The Evaluation of the Angled Antenna Based Direction Estimation Scheme for RFID Tags

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Abstract. Radio Frequency Identification (RFID) has been used to improve services such as inventory management and behavior analysis in recent industries. Since these services require tracking the movement of objects where an RFID tag is attached, the direction estimation scheme for RFID tags has been attracting attention. Conventional estimation schemes require a large space for antenna installation or assume expensive small antennas, which poses a challenge for implementation in the field. This paper evaluates the performance of the proposed direction estimation scheme for several types of RFID tags because the authors have conducted the initial evaluation. Since the proposed scheme uses an angled single antenna, it should be a valuable scheme in practical service if the proposed scheme generally works for several types of RFID tags. The proposed scheme focuses on the features of change in Received Signal Strength Indicator (RSSI) and phase value caused by an angled antenna. The evaluation result shows that the proposed scheme can estimate the direction of movement accurately for multiple types of tags.

Keywords: RFID · Direction estimation · Single antenna

1 Introduction

The usage of Radio Frequency Identification (RFID) is expanding for several services. RFID is a short-range wireless communication technology between a reader and a tag for identification [1]. In particular, RFID-based systems have been introduced in the industry to improve work efficiency and reduce labor costs. RFID-Based systems include behavior analysis, inventory management, and security systems using anti-theft gates [2,3]. In behavior analysis, RFID tags are attached to products to obtain data such as combinations of products that customers purchased and how they are moving around in a store [4,5]. By analyzing the acquired data, it is possible to make more detailed sales plans [6,7].

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RFID-based inventory management differs from conventional barcode management in that it uses wireless communication. This makes it possible to read RFID tags attached to luggage even they cannot be visually recognized. In addition, the ability to read tags in batches can be used to improve work efficiency [10]. Since these services are operated by attaching tags to luggage and commodities, they can be combined with anti-theft gates in stores. Therefore, there is no need to attach security tags as in the past. It can improve operational efficiency and reduce costs.

These RFID systems mainly use passive RFID tags. They don't require batteries or other power sources and can be used semi-permanently because they are powered by electromagnetic energy from the reader [8]. In addition, because of their low cost, they are used on the premise of being disposable and are attached to products and luggage [9]. Since it is necessary to track the movement of objects attached to passive RFID tags in behavioral analysis, inventory management, and anti-theft gates, schemes for estimating the direction of movement of RFID tags have attracted much attention [11–13].

As existing direction estimation schemes, sensor-antenna, double antennas, and gated antenna schemes have been used [14]. In the sensor-antenna scheme, the antenna is installed, and electric light sensors are put on both sides of the antenna. The system identifies RFID tags by acquiring their data using the installed antenna and estimates the direction of movement by detecting the passage of RFID tags by sensors. The sensors can detect the passage of an object but cannot identify the RFID tags. Therefore, it isn't easy to detect which tag passed in which direction when several tags passed simultaneously from different directions. The double antennas scheme places two antennas side by side and measures the time difference of reading a tag between each antenna. It requires a large space for installation due to place two antennas, which limits the installation environment. The gated antenna scheme identifies tags passing through the gate that installing multiple antennas in the tunnel-like structure. Since it uses multiple antennas, it can estimate the direction accurately. However, the use of multiple antennas and the need for materials to install them in the tunnel structure result in high installation costs and large installation space. These problems prevent the installation of RFID services based on direction estimation technology.

We have proposed a single-antenna direction estimation scheme that uses only one inexpensive general-purpose antenna. The proposed scheme solves the problems of the installation environment and installation cost of the conventional scheme due to the use of only one inexpensive antenna. The fundamental evaluation with one type of RFID tag has shown that the proposed scheme works well to detect the movement direction [15]. On the contrary, typical RFID tags have various variations according to the combination of an RFID chip and an antenna. The difference in the combination causes the difference in communication performance. Therefore, we should evaluate the performance of the proposed scheme with various types of RFID tags released in the industry. In this paper, we evaluate the feasibility of the proposed scheme by comparing the performance of each RFID tag. We prepare ten types of RFID tags for the evaluations. The evaluation result shows that the proposed scheme can estimate the movement direction accurately for several types of tags.

2 Proposed System

2.1 Overview

We proposed a new direction estimation scheme using a single general-purpose antenna. Since the proposed scheme uses only one antenna, it is difficult to estimate the tag's movement direction by using the difference of reading times as in the conventional scheme. Therefore, we use the changes of RSSI and phase values acquired during tag reading. In the proposed scheme, the antenna is installed at an angle. The installation angle causes the feature to change the RSSI and phase values with the direction of movement. The proposed scheme can estimate the tag's movement direction due to analysis and detect the feature. RFID tags contain an Electronic Product Code (EPC), and the reader identifies the tag by reading the EPC [16]. The EPC is a unique code that the tag has and serves as an identifier. When multiple tags are read, the changes in RSSI and phase values of each identified tag are analyzed to estimate the direction. Therefore, the proposed scheme can estimate the direction of each tag even in the presence of multiple tags.

