Design of WiPS: WLAN-Based Indoor Positioning System

Teruaki Kitasuka* · Tsuneo Nakanishi*,** · Akira Fukuda*

1. Introduction

THE recent emergence of ubiquitous computing has highlighted the need for context-aware applications that can change their behavior depending on the user's presence and preferences. The user's presence means the current situation of the user, such as location, schedule, time, and weather. Location is the most essential information parameter for context-aware applications, and must be obtained on the fly, in semi-real time. This feature is a major difference from ordinary location surveying.

A number of technologies have been developed to allow determination of user location. Of these, GPS[1] has been the most widely used location sensing technology since the 1980s. GPS is used for the navigation of ships, airplanes, cars, and people. As an application of GPS, many driving control systems based on GPS are also widely used by transport and taxi companies. GPS pseudolite (ground-based pseudo-satellite transmitters)[2] can work even near obstructions, where the signals from orbiting GPS satellites cannot reach. Cellular-based systems have also been developed, and are provided by a few cellular phone carriers.

However, inside buildings, the systems mentioned above cannot provide location information with satisfactory accuracy, or in the worst case do not provide any such information. GPS pseudolite is a good candidates for a practical indoor location sensing technology. There are many approaches to the provision of indoor location information that use infrared, ultrasonic, computer vision, and radio frequency (RF) signals. In this paper, we focus on indoor positioning technologies, especially RF-based systems.

This paper is organized as follows: Sec. II summarizes current positioning technologies. IEEE 802.11[3] is also described as an RF-based network. In Sec. III, we describe WiPS, a WLAN-based indoor positioning system. Simulation results obtained with WiPS are shown in Sec. IV. The conditions of simulation and future studies are discussed in Sec. V. Finally, our conclusions are presented in Sec. VI.

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2. Positioning Technologies

In this section, we summarize current positioning technologies and IEEE 802.11 wireless LAN networking.

2.1 Outdoor Positioning

GPS (Global Positioning System) is a satellite-based navigation system, which consists of 24 or more satellites and works worldwide. The first GPS satellite was launched in 1978. Each satellite is placed about 20,000 m above the ground and transmits RF signals to ground-based receivers. GPS satellites have a synchronized clock to determine their own orbit. GPS receivers use the signals from these satellites to determine their own location by using location of the satellites and the distance to them. The positioning accuracy of GPS after SA (selective availability) was turned off in 2000 is typically about 10 m. However, GPS signals cannot be received close to high-elevation obstructions or in buildings.

GPS pseudolite (ground-based pseudo-satellite transmitters) is a device that transmits GPS satellite-like signals. Using GPS pseudolite, a GPS receiver can determine its location, even in the vicinity of obstructions that block GPS signals from orbiting satellites, and can increase positioning accuracy.

Cellular phone carriers provide user location services using a number of systems, including A-GPS, TDOA, AOA/TDOA, and E-OTD. A-GPS (Assisted GPS)[4] uses the GPS infrastructure to determine user location. A-GPS is assisted by base stations, which provide information to the GPS measurement processing of a cellular phone. The cellular phone can search GPS signals quickly and sensitively using the aiding information. The cellular phone sends the captured GPS signal to the base station. Then, the base station calculates the location of the cellular phone. TDOA, AOA/TDOA, and E-OTD are also used by a few cellular phone carriers. In general, these technologies cannot achieve better positioning accuracy than A-GPS.

A number of applications use location information, including location-aware routing protocols and services on a manet, a mobile ad hoc network[5]. Location-aware ad hoc network routing protocols are called geographic position-assisted routing protocols. These are ad hoc network routing protocols aided by location, and they assume that location information is provided by GPS. In an ad hoc network, communication takes place through wireless links among mobile hosts without support of base stations. As the transmission range is limited, hosts have to relay a packet before it reaches its destination. Many routing protocols have been proposed for this purpose[6-8]. Location-aware routing protocols find a destination node by using its location information. GeoCast and LAR are location-aware routing protocols. GeoCast[9,10], which uses geographical information instead of logical node address, such as IP address, allows messages to be sent to all nodes in a specific geographical area. LAR[11] limits the search for a new route to a small zone, and can therefore reduce the number of routing messages significantly. LAR is an on-demand routing protocol based on source routing.

