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An indoor wireless positioning system based on wireless local area network infrastructure

***Y. Wang*, X. Jia, H.K. Lee**
Satellite Navigation and Positioning Group (SNAP)
School of Surveying and Spatial Information Systems
The University of New South Wales, Sydney, NSW 2052, Australia
Tel: +61-2-9385-4208; Fax: +61-2-9313-7493; Email: yufei@student.unsw.edu.au

G.Y. Li
No.10 Institute of Changjiang Water Resource Commission,
Ministry of Water Resources, 434001 Hubei, P.R. China
Tel: 86-13972334696; Fax: 8671-68315571; Email: lyt1994@sina.com

ABSTRACT

With the increasing use of mobile computing devices such as Personal Digital Assistants (PDA), and an expansion of Wireless Local Area Networks (WLAN), there is growing interest in an indoor Wireless Positioning Systems (WPS) based on WLAN infrastructure. This paper describes a WPS that uses the signal strength of WLAN transmissions from/to WLAN Access Points to determine the position of the mobile user. To some extent, this technique addresses one shortcoming of GPS positioning systems, which are ideal outdoors but which are generally not available indoors. In this paper, the authors describe the configuration of WPS. Experiments and a discussion of the accuracy are presented. The results of the experiments show that a wireless access point-based indoor positioning system is feasible and a positioning accuracy of 1-3m can be achieved, while an accuracy of 0.1m can be obtained under an idealized situation.

KEYWORDS: Wireless positioning, Wireless Local Area Network infrastructure, Signal propagation, Indoors positioning.

1. INTRODUCTION

Navigation and positioning technologies have entered the ‘pluralistic age’. On the one hand, with the widespread adoption of GPS technology, the price of GPS receiver declines, the size of the receiver decrease, and the GPS accuracy increase substantially after the removal of Selective Availability. Therefore GPS is largely unchallenged in the outdoor positioning domain where there is a clear view of the sky! Contrast this situation with positioning scenarios that are much more challenging, such high-dynamic navigation, indoor positioning, and positioning in urban environments. There is still a need for other positioning technologies to remedy the serious shortcomings of GPS technology. A variety of augmented systems have been proposed/developed, e.g. multi-sensor integrated systems, pseudo-satellite technology, assisted-GPS techniques, wireless signal positioning, TV signal positioning, IP address positioning, domain name system (DNS) positioning, and several mobile phone-based positioning techniques such as enhanced observed time difference (E-OTD), time of arrival (TOA) (Hjelm, 2002).

Compared with outdoor positioning, many investigators have overlooked indoor positioning. There are several reasons why the challenges of indoor positioning have failed to attract attention in the past. One reason was the limited market demand, and another reason is incomplete infrastructure. However, with more and more newly built wireless communications network infrastructure (e.g., more than 100 WLAN Access Points have been deployed in the past year around the University of New South Wales (UNSW) Kensington Campus), and an increasing interest in location-aware services, there is a need for an accurate location-finding technique for indoors. Therefore, with this motivation and in order to meet this impending requirement, the Satellite Navigation and Positioning (SNAP) group has been actively researching this topic. This paper is organized as follows: section 2 is an introduction to WPS systems; in section 3, experiments were conducted, and the results and data analysis are presented; section 4 gives the model improvement; and the final section gives a summary and conclusions.

2. SYSTEM DESIGN

2.1 Experimental Test Bed

A test bed was established on the fourth floor of the Electrical Engineering Building, in the main working zone of SNAP group at UNSW. The layout of this floor is shown in Figure 1. It has dimensions of 17.5m by 84m with about 40 different rooms, including classrooms, computer labs, offices, and storerooms.

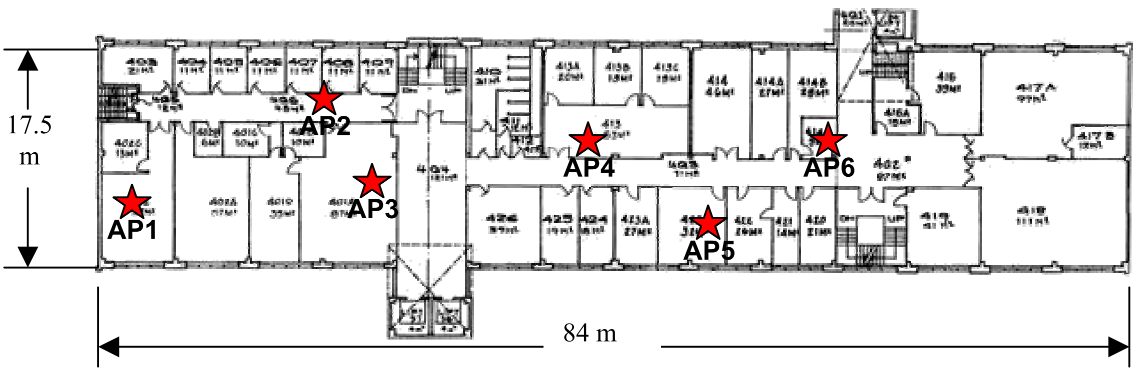

Figure 1. Test bed for the SNAP Wireless Positioning System (WPS) with location of WLAN access points (AP)

2.2 WLAN Infrastructure and Hardware

Six WX-1590 *SparkLAN* 11 Mbps WLAN Wireless Multi-Mode Access Points (http://www.sparklan.com) were installed at the locations indicated in Figure 1. The Access

Points (AP) act as the wireless signal transmitters or base stations. At the rover side, the authors used an Acer eXtensa 710T laptop computer (Windows 2000 operating system) (http://www.acer.com) and Compaq iPAQ 3970 (Pocket PC 2002 operating system) (http://www.compaq.com), with *Lucent Technology Wi-Fi* Orinoco Wireless Golden Card (Figure 2) (http://www.orinocowireless.com). These network cards can detect and synchronize the signal strength (*SS*) from the six wireless Access Points. The 802.11 b ('WiFi') Telecommunication Protocol is used in this system.