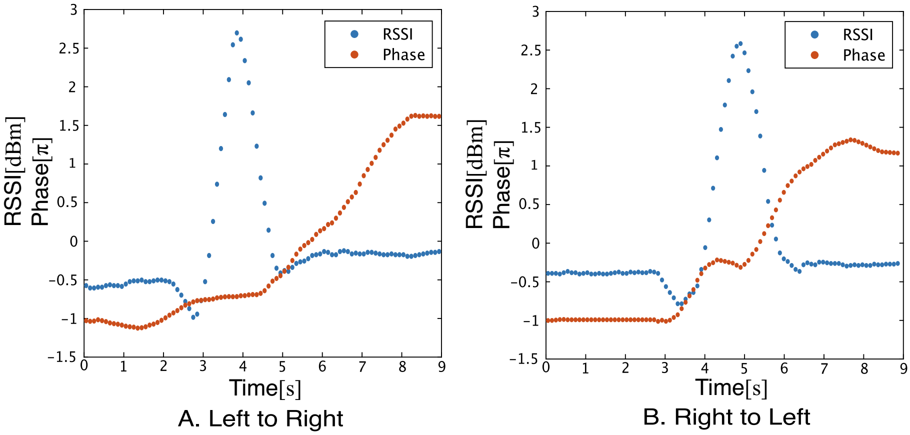

Fig. 1. Change process of RSSI and phase value in 0° antenna angle

2.2 The Installation Angle of Antenna

The conventional scheme places an antenna in parallel with the tag movement direction. Therefore, the characteristics of the RSSI and phase values are very similar when the tag passes to the right or the left. Figure 1 shows the change in RSSI and phase values when the tag moves in an arbitrary direction. The RSSI increases when the distance between the tag and the antenna gets closer. As a result, the RSSI increases and peaks in front of the antenna when the tag passes through. After reaching the peak, it decreases gradually.

Comparing the cases where the tag moves to the right and left, the process of RSSI and phase value is almost the same. Accordingly, it isn't easy to estimate the direction of the RFID tag when the antenna is installed parallel to the direction of movement. Therefore, we focus on the directivity of the antenna and install it with an angle. Figure 2 shows the change of RSSI and phase values when the antenna is installed with an angle.

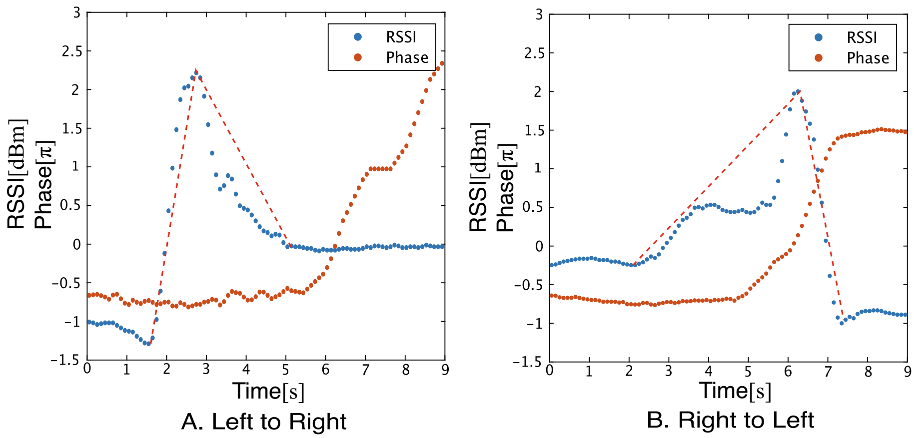

Fig. 2. Change process of RSSI and phase value in 45° antenna angle

When the antenna is angled to the right, and the tag is moved to the right direction, the RSSI increases rapidly until it reaches its peak and decreases slowly. On the contrary, the RSSI increases slowly until it reaches the peak and decreases rapidly when the tag moves to the left. In this way, the change process of RSSI before and after the peak differs according to the movement direction. The proposed scheme uses the features on the difference of change process of RSSI to estimate the direction of tag movement.

2.3 System Model

Figure 3 shows the proposed system model for the direction estimation system. Since it can control the RFID reader/writer, it requests a Query command to get the tag data from RFID tags. An RFID tag that received Query command backscatters its own data. The RFID reader/writer gets tag information such as EPC, RSSI, and phase value. The analysis module analyzes the tag information to estimate the direction of movement. Finally, the application obtains the estimation result.

