Radio Frequency Measurement and Weighted Least Squares Methods for Received Signal Strength Based Indoor Positioning

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(千葉大学審査学位論文)

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Contents

Abstract

The Global positioning system (GPS) address the main issue of geolocation. GPS can be used to navigate the planes, ships and vehicles, find someone or something anywhere on the earth. Everyone can benefit from the positioning capability to let their work and lives more comfortable and efficient.

However, due to the signal attenuate severely cased by construction materials, GPS cannot provide accurate positioning under indoor environments. On the other hand, there is an increasing demand in indoor positioning systems recently. With accurate indoor positioning systems, people can track the elderly in nursing homes and children who are away from supervision, detect the medical personnel or equipment in a hospital and navigate the fireman and police to complete their missions indoors. Therefore, the theory and algorithm of indoor positioning systems have been widely researched.

There are several existing indoor positioning systems on the market. The wireless access points (WAP) based positioning system is considered as a low cost and promising system which use the existing wireless infrastructure. In the WAP-based indoor positioning system, according to the transmitted and received signals, informations such as the time of signal propagation, phase offset, direction of the received signal and received signal strength (RSS) can be obtained. Since the synchronization is difficult among the devices, the time of signal propagation is hard to be

measured. Moreover, due to severe multipath fading effects and lack of line-of-sight (LOS) paths under indoor environments, the measurements of phase offset of signal and direction of the received signal contain large errors. Therefore, the attenuation-based method based on the RSS informations is considered as an optimal method in the WAP-based indoor positioning system.

There are two stages for the attenuation-based method. At first, the distance from mobile station (MS) to base stations (BS) can be estimated according to RSS and a proper radio propagation channel model. Then, based on the estimated distances and the known locations of the BSs, the position of MS can be determined. During the distance estimation stage, it is hard to estimate the distance accurately due to the severe multipath fading. During the location estimation stage, it is difficult to determine the location of MS based on the estimated distances with errors.

This dissertation focus on the accuracy improvement for WAP-based indoor positioning systems using attenuation-based method. A method is proposed to estimate the distance between BSs and MS by utilizing the average of pilot signal strength in frequency domain. Moreover, a weighted least-squares (LS) algorithm which determines the weighted coefficient based on the error degree of the RSS is proposed for the case that the Friis transmission equation can be applied as a radio propagation channel model. Computer simulations demonstrate that the proposed schemes can make improvement of the positioning accuracy compared to the conventional RSS based methods. When the radio propagation environment can not be simplified as a free space, this method of determining the weighted coefficient become inappropriate. In these situations, a unified method which determines the weighted coefficient in accordance with the characterization of the radio propagation channel is proposed. Computer simulations and experiments demonstrate that the schemes are superior compared with the conventional LS methods.

Chapter 1

General Introduction

1.1 Background and Significance

The Global positioning system (GPS), which is a space-based radio navigation system, address the main issue of geolocation. With an unobstructed line-of-sight (LOS) to minimum of four GPS satellites, the GPS can provide location and time information to the GPS signal receivers anywhere on the earth[1]. Recently, the differential GPS (DGPS) which can provide higher location accuracy about 10cm in case of good implementations has been widely used. The DGPS use a network of ground-based reference stations to broadcast the difference between the actual pseudo ranges and the measured pseudo ranges to correct location informations of the receiver stations. Japan has spent 1.9 billion dollars on its own global navigation satellite system, be known as Quasi-Zenith satellite system (QZSS). To improve its positioning accuracy in urban areas, a set of satellites is added to guarantee that at least one of them is visible directly overhead anytime.

Because GPS is free and dependable, there are hundreds of applications based on it. People can use GPS to navigate the planes, ships and vehicles, aid search and rescue efforts, find their location in a strange city. Everyone can benefit from the positioning capability to let their work and lives more comfortable and safe.

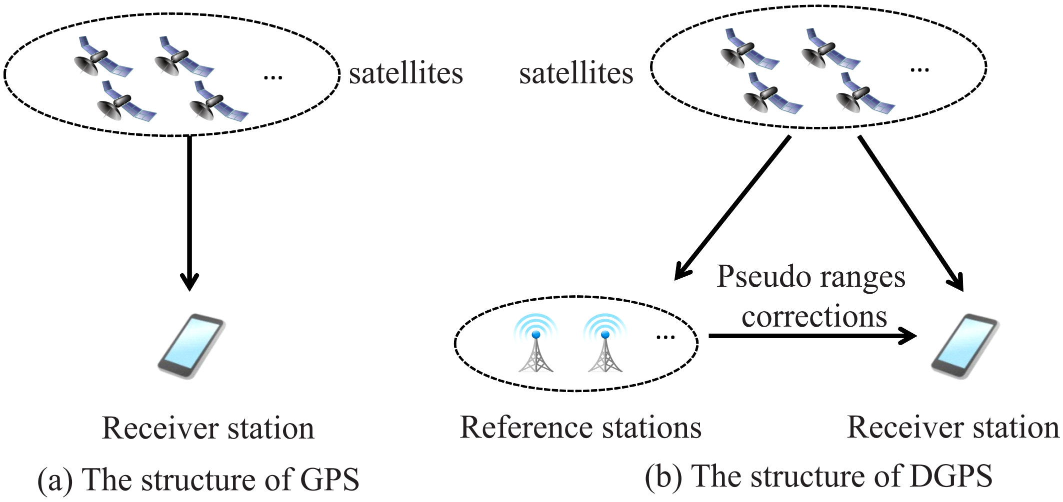

Figure 1.1: The structure of the GPS and DGPS.

However, due to the severe signal attenuation caused by construction materials, GPS cannot provide accurate positioning indoor. On the other hand, there is an increasing demand for accurate location finding techniques and location-based applications for indoor areas recently. To name a few, one can consider tracking the elderly in nursing homes and children who are away from supervision, detecting the medical equipment or personnel in a hospital, finding specific goods in a warehouse, navigating the firefighters and police officers to complete their missions indoors[2]. Therefore, the theory and algorithm of indoor positioning systems have been widely researched.

1.2 Indoor Positioning Systems

To locate the objects or people under indoor environment, several systems are proposed. Most of them are based on wireless technology. Some of these systems and the relative network infrastructure are built primarily for the indoor positioning application. The physical specification and the performance of the positioning accuracy are controllable by the designers. These systems can achieve high positioning accuracy, however, may need expensive special devices. The others of the systems use some existing wireless network infrastructure to accomplish the positioning function. Because of avoiding expensive infrastructure, these systems are widely researched. And the improvement of positioning accuracy in these systems is required.

1.2.1 Assisted GPS

In indoor environment, signals from satellites may attenuate severely caused by the walls of the building and the multipath propagation. It is difficult for the GPS receivers to determine their location by the weak GPS signals. Assisted GPS (A-GPS) is a system that can provide GPS signals indoor to achieve a significant improvement of the positioning accuracy. A-GPS uses cellular network towers to send satellite informations to cellular phones. Based on the location of the nearest cellular network tower to the cellular phone, the relevant satellites are chosen to accomplish the positioning function. It can enhance the positioning accuracy when the signals from satellites are weak. The A-GPS can locate a cellular phone with accuracy to 5m accuracy under an ideal indoor environment. [3].

1.2.2 RFID-Based

Radio frequency identification (RFID), which uses radio waves to transmit the identify and track tags which contain electronically information. During the second world war, the Britain firstly used it to identify airplane as part of the radar. In recent decades, RFID has been applied in many areas, such as transport, manufacturing, personnel access and baggage tagging, etc. Nowadays, The RFID system is considered as an emerging technology for indoor positioning [4].

A typical RFID system contains several basic components, such as tags, readers, and a host computer. There is a wire or wireless link between the host computer and readers. There are mainly two types of the RFID: passive and active systems.

In the passive systems, the reader provides power source to a passive tag. When the tag gets close to a reader, it will be powered on by the signal from the reader and reflect it back. The reader then receives the signal which has been modulated by the tag. After sending the information of the tag to the host computer, the location of the tag can be determined. The passive tags are cheaper and the reading range is short.

In the active systems, the active tag with a battery bulit in, transmits its information periodically. The advantage of the active systems is the longer range. An aggregation algorithm based on radio signal strength (RSS) analysis is proposed in [5]. The authors locate objects using homogenous sensor nodes, and estimate the distance between tags based on the received RSS values. To achieve higher positioning accuracy, many tags are required.

1.2.3 WAP-Based

The above mentioned systems have some drawbacks: The A-GPS based systems have low positioning accuracy and require internet access; the RFID-Based systems require plenty of tags to achieve ideal positioning accuracy.

Recently, wireless access points (WAP) have become ubiquitous in commercial and residential establishments, and most mobile devices are wireless enabled. Therefore, many people in commercial, industry and academia fields are involved in the studies of the theory and algorithm of WAP-based positioning systems. Access points (AP) can be identified by their parameters such as the service set identification (SSID) and the media access control (MAC) address. And the positioning function can be accomplished based on the information of the transmitted and received signals. This dissertation focus on the indoor positioning algorithms in the WAP-based systems.

There are several conventional algorithms using radio signals for indoor positioning systems. Some of them have been used in the WAP-based systems.

1.3 Positioning Algorithms in WAP-based Systems

Because of severe multipath effects, lack of line-of-sight (LOS) propagation environments, and reflection and refraction from numerous objects such as walls, ceilings and moving humans, it is hard to model the radio propagation under indoor environments. There are two major algorithms to realize the function of positioning, the triangulation algorithms and the scene analysis algorithms.

The triangulation methods use the geometric properties of distance or angle to estimate the target location. It mainly contains the time-of-arrival (TOA), time-difference-of-arrival (DTOA), angle-of-arrival (AOA), phase-of-arrival (POA) and the attenuation-based algorithm which is a type of the received signal strength (RSS) algorithms.

The scene analysis methods commonly use the location fingerprint algorithm, which is another type of the RSS algorithms.

1.3.1 TOA Method

For TOA-based systems, the distance from the Mobile station (MS) to AP is directly proportional to the propagation time. Therefore, the distance can be calculated according to the time of arrival and the transfer velocity of signals. Based on the TOA data from two APs, we can narrow the position of MS in a circle; From at least three APs, the position of MS can be estimated, as shown in Fig. 1.2.