Figure 2. WPS hardware

2.3 Software Development

The authors have developed a complete indoors WPS software package, including roving client side software for the iPAQ 3970 and Acer Laptop computer, and indoor tracking-monitoring program on the server side. The SNAP-WPS laptop version software was developed using Borland Delphi 7. The iPAQ version was developed using Embedded Visual C++ 3.0. In these experiments, the laptop was used as the roving client. Figure 3 shows the graphical user interface (GUI) of the application for the mobile client.

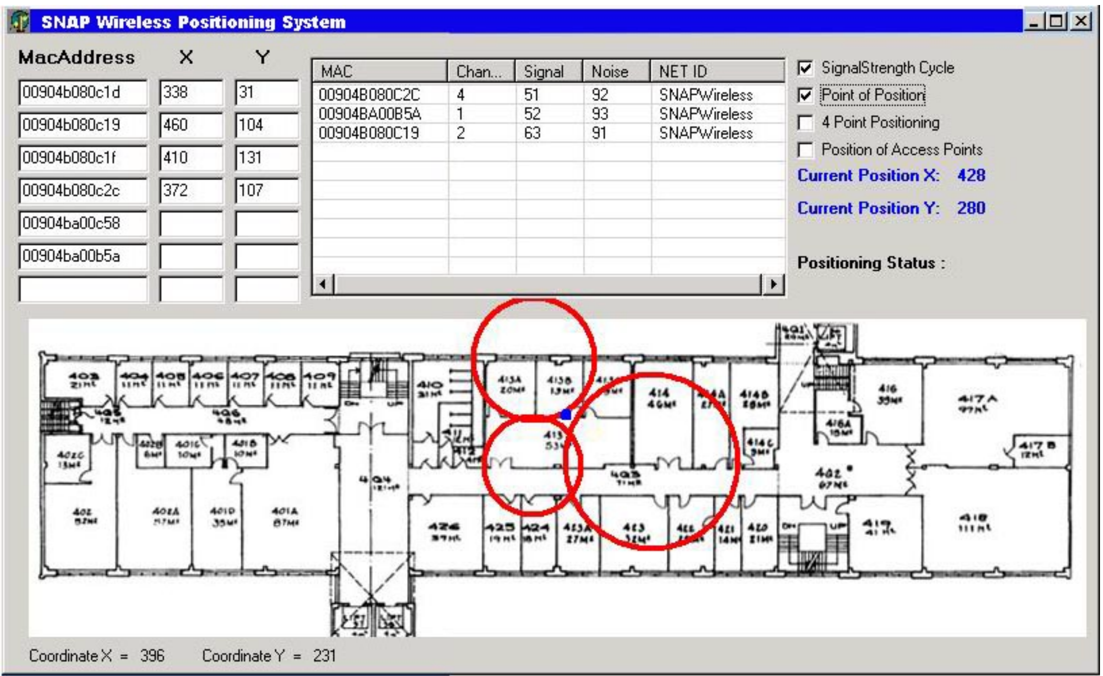

Figure 3. Mobile client's GUI interface for the laptop computer

2.4. The Software Architecture of Indoor Positioning and Tracking System

According to the system demands, and following the principle of Internet software, a three-tier design was implemented to demonstrate this WPS system, consisting of: (1) wireless positioning and tracking client side, (2) tracking and monitoring server side and, (3) remote monitoring client side (Figure 4).