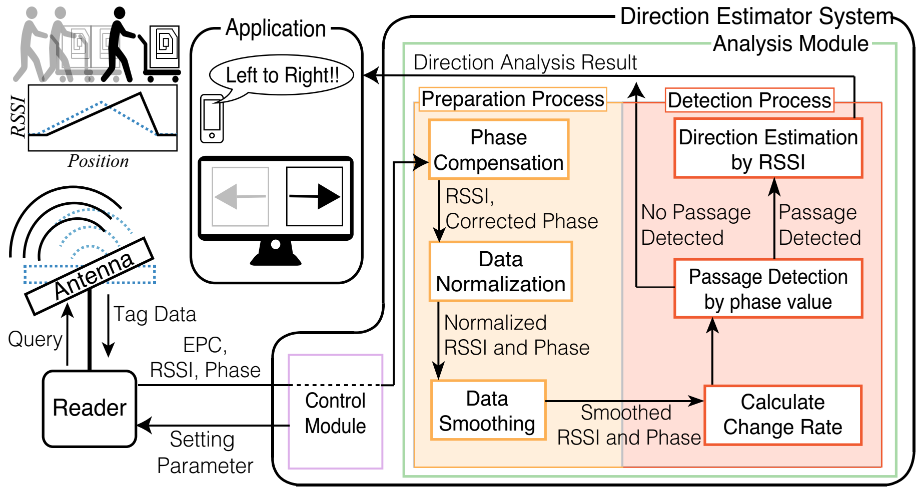

Fig. 3. System model

3 Analysis Module

3.1 Overview

The analysis module analyzes the RSSI and phase value calculated by the reader to estimate the direction of movement. The proposed algorithm for estimating the direction utilizes the features of RSSI and phase value change. The feature can be detected by using the change rate of RSSI and phase value. The processes phase compensation, data normalization, and data smoothing perform as preparation processes for feature detection. After the preparation processes, the analysis module calculates the change rate of RSSI and phase value. The change rate of phase value is used to detect tag passage. The result is sent to the application if the passage of the tag is not detected. When the tag passage is detected, the analysis module estimates the direction of tag movement and passes the result to the application.

3.2 Phase Compensation

The RFID reader/writer calculates RSSI and phase value when it receives tag information from the RFID tag. The calculated RSSI and phase value always contain some errors. In particular, the phase value often contains large errors. Figure 4 shows the phase value without and with the compensation.

Normally, the phase value will gradually increase to 1.0π, 1.1π, 1.2π, or decrease to 1.0π, 0.9π, 0.8π when the tag moves. However, the phase value calculated by the reader/writer is influenced by noise and reflected waves. The noise is caused by the thermal noise in the circuits of the reader/writer. A reflected wave occurs when a signal collides with an object or person, and it is reflected.

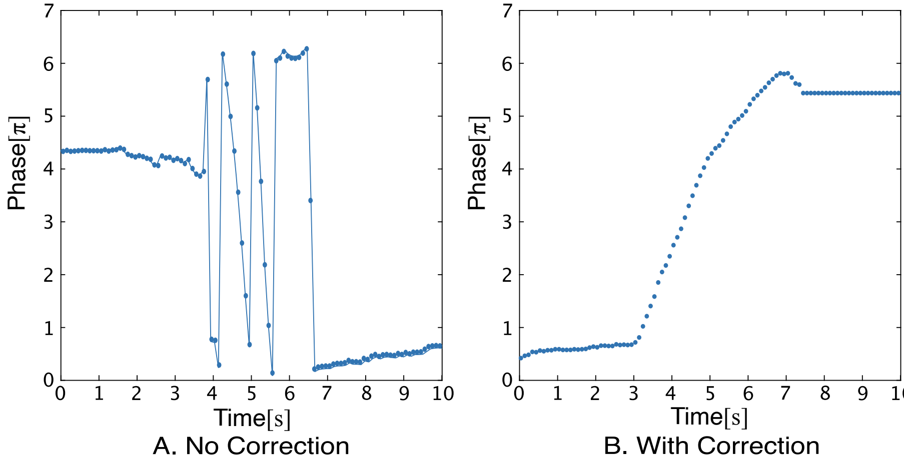

Fig. 4. Compare phase values without and with the compensation

The reflected wave travels a longer distance than the direct wave, which greatly affects the phase rotation of the high frequency. Because of these factors, the phase value may change drastically or even protrude from the previous one. Therefore, compensation processing is required to smoothing the phase value when the phase value changes dynamically.

In this paper, the phase value is corrected when the difference from the previous one is 0.5π or more. The first step in the correction process is to calculate the difference from the previous phase value. The corrected value is made by adding or subtracting the correction value to the original data. Table 1 shows the relationship between the difference from the previous phase value and the correction value.

Table 1. The difference between previous value

Difference of phase P $[\pi]$	compensation value$[\pi]$
$1.5 < P \leq 2.0$	$+1.5$
$1.0 < P \leq 1.5$	$+1.0$
$0.5 < P \leq 1.0$	$+0.5$
$-0.5 > P \geq -1.0$	-0.5
$-1.0 > P \geq -1.5$	-1.0
$-1.5 > P \geq -2.0$	-1.5

For example, the phase difference is 0.8π when the phase value fluctuates significantly, from 1.0π to 0.2π. Since the difference is greater than 0.5π and less than 1.0π, the analysis module corrects it to 0.7π by adding 0.5π to 0.2π. The correct phase value is shown in Fig. 4-B can be obtained with the compensation process.

3.3 Data Normalization

The scale of RSSI and phase value are different, and the amount of change in the values is significantly different. Therefore, the data should be normalized to facilitate the comparison of the data. With the original data as x, the mean as $\overline{x}$, and the standard deviation as s, the normalizes data x' is given in Eq. 1.

$$x' = \frac{x - \overline{x}}{s} \tag{1}$$

Figure 5 shows the data before and after normalization.

