Indoor Positioning System Utilizing Mobile Device with Built-in Wireless Communication Module and Sensor

March 2016

Masaaki Yamamoto

Indoor Positioning System Utilizing Mobile Device with Built-in Wireless Communication Module and Sensor

by

Masaaki Yamamoto

A dissertation submitted in partial satisfaction of

the requirements for the degree of

Doctor of Philosophy

in

Engineering

Graduate School of Science and Technology

Keio University, Yagami

Committee in charge:

Professor Tomoaki Ohtsuki, Chair

Professor Iwao Sasase

Professor Hiroshi Shigeno

Professor Yukitoshi Sanada

March 2016

Indoor Positioning System Utilizing Mobile Device with Built-in Wireless Communication Module and Sensor

by

Masaaki Yamamoto

Abstract

Indoor Positioning System Utilizing Mobile Device with Built-in Wireless Communication Module and Sensor

by

Masaaki Yamamoto

Doctor of Philosophy in Engineering

Keio University, Yagami

Professor Tomoaki Ohtsuki, Chair

Global positioning system (GPS) is utilized in a number of applications such as navigation service, since mobile phones and smartphones built-in a GPS receiver have been widely spread. However, GPS is difficult to determine the position of the receiver in an indoor environment. Some examples of applications in an indoor environment, a navigation service in a large-scale shopping mall and an employee-location-management service at a factory are desired. This dissertation focuses on an indoor positioning system utilizing a mobile device with a built-in long range wireless communication module (WLAN (wireless local area network), RFID (radio frequency identification)) and sensor for a large-scale indoor environment.

In Chapter 1, we present the motivations and objectives of this dissertation. We also present requirements for the indoor positioning system to realize the above mentioned applications.

In Chapter 2, the related work in the indoor positioning system is described. Then, issues for applying the indoor positioning system to these services are clarified. Regarding the navigation service, a low cost and high accuracy positioning system is desired. To achieve the high accuracy positioning with low cost, a novel WLAN positioning system is described in Chapter 3 and Chapter 4. Regarding the employee-

location-management service at factory, a main issue of applying a positioning system is cost to construct it. A general positioning system requires installation of many base stations. To resolve this problem, a novel RFID positioning system is proposed in Chapter 5.

In Chapter 3 and Chapter 4, to achieve accurate WLAN positioning using a smartphone in the case of sparse AP (access point) deployment in an indoor environment, a positioning method is proposed. The unexpected power absorption by the user causes the positioning error. Therefore, the proposed method utilizes a novel model of a power absorption by a user at dual frequency bands (i.e. 2.4 GHz and 5.2 GHz). The directivity of the power absorption is measured using a magnetic sensor built into the smartphone. The proposed method is realized to provide accurate positioning using the smartphone in the case of sparse AP deployment.

In Chapter 5, to construct the RFID positioning system without settlement of the base stations, the passive tag is set up instead of the base station in working area. A novel RFID mobile phone held by the worker receives a signal containing the identification data of the passive tag, when the worker stays in the working area. Then, the RFID mobile phone as a virtual base station transmits a signal. Consequently, the proposed RFID positioning system achieves to construct without settlement of the base station.

In Chapter 6, we conclude this dissertation and discuss future work.

To my family

Contents

List of Figures

List of Tables

Acknowledgments

First and foremost, I would like to show my greatest gratitude to Prof. Tomoaki Ohtsuki, my supervisor, for his generous support of my Ph.D. study and encouragement. Without his guidance and persistent help of this dissertation would not have materialized.

Besides my advisor, I would like to thank the rest of my dissertation committee: Prof. Iwao Sasase, Prof. Hiroshi Shigeno, Prof. Yukitoshi Sanada, for their insightful comments and hard questions to improve the quality of this dissertation. I would like to thank of Ohtsuki Lab. Members for all the help. My sincere thanks also go to Dr. Jihoon Hong, for his guidance writing this dissertation. I am extremely grateful to Chihiro Tamba, Yohei Shibata, and Yusuke Hino, who willingly participate in this study and provided invaluable data.

I would like to express my appreciation to KLL (Keio Leading Edge Laboratory), for offering a research grant to conduct several experiments. This research was partially supported by the Ministry of Internal Affairs and Communications in Japan, the project name is "Research and Development of Ubiquitous Platform Technologies (Ubiquitous Terminal Technology)".

Lastly, I am extremely obliged to my parents whose sacrifices and love. Special thanks to my beloved wife, Hiromi, for her great support, encouragement, and patience with me especially during a final stages of this Ph.D.

Chapter 1

Introduction

GPS (Global Positioning System [1]) is utilized in a number of applications such as a navigation service, since mobile phones and smartphones built-in a GPS receiver have been widely spread. A household penetration rate at the end of 2013 was 94.8% for the mobile phone and a PHS (Personal Handy-phone System), and that for smartphones was 62.6 % (up 52.9 % points from 3 years earlier) in Japan [2].

The GPS receiver built into the smartphones receives signals from many satellites in an outdoor environment. Hence, the GPS receiver calculates a position of itself. An application of the smartphones visualizes a route from the position to a destination on a digital map. A positioning error of GPS is about 5-10m that depends on a surrounding environment [3] [4].

To utilize a remote control vehicles such as tractors for an agriculture and dumps of a mine, an accurate positioning system is developed. Example of the accurate positioning system is known as RTK-GPS (Real Time Kinematic-GPS) [5] and QZSS (Quasi-Zenith Satellite System) [6].

However, GPS is difficult to determine the position of the receiver in an indoor environments, because a roof and walls block the transmitted signals from satellites in a building. A user of the navigation service may walk both outdoor and indoor environments. An indoor positioning system is therefore desired. In particular, the navigation service using the system in a large-scale shopping mall and an employee location management service using the system in a large-scale factory are desired. This dissertation focuses on the indoor positioning system for a large-scale indoor environment.

1.1 Motivations and Objectives

The indoor positioning system for a large-scale indoor environment is developed using a long range wireless communication system. The long range wireless communication systems for indoor positioning are WLAN (Wireless Local Area Network [7]) system and RFID (Radio Frequency Identification [8]).

The indoor positioning system using WLAN (hereafter "WLAN positioning system") estimates the position of a node held by a user. The node specifically receives signals from many APs (Access Points) and measures RSS (Received Signal Strength) of these signals. The WLAN positioning system estimates the position on the basis of the measured RSS.

In the WLAN positioning system, the APs are deployed sparsely, because a maximum communication distance between the AP and the node is 20m or more. Hence, the WLAN positioning system has an advantage to construct the WLAN positioning system with low cost in a large-scale indoor environment.

The WLAN positioning system using the fingerprint-based method [9] requires "radio map", which is a set of previously measured RSS of a radio map data at each coordinate in the indoor environment. Then, the system compares the radio map with the measured RSS at the user's position, and estimates the user's position. Measuring the radio map in the indoor environment is troublesome.

To resolve the problem, the model-based method [10] for WLAN positioning system is proposed. The model-based method does not require the measured radio map. The model-based method substitutes a simulated radio map for the measured one. However, an accurate simulation of the radio map is difficult because of a power absorption by a user and a multipath fading which is attributed to reflection of microwaves from walls and a floor. The power absorption by the user and the multipath fading causes a fluctuation of RSS. Thus, the positioning error of the model-based method is larger than that of the fingerprint-based method [10, 11].

To overcome those problems, in this dissertation, the WLAN positioning system using a novel model-based method is developed for the navigation service in a large-scale indoor environment. The model-based method utilizes a proposed model of the power absorption by the user and the magnetic sensor to estimate the power absorption and compensate it.

Due to development of the system, requirements of the system for the navigation service is listed in Table 1.1. According to the table, one of the requirements is already explained, that is no need of the radio map. In addition, to offer the navigation service to unspecified number of users, the system requires utilizing a device that user owns. The user's smartphone with the WLAN device is therefore adopted as the node in the proposed WLAN positioning system. The detail of the proposed WLAN positioning system using the novel model-based method is discussed in Chapter 3 and Chapter 4.

Furthermore, an indoor positioning system for the employee-location-management service in a large-scale factory is developed. Due to development of the system, requirements of the system for the employee-location-management service are listed in Table 1.2. According to the table, the system that does not interfere with the existing wireless communication systems (e.g. WLAN, Bluetooth) in a factory is required. The interference causes to drop the throughput of existing wireless communication systems [12].

Moreover, to estimate the position of a worker at all time, the system is required that the worker can carry unconsciously the node. The node is namely put in the chest pocket. The third requirement is same as that for the navigation service in a large-scale shopping mall that does not need measuring radio map. Because a layout of working areas is frequently changed in factory. In particular, in the case of manufacturing a little and various kinds of products in factory, the layout is changed every few hours. RSS of the radio map must be measured again when the layout is changed. The re-measurement is very troublesome.

Table 1.1 Requirements of the WLAN positioning system for a navigation service.

	Requirements
1	No need of measuring RSS at each coordinate in a large-scale indoor environment to make the radio map
2	Utilizing a device that user owns(e.g. smartphone)

Table 1.2 Requirements of the indoor positioning system for an employee-location-management service.

	Requirements
1	The system does not interfere with the existing wireless communication systems (e.g. WLAN, Bluetooth) in a factory.
2	The worker can carry unconsciously the node that is namely put in the chest pocket.
3	No need of measuring RSS at each coordinate in a large-scale indoor environment to make the radio map

A RFID positioning system using UHF band (about 950MHz) satisfies three requirements for the employee-location-management service. In the RFID positioning system, an active tag transmits a signal to base stations on UHF band. On the other hand, the existing wireless communication system (e.g. WLAN, Bluetooth) transmits the signal on 2.4 GHz (ISM: Industry-Science-Medical band) and 5.2 GHz. Hence, the RFID positioning system does not interfere with the WLAN and Bluetooth in a factory. Moreover, the active tag is able to be put in the chest pocket of worker's wear. In addition, when the RFID positioning system does not use the fingerprint-based method, it does not need measuring radio map. Other methods for positioning are known as a proximity detection and the model-based method and so on. A detail of these methods are explained in Chapter 2.

In the RFID positioning system, since an installation of many base stations is required, it is troublesome. To resolve such a problem, a novel RFID positioning system for the employee-location-management service is developed that enables to estimate the working area of workers. In particular, the passive tag is set up instead of the base station in the working area. The passive-tag reader held by the worker receives a signal containing the identification data of the passive tag. Moreover, the passive-tag reader transmits the identification data as the base station. The proposed system is able to be constructed without settlement of the base station. The detail of the proposed RFID positioning system is discussed in Chapter 5.

1.2 Applications Using Indoor Positioning System

Applications using indoor positioning system in a large-scale indoor environment are listed in Table 1.3. As listed in the table, the navigation service and the employee-location-management service are desired. The navigation service offers a route from a current position of consumers to a destination in a large-scale shopping mall, train station and airport. When the consumer visits a large-scale shopping mall at first time, the consumer utilizing the navigation service can quickly grasp the current position and the route.

In addition, the employee-location-management service offers the information of workers' position to a manager in a large-scale factory, warehouse and power plant. To optimize the number of workers at each working area, the manager transfers workers to other working area on the basis of the current workers' position and a progress of a manufacturing process. The optimal transferring of the workers is able to accelerate the progress of the manufacturing process.

Table 1.3 Applications using indoor positioning system.

	Applications	Contents	Environments
1	Navigation service	Offering a route from a current position of consumers to a destination to unspecified number of users	Shopping mall, train station, airport, and so on
2	Employee-location -management service	Offering an information of the current worker's position to optimize the number of workers at each working area.	Factory, warehouse, and so on

1.3 Contributions

This dissertation has contributions in the WLAN positioning system and the RFID positioning system. Regarding the WLAN positioning system, this dissertation has two major contributions; first contribution is a power-absorption-based model for power compensation using smartphone. To offer the navigation service in a large-scale shopping mall to unspecified number of users, the user's smartphone is therefore adopted as the node in WLAN positioning system. In this system, the user absorbs the power of the signal from AP [13]. The power absorption by the user causes the fluctuation of RSS. The unexpected fluctuation of RSS increases the positioning error. To remove the fluctuation of RSS attributed to the user, a conventional method for positioning [33], which utilizes RFID badges, in an outdoor environment estimates the power absorbed by the user and compensates it. It then estimates the user's position. The RFID badge is attached to the user's chest. To estimate the power absorption by the user, 28 anchor nodes are deployed in a square area measuring 6.4 m by 6.4 m. Sparser deployment of the anchor nodes, however, increases the estimation error of the power absorbed by the user; estimation error of the user's position thereby increases.

Therefore, to estimate an accurate position of the smartphone, a power-absorption-based model using smartphone is proposed. The parameters of the model are estimated using a maximum-likelihood estimation (MLE), and the directivity of the power absorption is measured using a magnetic sensor built into the smartphone. The proposed method compensates the power absorption and the influence of multipath fading. According to experimental evaluations, the root-mean-square error (RMSE) of the proposed method is 34 % lower than that of the conventional one. The distance between APs is 6 m. Namely, RMSE of the proposed method is 1.94 m in a room.

Second contribution is the WLAN positioning system utilizing RSS at the dual frequency bands to improve an accuracy of positioning by using the model-based method. From a practical perspective, a sparser AP deployment is expected. The positioning error increases when APs are deployed sparsely. The positioning error in WLAN positioning system using power-absorption-based model for single frequency band increases, when RSS of user's position is extremely lower than that of near fields (hereafter "deep fade").

Therefore, a WLAN positioning system for sparse AP deployment in an indoor environment is proposed to reduce the positioning error attributed to the deep fade. A method for the proposed system utilizes RSS at dual frequency bands (i.e. 2.4 GHz and 5.2 GHz) and the power-absorption-based model for dual frequency bands. According to the evaluation, RMSE of the conventional method was 2.56 m to 2.90 m. That of the proposed method was 2.11 m. It is therefore concluded from these results that the proposed method can provide accurate positioning in the case of sparse AP deployment (the distance between two APs is 9 m.) in an indoor environment.

Regarding the RFID positioning system, the major contribution of this dissertation is the RFID positioning system using the mobile phone with built-in active tag and passive-tag reader. To offer the employee-location-management service in a large-scale factory, many base stations must be installed in the conventional RFID positioning system [4]. Therefore, it is troublesome wiring the LAN (Local Area Network) and a power supply for many base stations.

To resolve such a problem, a novel RFID positioning system for the employee-location-management service is proposed. Specifically, in the proposed system, the passive tag is set up instead of the base station in the working area. The passive-tag reader held by the worker receives a signal containing the identification data of the passive tag. Moreover, the passive-tag reader transmits the identification data as the base station. To realize the proposed system, a small-sized RFID (24 mm × 57 mm × 4 mm) module inserted into the mobile phone is developed. The RFID module has functions of the passive-tag reader, the active tag and base station. According to evaluation in a factory, the proposed system is able to be constructed without settlement of the base station. Moreover, it is able to estimate the worker's position within the working area (20 m by 20 m) size.

To summarize, this dissertation has contributions in the WLAN positioning system and the RFID positing system. The problems of existing approaches and main contributions of this dissertation are summarized in Table 1.4. The publications from this work are also listed in Appendix.

Table 1.4 Problems of existing researches and main contributions of this dissertation.

Chapter 3	Topic	Power-absorption-based model in WLAN positioning system using smartphone
	Problems of existing approach [33]	To remove the fluctuation of RSS attributed to the user, a conventional method for positioning [33], which utilizes RFID badges, in an outdoor environment estimates the power absorbed by the user and compensates it. It then estimates the user's position. Sparse deployment of the anchor nodes increases the estimation error of the power absorbed by the user; estimation error of the user's position thereby increases.
	Proposed method	The proposed method is based on a model of power absorption by a user. The parameters of the model are estimated using a maximum-likelihood estimation (MLE), and the directivity of the power absorption is measured using a magnetic sensor built into the

		smartphone. The proposed method compensates the power absorption and the influence of multipath fading.
	Effect of proposed method	The root-mean-square error (RMSE) of the proposed method is 34% lower than that of the conventional one. Namely, RMSE of the proposed method is 1.94 m in a room.
Chapter 4	Topic	WLAN positioning system utilizing RSS at dual frequency bands
	Problems of existing approach [41]	WLAN positioning system using power-absorption-based model [41] can provide accurate positioning in the case of sparse AP deployment (the distance between APs is 6 m). However, from a practical perspective, a sparser AP deployment is expected. The positioning error increases when APs are deployed sparsely. The positioning error increases particularly, when RSS of user's position is extremely lower than that of near fields (hereafter "deep fade").
	Proposed system	A WLAN positioning system for sparse AP deployment in an indoor environment is proposed to reduce the positioning error attributed to the deep fade. A method for the proposed system utilizes RSS at dual frequency bands (i.e. 2.4 GHz and 5.2 GHz) and the power-absorption-based model.
	Effect of proposed system	RMSE of the conventional method is 2.56 m to 2.90 m. That of the proposed method was 2.11 m. Consequently, the proposed method can provide accurate positioning in

		the case of sparse AP deployment (the distance between two APs is 9 m).
Chapter 5	Topic	RFID positioning system using mobile phone built-in UHF active tag and passive-tag reader
	Problems of existing approach	The conventional RFID positioning system [4] requires installation of many base stations. Therefore, it is troublesome wiring the LAN and a power supply for many base stations.
	Proposed system	The passive tag is set up instead of the base station in the working area. The passive-tag reader held by the worker receives a signal containing the identification data of the passive tag. Furthermore, the passive-tag reader transmits the identification data as the base station. To realize the proposed system, a small-sized RFID (24 mm × 57 mm × 4 mm) module inserted into the mobile phone is developed. The RFID module had functions of the passive-tag reader, the active tag and base station.
	Effect of proposed method	The proposed system is able to be constructed without settlement of the base station. Moreover, it is able to estimate the worker’s position within the working area (20 m by 20 m) size.
Chapter 6	Conclusion	Key finding and future work

1.4 Outline of Dissertation

This dissertation consists of six chapters. The outline of this dissertation is summarized in Fig. 1.1.

In Chapter 2, the related work (e.g. WLAN positioning system, RFID positioning system, UWB (ultra-wideband) positioning system) is described. In addition, fundamental positioning methods are explained.

In Chapter 3 and Chapter 4, to realize the navigation service in a large-scale shopping mall, train station, airport and so on, a novel WLAN positioning system utilizing a model-based method is proposed. A power-absorption-based model for the WLAN positioning system using smartphone is described in Chapter 3. The Chapter 4 proposes the WLAN positioning system utilizing RSS at the dual frequency bands to improve the positioning accuracy of the system.

In Chapter 5 presents the RFID positioning system using the mobile phone with built-in UHF active tag and passive-tag reader to realize the employee-location-management service in a large-scale factory.

Finally, this dissertation concludes with key findings and future works in Chapter 6.

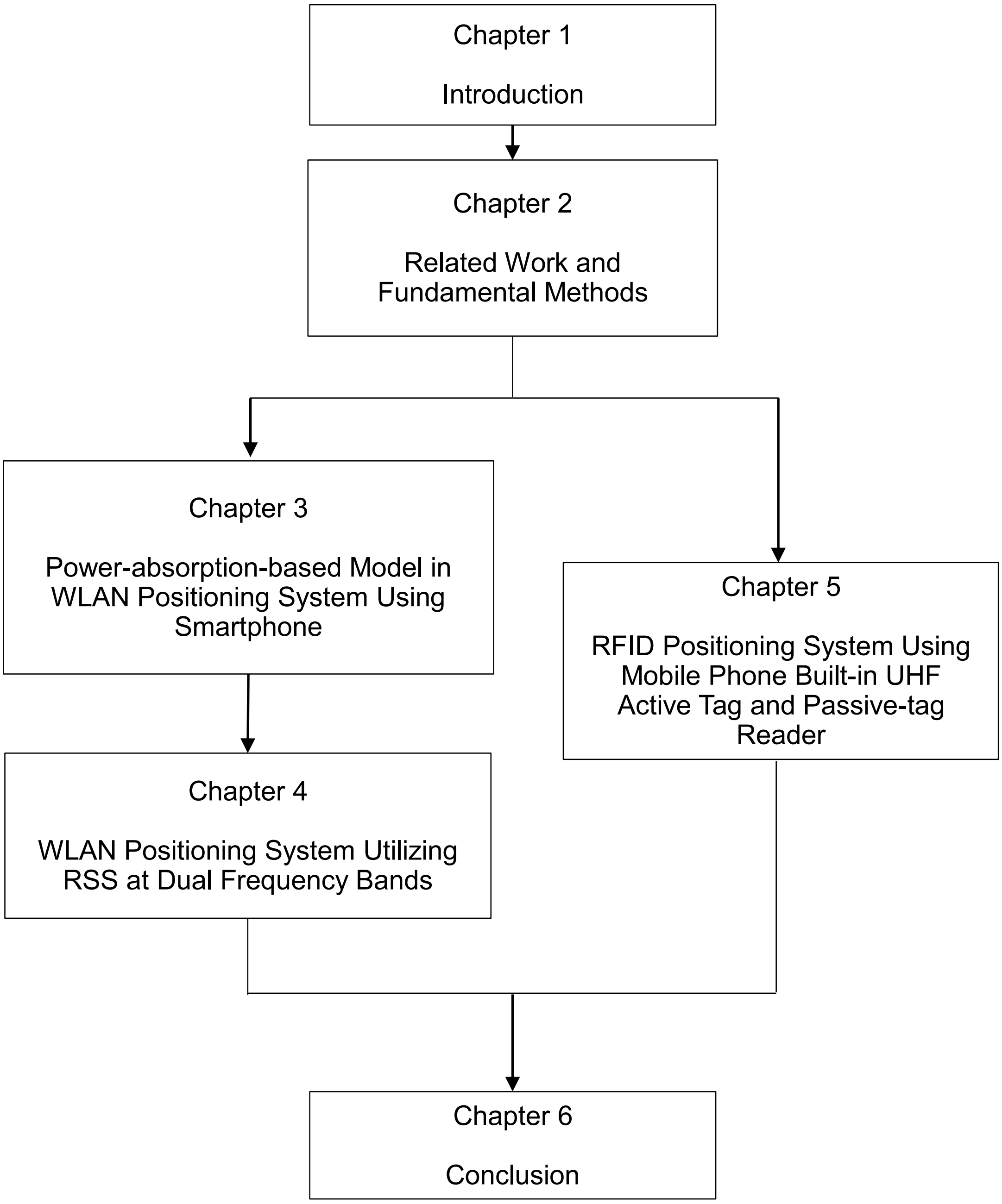

Figure 1.1 Outline of the dissertation.

Chapter 2

Related Work and Fundamental Method

In this chapter, the related work for the indoor positioning system is described to study the feasibility focused services in this dissertation. In addition, fundamental method for the indoor positioning system is presented.

2.1 Related Work

To study the feasibility focused services in this dissertation, several indoor positioning systems are discussed. These positioning systems are as follows: WLAN positioning system, Bluetooth positioning system, RFID positioning system, UWB positioning system, Ultrasound positioning system, the Visible-light positioning system and Magnetics positioning system. Then, the issue for applying these positioning systems to the navigation service and the employee-location-management service are clarified.

2.1.1. Ultra-Wideband (UWB) Radio

An UWB positioning system realizes high accurate positioning. The positioning error of the UWB positioning system in an ideal environment is 0.15m [14]. In a multipath fading environment, the positioning error of the UWB positioning system is about 0.7 m to 1.5 m [15]. The UWB positioning system is useful, when an application using the system must realize an accurate positioning. However, The UWB positioning system has to deploy densely the APs. A distance between APs is about 2 m.

The method for positioning is either TOA (Time of Arrival) method or TDOA (Time Difference of Arrival) method. TOA method must be synchronized between user's device and AP. TDOA method must be synchronized between any two APs. To synchronize APs, APs need to be connected using either wiring LAN or wireless communication system.

Hence, the issue for applying the UWB positioning system to the navigation service and the employee-location-management service is a cost to construct the UWB positioning system. In addition, to offer the navigation service to unspecified number of users, the system requires to utilize a device that user owns. Providing a UWB tag to the unspecified number of users is difficult for the navigation service.

2.1.2. Ultrasound (US)

An Ultrasound (US) positioning system utilizes TOA method to estimate the position. The positioning accuracy of the US positioning system is similar to that of the UWB positioning system. The positioning error of the US positioning is specifically 0.02 m in NLOS (non-light-of-sight) environment [16].

The standard microphone in smartphones can support 200 Hz to 20 kHz. On the other hand, our ear is less sensitive to the high frequency (15 kHz to 20 kHz) signal. The US positioning system using a smartphone is thereby proposed [17]. The user only installs the software to control the microphone in a smartphone. It does not need an additional device.

To achieve high accurate positioning, the US positioning system must deploy APs densely in NLOS environments. The distance between APs is about 2 m [16]. Consequently, the issue of the applying the US positioning system to the navigation service and the employee-location-management service is a cost to construct the system.

2.1.3. Visible Light (VL)

A Visible Light (VL) positioning system is composed of several LEDs (Light emission diode) and a control board and light sensor. The control board modulates the visible light using BFSK (binary frequency shift keying). The light sensor demodulates the received signal, and measures RSS. Then, the VL positioning system estimates the position of the light sensor on the basis of RSS. The positioning error of the VL positioning system [18] is 0.4 m in the NLOS environment. A distance between LEDs is about 3 m to 8 m.

The VL positioning system utilizes the existing LED on ceiling. The cost of constructing the VL positioning system is lower than that of constructing the other positioning systems (e.g. the UWB positioning system and the US positioning system). On the other hand, the user holding the smartphone with attached light sensor must help to rotate the smartphone to LED in the NLOS environment. The user's assist in this system is troublesome.

Consequently, the main issue for applying the VL positioning system to the navigation service and the employee-location-management service is need to be assisted by the user.

2.1.4. Wireless Local Area Network (WLAN)

A WLAN positioning system estimates the position of a node using RSS. The user's smartphone with a WLAN device is adopted as the node. Regarding a method for positioning, the fingerprint-based method and the model-based method is proposed.

The positioning error of the WLAN positioning system using the fingerprint-based method is about 2.2 m to 3.1 m [9, 10]. That of the WLAN positioning system using the model-based method is 2.9 m to 4.3 m [10, 11]. A distance between APs is about 4 m to 18 m. Therefore, the issue for applying the WLAN positioning system to the navigation service in a large-scale shopping mall is positioning error. In addition, regarding the fingerprint-based method, measuring RSS at each position in a large-scale shopping mall is troublesome to make the radio map.

The issue for applying the WLAN positioning system to the employee-location-management service in a factory is a possibility of the interference. The interference causes to drop the throughput of existing wireless communication systems (e.g. WLAN, Bluetooth) in a factory.

