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Estimating and Visualizing the position range of a BLE tag

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Abstract: When we lost something or search for things that are hidden in many similar things, such as a bicycle in the parking lot, it is necessary to know the position information of those things. In order to know the position information of the search target, there are some research works to detect an object by attaching a small size ID tag to the target in advance and using indoor-positioning technology to estimate the position of that ID tag. However, because of the narrow range of the ID tag's signal, if the seeker is far away, the radio wave cannot reach the seeker device and it becomes impossible to retrieve the position information of the target. We propose a method for estimating the position range of a BLE tag using the devices brought by others who pass by the area of the target object with which a BLE tag is attached. The estimated position range is also visualized as a heat map to support seeking an object. This method enables a seeker to find a lost object at a distant place from that object's location.

1. Introduction

In daily life, there are some situations where it is necessary to grasp the position information of a particular object or person. For example, when we lost something or search for things that are hidden in many similar things, such as a bicycle in the parking lot, or even find a victim in the disaster area, we need to know where the search target is.

If the search target is a mobile device which has cellular network, such as smartphones, it can send its own latitude/longitude coordinate acquired by GPS to a seeker through the Internet. Therefore, it is not difficult to search a lost mobile device. However, in the case of objects without Internet connection, for example a usb memory stick, a key and a bicycle, we cannot grasp their position through the Internet. The solution for this problem can be to attach a small size ID tag to the target in advance and use indoor-positioning technology [1][2][3][4] to estimate the position of that ID tag [5][6][7][8]. However, because of the narrow range of the ID tag's signal, if the object is far away from the seeker, the seeker's device cannot receive the radio waves of the ID tag. To solve that problem, we think of a method estimating the position of an ID tag by combining the coordinates of the mobile devices carried by unspecified people who pass by the range of the ID tag's signal and the distance from those devices to the ID tag.

In recent years, BLE (Bluetooth Low Energy) is supported by many mobile devices such as smartphones. Therefore, the mobile device users do not care for the battery consumption by Bluetooth and often turn on their Bluetooth function anytime. Through the Bluetooth's signal strength of a BLE tag received by such users' devices, it will be possible to estimate BLE tag's position by the method described above.

In this paper, we propose a method for estimating the position range of a BLE tag using the devices brought by others who pass by the area of the target object with which a BLE tag is attached. This method enables a seeker to find a lost object at a distant place from that object's location. Because estimating the specific position by calculating the distance between the devices and the ID tag is a low accuracy method, we estimate and provide to users the position range of the ID tag instead of a specific position. The estimated position range is also visualized as a heat map to support seeking an object. In order to evaluate the usefulness of the proposed method, we make some experiments. The results of experiments show that the proposed method is able to reduce the time and effort of users for seeking an object.

2. Searching for an ID tag

It is necessary to grasp the position information of things when we are looking for them. If the target which we are looking for is a mobile device having Internet connection, we just simply receive that device's longitude and latitude acquired by GPS through the Internet. For example, an iPhone device always has a built-in application called "Find My iPhone app". When a user lost an iPhone device, that user can track the lost iPhone's location through the Internet by other devices because the iPhone always sends its latitude/longitude coordinate everytime it connects to the Internet. However, if the targeted object has no Internet connection, we need another way to grasp its position information. One of the possible way is to seek the position range of an ID tag, which is attached to the object in advance, by using the signal strength received by some devices which pass by the ID tag's area. Below, we introduce some research works about finding an ID tag and their limitations.

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2.1 Related Works

One of the research works to find an ID tag is to support people to search for an RFID tag attached to items which are mis-placed in a large warehouse [6]. Some RFID readers are deployed at known positions to provide the position reference for positioning a tag. They are called "reference readers". The system uses the distance measurements from at least 3 reference readers for positioning a tag.

Because this system requires the reference readers to be placed in known positions, it can only support seeking a tag in a known region. However, when a person loses something outdoor, the lost thing is sometimes far away and sometimes that person even forgot where the lost thing's place was. In this situation, the seeker can request the people near the approximate location to help searching the lost thing [9] or apply some useful search strategies with the support of a technology [10]. However, tracking the position of objects will be the most useful way to search for a lost thing.