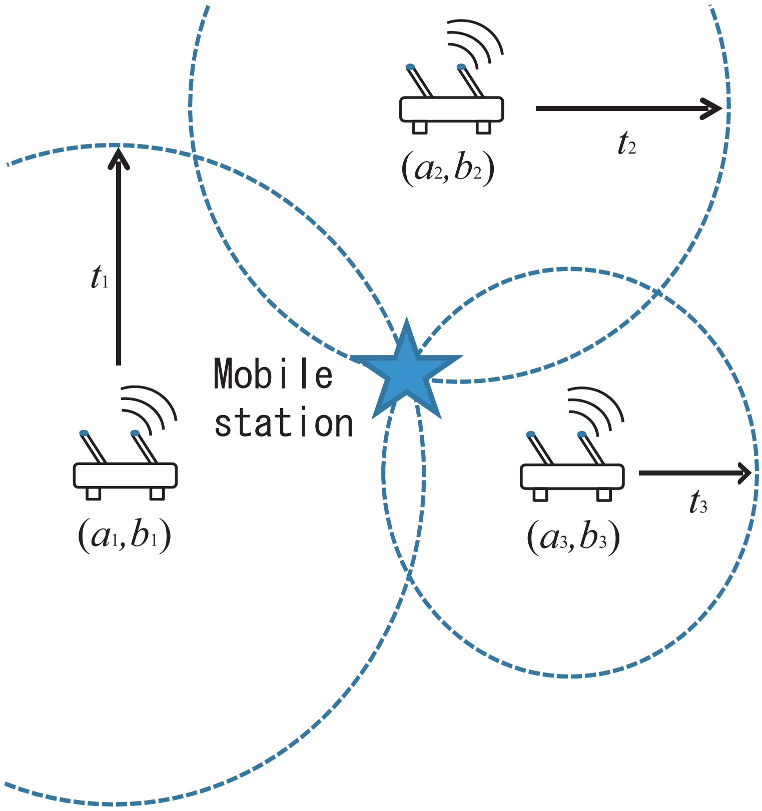

Figure 1.2: Positioning based on TOA measurement

In order to enable the position of the MS, the MS and APs in the TOA-based systems have to be precisely synchronized. Due to the different clock parameters of the APs and MS devices, the synchronization is difficult. Moreover, significant positioning error may be caused by a small difference between the clocks in devices. Therefore, TOA can be measured more accurately by some different signaling techniques, such as direct sequence spread-spectrum (DSSS) which transmit a spread spectrum signal and post process the sampled received signals[7], or the ultrawide band (UWB) measurements which can provide accurate TOA estimates due to the inherently fine temporal resolution[8].

Suppose that $i-th$ BS located at (a_i, b_i, c_i), the possible location of the MS is (x_m, y_m, z_m), and the TOA from the MS to the $i-th$ BS is t_i , the cost function can be expressed as

$$
\begin{aligned}
F(x_m, y_m, z_m) &= \sum_{i=1}^{N} {\delta_i}^2 \qquad (1.1)\\
&= \sum_{i=1}^{N} (\sqrt{(x_m - a_i)^2 + (y_m - b_i)^2 + (z_m - c_i)^2} - vt_i)^2,
\end{aligned}
$$

where the v is the the transfer velocity of signals. Each δ_1, δ_2, ...,δ_N could equal to zero with a proper choice of (x_m, y_m, z_m). The location of the MS can be estimated as $(\hat{x}_m, \hat{y}_m, \hat{z}_m)$ by minimizing the function $F(x_m, y_m, z_m)$ as

$$
(\hat{x}_m, \hat{y}_m, \hat{z}_m) = \arg\min F(x_m, y_m). \qquad (1.2)
$$

1.3.2 TDOA Method

Rather than the absolute arrival time of TOA, TDOA-based systems determine the position of the MS by examining the difference in time at which the signal arrives at multiple BSs. Basing on the TDOA data from two APs, we can narrow the position of MS in a hyperbolic curve according to the difference in time at which the signal arrives at the two APs and the transfer velocity of signals; From at least three APs, another pair of stations produce another hyperbolic curve, which intersects with the first one. Then the position of MS can be estimated, as shown in Fig. 1.3.

The hyperboloid can be expressed as

$$
\begin{aligned}
R_{i,j} = &\sqrt{(x_m - a_i)^2 + (y_m - b_i)^2 + (z_m - c_i)^2} \qquad (1.3)\\
&-\sqrt{(x_m - a_j)^2 + (y_m - b_j)^2 + (z_m - c_j)^2},
\end{aligned}
$$

where (a_i, b_i, c_i) and (a_j, b_j, c_j) represent the location of the $i - th$ and $j - th$ AP; and (x_m, y_m, z_m) represent the possible location of the MS.

The conventional methods use correlation techniques to determine the location of the MS. The location can be estimated according to two pairs of APs. Assume

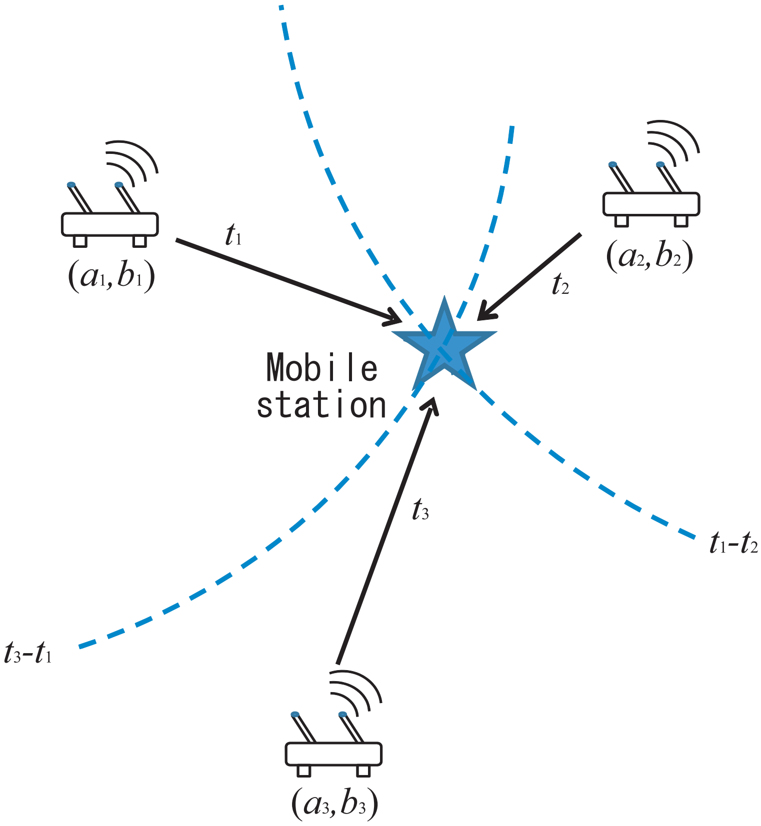

Figure 1.3: Positioning based on TOA measurement

that the transmitted signal of each AP is identical and given by $s(t)$, the received signal at MS from the $i-th$ AP is $r_i(t)$. In practice, $r_i(t)$ is affected by noise which is caused by natural and man-made sources, and sometimes delayed caused by non-line-of-sight(NLOS) propagation environment. Suppose that the noise is $n_i(t)$ and the delay is d_i, then $r_i(t) = s(t-d_i) + n_i(t)$. Similarly, the received signal from the $i-th$ AP $r_j(t) = s(t-d_j) + n_j(t)$, where the delay is d_j and the noise is $n_j(t)$. For the two received signal, the cross-correlation function can be formed by:

$$\phi_{ij}(\tau) = \frac{1}{T}\int_0^T r_i(t)r_j(t-\tau)dt. \tag{1.4}$$

The difference in time of the signal received from the $i-th$ and $j-th$ AP can be estimated by maximizing $\phi_{ij}(\tau)$, expressed as

$$\hat{\tau} = \arg\max \phi_{ij}(\tau). \tag{1.5}$$

Except for the solution to the equations shown above through nonlinear regression, an iterative algorithm which use a Taylor-series expansion to linearize the equations is proposed in [9].

Since the idea of TDOA examine the difference in time of the signal received from the APs, only synchronization among APs is required. TDOA-based systems are commonly used in military and civil applications, such as locate an aircraft, vehicle and mobile phone.

1.3.3 AOA Method

AOA-based systems determine the location of MS according to the intersection of several pairs angle direction lines which formed by the circular radius from a BS to the AP. The direction of the received signal can be obtained with directional antennae or array of antennae.

As shown in Fig. 1.4, AOA methods may use at least two BSs, and two measured angles θ_1, θ_2 to derive the 2-D location of the MS.

The advantages of AOA-based systems are that the location of MS can be determined with three APs for 3-D positioning or two APs for 2-D positioning, and synchronization is not required between devices. The disadvantages are that these systems require complex hardware and line-of-sight (LOS) path of signals[10].

1.3.4 POA Method

The POA-based systems use the carrier phase (or phase difference) to estimate the signal propagation distance. Suppose that the transmitted signals are sinusoidal

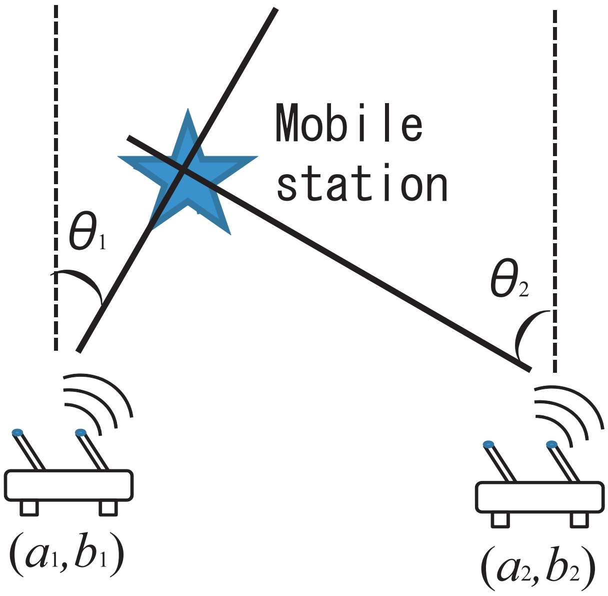

Figure 1.4: Positioning based on AOA measurement

with the same frequency and zero phase offset. Based on the phases and the wavelength of the received signals, the signal propagation distance can be calculated. Then the location of MS can be estimated based on the estimated distances, the same as the measurement in TOA-based positioning systems.

The weakness of the POA-based systems is that the carrier phase measurement is difficult and require LOS signal paths. Moreover, when the distance is longer than the wavelength, this method becomes inappropriate.

1.3.5 RSS Method

There are some deficiencies in the TOA, TDOA, AOA and POA schemes. The TOA and TDOA schemes requires precisely synchronization, which is difficult due to high costs and the different clock parameters of the APs and MS devices; The AOA schemes requires LOS propagation channel between the MS and the APs, which is difficult for indoor environments; The POA schemes require special phase measurement units which mobile devices such as smart phones and tablets are not commonly equipped with. An alternative method is to realize positioning function by mobile units based on their received signal strength. There are mainly two types of the RSS-basd positioning methods.

The first type is the location fingerprint method. This method is one of the types of scene analysis methods which collect features of actual scenes in advance, and determine the position of the object according to currently measurements and collected features. The location fingerprint method contains offline stage and online stage. During the offline stage, the location coordinates of the MS and respective signal strengths from AP are collected to build a database. During the online stage, according to the database and the currently observed signal strengths the location of the MS can be figured out. The main challenge to this method is the difficult management of the database.

The first accurate Global System for Mobile Communications (GSM) fingerprint-based positioning system is developed by Nokia research center [11]. The authors use the signal strength fingerprints from 6 cells which used in the GSM standard to achieve accuracy of 5 meters in a large building. Recently, a system named as Ekahau positioning engine is proposed for designing and analyzing Wi-Fi networks [12]. It has commercially available software to run on windows and macOS devices. This fingerprint-based positioning system combined with the previous data of the users to achieve accuracy within 1-5 meters under indoor environment.

The second type of RSSI is the attenuation-based method. There are also two stages of this method. At first, the distance can be estimated from MS to APs according to received signal strengths and a proper radio propagation channel model. Then, based on the estimated distances and the known locations of the BSs, the location of MS can be determined.

The first attenuation-based positioning method in a WAP-based positioning system is RADAR, developed by Bahl and Padmanabh [13]. RADAR gives a median spatial error distance of 2.94 meters using nearest neighbor algorithm. The median spatial error distance was reduced to 2.37 meters using a Viterbi-like algorithm which provided a continuous user tracking technique in the RADAR [14].

