A Location Estimation Scheme Utilizing RSSI and Phase Values with Angled Antennas

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***Abstract*—Radio Frequency Identification (RFID) technology has gained significant attention in retail due to its applications in self-checkout systems, inventory control, and anti-theft gates. Precise location estimation is crucial for enabling diverse functionalities of RFID. However, conventional methods face challenges in achieving miniaturization in complex installation environments. This paper introduces an innovative location estimation scheme for RF tags that leverages the distinct characteristics of the Received Signal Strength Indicator (RSSI) and phase values. By employing angled antennas, we establish non-uniform communication areas, enabling the implementation of our proposed system. Through real-world experiments, we evaluate and provide empirical evidence that validates the effectiveness of our approach in accurately estimating the location of RF tags.**

***Index Terms*—RFID, Location Estimation, Angled antenna, RSSI, Phase Value**

I. Introduction

RFID technology has been extensively embraced within the retail industry, specifically in applications such as self-checkout systems, inventory control, and anti-theft gates [1]–[6]. RFID technology identifies individual RFID tags through wireless communication between the RFID reader/writer and the RF tag [7]. The RF tag possesses a Unique Item Identifier (UII) as its identifier. The reader/writer performs tag identification based on the UII. In retail RFID systems, RF tags are embedded in price tags to identify products based on the UII of the RF tag. The High Frequency(HF) and Ultra High Frequency(UHF) bands are mainly used [8]. Among these, the UHF band is primarily used in the retail industry due to its ability to read and write data from multiple RF tags located several meters apart [9].

Accurate location estimation of tags is crucial for preventing false detections near a warehouse or store boundaries in services that manage the movement of tags. The system should determine whether they are within or outside the designated boundary. Conventional methods typically involve the use of multiple tags or antennas as reference points for location determination. Additionally, some methods use multiple antennas to obtain various information received from an RF tag at different positions. For instance, one existing method installs four reader/writer devices and antennas for each estimation target area [11]. RF tags are placed at specific intervals on the floor and walls to serve as reference points, and location estimation is performed using Received Signal Strength Indicator (RSSI) obtained from RF tags' response signals. Another method utilizes phase values for location estimation without relying on reference tags [10]. This method estimates the distance between the tag and each antenna based on phase values obtained from four antennas in the target area. The combination of the four estimation results provides the location estimation of the RF tag. However, adopting multiple pieces of equipment in such techniques poses challenges in achieving physical miniaturization within the installation environment. Therefore, location estimation systems require ease of installation. Therefore, there is a need for location estimation systems that are easy to implement.

This paper proposes a location estimation scheme for RF tags that utilizes two angled antennas and focuses on the uniqueness of RSSI and phase values. The proposed scheme enables grid-based location estimation by creating a radio environment with distorted characteristics through antenna placement. Since similarities in RSSI and phase values can lead to decreased estimation accuracy, we introduce angled antennas to create an asymmetric radio environment. The use of angled antennas generates a left-right asymmetric radio environment that enhances the uniqueness of the combination of RSSI and phase values. Additionally, RSSI is combined with phase values to improve estimation accuracy, as RSSI alone is unstable and easily influenced by the surrounding environment [12]–[14]. Hence, we combine RSSI with phase values for location estimation. Moreover, multiple grids are defined within the target area, and each grid's unique combinations of RSSI and phase values are used for estimation. In other words, the RSSI and phase values obtained when reading the RF tag are employed for machine learning to achieve grid-level location estimation. We developed a prototype of the proposed scheme and conducted evaluations as proof of concept. The evaluation results confirmed the high accuracy of the proposed scheme in estimating the positions of RF tags.

II. Proposed Method

This paper proposes a position estimation scheme for RF tags based on RSSI and phase values using angled antennas. The uniqueness of parameter combinations in the estimation target range is important to achieve stable and accurate position estimation when schemes utilize parameters calculated from response signals of RF tags. Therefore, the proposed method generates the imbalanced radio environment created by the installation angles of the antennas. Moreover, position estimation based solely on RSSI and phase values is challenging due to the influence of the angle between the antenna and the RF tag. Therefore, the proposed scheme combines RSSI and phase values with different factors of variation to estimate the position of the target RF tags accurately. Additionally, since RSSI and phase values are affected by the angle of the RF tag, comparing them with pre-measured values for position estimation may lead to a decrease in accuracy. Thus, the proposed scheme uses machine learning to determine the relationship between the position of RF tags and RSSI/phase values, enabling accurate position estimation. However, obtaining data for all points within the communication range would incur significant learning costs. Therefore, we divide the communication area into multiple grids and utilize grid estimation with classifiers to achieve efficient position estimation.