2.1.5. Bluetooth (BT)

A Bluetooth (BT) positioning system is almost same as the WLAN positioning system: the position of the node is estimated by using the fingerprint-based method and the model-based method, the user's smartphone with the BT device is adopted as the node. The positioning error of a conventional BT positioning system [19] is

2.31 m. The positioning error of other BT positioning system [20] is 3.76 m. A distance between APs is about 4 m to 12 m.

Hence, the issues for applying the BT positioning system to the navigation service and the employee-location-management service is same as that of WLAN positioning system: the issue of the WLAN positioning system in the navigation service is positioning error, the issue of the WLAN positioning system in the employee-location-management service is a possibility of the interference with the existing wireless communication systems.

2.1.6. Radio Frequency Identification (RFID)

An RFID positioning system consists of an active tag and several base stations (or called active-tag reader). These base stations received the signal from the active tag carried by a user. Then the RFID positioning system estimates the position of the user on the basis of RSS. The positioning error of conventional RFID positioning systems [21, 22, 23] is 2.4 m to 3.3 m. The distance between base stations is 3.6 m to 8 m.

Therefore, the issue for applying the RFID positioning system to the navigation service in a large-scale shopping mall is positioning error. In addition, to offer the navigation service to unspecified number of users, the system is required to utilize a device which the user owns. Providing the active tag to the unspecified number of users is difficult for the navigation service.

2.1.7. Magnetics (MG)

A Magnetic value differs at each coordinate in an indoor environment. The MG

(Magnetics) positioning system thereby utilizes the fingerprint-based method. A method for the MG positioning system requires “magnetic sensor map”, which is a set of previously measured values of a magnetics-sensor data at each coordinate in an indoor environment. The magnetics sensor built into the smartphone is held by a user. The MG positioning system estimates the position of user’s smartphone using RSS. Thus, the MG positioning system does not require the installation of APs.

The positioning error of the MG positioning system is 4.7 m [24]. To improve the positioning accuracy, mixing the WLAN positioning system and MG positioning system is proposed [25].

The issue for applying the MG positioning system to the navigation service is thereby the positioning error. In addition, the issue for applying the MG positioning system to the navigation service and the employee-location-management service is that the system requires the magnetic sensor map. Measuring the magnetic sensor map is troublesome.

2.2 Fundamental Methods

Fundamental methods for indoor positioning system are presented. Three methods, the proximity detection, the fingerprint-based method and the model-based method, are mainly used for indoor positioning system on the basis of the long-range wireless communication system such as WLAN system and RFID system. Other methods (TOA, TDOA) are briefly described.

2.2.1. Proximity Detection

Proximity detection estimates an approximate position of the node on the basis of strongest RSS. The proximity detection is shown in Fig. 2.1. According to the figure, the node receives signals from many APs, and measures the RSS. The signal (S_1) of the strongest RSS is collected. Then, the position of node is determined as a coordinate of AP_1 that transmits the signal S_1.

The signal of the strongest RSS is transmitted from the closest AP to the node in an ideal environment, such as a free space path-loss. The free space path-loss excludes the fluctuation of RSS related to the multipath fading. In the multipath fading environment, the signal of the strongest RSS is not always the signal from the closest AP to the node. The positioning error in the ideal environment is thereby smaller than that in multipath fading environment.

The proximity detection does not need the radio map. Accordingly, the proximity detection is effective to reduce the construction cost of the indoor positioning system.

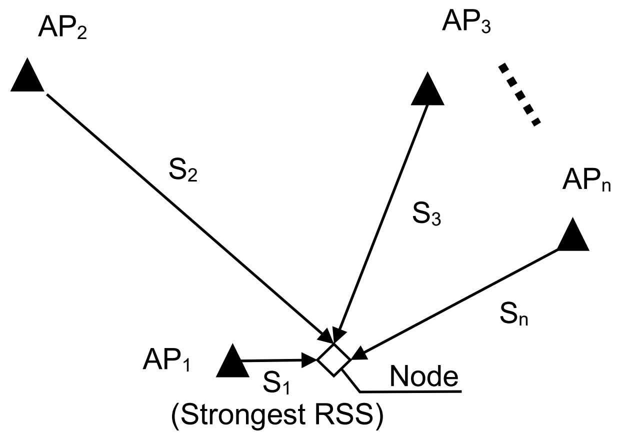

Figure 2.1 Proximity detection.

2.2.2. Fingerprint-based Method

A fingerprint-based method has an offline phase and an online phase for positioning. In offline phase, the node is set at anchor points (shown in Fig. 2.2) and measures RSS. A radio map is a set of measured RSS at each anchor point inside a room. During the online phase, the node held by user measures RSS. The observed signal is compared with the stored radio map for each of the anchor points. The position of the anchor point whose radio map most similarly matches with that of observation is determined as a user's position.

The main advantage is no need of the modeling the propagation environment. In addition, the fingerprint-based method does not require the data of the APs coordinate. On the other hand, when the propagation environment is changed, the radio map must be trained again. Measuring the radio map is troublesome. Moreover, the positioning system using this method must notice the change of the propagation environment.

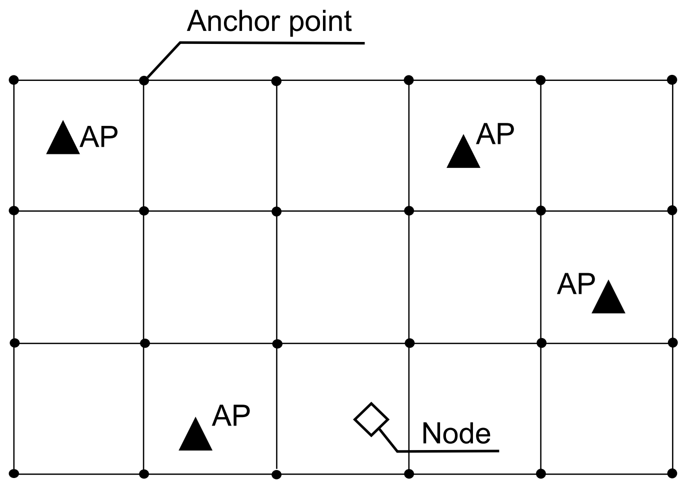

Figure 2.2 Fingerprint-based method.

2.2.3. Model-based Method

A model-based method does not require measuring the radio map. Instead, the model-based method simulates the radio map using a model related to the propagation environment. RSS is calculated using a conventional model [26] as

$$P(d) = P_0 - 10\mu \, log_{10} \frac{d}{d_0} + X \tag{2.1}$$

where $P(d)$ is RSS, P_0 is the signal strength at distance d_0 from AP, μ is the rate related to the path-loss, d is a distance between the anchor point and AP, and X represents the fluctuation of RSS attributed to the multipath fading. P_0, μ and X are determined according to the experiment.

Then, the radio map ($RSS_{ES}(n, \delta)$) is a set of calculated RSS at each anchor point (δ) inside a room. N is defined as the number of APs. In the online phase, the node receives signal from APs, and measures RSS ($RS_{ME}(n)$). $RSS_{ME}(n)$ is then subtracted from $RSS_{ES}(n, \delta)$ estimated at each coordinate (δ). δ that gives maximum $1/\left|RSS_{ES}(n, \delta) - RSS_{ME}(n)\right|$ is determined and denoted as a δ_{ML}, which is taken as the position of the node and given as

$$\delta_{ML} = \arg\max_{\delta} \sum_{n=1}^{N} \frac{1}{\left|RSS_{ES}(n, \delta) - RSS_{ME}(n)\right|} \tag{2.2}$$

2.2.4. Other Methods

TOA (time of arrival) method is shown in Fig. 2.3. According to the figure, the intersection of circles is defined as the position of the node. The radius of circles is defined as a distance between the node and AP. The distance is calculated on the basis of the time of arrival. To calculate the distance, a synchronization between user's device and AP is required in TOA method. To estimate the position in two-dimension, minimum number of APs is three.

TDOA (time difference of arrival) method estimates the position of the node using the time difference of arrival. To calculate the time difference of arrival, a synchronization between each APs is required in TDOA method.

AOA (angle of arrival) method estimates the position of the node using an angle of arrival. To measure the angle of arrival the node has to equip with a directional array antenna. A minimum number of APs in two-dimension is two.

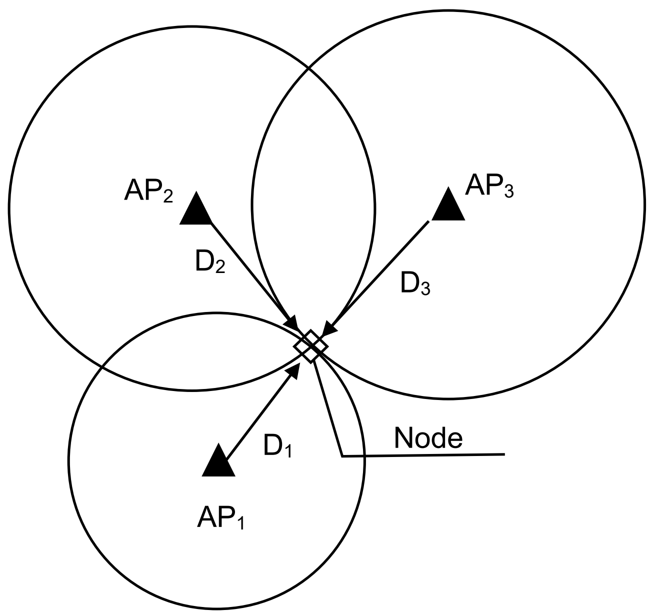

Figure 2.3 TOA method.

2.3 Conclusion

In this chapter, the issue for applying several positioning systems to the navigation service and the employee-location-management service are clarified. Applicable indoor positioning systems for the navigation service in a large-scale shopping mall are listed in Table 2.1. As listed in the table, the WLAN (or Bluetooth) positioning system using model-based method and the Ultrasound (US) positioning system satisfy the requirements for the navigation service. These systems can be applied to the navigation service.

Furthermore, a low cost and high accuracy positioning system is desired in the navigation service. The main factor of the cost is defined as a density of APs. Other factors of the cost such as training are included in the requirements (Table 2.1). The positioning accuracy versus density of APs is shown in Fig. 2.4. According to the figure, the positioning error of the US positioning system is less than 2 m. Deployment of APs in the US positioning system is dense. A distance between APs is about 2 m. On the other hand, the distance between APs of the WLAN (or Bluetooth) positioning system using model-based method is about 4 m to 18 m. However, the positioning error of the WLAN (or Bluetooth) positioning system is larger than that of the US positioning system.

To achieve the high accuracy positioning and sparse AP deployment, this dissertation focuses on the WLAN positioning system using model-based method. Then, a novel WLAN positioning system using model-based method is proposed. The detail is described in Chapter 3 and Chapter 4.

Table 2.1 Applicable indoor positioning system for the navigation service.

#	Requirements	UWB [14, 15]	US [17]	VL [18]	WLAN, BT [9, 10, 11, 19, 20]		RFID [21-23]	MG [24]
					Finger -print	Model		
1	No need of training (e.g. radio map)	Yes	Yes	Yes	No	Yes	Yes	No
2	Utilizing a device that user owns (e.g. smartphone)	No	Yes	No	Yes	Yes	No	Yes

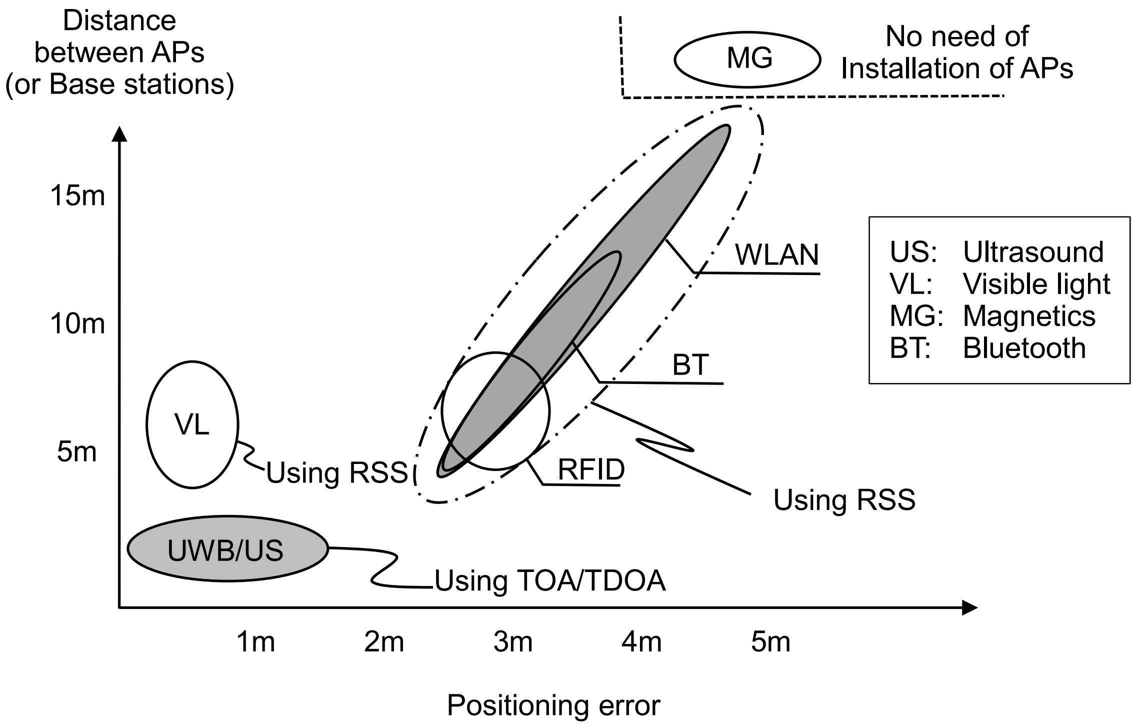

Figure 2.4 Outline of indoor positioning systems.

Applicable indoor positioning systems for the employee-location-management service in a large-scale factory are listed in Table 2.2. As listed in the table, RFID, UWB and US positioning systems satisfy the requirements for the employee-location-management service.

To optimize the number of workers at each working area in the service, a working area size (e.g. 20 m) of positioning accuracy is required. In addition, the distance between base stations of the RFID positioning system is longer than that of UWB and US positioning systems. Therefore, the RFID positioning system is focused in this dissertation. The detail is described in Chapter 5.

Table 2.2 Applicable indoor positioning system for the employee-location-management service.

#	Requirements	UWB [14, 15]	US [17]	VL [18]	WLAN, BT [9, 10, 11, 19, 20]		RFID [21-23]	MG [24]
					Finger-print	Model		
1	The system does not interfere with the existing wireless communication systems (e.g. WLAN, Bluetooth) in a factory.	Yes	Yes	Yes	No	No	Yes	Yes

2	The worker can carry unconsciously the node that is namely put in the chest pocket.	Yes	Yes	No	Yes	Yes	Yes	Yes
3	No need of training (e.g. radio map)	Yes	Yes	Yes	No	Yes	Yes	No

Chapter 3

Power-absorption-based Model in WLAN Positioning System Using Smartphone

3.1 Introduction

A WLAN (Wireless Local Area Network) positioning system utilizing a smartphone to provide a navigation service in places like a large-scale shopping malls and train stations is attracting considerable attention [27]. Given this background, many methods for the WLAN positioning system using a smartphone and WLAN infrastructure have been proposed [9, 11, 26, 28, 29, 30, 31]. Applying these methods, the smartphone receives signals transmitted from many access points (APs) in WLAN. It then measures received signal strength (RSS) and estimates its position on the basis of the RSS.

A key issue concerning the WLAN positioning system is that any unexpected fluctuation in RSS increases estimation error. The fluctuation of RSS is mainly caused by the three factors shown schematically in Fig. 3.1. The first factor is so-called "multipath fading" which is attributed to reflection of microwaves from walls and the floor. The second factor is pedestrians that temporarily block the microwave signals from certain APs to the smartphone. The third factor is the user holding the smartphone, who is always blocking the microwave signals from certain APs to the smartphone [32]. Fluctuation of RSS attributed to the multipath fading and pedestrians can be reduced by using average RSS [10].

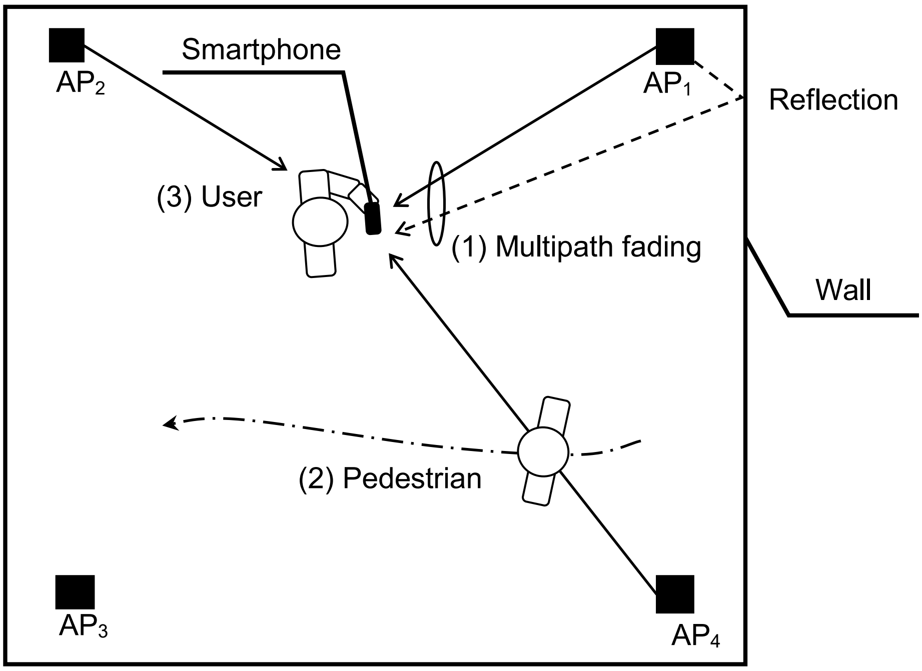

Figure 3.1 Main factors concerning fluctuation of RSS in WLAN positioning system.

To remove the fluctuation of RSS attributed to the user, a conventional method for positioning [33], which utilizes RFID badges, in an outdoor environment estimates the power absorbed by the user and compensates it. It then estimates the user's position. The RFID badge is attached to the user's chest. To estimate the power absorption by the user, 28 anchor nodes were deployed in a square area measuring 6.4 m by 6.4 m in an outdoor environment [33]. The anchor nodes receive signals transmitted from the RFID badge. They then measure RSS. The power absorbed by the user is estimated on the basis of maximum-likelihood estimation (MLE) by using a model of the power absorption by the user. The model is designed based on a simple cosine function.

A sparser deployment of the anchor nodes, however, increases the estimation error of the power absorbed by the user; estimation error of the user's position thereby increases too. For example, when 28 anchor nodes were deployed in a square area measuring 6.4 m by 6.4 m, estimation error is 0.87 m. When 4 anchor nodes are deployed in the same area, estimation error is 3.36 m [33].

Regarding WLAN positioning in an indoor environment, deployment of many APs is limited, because the installation of many APs is troublesome. Namely, APs are required to be installed in many places. APs must be connected to the power-supply unit, which is generally mounted on a wall. It is therefore necessary to achieve accurate positioning even if deployment of APs is sparse.

Accordingly, the purpose of the current study is to achieve accurate WLAN positioning using a smartphone in the case of sparse AP deployment in an indoor environment. The accuracy of positioning is measured by means of a root-mean-square error (RMSE). The target of this study is to achieve a smaller RMSE than the conventional RFID-based method [33]. Moreover, the target is set to achieve almost same RMSE as the conventional fingerprint-based methods [9] [10] for positioning in an indoor environment. RMSE of the conventional fingerprint-based methods is 2 m to 3 m, when the distance between two APs is 6 m to 9 m. The target is specifically set to be RMSE of less than 2.5 m.

In this Chapter, a directivity and the influence of multipath fading on the power absorbed by a user are clarified experimentally (Section 3.2). Then, a general model of the power absorbed by a user is proposed on the basis of the experimental results

(Section 3.3). The power absorbed by the user is estimated by using the model and the magnetic sensor built into smartphones. In conventional methods [34, 35], the magnetic sensor is used to measure a pedestrian's heading based on PDR (Pedestrian Dead Reckoning). A conventional method [24] requires "magnetic sensor map", which is a set of previously measured values of a magnetic-sensor data at each coordinate inside a room. Then, the method compares the magnetic sensor map with the reading of the magnetic sensor at the pedestrian's position, and estimates the pedestrian's heading and positioning. In our study, to estimate the directivity of the power absorption by the user, the magnetic sensor is utilized, too. A method for estimating the position of the smartphone is then proposed (Section 3.4) [36]. To evaluate the effectiveness of the proposed position-estimation method, RMSE of the proposed method is evaluated by indoor testing and compared with that of the conventional method. To clarify the influence of pedestrians in the proposed method, RMSE is evaluated when pedestrians walk around the room (Section 3.5).

3.2 Power Absorption by User

To clarify the directivity of the power absorption by a user, RSS at a smartphone held by hand in an anechoic chamber is measured. The anechoic chamber is equipped with many microwave absorbers that reduce reflections of microwaves on the walls and floor. The measurement environment is shown schematically in Fig. 3.2. The distance from the smartphone to an AP is 1 m.

RSS for all angles (φ) between 180 and −180 degrees, where φ is the angle between a line connecting the smartphone and the AP (chained line in Fig. 3.2) and a line perpendicular to the smartphone (dashed line in Fig. 3.2), is measured. The interval of the angle φ is 30 degrees. RSS is averaged by using 60 samples. Three different kinds of smartphone are used in the RSS measurement. To measure RSS, a self-developed application is used. The application runs on Android operating system. The measurement frequency of AP is 2.412GHz. Average RSS for all angles is assumed to be 0 dB as a standard value.

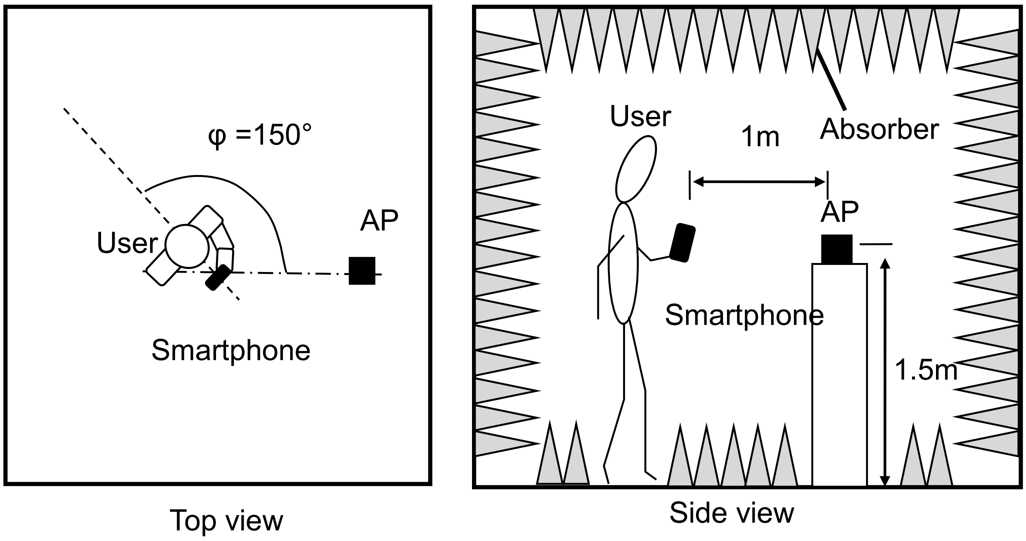

Figure 3.2 Experimental environment used for measuring power absorption by a user in an anechoic chamber.

Measured RSS when the smartphone is held in the left hand is plotted in Fig. 3.3, and that when it is held in the right hand is plotted in Fig. 3.4. According to these figures, maximum amplitude (α) of the power absorption by the user is 20 dB to 23 dB.

When the smartphone is held in the left hand, φ for minimum RSS was 30 degrees. In contrast, when it is held in the right hand, φ for minimum RSS is −30 degrees. Hence, the angle for maximum power absorption by the user depends on the state in which the phone is held (hereafter, “smartphone-holding state”) and varies between 30 and −30 degrees. The variation is denoted as angular offset $\varphi_{\mathrm{offset}}$.

The “angular range (θ)” of the standard power absorption (0 dB) is 150 degrees when the smartphone is held in the left hand. The corresponding θ is 120 degrees when it is held in the right hand. Hence, θ depends on the smartphone-holding state.

The above-described results clarify that the directivity of the power absorption by the user in the case where the smartphone is held in the left hand (hereafter, “left-case”) and that in the case where the smartphone is held in the right hand (hereafter, “right-case”) have asymmetric shape. One of the possible reasons is that a directivity of WLAN antenna built into the smartphone is asymmetric [37] [38].

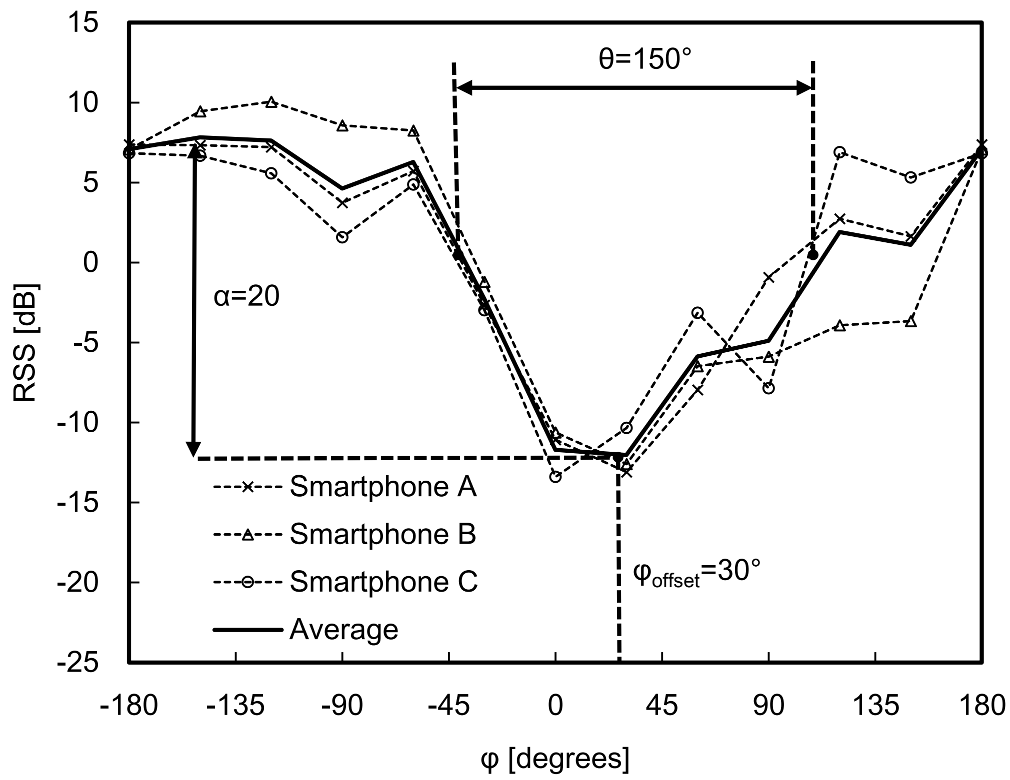

Figure 3.3 Directivity of power absorption by a user when a smartphone is held in the left hand in an anechoic chamber.