Previous studies have used ad hoc networks and sensor networks for positioning[12,13]. In these studies, position information was provided by the network itself, and GPS was not used for positioning. These are called infrastructure-free positioning systems. These algorithms provide positions relative to other hosts.

2.2 Indoor Positioning

For indoor environment, a number of different systems using infrared, ultrasonic, RFID tags, and RF devices have been designed to determine the user position.

The Active Badges system[14,15] is an infrared-based location system, which typically provides room-size-location information. A base station is placed in each room and users carry a badge that emits its ID over infrared. The base station senses the ID, and a central server collects the data from the base stations.

The Active Bat system[16] is an ultrasonic-based location system, which determines Bat tag position by ultrasound time-of-flight measurement. In this system, users carry a Bat that acts as an ultrasonic generator. Receivers are mounted in the ceiling and measure the distance to the Bat, and a central controller determines the Bat location. This system provides accuracy of 95% within 9 cm of true position.

Although they have many applications, RFID tags are typically used as a substitute for bar-codes. RFID tags can also be used for location determination. In such systems, RFID tags are placed at key points and the relation between tag ID and location is entered into a database. When a user moves the tag reader closer to a tag, the reader reports the location of the tag to the user.

RF-based systems mainly use IEEE 802.11 wireless LAN networks and attempt to deal with the noisy characteristics of wireless radio. Multipath fading is the major reason for this noise. RADAR[17] is probably the first example of a positioning system using an IEEE 802.11 network. They overcome the noisy environment by creating a Radio Map in the off-line phase by collecting signal strength samples for each user location and orientation. In the real-time phase, each access point measures signal strength of the mobile terminal and searches through the Radio Map database to determine the location of the mobile terminal. The Radio Map-based method is an empirical method. A mathematical method using a mathematical model of indoor RF propagation and floor layout information instead of a Radio Map has also been proposed for RADAR.

CMU-TMI[18], developed and demonstrated at Carnegie Mellon University, is a client-centric triangulation-based remapped interpolated approach. CMU-TMI reduces training complexity over RADAR by a factor of eight and has better accuracy. For privacy, a client-centric approach is selected, providing users complete control over the visibility of their location. However, power consumption is increased to measure the signal strength on the client side. Accuracy, training complexity, power consumption, usability, and privacy were discussed previously[18].

Ekahau Positioning Engine 2.0[19], released by Ekahau Inc. in October 2002, also uses an IEEE 802.11 network to provide location information. It achieves 1 m average accuracy with at least 3 audible channels in each location. This system requires site calibration up to 1 hour per 1,200 m^2.

Hitachi[20,21] released TDOA (time difference of arrival)-based location technology in October 2002. This system uses two types of access points, a Master AP and a Slave AP. Slave APs synchronize their clocks with that of a Master AP. Slave APs measure the arrival time from a mobile terminal, and the Master AP determines the location of the mobile terminal by using the time difference of arrival between the signal reception time at multiple Slave APs.

Many location systems for ubiquitous computing were reviewed previously[22].

2.3 IEEE 802.11 Standard

There are a number of short-range wireless technologies. Over the past few years, short-range systems with ranges of 10 to 100 m have emerged. Short-range wireless technologies show four trends in their growth: (1) growing demand for wireless data capability in portable devices, (2) crowding in radio spectra, (3) growth of high-speed wired access to the Internet, and (4) shrinking semiconductor cost and power consumption[23]. Among these technologies, the IEEE 802.11 standard is currently the most popular.

IEEE 802.11 technology is generally called WLAN. Most new laptops and PDAs are equipped with WLAN devices, and cellular phones should be equipped with WLAN devices to provide VoIP function in the near future.