A. Relation between the antenna and RSSI

The installation of angled directional antennas is a crucial aspect of the proposed method. Since passive RF tags are commonly used in modern RFID systems, directional antennas emit radio waves in a specific direction, and passive RF tags receive power from the emitted waves. These tags operate by receiving power from the radio waves emitted by the antenna. Hence, sufficient power supply is necessary for the RF tag to operate and be readable by the antenna. Front-facing directional antennas are commonly designed to enhance reading accuracy and ensure uniform communication sensitivity within the range. When the antenna is facing forward, RSSI achieves its maximum value directly in front of the antenna and decreases as it moves to the left or right. The RF tag's movement exhibits left-right symmetry with respect to the antenna's center, resulting in challenges in determining the precise location.

Fig. 1-A illustrates the relationship between the location of the RF tag and the RSSI and phase values when the directional antenna is facing forward. The RSSI achieves its maximum value at the point directly in front of the antenna and decreases as the antenna moves to the left or right. Furthermore, as the RF tag moves, the RSSI and phase values exhibit left-right symmetry with respect to the antenna's center. In other words, when performing position estimation with the antenna facing forward, there are two possible candidate locations, making it challenging to determine the precise position. Therefore, to

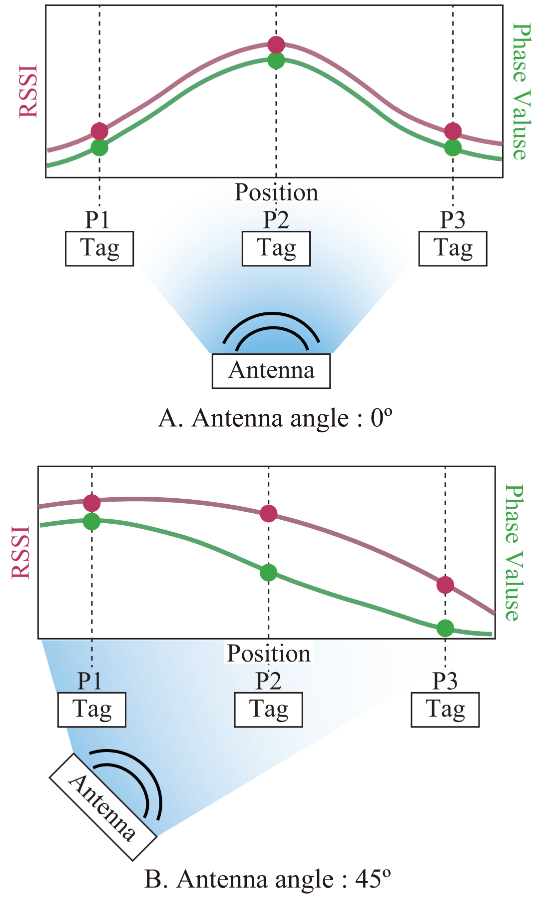

Fig. 1. The variation of RSSI and phase values with antenna angle

achieve accurate location estimation, it is necessary to create a radio environment where the uniqueness of RSSI is enhanced at any arbitrary point within the communication range.

Therefore, the proposed approach generates distortion in the radio environment by tilting the directional antenna. RSSI decreases as the distance the antenna's emitted radio waves cover increases. Moreover, RSSI is a parameter associated with receiver sensitivity, and thus, it is greatly influenced by the antenna's orientation. Specifically, RSSI values increase as the distance between the antenna and the tag decreases and when the RF tag is positioned in front of the antenna. Based on these observations, tilting and adjusting the antenna installation can manage the balance of the radio environment.

Fig. 1-B illustrates the relationship between the position and RSSI when the antenna is tilted at a 45-degree angle. Tilting the antenna decreases RSSI as the distance covered by the emitted radio waves increases. The antenna's orientation greatly influences RSSI, and tilting and adjusting the antenna installation can manage the balance of the radio environment. In this figure, the variation in RSSI is asymmetric due to the distortion of the radio environment caused by the antenna's tilt. By generating a radio environment that enhances the uniqueness of RSSI at any arbitrary point within the communication area, we enable accurate position estimation using the antenna