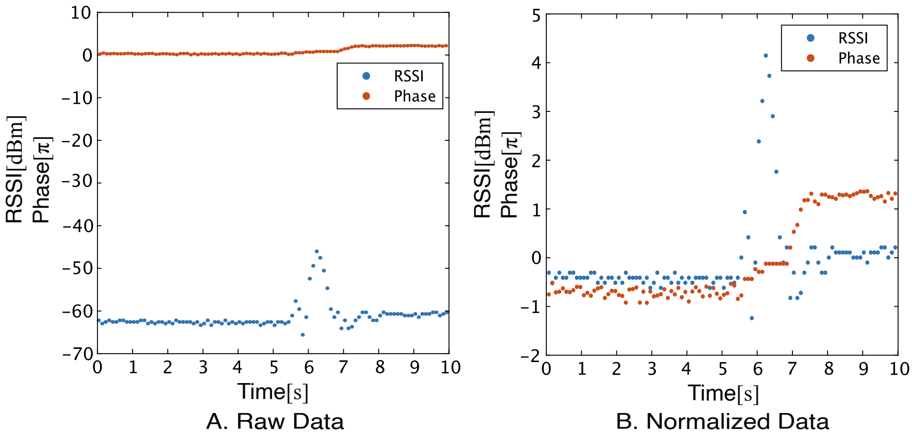

Fig. 5. The data before and after normalization

As shown in Fig. 5-A, the amount of change in the phase value before normalization is significantly different from that of RSSI. On the other hand, the data after normalization is based on the mean value, showing how far it is from that mean value. Therefore, the analysis module can compare the data with different units or when the amount of change in the original data is significantly different.

3.4 Data Smoothing

As shown in Fig. 5, there is variability in the data after normalization. The variability of the data makes it difficult to detect the feature of its change accurately. Therefore, a smoothing process is applied to facilitate feature detection. Figure 6 shows the normalized data and the smoothed data.

As shown in Fig. 6, the smoothed data is soother and with less change than the data before the smoothing process. The reduced variability of the data makes it easier to detect the characteristics of the change accurately.

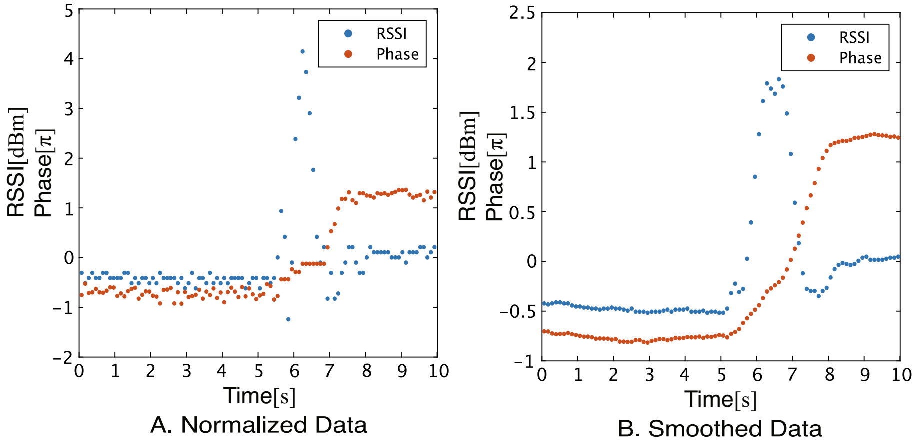

Fig. 6. The normalized data and smoothed data

3.5 Calculate the Rate of Change

The analysis module calculates the change rate of the data. The analysis module uses the change rate to detect the tag's passage and estimate the movement direction. The change rate CR_k between the kth data D_k and the j previous data D_{k-j} is given in Eq. 2.

$$CR_k = \frac{D_k - D_{k-j}}{j} \tag{2}$$

The change of data is milder when the rate of change is closer to 0. On the contrary, the data change is more rapid when the change rate is farther from 0.

3.6 Passage Detection by Phase

As shown in Fig. 6, the phase value changes when a tag passes in front of the antenna. In the proposed scheme, the change of phase value is used to detect the passage of the tag. In the case of the tag passing through, there is a difference between the value at the beginning and the end of the phase value change. In contrast, the value at the beginning and the end are almost equal when a tag doesn't pass. Therefore, it is possible to detect the passage of a tag by comparing the phase values at the beginning and end of the change.

3.7 Estimating the Direction of Movement by RSSI

Since the proposed system uses an angled antenna, RSSI dynamics' change rate differs depending on RFID tag movements' direction. Figure 7 shows the RSSI when the tag moves to the right and left. Figure 8 shows the rate of change when the tag moves in each direction. When the tag moves to the right, the