Our research proposes a method which enables users to search for a thing even being in unknown and far away location by specifying its position range.

Another research work has been conducted to support rescuing victims from a disaster's area [8]. In order to seek for victims who are carrying a beacon in the ski area, they use beacon-seeking devices to detect if those devices could receive signals from the beacon. The rescuers are not supposed to know the specific position of the victims. They just do a simple task of going toward the direction with stronger signals of the beacon.

Our method supports users to know even where the search target located area is.

2.2 Problems

The methods of the research works presented in section 2.1 have the same limitation. They do not enable people to seek a tag far away from that seeker's current location. Because the signal area of an ID tag is generally small, in most cases, the seeker's device is outside of the signal area. For example, as seen in Figure 1, if the ID tag's signal area is a circle of which radius is 15 metres, the seeker at 100 metres far from the ID tag cannot seek the tag. Therefore, to apply those methods, first of all, the seeker has to approach the tagged object location. However, in the most situations, for example when people dropped things, lost things or when rescuing a victim in the disaster area, the seeker do not know where to start seeking.

Our method solves this problem by using some mobile devices with GPS passing by the signal area of the BLE tagged object to collect the information which can be used for deriving the latitude/longitude coordinate of the tagged object. The BLE tag is cheap and it can broadcast its ID for months without changing the battery. Moreover, BLE is supported by many mobile devices such as smartphones. Because of low energy consumption, the mobile device users often turn on their Bluetooth function anytime. Through the Bluetooth's signal strength of a BLE tag received by such users' devices, it is possible to estimate BLE tag's position. The details of this method is presented in section 3.

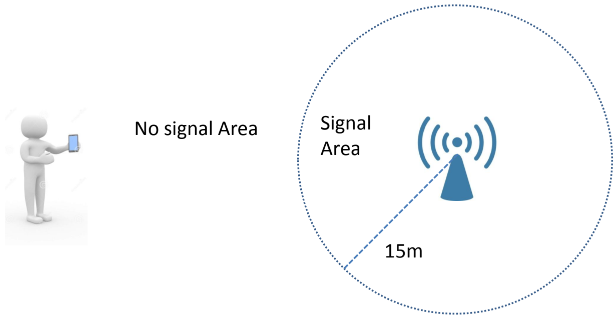

Fig. 1 Seeker's device can not catch the signal from far away

2.3 Research purposes

In this research, we propose a method for estimating the position range of a BLE tag by collecting the latitude/longitude coordinate data of the device which enters the region of the BLE tag and the RSSI (Received Signal Strength Indicator) value of a signal received from a BLE tag by that device. This method supports people to find an object located outdoor which has a fixed position in an unknown location and is hidden in many similar things.

Based on the data collected by surrounding devices, we build the heat map to visualize the possibility of whether the BLE tag's position is on an specific area or not.

We also evaluate the usefulness of the proposed method by making some experiments in the case of the seeker finding an object with our method and the case of the seeker not being applied our method.

3. Estimating and visualizing the position range of a BLE tag

We propose a method for estimating and visualizing the position range of a BLE tag as below.

3.1 Overview

The latitude/longitude coordinates acquired by GPS of the mobile devices passing by the BLE tag's signal area are used as reference positions. In order to estimate the position range of a BLE tag in unknown location, first of all, it is necessary to estimate the relative position range of the BLE tag in relation with a reference position. The absolute position range of the BLE tag is specified by a combination of a reference coordinate and the relative position range.

The relative position range can be estimated by the distance measurements from multiple reference positions. The distance measurements of the BLE tag from a reference device has a correlation with the RSSI value of a signal transferred between the BLE tag and the device [11]. Therefore, our method collects these RSSI values and accumulates them in a server. The more data collected, the more accurate position range can be estimated.

When the absolute position range is estimated, it is visualized as a heat map for supporting a seeker to find a BLE tagged object.

