# Investigation of Seamless Indoor and Outdoor Positioning Integrating WiFi and GNSS

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**Key words**: GNSS, WiFi positioning, Seamless indoor and outdoor positioning, Signal strength to distance conversion.

## SUMMARY

Location-Based Services (LBS) cover a wide spectrum of applications including fleet management, travel aids, location identification, emergency services and vehicle navigation. Applications of this service can be further extended if reliable and reasonably accurate 3-dimensional positional information of a mobile device can be determined seamlessly in both indoor and outdoor environments. Current geolocation methods for LBS may be classified as GNSS-based, cellular network-based, or their combinations. GNSS-based methods rely very much on the satellite visibility and the receiver-satellite geometry. This can be very problematic in dense high rise urban environments and when transferring to indoor environment. Especially in Hong Kong the urban canyon will affect very much the reception of the GNSS signals. Moreover positioning in the indoor/outdoor transition area would experience signal quality and signal reception problems, if GNSS alone systems are employed. The authors have proposed the integration of GNSS with wireless positioning techniques (Mok and Xia, 2006; Xia et al., 2006), and a fingerprinting positioning method based on WiFi signal strength observations has been tested with results analyzed (Retscher et al., 2006). Further developments have been made on signal strength to distance conversion of WiFi data for integration with GNSS and other range data sources. Recent test results in the outdoor area are presented in this paper.

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## 1. INTRODUCTION

Current geolocation methods for Location-Based Services (LBS) may be classified in satellite-based (GNSS), wireless network-based (cellular phone networks, WiFi or UWB), or their combinations. LBS provides thereby wireless users with different applications in the field of vehicle navigation and fleet management, location identification and emergency services. These services are widely recognized as a value added service and due to the diversity of user requirements research efforts are needed to improve the location determination capability and its accuracy and reliability. Recently the mobile device development has mainly concentrated on system integration of GPS, WiFi and cellular wireless networks to cater for different LBS applications. For the integration of all sensor observations an optimized model is required for otimal estimation of the current user's location.

In the area of satellite positioning a lot of research effort is put in the development of the new European satellite navigation system Galileo. Having seen the importance of the synergy between navigation services and communication facilities for a wide spectrum of LBS market demand, the navigation and communication integration is in fact one of the architecture requirements in the design of Galileo. Additional data or information from the so-called Local Elements (LE) can be integrated into the Galileo core system through communication networks to improve service performance. Suggested categories of the LE include cellular network positioning, network assisted navigation (Assisted GNSS) and indoor positioning such as WiFi or UWB. This fusion lays a very sound foundation for future development of a high accuracy and seamless threedimensional indoor and outdoor positioning system. Research on establishment of an optimized model and method to accommodate location under complex conditions is of practical significance under such a development trend.

For indoor location determination most commonly nowadays WiFi positioning techniques based on Wireless Local Area Network (WLAN) or Wireless Personal Area Network (WPAN) is employed. Recent tests have shown that indoor positioning with WiFi systems can generally achieve 1 to 4 m indoor and 10 to 40 m in the outdoor environments (Cheng et al., 2005; Retscher et al., 2006). Like in other countries, WiFi communication ability is almost a key consideration for PDA and computer buyers in Hong Kong, and due to the inexpensive development cost of WiFi networks, the number of WiFi users has been increasing.

Although WiFi positioning can fulfill the general geolocation positioning requirements in the indoor and some outdoor environments, positioning accuracy for different LBS can be further improved with the emerging Ultra Wideband (UWB) technology, to enable more reliable, accurate and efficient emergency decisions. The increasing demand for high speed wireless transmission of multimedia information and precise geolocation positioning in indoor environments have led to specific interests on UWB; a radio-communication technology originally developed for military applications in 1960 (see e.g. Barrett, 2000). Using UWB it is claimed by product vendors that a positioning accuracy of 0.3 to 0.6 m can be achieved for indoor location determination (Alabacak, 2002; Eshima, 2002). It is not difficult to predict that, the fusion of UWB, GNSS and wireless networks will be the trend for providing sub-metre level (or less) ubiquitous 3-D positioning services. To enable successful development of such a system, it requires investigations into an optimized location model for UWB in indoor and outdoor environments, and ground network (like UWB, WiFi) and GNSS integration algorithms. The principle of the integration algorithm for location determination using different data sources was presented in Mok and Xia (2005). In the following section the fundamentals and the integration of WiFi and UWB data with GNSS are summarized.