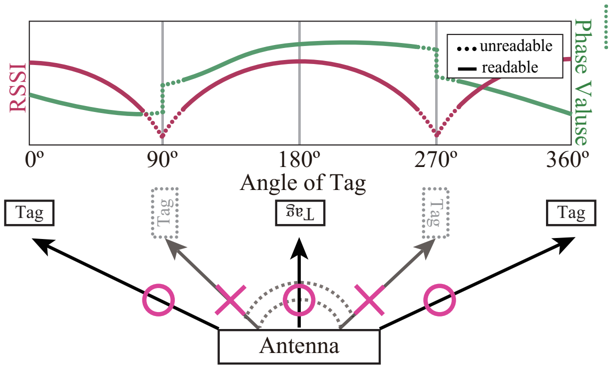

Fig. 2. The variation of RSSI and phase values with RF tag angle

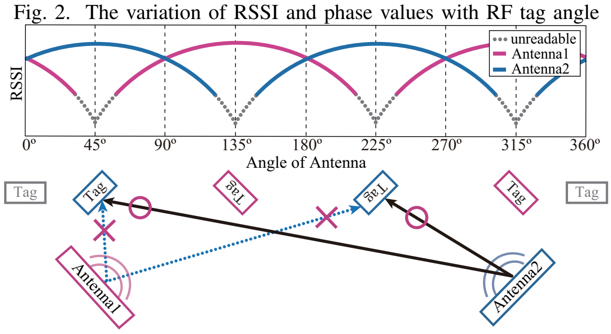

Fig. 3. RSSI concerning the angle between the RF tag and the antenna

angle.

B. Relation between the antenna and RSSI

The phase value is a parameter related to the wavelength of the radio wave and the communication distance. It is greatly influenced by the physical positioning of the antenna and the RF tag, serving as a metric for the distance between them. The phase value is maximum when the distance between the antenna and the RF tag is the shortest for the front-facing antenna. It also varies with the distance between the antenna and the RF tag, even with the 45° degree antenna. As a result, tilting the antenna causes an asymmetric change in the phase value, similar to RSSI.

C. Angle between the antenna and the RF tag

The angle between the tag and the antenna affects the power supply received by the RF tag, leading to variations in RSSI and phase values. When the antenna and the RF tag face each other, the RF tag receives an efficient power supply, resulting in maximum RSSI at angles of 0 ° and 180 ° . Conversely, near orthogonal angles, the power supply decreases, leading to decreased RSSI and operational issues caused by insufficient power, particularly around 90 ° and 270 ° . The phase values also exhibit significant fluctuations near perpendicular angles. Since RF tags are attached to objects with various angles, location estimation techniques must support these variations.

Fig. 2 illustrates the variations in RSSI and phase values caused by the angle between the RF tag and the antenna. When the antenna and the RF tag face each other, the RF tags efficiently receive power supply. Increased power supply enables the RF tag to transmit its data with stronger signal strength. Consequently, RSSI is at its maximum when the angle between the antenna and the RF tag is 0° and 180°. Conversely, when the angle between the antenna and the RF tag is close to orthogonal, the power received by the RF tag decreases. As a result, RSSI decreases, leading to operational issues caused by insufficient power, particularly around 90° and 270°. The phase values also exhibit significant fluctuations near the point where the angle between the antenna and the RF tag is perpendicular. The phase values vary significantly based on the angle, even at the same measurement point. The proposed method assumes services such as inventory management and theft prevention gates, where an approximate location of the RF tags is required. Since RF tags are typically attached to objects, it is challenging to maintain a fixed orientation for the tags. Therefore, position estimation techniques need to support various angles of RF tags.

The proposed method uses two antennas to cover a wide range of angles between the antenna and the RF tag. By using two antennas, the adverse signal conditions of one antenna can be compensated by the other, ensuring compatibility with various angles between the antenna and the RF tag.

Fig. 3 illustrates the fluctuation of RSSI based on the angle between the RF tag and the antenna. Each antenna is tilted 45° towards the center. When the RF tag and the antenna face each other directly, the power supply to the RF tag is most efficient. At angles of 135° and 315°, the RF tag and Antenna1 are in a frontal alignment, resulting in maximum RSSI. Conversely, when the RF tag and the antenna are orthogonal, the reception sensitivity decreases, making tag reading difficult. At angles of 45° and 225°, the RF tag and Antenna1 are almost orthogonal, decreasing RSSI. On the other hand, the RF tag and Antenna2 face each other directly, maximizing the RSSI. Thus, even when reading becomes challenging due to inadequate power supply in Antenna1, power supply and RF tag reading can still be achieved through Antenna2. This way, when one antenna faces difficulty in the power supply or reading, the other can compensate. Therefore, installing two directional antennas tilted at the same angle towards the center makes reading RF tags at various angles possible, thereby preventing missed tag reads. Hence, two directional antennas are installed to accommodate various RF tag angles.