The applications of mentioned algorithms in the WAP-based systems are limited by some factors such as environment and cost. The TOA and TDOA methods require precise synchronization, which is difficult for the devices; The POA and AOA methods require LOS signal path, which is difficult for the indoor environment. With the popularization of the WLAN systems and measurement of received signal strength (RSS) has becoming a part of mobile devices standards, the RSS based methods are considered to be a promising approach for the WAP-based positioning systems. Because the fingerprint-based require difficult management for the database, the attenuation-based method in a WAP system is considered as an effective and economical indoor positioning method.

1.4 Research Focus of the Thesis

Since the conventional positioning systems such as GPS can not provide accurate positioning under indoor environments, the research on indoor positioning systems is attracting much attention. Recently, with the popularization of wireless access points, the WAP-based positioning systems are widely researched in academia and industry fields.

This dissertation focus on the accuracy improvement for WAP-based indoor positioning systems using the attenuation-based method. To accomplish the positioning function, firstly, the distance from APs to MS is estimated according to the attenuation of emitted signal strength and a proper radio propagation channel model. However, the distance is difficult to estimate accurately due to the multipath fading under indoor environments. Secondly, based on the estimated distances and the known locations of BSs to estimate the location of the MS. Generally, in order to perform the location estimation based on several estimation distances, the least-squares method is used. The method obtains the optimum positioning identity property with the minimum squared error of the cost function. Due to severe multipath fading in the indoor environment, it is difficult to ensure the estimated distances with high accuracy. Moreover, Some of the received signal power attenuate severely caused by long distance propagation and obstacles between the MS and APs. The attenuation-based method shows the low estimation accuracy for low SNR situation. Therefore, the methods to reduce the error in distance estimation and location estimation are worthy of study.

The dissertation is organized as follows. In Chapter 2, during the distance estimation stage, a method which estimate the distances between APs and the MS using the average of pilot signal strength in frequency domain is proposed. During the location estimation stage, a weighted least-squares algorithm which determines the weighted coefficient based on the error degree of the received signal power in case that the Friis transmission equation can be applied as a radio propagation channel model is proposed; In Chapter 3, consider that when the radio propagation environment can not be simplified as a free space, the above method of determining the weighted coefficient become inappropriate. A novel weighted least-squares algorithm using RSSI method for WLAN indoor positioning system for the general case is proposed. Chapter 4 offers the conclusion.

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Chapter 2

Positioning Methods based on the Pilot Signals

2.1 Introduction

In recent years, there is an increasing demand in accurate location finding techniques and location-based applications for indoor areas. The Global Positioning System(GPS) which is a space-based satellite navigation system address the issue of geolocation outdoor [1]. However, due to the severe signal attenuation cased by construction materials, GPS cannot provide accurate geolocation indoor. Therefore, the theory and algorithm of indoor positioning systems have been widely researched.

Accurate indoor geolocation is an important technology for commercial and public safety [2]. In commercial applications such as in nursing homes and residential quarter, indoor geolocation systems can be used to track the elderly, and children who are away from supervision, to navigate the blind, and to find specific goods in warehouse. In public safety applications there is an increasing need to track inmates in prisons and navigating fire fighters and policeman to complete their missions indoors [3].

Geolocation using radio signals have several conventional techniques which include the time-of-arrival (TOA), time-difference-of-arrival (TDOA), angle-of-arrival (AOA) and received signal strength indication (RSSI) based schemes [4, 5]. For TOA-based systems, the distance from the mobile station (MS) to base stations (BSs) is directly proportional to the propagation time. In order to enable the position of the MS, the MS and BSs in the TOA-based systems have to be precisely synchronized. Rather than the absolute arrival time of TOA, TDOA-based systems are to determine the position of the MS by examining the difference in time at which the signal arrives at multiple BSs. For TDOA-based systems, synchronization among BSs is required. In AOA-based systems, the location of the MS can be found by the intersection of several pairs of angle direction lines which formed by the circular radius from a BS to th MS. AOA Measurements can be made without the requirement of synchronization. However, for the above three schemes, geolocation accuracy can be severely degraded in the indoor environment caused by lack of line-of-sight (LOS) path [6].

In recent years, many commercial and residential establishments are already equipped with wireless access-point(AP) and most mobile devices are wireless enabled. Most of these devices can measure received signal strength as part of their standards. Therefore, the most common geolocation method is the RSSI technology in a WLAN, which has low communication load and low complexity [7]. Many research efforts have been devoted to this region for more reliably and more accurately. In RSSI-based systems, two steps are needed to accomplish the geolocation. The first step is to calculate the propagation loss according to the strength of transmitting signals from the APs and that of receiving signal from the MS, and then utilize a radio propagation channel model to estimate the distances from APs to MS. The second step is to estimate the location of the MS basing on the known locations of APs and the estimated distances.

In this chapter, two schemes are proposed to accomplish the RSSI-based geolocation systems more accurately. Firstly, a method to estimate the distances between APs and the MS using the average of pilot signal strength in frequency domain is proposed. And then, a novel weighted least-squares algorithm is proposed to estimate the location of the MS.

2.2 System Model

2.2.1 Conventional Distance Estimation Method

Under idealized condition, the Friis transmission equation is used to calculate the power received by one antenna transmitted from another antenna some distance away [8]. Suppose P_t is the power of the transmitted signal, P_t is the power of the received signal, d is the distance between the transmitteing node and the receiving node, λ is the wavelength and the antenna gains of the transmitting and receiving antennas are G_t and G_r, respectively. The Friis transmission equation is defined as

$$P_r = G_t G_r \left(\frac{\lambda}{4\pi d} \right)^2 P_t \tag{2.1}$$

In most cases, G_t, G_r, P_t and λ are known parameters. Therefore, under idealized conditions, d can be calculated as

$$d = \frac{\lambda}{4\pi} \sqrt{\frac{G_t G_r P_t}{P_r}} = \frac{\lambda}{4\pi} \sqrt{\frac{G_t G_r}{\alpha}}, \tag{2.2}$$

where α is the ratio of transmitted to received power. However, in the indoor conditions, the receiving power is interfered with severe multipath and specific site parameters such as floor layout, moving humans and numerous reflecting surfaces. Under indoor conditions, suppose $P_r^{'}$ is the power of the received signal, H is the channel response, N is the additive Gaussian white noise(AGWN). Then we have

$$P_r^{'} = \alpha H P_t + N \tag{2.3}$$

The conventional method, named as RSS-based method, determine α by utilizing the ratio of the mean of P_t to $P_r^{'}$, which results in large errors. Therefore, it is crucial to find a method to estimate α accurately.

2.2.2 Conventional Location Estimation Method

In WLAN based systems, after estimate the distances between APs and the MS, the location of the MS will be estimated utilizing the geometric properties of triangles conventionally. In order to enable 2-D positioning, measurements must be made with respect to signals from at least three APs [9] as shown in Fig. 2.1.

Under idealized condition, there is one intersection point of the circles with radius of estimated distances and centered at APs. However in practice, there will be several intersections due to the errors in distance estimations. In this case the location of the MS can be estimated according to the average of these intersections. Suppose (x_1, y_1), (x_2, y_2), (x_3, y_3) are the intersections of the circles centered at AP_1, AP_2 and AP_3, respectively. The position of the MS is determined to (A, B), as shown in Fig. 2.2.

$$A = \frac{x_1 + x_2 + x_3}{3}, B = \frac{y_1 + y_2 + y_3}{3}. \tag{2.4}$$

The conventional method estimate the position of the MS using all the APs detected by the MS. However, with the irregular movement of the MS, the signal will attenuate severely caused by long distances and obstacles between the MS and APs. The positioning can be made with the estimated distances from three APs. Thus, A method named as adaptable APs method which select three APs from whose received signal strengths are greatest is proposed [10].

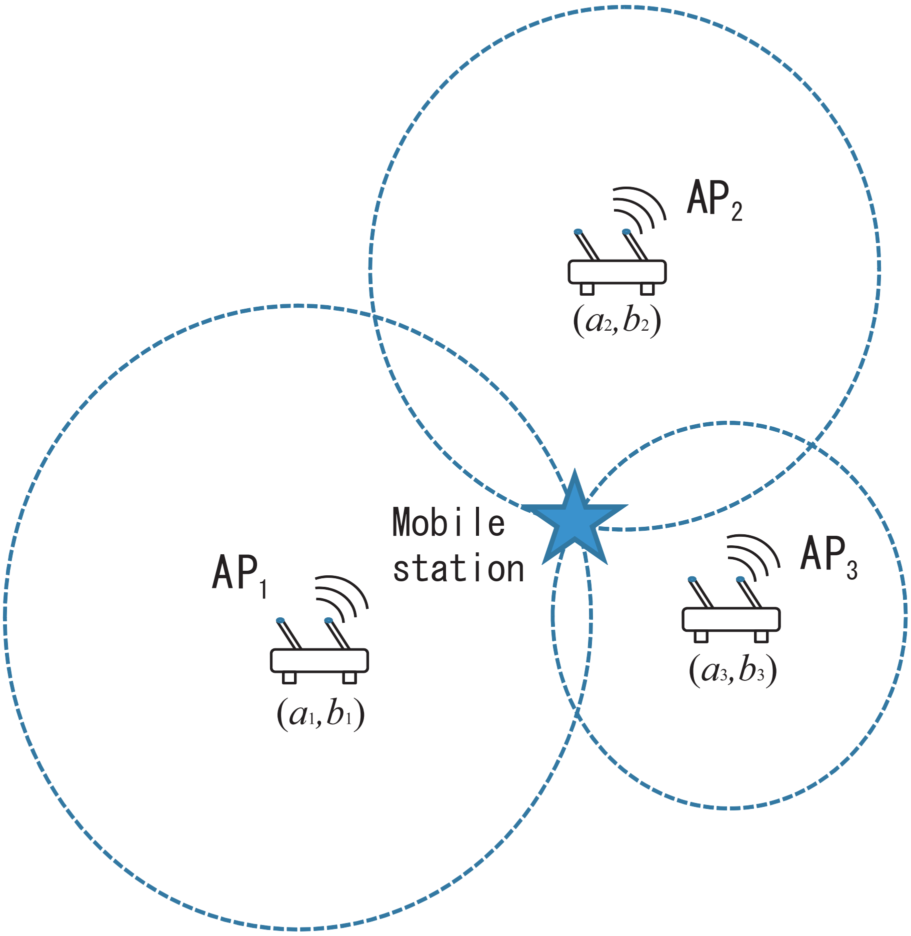

Figure 2.1: Positioning under ideal condition

For instance, assume that there are seven APs(AP_1, AP_2 ... AP_7) and one MS in an indoor environment, as shown in Fig. 2.3. The signals attenuate severely caused by long distances between the MS and AP_5, AP_6, AP_7. Moreover, the human between the MS and AP_3 also cause severely attenuation. Under this condition, the adaptable APs method is to select AP_1, AP_2 and AP_4 which have the greatest received signal strengths to estimate the position of the MS.