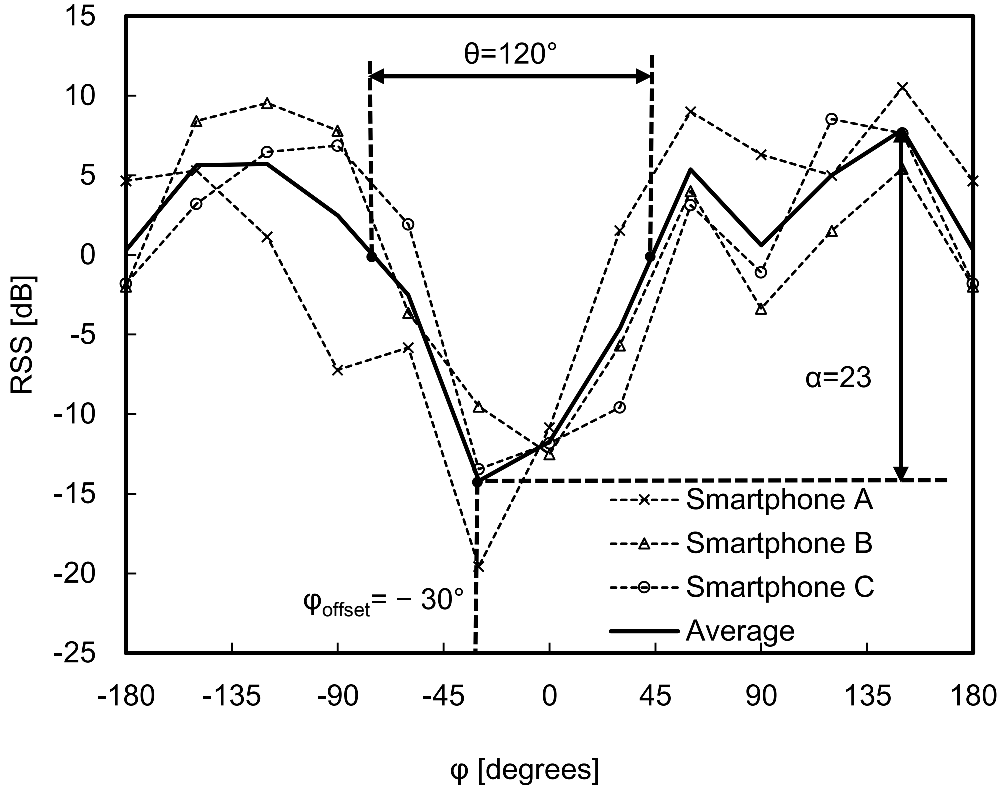

Figure 3.4 Directivity of power absorption by a user when a smartphone is held in the right hand in an anechoic chamber.

To clarify the influence of multipath fading on the power absorption by a user, RSS is measured in a typical room. The room measured 6.5 m by 4 m. The experimental environment of the room is set in a similar manner to that of the anechoic chamber in Fig. 3.2, except that the microwave absorbers are removed. Most of the walls and floor in the experimental room are made of concrete. RSS is measured for φ of 180 to −180 degrees when the smartphone is held in the left hand. The interval of the angle φ is 45 degrees. Average RSS for all angles is assumed as 0 dB as the standard value.

The RSS values measured in the room are compared with those measured in the anechoic chamber. The room-measured RSS and the anechoic-chamber-measured RSS when the smartphone is held in the left hand are plotted in Fig. 3.5. According to the figure, three parameters (α, $\varphi_{\mathrm{offset}}$, and θ) for the room differ from those for the anechoic chamber.

The above-described results clarify that α, $\varphi_{\mathrm{offset}}$, and θ depend on the smartphone-holding state and multipath fading in a room. To estimate the position of the smartphone, the proposed method therefore estimates α, $\varphi_{\mathrm{offset}}$, and θ in consideration of power absorption by the user and compensates it.

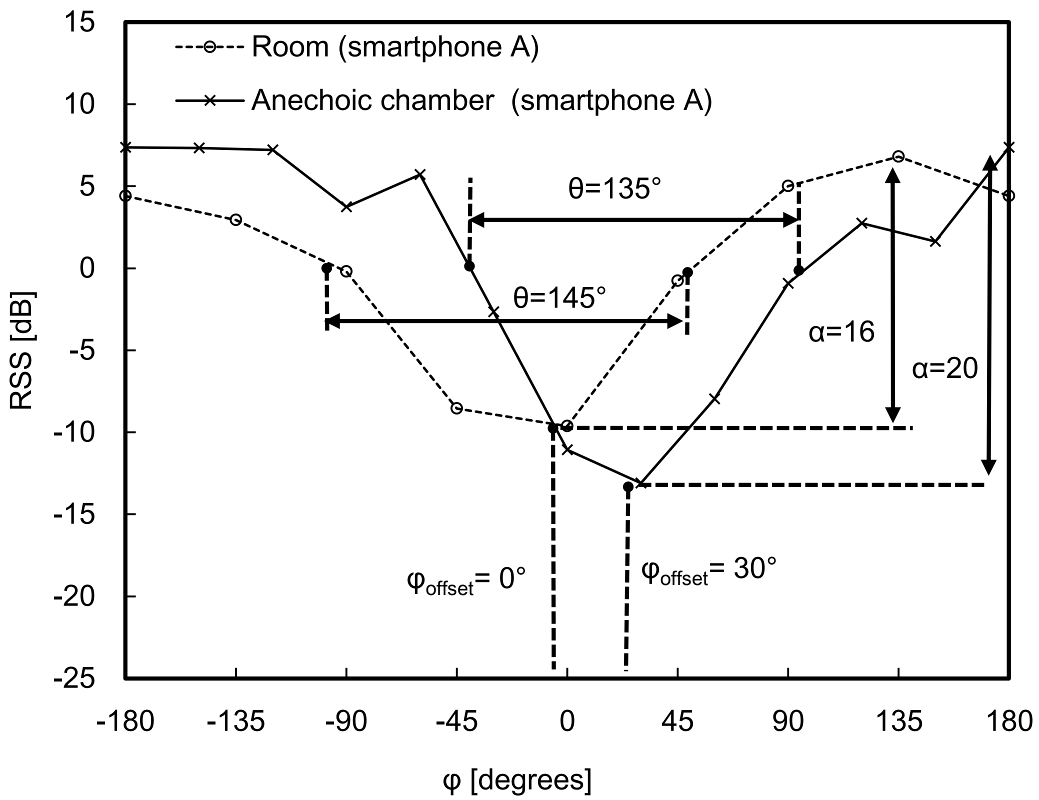

Figure 3.5 Directivity of power absorption by the user when the smartphone is held in the left hand.

3.3 Model of Power Absorption by User

To estimate the power absorption by a user and compensate it, a general model of the power absorption is designed on the basis of the experimental results presented in Section 3.2. The power absorption by the user in the left-case and that in the right-case are asymmetric. Specifically, $\varphi_{\mathrm{offset}}$, and θ depend on the smartphone-holding state and multipath fading. It is difficult for the conventional RFID-based method using a cosine function to simulate asymmetric power absorption. Because, the cosine function can represent only symmetric shape. To simulate asymmetric power absorption (which depends on the smartphone holding state and multipath fading), the three parameters (α, $\varphi_{\mathrm{offset}}$, and θ) are embedded in the model based on the cosine function. The power absorption is modeled on the basis of the following equations,

$$L_P = \begin{cases} -\frac{\alpha}{2}\left\{1+\cos\left(\frac{2\pi\,\beta}{\theta}\right)\right\}, & \text{if } |\beta| \le \frac{\theta}{2} \\ 0, & \text{if } |\beta| > \frac{\theta}{2} \end{cases}, \qquad (3.1)$$

$$\beta = \varphi - \varphi_{\mathrm{offset}} . \qquad (3.2)$$

The modeled power absorption is plotted in Fig. 3.6. Average RSS for all angles is assumed to be 0 dB as a standard value. The model is calculated by assigning values of α, $\varphi_{\mathrm{offset}}$, and θ in eq. (3.1). The parameters listed in Table 3.1 are measured in the anechoic chamber.

According to the figure, the power absorptions simulated by model agree well with the two measured power absorptions (i.e., right hand and left hand). To confirm the similarity between power absorption simulated with the model and measured power absorption, a correlation coefficient is calculated. The correlation coefficient is 0.86 when the smartphone is held in the left hand, and it is 0.83 when it is held in the right hand. The correlation coefficient is high (0.83 or more) in both cases. It is assumed that the model can simulate various power absorptions by the user. To estimate various power absorptions by the user and compensate them, the parameters of the model must be estimated first. How to estimate these parameters is described in the next section.

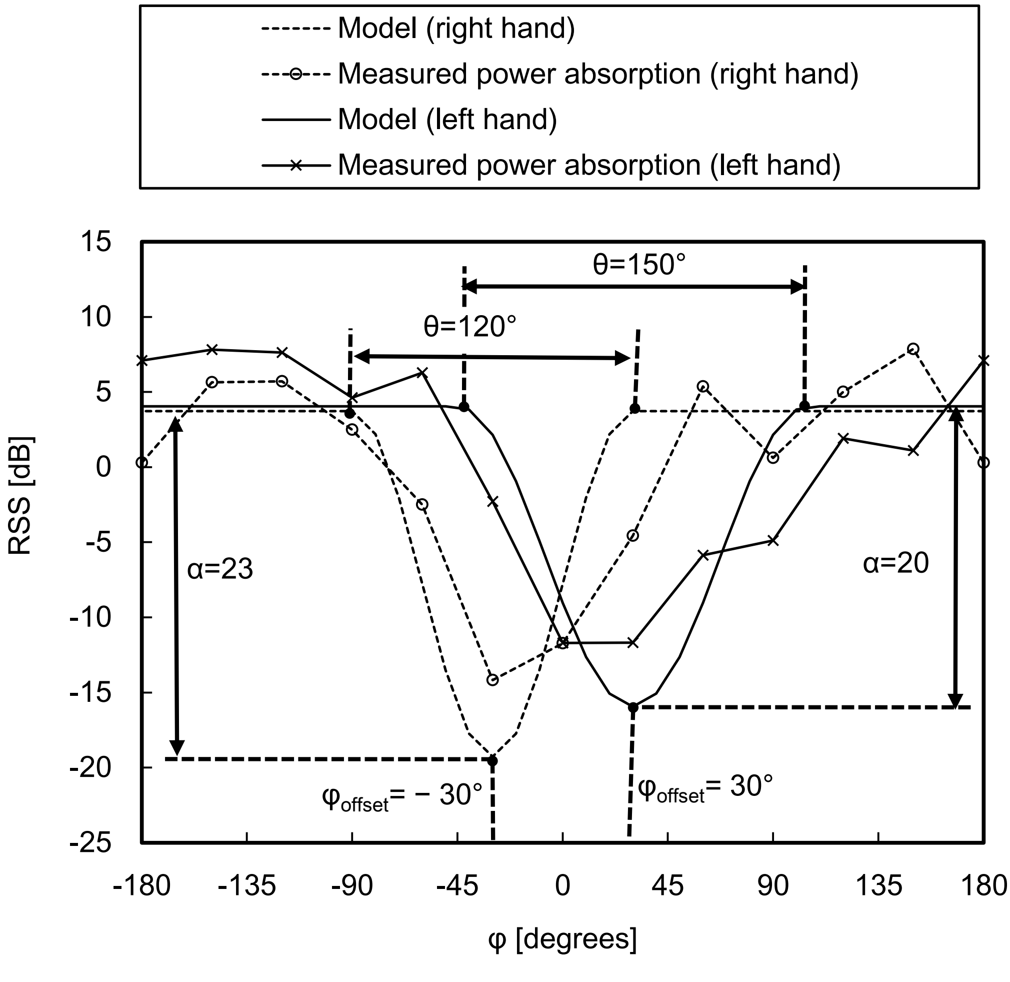

Figure 3.6 Power-absorption model for a user holding smartphone.

Table 3.1 Measured parameters for anechoic chamber.

	Left hand	Right hand
α	20 dB	23 dB
φ_{offset}	30 degrees	− 30 degrees
θ	150 degrees	120 degrees

3.4 Proposed Method

To achieve accurate WLAN positioning for sparse AP deployment in an indoor environment, the power absorption by a user is estimated and compensated by using the model and a magnetic sensor built into the smartphone. Sparse AP deployment is defined as APs separated by 6 m or more. The precondition of the physical user activity is defined as either the standing or the sitting. Moreover, it is defined as the user looking at the display of the smartphone. The position of the user's smartphone is then estimated on the basis of MLE.

In detail, RSS of signals transmitted from four APs is estimated. Measured RSS ($RSS_{ME}(n)$) is then subtracted from $RSS_{ES}(n,\delta)$ estimated at each coordinate (δ) inside an area of square set APs at four corners. n is defined as an index of AP. δ that gives maximum $1/|RSS_{ES}(n,\delta) - RSS_{ME}(n)|$ is determined and denoted as a δ_{ML}, which is taken as the position of the smartphone and given as

$$\delta_{ML} = \arg\max_{\delta} \sum_{n=1}^{4} \frac{1}{|RSS_{ES}(n,\delta) - RSS_{ME}(n)|}. \quad (3.3)$$

δ_{ML}' is the average coordinate calculated from N samples of δ_{ML}, and N is any positive integer. $RSS_{ES}(n,\delta)$ is calculated as

$$RSS_{ES}(n, \delta) = P_{AP}(n) + L_S(n, \delta) + F + L_P \,, \quad (3.4)$$

where $P_{AP}(n)$ represents a known output power of the AP, and F represents an unknown fluctuation of RSS due to multipath fading, where F is estimated by using MLE. $L_S(n, \delta)$ is defined as free-space path loss [39] given by

$$L_S(n, \delta) = -20 \log\left(\frac{4\pi d(n, \delta)}{\lambda}\right), \quad (3.5)$$

$$\lambda = \frac{c}{f}, \quad (3.6)$$

where the length of a path from a coordinate of AP(n) to δ is denoted by $d(n, \delta)$, the speed of light is denoted by c, and carrier frequency f is taken as 2.4 GHz.

To accurately estimate the power absorption by the user, L_P is estimated by using the model and a magnetic sensor built into the smartphone. φ used in the model is measured using a magnetic sensor built into the smartphone (Fig. 3.7).

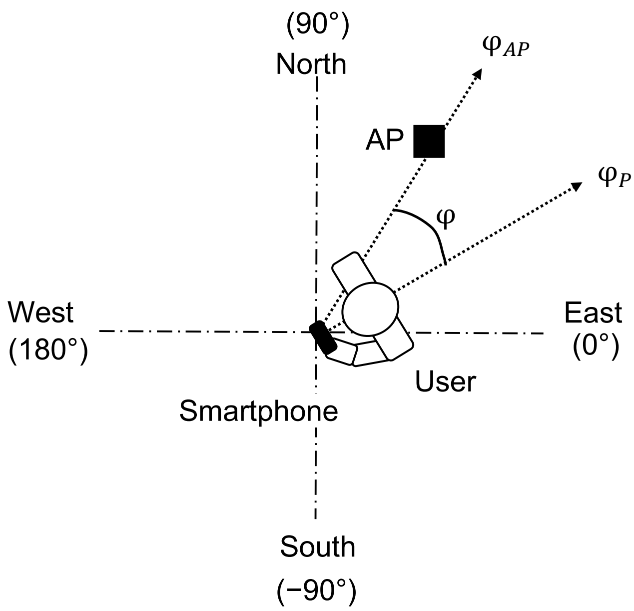

Figure 3.7 Definition of angle φ for a smartphone.

According to the figure, φ is the angular difference between angle φ_{AP} representing the AP and φ_P representing the user. φ_{AP} can be calculated on the basis of a known coordinate of the APs and each coordinate (δ) inside the area of a room. φ_P is measured by the magnetic sensor in the smartphone. The precondition of the measurement is defined as the user standing and looking at the display of the smartphone.

To confirm the performance of the magnetic sensor built into the smartphone, RMSE for φ_P is evaluated in the room in four cases: φ_P = 0 degrees, φ_P = 90 degrees, φ_P = − 90 degrees, and φ_P = 180 degrees. The evaluated RMSEs for φ_P are listed in Table 3.2. According to the table, average RMSE for φ_P in the room was 8.6 degrees.

Table 3.2 RMSE of magnetic sensor in indoor environment.

	RMSE(φ_P) [degrees]
Left hand	6.9
Right hand	10.3
Average	8.6

The parameters of the model, α, φ_{offset}, and θ depend on the smartphone holding state and multipath fading. They are therefore determined on the basis of the measured power absorption by the user. Specifically, they are selected from the ranges listed in Table 3.3. The parameter ranges are determined experimentally by three kinds of smartphone in the anechoic chamber and the room. The user holding smartphone is a male. He is 176 cm tall, and weighs 68 kg. In addition, F is selected from the range listed in Table 3.3. The parameter range of F is determined on the basis of a measured value in a building [31].

Table 3.3 Range of the parameters for MLE.

	Minimum value	Maximum value
α	16 dB	23 dB
φ_{offset}	− 45 degrees	30 degrees
θ	120 degrees	160 degrees
F	− 10 dB	10 dB

3.5 Evaluation

To confirm the performance of the proposed method, RMSE of WLAN positioning based on this method is evaluated in a room. Moreover, RMSE is evaluated when pedestrians walked around the room.

In this evaluation, it is assumed that the user wants to know his or her position within a few seconds (i.e., 3 to 5 s). On the other hand, it takes the smartphone 1 s to simultaneously receive four signals from four APs. Three samples (N=3) of the transmitted signal from each AP are therefore used to estimate the user's position.

3.5.1. Evaluation of RMSE

RMSEs of WLAN positioning by the conventional and proposed methods are evaluated in a room, namely, the experimental environment shown schematically in Fig. 3.8. In this environment, no pedestrians are present; four APs are set at a height of 1.5 m above the floor; the distance between two APs is 6 m; and the size of the room is 8 m by 8 m. The metal desks, a shelf, walls and a floor in the room cause multipath fading.

Regarding the evaluation method, a user held a smartphone in the hand while standing sequentially at 16 locations. At each location, the user faces 2 directions: the direction shown in Fig. 3.8, and the opposite direction. The RMSE values of the 32 settings (16×2) are evaluated.

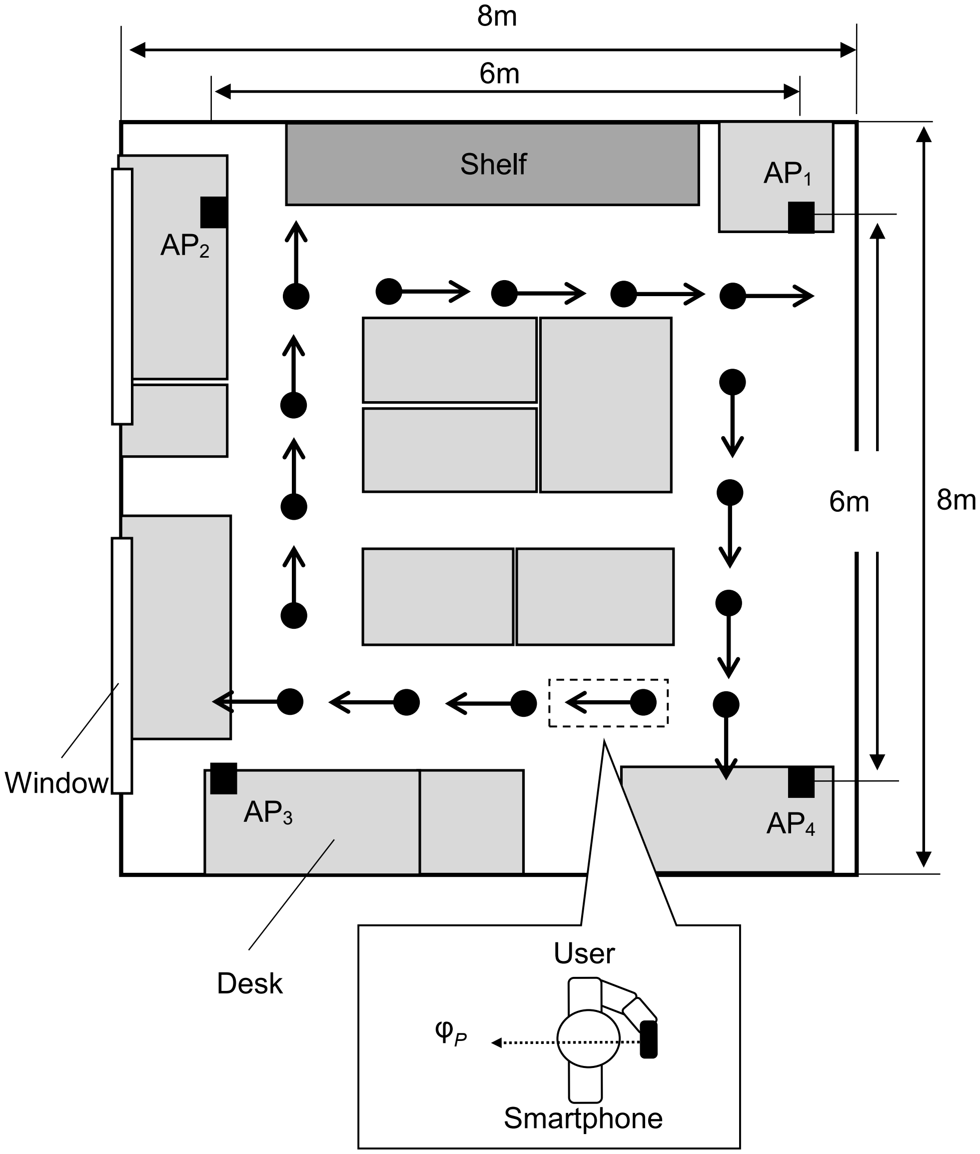

Figure 3.8 Experimental setup in the room.

An uncompensated method (which does not compensate power absorption by the user), the conventional method, and the proposed method are evaluated. The conventional method [33] estimates α and φ by using MLE. In other words, the model of power absorption by the user used in the conventional method does not include $\varphi_{\mathrm{offset}}$ and θ. To evaluate the conventional method by using the model, $\varphi_{\mathrm{offset}}$ and θ are respectively fixed to 0 degrees and 360 degrees.

The proposed method estimates α, $\varphi_{\mathrm{offset}}$, and θ by using MLE and the model in the range listed in Table 3.3. In addition, φ is measured by utilizing the magnetic sensor built into the smartphone. The conventional and proposed methods then both compensate the fluctuation of RSS that is attributed to these parameters.

The evaluated RMSEs are shown as bar graphs in Fig. 3.9. As shown in the figure, RMSE of the uncompensated method is 4.29 m; that of the conventional method is 3.11 m; and that of the proposed method is 2.17 m. In other words, the proposed method is more accurate than the conventional ones in estimating the position of the smartphone in the case of sparse AP deployment in the room.

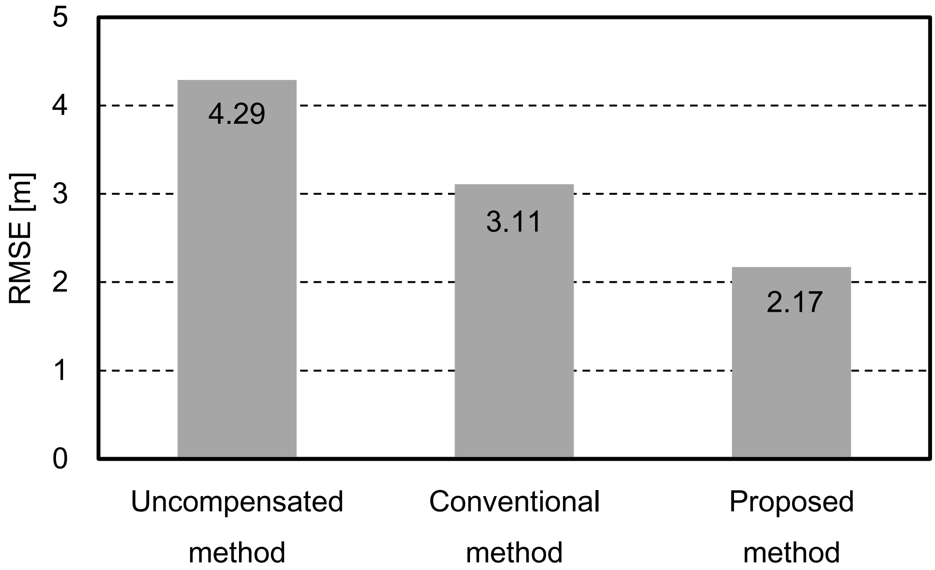

Figure 3.9 RMSE of different positioning methods used for a room.

To confirm the reduction of RMSE by estimating φ_{offset} and θ, RMSE in the case that θ is estimated and that in the case that θ fixed (i.e., 360 degrees) for the proposed method are evaluated. RMSEs of the proposed method are shown in Fig. 3.10. In this evaluation, the range of $\pm\varphi_{offset}$ is varied from 0 degrees to 180 degrees.

RMSE of the proposed method with estimated θ is lower than that with fixed θ (360 degrees). The proposed method determines θ on the basis of the measured power absorption by the user, which is selected from the ranges listed in Table 3.3. It is therefore concluded that estimating θ reduces RMSE of the positioning method.

With the proposed method, RMSE for $\pm\varphi_{offset}$ of 17 degrees, 34 degrees, and 51 degrees is lower than that for fixed φ_{offset} of 0 degrees. In other words the estimated φ_{offset} from the range listed in Table 3.3 reduces RMSE.