## 2. PRINCIPLE OF THE INTEGRATION ALGORITHM FOR LOCATION DETERMINATION USING DIFFERENT DATA SOURCES

The integrated observation and positioning model does not only include the observation equations for the satellite positioning systems (i.e., GPS, GLONASS, future Galilieo), but also the range observations from ground based transmitters (i.e., the base stations of the cellular phone network or the WiFi access points). This leads to the following functional model:

$$\begin{bmatrix} \gamma_{i\,(t)}^{1} \\ \gamma_{i\,(t)}^{2} \\ \gamma_{i\,(t)}^{3} \\ . \\ \gamma_{i\,(t)}^{k} \\ \gamma_{i\,(t)}^{g1} \\ . \\ \gamma_{i\,(t)}^{gk} \end{bmatrix} = \begin{bmatrix} \rho_{i0(t)}^{1} \\ \rho_{i0(t)}^{2} \\ \rho_{i0(t)}^{3} \\ . \\ \rho_{i0(t)}^{k} \\ \rho_{i0(t)}^{g1} \\ . \\ \rho_{i0(t)}^{gk} \end{bmatrix} - \begin{bmatrix} l_{i(t)}^{1} & m_{i(t)}^{1} & n_{i(t)}^{1} & -1 \\ l_{i(t)}^{2} & m_{i(t)}^{2} & n_{i(t)}^{2} & -1 \\ l_{i(t)}^{3} & m_{i(t)}^{3} & n_{i(t)}^{3} & -1 \\ . & . & . & . \\ l_{i(t)}^{k} & m_{i(t)}^{k} & n_{i(t)}^{k} & -1 \\ l_{i(t)}^{g1} & m_{i(t)}^{g1} & n_{i(t)}^{g1} & 0 \\ . & . & . & . \\ l_{i(t)}^{gk} & m_{i(t)}^{gk} & n_{i(t)}^{gk} & 0 \end{bmatrix} \begin{bmatrix} \delta X_i \\ \delta Y_i \\ \delta Z_i \\ \delta \rho_i \end{bmatrix} \tag{1}$$

where $\gamma_{i\,(t)}^{k}$ are the pseudorange observations from point *i* to satellite *k*,

$\gamma_{i\,(t)}^{gk}$ are the equivalent pseudorange observations from ground based transmitters between point *i* to base station *k*,

$\rho_{i0(t)}^{k}$ indicates the user point vector in the corresponding frame for station *i*,

$\rho_{i0(t)}^{gk}$ indicates the position vector of the base station for the ground transmitter network,

$l_{i(t)}^{k}$, $m_{i(t)}^{k}$ and $n_{i(t)}^{k}$ are the direction numbers from the observation point *i* to the tracked satellite *k*,

$l_{i(t)}^{gk}$, $m_{i(t)}^{gk}$ and $n_{i(t)}^{gk}$ are the direction numbers from the observation point *i* to the ground transmitter *k*,

$\delta X_i$, $\delta Y_i$ and $\delta Z_i$ are the coordinate differences for point *i*.

Thereby in equation (1) it is assumed that the position vector of the base station for the ground transmitter network $\rho_{i0(t)}^{gk}$ is given in the same reference frame as GNSS. Its least squares solution can be expressed by the well-known form

$$\delta X = -(A^T PA)^{-1} A^T PL \tag{2}$$

with the exception that observation weight matrix P will contain two parts that corresponds to GNSS psudoranges and range observations from ground transmitter stations. If $\sigma_{GNSS}$ and $\sigma_G$ are used to indicate the standard deviations of the unit weight for satellite psuedoranges and ground transmitter network ranges respectively, and different observation types are assumed to be uncorrelated, it has the form:

$$P = \begin{bmatrix} 1/\sigma_{GNSS}^2 & & & & & \\ & 1/\sigma_{GNSS}^2 & & & & \\ & & 1/\sigma_{GNSS}^2 & & & \\ & & & 1/\sigma_G^2 & & \\ & & & & 1/\sigma_G^2 & \\ & & & & & 1/\sigma_G^2 \end{bmatrix} \tag{3}$$

The standard deviation $\sigma_{GNSS}$ can be given according to satellite source and positioning mode. The standard deviation $\sigma_G$ can be set according to the different kind of the ground transmitter network.