The way how to collect data, estimate the position range and visualize that estimated position ranged as a heat map is presented below.

3.2 Collecting data from nearby devices

Figure 2 depicts how data is collected for estimating the position range of a BLE tag with this method.

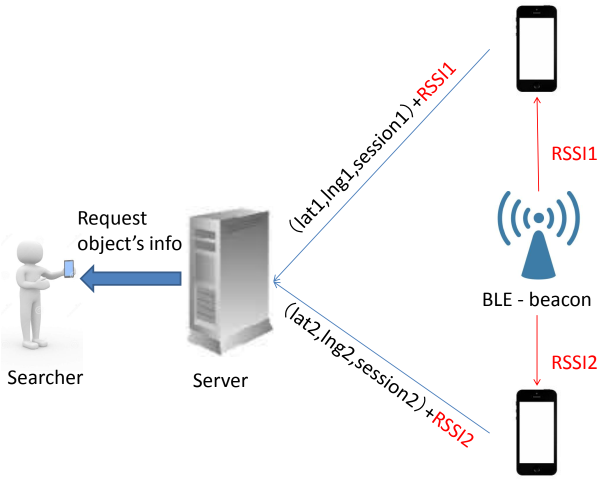

Fig. 2 Collecting data from nearby devices

A BLE tag always broadcasts its ID. If a mobile device such as a smartphone enters the broadcasting area, it catches the signal of the BLE tag and the RSSI value is updated each second. We found that when the mobile device exits and re-enters that area, the RSSI value of the same position updates with more error than when the mobile device continuously in the signal area. Therefore it is necessary to divide the RSSI data set to multiple sessions. Each session starts when the mobile device enters the signal area and ends when it leaves that area. During a session, those devices start catching the signal of a BLE tag and sending to the server the data for that BLE tag. Each data combination contains the device's latitude/longitude coordinate, the RSSI value and a session number generated for that device. The latitude/longitude coordinate is acquired by GPS. The RSSI value presents the strength of the signal transferred between BLE tag and the device. When the searcher needs to estimate the position range of the BLE tag, that searcher's device receives from the server the accumulated data and processes them at its local environment. We describe how to process that data for estimating the position range in section 3.3.

Figure 3 describes how to accumulate data during a session. When a device entered the area which has BLE tag's signal, that device sends to the server a request to obtain a new session number. The server generates a session number and responses that new session number to the device. Everytime the latitude/longitude pair or the RSSI value is updated, the device sends the new data combination to the server. When the device left the signal area, the session is closed.

Data is accumulated on the server as described in Figure 4. For each data combination, the server automatically adds a timestamp. Searcher's device is able to request an amount of data collected after a specified timestamp.

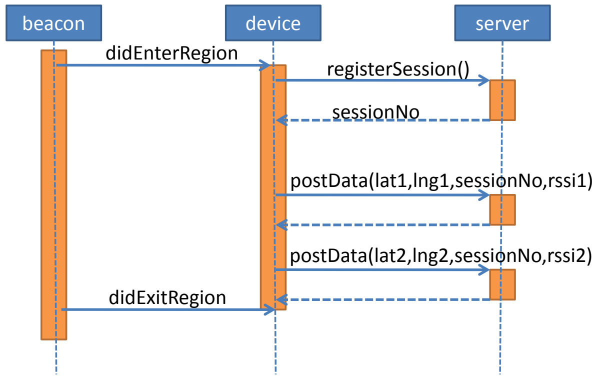

Fig. 3 Accumulating data during a session

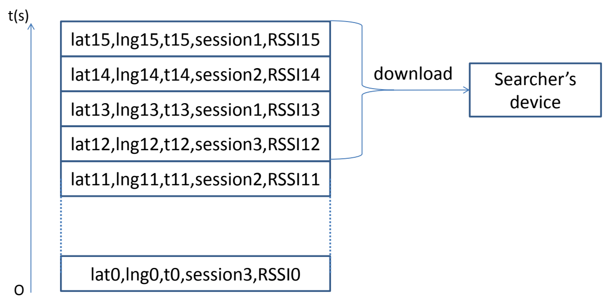

Fig. 4 Data accumulation

3.3 Estimating the position range

The relation between a distance D from a device to a BLE tag and $RSSI$ value is expressed as the equation (1) [12]. A is the RSSI value at 1 meter distance. K is the slope.