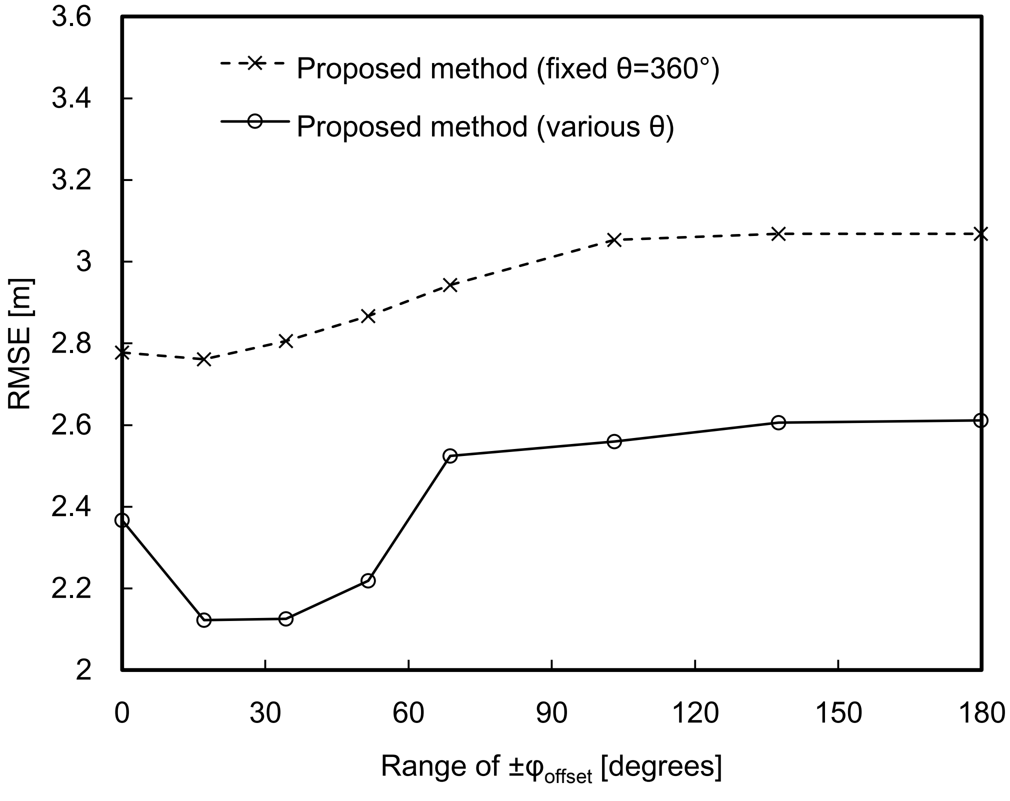

Figure 3.10 RMSE of the proposed method with optimized φ_{offset} and θ for a room.

A cumulative distribution function (CDF) is used to verify that the proposed method can be used to estimate the user's position with good accuracy regardless of the smartphone holding state. The CDF of estimation error used in the proposed method is shown in Fig. 3.11. According to the figure, the median error is 1.7 m when the smartphone is held in the left hand and 1.7 m when the smartphone is held in the right hand. The estimation errors of the proposed method in the left-case and that in the right-case are almost same. Therefore, the proposed method can estimate the asymmetric power absorption by the user and compensate it.

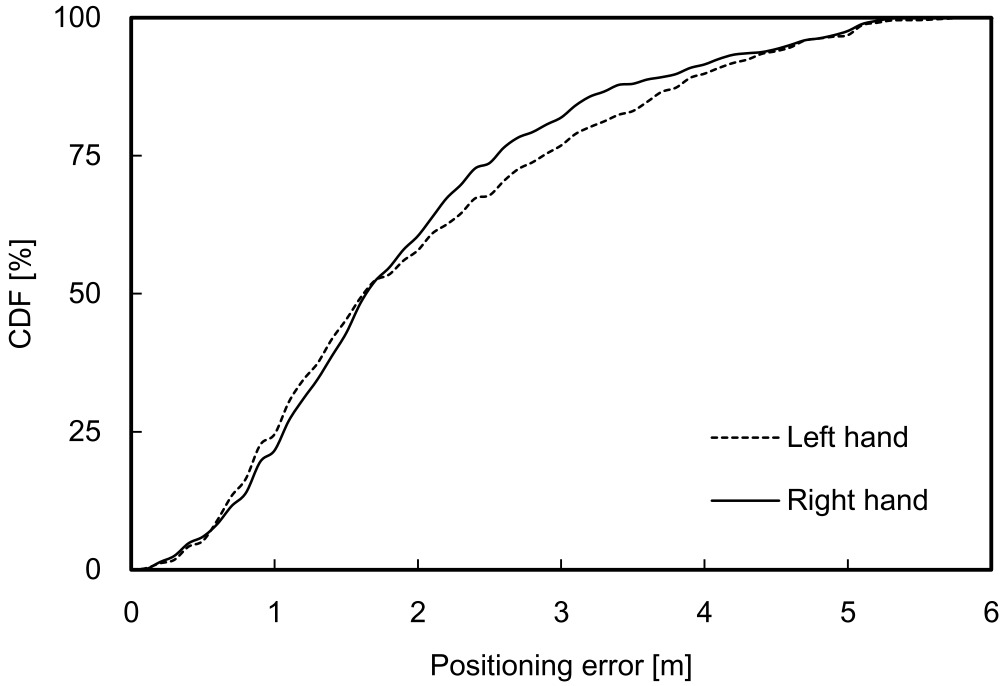

Figure 3.11 CDF of estimation error used in the proposed method.

3.5.2. Influence of Pedestrians on RMSE

RMSEs of WLAN positioning by the conventional and proposed methods are evaluated when pedestrians walked around a room. An experimental environment is shown in Fig. 3.12. According to the figure, the distance between two APs is 6 m, and the size of the room is 7.6 m by 6.6 m. The metal desks, the black boards, walls and floor in the room cause multipath fading.

Regarding the evaluation method, a user holds a smartphone in the left hand while standing sequentially at four locations. The number of pedestrians in the lecture room is varied from zero to three. A scene from the actual experiment, in which two pedestrians randomly walk around the lecture room, is shown in Fig. 3.13.

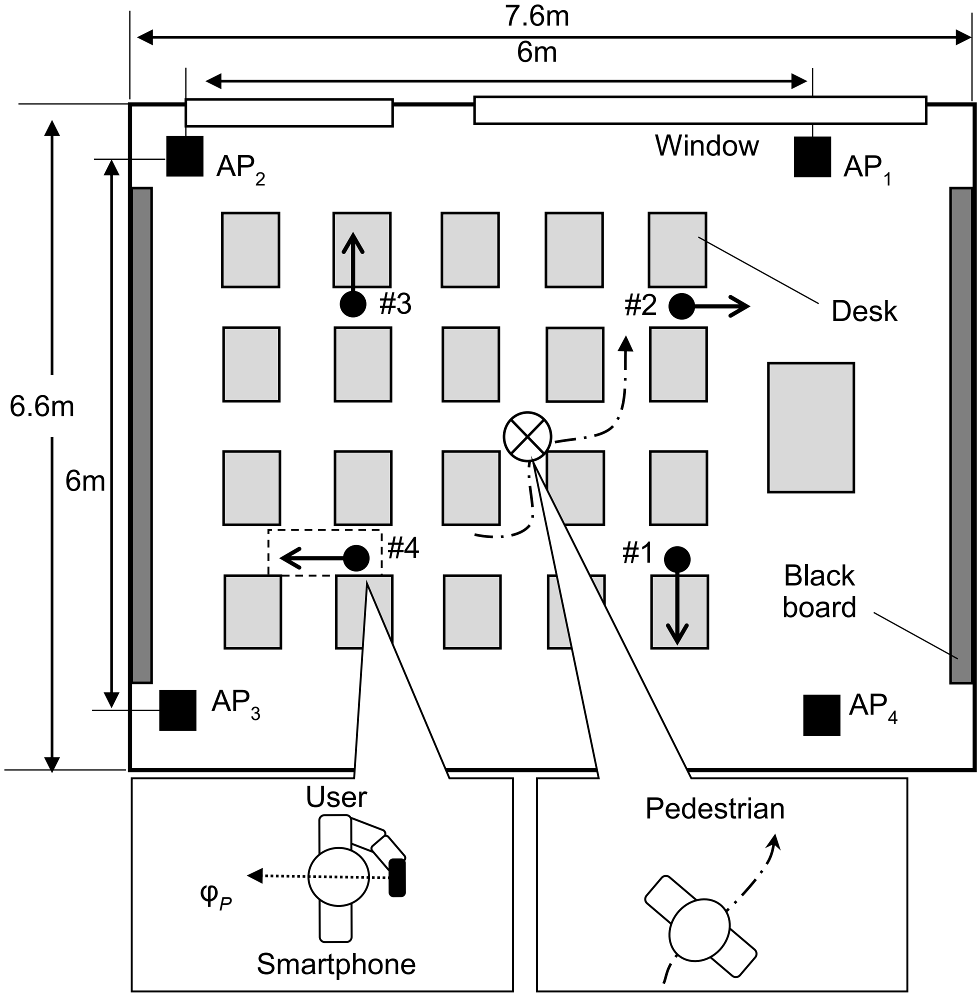

Figure 3.12 Experimental setup with pedestrians.

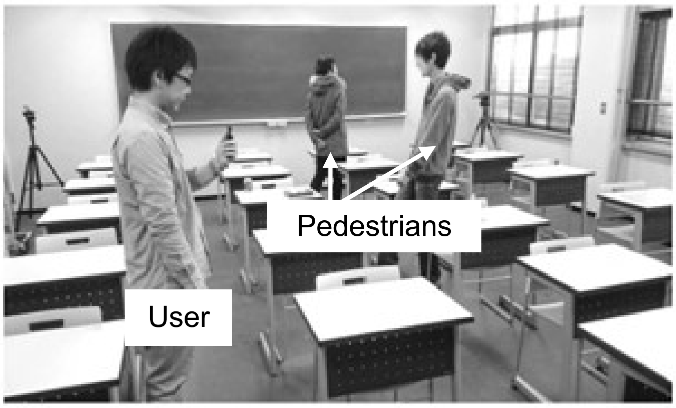

Figure 3.13 Scene from actual experiment in the lecture room.

The evaluated RMSEs are shown as bar graphs in Fig. 3.14. According to the figure, RMSE of the proposed method is the lowest among the three methods. In the case of three pedestrians, RMSE of the uncompensated method is 4.12 m, that of the conventional one is 2.94 m, and that of the proposed one is 1.94 m. In other words, RMSE of the proposed method is 34 % lower than that of the conventional one when the pedestrians walk around the lecture room.

In detail, the positioning error of the proposed method at 4 locations in the lecture room is shown in Fig. 3.15. As shown in the figure, the positioning error is not proportional to the number of pedestrians at all locations. To clarify the reason why the positioning error is not proportional to the number of pedestrians, the measured RSS is analyzed. As a result of the analysis, the fluctuation of RSS is found to be unproportional to the number of pedestrians, when a few pedestrians (3 or less) walk around in the room. On the other hand, the fluctuation of RSS is proportional to the positioning error [40].

These findings explain the above-mentioned relation between the positioning error and the number of pedestrians. Clarifying a relation between the positioning error and the number of pedestrians in the case of many pedestrians (i.e. 4 or more) is a future work.

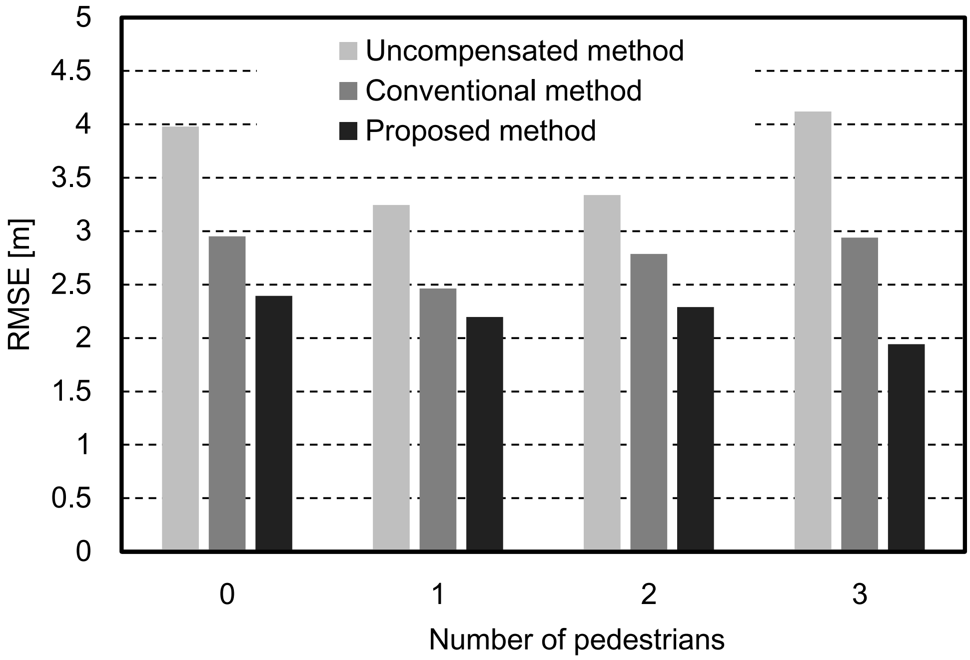

Figure 3.14 RMSE versus a number of pedestrians.

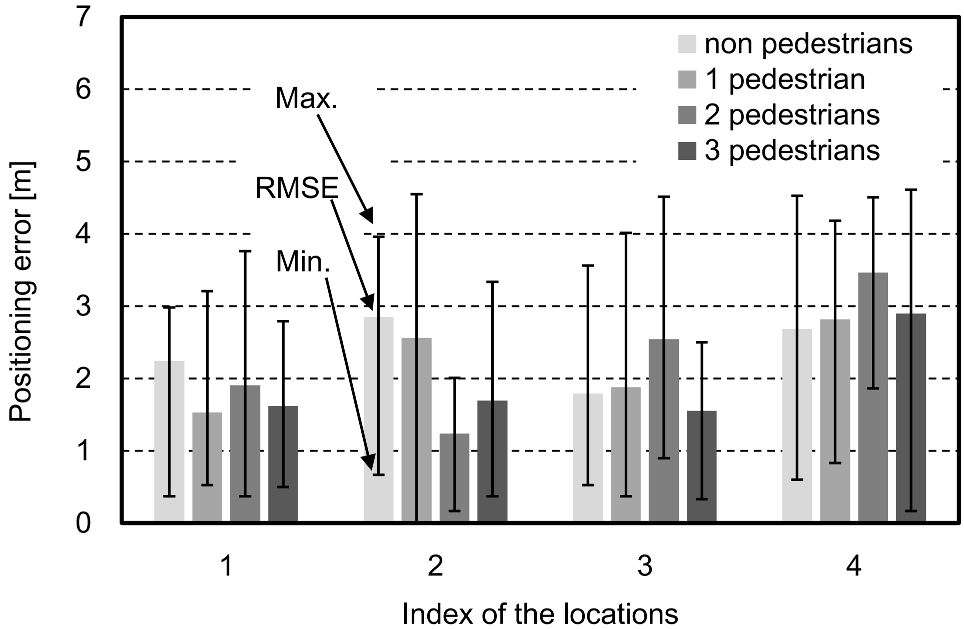

Figure 3.15 The positioning error of the proposed method at 4 locations in the lecture room.

RMSEs of the proposed method and the conventional one are evaluated in regard to the number of averaged samples, N. The evaluated RMSE values are plotted in Fig. 3.16. According to the figure, RMSE of the proposed method is lower than that of the conventional one and does not depend on N.

These results presented here indicate that the proposed method is more accurate than the conventional one in estimating the position of the smartphone in the case of sparse AP deployment in a room.

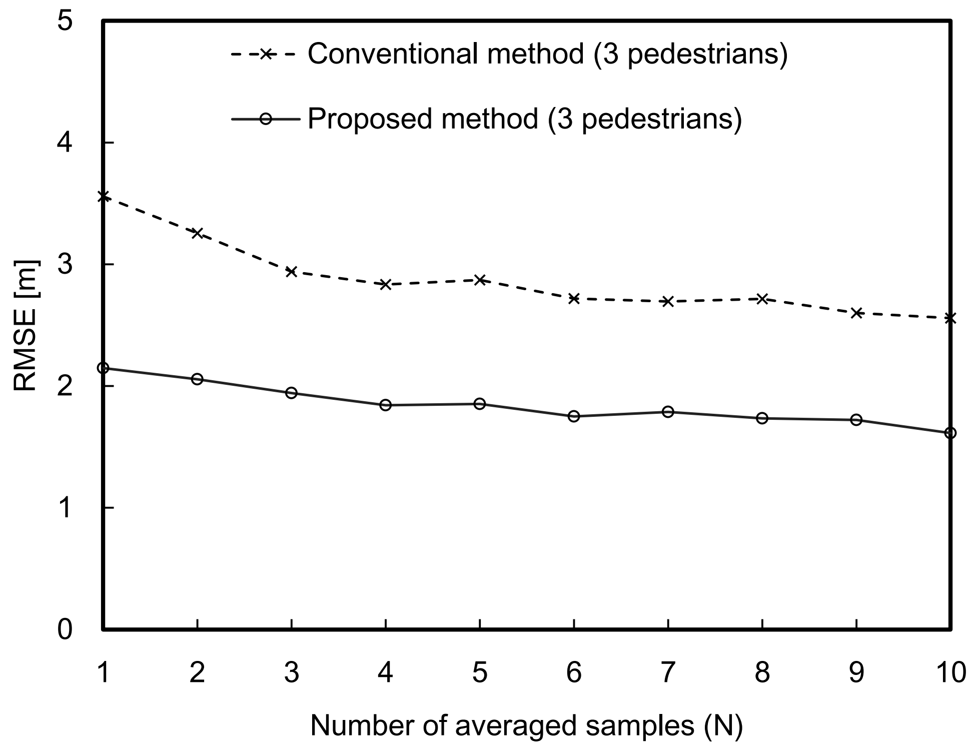

Figure 3.16 RMSE versus the number of averaged samples.

3.6 Conclusion

An accurate positioning method for sparse AP deployment in an indoor environment is proposed. The proposed method is based on a model of power absorption by a user. The parameters of the model are estimated using MLE, and the directivity of the power absorption is measured using a magnetic sensor built into the smartphone. The proposed method compensates the power absorption and the influence of multipath fading. To verify the effectiveness of the proposed method, RMSE of the proposed method is evaluated in a lecture room and compared to that of the conventional method. The distance between APs is 6m. RMSE of the proposed method is 34 % lower than that of the conventional one when pedestrians walk around the room. In detail, RMSE of the proposed method is 1.94 m, which satisfies the target assumed in this study (i.e., less than 2.5 m). In other words, RMSE of proposed method is the same as that of fingerprint-based method. It is therefore concluded from these results that the proposed method can provide accurate positioning using a smartphone in the case of sparse AP deployment in an indoor environment.

From a practical perspective, a sparser AP deployment is expected. This study assumes that RMSE increases when APs are deployed sparsely. Improvement of RMSE in the case of sparser AP deployment is therefore discussed in the next chapter.

Chapter 4

WLAN Positioning System Utilizing RSS at Dual Frequency Bands

4.1 Introduction

In this chapter, to improve the positioning accuracy in the case of sparse AP deployment, we discuss the WLAN positioning system utilizing RSS at the dual frequency bands. In Chapter 3, the WLAN positioning system using power-absorption-based model at single frequency band (2.4 GHz) [41] can provide accurate positioning in the case of sparse AP deployment (the distance between APs is 6 m) in an indoor environment. However, from a practical perspective, a sparser AP deployment is expected. This study assumes that positioning error increases when APs are deployed sparsely.

To resolve this problem, a WLAN positioning system is proposed. In WLAN positioning system, the smartphone receives signals transmitted from many APs. It then measures RSS and estimates its position on the basis of the RSS. A key issue concerning WLAN positioning is that any unexpected fluctuation in RSS increases positioning error. The fluctuation of RSS is mainly caused by the three factors, which are the multipath fading, pedestrians and the power absorption by the user. In Chapter 3, a model for WLAN positioning system is proposed to compensate the power absorption by the user at single frequency band. In addition, the fluctuation of RSS attributed to the multipath fading and pedestrians is reduced by using the average RSS.

However, the positioning error in WLAN positioning system using power-absorption-based model for single frequency band increases, when the average RSS of user's position is extremely lower than that of near fields (hereafter "deep fade"). To reduce the positioning error attributed to the deep fade, the conventional fingerprint-based method [42] utilizes RSS at the dual frequency bands (2.4 GHz and 5.2 GHz). The fingerprint-based method requires "radio map", which is a set of previously measured RSS. Measuring the radio map in the indoor environment is troublesome.

To overcome the problem, a model-based method for positioning utilizing RSS at dual frequency bands is proposed. The model-based method does not require the measured radio map. The positioning error is measured by means of a root-mean-square error (RMSE). The target of this study is to achieve less RMSE than the conventional method using the power-absorption-based model at single frequency band [41].

In this chapter, the deep fade in indoor environment is confirmed experimentally. Then to reduce the positioning error attributed to the deep fade, a fundamental idea for WLAN positioning system is proposed (Section 4.2). To implement the idea in WLAN positioning system, a WLAN positioning system utilizing RSS at dual frequency bands is proposed (Section 4.3). To clarify the positioning accuracy of the proposed system, RMSEs of both the proposed method and the conventional method using the power-absorption-based model are evaluated in a conference room. (Section 4.4).

4.2 Multipath Fading

To improve the positioning accuracy in the case of sparse AP deployment, the deep fade in an indoor environment is confirmed experimentally. Then to reduce the positioning error attributed to the deep fade, a fundamental idea for WLAN positioning system is proposed

To confirm the deep fade attributed to the multipath fading in an indoor environment, RSS is measured in a conference room. The experimental environment is shown schematically in Fig. 4.1. As shown in the figure, AP is set at a height of 1.2 m above the floor. The precondition of the measurement is defined as the user standing and looking at the display of the smartphone. The user faces the AP. The smartphone is held in a left hand.

RSS is measured at a distance between AP and the smartphone of 1 to 10 meters. The interval of the distance is 0.5 m. 30 samples for RSS is measured at each locations.

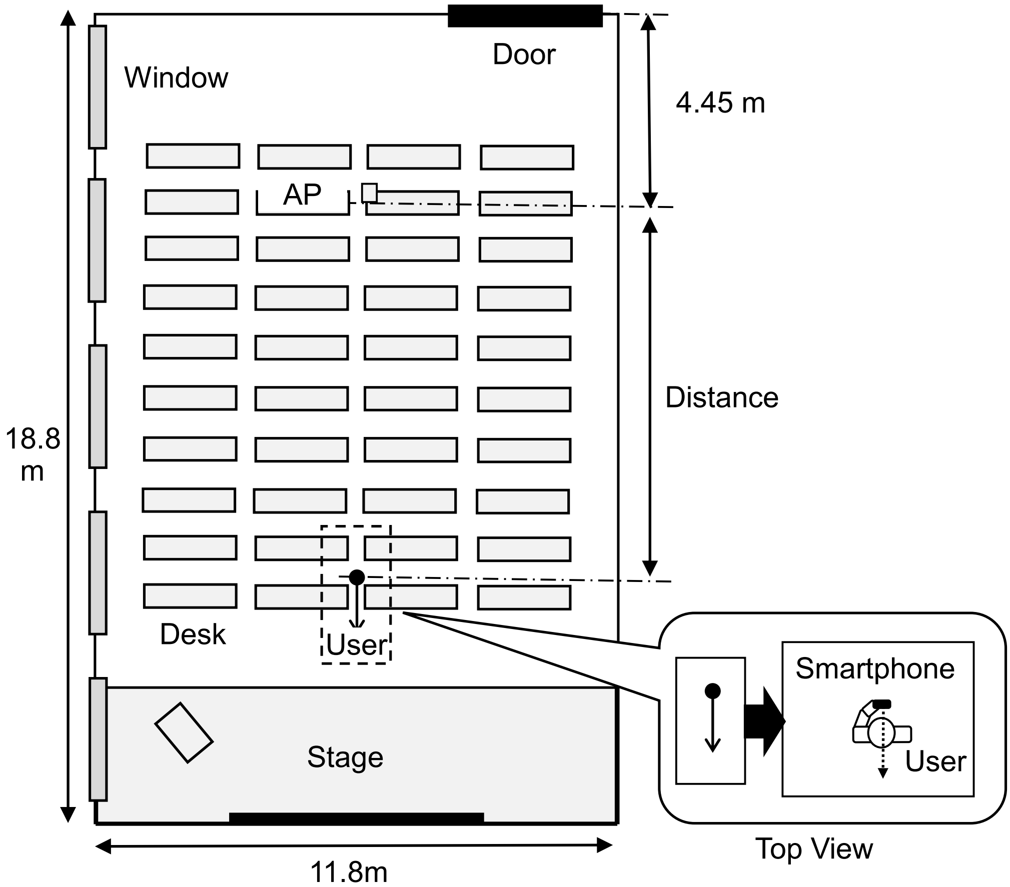

Figure 4.1 Experimental setup for RSS measurement in a conference room.

Measured RSS in the conference room is shown in Fig. 4.2. As shown in the figure, the maximum fluctuation of RSS was 14 dB. The average RSS at 7 m is about 10 dB lower than that at 9.5 m. The deep fade attributed to the multipath fading thereby exists at 7 m. The deep fade causes the positioning error in WLAN positioning system using the model-based method. Because the model-based method for positioning is designed on the assumption that the average RSS is decreased as the distance from AP is longer.

To reduce the positioning error attributed to the deep fade, microwave absorbers cover a ground, a ceiling and walls in a chamber room. However, it is difficult to construct the microwave absorber on the ground in a shopping mall.

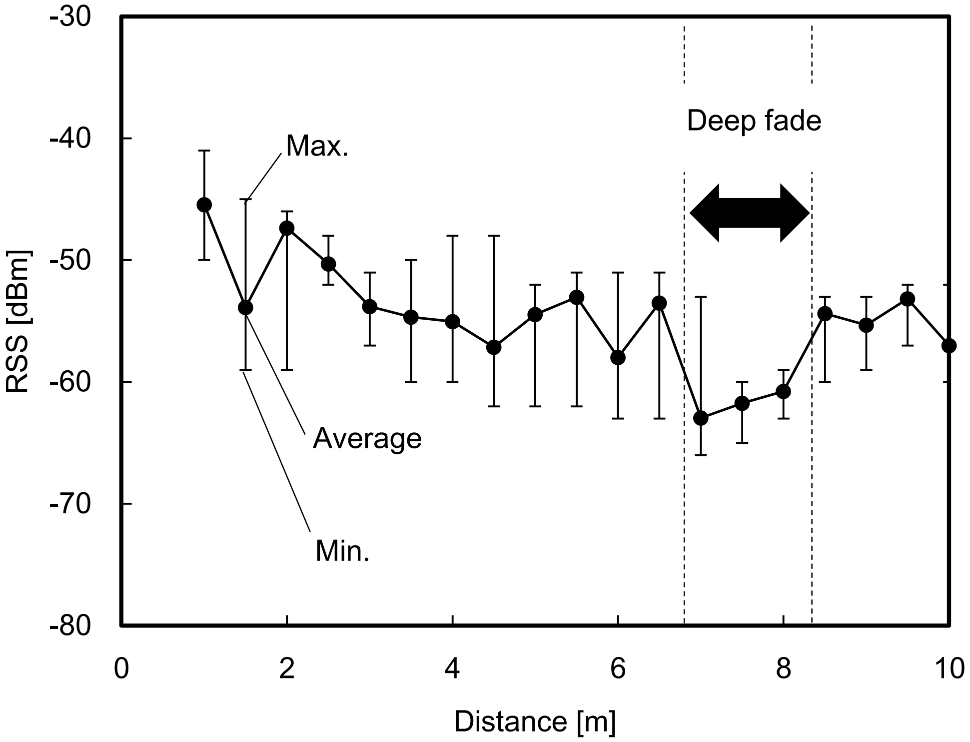

Figure 4.2 Measured RSS attributed to the multipath fading in the conference room.