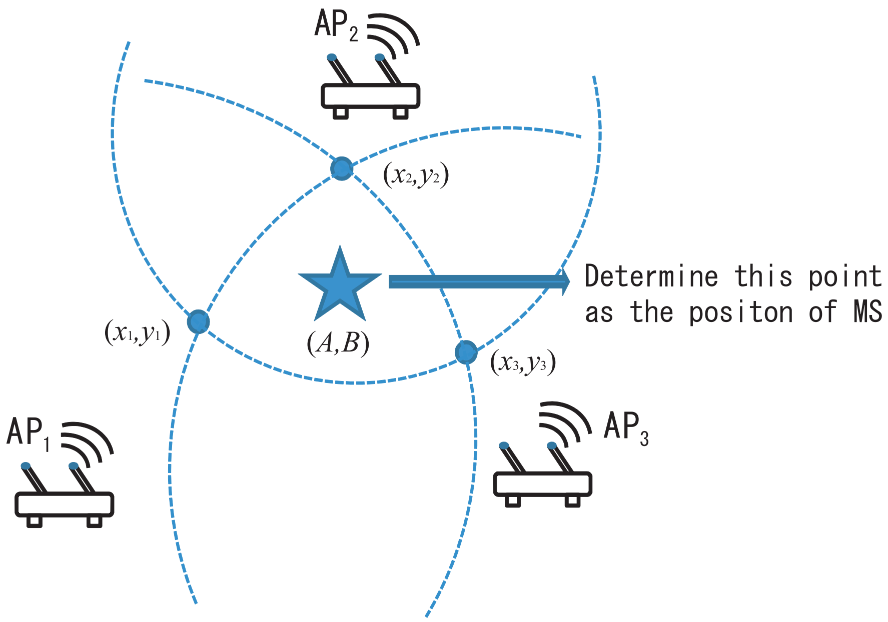

Figure 2.2: Positioning in practice by the conventional method

2.3 Proposed Methods

2.3.1 Proposed Frequency-average Method

In the indoor conditions, the receiving power is interfered with severe multipath and specific site parameters such as floor layout, moving humans and numerous reflecting surfaces. For these conditions, suppose P_r' is the power of the received signal, H is the channel response, N is the additive Gaussian white noise(AGWN). Then we have

$$P_r' = \alpha H P_t + N \tag{2.5}$$

The conventional method, named as RSS-based method, determine α by utilizing the ratio of the mean of P_t to P_r', which results in large errors. Therefore, it is crucial to find a method to estimate α accurately.

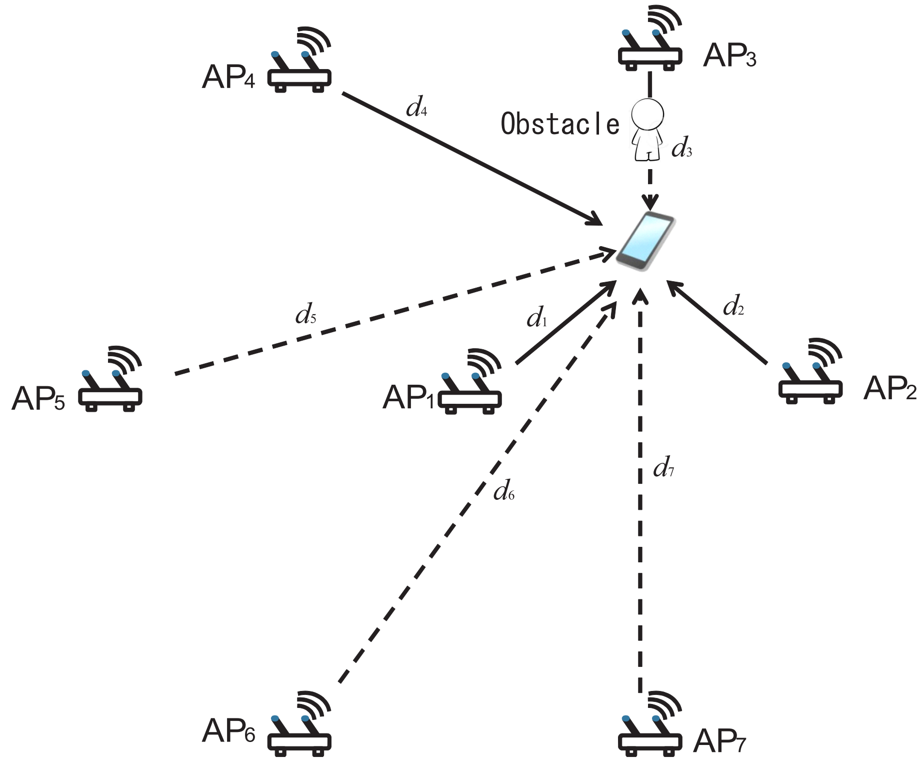

Figure 2.3: Estimate the position of the MS by the adaptable APs method

Radio propagation in indoor environments suffer from multipath effect. The effects of multipath include constructive and destructive interference, and phase shifting of the signal. The magnitudes of the signals arriving by the various paths have a distribution known as the Rayleigh distribution. The received signal strength changing rapidly, therefore it is difficult to determine α in time domain [11].

To estimate α accurately, a novel estimation algorithm is proposed which utilize the average of pilot signal strength in frequency domain. In frequency domain, frequency selective fading is generated caused by multipath. The power of each sub-carriers is quite different due to the multipath fading. However, if we neglect the attenuation in the propagation, the averaged received power would approach to the transmitted power since the expectation of the value of the channel response matrix is

$$E(h_k) \simeq 1, \tag{2.6}$$

where h_k means the channel response of the kth sub-carrier. We assume the channel response approaching to 1, then we have

$$\overline{P}_r \simeq \alpha \overline{P}_t + N', \tag{2.7}$$

where

$$\begin{aligned} \overline{P}_t &= \frac{\sum_{k=1}^{N_c} p_t(k)}{N_c} \\ \overline{P}_r &= \frac{\sum_{k=1}^{N_c} p_r(k)}{N_c}, \end{aligned} \tag{2.8}$$

where $P_t(k)$ and $P_r(k)$ are the transmitted and received pilot signal strength and N_c is the number of sub-carriers. $\overline{P}_t$ is a known parameter and $\overline{P}_r$ can be calculated at the receiving node. Therefore we can estimate α then determine d accurately to compare with the conventional RSS-based method.

2.3.2 Proposed Weighted Least-squares Method

We assume that the MS, located at (x_{MS}, y_{MS}), the N APs located at (a_1, b_1), (a_2, b_2), ..., (a_N, b_N), the estimated distances are D_1, D_2, ..., D_N . As a performance measure, the cost function can be formed by

$$F(x) = \sum_{i=1}^{N} w_i \Delta d_i^2, \tag{2.9}$$

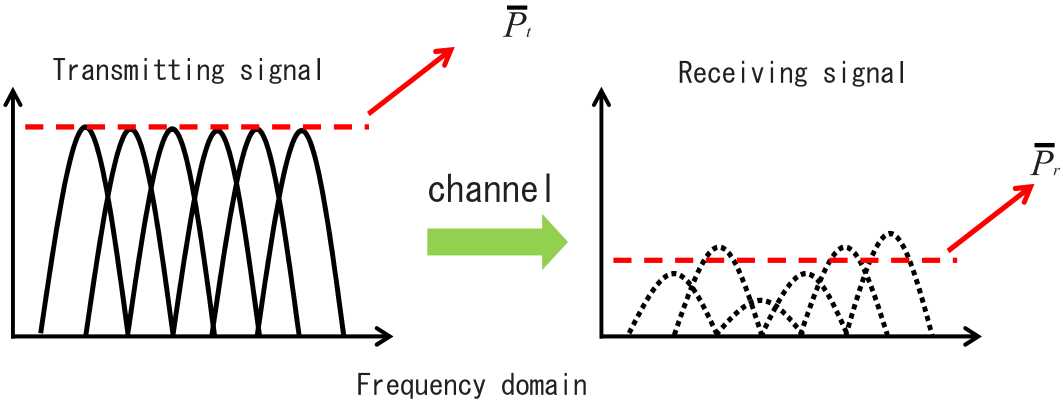

Figure 2.4: Frequency selective fading

where w_i reflects the reliability of the signal from the AP_i, and Δd_i is given as

$$\Delta d_i = \sqrt{(x_{MS} - a_i)^2 + (y_{MS} - b_i)^2} - D_i. \tag{2.10}$$

The reliability of the signal w_i can be considered as the ratio of the power of the desired signal to the error. From Eqs. (2.3) and (2.5), the definition of the received signal power as

$$P_r^{'} = HG_tG_r \left(\frac{\lambda}{4\pi d}\right)^2 P_t + N, \tag{2.11}$$

and the power of the error is defined as

$$\varepsilon = |P_r^{'} - P_r|. \tag{2.12}$$

The reliability of the signal w_i is

$$
\begin{aligned}
w &= \frac{P_r}{\varepsilon} = \frac{P_r}{|P'_r - P_r|} \\
&= \frac{P_r}{|(H-1)G_tG_r(\frac{\lambda}{4\pi d})^2P_t + N|} \\
&= \frac{1}{|(H-1) + \frac{N}{P_r}|}.
\end{aligned}
\tag{2.13}
$$

If the channel response approach to 1, the above equation can be rewritten as

$$
\begin{aligned}
\mathbf{w} &\simeq \frac{1}{|(1-1) + \frac{N}{P_r}|} \\
&= |\frac{P_r}{N}|.
\end{aligned}
\tag{2.14}
$$

Assume that the N_i of signal from AP_i can be characterized by the normal distribution with the same deviation. We can obtain the following condition

$$
w_1 : w_2 : ... : w_n = P_{r1} : P_{r2} : ... : P_{rn}. \tag{2.15}
$$

In this case, the reliability of the signal w_i from AP_i, can be replace with the received signal power P_r. From this reason, the proposed method can identify the accurate position of the MS compare with the conventional method.

2.4 Simulation Results

Simulations have been conducted to evaluate the performance of the proposed methods. Suppose that an OFDM system with 62 subcarriers which have a frequency of 2.4GHz. Table I shows the simulation parameters. Modulation mode is QPSK. Rayleigh fading model is selected for the indoor environment. Transmitting signal strength is 15dBm and Gaussian white noise strength is -90dBm. Considering the complexity of calculation and analysis, we set one AP to the center and six APs to the vertices of a regular hexagon of side length 400m, respectively. Suppose d is distance between the MS and the center of the hexagon. The simulation model is set as shown in Fig. 2.5.

Table 2.1: simulation parameters

Transmitting signal strength	15dBm
Gaussian white noise strength	-90dBm
FFT size	64
Guide interval	16
Modulation mode	QPSK
Carrier frequency	2.4GHz
Pilot number	4
Channel model	Rayleigh fading
Multipath number	5
Attenuation model	Friis
Doppler	10 Hz

We assumed that the MS move from the center of hexagon (the position of AP_1) outward with the distance d from the center. We estimate the location of the MS utilizing the conventional method which use all the APs, and the adaptable APs method which use the three APs with greatest signal strengths, respectively. Then we have the simulation results as shown in Fig. 2.6 and Fig. 2.7.