$$RSSI = -K \ln D + A \tag{1}$$

From the equation (1), making some conversions, we have the equation (2) for estimating the distance from the $RSSI$ value.

$$D = e^{\frac{(A-RSSI)}{K}} \tag{2}$$

The equation (2) is an exponential function with different constants A and K for each environment. Therefore, when estimating distance from RSSI, it is necessary to collect a lot of RSSI samples at multiple distances and use the collected data and regression model to find the best fit exponential function for each environment.

If the distance of a BLE tag from many positions can be estimated, the relative position of that BLE tag in relation with the device's position also can be estimated. By combining this relative position with the latitude/longitude coordinate of a specified nearby device, the latitude/longitude coordinate of the BLE tag can be estimated.

As seen in Figure 5, for the estimated relative position ($\Delta lat, \Delta lng$) and the device's position ($lat1, lng1$), the BLE tag's latitude/longitude coordinate are calculated by the equations below.

$$lat = lat1 + \Delta lat \quad (3a)$$
$$lng = lng1 + \Delta lng \quad (3b)$$

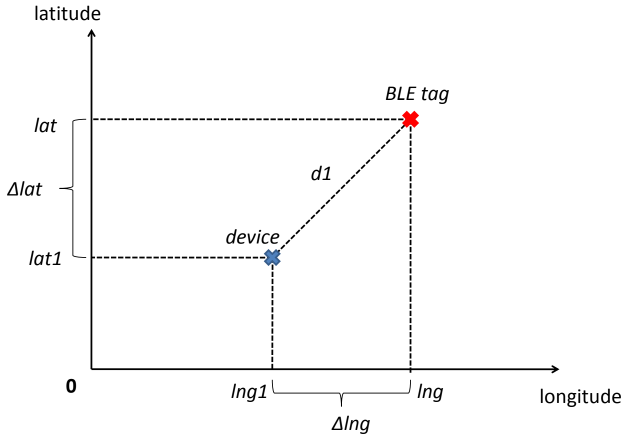

Fig. 5 Estimating BLE tag's latitude and longitude from relative position

An indoor environment makes the latitude/longitude coordinate ($lat1, lng1$) which is acquired by the GPS service become inaccurate. Therefore, our method is only applied for devices in outdoor environment.

Besides, positioning system which uses RSSI is inaccurate because of the unreliability of RSSI value [12][13][14][15]. Because the probability of the hypothesis "the BLE tag is placed on d (metres) far from position i" follows normal distribution (Gaussian distribution)[16], that probability is calculated by the equation (4). The position i has the latitude/longitude coordinate (lat, lng) where a device detected BLE tag's signal. Pi is the probability of the hypothesis. di is the distance from the position i to the position where the probability of the hypothesis is being estimated. Di is the value of distance di where the probability of the hypothesis is the highest.

$$P_i(lat, lng) = \frac{1}{\sqrt{2\pi}\sigma} exp\left(-\frac{(d_i(lat, lng) - D_i)^2}{2\sigma^2}\right) \quad (4)$$

Figure 6 shows the graph of the probability distribution.

Actually, the distance value which is calculated by the equation (2) is just the median value Di of the probability distribution. That median value indicates a set of positions (a circle as seen in Figure 6) which are the most possible position.

Because of the low accuracy, for supporting people to find a thing, it's more useful if we provide and visualize the possibility of every visible position on a map than just showing the most recommended position.