In other method for the positioning, many signals from APs are utilized to reduce the positioning error attributed to the deep fade. When the deep fade occurs in one of the received signals, the other signals are useful to reduce the positioning error. In this method, many additional APs must be installed. It is however complicated. Namely, many areas for the installation of APs are required. APs must be connected to the power-supply unit, which is generally mounted on a wall.

To resolve these problems, a fundamental idea for WLAN positioning system is proposed. A principle [43] of generating the deep fade is shown in Fig. 4.3. As shown in the figure, the deep fade is generated when a direct wave is combined with a reflected-wave shift by half a wavelength of the direct wave, that is, phase π. If the differential phase is shifted by phase π, the deep fade is not generated.

In detail, the deep fade of the WLAN positioning system can be simulated by a ray tracing (Fig. 4.4). A path of the direct wave is the segment from the AP to the smartphone. To determine the path of the reflected wave, the position of a virtual smartphone is calculated. The path of the reflected wave is presumed to depend on the positions of the smartphone, floor, and any obstacles. The received signal strength of the smartphone is calculated by synthesizing multipath.

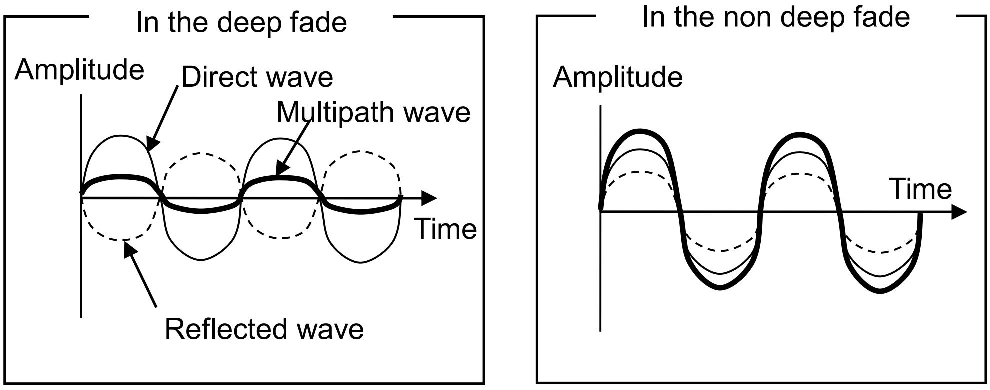

Figure 4.3 Principle of generating the deep fade.

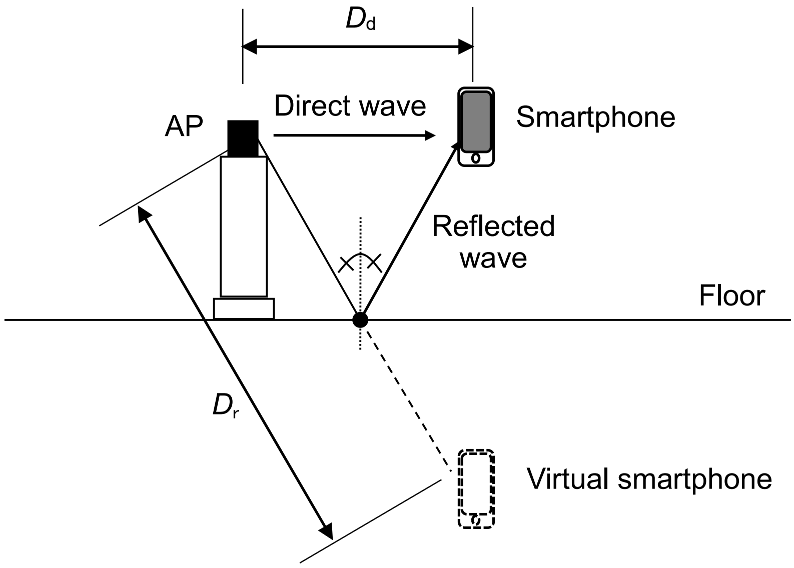

Figure 4.4 Simulated model for multipath fading by ray tracing.

The power of the direct-wave signal is represented by the following equation,

$$S_d(f, D_d) = V_{pp}(f, D_d)\ \cos\left(2\pi f\left(t - \frac{D_d}{c}\right)\right), \qquad (4.1)$$

where the speed of light is denoted as c, the length of path is denoted as D_d, and f is defined as the carrier frequency. In addition, $V_{pp}(f, D_d)$ is defined as the amplitude of power when the direct wave arrives at the smartphone. $V_{pp}(f, D_d)$ is given by

$$V_{pp}(f, D_d) = \sqrt{0.4 \times 10^{\frac{P(f, D_d)}{10}}}\ , \qquad (4.2)$$

where $P(f, D_d)$ is calculated from equation (4.3) based on the Friis transmission formula [39]. Output power of the AP is denoted as P_0.

$$P(f, D_d) = P_0 - 20\log\left(\frac{4\pi D_d}{\lambda}\right), \qquad \lambda = \frac{c}{f}. \qquad (4.3)$$

The phase of the reflected wave is shifted, and the amplitude is thus reduced. The reflected wave is therefore represented by the following equation, in which a reflectance ratio R and a rotation of phase ρ are added to equation (4.1). The distance between AP and the virtual smartphone is denoted as D_r. n is the number of the reflected waves.

$$S_r(f, D_r, n) = R\ V_{pp}(f, D_r)\ cos\left(2\pi f\left(t - \frac{D_r}{c}\right) + \rho\right). \qquad (4.4)$$

Accordingly, the multipath is composed of direct-wave path and N paths of the reflected waves. The received signal is represented by the following equation.

$$S(f, D_d, D_r) = S_d(f, D_d) + \sum_{n=0}^{N-1} S_r(f, D_r, n). \qquad (4.5)$$

According to these above equations, when the height of AP is changed, the distance D_r is varied. Therefore, the differential phase between $S_d(f, D_d)$ and $S_r(f, D_r, n)$ is varied. Changing the height of AP causes to shift the position of the deep fade. Moreover, changing the carrier frequency (f) causes to shift the position of the deep fade, too.

Consequently, to vary the height of the AP periodically is difficult. Therefore, the fundamental idea for WLAN positioning system is thereby utilized RSS at dual frequency bands to shift the position of the deep fade.

4.3 Proposed System

To reduce the positioning error attributed to the deep fade, a WLAN positioning system utilizing RSS at dual frequency bands and the power-absorption-based model is proposed. The configuration of the proposed system is shown in Table 4.1. According to the table, AP simultaneously transmits signals at dual frequency bands (2.4 GHz and 5.2 GHz). The AP is commercially available.

The positioning method utilizing RSS at dual frequency bands and the power-absorption-based model [41] is proposed. The model can simulate the power absorption by the user at 2.4 GHz to compensate it. In this section, to utilize the model [41] at 2.4 GHz and 5.2 GHz, the feasibility of modeling the power absorption by the user at the dual frequency bands is evaluated.

Then, to reduce the positioning error attributed to the deep fade, the method for WLAN positioning system utilizing RSS at dual frequency bands is presented.

Table 4.1 Configuration of proposed WLAN positioning system using RSS at dual frequency bands.

AP	Two signals are simultaneously transmitted at the dual frequency (2.4 GHz and 5.2 GHz).
User's device	Smartphone with built-in magnetics sensor and WLAN module
Method	A method utilizing RSS at dual frequency bands and the power-absorption-based model [41] is proposed

4.3.1. Power Absorption at Dual Frequency Bands

To evaluate the feasibility of modeling the power absorption by user at dual frequency bands, RSS at a smartphone held by hand in an anechoic chamber was measured. The distance from the smartphone to an AP is 1 m. RSS for all angles (φ) between 180 and -180 degrees, where φ is the angle between a line connecting the smartphone and the AP (chained line in Fig. 4.5) and a line perpendicular to the smartphone (dashed line in Fig. 4.5), is measured.

The interval of the angle φ is 30 degrees. RSS was averaged by using 30 samples. Average RSS for all angles is assumed to be 0 dB as a standard value. The measurement frequency of AP were 2.4 GHz and 5.2 GHz.

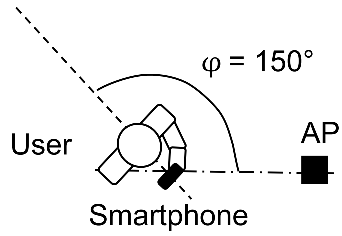

Figure 4.5 Angle between a line connecting the smartphone and the AP and a line perpendicular to the smartphone.

Measured RSS when the smartphone was held in the left hand is plotted in Fig. 4.6, and that when it is held in the right hand is plotted in Fig. 4.7. The parameters of power absorption is shown in Table 4.2. According to these figures and the table, maximum amplitude (α_m) of the power absorption by the user is 19.4 dB to 24.3 dB. φ for minimum RSS is -30 to 30 degrees, that is denoted as angular offset $\varphi_{\mathrm{offset}\_m}$. The "angular range ($\theta_m$)" of the standard power absorption (0 dB) is 100 to 145 degrees. To confirm the similarity between power absorption at 2.4 GHz with that at 5.2 GHz, a correlation coefficient is calculated. The correlation coefficient is 0.83 when the smartphone is held in the left hand, and it is 0.76 when it is held in the right hand.

On the other hand, a correlation coefficient between power absorption simulated with the model and measured power absorption at 2.4 GHz, is about 0.8 (it is described in section 3.3).These results are therefore assumed that the model [41] can simulate the power absorption at 2.4 GHz and 5.2 GHz.

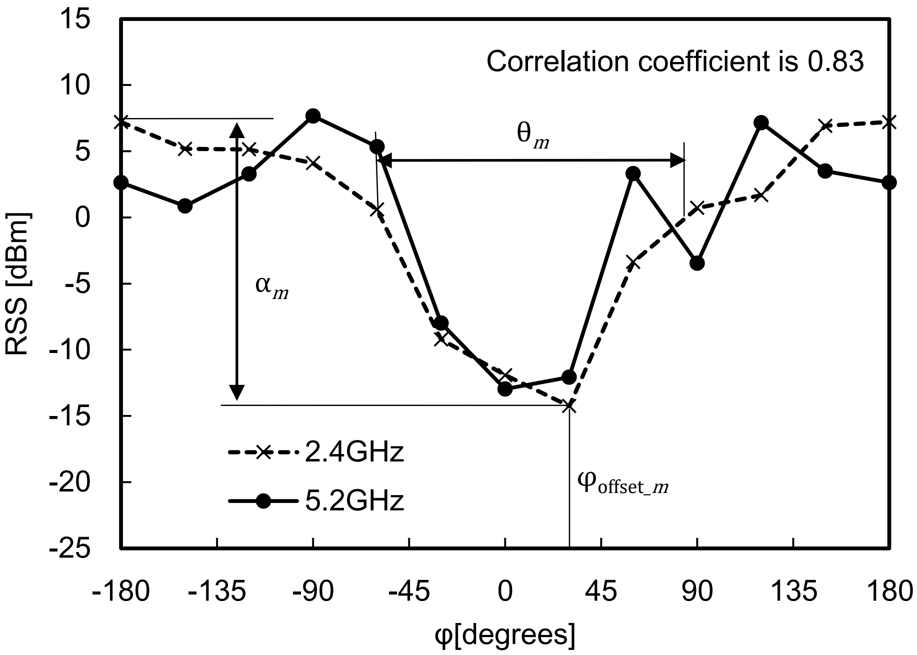

Figure 4.6 Directivity of power absorption by a user at dual frequency bands when a smartphone is held in the left hand in an anechoic chamber.

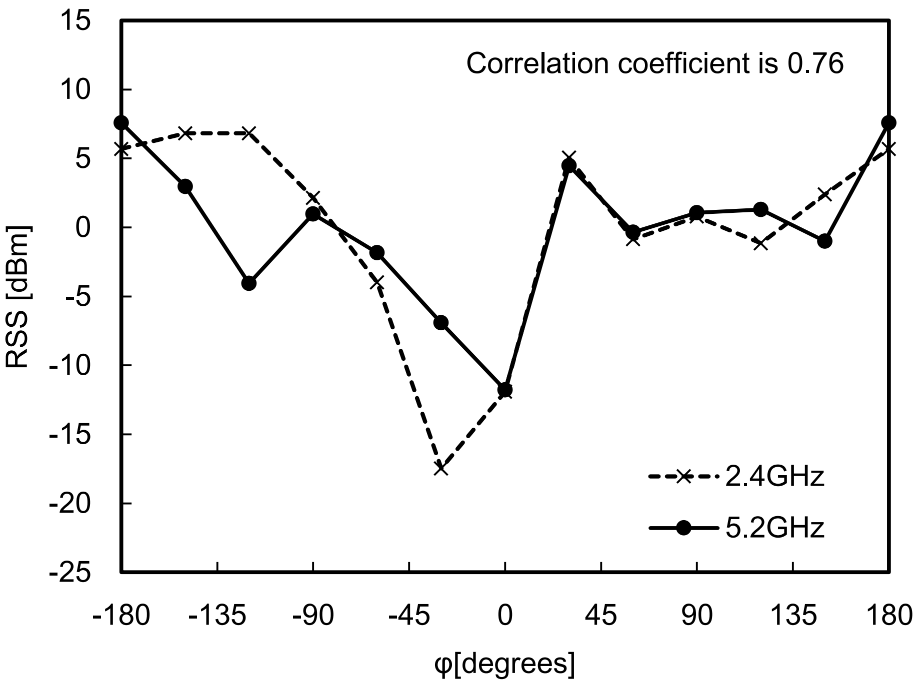

Figure 4.7 Directivity of power absorption by a user at dual frequency bands when a smartphone is held in the right hand in an anechoic chamber.

Table 4.2 Parameters of the power absorption by a user.

	Right hand		Left hand	
Frequency [GHz]	2.4	5.2	2.4	5.2
α_m [dB]	24.3	19.4	21.5	20.6
$\varphi_{\text{offset}\_m}$ [degrees]	-30	0	30	0
θ_m [degrees]	100	100	145	100

4.3.2. Method for Positioning

To reduce the positioning error attributed to the deep fade, a method for WLAN positioning system utilizing RSS at dual frequency bands is proposed. The method uses the power-absorption-based model [41] to compensate the power absorption by the user at dual frequency bands.

The position of the user's smartphone is then estimated on the basis of MLE. In detail, the measured RSS ($RSS_{ME}(n,m)$) is then subtracted from $RSS_{ES}(n,m,\delta)$ estimated at each coordinate (δ). n is defined as an index of AP. In the case of $m = 1$, the carrier frequency (f) is 2.4 GHz. In the case of $m = 2$, f is 5.2 GHz. δ that gives maximum $1/|RSS_{ES}(n,m,\delta) - RSS_{ME}(n,m)|$ is determined and denoted as a δ_{ML}, which is taken as the position of the smartphone and given as

$$\delta_{ML} = \arg\max_{\delta} \sum_{n=1}^{4} \sum_{m=1}^{2} \frac{1}{|RSS_{ES}(n,m,\delta) - RSS_{ME}(n,m)|}. \quad (4.6)$$

δ_{ML}' is the average coordinate calculated from N samples of δ_{ML}, and N is any positive integer. $RSS_{ES}(n,m,\delta)$ is calculated as

$$RSS_{ES}(n, m, \delta) = P_{AP}(n, m) + L_S(n, m, \delta) + F(m) + L_P(m)\,, \qquad (4.7)$$

where $P_{AP}(n, m)$ represents a known output power of the APs, and $F(m)$ represents an unknown fluctuation of RSS due to multipath fading, where $F(m)$ is estimated by using MLE. $L_S(n, m, \delta)$ is defined as a free-space path loss [39] given by

$$L_S(n, m, \delta) = -20 \log\left(\frac{4\pi c d(n, \delta)}{f(m)}\right), \qquad (4.8)$$

where the length of a path from a coordinate of $AP(n)$ to δ is denoted by $d(n, \delta)$, the speed of light is denoted by c. $L_P(m)$ is defined as the model of power absorption [41] given by

$$L_P(m) = \begin{cases} -\frac{\alpha_m}{2}\left\{1 + \cos\left(\frac{2\pi\,\beta_m}{\theta_m}\right)\right\}, & \text{if } |\beta_m| \leq \frac{\theta_m}{2} \\ 0\,, & \text{if } |\beta_m| > \frac{\theta_m}{2} \end{cases}, \qquad (4.9)$$

$$\beta_m = \varphi - \varphi_{\mathrm{offset\_}m}\,. \qquad (4.10)$$

φ is measured using a magnetic sensor built into the smartphone. The other parameters (α_m, $\varphi_{\mathrm{offset\_}m}$, θ_m) are estimated by MLE.

The parameters of the model are determined on the basis of the measured power absorption by the user. Specifically, they are selected from the ranges listed in Table 4.3. The parameter ranges are determined experimentally by three kinds of smartphone at 2.4 GHz in the anechoic chamber and the room. In addition, $F(m)$ is selected from the range listed in Table 4.3. The parameter range of $F(m)$ is determined on the basis of a measured value in a building [31].

Table 4.3 Range of the parameters for MLE.

	Minimum value	Maximum value
α_m	16 dB	23 dB
$\varphi_{\text{offset}\_m}$	− 45 degrees	30 degrees
θ_m	120 degrees	160 degrees
$F(m)$	− 10 dB	10 dB

4.4 Evaluation

To clarify the performance of the proposed system using RSS at the dual frequency bands, a positioning accuracy of WLAN positioning is evaluated in a conference room. The positioning accuracy is defined as the RMSE (root-means-square error). RMSE of WLAN positioning by the conventional and proposed methods is evaluated in the conference room, namely, the experimental environment is shown schematically in Fig. 4.8. A scene from the actual experiment in the conference room is shown in Fig. 4.9.

As shown in the figure, four APs are set at a height of 0.8 m above the floor; the distance between two APs is 9m; and the size of the room is 18.8 m by 11.8 m. Many desks, walls and floor in the conference room cause multipath fading. The user holds a smartphone in the hand while standing sequentially at 8 locations.

In this evaluation, it is assumed that the user wants to know his or her position within a few seconds (i.e., 3 to 5 s). On the other hand, it takes the smartphone 1 s to simultaneously receive eight signals from four APs. The APs simultaneously transmit two signals at both of 2.4 GHz and 5.2 GHz.

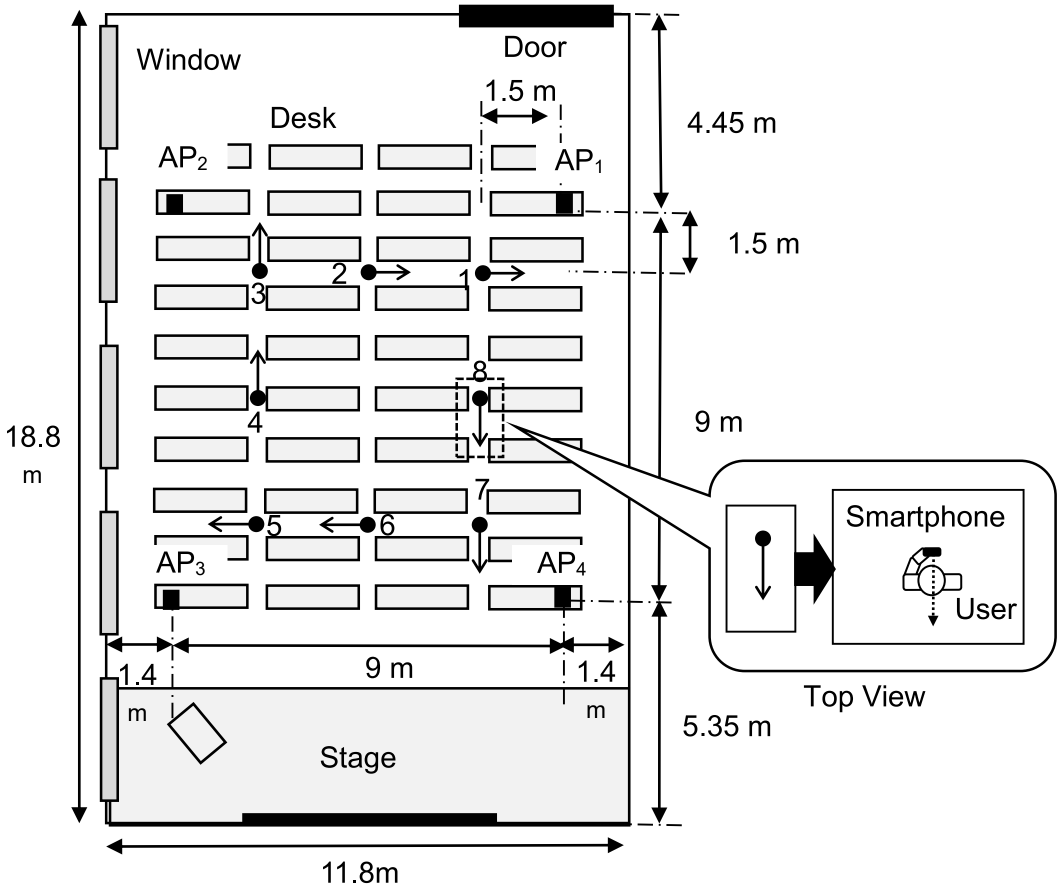

Figure 4.8 Experimental setup in the conference room.

Figure 4.9 Scene from actual experiment in the conference room.

RMSEs of the uncompensated method (which does not compensate power absorption by the user), the conventional method using the power-absorption-based model, and the proposed method are evaluated. The evaluated RMSEs are shown in Fig. 4.10. As shown in the figure, RMSE of the uncompensated method is 4.64 m to 5.31 m; that of the conventional method using RSS at 2.4 GHz is 2.90 m; that of the conventional method using RSS at 5.2 GHz is 2.56 m; and that of the proposed method is 2.11 m. RMSE of the proposed method is lower than that of the conventional one.

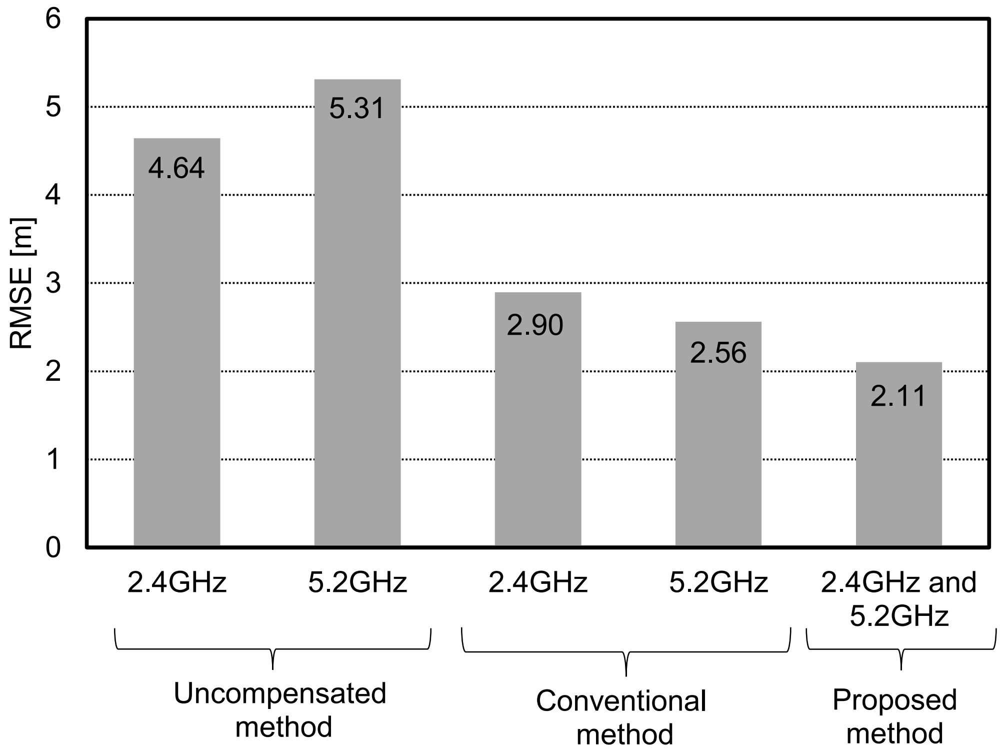

Figure 4.10 RMSE of different positioning methods used for a conference room.

In detail, the positioning error at 8 locations measured RSS in the conference room is shown in Fig. 4.11. As shown in the figure, in the terms of the conventional method, the positioning error (RMSE) at 5.2 GHz attributed to the deep fade is smaller than that at 2.4 GHz, when the index of location is 1, 3, 4 and 5. Simultaneously, RMSE of proposed method is almost same as that of conventional one using RSS at 5.2 GHz.

In the other locations, RMSE of the conventional method using RSS at 2.4 GHz is smaller than that of conventional one using RSS at 5.2 GHz; RMSE of proposed method is almost same as that of conventional one using RSS at 2.4 GHz. Consequently, the proposed method reduces the positioning error attributed to the deep fade at 8 locations in the conference room.