To obtain the most optimal location result, ranges to UWB and WiFi transmitters are integrated with GNSS pseudoranges. The varied forms of observations can be pseudoranges, time delays, time delay differences or signal strengths. They can all be converted to the geometrical distance after some transformation. For instance, the distance can be estimated from the signal strength which is based on the relation of the signal propagation loss on the traveling path. All observations from UWB, GNSS or WiFi can be used in a tightly coupled processing model in form of a Kalman filter based on the observation domain, from which both position and velocities are derived (Mok and Xia, 2005).

An important consideration for hybrid positioning is the coexistence of different kinds of observations such as GNSS, GSM, UWB or WiFi. Each has its own quality feature that is described by variance value of unit weight. Therefore in data processing, system performance evaluation based on observation residuals will reflect system performance if the unit weight variance is unique. To objectively evaluate hybrid location performance, Helmert variance estimate model was proposed to optimize quality evaluation based on iterative estimate for unique variance of unit weight in hybrid location determination. Further details can be found in the papers of Mok and Xia (2005) and Xia et al. (2006).

In line with the above, investigations have recently been made on the signal strength to distance conversion of WiFi data for integration with GNSS and other range data sources and the proposed processing method as well as test results are presented in the following.

## 3. EVALUATION OF THE WIFI SYSTEM PERFORMANCE

### 3.1 Field Test Sites

Theoretically, the WiFi signal strength (SS) is inversely proportional to the square of the distance. However, in real practice, this mathematical relationship may be seriously affected by radio interference and multipath effects, particularly in the indoor environments. In order to integrate signal strength data from WiFi systems with other range data such as from GNSS and UWB, it is important to investigate how well this mathematical relationship can be maintained in the indoor-outdoor transition and the outdoor environments, how distances can be best estimated with provision of signal strength data, and the quality of the estimated distances. To answer these questions, field tests were respectively carried out at the Hong Kong Polytechnic University (HKPolyU) and Vienna University of Technology (TU Vienna).

Figure 1 shows the set up of the field test carried out at the HKPolyU, with a 40 metre baseline established at the podium of the university campus. A Linksys WiFi access point, supported by a tripod and about 1.5 metre in height from the ground was located at the 'zero' mark of the tape. A PC computer installed with an external WiFi PC card was used to collect the signal strength data at 1-metre intervals, in $0^\circ$ and $180^\circ$ directions as shown in Figure 2.

**Figure 1:** Set up of the field test carried out at the HKPolyU

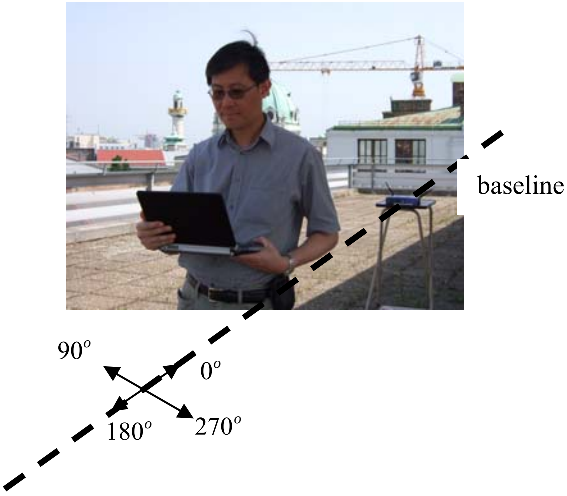


**Figure 2:** Signal strength observations in four directions referenced to the baseline alignment

Further field testing was carried out on the roof of a University building of the TU Vienna, with equipment set up similar to that of the HKPolyU's field test (refer to Figure 3). Signal strength data were collected at 1-metre intervals over the 25 metre baseline, at directions 0°, 90°, 180°, and 270°.

**Figure 3:** Set up of the field test carried out at the TU Vienna

### 3.2 Test Results

#### 3.2.1 HKPolyU Test Result

Figure 4 shows the result of the test carried out in the HKPolyU campus. The SS varies around -30 and -60 dBm. Both the 0° and 180° plots are in general very similar, indicating that the SS of the area under test has no significant difference in the two directions. However, it is noted that the discrepancy of SS between the two directions can be as big as 10 dBm at around 7 and 17 metres. Using the 4$^{th}$ degree polynomial curve fitted to the data indicates the obvious change in SS from 0 to around 20 metres, and the SS fluctuates between -53 and -60 dBm for distances longer than 20 metres.