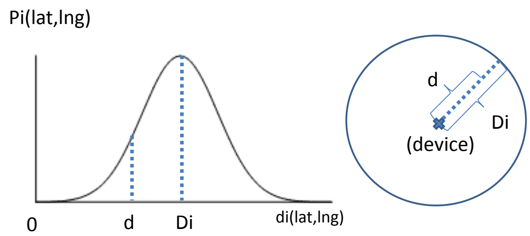

Fig. 6 Probability distribution

We divide the displayed area of a map to multiple tiny cells (15 cm x 15 cm for each cell) and assign a weight value for each cell. The weight value expresses the possibility whether the position of the BLE tag is inside this cell. Every position which is inside a cell has the same weight value. The weight value of a position is calculated by the equation (5) as a sum of all average values of Pi for every session number. Pi is the probability value which is calculated from an accumulated data combination by the equation (4).

$$weight = \sum^{sections} \sum_{i=1}^{n} \frac{P_i(lat, lng)}{n} \quad (5)$$

Finding the weight value for all cells, then we get the weight matrix. Figure 7 is an example of a weight matrix. The vertical - horizontal axis expresses the latitude and longitude. The cells filled in red are the positions where a device sent its own position and the RSSI value received from the BLE tag. Each cell filled in red is surrounded by a circle which expresses the median of probability distribution. Because the probability distribution graph is symmetric, a position near the median value (corresponding to the arcs in Figure 7) has higher probability value. Therefore, a position near multiple arcs has a high weight and also high possibility for the existence of the targeted BLE tag (the red float number in Figure 7).

3.4 Visualizing the position range

Based on the weight matrix, each cell is filled with a color on a map. As shown in Figure 8, we use 12 color levels from green to red. Considering the highest weight in all positions corresponding to level 12, every weight value is converted to scale 12. For example, if the highest weight value in all positions is 4, the weight value of every position is scaled to 12 : 4 = 3 (times). The value after scaling is the color level of the cell. The higher color level, the higher possibility for the targeted BLE tag can be found.

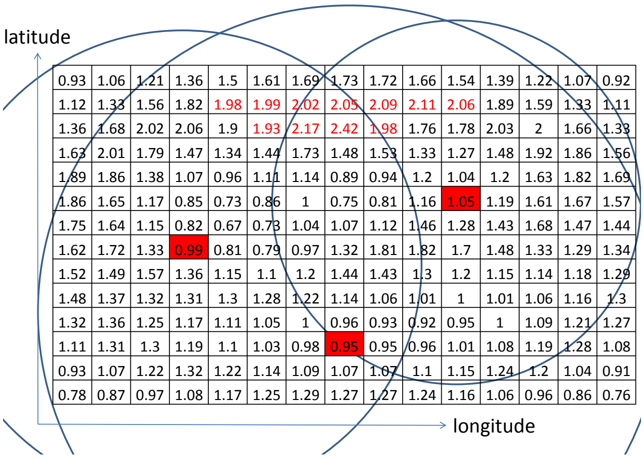

Fig. 7 Weight-matrix

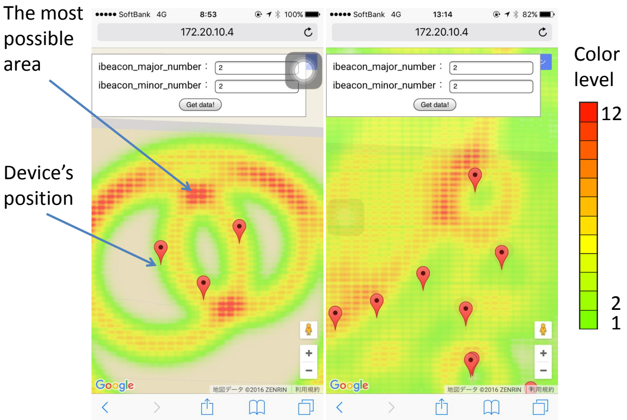

Fig. 8 Heat Map

4. Experiments and Evaluation

4.1 Pre-experiments for estimating the trendline of distance

4.1.1 The purposes and processes of experiments

Because the relation between distance and RSSI value also depends on the environment around the BLE tag, the constants A and K in the equation (2) are different for each environment. Therefore, we make experiments for specifying the trendline function of distance in each environment. Without these experiments, the proposed method cannot estimate distance based on RSSI values. In each environment, we measure and record RSSI value when device is in 0.1, 1, 2, 3, 4, 5, 6, 7 metres away from the BLE tag. In this study, we repeat this measurement 30 times in each of no-obstacle environments and bicycle-parking area. Based on the results, we use the regression model to derive the exponential trendline of distance.