The conventional method utilizing the ratio of the mean signal strength and all of the APs , which results in large errors; The proposed frequency-average method which estimated the distance between APs and the MS accurately, improved the accuracy significantly; Combined with the weighted least-squares method, the mean

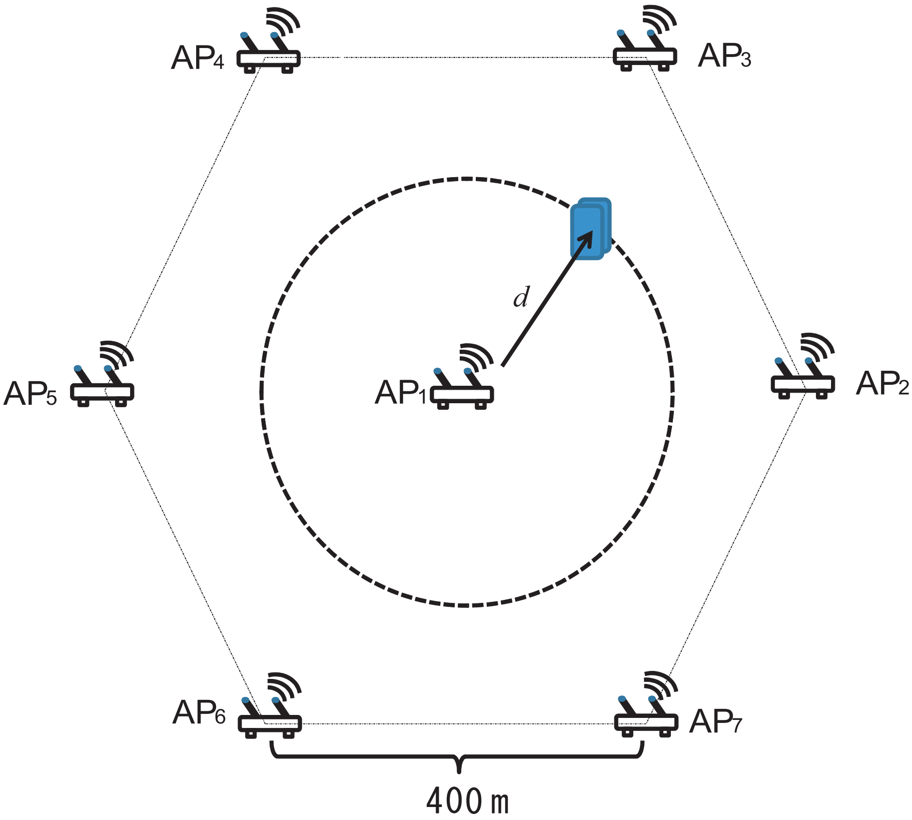

Figure 2.5: Simulation model

location error is reduced under 12m with 7 APs as shown in Fig. 6, and reduced under 10m with adaptable 3 APs as shown in Fig. 2.7. Considering the results, the proposed methods has better performance than the conventional method.

2.5 Conclusion

In this chapter, two novel methods were proposed to determine the location of the MS more accurately In WLAN based systems. Frequency-average method based on RSSI was proposed to estimate the distance between APs and the MS using the average of pilot signal strengths in frequency domain. When determined the position

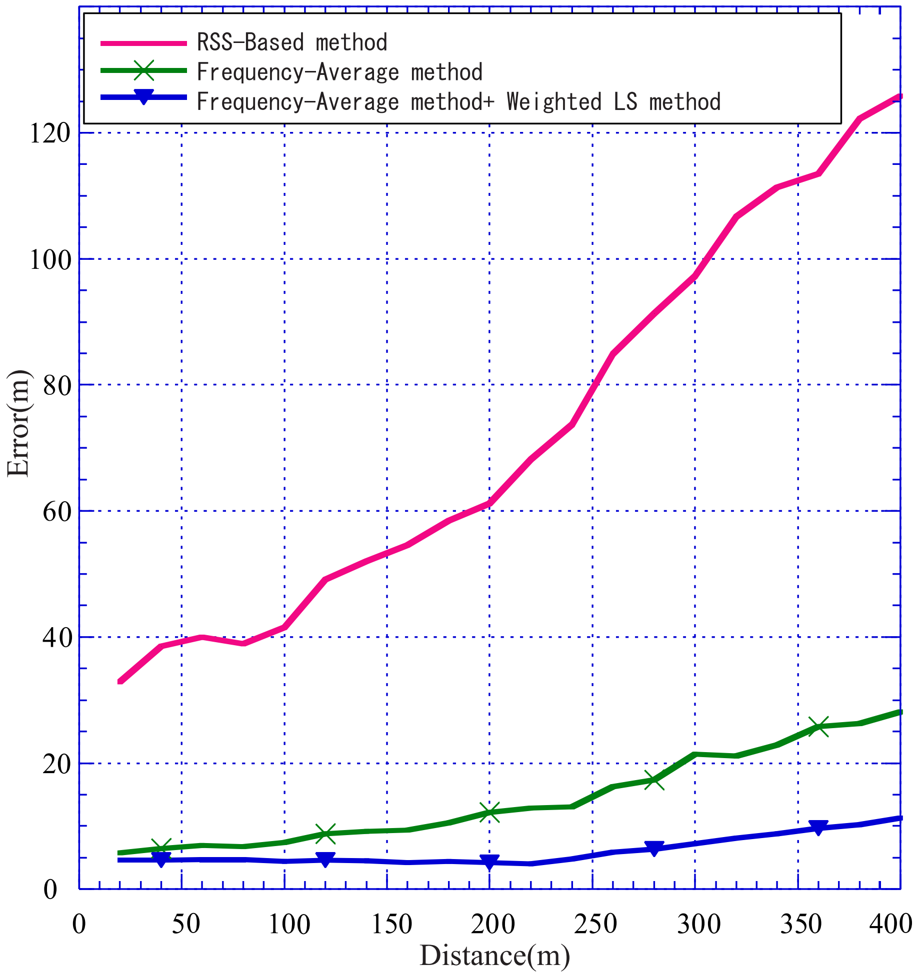

Figure 2.6: The simulation result with 7 APs

of the MS by its estimated distances from multiple APs, weighted LS method was proposed to determine the location more accurately. The conventional location estimation method is a straightforward approach, which compute the center of the intersection points of the circles with radius of estimated distances to identify the location of the MS. The location of the MS also can be identified by minimizing the sum of squares of a cost function, i.e., least-squares algorithm, which do not lead to a significant performance improvement. However, since signals received from different

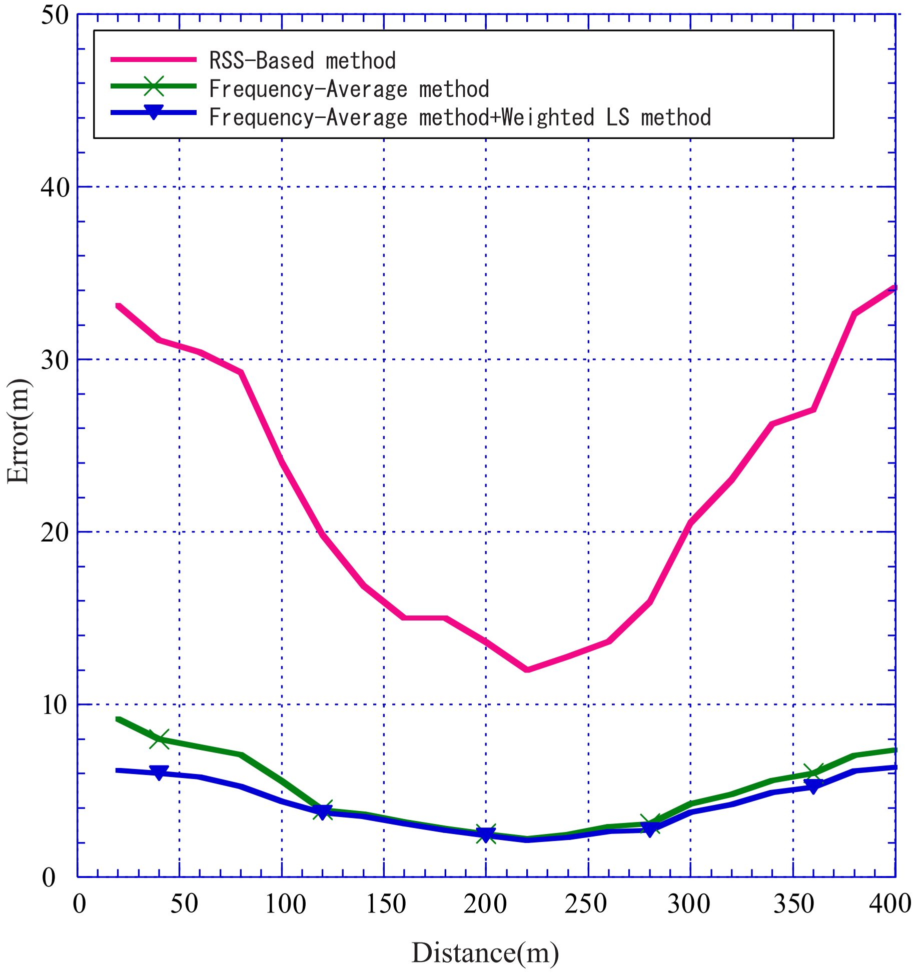

Figure 2.7: The simulation result with adaptable 3 APs

APs have different propagation distances, mutipath fading, and noises, estimating the location of the MS based on the reliability of the signals received from APs was considered to be a reasonable scheme. Therefore, a novel method was proposed to identify the location of the MS by minimizing the sum of suquares of a nonlinear cost function, i.e., weighted least-squares algorithm. The result of the simulations and experiments showed that in the indoor environment, using the proposed methods has a higher degree of accuracy than conventional methods.

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Chapter 3

A Weighted Least-Squares Method for RSSI based systems

3.1 Introduction

Generally, in order to perform the accurate location estimation based on several estimated distances, the least-squares method is widely used[1]. These methods obtain the optimum positioning identity property with the minimum squared error of the cost function. Since some of the received signal power attenuate severely caused by long distance propagation and obstacles between the MS and APs, the cost function shows the poor estimation accuracy for low SNR situation. Previously, we have proposed a weighted least-squares algorithm which determined the weighted coefficient based on the error degree of the received signal power in case that the Friis transmission equation can be applied as a radio propagation channel model[2, 3]. When the radio propagation environment can not be simplified as a free space, this method of determining the weighted coefficient became inappropriate. In this chapter, we propose a novel weighted least-squares algorithm using RSSI method for WLAN indoor positioning system.

3.2 System Model

3.2.1 Distance Estimation based on RSSI

Under idealized condition, the power received by one antenna transmitted from another some distance away can be calculated by the Friis transmission equation. Suppose P_t is the power of the transmitted signal, P_r is the power of the received signal, d is the distance between the transmitting node and the receiving node, λ is the wavelength and the antenna gains of the transmitting and receiving antennas are G_t and G_r, respectively. The Friis transmission equation is defined as

$$P_r = G_t G_r \left(\frac{\lambda}{4\pi d} \right)^2 P_t \tag{3.1}$$

In practice, for the outdoor situations, Rayleigh fading model and Rician distribution model are used generally; For the indoor situations, due to the severe multipath and specific site parameters such as floor layout, moving humans and numerous reflecting surfaces, wall attenuation factor (WAF) and floor attenuation factor (FAF) propagation models are used[4].

In most of the propagation models, the power of the received signal which affected by multipath interference and noise, is gradually weakened as the transmission distance increased. Suppose the $P_{t,i}$, $P_{r,i}$ is the power of the transmitted signal and received signal of the i_{th} AP ($i = 1, 2, ...N$, where N is the total number of APs). We can express the power of the received signal as

$$P_{r,i} = K_i \frac{P_{t,i}}{d_i^{\alpha_i}} + n_i, i = 1, 2, ..., N, \tag{3.2}$$

where d_i is the distance from the MS, n_i is measurement error in the received signal, and K_i represent the rest of all other factors that affects the power of the received signal including the wavelength, antenna height and antenna gain, etc, and α_i is the propagation constant for the i_{th} AP. For idealized condition (free space), α_i is equal to 2; In practice, α_i can be from 2 to 6[5].