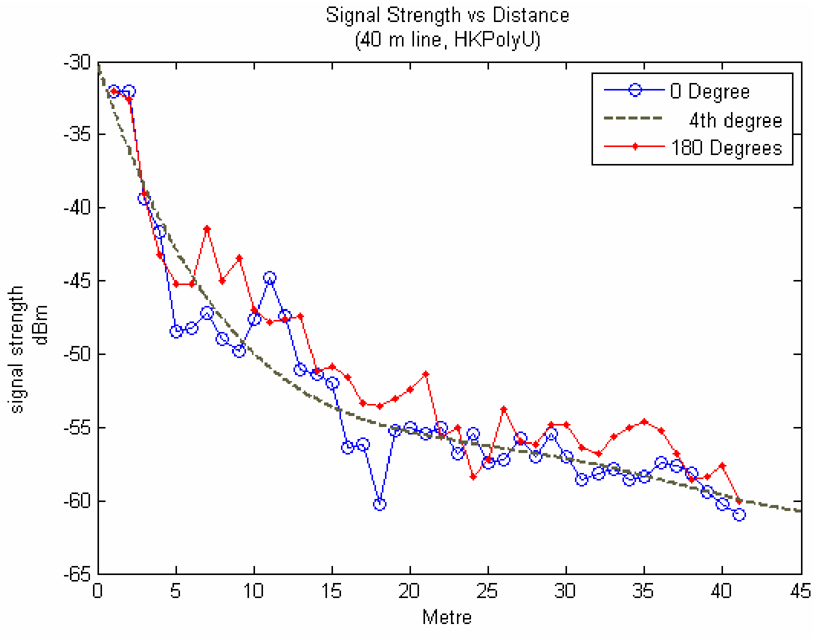


**Figure 4:** Test result of signal strength vs. distance over a 40 metre baseline in HKPolyU

#### 3.2.2 TU Vienna Test Result

Figure 5 shows the result of the test carried out at TU Vienna. The trend is similar to that of the HKPolyU result for directions 0°, 90°, and 270°, with SS varying between -38 and -60 dBm; but with stronger fluctuations. It can be seen in Fig.5(b) that the 270° data set is extremely noisy, although a general downward trend of SS to distance relationship can be traced. No obvious trend can be seen in the 180° curve. The significantly higher SS over the 25 metre distance indicates that the WiFi signal is more susceptible to noise in this test site.

### 3.3 General Observations

The above results have shown the dramatic change in site condition in the indoor-outdoor transition, and the outdoor environments which would give rise to very different distance to SS relationship at different directions. For areas having less interference to WiFi signals, a least squares polynomial curve fitting may be able to establish a reasonable mathematical relationship between SS and distance, for distance estimation with this polynomial model. However, for areas with WiFi signals susceptible to radio interference and multipath effect, a curve fitting model may filter out the useful SS characteristics at particular distances. Purely substitute the SS value to a polynomial curve model parameters may only result in incorrect distance estimation, as an example illustrated in Fig.6. A point P about 7 metres from the access point has a signal strength of –60 dBm at direction 270°. According to the calibration data, there is a fluctuation in SS in the range of –45 dBm to –65 dBm (A-B-C in Fig. 6) between 6 and 8 metres. Substituting the –60 dBm into the mathematical model would give an incorrect answer of P', which is around 17.5 metres.

Furthermore, the WiFi signal reception direction changes dynamically with respect to location and orientation between the access point and signal reception antenna. Therefore, in formulating a SS to distance conversion algorithm, the SS characteristics at different ranges and at different orientations should be considered. In the following section, the authors would like to propose a SS to distance conversion methodology taking into account of these two important site condition related factors.