4.1.2 Results

Table 1 and 2 respectively show the results of experiments in each of no-obstacle environments and bicycle parking area. For each distance, we calculate the average RSSI value of 30 times and use this chain of average RSSI values to derive the best fit curve for the equation (2). This curve is an exponential trendline.

The equation (2) can be converted to the equation (6).

$$\ln D = \frac{A}{K} - \frac{1}{K} RSSI \tag{6}$$

If assigning $y = \ln D$ and $x = RSSI$, the equation (6) has the format $y = B + Cx$. Therefore, the relation between $\ln D$ and $RSSI$ is linear. To find the best fit curve for the equation (2), first of all, it is necessary to fit $\ln D$ against $RSSI$ by linear regression with the samples of $\ln D$ and $RSSI$ shown in Table 1 and 2.

Table 1 RSSI values in no-obstacle environments

distance D (m)	$\ln D$	average RSSI (dB)
0.1	-2.3026	-37.03
1	0	-64.93
2	0.693	-73.3
3	1.0986	-77.47
4	1.3863	-80.53
5	1.6094	-81.8
6	1.7918	-84.1
7	1.9459	-86.53

Table 2 RSSI values in bicycle-parking area

distance D (m)	$\ln D$	average RSSI (dB)
0.1	-2.3026	-41.13
1	0	-68.6
2	0.6931	-73.23
3	1.0986	-80.97
4	1.3863	-83.47
5	1.6094	-85.8
6	1.7918	-86.73
7	1.9459	-87.9

The equations (7) and (8) are respectively the results of linear regression with the samples of $\ln D$ and $RSSI$ in no-obstacle environments and bicycle-parking area.

- In no-obstacle environments:

$$\ln D = -0.086 RSSI - 5.558 \tag{7}$$

- In bicycle-parking area:

$$\ln D = -0.089 RSSI - 5.999 \tag{8}$$

Figure 9 and 10 show the best fit lines of $\ln D$ in the two environments.

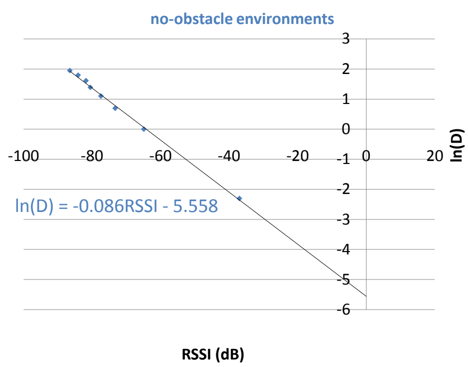

Fig. 9 Fitting $\ln D$ against $RSSI$ (no-obstacle environments)

By taking exponent of both sides, the equation (7) and (8) can be respectively converted to the equation (9) and (10) which are the best fit curves to calculate the distance in two environments.

- In no-obstacle environments:

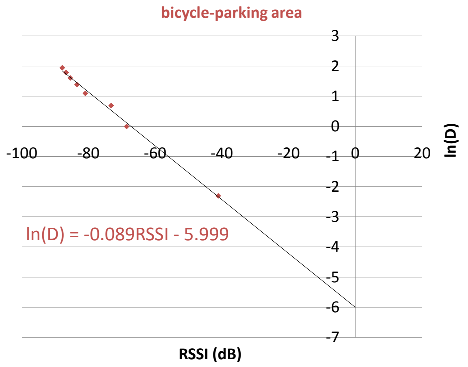

Fig. 10 Fitting $\ln D$ against $RSSI$ (bicycle-parking area)

$$D = 0.0036e^{-0.086RSSI} \quad (9)$$

- In bicycle-parking area:

$$D = 0.0025e^{-0.089RSSI} \quad (10)$$

Figure 11 shows the exponential trendline for two environments.