The received signal can be obtained by virtually all IEEE 802.11 WLAN interface cards, and the 2.400-2.500, 4.915-5.825 GHz band are sub-divided into channels with a center frequency and bandwidth. Therefore, the signals from different APs can be distinguish and the interference between different APs can be reduced efficiently.

In most cases, the power of the transmit signal $P_{t,i}$ and the parameter K_i are known; the propagation parameter α_i can be estimated from the path loss slope by measurement. Then the d_i can be calculated as

$$d_i = \left(K_i \frac{P_{t,i}}{P_{r,i} - n_i} \right)^{\frac{1}{\alpha_i}}. \tag{3.3}$$

3.2.2 Location Estimation by LS Method

After the distance estimation based on RSSI, the location estimation of the MS can be performed. In WLAN based systems, we used AP as BS. In order to enable 2-D positioning, at least three APs are needed. Under idealized condition, we can determine the location of the MS by the intersection point of the circles with radius of estimated distances and centered at APs, as shown in Fig. 3.1.

However in practice, due to the errors in the distance estimations, the location estimation will be difficult since there will be multiple intersections, or none. In this case, we can identify the location of the MS by minimizing the cost function, i.e., LS algorithm. According to the estimation distances, the location estimation of the MS can be performed utilizing the LS method. Suppose that i^{th} AP located at (a_i, b_i), and the possible location of the MS is (x_m, y_m), the location of the MS can be estimate as

$$(\hat{x}_m, \hat{y}_m) = \arg\min \sum_{i=1}^{N} {\delta_i}^2, \tag{3.4}$$

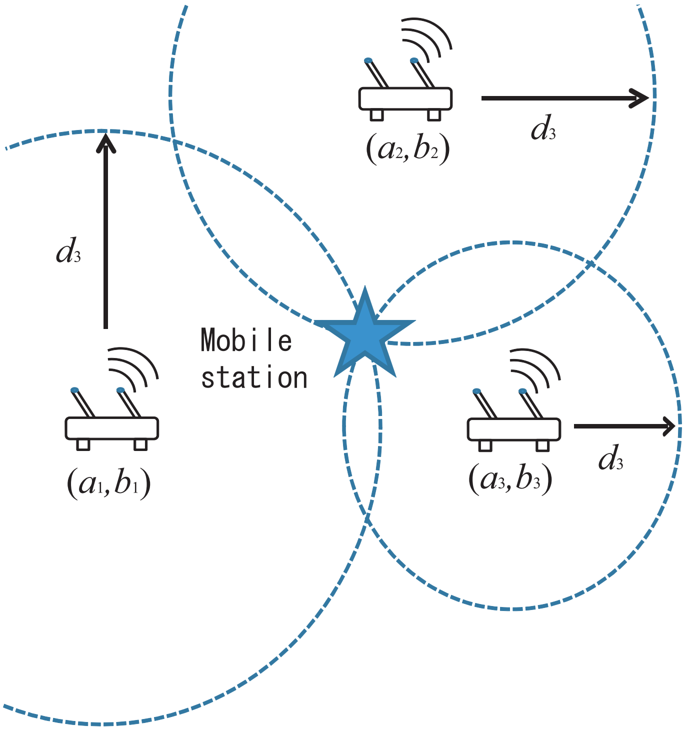


Figure 3.1: Positioning under ideal condition

where

$$\delta_i = \sqrt{(x_m - a_i)^2 + (y_m - b_i)^2} - d_i. \tag{3.5}$$

For the indoor situations, with the irregular movement of the MS, signals from the APs that propagated over long distance or affected by obstacle attenuate heavily. The distance estimation results would contain considerable error due to the low Signal Noise Ratio (SNR). Therefore, perform the location estimation according to the error degrade of the estimated distances, should be a reasonable scheme.

3.3 Proposed Method

Since the signals received from different APs have different propagation distances, affected by different multipath fading and noise, estimating the location of the MS based on the reliability of the estimated distances is considered to be a reasonable scheme. We proposed a weighted LS algorithm basing on the error degree of the estimated distances to perform the location estimation. We added a weighting coefficients to Eq. (3.4) as

$$\begin{aligned}(\hat{x}_m, \hat{y}_m) &= \text{arg min} \sum_{i=1}^{N} \omega_i {\delta_i}^2 \\ &= \text{arg min} \sum_{i=1}^{N} \omega_i [\sqrt{(x_m - a_i)^2 + (y_m - b_i)^2} - d_i]^2.\end{aligned}$$

The estimated distances based on the received signal power which attenuated heavily have low reliability, so a smaller weighting coefficient should be assigned (Fig. 3.2). To find the weighting coefficient ω_i, we studied the disturbance in d_i.

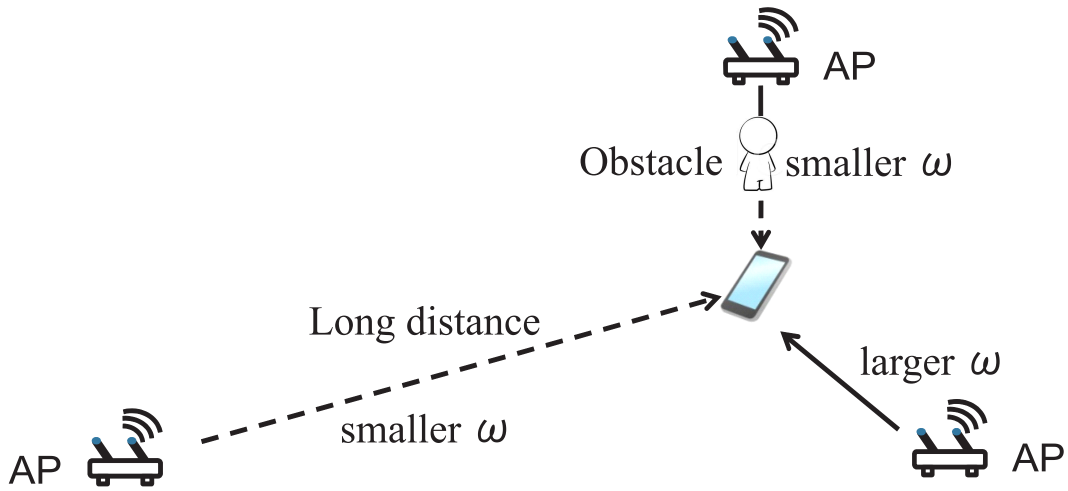


Figure 3.2: Assign a weighting coefficient basing on the reliability

For ease of analysis, assume that all the received signals have the similar measurement errors which have a probability distribution with zero mean and the same corresponding variance σ. Then the Eq. (3.3) can be rewritten as

$$d_i = \left(K_i \frac{P_{t,i}}{P_{r,i} - n} \right)^{\frac{1}{\alpha_i}}. \tag{3.6}$$

The disturbance in the estimated distance d_i can be written as

$$\begin{aligned} \epsilon_i &= \left(K_i \frac{P_{t,i}}{P_{r,i} - n} \right)^{\frac{1}{\alpha_i}} - \left(K_i \frac{P_{t,i}}{P_{r,i}} \right)^{\frac{1}{\alpha_i}} \\ &= \left[\frac{K_i P_{t,i}}{P_{r,i}(P_{r,i} - n)} \right]^{\frac{1}{\alpha_i}} \left[P_{r,i}^{\frac{1}{\alpha_i}} - (P_{r,i} - n)^{\frac{1}{\alpha_i}} \right], \end{aligned} \tag{3.7}$$

assuming the power of the noise is sufficiently smaller than the received signal $P_{r,i}$, we can obtain the approximate equation as

$$\frac{1}{P_{r,i} - n} \simeq \frac{1}{P_{r,i}},$$

and basing on the Taylor series we can have

$$(P_{r,i} - n)^{\frac{1}{\alpha_i}} \simeq P_{r,i}^{\frac{1}{\alpha_i}} - \frac{n}{\alpha_i} P_{r,i}^{\frac{1-\alpha_i}{\alpha_i}}.$$

Finally, we have

$$\begin{aligned} \epsilon_i &\simeq \left(\frac{K_i P_{t,i}}{P_{r,i}^2} \right)^{\frac{1}{\alpha_i}} \frac{n}{\alpha_i} P_{r,i}^{\frac{1-\alpha_i}{\alpha_i}} \\ &= \frac{n}{\alpha_i} K_i P_{t,i}^{\frac{1}{\alpha_i}} P_{r,i}^{-\frac{\alpha_i+1}{\alpha_i}}. \end{aligned} \tag{3.8}$$

The variance of the disturbance is thus of the form as

$$\begin{aligned} \mathrm{Var}(\epsilon_i) &= \mathrm{E}[(\frac{n}{\alpha_i} K_i^{\frac{1}{\alpha_i}} P_{t,i}^{\frac{1}{\alpha_i}} P_{r,i}^{-\frac{\alpha_i+1}{\alpha_i}})^2] \\ &= \frac{\sigma^2}{\alpha_i^2} K_i^{\frac{2}{\alpha_i}} P_{t,i}^{\frac{2}{\alpha_i}} P_{r,i}^{-\frac{2(\alpha_i+1)}{\alpha_i}}. \end{aligned} \tag{3.9}$$

Under the above assumptions, the optimum weighting coefficient ω_i is $\mathrm{Var}^{-1}(\epsilon_i)$. In the case that the power of transmitted signals $P_{t,i}$, the parameter K_i and propagation constant α_i for each AP are sufficiently similar, can be uniformed by P_t, K

and α,respectively. The following condition can be obtained

$$
\begin{aligned}
& \omega_1 : \omega_2 : ... : \omega_n \\
= \; & \mathrm{Var}^{-1}(\epsilon_1) : \mathrm{Var}^{-1}(\epsilon_2) : ... : \mathrm{Var}^{-1}(\epsilon_n) \\
= \; & P_{r,1}^{\frac{2(\alpha+1)}{\alpha}} : P_{r,2}^{\frac{2(\alpha+1)}{\alpha}} : ... : P_{r,n}^{\frac{2(\alpha+1)}{\alpha}}.
\end{aligned}
\tag{3.10}
$$

In this case, the weighting coefficient ω_i can easily be determined according to the power of the received signal $P_{r,i}$ and the propagation constant α.

3.4 Simulation and Experiment Results

3.4.1 Simulation

Computer simulation has been conducted to evaluate the performance of the proposed method for the case of 4 APs. The APs are set at the corner of a square with each side 10 meters long(at $[0, 0]$m, $[0, 10]$m, $[10, 10]$m, $[10, 0]$m). Considering the complexity of calculation and analysis, we assume that the transmitted power $P_{t,i}$, the parameter K_i and propagation constant α_i for 4 APs are sufficiently similar, and can be uniformed by P_t, K and α, respectively.

Assume the propagation constant can be determined accurately as $\alpha = 3$. The location of MS was situated at intervals of 2 meters inside this region, as shown in Fig. 3.3. For convenience, assume $K = 1$. Table I shows the simulation parameters.

We estimate the location of the MS utilizing the conventional LS method and the proposed weighted LS method. Figs. 3.4 and 3.5 show the simulated results for the conventional and the proposed methods.