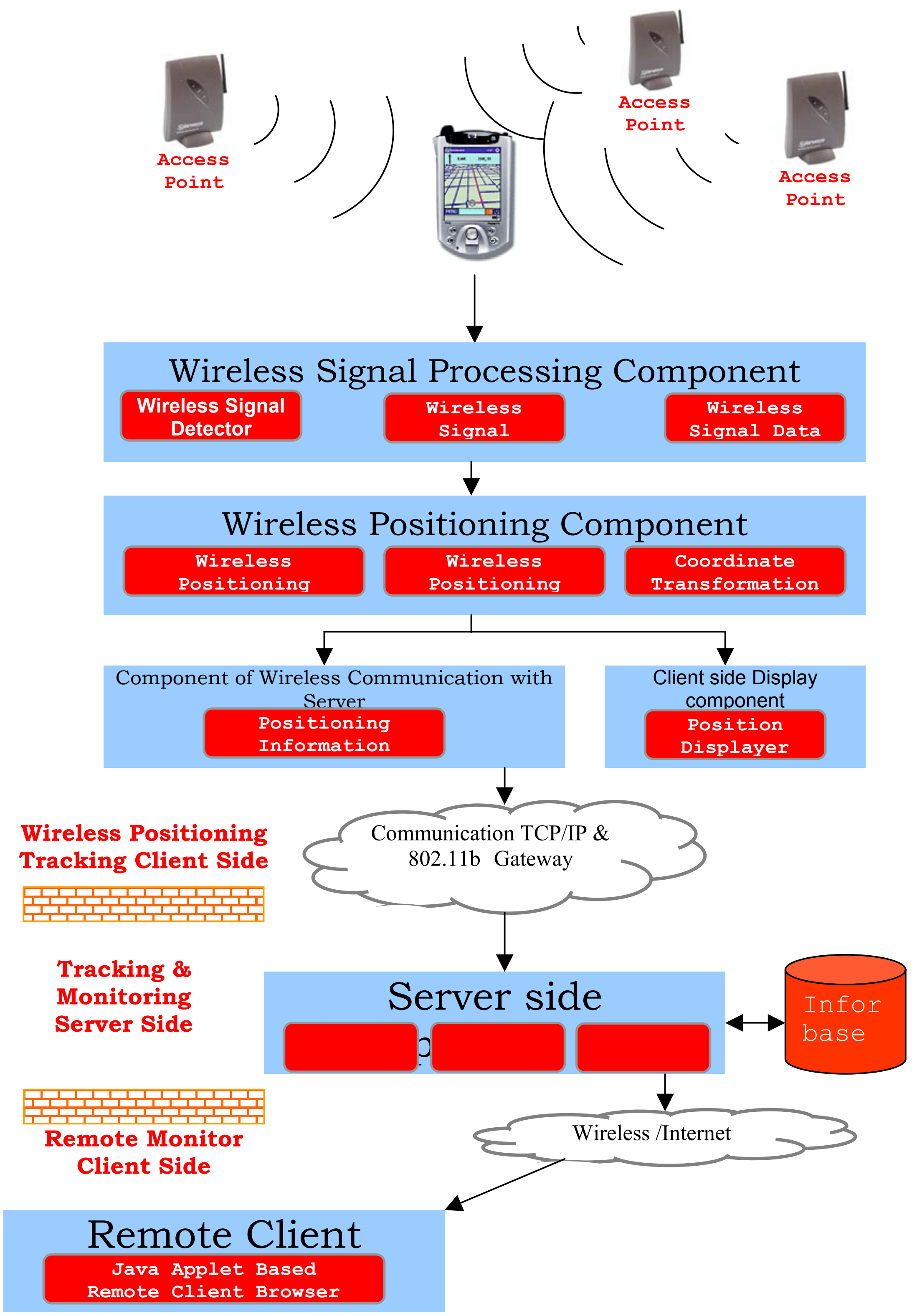

Figure 4. WPS Architecture

3. RESEARCH METHODOLOGY AND TYPICAL EXPERIMENTS

Experiments were carried out in order to test the feasibility and reliability of wireless positioning based on the aforementioned WLAN infrastructure. The results from the experiments are presented below.

While conducting the experiments, a huge amount of data was recorded in files and the data records include the *time* information (t), *MAC* address of the AP, *Signal Strength (SS)* information, *Noise*, *Signal-To-Noise Ratio (SNR),* transmitter channel of AP, basic service set identifier (*BSSID)*, etc. *SS* information is recorded in units of dBm, that is, a signal strength of *s* watts is equivalent to $10*log_{10}(s/0.001)$ dBm.

3.1 Stability of 2.4GHz WLAN Infrastructure Radio Signal Strength

The radio signal, as a ranging signal, should be 'stable' and 'consistent' at a fixed point. In order to test this, a stationary measurement experiment was conducted. A 24-hour dataset of 142,717 measurements was collected from one AP. The sampling rate was 0.5s. Figure 5 shows the *SS* against time.

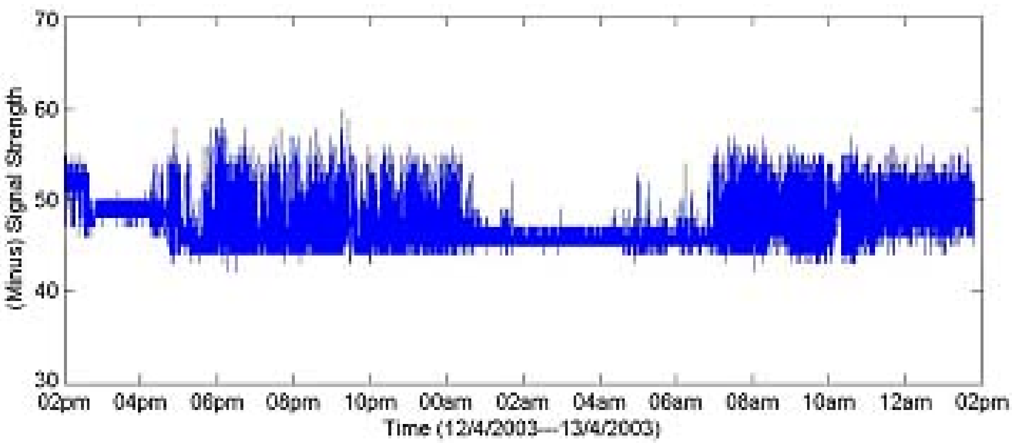

Figure 5. Twenty-four-hour static signal strength (SS) measurement (units in dBm)

From Figure 5, it can be seen that the *SS* is quite stable and consistent over time, with *SS* in the range of 45 dBm to 48 dBm (with a mean of 47.17 dBm and a standard deviation of 2.26 dBm). All of these results are considered acceptable, because some environment elements such as the movement of people, computer noise, and the influence of other radio signals, will change *SS* by amounts of the order of 5 dBm to 10 dBm. During the daytime (notably office hours) period, the *SS* shows a significant fluctuation. On the other hand, at night, the experimental situation is ideal, with very little signal fluctuation.