The results show that the RSSI value is stronger when there is no obstacle. Based on the trendline, the median value *Di* of the probability distribution in the equation (4) can be calculated. Therefore, the weight value of a position which expresses the possibility whether that position is the position of the BLE tag can be estimated. Based on the matrix of those weight values, the heat map can be built for visualizing the possibility of whether the BLE tag is placed on a specific area or not.

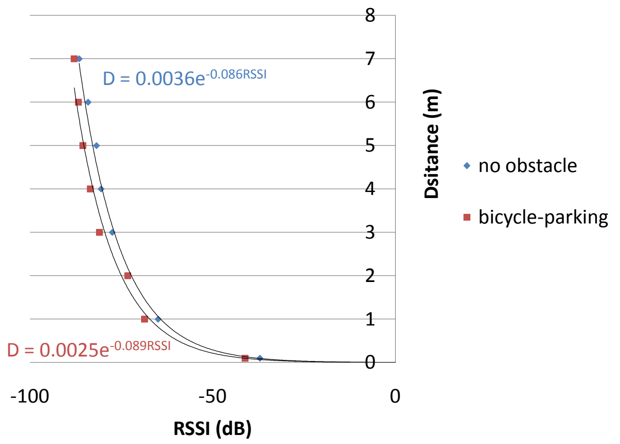

Fig. 11 Exponential trendline of distance

4.2 Pre-experiments for finding a search strategy

4.2.1 The purposes and processes of experiments

We make experiments to understand how to apply the proposed method usefully in the situations of searching an object with a BLE tag attached. In other words, we make experiments to find a useful strategy to search an object with the support of the proposed method. Specifically, we investigate how frequently the BLE tag is found for each color level. These experiments are also for checking if the designed system works properly.

We separately do experiments for 3 times at 30 outdoor places in our university campus where there is no obstacle. At each place, we set a BLE tag and then move with a device randomly around that BLE tag in one minute. After that we record the color level of the position where the BLE tag is actually placed.

4.2.2 Results

Table 3 shows how many times the BLE tag is placed on each color level. The average color level of the position where the BLE is actually placed is 6.71.

Table 3 The number of times which the BLE tag is placed on each color level

color level	the number of times
0	2
1	3
2	5
3	4
4	4
5	8
6	12
7	12
8	12
9	16
10	5
11	7
12	0

Based on the results shown in Table 3, the distribution of each color level is caculated and shown in Figure 12.

The BLE tag was not positioned in any area of color level 12 because that area is always very narrow and it is very difficult for any position estimation to be absolutely accurate. The percentage for the BLE tag placed in the area of color level 0 (no color) is just 2%. This is the case when the estimated position was very inaccurate. The pie graph shows that the percentage of color level 6 or higher in total is over 70%.

This result shows that while searching a BLE tag, it is more effective if the seeker first probes the tag in the area where the color level is higher than or equal to 6 before probing the tag in the other area.

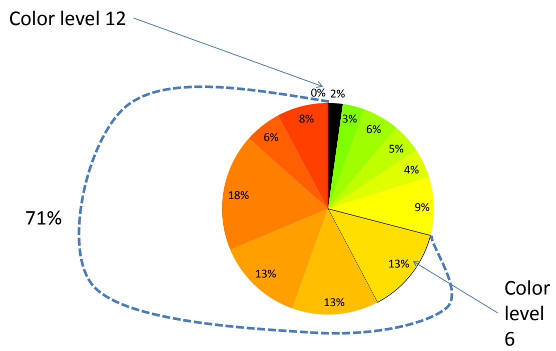

Fig. 12 Percentage of each color level

4.3 Experiments for evaluation of the proposed method

4.3.1 The purposes and processes of experiments

We also make experiments for evaluating the usefulness of this method when it is applied in a strategy for searching an object attached with a BLE tag.

Six graduate students in computer science are chosen as subjects. They have to find a bicycle from about other 800 bicycles in a 25 m x 15 m parking area. These bicycles are separated to 6 lines as seen in Figure 13.