The IEEE 802.11 standard, which has become very popular in recent years, is used for Wireless LAN MAC and PHY. IEEE 802.11b/11g operate in the 2.4 GHz ISM (industrial, scientific, and medical) band. 802.11b has two types of PHY, called DSSS (direct sequence spread spectrum) and FHSS (frequency-hopping spread spectrum) the latter of which is used only in the low data rate mode. PHY has data rates of 1 to 11 Mbits/s, but 802.11g, which uses OFDM (orthogonal frequency division multiplexing) instead of spread spectrum, was ratified in June 2003 to extend the data rate of 802.11b to 54 Mbits/s. 802.11a operates in the 5.4GHz band and uses OFDM with a data rate up to 54 Mbits/s. 802.11a and 11g have the same data rate, but 802.11a achieves a better effective data rate than 802.11g.

As medium sharing mechanism of the MAC layer, CSMA/CA (carrier sense multiple access with collision avoidance) with ACK, is employed instead of CSMA/CD on wired LANs. RTS and CTS packets are supported as an option to resolve hidden terminal problems.

The received signal strength of a WLAN fluctuates in an indoor environment because of signal reflection, diffraction, and scattering. An indirect path is mainly generated by reflection, and the transmitted signal reaches the receiver *via* both direct and indirect paths. This multipath phenomenon, or multipath fading, strongly influences the signal strength. There have been many studies to overcome this influence as described in Sec. II-B.

3. WiPS (WLAN-BASED INDOOR POSITIONING SYSTEM)

3.1 Concept and Features

WiPS uses the wireless LAN infrastructure and provides location information to mobile users. Both Microsoft Research[17] and Ekahau Inc.[19] performed similar studies. The concept of WiPS has been presented previously[24,25]. In the present study, we attempted to design WiPS as a calibration-free positioning system or a very short-term calibration system. The major features of WiPS are as follows:

- As the density of mobile users (*i.e.*, WLAN terminals) increases, the accuracy of location information becomes higher.
- Under conditions where the density of location reference points, such as access points, is sparse, WiPS provides more precise location information than existing systems.

The first feature corresponds to a rendezvous in a crowded place, such as an exhibition hall, and the second feature reduces the cost of setting many access points.

The WLAN radio signal strength is used for calculation of the location. However, the signal strength does not reflect the distance between terminals directly, because the signal fades not only with distance but also due to multipath fading, obstructions, and other causes.

To provide these features, WiPS measures the signal strength at not only access points but also at mobile terminals. In addition, each mobile terminal measures the signal strength of access points and neighboring mobile terminals. Then, WiPS determines the mobile terminal's location by using more observations than in the systems described previously[17,19].

As an example, in Fig. 1 a mobile terminal A measures the signal strength of access points G1, G2, and G3, and also of mobile terminals B, C, and D. On existing works such as that described by Bahl and Padmanabhan[17], only access points measure the signal strength of mobile terminals, or mobile terminals measure

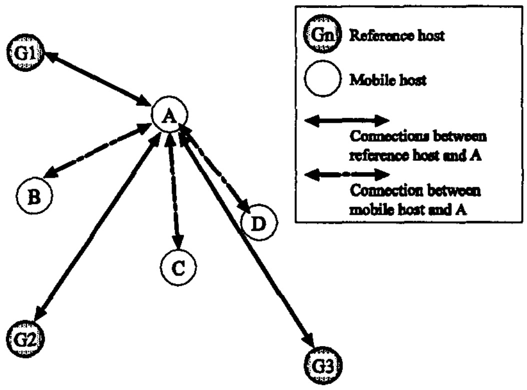
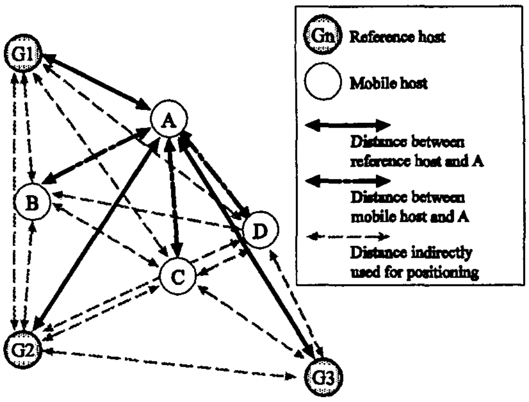


Fig. 1. Basic design of WiPS. A mobile terminal A measure the signal strength of not only access points G1, G2, and G3, but also mobile terminals B, C, and D.