The entire *SS* data sample distribution is shown in Figure 6. Due to the influence of environmental elements, it is mono-directional to *SS,* which means that the external environmental elements always tend to weaken the *SS*.

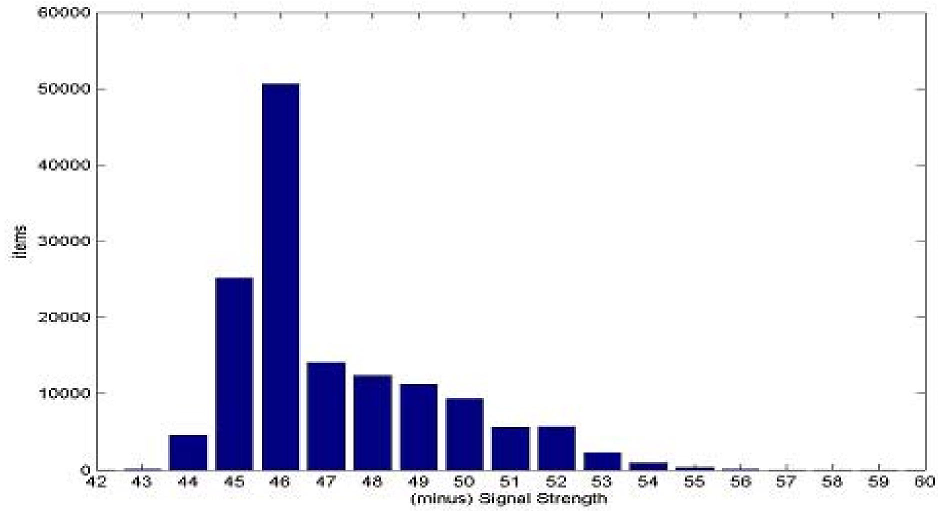

Figure 6. The *SS* data distribution over a 24-hour period

From a data analysis of the 24-hr stationary measurement experiment, one can conclude that the 2.4 Ghz WLAN infrastructure radio signal is stable and consistent, and can therefore be used as a measuring signal.

3.2 Reliability Experiment of the 2.4 GHz WLAN Infrastructure Radio Signal

The *SS*[1] will be location sensitive, which means that with the change of distance between rover and AP base station, the *SS* should change accordingly. Moreover, the distance should be a function of *SS*. In order to validate this, a reliability experiment was designed in order to determine the relationship between distance and *SS,* based on an empirical signal propagation model.

In free space (i.e., remote from any obstruction), VHF and UHF radio signal propagation follows the free-space or Friis equation (Parsons and Gardiner, 1989; Blake, 1986):

$$\frac{P_R}{P_T} = G_T G_R (\frac{\lambda}{4\pi d})^2 \tag{1}$$

where P_T is the power supplied to the antenna, P_R is the power available at the receiving antenna, G_T is the transmitter antenna gain, G_R is the receiver antenna gain, d represents the distance between transmitter and receiver, while λ is the carrier wavelength.

Then the propagation loss is:

$$L_F = 10\log_{10} {P_R}/{P_T} = 10\log G_T + 10\log G_R - 20\log f - 20\log d + K \tag{2}$$

where

1 Besides Signal Strength (*SS*), *Noise* and *Signal-to-Noise ratio* (*SNR*) information is collected, but *Noise* is a relative random value at a given situation, so it cannot be used as a signal. As for *SNR*, it is always influenced by random *Noise*, hence it also cannot be regarded as a signal.

$$K = 20\log\frac{3*10^8}{4\pi} = 147.56 \tag{3}$$

For unity-gain (isotropic) antennas, one can define a "basic transmission loss":

$$L_B = -32.44 - 20\log f_{MHz} - 20\log d_{KM} \tag{4}$$

However, this type of propagation model is only good in theory. It is often too difficult to implement in practice if a high degree of accuracy is required. Therefore, the authors did not consider the influence on the radio signal of environmental elements such as walls, the movement of people, the operation of electrical devices. Therefore the test bed area is assumed to represent a balanced and uniform (or idealized) situation.

There were 20 distributed points in the test bed area selected. At every point, 20 *SS* sampling records to three different AP base stations were recorded. The average value of *SS* was obtained. At the same time, one can calculate the linear distance between the feature points to every AP (see Figure 7). From Figure 7, one can see that the *SS* decreases exponentially with increasing distance.