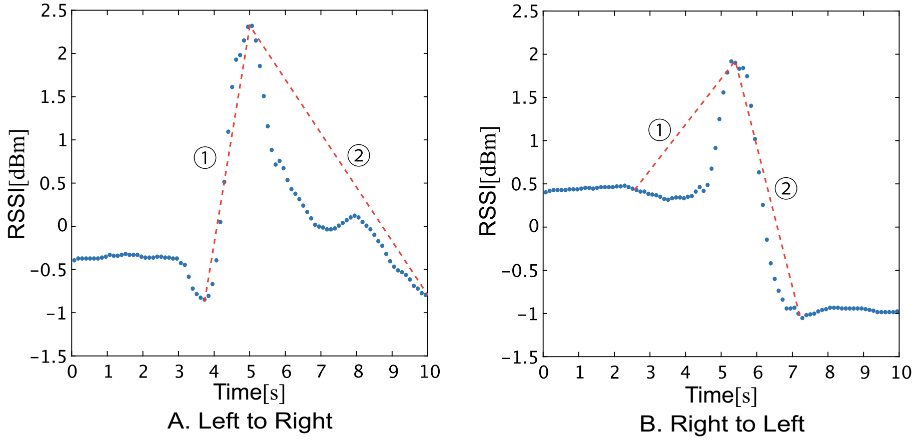

Fig. 7. The feature of change of RSSI

RSSI increases rapidly until the peak and decreases slowly. The rate of change is high when RSSI changes rapidly. On the other hand, the rate of change is low when RSSI changes slowly. In Fig. 7-A, the inclination of redline 1 is large, and that of redline 2 is small. Therefore, comparing the peaks of the rate of change in Fig. 8-A, it can be seen that the absolute value of the maximum is greater than that of the minimum (e.g., 0.35 for the maximum and 0.19 for the minimum). In contrast, when the tag moves to the left, the RSSI increases slowly until the peak decreases rapidly. Consequently, the absolute value of the minimum rate of change is greater than that of the maximum, as shown in Fig. 8-B. The proposed system focuses on the phenomenon to estimate the movement direction according to RSSI dynamics.

4 Implementation

We have implemented the prototype of the proposed system. The experiment uses an angled antenna called YAP-101CP from Yeon for Speedway Revolution R420 from Impinj as the RFID reader/writer. We also used the Impinj Octane SDK as the control module for the reader/writer and Visual Studio for Mac to implement the analysis module. The simple moving average method is used as the smoothing method in the analysis module. J in Eq. 2 was set to 1 for calculating the rate of change.

The phase value and the change rate after the compensation process are used to detect the passage of the RFID tag. It detects the passage of a tag by comparing the value at the start and end of the phase value change. Figure 9 shows the phase value and change rate of it.

The moment that the rate of change exceeds the threshold k is the starting point of change. The rate of change always has both positive and negative peaks. Therefore, if the negative peak is reached first when the value becomes less than

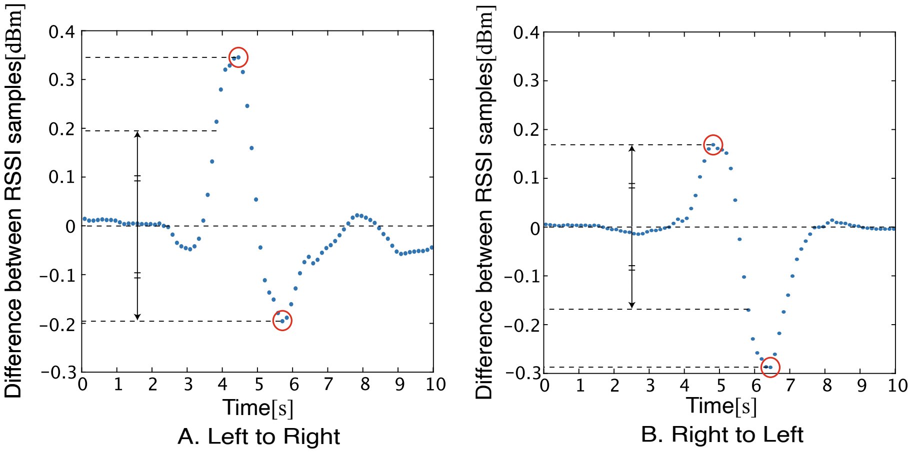

Fig. 8. The change rate of RSSI

zero for the first time after the positive peak is set as the endpoint. On the contrary, if the positive peak is reached first when the value becomes equal to or greater than zero for the first time after reaching the negative peak is set as the endpoint. The analysis module compares each phase value after detecting the start and endpoints. When the difference of the phase value is greater than or equal to the threshold L, the analysis module judges that the tag has passed. In this paper, we use $k = 0.03$, $L = 0.5$ for the evaluation.

The analysis module can estimate the direction of movement by comparing the absolute values of the maximum and minimum RSSI change rates. It detects the maximum and minimum values of the acquired RSSI data and calculates the absolute value. In this paper, since the antenna is angled to the right, the analysis module judges that the tag moved to the right when the absolute value of the maximum is larger. On the contrary, when the absolute value of the minimum value is larger, it is judged the tag moved to the left.

5 Evaluation

This paper evaluates the accuracy of the direction estimation according to the change of the installation angle, the moving speed of the RFID tag, and the type of tags. Figure 10 shows the RFID tags that we used. These tags are different in vendor, shape, and size. Different antenna shapes and sizes are expected to cause different features such as RSSI and phase value change. These differences are considered to affect the accuracy of direction estimation. Therefore, this evaluation clears the performance of the proposed system with different types of RFID tags.

