62
R	43.54	**39.76**	47.82	40.87
U	40.48	73.34	34.50	**29.92**
D	43.83	42.85	**34.59**	42.14
UR	27.85	29.73	**25.30**	27.94
LR	49.70	67.39	**39.15**	42.31
UL	38.55	43.05	34.98	**34.69**
LL	40.99	52.11	**38.74**	40.82



(a) (b) (c) (d)

Fig. VI. Position estimation error for each placement pattern using 4 beacons in experiment A

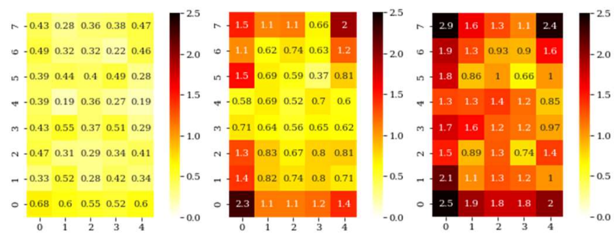
B. Accuracy comparison by number of beacons

Figure VII shows a heat map of the location estimation errors when the number of beacons is 4, 6, and 8. The beacon placement pattern (b) used in experiment A is recited here for the 4 beacons case. We chose placement pattern (b) for the 4 beacons because this placement seems to be in line with the placement patterns for 6 and 8 beacons shown in Fig. V, where all beacons are placed in a square pattern. The average estimation error at each coordinate is 0.382 [m] for Fig. VII (a) with 8 beacons and 0.864 [m] for Fig. VII (b) with 6 beacons. It is also 2.425[m] with four beacons in Fig. VII (c), which again is equivalent to the pattern (b) of Experiment A, shown in Fig. IV (b). Although the estimation accuracy improves with the number of beacons, our system shows that the estimation error less than 1 m with 6 and 8 beacons. An estimation error of less than 1 m is also possible with 4 beacons if they are spread out throughout the room, as was shown in Section IV.A. When there are eight beacons, the estimation error is less than 1 m for all of the estimated grid points, which is desirable for practical applications. With 6 and 4 beacons, there are locations inside the room where the estimation error is significantly larger than surrounding locations. Table III also shows the estimation error of the moving direction when the number of beacons is 4, 6, and 8. Table III shows that the estimation accuracy improves with the number of beacons as well as the location estimation results. From Table III, the estimation accuracy is calculated using Eq. (2) where $\theta_{estimate}$ is the angle estimation error.

$$1-\frac{\theta_{estimate}}{180}\ [\%] \qquad (2)$$

According to Eq. (2), the estimation accuracy of 4 beacons is 73.3%, that of 6 beacons is 83.6%, and that of 8 beacons is 92.2%. Therefore, the estimation accuracy of 8 beacons is 18.9% higher than the estimation accuracy of 4 beacons.

The position and direction of movement estimation error versus the number of beacons are shown in Figure VIII. From Fig. VIII, it can be seen that both the position and direction of movement estimation errors tend to decrease as the number of beacons increases. From this result, we can expect a further improvement of the accuracy by increasing the number of beacons. However, we point out that with 8 beacons, the average position estimation error is 0.382 m, and the average direction of movement estimation error is 14.00°, which we believe is quite sufficient for practical indoor navigation.

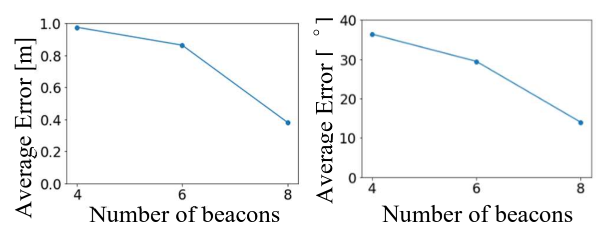


(a) 8 beacons (b) 6 beacons (c) 4 beacons

Fig. VII. Location estimation error for each number of beacons deployed in experiment B

Table III. Direction of movement estimation error for each number of beacons deployed in experiment B

Direction	Average Estimation Error [°]		
	(a)	**(b)**	**(c)**
All	**14.00**	29.48	48.04
L	**12.13**	24.93	43.07
R	**17.54**	19.96	39.76
U	**12.42**	49.97	73.34
D	**14.45**	25.36	42.85
UR	**7.66**	21.49	29.73
LR	**20.62**	45.53	67.39
UL	**11.20**	25.39	43.05
LL	**15.43**	23.12	52.11



(a) Position error (b) Direction error

Fig. VIII. Position and direction estimation error versus number of beacons in experiment B

V. CONCLUSION

We investigated the optimal placement pattern and number of beacons for an indoor location and the motion direction estimation system using BLE beacons. We found that even with four beacons, it is possible to estimate the location within an average of under 1 m, which is necessary for the navigation of pedestrians including the visually impaired, by carefully placing the beacons sparsely and evenly inside the rooms. However, the estimation accuracy at each point varied greatly, with the maximum error exceeding 2 m. Four beacons may be insufficient for stable navigation of visually impaired persons. However, we succeeded in improving and stabilizing the estimation accuracy by increasing the number of beacons used. In the case of eight beacons, the average position estimation error was 0.382 m. Estimates of less than 1 m were obtained stably at all of the locations tested inside the room. As for the direction of movement, the average estimation error in the case of eight beacons was 14.00°, indicating that the estimation accuracy was sufficient for navigation in eight directions: vertical, horizontal, and diagonal.

In the future, we will attempt to use the results gained here to implement an indoor voice navigation system by localizing navigation speech towards the target direction. We expect that utilizing localized sound will enable auditory navigation without looking at the screen of a smartphone and that visually impaired people will be able to use this system and will be equally beneficial for those with normal vision as well. For navigation using localized sound, it is necessary to create a special sound source to convey the exact direction to the user. Specifically, we will attempt to create a sound source that makes the directions even easier to understand by applying sound image localization to a voice that has been convolved with the head transfer function corresponding to the direction we want to steer the user towards. We will also conduct a simple indoor navigation field experiment using this system to verify its practicality.

Reference

[1] B. Wang, Q. Xu, C. Chen, F. Zhang, and K. J. R. Liu, “The Promise of Radio Analytics,” IEEE Signal Process. Mag., pp. 59–80, May 2018.

[2] Y.-S. Kuo, P. Pannuto, K.-J. Hsiao and P. Dutta, “Luxapose: Indoor Positioning with Mobile Phones and Visible Light,” In Proc. MobiCom, Sept. 2014.

[3] K. Echizenya, K. Kondo and T. Kitagawa, “Evaluation of the real-time indoor location and motion direction estimation system applying DNN to RSSI fingerprints of BLE beacons,” Proc. IEEE Global Conf. Consumer Electronics, Oct. 2020.

[4] K. Echizennya, K. Kondo, “Estimation of indoor position and motion direction for smartphones using DNN to BLE beacon signal strength,” Proc. IEEE Intern. Conf. on Consumer Electronics Taiwan, Sept. 2020.