The root mean square errors (RMSEs) are defined as

$$
E[\sqrt{(\tilde{x}_m - \hat{x}_m)^2 + (\tilde{y}_m - \hat{y}_m)^2}], \tag{3.11}
$$

Table 3.1: simulation parameters

Transmitting signal strength	15dBm
Gaussian white noise strength	-40dBm
FFT size	64
Guide interval	16
Modulation mode	QPSK
Carrier frequency	2.4GHz
Pilot numbers	4
Channel model	Rayleigh fading
Multipath number	5
Attenuation model	Friis model
Doppler	10 Hz

where $\tilde{x}_m, \tilde{y}_m$ is the true position, and the $\hat{x}_m, \hat{y}_m$ is the estimated position of the MS, respectively.

According to the simulation result, it can be seen that the RMSE of the conventioanl LS method is about 1.5m at the edge of the square of the simulation model and the closer the distance to the center of the square, the smaller the RMSE (Fig. 3.4). That is because compared to the MS at edge, the MS at center is closer to each APs and have better relative location to the APs for positioning. The Fig. 3.5 shows that the RMSE of the proposed weighted LS method is about 0.9m at the edge of the square, superior to the conventional LS method about 0.6m.

3.4.2 Experiment

The devices of CC2430 and CC2431 are used for the experiments. These devices contain system on chip (SoC) processors which specifically tailored for IEEE 802.15.4

and ZigBee applications. Zigbee is an IEEE 802.15.4-based specification used to create a low data rata and low power wireless adhoc network. The CC2430 which can be configured with X and Y values that correspond to the physical location, can be used as APs. And CC2430 includes a location detection hardware module which can be used as MS to receive signals from nodes with known location ' s of APs. Based on the information collected by CC2431, the postion of MS can be calculated based on the LS method or the proposed WLS method. All experiments were performed in the gymnasium of Chiba University, as shown in Fig. 3.6.

To estimate the weighting coefficients, the propagation constant need to be determined in advance. For each AP, the propagation constant is measured. Situate the MS at a cirecle which centered in the $i-th$ AP, and increase the distance step by 0.5m. The received signal strengths are measured in four directions for each distance. To reduce the impact of signal reflection on the floor, all the devices are set about 2m above the ground. The experiment model and environment of propagation constants measurements are shown in Fig. 3.7, and the experiment results of the propagation constant is shown as Fig. 3.8.

Based on the results, the propagation constants can be fixed for the APs as 2.786, 2.432, 2.690 and 2.593, respectively. The average value 2.625 is used to estimate the weighting coefficients based on Eq. (3.10). Using the same model in the simulation part, the experiment results are shown as Fig. 3.9 and Fig. 3.10.

According to the experiment results, it can be seen that the RMSE of the conventioanl LS method is about 1.8m at the edge of the square of the experiment model (Fig. 3.9). The Fig. 3.10 shows that the RMSE of the proposed weighted LS method is about 1.5m at the edge of the square, superior to the conventional LS method about 0.3m.

The simulation and experiment results show that the proposed method have better performance of positioning accuracy in the simulation and the experiment to the conventional LS method. However, compared to the improvement of accuracy about 0.6m in simulation, there is 0.3m in experiment. The reason is that the experiment is conducted in the gymnasium, which has more radio propagation channels caused by reflection and refraction from numerous objects such as walls, ceilings and floors. The multipath fading is more severe in practice than simulation. For the same reason , when the MS is set to some specific location such as $[8, 10]$m, $[10, 8]$m and $[10, 8]$m in experiment, the positioning degrade severely. The received signals is influenced by more severe multipath fading at these location.

3.5 Conclusion

Since the complex environment in indoor situation, the error in the distance estimation is unavoidable. Based the error degree of the estimated distances, a novel weighted least-squares algorithm using RSSI method for WLAN indoor positioning system is proposed. The weighting coefficient is determined according to the disturbance in the estimated distance. The result of the simulations shows that in the same SNR situations, the proposed method achieved a higher degree of accuracy than conventional methods.