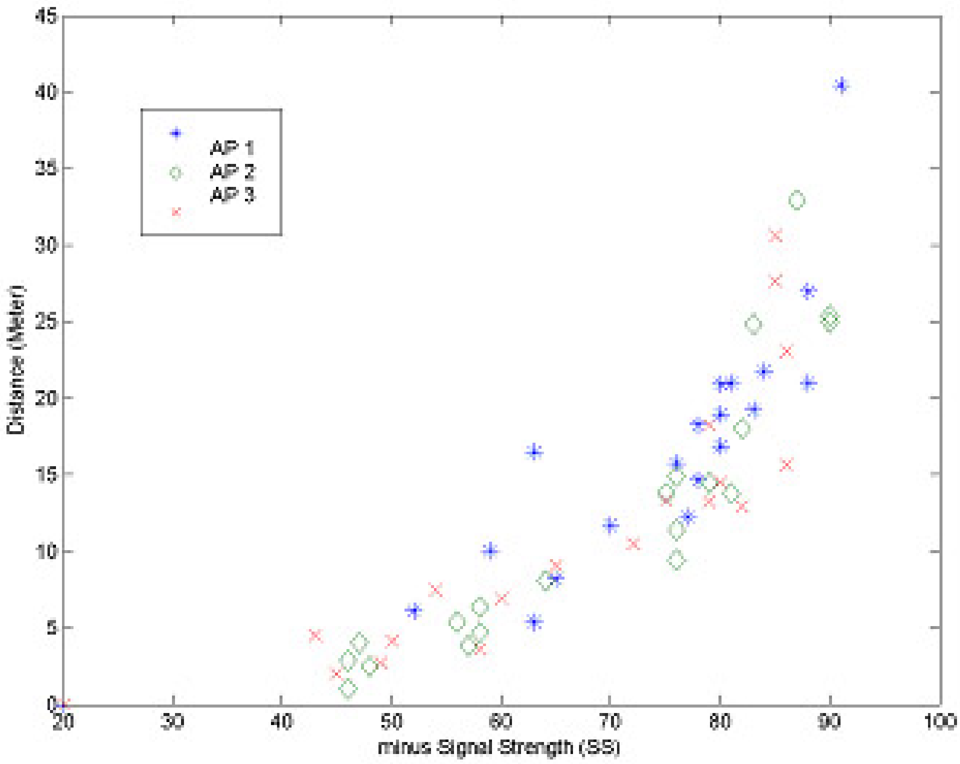

Figure 7. *SS* and distance relation under the assumption of 'thick free space'

In order to determine the mathematical relation, without considering physical properties, an empirical model based on regression was assumed (Figure 8). From Figure 8, the positioning accuracy residuals of linear and quadratic regression models (35.83 m and 28.47 m respectively) are high. Comparing the residuals among cubic (26.59 m), fourth degree (26.05 m), fifth degree (26.05 m) and sixth degree (25.99 m) polynomials, the differences are quite small.

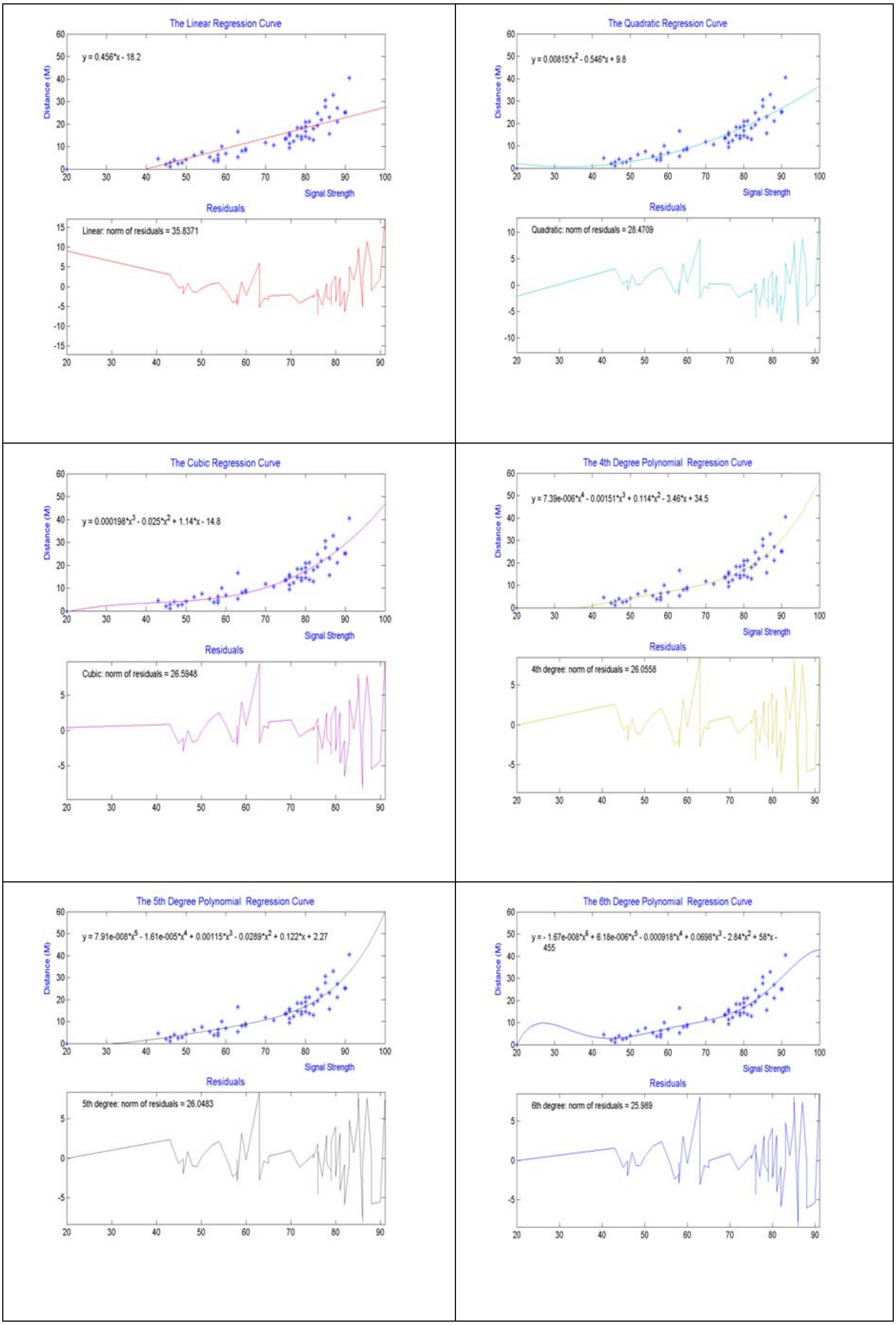

Figure 8. Polynomial regressive curves and residuals

It was therefore decided that a cubic regressive equation would be adequate for the empirical model (EM)[2]

$$d = 0.000198*S^{3}-0.025*S^{2}+1.14*S-14.8 \quad (5)$$

where S is signal strength (SS) in dBm (normally S is between 15-90 dBm) and d is the distance between receiver and AP in metres.