D. System model

Fig. 4 shows the system model of the proposed RF tag location estimation system. The proposed method leverages the uniqueness of calculated values from RF tags within the target area to enhance estimation accuracy. Therefore, the proposed method utilizes the imbalanced radio environment resulting from the placement angle of antennas. The location estimation system controls the reader/writer, captures RSSI, phase value, and UII values from the RF tags, and performs grid-based location estimation using machine learning techniques.

In the preparatory stage, the system preprocesses the acquired data to transform it into a suitable format for machine learning. The machine learning process includes the learning

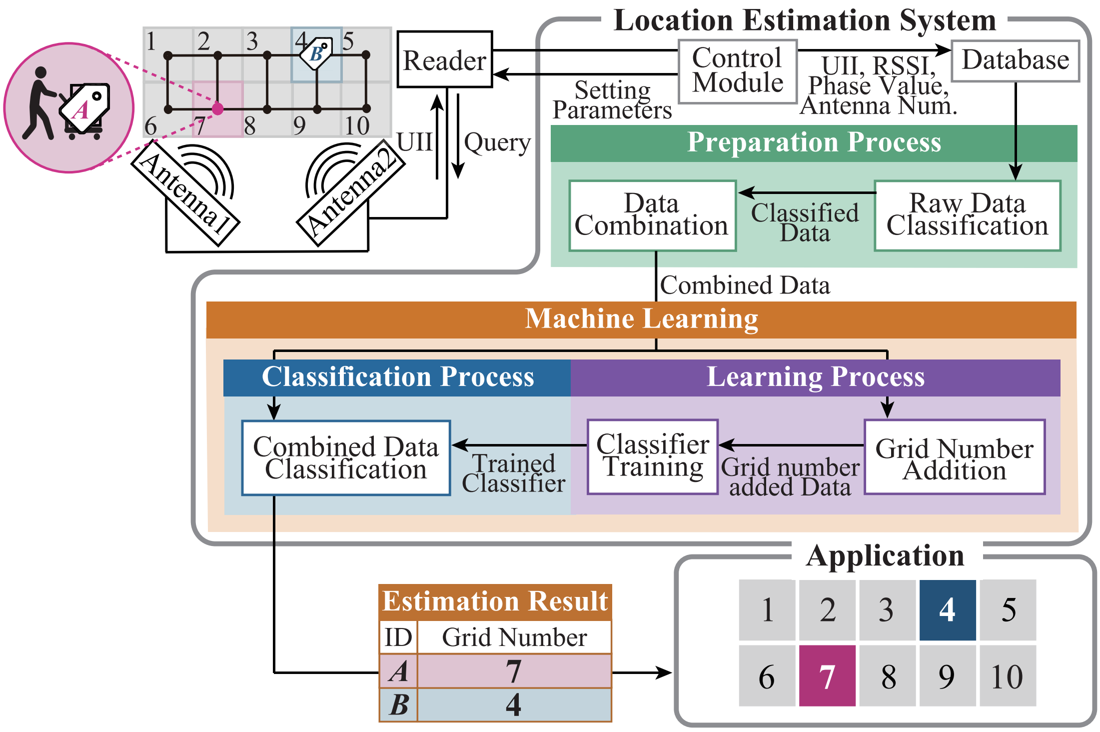

Fig. 4. System model of the location estimation system

and classification stages. During the learning process, a classifier is created using RSSI, phase values, and grid numbers as ground truth labels. The trained classifier and the RF tag's RSSI and phase values are used to estimate their locations in the classification process.

III. Evaluation

We validate the accuracy of the location estimation in the proposed system. We implemented a system prototype for this validation and conducted experiments to collect data. During the validation process, we utilize the data collected from empirical experiments to evaluate the location estimation accuracy using machine learning techniques. Finally, we assess the accuracy of the proposed method by employing a single antenna with an installation angle, aiming to minimize the required installation environment.

The experiments are conducted using the Impinj Speedway Revolution R420 RFID reader/writer and the Yeon YAP-101CP antenna. The Impinj Octane SDK ReadTags module is employed as the control module, and machine learning is implemented using the Scikit-learn Python library, a Python library for machine learning. As the default parameters of Scikit-learn functions proved to be adequate, we utilized them in our implementation.

Fig. 5 illustrates the experimental setup. In this experiment, we installed two antennas with a 30-degree inward tilt. The RF tag and antennas were set at a height of 60 cm. Additionally, we performed data collection with the RF tags rotated to capture various tag angles. Fig. 6 presents the grid configuration employed in this experiment. Considering the system's intended application in stockrooms and anti-theft gates, the estimated target area measures 2 m in length and 1 m in width. Within this area, we established 50 grids, each covering an area of 20 square centimeters. We collected 20,000 data samples at each grid. Consequently, a total of 1,000,000 data samples were obtained for the entire estimated target area.