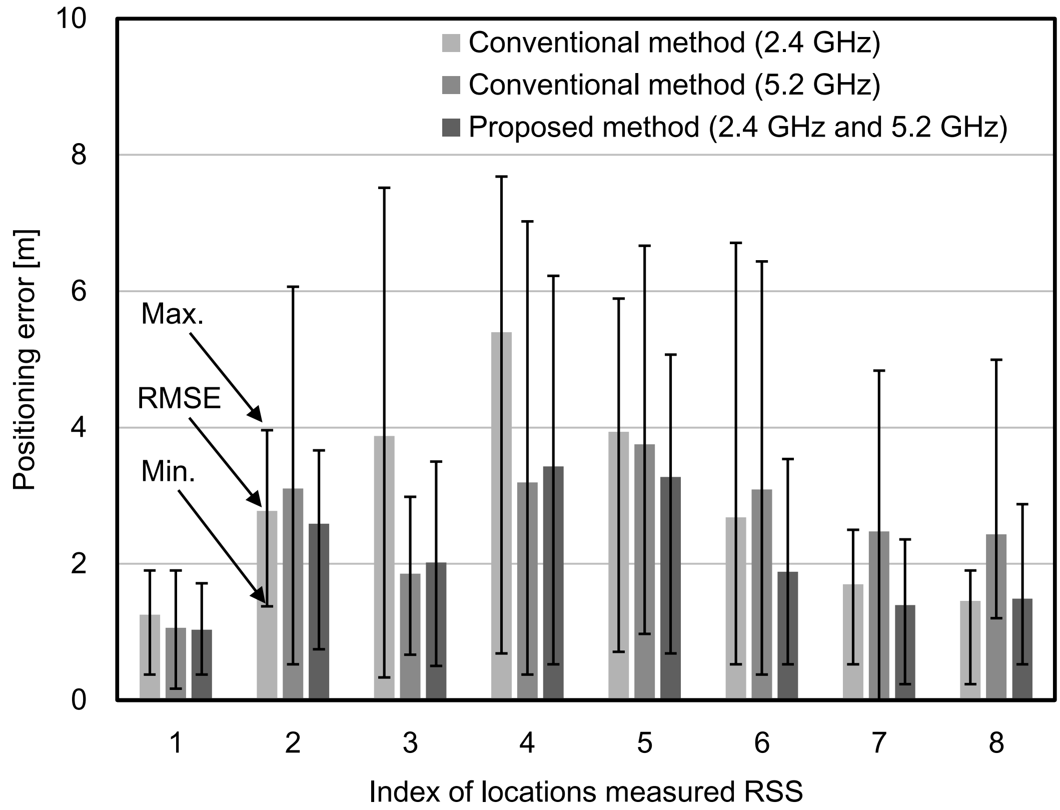

Figure 4.11 The positioning error at 8 locations in the conference room when a smartphone is held in the left hand.

Moreover, a cumulative distribution function (CDF) of positioning error used in the proposed method and conventional one is shown in Fig. 4.12. As shown in the figure, the positioning error in 95 % (2 standard deviation) of the proposed method is 41 % lower than that of the conventional one using RSS at 2.4 GHz; the positioning error in 68 % (a standard deviation) of the proposed method is 28 % lower than that of the conventional one. These results indicate that the proposed method is particularly useful to reduce a large positioning error (i.e. 4 m or more).

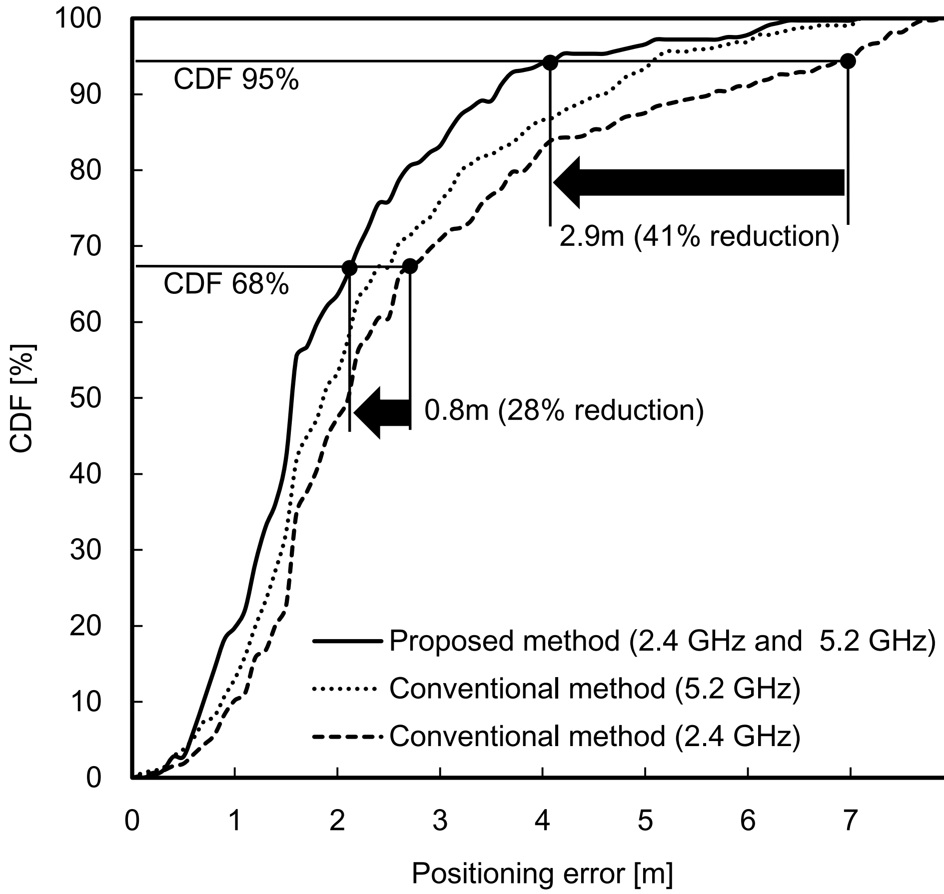

Figure 4.12 CDF of positioning error used in the proposed method and the conventional method [41].

RMSEs of the proposed method and the conventional one are evaluated in regard to the number of averaged samples, N. The evaluated RMSE values are plotted in Fig. 4.13. According to the figure, RMSE of the proposed method is lower than that of the conventional one.

These results indicate that the proposed method is more accurate than the conventional one using RSS at single frequency band in the case of sparse AP deployment (9 m×9 m) in the conference room. RMSE of proposed method satisfies the target assumed in this study (i.e. less than RMSE of conventional method).

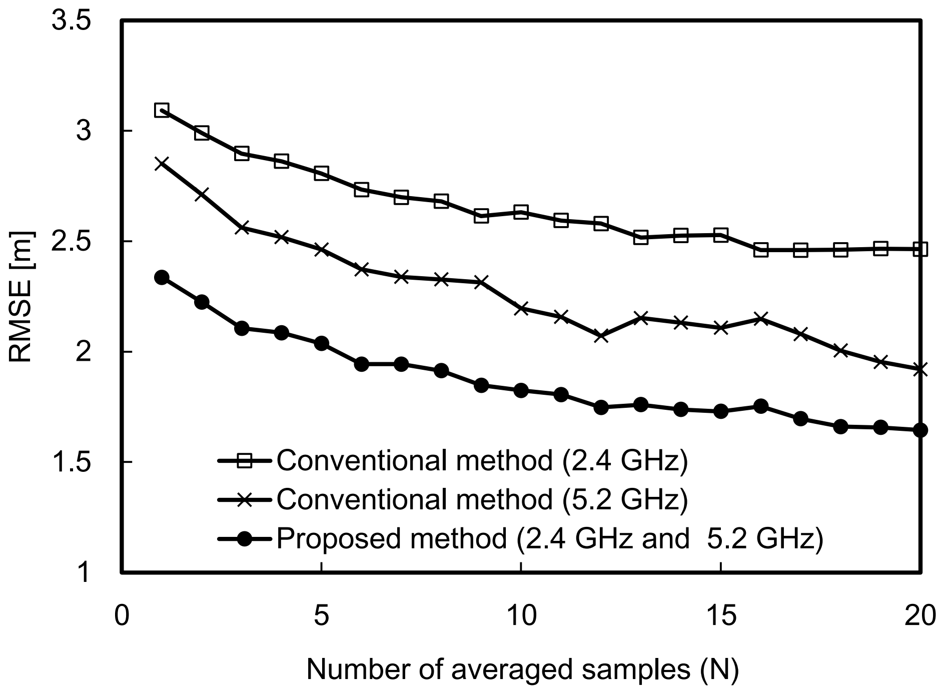

Figure 4.13 RMSE versus the number of averaged samples.

4.5 Conclusion

A WLAN positioning system for sparse AP deployment in an indoor environment is proposed to reduce the positioning error attributed to the deep fade. A method for positioning utilizes RSS at dual frequency bands (i.e. 2.4 GHz and 5.2 GHz). In addition, to compensate the power absorption by the user at dual frequency bands, the power-absorption-based model [41] is used. To verify the effectiveness of the proposed method, RMSE of the proposed method is evaluated in a conference room and compared to that of the conventional method using the power-absorption-based model at single frequency band. The distance between two APs was 9m in the conference room. RMSE of the conventional method was 2.56 to 2.90 m. That of the proposed method was 2.11m, which satisfies the target assumed in this study (i.e., less than that of conventional method). It is therefore concluded from these results that the proposed method can provide accurate positioning in the case of sparse AP deployment in an indoor environment.

Chapter 5

RFID Positioning System Using Mobile Phone Built-in UHF Active Tag and Passive-tag Reader

5.1 Introduction

To improve an efficient of manufacturing processes in a factory, RFID system is attracting considerable attention. An active tag uses battery to realize a long-range communication. A maximum communication distance of the active tag is over 20 meters [44], thus the active tag is used for RFID positioning system to detect a position of workers in a large-scale indoor environment, such as a factory. A conventional RFID positioning system is required installation of many base stations [45], it is however complicated.

A passive tag is a low cost device, because it does not have the battery. The passive tag therefore can be attached to many objects in the factory. Hence, the passive tag is used for a large amount of inventory management [46]. In the case of the inventory management, a conventional passive-tag reader receives a signal containing an identification data of passive tag is too large to carry [47].

To overcome these problems, a compact RFID module inserted into a mobile phone is developed. The RFID module has three functions; a reader function, an active-tag function, a base-station function [48]. RFID positioning system using the RFID module is developed to estimate the working area of workers. It is not required installation of the base station. Then, a performance of the RFID positioning system is evaluated in a factory.

5.2 Development of RFID Module

The functions of the mobile phone with built-in the RFID module (hereafter, "RFID mobile phone") is shown in Fig. 5.1. As shown in the figure, in the passive-tag communication, the RFID mobile phone receives the signal containing an identification data of the passive-tag using the reader function. In the active-tag communication, the RFID mobile phone utilizing active-tag function received a signal from other RFID mobile phone using the base-station function.

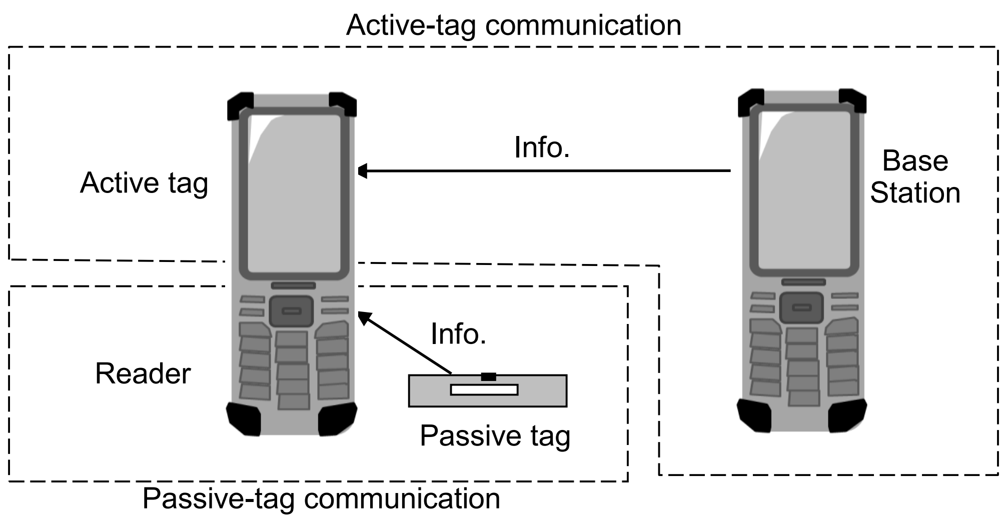

Figure 5.1 Functions of the RFID mobile phone with built-in RFID module.

5.2.1. Specification of RFID Module

The specification of the developed RFID module is shown in Table 5.1. As listed in the table, the RFID module is inserted to a SDIO (Secure Digital Input / Output) interface on the mobile phone. Hence, the specification of the RFID module size is set as SDIO slot size (24× 57× 4 mm). The mobile phone controls the RFID module via the SDIO interface. In addition, SDIO interface supplies a power to the RFID module from the mobile phone's battery.

Table 5.1 Specification of the developed RFID Module.

<table>
<tr><td>Item</td><td colspan="2">Specification</td></tr>
<tr><td>Mobile-phone Size</td><td colspan="2">48 mm × 138 mm × 19.7 mm</td></tr>
<tr><td>RFID-Module Size</td><td colspan="2">24 mm × 57 mm × 4 mm</td></tr>
<tr><td>Supply Voltage</td><td colspan="2">1.8 V, 3.3 V</td></tr>
<tr><td>Interface for connecting with mobile phone</td><td colspan="2">SDIO</td></tr>
<tr><td rowspan="2">Distance</td><td>Passive tag</td><td>More than 3 cm
(RF Power: 10 mW)</td></tr>
<tr><td>Active tag</td><td>More than 20 m
(RF Power: 1 mW)</td></tr>
</table>

Regarding the passive-tag communication, it is assumed that the RFID mobile phone is touched to the passive tag to read the identification data. A target of reading distance is therefore set as 3 cm or more. In addition, the passive-tag communication protocol is compatible with the international Standard (ISO/IEC18000-6C [49]).

To detect the working area of the workers holding the RFID mobile phone in a factory, the active tag must receive the signal at a long distance from the base station. Therefore, a target of the maximum communication distance for the active tag is set to be longer than that of a conventional active-tag communication (IEEE 802.15.4 standard), that is, 20 m or more [44].

5.2.2. Architecture and Design

To mount the conventional active-tag communication [44] and passive-tag communication onto the RFID module, the RFID module must be implemented the two kinds of components, such as RF circuits, modulators, and antennas and so on. A size of the components for the conventional active-tag communication is 30 × 30 mm [50] and it is occupied 68 % of the RFID module. Thus, if the two kinds of components are embedded in the RFID module, the RFID module size would be bigger than target specification size. (24 mm × 57 mm × 4 mm)

To avoid the problem, a novel active-tag communication is proposed. An air interface for the proposed active-tag communication is shown in Table 5.2. According to Table 5.2, to realize the target size of the RFID module, the active-tag and passive-tag communications use the same carrier frequency, modulation, coding, and transmission rate. They can therefore share the same modulators, the RF circuit, and the antenna.

Moreover, as a frame format of the proposed active-tag communication, communication protocol is designed on the basis of an international standard for passive-tag communication (ISO/IEC18000-6C). The frame format of the proposed active-tag communication is shown in Fig. 5.2. According to the figure, the frame format consists of a preamble using FM0 coding and a cyclic redundancy check (CRC), which are the same as those used in passive-tag communication.

To permit a change of data length, a length field is added in front of the data field. To select either one-way communication or interactive communication, a property field is added too. The property field distinguishes whether transmitter is the base station or active-tag. The property is defined “1” for the base station and “0” for the active-tag.

Table 5.2 Air interface for the proposed active-tag communication.

		Passive-tag Communication	Proposed Active-tag Communication
Carrier Frequency		951.0 -957.4 MHz	951.0 - 957.4 MHz
Modulation		ASK	ASK
Coding	Tx	PIE	FM0
	Rx	FM0	
Transmission rate	Tx	40 kbps	40 kbps
	Rx		

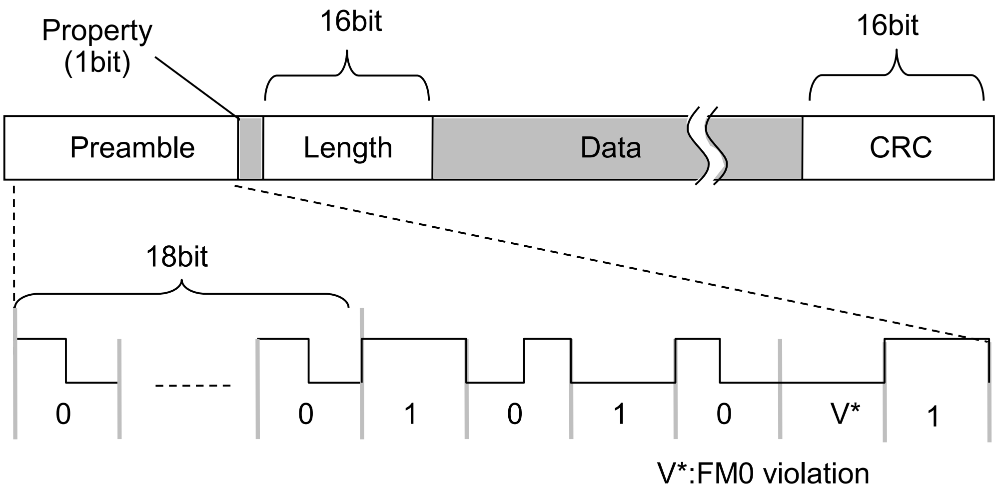

Figure 5.2 Frame format for the proposed active-tag communication.

Fig. 5.3 shows the circuit block of RFID module [51]. As shown in the figure, circuit components are composed of internal antennas [52], SAW filter (Surface Acoustic Wave), a directional coupler, an amplifier and LSI.

The passive-tag communication is shown schematically in Fig. 5.4. When the reader receives a response from a passive tag, the reader has to send a continuous wave (CW) to supply power to the passive tag, and the CW interferes with the reception. To reduce the interference, the directional coupler is therefore embedded in between a receiving circuit and a transmitting circuit.

In the active-tag communication, CW is not needed because the power for activating the active tag is supplied from a battery. In addition the directional coupler is not needed too. The RF circuit therefore switches the received signal path to bypass the directional coupler, which causes a power loss of the received signal.

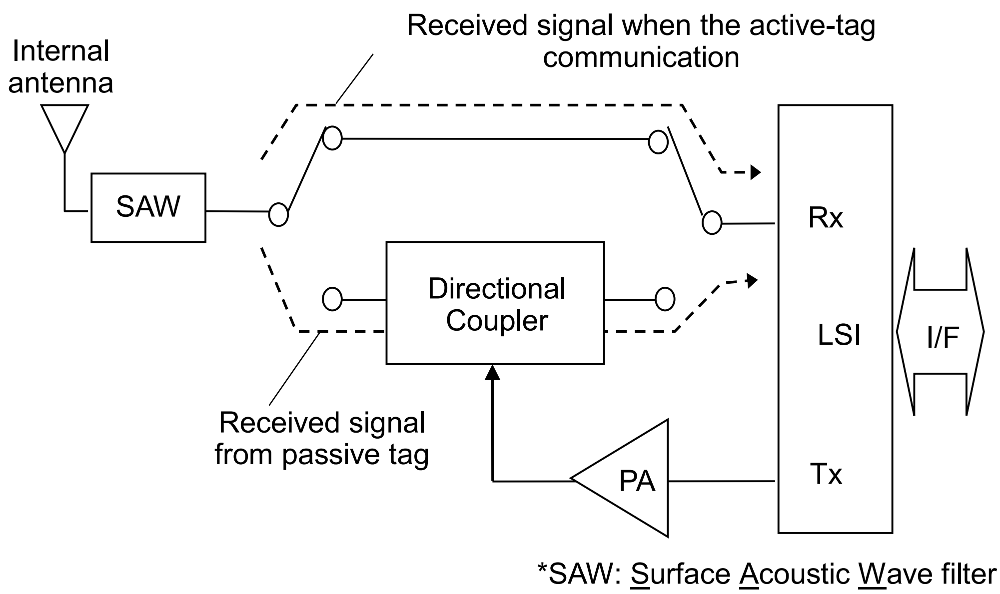

Figure 5.3 Circuit block of developed RFID module.

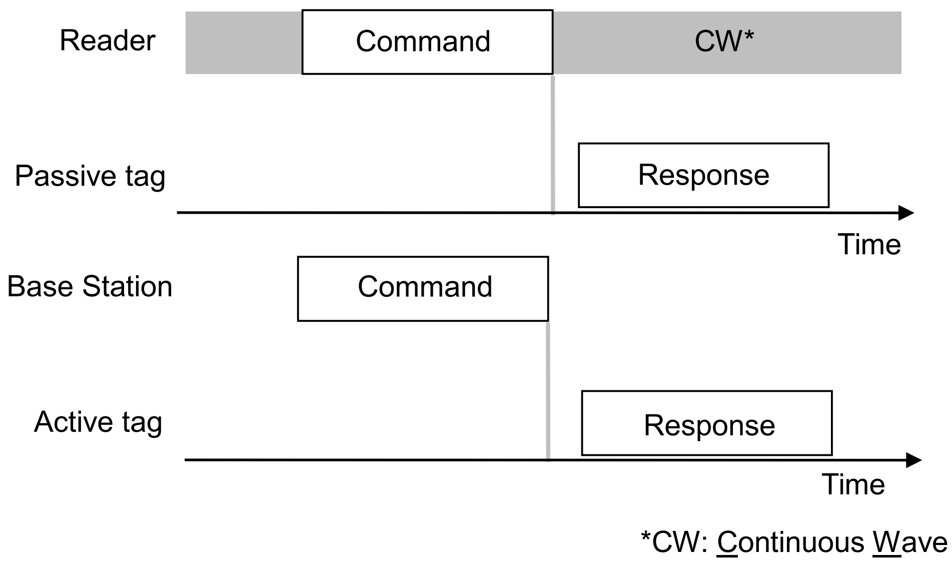

Figure 5.4 Communication of passive tag and active tag.

5.2.3. Active-tag Communication Protocol

To share the components for the passive-tag communication with the active-tag communication, a protocol for the active-tag communication is developed. The active-tag communication protocol [53] is shown in Fig. 5.5.

According to the figure, to avoid interference with nearby base stations, the base station can set any channel and execute carrier sensing over 10 ms. During the carrier sensing, the base station measures the carrier-wave power on a transmission channel. If the carrier-wave power is less than -75 dBm, the base station can transmit signals on the channel [54].

The base station continuously transmits the signal for 1000 ms or less. It stops transmitting the signal for 100ms or more after the initial 1000 ms transmission. The continuous-transmission period of time and the transmission-off period of time are set according to Japanese standard, ARIB-STD-96 [54].

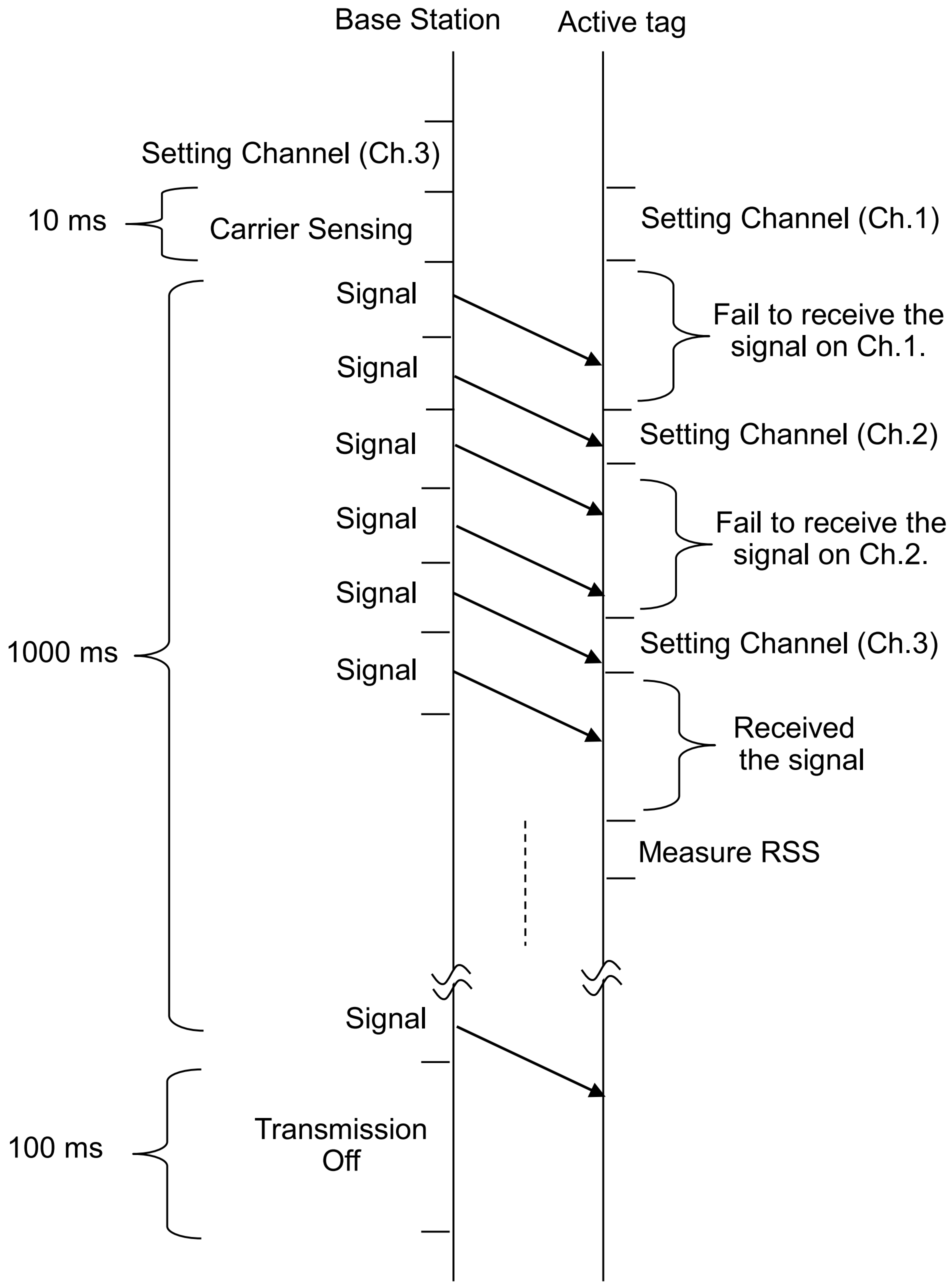

Figure 5.5 Active-tag communication protocol.

The active tag selects a channel to receive the signal from the base station. A period of time on each channel is set as more than the length of two signals and that of stopping transmission (100 ms). If the active tag receives only half of the signal, the active tag thereby can receive the next signal completely. Then, to estimate a position of the active tag carried by the worker, the active tag measures RSS of the signal.

Actual transmission signal from base station is shown in Fig. 5.6. As shown in the figure, a transmission interval of a 128-bit signal is approximately about 17.3 ms. Therefore the period of time on each channel is set as more than 134.6 ms. The proposed active-tag communication protocol is applied to one-way communication; however, it was possible to be extended to interactive communication, too.