3.3 Verification of the Empirical Model and Effect of Geometry of Distribution (GOD)

In order to verify the accuracy of the EM, another two single-point stationary positioning experiments were conducted, and eight hours of data were collected.

For the first group of data, the receiver was placed at the point with relative coordinate[3] x: 41.98m, y: 27.55m, and the relative position with respect to the three APs (non-equilateral triangle) is indicated in Figure 9a. The distance-SS-relation EM model (and triangulation method) was used to determine the coordinates of a single point. In total, 10634 records were recorded (Figure 10a).

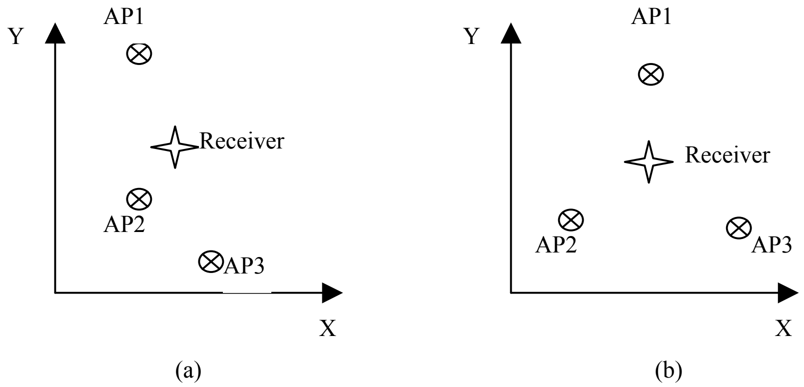

Figure 9. The GOD between three APs and a receiver

For the second group of data the receiver was placed at the centre with coordinate x: 43.62m, y: 31.16m, of an equilateral triangle defined by three APs (Figure 9b). After 8-hrs of data collection, 13160 records were obtained. The coordinate distribution is as shown in Figure 10b. After data processing, the statistics are summarized in Table 1.

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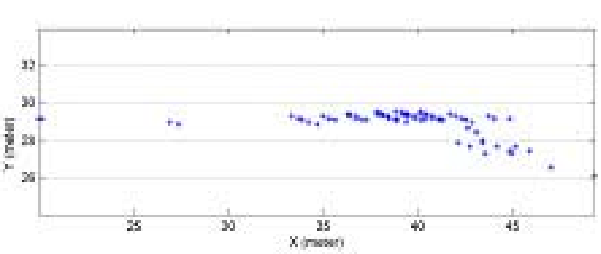
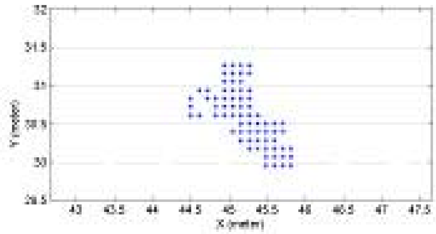
[2] Different Access Points should have different empirical models (EM) because the transmission power of APs is different. Therefore, this empirical model is only applicable to the WX-1590 AP.

[3] The left-top point of the test bed (Figure 1) was taken as the coordinate origin. The horizontal direction from left to right is X-axis; the vertical direction from top to bottom is Y-axis. In the experiment, the true coordinates are determined via measurement with tape.



(a)



(b)

Figure 10. Single point positioning coordinate distribution

Group	True position	Mean and Δ (m)	Min and Δ (m)	Max and Δ (m)	STD (m)
1	X= 41.98m Y= 27.55m	X=39.52 (2.46) Y=29.23 (1.68)	X=20.01 (21.97) Y=26.13 (1.42)	X=49.31 (7.33) Y=29.52 (1.97)	Std (X)=1.16 Std (Y)=0.16
2	X=43.62m Y=31.16m	X=44.97 (1.35) Y=30.77 (0.39)	X=44.50 (0.88) Y=29.96 (1.2)	X=45.81 (2.19) Y=31.27 (0.11)	Std (X)=0.12 Std (Y)=0.13

Table 1. Results of positioning tests

From the data analysis of the two different groups, one can see that with the empirical model, there is an error of:

Group 1 at GOD (a) Δd= SQRT ($\Delta X^2+\Delta Y^2$)= $2.46^2+1.68^2$= 2.98m

Group 2 at GOD (b) Δd= SQRT ($\Delta X^2+\Delta Y^2$)= $1.35^2+0.39^2$= 1.41m,

Therefore, it can be concluded that the accuracy level is approximately 1-3m.

The GOD is a very important factor in assessing positioning quality. From Figure 9(a), one can see that the distance between AP2 and AP3 is short compared to the distances AP1-AP2 and AP1-AP3. The biggest error in the x-axis can reach 20m, whereas it is only 2m or so in the y-axis direction. Without considering the true position (i.e., precision not accuracy), the standard deviation is 1.16m and 0.16m in the x-axis and y-axis directions, respectively. This is a ratio of about 1:8.