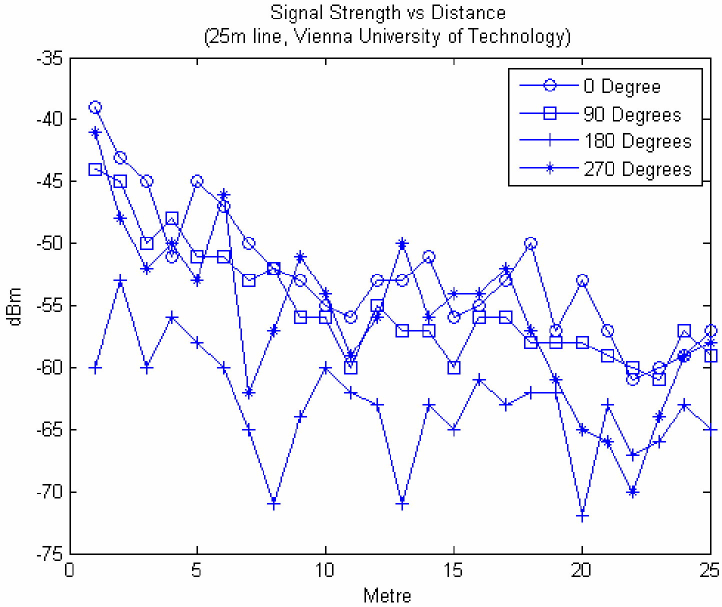


**Figure 5 (a):** Test result of signal strength vs distance over a 25 metre baseline at TU Vienna

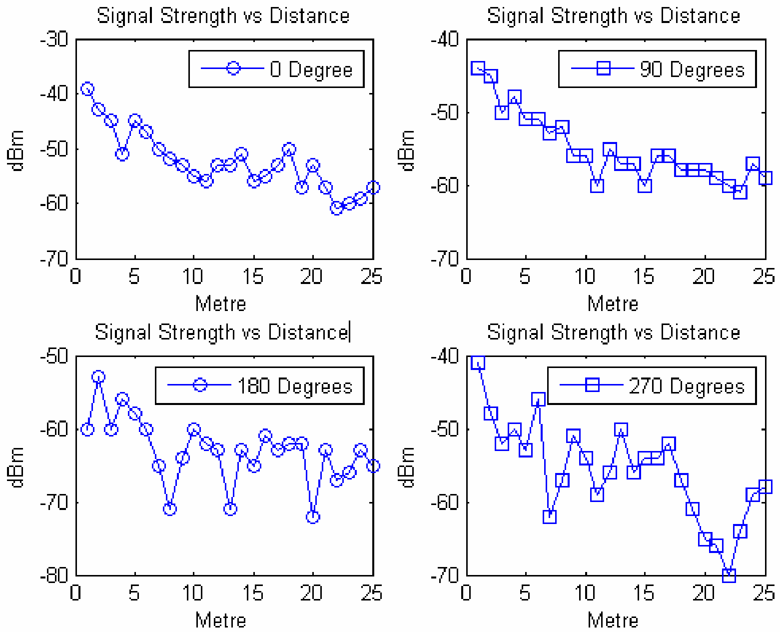


**Figure 5 (b):** 25 metre baseline test at TU Vienna: Plot of data collected in the directions 0°, 90°, 180° and 270°

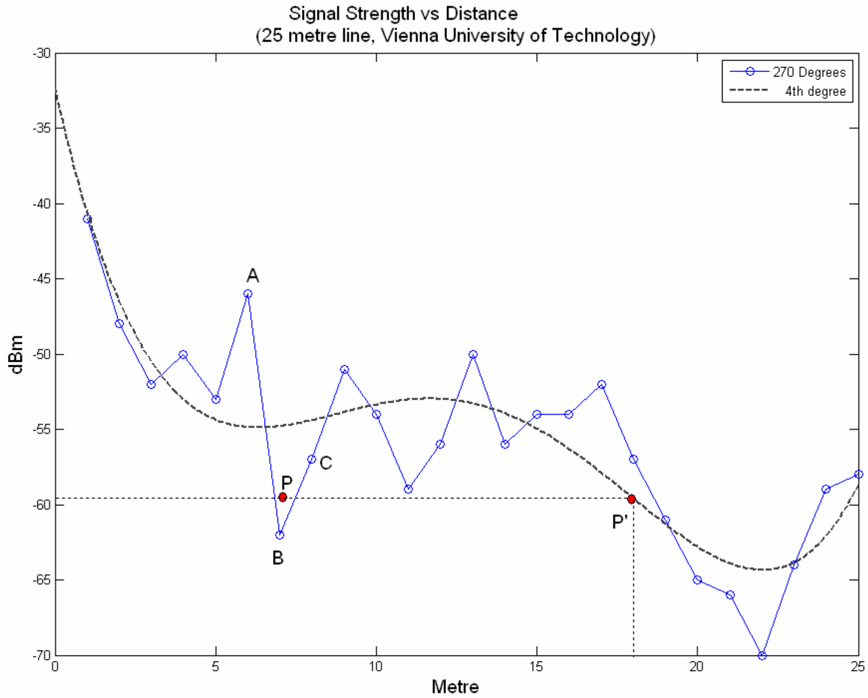


**Figure 6:** Illustration of incorrect SS to distance conversion based on curve fitting

## 4. SIGNAL STRENGTH TO DISTANCE ESTIMATION ALGORITHM

Based on the field test results, the SS to distance conversion is considered to be effective and more reliable within 20 metres when a Linksys access point and a WiFi PC card is used. The algorithm proposed here is therefore limited to areas within ± 180° of circular sector with 20 m radius. A baseline was first established in the middle of this area, and the SS pattern along the baseline was determined by observing the signal strengths at 1 metre intervals, at four directions (i.e., at 0°, 90°, 180° and 270°) as described in the field test section above (section 3.2).

The SS pattern of the baseline over the four directions are obtained after this calibration procedure. If the distance of a point P needs to be estimated with 4 directions' signal strength data $\alpha_0, \alpha_{90}, \alpha_{180}, \alpha_{270}$, a series of interval tests is proposed to be carried out at each direction, by comparing the $\alpha$ value with the trend of change in signal strength at each range interval. If $\alpha$ falls into the j and j+1 metre range, where j=1, 2, … 19 when the effective range is set to 20 metres, the probable range for this test is considered to be at the middle of j and j+1 metre range. It should be noted that, for each direction under test, the number of probable range that $\alpha$ falls into could vary from none to 'x', where 'x' could be more than one depending on the degree of fluctuation of SS along the calibration line. However, insufficient information is available to decide which estimated range is closest to the true range. The experience gained in the filed tests is that, in areas such as the test site in the HKPolyU campus, where SS interference is not serious, the mean of the possible ranges determined in the interval test would be very close to the true range. Hence the most probable range for the data set of each direction can be estimated by taking the mean of all possible ranges.