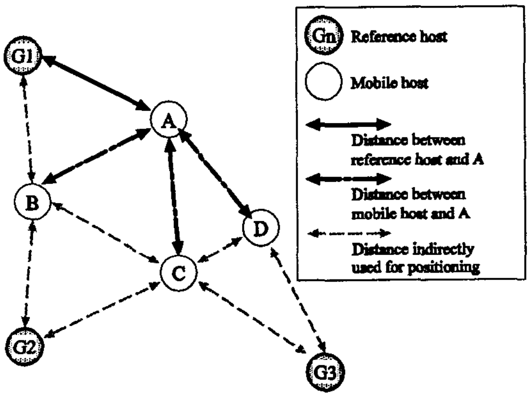
the signal strength of only access points. Generally in WiPS, many observed signal strength data are used to determine the position of mobile terminals. The number of observations of the signal strength are increased in $o(n^2)$, where n is the number of terminals and access points. These observations indicate that WiPS can achieve the above two features.

Fig. 2 shows the detailed features of WiPS. Fig. 2 (a) shows the case with a high density of mobile terminals. In this case, WiPS makes many observations of signal strength, which are then converted into the distance. Estimated positions of mobile terminals are precise as the influence of error in distance measurement is reduced. Existing systems attempt to measure only the distance to neighboring access points, while WiPS to measures the distance to mobile terminals as well as neighboring access points.

Fig. 2 (b) shows the case where the density of reference points is low. Radio range is assumed to be shorter than that in Fig. 2 (a). In this case, WiPS attempts to locate mobile terminals using position relative to adjacent terminals. In existing systems, each mobile terminal position cannot be estimated by triangulation because there are less than three adjacent access points for each mobile terminal.



(a) Under conditions with high mobile terminal density, WiPS makes many observations of signal strength and distance.



(b) Under conditions with low reference point density, WiPS estimates the position of mobile terminals. The radio range is shorter than in (a).

Fig. 2. Features of WiPS. WiPS is suited to use under conditions of high mobile terminal density and sparse reference points.

3.2 Algorithm

In WiPS, each mobile terminal measures the signal strength of both neighboring mobile terminals and neighboring access points. Mobile terminals notify the location server of the list of neighbors' IDs and their signal strength values. Each access point also measures the signal strengths of its neighbors. Access points notify the location server of the list of neighbors' IDs and their signal strength values. In addition, access points also notify the location server of their absolute locations. The location server calculates locations of mobile terminals using this information.

The process of location calculation on the location server is described below. Basically the steepest descent method is used as follows.

1. Gather the list of signal strength values from mobile terminals and access points. Also, gather the absolute locations of access points.
2. Convert the signal strength into the distance.
3. Determine the initial positions of mobile terminals.
4. Iterate the modification of the positions of mobile terminals, until convergence.
5. Notify mobile terminals of their locations.

In Step 1, each mobile terminal and access point send a packet containing a list of the signal strengths of neighboring mobile terminals and access points to the server. In this case, "neighbor" means that the terminal is within radio communication range of another terminal. Each access point adds its own location to the packet. In the case shown in Fig. 2 (a), there are three access points, G1, G2, and G3, and four mobile terminals, A, B, C, and D, all of which send the server a packet containing the signal strengths of neighboring access points and mobile terminals. Three access points also send the server a packet containing their physical position. In Step 2, the server converts each signal strength value into the distance.

In Step 3, the server calculates the initial positions of mobile terminals by using the positions of neighboring access points and neighboring initialized terminals. The initial positions of mobile terminals are determined roughly. Rough initialization at this step can avoid large errors between the final estimated position and the real position, and reduce the iteration in Step 4. When the server starts to initialize the position of mobile terminal A, the server finds a set of the neighboring mobile terminals N_A and a set of the neighboring access points G_A. N_A is subdivied into a set of initialized terminals and a set of non-initialized terminals. Initialized mobile terminals are selected from N_A and named $N'_A(\subseteq N_A)$. N_A and N'_A are the sets of mobile terminals. G_A is the set of access points. The position of X, which is either a terminal or an access point, is denoted by $\vec{P}_X$. The initial position of terminal A is determined by

$$\vec{p}_A = \frac{\sum^{X\in G_A} \vec{p}_X + \sum^{X\in N'_A} \vec{p}_X}{n(G_A)+n(N'_A)},$$

where $n(G_A)$ and $n(N'_A)$ are the number of hosts in G_A and N'_A, respectively. Initialization is performed cyclically until all initial positions of mobile terminals are determined. The order of initialization is determined arbitrarily. For example, in the case of Fig. 2 (a), there are four mobile terminals and the order of initialization can be A, B, C, D, or A, C, B, D, *etc.*