The antenna angles changes from 10°, 20°, 30°, 45°, 60°, 70° and 80°. The RFID tag moves with a speed of 1 m/s or 2 m/s on a straight line of 0.5 m away

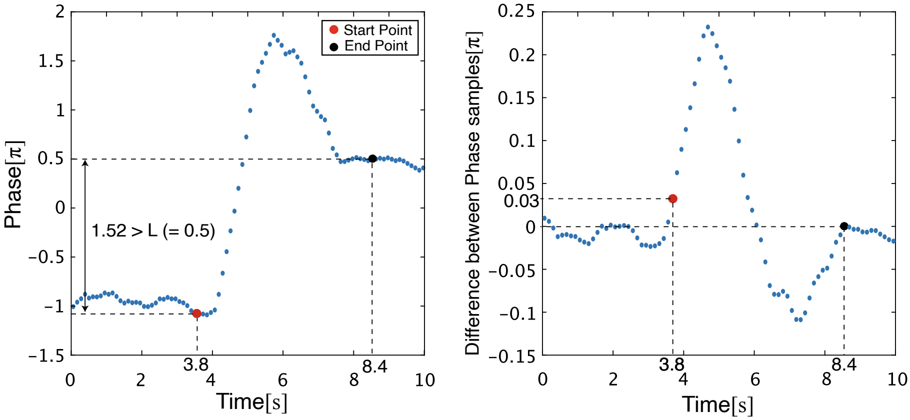

Fig. 9. Phase value and change rate

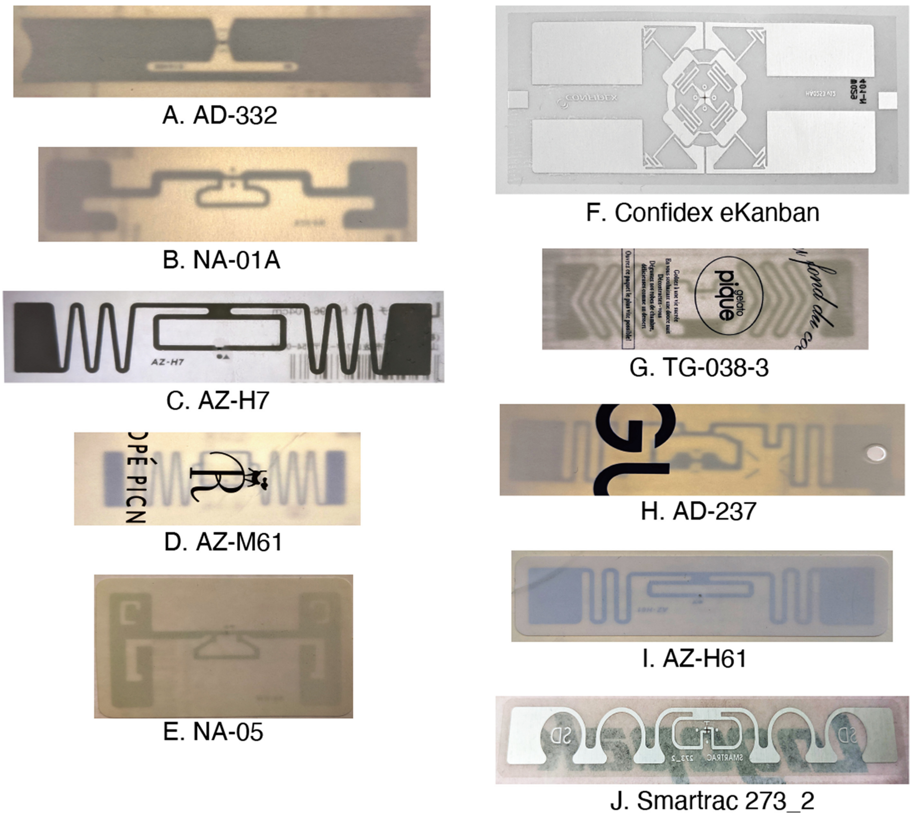

Fig. 10. The type of tags used

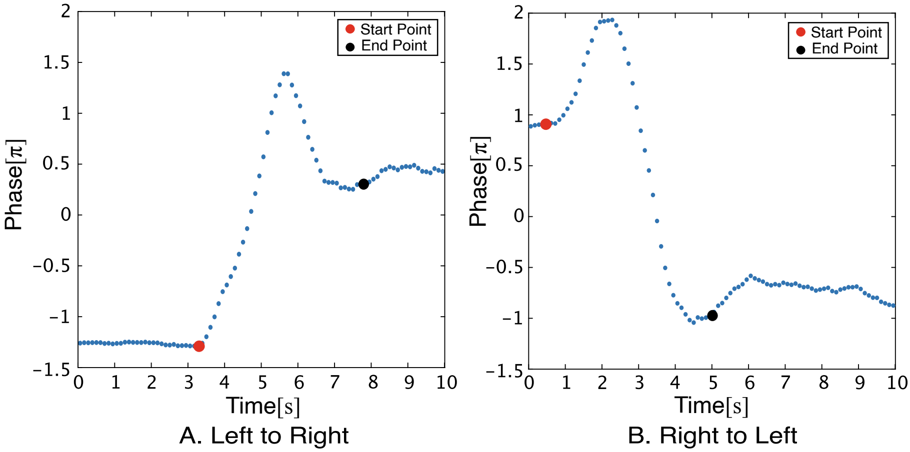

Fig. 11. The result of detecting the start and end point of phase change

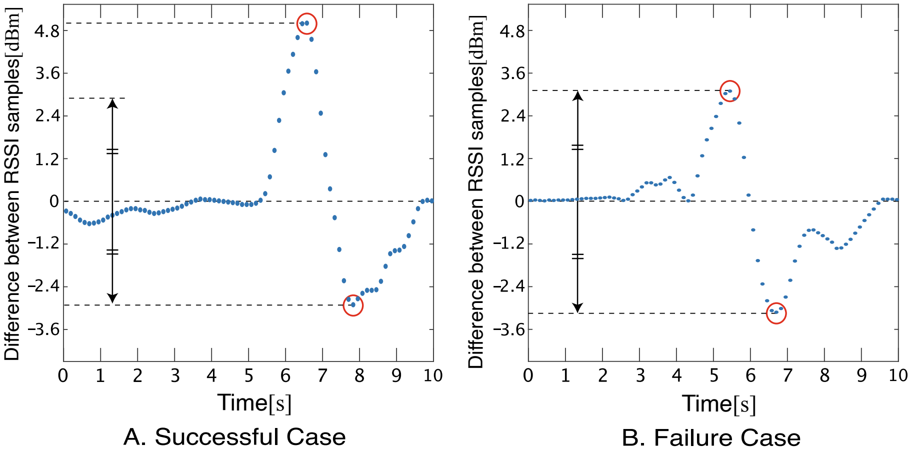

Fig. 12. Experimental successful and failure case

from the antenna and is the same height as the antenna's center. Under each condition, ten different tags are passed through 30 times.

Figure 11 shows the result of detecting the start and endpoints of the phase value change. From Fig. 11, we can see that the start and endpoints of change are detected almost accurately. Figure 12 shows the change rate of RSSI for successful and failure cases of direction estimation. In the success case, we can find that the maximum's absolute value is greater than the minimum. Therefore, the system estimated the accurate direction to the right. In the failure case, the absolute values of the maximum and the minimum are almost the same. As a result, the estimation process does not work well.

Table 2. The accuracy of direction estimation

	Speed \ Angle	10°	20°	30°	45°	60°	70°	80°
A	1 m/s	83%	87%	93%	96%	90%	100%	100%
	2 m/s	80%	90%	90%	97%	100%	100%	100%
B	Speed \ Angle	10°	20°	30°	45°	60°	70°	80°
	1 m/s	80%	90%	90%	97%	100%	97%	100%
	2 m/s	80%	90%	97%	90%	93%	100%	100%
C	Speed \ Angle	10°	20°	30°	45°	60°	70°	80°
	1 m/s	83%	87%	90%	97%	97%	100%	100%
	2 m/s	83%	83%	93%	97%	97%	97%	97%
D	Speed \ Angle	10°	20°	30°	45°	60°	70°	80°
	1 m/s	80%	80%	87%	93%	100%	100%	97%
	2 m/s	83%	80%	90%	100%	93%	100%	93%
E	Speed \ Angle	10°	20°	30°	45°	60°	70°	80°
	1m/s	83%	87%	87%	93%	93%	97%	93%
	2 m/s	80%	87%	83%	90%	93%	90%	93%
F	Speed \ Angle	10°	20°	30°	45°	60°	70°	80°
	1 m/s	87%	97%	90%	93%	100%	100%	97%