The above interval searching algorithm can be simply programmed as follows:

```
for i=1 to 4
    counter(i)=0;
    for j = 1 to 19
        if SS_line(i, j)–α (i) < 0 &  α (i) – SS_line(i, j) <0
        counter(i)=counter(i)+1;
        pd(i, counter(i))=j+0.5;
   elseif (SS_line(i, j)–α (i) > 0 &  α (i) – SS_line(i, j) >0
       counter(i)=counter(i)+1;
       pd(i, counter(i))=j+0.5;
   elseif (SS_line(i, j)–α (i) ==0)
       counter(i)=counter(i)+1;
       pd(i, counter(i))=j;
    end
end
```

where   i = 1, 2 ,3, 4 ; representing 0, 90, 180 and 270 directions,
j = basline length from 1 to 19 ; considering the effective SS to distance conversion is within 20 metres,
$\alpha$(i) = signal strength of point P at direction (i),
SS_line(i,j) = signal strength along the baseline, at distance (j) and in the direction of (i),
pd = possible distance.

The above procedure introduces the procedure for obtaining the most probable range of a point P in direction (i). For this algorithm to be effective and to obtain more reliable results, it is proposed that 4 scenarios (S1 to S4) of interval searching and distance estimation to be carried out, and final solution to be determined by the median of results obtained in these 4 scenarios. The followings are the proposed scenarios:

Scenario 1: The mean of
- (i) interval test result of SS at 0°
- (ii) interval test result of SS at 90°
- (iii) interval test result of SS at 180°
- (iv) interval test result of SS at 270°

Scenario 2: The mean of
- (i) interval test result using mean SS of 0°, 90°
- (ii) interval test result using mean SS of 0°, 180°
- (iii) interval test result using mean SS of 0°, 270°
- (iv) interval test result using mean SS of 90°, 180°
- (v) interval test results using mean SS of 90°, 270°
- (vi) interval test results using mean SS of 180°, 270°

Scenario 3: The mean of
- (i) interval test result using mean SS of 0°, 90°, 180°
- (ii) interval test result using mean SS of 0°, 90°, 270°
- (iii) interval test result using mean SS of 0°, 180°, 270°

(iv) interval test result using mean SS of 90°, 180°, 270°

Scenario 4: The mean of interval test using mean SS of 0°, 90°, 180°, 270°

With this approach, interval searching will be performed using a spectrum of signal strength patterns falling within the SS characteristic envelop as shown in Fig. 7.