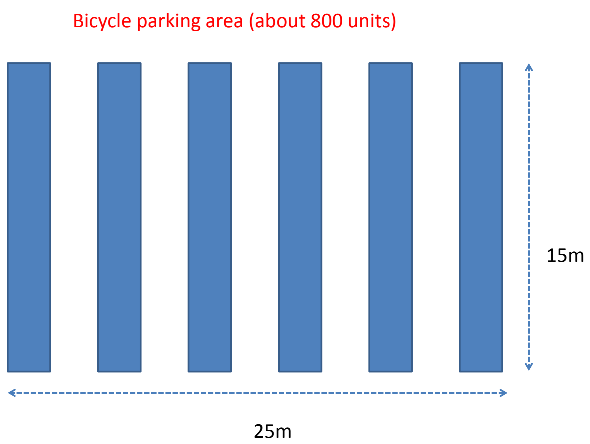

Fig. 13 Experiment place

Before doing the experiments, every student sees the targeted bicycle. After the students remember the characteristics of the targeted bicycle, the students leave the experiment place, then that bicycle is hidden at somewhere in the parking area. Each student is requested to find the targeted bicycle in two cases. We record the total time starting when the student starts searching and ending when the targeted bicycle is found in both two cases.

- Case 1
  - The students do not use the method proposed in this paper.
- Case 2
  - A BLE tag is attached to the bicycle and the targeted bicycle is hidden once again. The distance from the target bicycle to a place where the student starts searching is the same with case 1.
  - A device is moved randomly around the bicycle in one minute to accumulate position information of the BLE tag.
  - The student uses the visualized heat map and probes the bicycle in the area where the color level is higher than or equal to 6.
  - If the bicycle is not found, the student continues finding in the area where the color level is lower.

4.3.2 Results

The result of experiments is shown in Table 4. The result shows that when applied the proposed method, most students reduced 2-4 times of the time cost for searching the bicycle.

Only the student B took less time to find out the targeted bicycle without a support by the proposed method. Because the student B is originally good at looking for things, he could detect the targeted bicycle from far distance by eyes.

Both the student B and the student F did not find out the bicycle more effectively in case 2 because the bicycle was not actually placed at any area with the color level higher than or equal to 6.

Table 4 The results of experiments for evaluation of the proposed method

	case 1	case 2	square (color level ≥ 6) (%)
student A	2 min 51 sec	43 sec	14.2
student B	20 sec	59 sec	18.44
student C	2 min 41 sec	49 sec	22.73
student D	1 min 23 sec	21 sec	16.41
student E	1 min 19 sec	32 sec	14.22
student F	1 min 49 sec	1 min 11 sec	12.22

4.4 Discussion and Evaluation

When we apply the proposed method and probe the area with the color level higher than or equal to 6, the students found out the targeted bicycle very quickly in comparison with the case when they are not applied the proposed method.

In the case of the students not being applied the proposed method, they even could not realize that they were passing the area where the bicycle was placed. That is the reason why it took so much time to find out the bicycle without being supported by the method.

Besides, because the area with the color level higher than or equal to 6 is narrow, it takes less effort for finding out an object with this method. However, sometimes the proposed method takes the student more time to find out the object when that object is not actually placed in the area with the color level higher than or equal to 6.

Requiring a derivation of the exponential trendline of distance for each environment is one of the limitations of this method. Because each environment has a different relation between distance and RSSI, there is no generic exponential trendline of distance which can be used for estimating the distance in any environment.

5. Conclusions and Future works

We proposed a method for estimating the position range of a BLE tag by collecting the coordinate data of the device which enters the region of the BLE tag and the RSSI value received from the BLE tag by that device. Based on the data collected by surrounding devices, we build the heat map to visualize the possibilities of whether the BLE tag lay on a specific area or not. This method is useful to support finding things outdoor which have fixed-position, and hidden in many similar things.

However, the proposed method has some limitations such as requiring a derivation of the exponential trendline of distance for each environment. In future, this method needs to be improved for increasing the accuracy of the estimation and supporting users to find a moving object.

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