	2 m/s	83%	97%	93%	87%	100%	100%	100%
G	Speed \ Angle	10°	20°	30°	45°	60°	70°	80°
	1 m/s	83%	93%	90%	97%	93%	100%	100%
	2 m/s	83%	87%	83%	90%	87%	100%	100%
H	Speed \ Angle	10°	20°	30°	45°	60°	70°	80°
	1 m/s	97%	100%	100%	100%	100%	97%	100%
	2 m/s	83%	90%	93%	100%	97%	100%	93%
I	Speed \ Angle	10°	20°	30°	45°	60°	70°	80°
	1 m/s	90%	87%	90%	97%	97%	100%	97%
	2 m/s	83%	90%	83%	93%	90%	90%	97%
J	Speed \ Angle	10°	20°	30°	45°	60°	70°	80°
	1 m/s	93%	93%	93%	97%	100%	93%	100%
	2 m/s	87%	90%	93%	93%	97%	93%	97%

Table 2 shows the estimation accuracy with a different installation angle of the antenna, difference speed, and different types of RFID tags. The result shows that the estimation accuracy is more than 80% in all tags. Additionally, the accuracy tends to be better when the angle is larger for most of the tags. This result is that detecting the feature is more difficult when the antenna angle is smaller.

When the installation angle is small, the difference between the absolute values of the maximum and the minimum of RSSI change rate is smaller than when the angle is large. Therefore, it is considered that false detection is more likely to occur. As the speed of RFID tags, the slower speed is better to estimate the direction accurately. The RSSI changes slowly before or after the peak when the tag passes in front of the antenna. If the change in RSSI is gradual, the change rate is low. The tag moves faster, the RSSI changes dynamically, and so the rate changes larger. Therefore, when the moving speed is high, the RSSI, which originally changes slowly, changes relatively rapidly. Since the change rate of the RSSI fluctuates greatly as the moving speed increases, the difference between the absolute values of the minimum and maximum becomes smaller. This makes it difficult to detect the characteristics of RSSI changes accurately, which is likely to lead to false detection of the direction of movement.