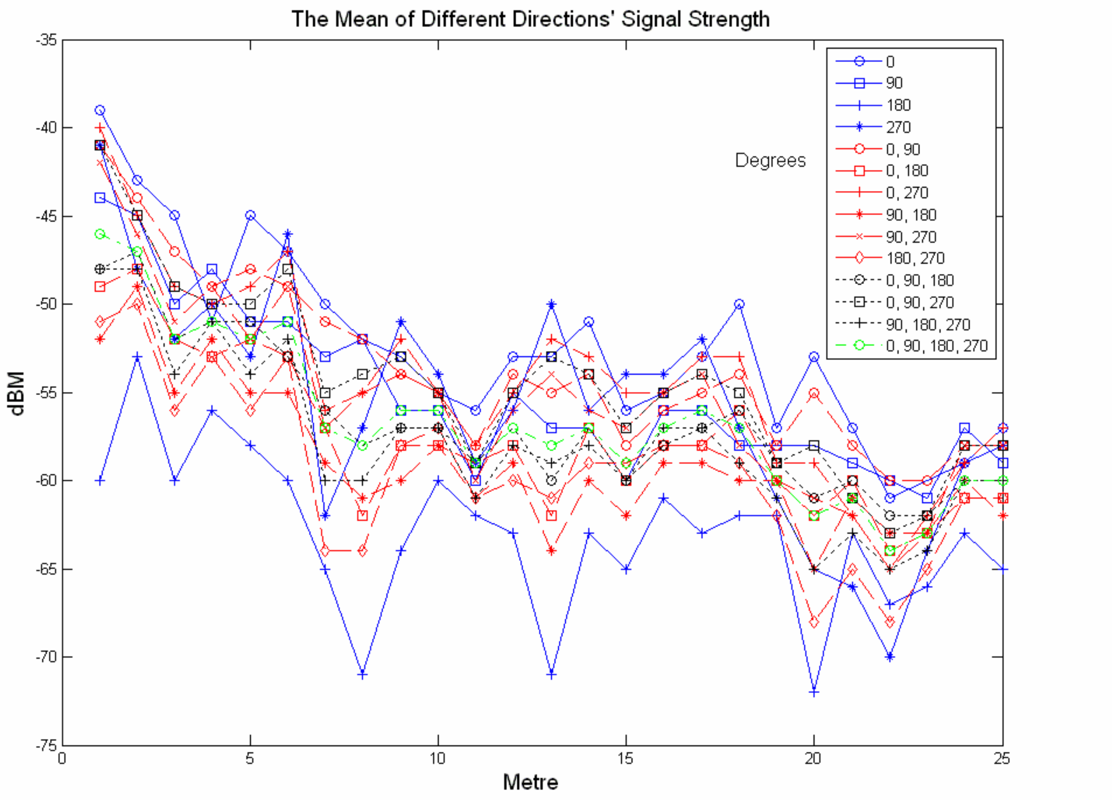


**Figure 7:** Different mean combinations of signal strength data used for interval searching

## 5. VERIFICATION OF THE PROPOSED ALGORITHM

Twenty points inside the 20 m effective area were randomly selected to verify the proposed algorithm. The signal strengths of 4 directions were observed, and their distances from the access point position were recorded for calculating the error. Table 1 shows the test points that were randomly scattered from about 1 to 17 metres, and the errors of estimated distances from different data sets. Figure 8 presents the errors in graphical form for easy comparison. Obvious improvements in the results can be found by comparing processing results from the approach if only one direction's data set is used, the use of the proposed scenarios (S1, S2, S3, S4), and the final solution by taking the median values of the results from different scenarios. In the final solution 65 % of the determined distances are within 3 m from the true distance. The success rate of this algorithm in this test is 90 % if the threshold for the acceptable error is 5 m.