However, consider the situation in Figure 9(b). Although the difference between the true position and the mean value of measurements also reaches 1.41m, the standard deviation in the x-axis and y-axis directions are 0.12m and 0.13m, respectively. Hence under an idealized situation, it is possible to obtain a positioning accuracy at the 0.1m-level.

3.4 Wall Penetration Loss Experiment

Several radio signal penetration studies indicate that penetration loss increases as the frequency increases (e.g., Devasirvatham *et al.*, 1994). In addition, Aguirre *et al.* (1994) performed a penetration experiment and reported loss values of 7.7, 11.6 and 16.1 dB at frequencies of 912, 1920, and 5990 MHz, respectively. Similar loss has also been reported by Durgin *et al*. (1998).

In the pure indoor environment, Seidel and Rappaport (1992) derive a *Floor Attenuation Factor (FAF)* propagation model, which takes into account large-scale path loss and penetration loss. However, these current authors have disregarded the effects of the floor and instead considered the effects of obstacles (e.g., different walls) between the AP base station and rover receiver. The current authors refer to this as the *Wall Effect Model (WEM):*

$$P_d = p_{d_0} - 10n\log(\frac{d}{d_0}) + WEF \tag{6}$$

where n indicates the rate at which the path loss increases with distance, $P(d_0)$ is the signal power at some reference distance d_0, and d is the AP and receiver separation distance. *WEF* is the Wall Effect Factor.

In general, the values of n and *WEF* depend on the building layout and construction material, and are best derived empirically. The $P(d_0)$ can either be derived empirically or obtained from the physical parameters defining the wireless network (Bahl and Padmanabhan, 2000; Small *et al*., 2000). In order to test the effect of a brick wall, an experiment was conducted as indicated in Figure 11.

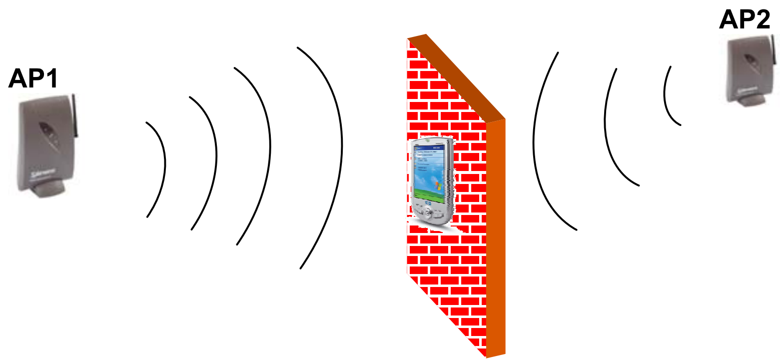
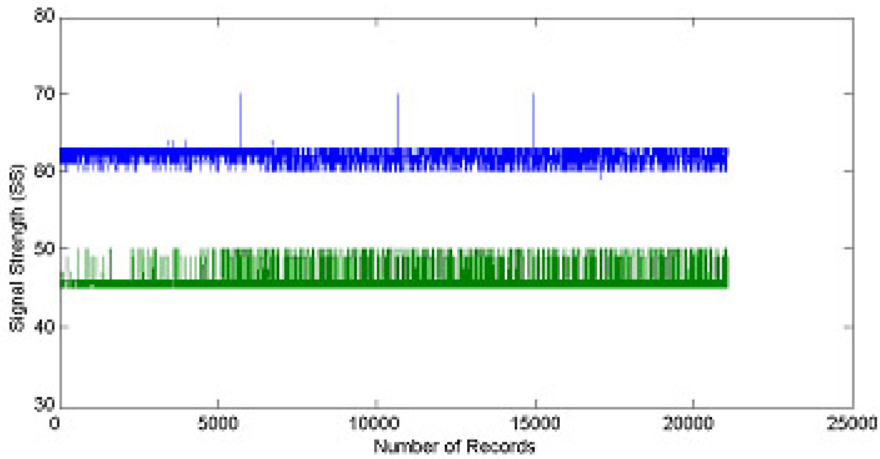
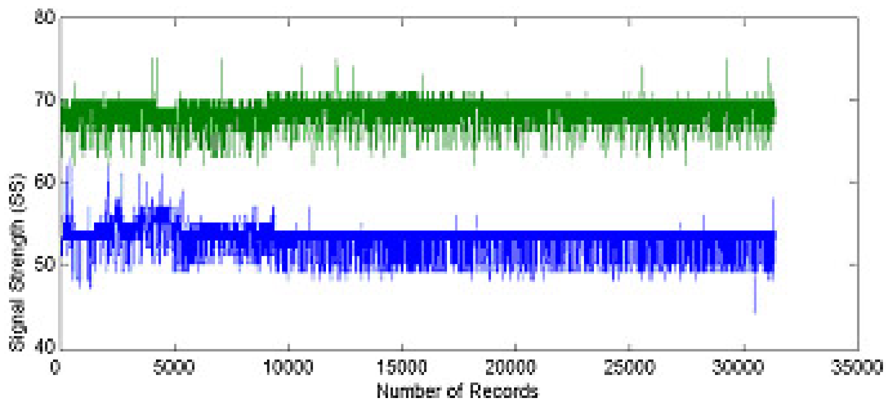


Figure 11. Experiment to consider wall penetration loss

Two APs (AP1 & AP2) were placed on either side of the wall. Two sets of *SS* data were collected (see Figure 12). From Figure 12a, the mean value of the top curve is 62.05 dBm, while for the bottom curve, the value is 45.85 dBm (a difference of 16.2 dBm). Similarly, from Figure 12b, the top mean value is 53.38 dBm and the lower mean value is 68.93 dBm (a difference of 15.6 dBm). The averaged value 15.9 dBm is the *WEF* value the authors have adopted. The other type of wall in the test bed area is calcareous board wall (Figure 13), and the *WEF* was found to be 3.4 dBm.