In Step 4, mobile terminal positions are refined by the steepest descent method to minimize the expression:

$$\sum_{i=0}^{n-1}\sum_{j=i+1}^{n}\left|\left|\vec{p}_i-\vec{p}_j\right|-d_{i,j}\right|,$$

where n is the total number of hosts - both mobile terminals and access points, $\vec{p}_i$ is the position of the i-th host, and $d_{i,j}$ is the measured distance between i-th and j-th hosts.

The position $\vec{p}_i^{(k+1)}$ which is the position of the i-th host, in $(k+1)$-th iteration is calculated by:

$$\vec{p}_i^{(k+1)}=\vec{p}_i^{(k)}+\alpha\nabla(i).$$

When α is a suitable small value α ($\alpha=0.05$ is used in later simulation), $\nabla(i)$ is defined by

$$\nabla(i)=\sum_{j=0}^{n}\vec{u}_{i,j}\times f(i,j),$$

where $\vec{u}_{i,j}$ is a unit vector from $\vec{p}_j^{(k)}$ to $\vec{p}_i^{(k)}$ and $f(i,j)$ is the difference between the measured distance $d_{i,j}$ and the current estimated distance between i-th and j-th hosts. $\vec{u}_{i,j}$ and $f(i,j)$ are defined as follows:

$$\vec{u}_{i,j}=\frac{\vec{p}_i^{(k)}-\vec{p}_j^{(k)}}{l_{i,j}},$$

$$l_{i,j}=\left|\vec{p}_i^{(k)}-\vec{p}_j^{(k)}\right|,$$

$$f(i,j)=\begin{cases} d_{i,j}-l_{i,j} & \text{if } i \text{ and } j \text{ are neighbors,} \\ 0 & \text{if } i \text{ and } j \text{ are not neighbors and } l_{i,j}>d_{\max}, \\ d_{\max}-l_{i,} & \text{if } i \text{ and } j \text{ are not neighbors and } l_{i,j}\leq d_{\max}. \end{cases}$$

$d_{\max}$ is the typical radio communication range.

The iteration is finished when the maximum value of $\nabla(i)$ is smaller than a suitable value γ ($\gamma=0.01$ is used in later simulation)

4. Simulation Environment and Results

4.1 Simulation Environment

To evaluate the precision of location information provided by WiPS, we simulated WiPS in a plane measuring $200\times200\text{m}^2$. We assumed that the radio communication range of each host is 100 m. Four, five, or nine access points were located in the plane. The number of mobile terminals was increased from 5 to 50 at five intervals. Nine access points represent sufficient density, while the cases with four and five access points represented sparse distributions.

In this simulation, our major aim was to confirm the advantage of our method of distance measurement between mobile terminals. We compared our method with that in which only access points measure the distance to mobile terminals. The probabilistic error of the estimated distance is dealt with in this simulation. Movement of each mobile terminal, communication delay, and method of distance estimation from signal strength were ignored.

Fig. 3 shows the locations of access points 1 through 9 used in the simulation. In the case where four or five access points were used, they were numbered 1 to 4 or 5, respectively. Mobile terminals were placed in the plane in a random manner and they did not move.