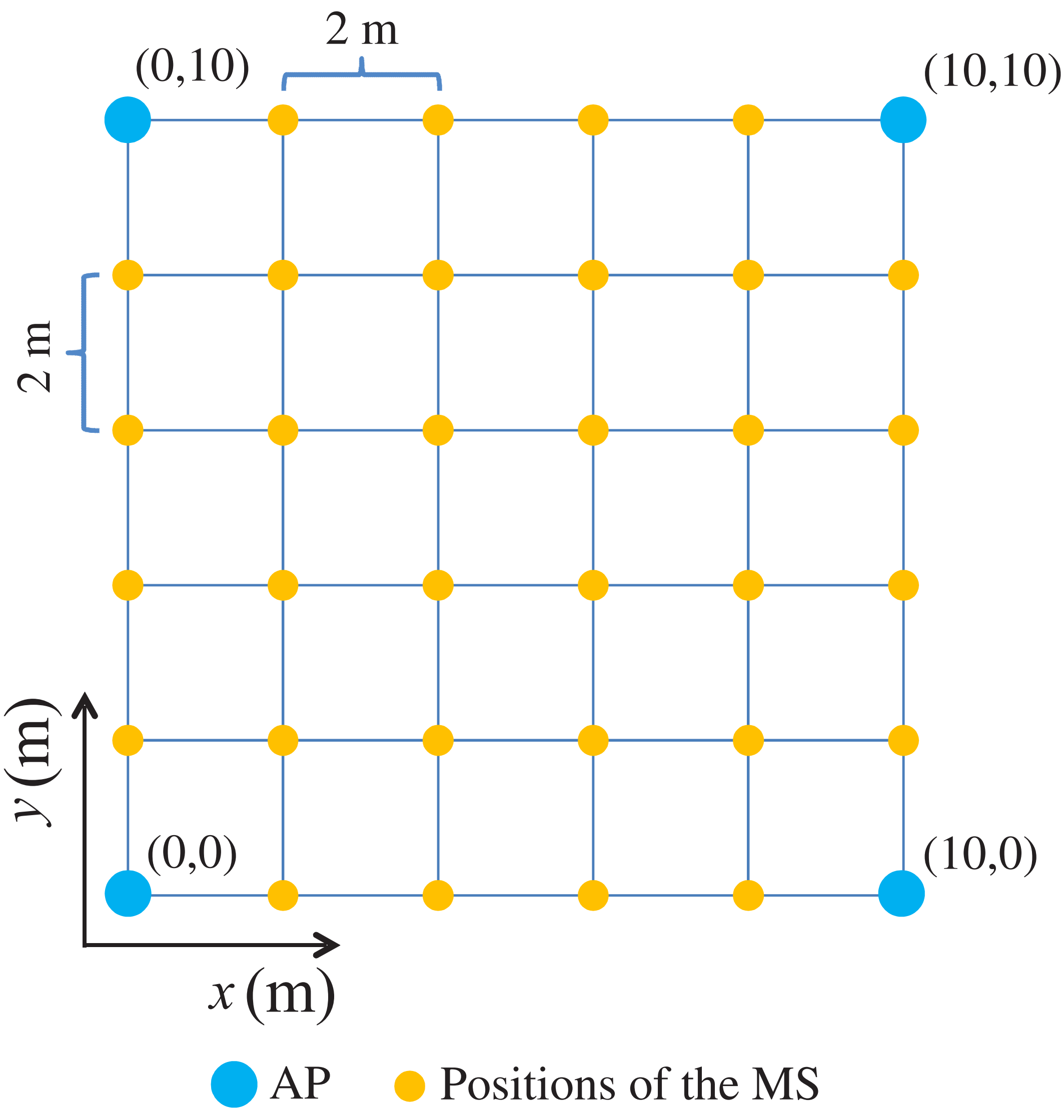


Figure 3.3: Simulation model

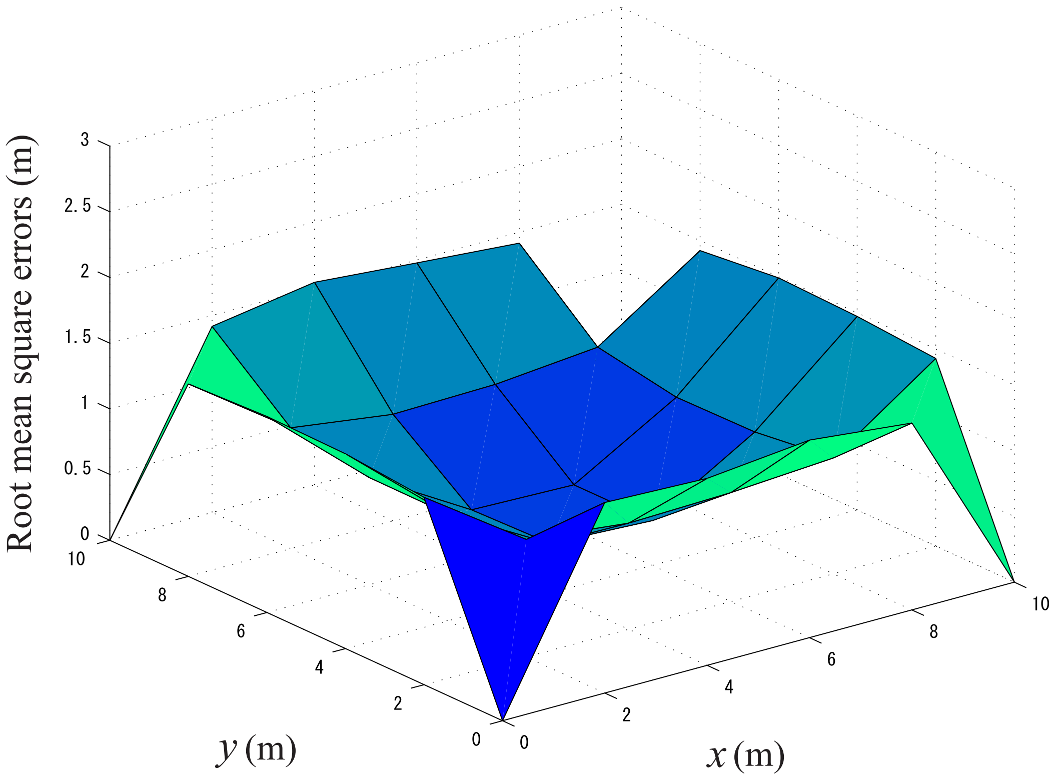


Figure 3.4: The simulation results with conventional method

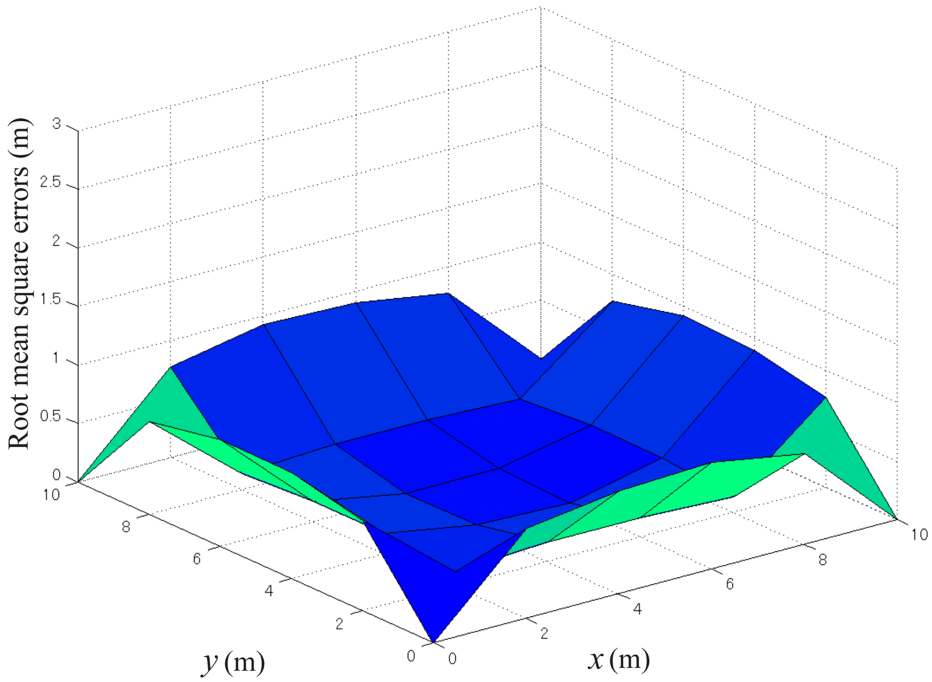
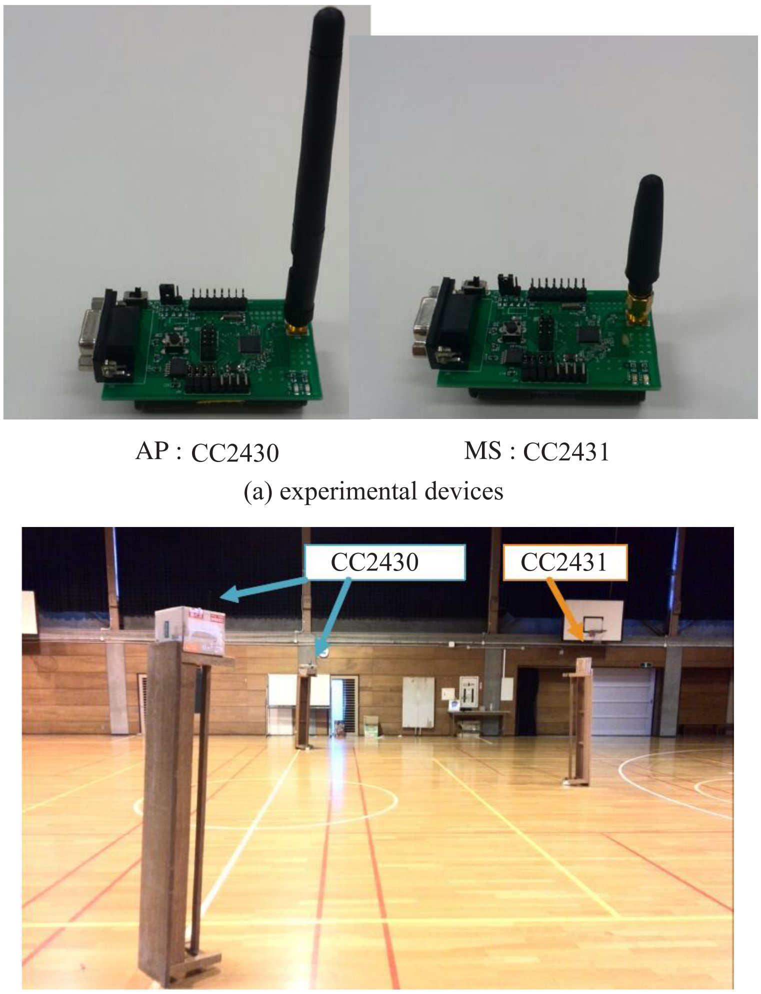


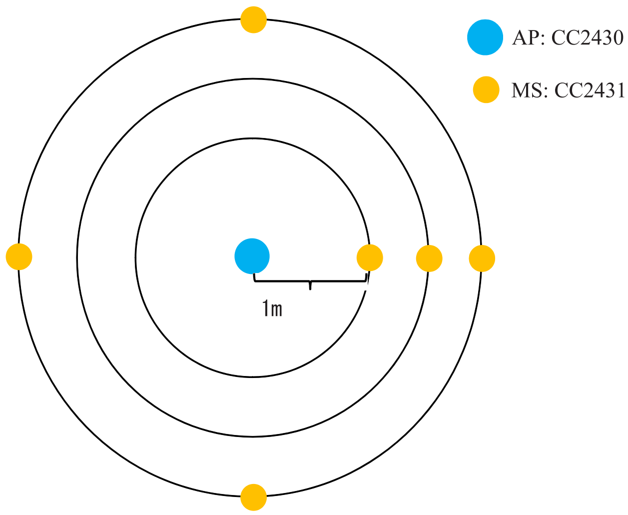
Figure 3.5: The simulation results with proposed method



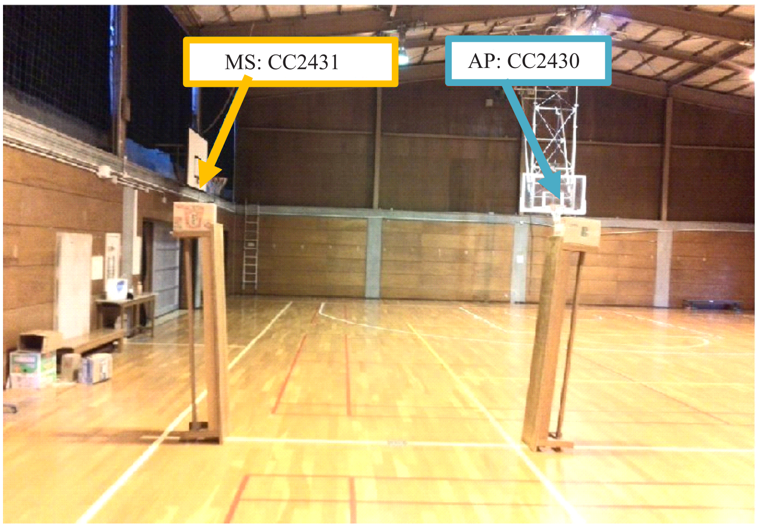
(a) experimental devices

(b) experimental environment

Figure 3.6: The experiment devices and the experiment environment



(a)experiment model



(a)experimental environment

Figure 3.7: Experiment model and environment of propagation constants measurements

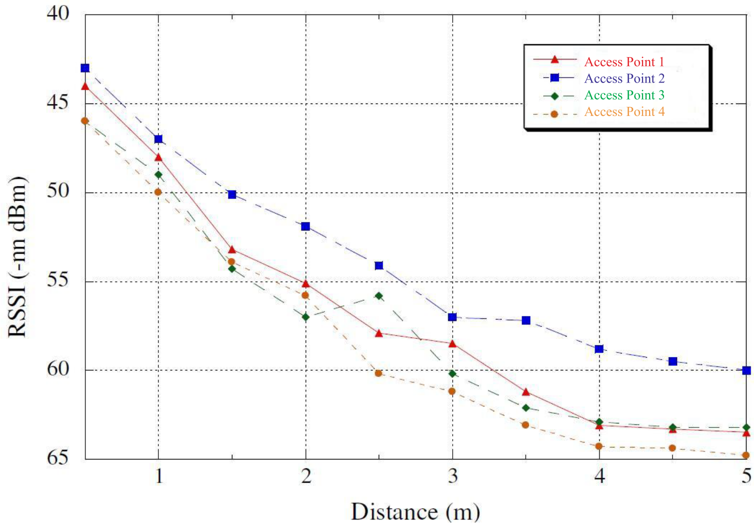


Figure 3.8: Experiment results of propagation constants measurements

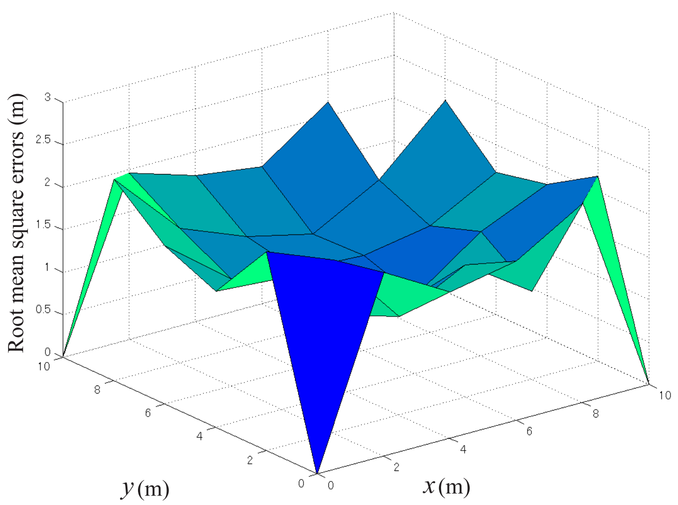


Figure 3.9: The experiment results with conventional method

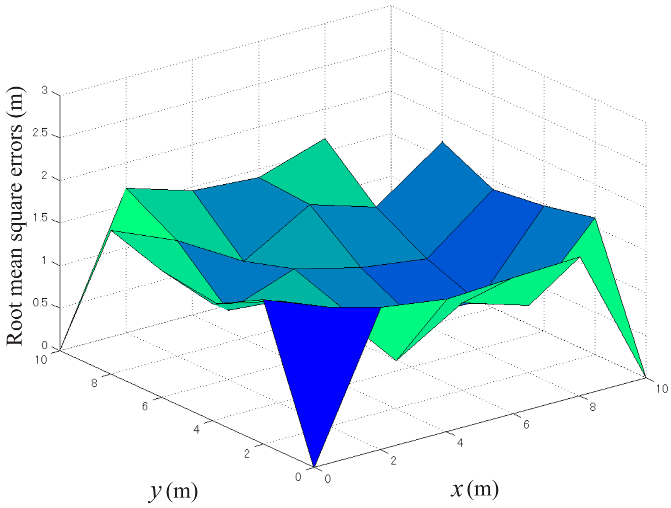


Figure 3.10: The experiment results with proposed method

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Chapter 4

Conclusion

Because of the lack of accucary in the conventional positioning systems such as GPS, the research on indoor positioning systems is attracting much attention. With the popularization of wireless access points, the WAP-based systems are considered to be an optimal method for accomplishing the positioning functions under indoor environments.

The dissertation focus on the accuracy improvement for WAP-based indoor positioning systems using attenuation-based method. During the distants estimation stage, a method which estimate the distance between AP and mobile station (MS) using the average of pilot signal strength in frequency domain is proposed. During the distants estimation stage, a simple and efficient weighted LS method which determine the weighted coefficient in case that the Friis transmission equation can be applied. Moreover, a unified weighted LS method was proposed when the radio propagation environment can not be simplified as a free space.

In Chapter 2, two novel methods are proposed to determine the location of the MS more accurately. In WAP-based systems. Frequency-average method based on RSSI was proposed to estimate the distance between APs and the MS using the average of pilot signal strengths in frequency domain. When determined the position of the MS by its estimated distances from multiple APs, weighted LS method was proposed to determine the location more accurately. The result of the simulations showed that under indoor environments, using the proposed methods had a higher degree of accuracy than conventional methods. The result of the simulations showed that in the same signal noise ratio (SNR) situations, using the proposed frequency-average method and the weighted LS algorithm achieved a better performance than the conventional RSS methods.

In Chapter 3, considered of the complex environment under indoor environments, the error in the distance estimation is unavoidable. Based the error degree of the estimated distances, a unified weighted LS algorithm was proposed. The results of the simulation and experiment showed that under indoor environments, the proposed unified weighted LS algorithm achieved a higher degree of accuracy than conventional LS methods.

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List of Related Papers

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