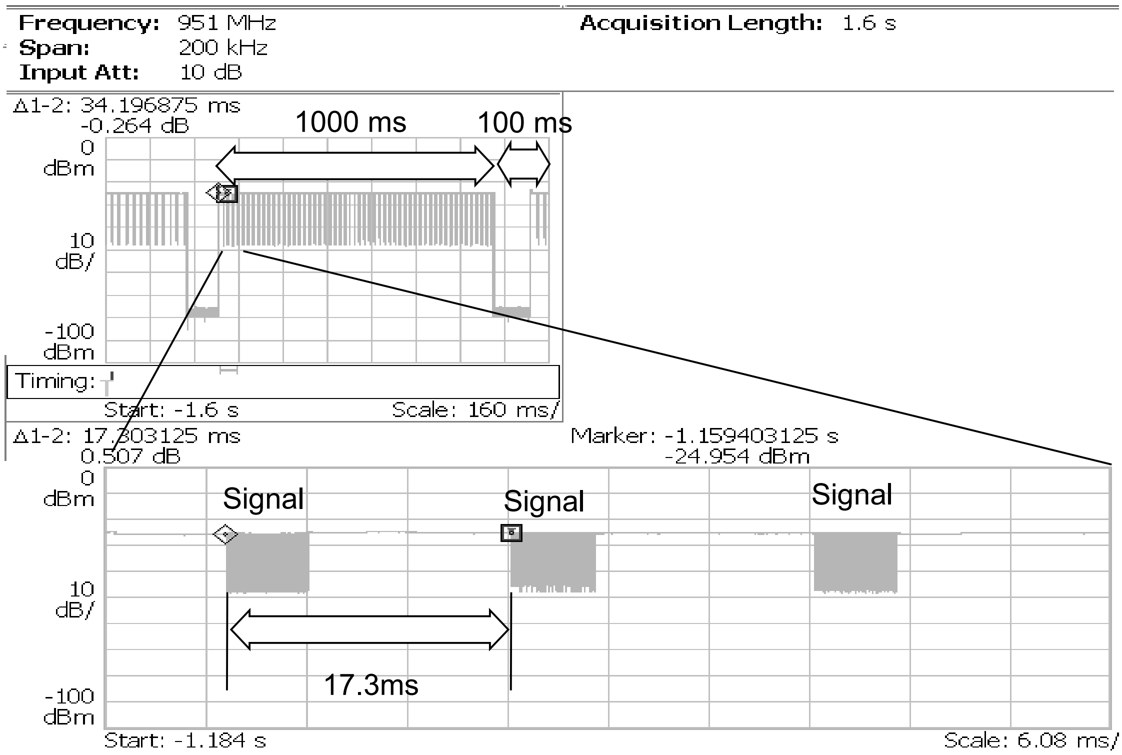

Figure 5.6 Transmission signal wave from base station.

5.2.4. Performance Evaluation

The developed RFID module (and a mobile phone into which it is inserted) is shown schematically in Fig. 5.7. The size of the RFID module is 24 mm × 57 mm × 4 mm, which meets the specification for the RFID module.

To clarify the performance of the RFID module inserted in the mobile phone, the maximum communication distance is evaluated as explained in the following. The distance for the active-tag communication and the passive-tag communication is evaluated in outdoor testing. The carrier frequency is set as 951MHz.

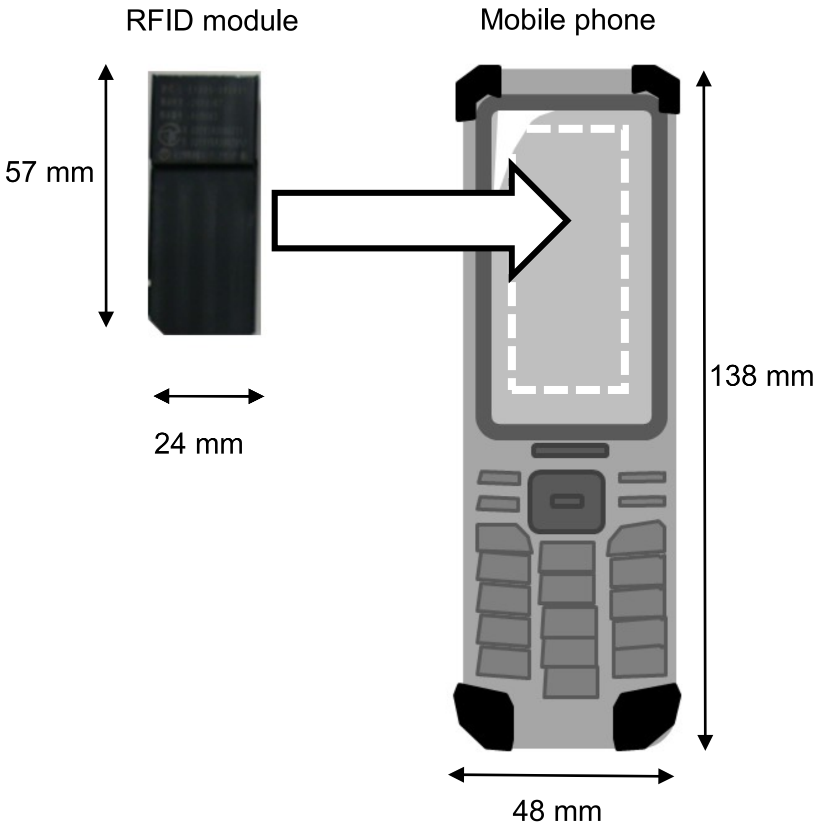

Figure 5.7 Developed RFID module with Mobile phone.

The evaluated results are shown in Table 5.3. According to these results, the maximum distance of active-tag communication is 75 m, while that of passive-tag communication is 5 cm. In other words, the developed RFID module meets the specification for the maximum communication distance (i.e., 20 m or more for active-tag communication, 3 cm or more for passive-tag communication).

Table 5.3 The maximum communication distance in outdoor testing.

	Active-tag Communication	Passive-tag Communication
Distance (max.)	75 m	5 cm

5.3 Development of RFID Positioning System

To detect working area of workers in a large-scale factory, an RFID positioning system is developed. A conventional RFID positioning system using RSS [45] is shown in Fig. 5.8. According to the figure, the conventional system is that the active tag carried by the worker transmitted a signal to base stations installed in the factory. Then, these base stations measure RSS. Thereafter, a positioning server estimates a position of the worker using the measured RSS.

The conventional RFID positioning system requires connecting between many base stations and a positioning server via LAN cables. It is troublesome to construct the RFID positioning system. In particular, it has become a barrier to implement the RFID positioning system, because the system requires rebuilding in the case of changing the layout of facilities in a factory. Therefore, a novel RFID positioning system without settlement of base stations is developed.

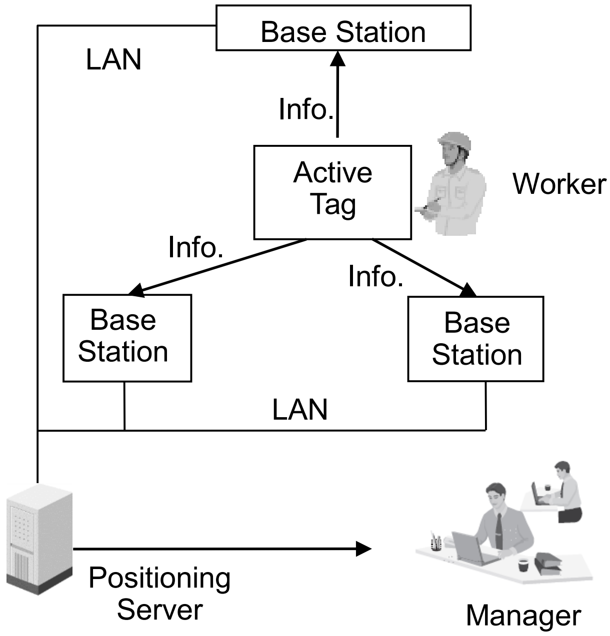

Figure 5.8 Conventional RFID positioning system.

5.3.1. RFID Positioning System

To construct the RFID positioning system without the settlement of base stations, a proposed RFID positioning system is shown in Fig. 5.9. As shown in the figure, the worker (A) works in fixed area with the RFID mobile phone (A). In this case, the RFID module built into the RFID mobile phone (A) is used as the base station.

In detail, the passive tag is set up in working area. The RFID mobile phone (A) receives a signal containing the identification data of the passive tag, when the worker (A) stays in the working area. Then, the RFID mobile phone (A) transfers the identification data to the positioning server using an internet function. The internet function is able to transmit the identification data to the positioning server via the internet. The positioning server estimates the position of the worker (A) in the working area related to the identification data.

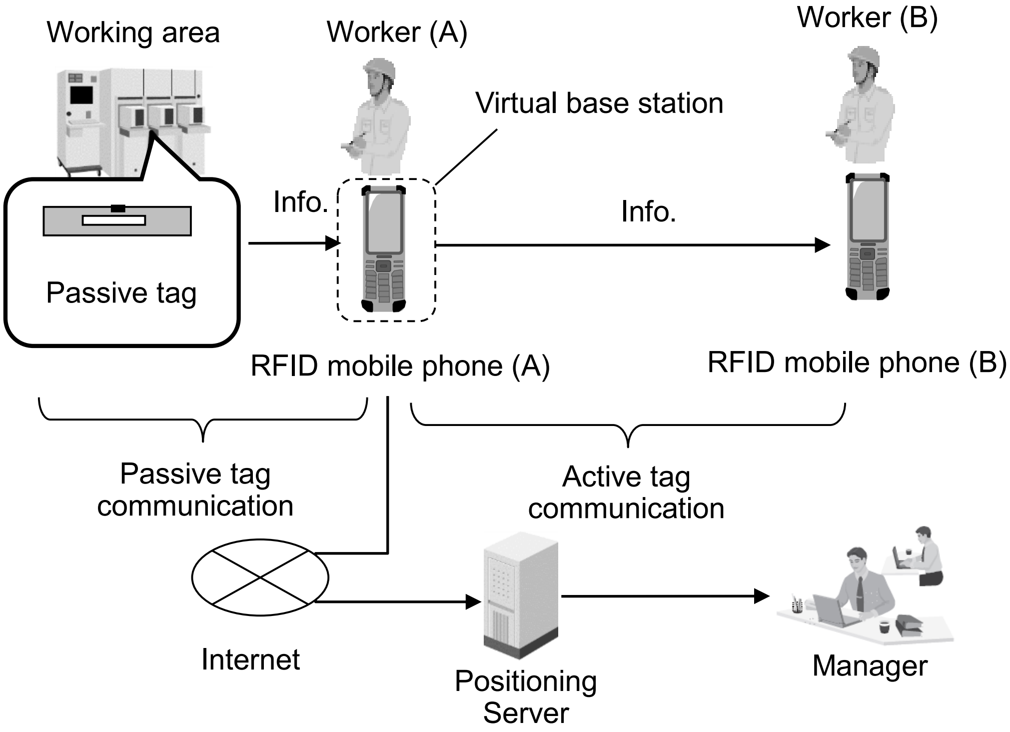

Figure 5.9 Proposed RFID positioning system.

Then, the RFID mobile phone (A) as a virtual base station transmits a signal to the RFID mobile phone (B). On the other hand, the RFID mobile phone (B) held by the worker (B) receives the signal. The RFID mobile phone (B) transfers the measured RSS and the identification data by using the internet function to the positioning server.

The positioning server estimates the position of the worker (B) using RSS and the identification data related to the working area. More precisely, the positioning server compares several RSS of received signals transmitted from RFID mobile phones in various working areas. Then, the signal of the strongest RSS is collected. The position of the worker (B) is determined as the working area set the RFID mobile phone transmits the signal of the strongest RSS. Accordingly, a manager is possible to grasp where the workers are by accessing the positioning server.

The proposed system requires an operational procedure that the worker puts the RFID mobile phone on the passive-tag during the work in this area. A use case is assumed that a worker is not frequently required leaving from the designated area. For instance, the worker assembles parts at designated area through a long period of time.

Consequently, the proposed system is constructed without settlement of the base station. In addition, the proposed system is possible to detect the position of all workers.

5.3.2. Control Method for RFID Mobile Phone

To realize the proposed RFID positioning system, a novel control method for the RFID mobile phone is proposed. The RFID mobile phone using the control method can recognize the state of the worker by only placing itself close the passive tag in the working area, and switch four functions (i.e. the reader function, the base station function, the active-tag function and the internet function) according to the state.

A state-transition diagram for controlling the RFID mobile phone is shown in Fig. 5.10. As shown in the figure, the RFID mobile phone has two basic transitions (C1, C2), and four states (S1to S4).

RFID mobile phone is controlled based on the basic transition C1, when the RFID mobile phone is placed nearby the passive tag in the working area. In this case, the RFID mobile phone receives a signal containing the identification data of the passive tag using the reader function, and recognizes the state in which the RFID mobile phone is placed nearby the passive tag (the state S1 in Fig. 5.10). The identification data is transferred to the positioning server through the internet function of the RFID mobile phone (the state S2 in Fig.5.10). Then, the base-station function is used to transmit the signal that includes the identification data (the state S3 in Fig. 5.10). The RFID mobile phone switches the function from the base-station function to the reader function after prescribed period (the state S1).

Therefore, the RFID mobile phone transmits the signal as the base station, when the RFID mobile phone is placed nearby the passive tag in the working area. The positioning server is simultaneously able to estimate the position of the worker on the basis of the identification data. Because, the RFID mobile phone periodically read the identification data of the passive tag related to the working area.

If the distance between the RFID mobile phone and the passive tag is 5 cm or more, the active-tag function of the RFID mobile phone is automatically enabled.

The RFID mobile phone is controlled based on the basic transition C2, when the RFID mobile phone is carried by the moving worker. In this case, the RFID mobile phone tries to receive a signal containing the identification data by using the reader function (the state S1 in Fig. 5.10). However, the RFID mobile phone fails to receive the signal containing the identification data of the passive tag.

Then, the active-tag function of the RFID mobile phone is enabled to receive the signal from other RFID mobile phone (the state S4 in Fig. 5.10). The received signal and RSS are transferred to the positioning server using the internet function (the state S2 in Fig. 5.10).Then, the reader function of the RFID mobile phone is enabled again (the state S1).

Consequently, the positioning server is able to estimate the position of the moving worker based on RSS because the active-tag function of the RFID mobile phone is enabled periodically in the basic transition C2.

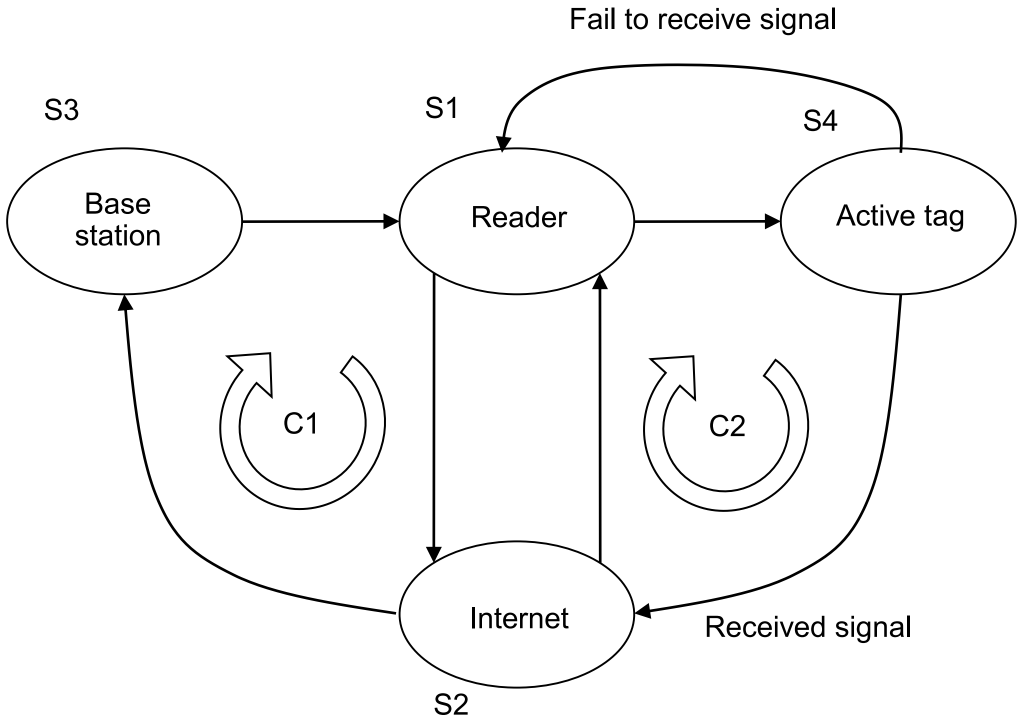

Figure 5.10 State-transition diagram for controlling the RFID mobile phone.

5.4 System Evaluation

To evaluate the feasibility of estimating a worker's position by using the proposed RFID positioning system, a radio propagation in a factory is measured. Then, the proposed RFID positioning system is constructed and the accuracy of the estimated worker's position is evaluated.

5.4.1. Radio Propagation in Factory

To evaluate the radio propagation in a factory, RSS is measured as follows. RSS was measured at a distance between two RFID mobile phones of 10 m to 70 m. One of the

RFID mobile phones as the base station is fixed in an aisle. Other RFID mobile phone is put in a chest pocket of the worker. Then, the measured RSS is compared with the RSS calculated based on the free-space path loss model [39] given by

$$RSS = P_{BS} - 20\log\left(\frac{4\pi d}{\lambda}\right), \ \ \lambda = \frac{c}{f}, \qquad (5.1)$$

where P_{BS} is the transmission power of RFID mobile phone as the base station, d is distance, c is the speed of light, and carrier frequency f is taken as 951 MHz .

In the experimental environment, many metal cabinets and facilities are dotted in about 100 m scale factory. The active-tag communication between two RFID mobile phones is basically line-of-sight communication. However, RSS is measured under the situation that a number of workers passed frequently between the RFID mobile phones.

The measured RSS in the factory is shown in Fig. 5.11. As shown in the figure, a dispersion value is defined as the range between the maximum RSS and minimum RSS. Maximum dispersion value is 16 dB. The average of measured RSS has mostly the same characteristics as the estimated RSS. Thus, this result indicates that using the average of measured RSS is effective for positioning the worker with high accuracy.

To estimate the position of worker walked in a factory, the dispersion of moving average is measured when the worker carrying the RFID mobile phone walks at a constant speed (1.0m/s). The moving average is calculated by using 5 samples. Fig. 5.12 shows the result of moving average. As shown in the figure, the dispersion of moving average is approximately 5 dB and it is less than that in the case of without averaging (Fig. 5.11). Therefore, we apply moving average of RSS for estimation of workers' position in the RFID positioning system.

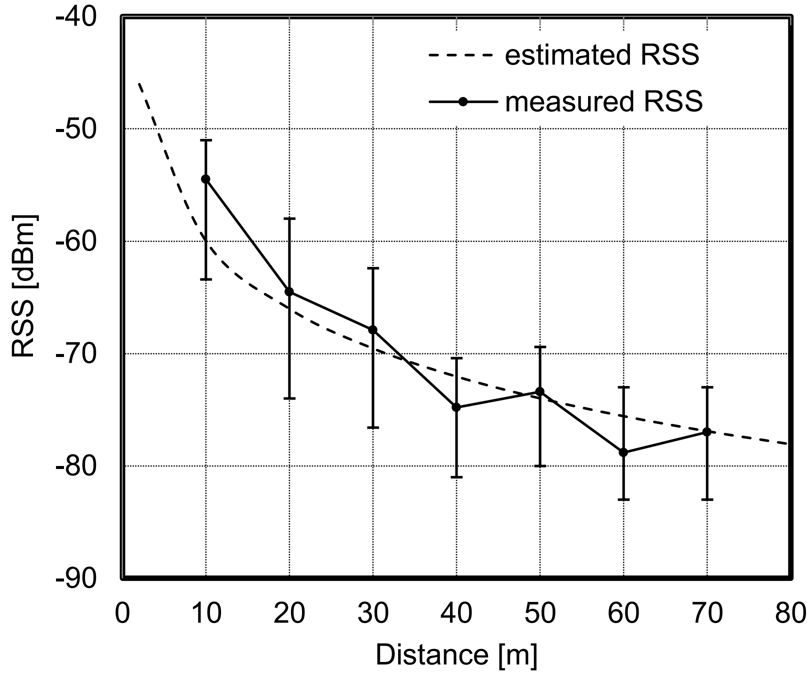

Figure 5.11 RSS in a factory.

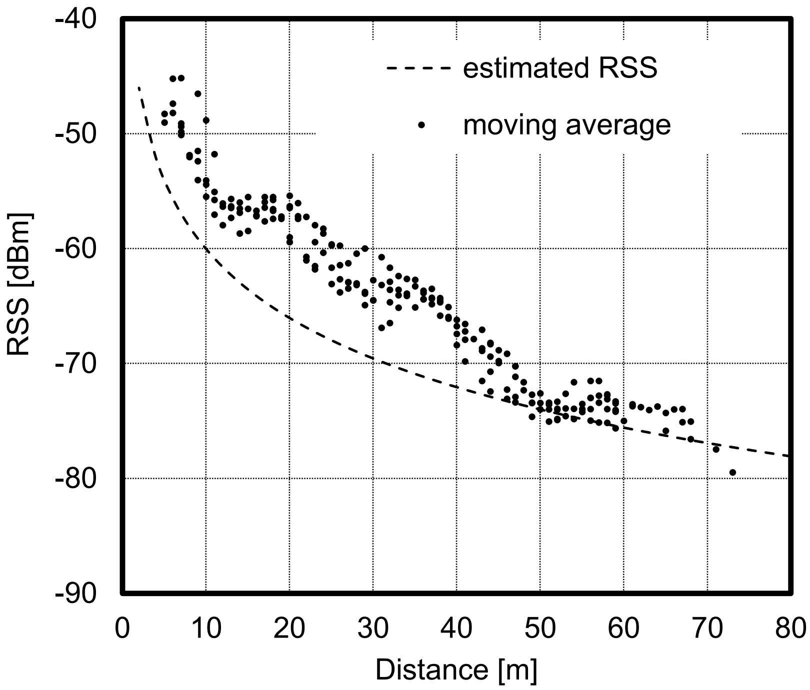

Figure 5.12 Moving average of RSS in a factory.

5.4.2. Positioning Accuracy

To evaluate the feasibility of the RFID positioning system, RFID positioning system is constructed and the accuracy of the estimated worker's position is evaluated. The experimental setup for positioning is shown in Fig. 5.13. As shown in Fig. 5.13, the passive tags (A) (B) are set at the center of the two working areas, and the RFID mobile phones (A) (B) receive the signal containing the identification data of passive-tag using the reader function. Then, the RFID mobile phones (A) (B) transmit the signal using the base-station function. In this experiment, the RFID mobile phones are placed in the working areas based on the assumption that the RFID mobile phones are not carried by the workers because the workers work at designated place for long hours. Each carrier frequency of the RFID mobile phones is set to 951 MHz and 951.6 MHz for each.

Other worker carrying the RFID mobile phone (C) walks at constant speed (1.0m/s) in the working area. Many metal cabinets and facilities are dotted in the working area. The worker accordingly adjusts the walking direction to walk evenly inside the working area for 5 minutes.

A positioning method for the RFID positioning system utilizes the proximity detection (the detail is described in 2.2.1). The proximity detection estimates the worker's position based on the strongest RSS. In this evaluation, the RFID positioning system compares the RSS of the transmitted signal from RFID mobile phone (A) with that from RFID mobile phone (B). The RFID positioning system determines the worker's position as the area (A), when the signal of the strongest RSS is transmitted from RFID mobile phone (A). The positioning accuracy is evaluated using the 50 samples of RSS.

The positioning accuracy is shown in Fig. 5.14. According to the figure, the positioning accuracy was 100% when the moving average of RSS is used for positioning. The positioning accuracy is 92 to 96 % when one sample of RSS was used for positioning. Therefore, this result indicates that moving average of RSS reduced RSS fluctuations caused by multipath fading attributed to the reflection of microwaves from metal facilities, walls and floor. According to the result, the proposed RFID positioning system is able to be constructed without settlement of the base station. Moreover, it is able to estimate the worker's position within the working area (20 m by 20 m) size

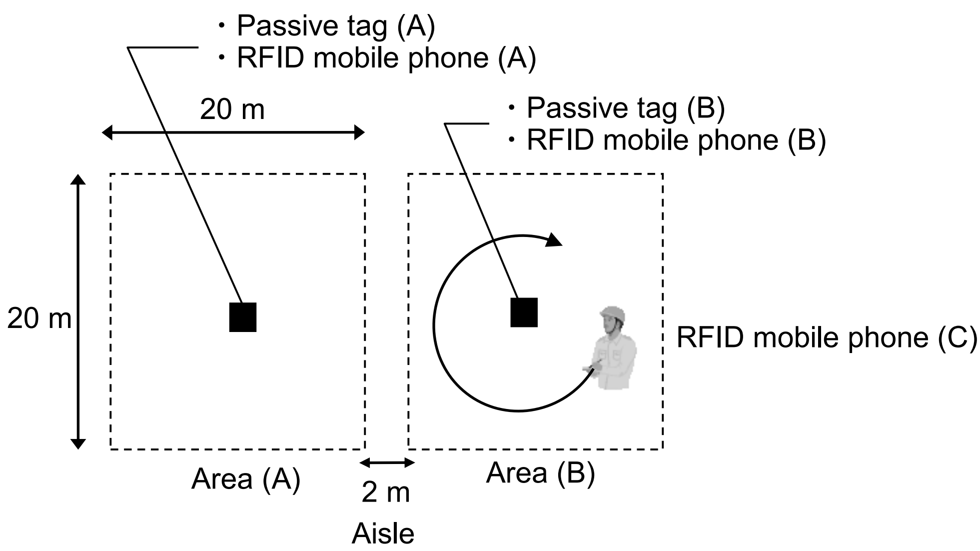

Figure 5.13 Experimental setup for positioning.

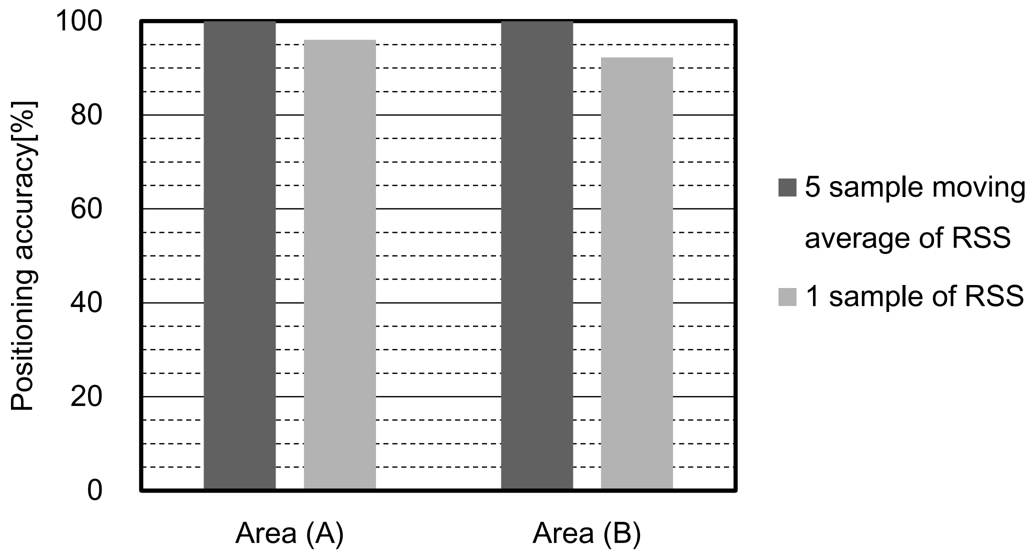

Figure 5.14 Positioning accuracy in factory.