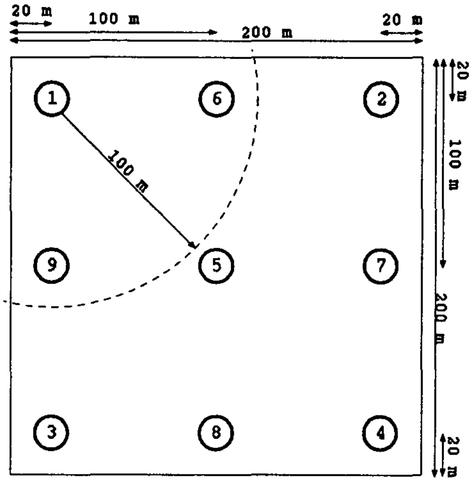


Fig. 3. Simulation environment.

The coverage ratios of access points for each case, calculated from how many access points could be accessed in each location, are shown in Table 1. For example, a location in which three access points could be accessed directly was classified as an area with three adjacent access points. In the case where nine access points were used, three or more access points could be reached directly in about 95% of the $200 \times 200m^2$ plane, but in 0.03% and 4.37% of the area only one and two access points could be reached, respectively. When five access points were used, three access points could be reached in only 23.88% of the area, two access points in 53.04%, and only one access point in 23.07%. When four access points were used, there were no areas in which three access points could be reached directly, and in 1.81% of the plane no access points could be reached. Only one and two access points could be reached in 74.10% and 24.08% of the area, respectively.

Table 1. Coverage ratio of reference hosts in the simulation environment

Adjacent access points	Number of reference points		
	4	5	6
0	1.81%	0.00%	0.00%
1	74.10%	23.07%	0.03%
2	24.08%	53.04%	4.37%
3	0.00%	23.88%	20.79%
4	0.00%	0.00%	54.55%
5 and over	0.00%	0.00%	20.23%

We performed the simulations under two assumptions regarding the distance measurement between hosts. The method used for measurement of the distance between hosts is not the main topic of this paper. The first assumption was that the measured distance between hosts contains probabilistic error, the properties of which are described in the next paragraph. The second assumption was that measured distance was the same as real distance. This second assumption is not suitable for use in a real environment if the distance is estimated from the radio signal strength. However, we used the second assumption to demonstrate availability when the density of access points is very low.

In the first assumption, the measured distance is the sum of the real distance and the probabilistic error distance, the latter of which is chosen under the normal distribution and its dispersal is in proportion to the real distance. The proportional error means that, if the real distance between hosts is 100 m, we use the measured distance selected in the normal distribution, *i.e.*, between 80 and 120 m in 95.5% of cases. If the distance is half, the error is also half. Fig. 4 shows probability density functions in cases where real distances are 50 and 100 m. In related studies[17,19], the estimated distance was determined from the signal strength. We did not do this in the simulation.

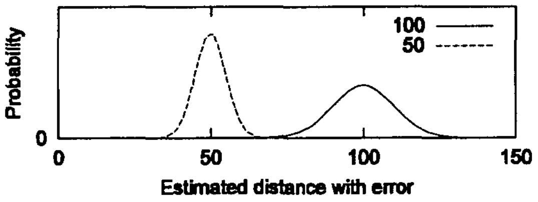


Fig. 4. Probabilistic error was added to real distance in the simulation.

4.2 Simulation Results

Fig. 5 shows the results under the assumption that the measured distance contains 20% error in a normal distribution. The X- and Y-axes indicate the number of mobile terminals and the average error distance of estimated location, respectively. The error distance is defined as the difference between the real and estimated positions of each mobile terminal. On the access point-based method, the average error rate is shown as I-R4-E1, I-R5-E1, and I-R9-E1. The lines show the results for the cases of four, five, and nine access points, respectively. The average errors were 42.2 m, 16.8 m, and 6.5 m, respectively. The averages were almost the same even if the number of mobile terminals was changed.