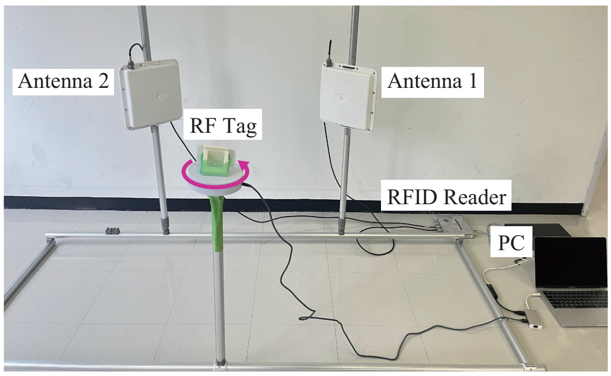

Fig. 5. Experimental environment

In this verification, we compare location estimation accuracy using multiple classification algorithms. We utilized the Random Forest (RF), Decision Tree (DT), and k-Nearest Neighbor (k-NN) algorithms as classification methods. Table I presents the estimation accuracy when using two antennas. We found that the RF algorithm enables precise and highly accurate location estimation. However, the estimation accuracy of DT and k-NN was below 90This decline in accuracy can be

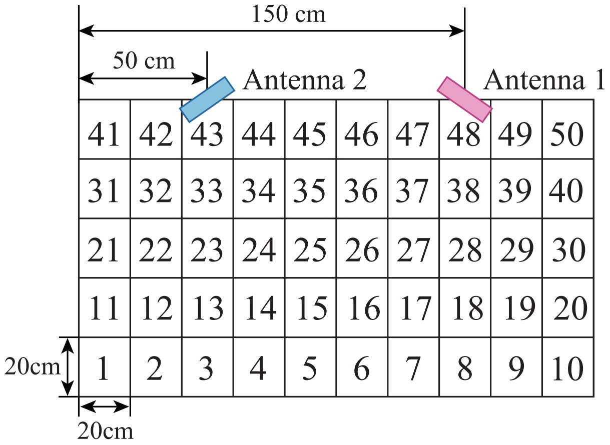

Fig. 6. Grid numbers

TABLE I
THE ESTIMATION ACCURACY OF EACH CLASSIFICATION MODEL

model \ metric	$accuracy$	$precision_M$	$recall_M$	$f1-score_M$
RF	0.9142 $\pm 0.0001\%$	0.9155 $\pm 6.6030\%$	0.9142 $\pm 9.1358\%$	0.9146 $\pm 7.7732\%$
DT	0.8723 $\pm 0.0001\%$	0.8723 $\pm 0.0001\%$	0.8723 $\pm 0.0001\%$	0.8723 $\pm 0.0001\%$
k-NN	0.8405 $\pm 0.0002\%$	0.8464 $\pm 0.0002\%$	0.8405 $\pm 0.0002\%$	0.8413 $\pm 0.0002\%$

attributed to the challenge of accurately classifying multiple grids with similar RSSI and phase values, which may arise due to tag rotation.

Table II displays the estimation accuracy of the proposed system when using a single antenna and employing the Random Forest algorithm. The accuracy achieved with a single antenna was around 60%, exhibiting a decrease of approximately 30% compared to the estimation accuracy obtained with two antennas. Dealing with the influence of the angle between the RF tag and the antenna was found to be challenging in the case of a single antenna.

IV. Conclusion

This paper has presented a scheme for estimating the position of RF tags at the grid level by utilizing the RSSI and phase values as grid features. The proposed approach leverages the distortion of the radio environment caused by the placement of antennas to enable grid-based location estimation. To address the issue of decreased estimation accuracy resulting from similarities in RSSI and phase values, we introduce angled antennas to create an asymmetric radio environment. The use of angled antennas generates a left-right asymmetric radio environment, enhancing the uniqueness of the combination of RSSI and phase values. To validate the effectiveness of the proposed method, we have developed a prototype and conducted comprehensive evaluations. Experimental results demonstrate that selecting appropriate classification algorithms can lead to high estimation accuracy, thus validating the feasibility and potential of the proposed scheme.

TABLE II
THE ESTIMATION ACCURACY OF RANDOM FOREST ALGORITHM WITH AN ANTENNA

$accuracy$	$precision_M$	$recall_M$	$f1-score_M$
0.5876 $\pm 0.0002\%$	0.6121 $\pm 0.0002\%$	0.5876 $\pm 0.0001\%$	0.5928 $\pm 0.0002\%$

Acknowledgment

The collaborative research project with Ultimatrust Co., Ltd., Japan, and AIM Japan partly supports this work.

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