5.5 Conclusion

In this Chapter, the small-sized RFID (24 mm × 57 mm × 4 mm) module inserted into the mobile phone is developed, which has functions of the passive-tag reader, the active tag and base station. Further, mixing use of the passive-tag reader and the active tag in the RFID module, the RFID positioning system is proposed, and the system is evaluated in a factory.

The proposed system is able to be constructed without settlement of the base station. Moreover, it is able to estimate the worker's position within the working area (20 m by 20 m) size.

From a practical perspective, a large-scale RFID positioning system is needed to assign a channel to avoid the interference between the RFID mobile phones transmitted a signal using the base-station function. Assignment of the channel for the RFID positioning system is a future work.

Chapter 6

Conclusion

In this chapter, we conclude this dissertation and discuss future work.

6.1 Contributions

To apply the indoor positioning system to a navigation service in a large-scale shopping mall and an employee-location-management service at a large-scale factory, the indoor positioning system using a long range wireless communication system (e.g. WLAN, RFID) is developed. Regarding the navigation service, low cost and high accuracy positioning system is desired. In this study, the cost is defined as a density of APs (access points). To achieve the high accuracy positioning and sparse AP deployment, WLAN positioning system is proposed. Regarding the employee-location-management service, a main issue of applying a positioning system is cost to construct it. A conventional positioning system requires installation of many base stations. To overcome this problem, a novel RFID positioning system is developed. In conclusion, we summarize the main contributions of this dissertation.

Power-absorption-based Model in WLAN Positioning System Using Smartphone:

To achieve accurate WLAN positioning using a smartphone in the case of sparse AP deployment in an indoor environment, the positioning method is proposed. The method utilizes a proposed model of power absorption by a user. The directivity of the power absorption is measured using a magnetic sensor built into the smartphone. RMSE of the proposed method is 34 % lower than that of the conventional one. In detail, RMSE of the proposed method is 1.94 m in a room (distance between APs is 6 m).

It is therefore concluded from these results that the proposed method can provide accurate positioning using a smartphone in the case of sparse AP deployment in an indoor environment.

WLAN Positioning System Utilizing RSS at Dual Frequency Bands:

To improve the positioning accuracy in the case of sparser AP deployment, the WLAN positioning system is proposed. In particular, to reduce the positioning error attributed to the deep fade, the proposed method utilizing RSS at dual frequency bands (i.e. 2.4 GHz and 5.2 GHz) is proposed. In addition, to compensate the power absorption by the user at dual frequency bands, the power-absorption-based model is used. RMSE of the proposed method is lower than that of the conventional one. RMSE of the proposed method is 2.11 m in a conference room (distance between APs is 9 m).

This result indicates that the proposed method can improve the positioning accuracy in the case of sparser AP deployment.

RFID Positioning System Using Mobile Phone Built-in UHF Active Tag and Passive-tag Reader:

The small-sized RFID (24 mm × 57 mm × 4 mm) module inserted into the mobile phone is developed, which has functions of the passive-tag reader, the active tag and base station. Further, mixing use of the passive-tag reader and the active tag in the RFID module, the RFID positioning system is proposed.

The proposed system is able to be constructed without settlement of the base station. Moreover, it is able to estimate the worker's position within the working area (20 m by 20 m) size.

6.2 Future Works

The proposed WLAN positioning system using smartphone realized the sparse AP deployment in an indoor testing such as a conference room and a lecture room. These rooms are not equipped with partitions and tall shelves. These equipments are set often in a shopping mall and a factory, then it blocks the signals from APs. Therefore, to use the proposed system in the above environment, development of a model related to the power absorption by the partition and tall shelf is required.

In addition, the height of AP is 1.2 m to 1.5 m in the indoor testing. AP sometimes is set on ceiling. Clarifying the power absorption by the user in the case of a multiple height of AP is thereby needed.

To clarify the influence of pedestrians in the proposed system, RMSE is evaluated when pedestrians walked around the room. RMSE is not proportional to the number of pedestrians. As a result of the analysis, the fluctuation of RSS is found to be unproportional to the number of pedestrians. This finding explains the above-mentioned relation between RMSE and the number of pedestrians in this evaluation. Clarifying a general relation between RMSE and the number of pedestrians is a future work.

The proposed RFID positioning system is able to estimate the worker's position within the working area (20 m by 20 m) size in a factory. The proposed system is evaluated in the case of two working areas. From a practical perspective, a large-scale RFID positioning system is needed to assign a channel to avoid the interference between the RFID mobile phones transmitted a signal using the base-station function. Assignment of the channel for the RFID positioning system is a future work.

Bibliography

[1] G. Retscher and T. Hecht, "Investigation of Location Capabilities of four Different Smartphones for LBS Navigation Applications," in *Proc.* IEEE International Conference on Indoor Positioning and Indoor Navigation (IPIN), pp.1-6, Nov. 2012.

[2] Ministry of Internal Affairs and Communications, Japan "2014 White Paper on Information and Communications in Japan," pp.56, 2014.

[3] Z. Ma, Y. Qiao, B. Lee, E. Fallon, "Experimental evaluation of mobile phone sensors," in *Proc.* IEEE Signals and Systems Conference (ISSC 2013), pp.1-8, Jun. 2013.

[4] M. Kitamura, T. Suzuki, Y. Amano, T. Hashizume, "Evaluation for Vehicle Positioning in Urban Environment using QZSS L1-SAIF Augmentation," in *Proc.* IEEE SICE Annual Conference (SICE2011), pp.491-494, Sept. 2011.

[5] K. Ishikawa, Y. Amano, T. Hashizume, J. Takiguchi, "A study of precise road feature localization using mobile mapping system," in *Proc.* IEEE/ASME international conference on Advanced intelligent mechatronics, pp.1-6,Sept. 2007.

[6] M. Kitamura, T. Suzuki, Y. Amano and T. Hashizume, "Evaluation for Vehicle Positioning in Urban Environment using QZSS L1-SAIF Augmentation," in *Proc.*

SICE Annual Conference (SICE), pp.491 – 494, Spt. 2011.

[7] E. Benítez, N. Blanco, G. Gimón, R. González, M. Huerta, S. Moreau, A. Mundo, "A traffic testbed to help in a site survey procedure for the deployment of a WiFiPhone network," in *Proc.* IEEE Latin-America Conference on Communications (LATINCOM), pp.1-7, Nov. 2012.

[8] E. Colin, A. Moretto and M. Hayoz, "Improving Indoor Localization within Corridors by UHF Active Tags Placement Analysis," in *Proc.* IEEE RFID Technology and Applications Conference (RFID-TA), pp. 181-186, Sept. 2014.

[9] I. Bisio, F. Lavagetto, M. Marchese and A. Sciarrone, "Performance comparison of a probabilistic fingerprint-based indoor positioning system over different smartphones," in *Proc.* 2013 International Symposium on Performance Evaluation of Computer and Telecommunication Systems (SPECTS), pp. 161-166, July 2013.

[10] P. Bahl and V. N. Padmanabhan, "RADAR: An In-Building RF-based User Location and Tracking System," in *Proc.* IEEE INFOCOM 2000, pp. 775–784, Mar. 2000.

[11] S. Boonsriwai and A. Apavatjrut, "Indoor WIFI localization on mobile devices," in *Proc.* 10th International Conference on Electrical Engineering/Electronics, Computer, Telecommunications and Information Technology (ECTI-CON), pp. 1-5, May 2013.

[12] A. Eisenblatter, H. Geerdes, and I. Siomina, "Integrated Access Point Placement and Channel Assignment for Wireless LANs in an Indoor Office Environment," in *Proc.* IEEE International Symposium on a World of Wireless, Mobile and Multimedia Networks, pp. 1-10, June 2007.

[13] G. H. H. Sung, T. Aoyagi, K. Hamaguchi and R. Kohno, "Study of signal propagations at 2.45 GHz for wireless BAN applications," 2010 IEEE 11th

International Symposium on Spread Spectrum Techniques and Applications (ISITA), pp.108-111, Oct. 2010.

[14] S. Krishnan, P. Sharma, Z. Guoping and O. H. Woon , "A UWB based localization system for indoor robot navigation," in *Proc.* IEEE International Conference on Ultra-Wideband (ICUWB),pp.77-82, Sept. 2007.

[15] J. K. Zaleski, T. Yamazato, "UWB positioning using known indoor features - environment comparison," in *Proc.* International Conference on, Indoor Positioning and Indoor Navigation (IPIN), pp.1-6, Sept. 2012.

[16] S. Murata, C. Yara, K. Kaneta, S. Ioroi and H. Tanaka, "Accurate Indoor Positioning System using Near-Ultrasonic Sound from a Smartphone," in *Proc.* 2014 Eighth International Conference on Next Generation Mobile Apps, Services and Technologies, pp.13-18, Sept. 2014.

[17] K. Liu, X. Liu, and X. Li, "Guoguo: Enabling Fine-grained Smartphone Localization via Acoustic Anchors," IEEE Transactions on Mobile Computing, pp.1-14, Sept. 2015.

[18] L. Li, P.Hu, C. Peng, G. Shen, F. Zhao, "Epsilon: A Visible Light Based Positioning System," in *Proc.* 11th USENIX Conference on Networked Systems Design and Implementation, pp.331-343, Apr. 2014.

[19] I. Okar, "A Bluetooth signal strength based indoor localization method," in *Proc.* 2014 International Conference on Systems, Signals and Image Processing (IWSSIP), pp.251-254, May 2014.

[20] A. Kotanen, M. Hännikäinen, H. Leppäkoski, T. D. Hämäläinen, "Experiments on local positioning with Bluetooth," in *Proc.* International Conference on Information Technology: Coding and Computing, pp.297-303, Apr. 2003.

[21] J. Hightower, R. Want and G. Borriello, "SpotON: An indoor 3D location sensing technology based on RF signal strength," Technical report, Univ. of Washington,

Dep. of Comp. Science and Eng., Seattle, WA, Feb. 2000.

[22] K. Weekly, H. Zou, L. Xie, Q. Jia and A. M. Bayen, "Indoor occupant positioning system using active RFID deployment and particle filters," in *Proc.* 2014 IEEE International Conference on Distributed Computing in Sensor Systems (DCOSS), pp.35-42, May 2014.

[23] X. Zheng, H. Liu, J. Yang, Y. Chen, J. Francisco, R. P. Martin, X. Li, "Characterizing the impact of multi-frequency and multi-power on localization accuracy," in *Proc.* 2010 IEEE 7th International Conference on Mobile Adhoc and Sensor Systems (MASS), pp.156-165, Nov. 2010.

[24] J. Chung, M. Donahoe, C. Schmandt, I. Kim, P. Razavai, and M. Wiseman, "Indoor Location Sensing Using Geo-Magnetism," in *Proc.* ACM the 9th international conference on Mobile Systems, Applications, and Services, pp. 141-154, Jun. 2011.

[25] G. Berkovich, "Accurate and reliable real-time indoor positioning on commercial smartphones," in *Proc.* 2014 International Conference on Indoor Positioning and Indoor Navigation (IPIN), pp.670–677, Oct. 2014.

[26] J. Koo and H. Cha, "Unsupervised Locating of WiFi Access Points Using Smartphones," IEEE Transactions on Systems, Man, and Cybernetics—Part C: Applications and Reviews, vol. 4, no. 6, pp. 1341-1353, Nov. 2012.

[27] A. Kushki, K. N. Plataniotis, and A. N. Venetsanopoulos, "WLAN Positioning Systems," Cambridge University Press, pp. 12-29, 2012.

[28] S. Sorour, Y. Lostanlen, and S. Valaee, "RSS Based Indoor Localization with Limited Deployment Load," in *Proc.* IEEE Global Communications Conference (Globecom), pp. 321-326, Dec. 2012.

[29] L. Pei, J. Liu, R. Guinness, Y. Chen, T. Kroger, R. Chen, and L. Chen, "The evaluation of WiFi positioning in a Bluetooth and WiFi coexistence environment,"

in *Proc.* 2012 Ubiquitous Positioning, Indoor Navigation, and Location Based Service (UPINLBS), pp. 1-6, Oct. 2012.

[30] Y. Cho, M. Ji, Y. Lee, and S. Park, "WiFi AP position estimation using contribution from heterogeneous mobile devices," in *Proc.* 2012 IEEE/ION Position Location and Navigation Symposium (PLANS), pp. 562-567, Apr. 2012.

[31] N. L. Dortz, F. Gain, and P. Zetterberg, "WiFi fingerprint indoor positioning system using probability distribution comparison," in *Proc.* 2012 IEEE International Conference on Acoustics, Speech and Signal Processing (ICASSP), pp. 2301-2304, Mar. 2012.

[32] K. Kaemarungsi and P. Krishnamurthy, "Properties of Indoor Received Signal Strength for WLAN Location Fingerprinting," in *Proc.* IEEE the First Annual International Conference on Mobile and Ubiquitous Systems: Networking and Services (MobiQuitous), pp. 14-23, Aug. 2004.

[33] Y. Zhao, N. Patwari, P. Agrawal and M. G. Rabbat, "Directed by Directionality Benefiting from the Gain Pattern of Active RFID Badges," IEEE Transactions on Mobile Computing, Vol. 11, No. 5, May 2012.

[34] T. Gadeke, J. Schmid, W. Stork and K. D. Muller-Glaser, "Pedestrian Dead Reckoning for Person Localization in a Wireless Sensor Network," in *Proc.* 2011 International conference on indoor positioning and indoor navigation, pp. 1-4, Sept. 2011.

[35] J. Bird and D. Arden, "Indoor navigation with foot-mounted strap down inertial navigation and magnetic sensors [Emerging Opportunities for Localization and Tracking]," IEEE Wireless Communications, Vol.18, No.2 pp. 28-35, Apr. 2011.

[36] M. Yamamoto and T. Ohtsuki, "Power Compensation in WLAN Positioning Using a Smartphone," in *Proc.* 2014 IEEE Ninth International Conference on Intelligent Sensors, Sensor Networks and Information Processing (ISSNIP), pp.

1-6, Apr. 2014.

[37] S. S. Aljaafreh, Y. Huang, and L. Xing, “A Compact, Wideband and Low Profile Planar Inverted-L Antenna,” in *Proc.* The 8th European Conference on Antennas and Propagation, pp. 3283-3286, Apr. 2014.

[38] G. Augusitn, B. P. Chacko and T. A. Denidni, “Printed Folded Monopole Antenna for Portable Devices operating in LTE/GSM/UMTS/WiFi bands,” in *Proc.* The 16th International Symposium on Antenna Technology and Applied Electromagnetics, pp. 1-2, July 2014.

[39] D. C. Hogs, “Fun with Friis Free-Space Transmission Formula,” in *Proc.* IEEE Antennas and Propagation Magazine, pp. 33-35, Aug. 1993.

[40] Y. Song and H. Yu, “A RSS Based Indoor Tracking Algorithm via Particle Filter and Probability Distribution,” in *Proc.* 4th International Conference on Wireless Communications, Networking and Mobile Computing (WiCOM), pp.1-4, Oct. 2008.

[41] M. Yamamoto and T. Ohtsuki, “Power-absorption-based Model for Power Compensation in WLAN Positioning Using Smartphone,” IEICE Transactions on Communications, Vol.E98-B, No.6, pp.1125-1132, June 2015.

[42] C. Sertthin, T. Fujii, T. Ohtsuki, and M. Nakagawa, “Multi-band Received Signal Strength Fingerprinting Based Indoor Location System,” IEICE Transactions on Communications, Vol.E93-B, No.8, pp. 1993–2003, Aug. 2010.

[43] M. Yamamoto and T. Yamazoe, “A Null-zone Control Method for RFID Systems,” in *Proc.* 2011 IEEE Radio and Wireless Symposium (RWS), Phoenix, Arizona, U.S., Jan. 2011.

[44] K. Benkic, M. Malajner, P. Planinsic, Z. Cucej, “Using RSSI value for distance estimation in wireless sensor networks based on ZigBee,” in *Proc.* 15th International Conference on Systems, Signals and Image Processing, pp.303-

306, June. 2008.

[45] M. Laaraiedh, L. Yu, S. Avrillon, and B. Uguen “Comparison of hybrid localization schemes using RSSI, TOA, and TDOA,” European Wireless 2011 Sustainable Wireless Technologies, pp.626-630, Apr. 2011.

[46] A. Honzawa, Y. Kobayashi, S. Fukushima, T. Yamazoe, “The achievement of hibiki project for the spread use of RFID”, in *Proc.* The 2007 International Symposium on Applications and the Internet Workshops (SAINTW), pp.18-21, Jan. 2007.

[47] L. Ukkonen, L. Sydänheimo, M. Kivikoski, “Read range performance comparison of compact reader antennas for a handheld UHF RFID reader,” in *Proc.* IEEE International Conference on RFID, pp.63-70, Mar. 2007.

[48] T. Yamazoe, M. Yamamoto, M. Wakabayashi, S. Fukushima, Y. Katsuie, H. Hamada, “Ubiquitous Terminal Technology,” in *Proc.* IEICE Society Conference, Hokkaido, Japan, Sept. 2011.

[49] ISO/IEC 18000-6C, “Radio-frequency identification for item management - part 6: parameters for air interface communication at 860 MHz - 960 MHz,” 2007.

[50] P. Choi, H. C. Park, S. Kim, S. Park, I. Nam, T. W. Kim, S. Park, S. Shin, M. S. Kim, K. Kang, Y. Ku, H. Choi, S. M. Park, K. Lee, “An experimental coin-sized radio for extremely low-power WPAN (IEEE 802.15.4) application at 2.4 GHz,” IEEE Journal of solid-state circuits, vol.38, no.12, pp. 2258-2268, Dec. 2003.

[51] S. Nakao, T. Norimatsu, T. Yamazoe, T. Oshima, K. Watanabe, K. Minatozaki, Y. Kobayashi, “UHF RFID mobile reader for Passive- and Active-tag Communication,” in *Proc.* IEEE International Conference on RWS, pp.311-314, Jan. 2011.

[52] K. Takei, “Computational design of wireless interface for RFID reader module applied to mobile devices,” in *Proc.* 5th European Conference on Circuits and

Systems for Communications, pp.216-219, Nov. 2010.

[53] M. Yamamoto, M. Wakabayashi, S. Fukushima and T. Yamazoe, “Active-tag Protocol on UHF band,” in *Proc.* IEICE Society Conference, Hokkaido, Japan, Sept. 2011.

[54] ARIB, “950MHz-Band Telemeter, Telecontrol and Data Transmission Radio Equipment for Specified Low Power Radio Station,” http://www.arib.or.jp/tyosakenkyu /kikaku_tushin/index.html.

Appendix A

List of Papers by Author

A.1. Journals

[1] M. Yamamoto and T. Ohtsuki, “Power-absorption-based Model for Power Compensation in WLAN Positioning Using Smartphone,” IEICE Transactions on Communications, Vol.E98-B, No.6, pp.1125-1132, June 2015.

[2] M. Yamamoto, T. Abe, N. Furukawa, and T. Yamazoe, “Development and Evaluation of Simple Indoor Localization System Using Mobile Phone Built-in UHF Passive Tag Reader and Active Tag,” IEICE Transactions on Communications, Vol.J95-B, No.11, pp.1427-1434, Nov. 2012 (in Japanese).

[3] H. Ohashi, T. Akiyama, M. Yamamoto and A. Sato, “Modality Classification Method Based on the Model of Vibration Generation while Vehicles are Running,” Journal of Information Processing, Vol.56, No.1, pp.23-34, Jan. 2015 (in Japanese).

[4] F. Wang, M. Yamamoto, K. Naito, K. Mori and H. Kobayashi, “Proposal of Residual Frequency Offset Compensation Method for OFDM Systems,” ITE

Journal, Vol.60, No.5, pp.773-780, May 2006 (in Japanese).

A.2. International Conferences

[1] M. Yamamoto and T. Ohtsuki, "Power Compensation in WLAN Positioning Using a Smartphone," in *Proc.* 2014 IEEE Ninth International Conference on Intelligent Sensors, Sensor Networks and Information Processing (ISSNIP), Singapore, Apr. 2014.

[2] M. Yamamoto, T. Ohtsuki, H. Utsumi, and N. Furukawa, "Mobile-phone Indoor Localization Based on Microwave Identification Using Web-access Time," in *Proc.* 2014 IEEE Radio and Wireless Week (RWW), Newport Beach, California, U.S., Jan. 2014

[3] M. Yamamoto and T. Yamazoe, "A Null-zone Control Method for RFID Systems," in *Proc.* 2011 IEEE Radio and Wireless Symposium (RWS), Phoenix, Arizona, U.S., Jan. 2011.

[4] H. Ohashi, P. X. Nguyen, T. Akiyama, M. Yamamoto and A. Sato, "Sensor-Based Trip-Separation Method Based on Ergodic HMM," in *Proc.* 7th ACM SIGSPATIAL International Workshop on Computational Transportation Science (IWCTS), Dallas, Texas, U.S., Nov. 2014.

[5] H. Ohashi, T. Akiyama, M. Yamamoto and A. Sato, "Automatic Trip-separation Method using Sensor Data Continuously Collected by Smartphone," in *Proc.* 2014 IEEE 17th International Conference on Intelligent Transportation Systems (ITSC), Shandong, China, Oct. 2014.

[6] H. Ohashi, T. Akiyama, M. Yamamoto and A. Sato, "Modality Classification Method Based on the Model of Vibration Generation while Vehicles are Running," in *Proc.* 6th ACM SIGSPATIAL International Workshop on Computational

Transportation Science (IWCTS), Orlando, Florida, U.S., Nov. 2013.

A.3. Domestic Conferences

[1] M. Yamamoto and T. Ohtsuki, "Power Compensation in WLAN Positioning," in *Proc.* IEICE General Conference, Shiga, Japan, Mar. 2015 (in Japanese).

[2] M. Yamamoto, T. Ohtsuki, H. Utsumi, and N. Furukawa, "Mobile-phone Indoor Localization Based on Microwave Identification Using Web-access," in *Proc.* IEICE Society Conference, Fukuoka, Japan, Sept. 2013 (in Japanese).

[3] M. Yamamoto, Y. Niimura, Y. Usami, T. Yamagishi, S. Iwata and N. Furukawa, "Indoor Localization System for Stock Control Using UHF band RFID tags," in *Proc.* IEICE Society Conference, Toyama, Japan, Sept. 2012 (in Japanese).

[4] M. Yamamoto, M. Wakabayashi, S. Fukushima and T. Yamazoe, "Active-tag Protocol on UHF band," in *Proc.* IEICE Society Conference, Hokkaido, Japan, Sept. 2011 (in Japanese).

[5] M. Yamamoto, H. Ozaki, K. Watanabe and T. Yamazoe, "Development of Communication Performance Analyzer for Large-Scale RFID Systems," in *Proc.* IEICE Society Conference, Niigata, Japan, Sept. 2009 (in Japanese).

[6] M. Yamamoto and T. Yamazoe, "Developing Security Method of UHF RFID to Realize Privacy Protection," IEICE Technical Report, Vol.107, No.373, pp. 57-61, Hyogo, Japan, Dec. 2007 (in Japanese).

[7] M. Yamamoto, A. Honzawa, S. Fukushima and T. Yamazoe, "Evaluation of Hibiki Tag and System: The Result of Hibiki Project," IEICE Technical Report, Sendai, Vol.106, No.373, pp. 1-6, Japan, Nov. 2006 (in Japanese).

[8] H. Ohashi, T. Akiyama, M. Yamamoto and A. Sato, "Automatic Trip-extraction Method using Sensor Data Collected by Smartphone," in *Proc.* IEICE Society

Conference, Tokushima, Japan, Sept. 2014 (in Japanese).

[9] T. Yamazoe, M. Yamamoto, M. Wakabayashi, S. Fukushima, Y. Katsuie, H. Hamada, "Ubiquitous Terminal Technology," in *Proc.* IEICE Society Conference, Hokkaido, Japan, Sept. 2011 (in Japanese).

[10] A. Sato, H. Hayashi, Y. Teramoto, M. Yamamoto, M. Kakegawa and K. Iida, "Ubiquitous Spatial Information Platform Technology," in *Proc.* IEICE Society Conference, Hokkaido, Japan, Sept. 2011 (in Japanese).

[11] H. Ozaki, M. Yamamoto and T. Yamazoe, "Design and Characteristic Analysis of Small RFID Tag for UHF Band Long Distance Communications," IEICE Technical Report, Vol.110, No.322, pp.41-46, Nara, Japan, Dec. 2010 (in Japanese).

[12] H. Ozaki, M. Yamamoto, K. Watanabe and T. Yamazoe, "Development of Communication Characteristic Optimization Technique for Large-Scale RFID Systems," in *Proc.* IEICE Society Conference, Niigata, Japan, Sept. 2009 (in Japanese).

[13] H. Ozaki, K. Watanabe, M. Yamamoto and T. Yamazoe, "Improvement of UHF Passive RFID Performance using 2-Carriers with Different Frequency," IEICE Technical Report, Vol.107, No.373, pp.19-24, Hyogo, Japan, Dec. 2007 (in Japanese).

A.4. Awards

[1] The Best Paper Award of IEICE Transactions on Communications (Japanese Edition) in 2013. M. Yamamoto, T. Abe, N. Furukawa, and T. Yamazoe, "Development and Evaluation of Simple Indoor Localization System Using Mobile Phone Built-in UHF Passive Tag Reader and Active Tag," IEICE

Transactions on Communications, Vol.J95-B, No.11, pp.1427-1434, Nov. 2012 (in Japanese).

[2] The Niwa-takayanagi Award 2006 of ITE. F. Wang, M. Yamamoto, K. Naito, K. Mori and H. Kobayashi, "Proposal of Residual Frequency Offset Compensation Method for OFDM Systems," ITE Journal, Vol.60, No.5, pp.773-780, May 2006 (in Japanese).

[3] The Best Paper Award of IWCTS 2014 workshop of the ACM SIGSPATIAL conference. H. Ohashi, P. X. Nguyen, T. Akiyama, M. Yamamoto and A. Sato, "Sensor-Based Trip-Separation Method Based on Ergodic HMM," in *Proc.* 7th ACM SIGSPATIAL International Workshop on Computational Transportation Science (IWCTS), Dallas, Texas, U.S., Nov. 2014.