(a)



(b)

Figure 12: Wall Effect Factor (*WEF*) determination[4]

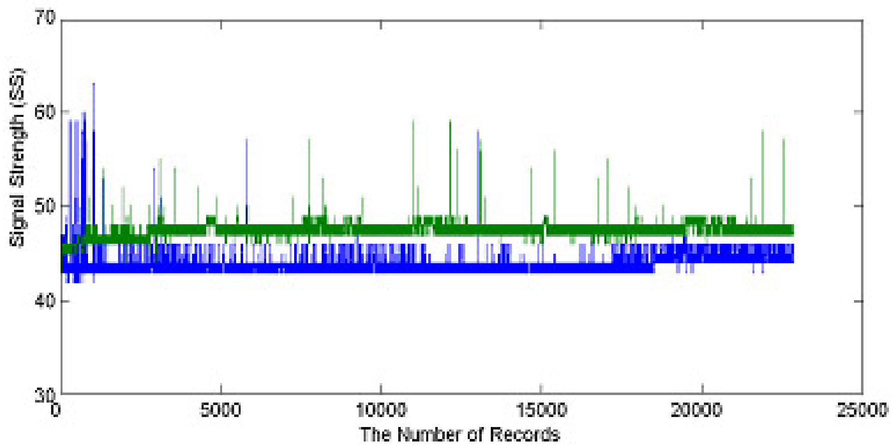


Figure 13. Experiment result for calcareous board wall *WEF* determination

[4] Because the measuring time period is different, in Figure 12a the top curve is thinner than the lower one, which means that the *SS* is more stable than the lower one. The same applies to Figure 12b.

4. IMPROVING THE WIRELESS SIGNAL PROPAGATION MODEL

After considering the effect of wall penetration loss, the relation between *SS* and distance in Figure 7, becomes as indicated in Figure 14. This improved model presents a closer description of the practical situation.

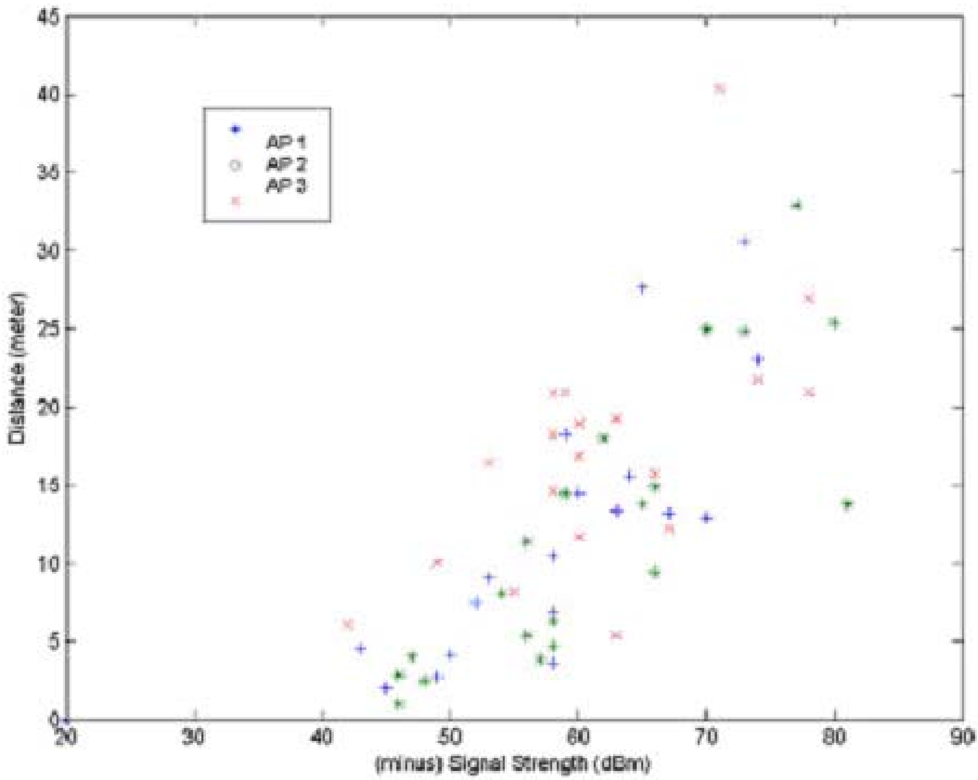


Figure 14. *SS* and distances relation after wall penetration loss correction

5. CONCLUDING REMARKS

From the results of the experiments and data analyses, the authors conclude that a wireless access point-based indoor positioning system is feasible. Experimental results show a positioning accuracy of 1-3m, while an idealised situation will be able to provide accuracy at the 0.1m-level. To some extent, WPS enriches the positioning methods available for applications, and attempts to remedy the shortcomings of GPS for indoor positioning. Further research is necessary, with a physical semantic model, e.g. a neural-network based model, to be tested in subsequent experiments. In addition, some dynamic positioning or navigation experiments will also need to be conducted.

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