6 Conclusion

This paper has evaluated the accuracy of the proposed scheme. Since the RSSI and the phase value have special characteristics according to the movement directions, the proposed system can estimate the movement direction of RFID tags with an angled antenna. We have implemented the prototype of the proposed system and evaluated the accuracy of direction estimation. The evaluation result shows that the proposed system can estimate the direction with more than 80% accuracy for the ten types of tags.

Additionally, we can find the trend that the accuracy is higher when the antenna angle is larger. The result also shows that the estimation accuracy tends to be better when the speed of the RFID tag is slower. The future challenge is to improve the estimation accuracy by modifying the method of calculating the rate of change and making it possible to detect the changing features of RSSI and phase value more accurately. It is also necessary to evaluate how the accuracy changes when multiple tags are passed simultaneously.

References

1. Li, C., Lao, K., Tam, K.: A flooding warning system based on RFID tag array for energy facility. In: 2018 IEEE International Conference on RFID Technology Application (RFID-TA), pp. 1–4 (2018). https://doi.org/10.1109/RFID-TA.2018.8552767
2. Zhang, Y., Xie, L., Bu, Y., Wang, Y., Wu, J. and Lu, S.: 3-dimensional localization via RFID tag array. In: 2017 IEEE 14th International Conference on Mobile Ad Hoc and Sensor Systems (MASS), pp. 353–361 (2017). https://doi.org/10.1109/MASS.2017.22
3. Liu, Z., Wang, M., Qi, S., Yang, C.: Study on the anti-theft technology of museum cultural relics based on Internet of Things. IEEE Access **7**, 111387–111395 (2019). https://doi.org/10.1109/ACCESS.2019.2933236
4. Han, J., et al.: CBID: a customer behavior identification system using passive tags. IEEE/ACM Trans. Netw. **24**(5), 2885–2898 (2016). https://doi.org/10.1109/TNET.2015.2501103

5. Landmark, A.D., Sjøbakk, B.: Tracking customer behaviour in fashion retail using RFID—emerald insight. Int. J. Retail Distrib. Manage. **45**(7), 844–858 (2017). https://doi.org/10.1108/IJRDM-10-2016-0174
6. Pradel, B., et al.: A case study in a recommender system based on purchase data. In: Proceedings of the 17th ACM SIGKDD International Conference on Knowledge Discovery and Data Mining, KDD 2011, New York, NY, USA, pp. 377–385. Association for Computing Machinery (2011). https://doi.org/10.1145/2020408.2020470
7. Vijayakumar, V., Neelanarayanan, V. (eds.): Proceedings of the 3rd International Symposium on Big Data and Cloud Computing Challenges (ISBCC–2016). SIST, vol. 49. Springer, Cham (2016). https://doi.org/10.1007/978-3-319-30348-2
8. Finkenzeller, K.: RFID Handbook: Fundamentals and Applications in Contactless Smart Cards, Radio Frequency Identification and Near-Field Communication, 3rd edn. Wiley, New York (2010)
9. Inc., H.I.: Radio Frequency Identification (RFID) Frequently Asked Questions (2016)
10. Anssens, C., Rolland, N., Rolland, P.: A sensornetwork based on RFID inventory for retail application. In: 2011 IEEE International Conference on RFID-Technologies and Applications, pp. 64–67 (2011). https://doi.org/10.1109/RFID-TA.2011.6068617
11. Jie, W., Minghua, Z., Bo, X., Wei, H.: RFID based motion direction estimation in gate systems. In: 2018 IEEE 22nd International Conference on Computer Supported Cooperative Work in Design (CSCWD), pp. 588–593 (2018). https://doi.org/10.1109/CSCWD.2018.8465374
12. Buffi, A., D'Andrea, W., Lazzerini, B., Nepa, P.: UHF-RFID smart gate Tag action classifier by artificial neural networks. In: 2017 IEEE International Conference on RFID Technology Application (RFID-TA), pp. 45–50 (2017). https://doi.org/10.1109/RFID-TA.2017.8098900
13. Alvarez-Narciandi, G., Motroni, A., Pino, M.R., Buffi, A., Nepa, P.: A UHF-RFID gate control system based on a Convolutional Neural Network. In: 2019 IEEE International Conference on RFID Technology and Applications (RFID-TA), pp. 353–356 (2019). https://doi.org/10.1109/RFID-TA.2019.8892080
14. Oikawa, Y.: Tag movement direction estimation methods in an RFID gate system. In: 2009 6th International Symposium on Wireless Communication Systems, pp. 41–45 (2009). https://doi.org/10.1109/ISWCS.2009.5285228
15. Mizuno, K., Naito, K., Ehara, M.: Direction estimation scheme for RFID tag with an angled single antenna. In: IEEE International Conference on Radio Frequency Identification (RFID 2021), vol. 1(1), pp. 1–2 (2021)
16. Jechlitschek, C.: A survey paper on Radio Frequency Identification (RFID) trends (2010)