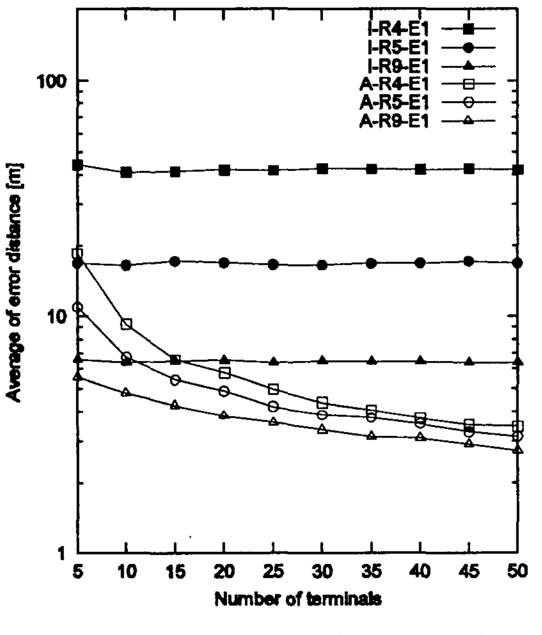


Fig. 5. Simulation results in cases where distance measurement has probabilistic error. I-, The results obtained with the access points-based method. A-, The proposed method. -Rn-, The case of n access points.

The results obtained using the proposed method are shown as A-R4-E1, A-R5-E1, and A-R9-E1 in Fig. 5 where A-Rn-E1 is the results in the case of n access points. In the proposed method, the average error decreased as the number of mobile terminal increased. With five mobile terminals, the average errors in the cases of four, five, and nine access points were 18.5 m (44% of the value obtained with the access point-based method), 10.9 m (65%), and 5.5 m (86%), respectively. With fifty mobile terminals, the average errors were 3.4 m (8%), 3.1 m (19%), and 2.8 m (42%) in the cases where four, five, and nine access points were used, respectively.

Fig. 6 shows the results where the measured distance was assumed to be equal to the real distance between each pair of hosts. The lines I-R4-E0 and I-R5-E0 show the results obtained by the access point-based method, while A-

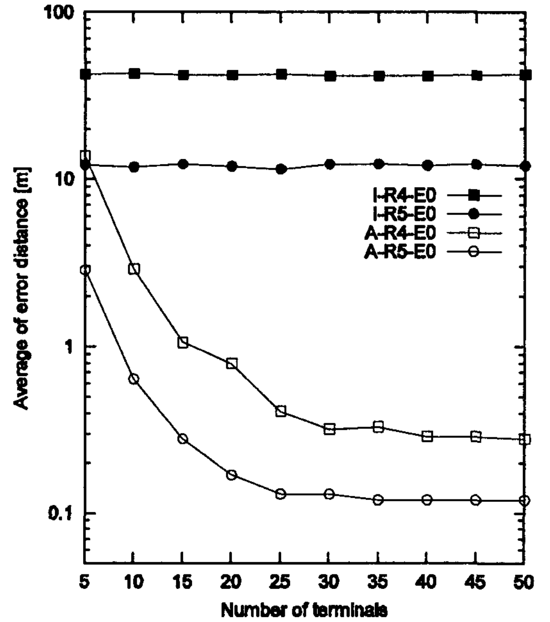


Fig. 6. Simulation results in the cases of error-free distance measurement. I-, The results obtained with the access points-based method. A-, The proposed method. -Rn-, The case of n access points.

R4-E0 and A-R5-E0 show the results obtained with the proposed method. *-R4-* and *-R5-* cases are where four and five access points were used, respectively. The results of the case using nine access points are not shown in Fig. 6 as the errors were almost zero in both the access point-based method and the proposed method.

The access point-based method showed no improvement with increases in the number of mobile terminals (Fig. 6). In contrast, the proposed method showed improvement in the average error with increasing number of mobile terminals. In the case of four access points, the average error with the access point-based method was 42.0 m, while with the proposed method, the average errors were 13.8 m (33% of 42.0 m) and 0.3 m (0.7%) with use of five and fifty mobile terminals, respectively. In the case of five access points, the average error with the access point-based method was 12.1 m, while the proposed method yielded average errors of 2.9 m (24% of 12.1 m) and 0.1 m (1.0%) with five and fifty mobile terminals, respectively.

Comparison of Fig. 5 with Fig. 6 indicates that the error of measured distance between hosts has a great influence on the accuracy of location estimation. However, in both figures, the number of mobile terminals has an important effect in the proposed method. The effect is greater when the access points are sparse, such as when four or five access points were used, than in the case of nine access points.

Finally, Fig. 7 shows the number of iterations for each case. The operation of each iteration is described in Sec. 3. The parameters of iteration were α=0.01 and γ=0.01. We confirmed that the number of iterations did not increase even when the number of mobile hosts increased. Especially, in the case where access points were sparse, such as when only four or five access points were used, iterations decreased as the number of mobile terminals increased. Complexity of the iteration is not greater than $o(n^2)$, where n is the number of hosts, both access points and mobile terminals. Then, the complexity of estimation of all mobile terminals is $o(n^2)$ or below.

5. Discussion

In this section, the following topics are discussed.

- movement speed of mobile terminals
- communication delay
- scalability of the location server
- privacy

These conditions are ignored in this simulation.

One of movement speed and communication delay is assumed to be zero in the simulation. Movement speed of mobile terminal and delay of communication are related to each other. If one of them is zero, the other can take any values. However this assumption can not be accepted in a real environment. If the movement speed is slower enough than the communication delay, movement speed of mobile terminal has little effect to the accuracy of location estimation. Total delay of providing location information is described by

$$t_{total} = t_{d1} + t_c + t_{d2},$$

where t_{total} denote the total delay, and t_{d1}, t_c, and t_{d2} represent the delay of communication from a mobile terminal to the server, the computation period in the server, and the communication delay from the server to the mobile terminal, respectively. If we assume that the total delay t_{total} is 0.5 sec, the estimated location received by user's mobile terminal is the location of 0.5 sec previously. If the user walks at a speed of 80 m/min(=1.3 m/sec), the user moves 0.65 m in 0.5 sec. Moreover, mobile terminals are not synchronized with each other. Moreover, the server has to use packets that have different timestamps to calculate location. This results in degradation of the accuracy of location information.

Scalability of the location server is not evaluated clearly in the simulation. Fig. 7 shows the average number of iterations of the proposed algorithm. The complexity of location computation is not over $o(n^2)$, where n is the number of hosts. To employ WiPS in a building, we will prepare a server for each floor. Each server will manages its floor separately. In this environment, mobile terminals have to find a suitable server on each floor - this constitutes the multiple server problem. Many service discovery techniques have been proposed, and these can be used to solve the multiple server problem.

Finally, privacy is one of the most important issues in positioning. Users generally wish to control their own location information. An obvious solution is client-side location computation, as employed by Smailagic and Kogan

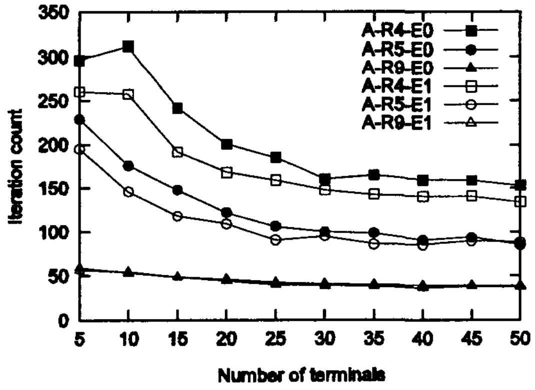


Fig. 7. Number of iterations until convergence.

[18]. In WiPS, the server has to support access control of location information for each user.

6. Conclusion

In this paper, we presented the concept, features, and the algorithm of WiPS, a wireless LAN-based indoor positioning system. WiPS can provide precise location information where the density of user is high. In addition, the precision remains high even where the density of access points is low. We showed the results of simulations to confirm these features.

Simulation experiments showed that WiPS decreases the average error to between 44% and 86% when the number of mobile terminals is only five in a plane measuring 40,000m^2. With fifty mobile terminals, average error decreased to 42% in the worst case.

Currently, we are evaluating WiPS in a real indoor environment (our lab). We have begun to evaluate this system using commercial access points and notebook PCs, but in the near future we will evaluate WiPS with PDAs in our lab.

Acknowledgment

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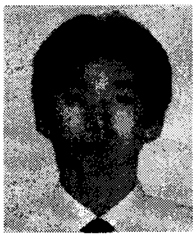

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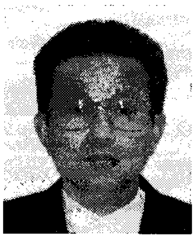

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