**Table 1:** Errors in distance estimation using different data set for interval searching

| True Distance | 0 Degree Error (metre) | 90 Degrees Error (metre) | 180 Degrees Error (metre) | 270 Degrees Error (metre) | S1 Error (metre) | S2 Error (metre) | S3 Error (metre) | S4 Error (metre) | Median of S1, S2, S3 S4 Error (metre) |
|---|---|---|---|---|---|---|---|---|---|
| 1.4 | -0.6 | -1.6 | -0.6 | -3.6 | -1.6 | -0.6 | -0.6 | -1.6 | -1.1 |
| 2.3 | -2.7 | -0.7 | 0.3 | -2.7 | -1.7 | -0.7 | -0.7 | -0.7 | -0.7 |
| 3.6 | -1.4 | -0.4 | -1.4 | -7.4 | -3.4 | -2.4 | -1.4 | -3.4 | -2.9 |
| 3.4 | 1.4 | -0.6 | 0.4 | -1.6 | -0.6 | 0.4 | 0.4 | 0.4 | 0.4 |
| 4.9 | -9.1 | 0.9 | -9.1 | -7.1 | -7.1 | -3.1 | -2.1 | -2.1 | -2.6 |
| 6.3 | -1.7 | -3.7 | -6.7 | -4.7 | -4.7 | -3.7 | -6.7 | -5.7 | -5.2 |
| 10.8 | NS | -2.2 | -2.2 | -1.2 | -1.2 | -6.2 | -1.2 | -8.2 | -3.7 |
| 13.4 | NS | 0.4 | 10.4 | 2.4 | 4.4 | -2.6 | 0.4 | -1.6 | -0.6 |
| 16.3 | 1.3 | 3.3 | 2.3 | 5.3 | 2.3 | 1.3 | 1.3 | -3.7 | 1.3 |
| 15.5 | NS | 1.5 | 10.5 | 4.5 | 4.5 | 0.5 | 2.5 | 2.5 | 2.5 |
| 17.1 | 3.1 | 2.1 | 4.1 | 5.1 | 3.1 | 2.1 | 4.1 | 5.1 | 3.6 |
| 13.5 | -1.5 | 0.5 | 11.5 | 8.5 | 2.5 | -0.5 | 2.5 | 6.5 | 2.5 |
| 10.8 | -8.2 | -2.2 | -3.2 | -0.2 | -2.2 | -3.2 | -2.2 | -4.2 | -2.7 |
| 9.3 | -9.7 | NS | 4.3 | -1.7 | 0.3 | -3.7 | -3.7 | -5.7 | -3.7 |
| 7.1 | NS | NS | 4.1 | -4.9 | -1.9 | -5.9 | -5.9 | -5.9 | -5.9 |
| 4.2 | -9.8 | -5.8 | NS | -0.8 | -6.8 | -8.8 | -0.8 | -0.8 | -3.8 |
| 8.4 | NS | -4.6 | -5.6 | -2.6 | -3.6 | -6.6 | -4.6 | -3.6 | -4.1 |
| 8.3 | 0.3 | -6.7 | NS | 4.3 | -2.7 | -3.7 | 3.3 | 4.3 | 0.3 |
| 14.5 | -0.5 | NS | 3.5 | 2.5 | 1.5 | 0.5 | 1.5 | 1.5 | 1.5 |
| 13.0 | -3.0 | 0.0 | 1.0 | 8.0 | 1.0 | 2.0 | 1.0 | 1.0 | 1.0 |

Remark: NS stands for no solution.

## 6. CONCLUDING REMARKS

For the signal strength data of the WiFi data to be successfully incoporated into the integrated processing model as suggested in the papers of Mok and Xia (2005) and Xia et al. (2006) an algorithm for converting the WiFi signal to the corresponding distance is essential. In this paper the authors have carried out field tests in the Hong Kong Polytechnic University and Vienna University of Technology. Results have shown that the signal strength quality varies significantly under different environmental conditions including the radio intereference and multipath effects. For environments with less environmental interference a least squares polynomial fitting may be able to establish a reasonable signal strength to distance conversion relationship. However, for site conditions where signal strength is susceptible to radio intereference and multipath effects it is unlikely that polynomial fitting will provide correct solution in the SS to distance conversion. The authors have proposed an algorithm by making full use of the signal strength propagation characteristics to estimate distance from the measured signal strength data. This algorithm has been verified in an unfavourable site condition and has proven to be successful with a 90 % success rate in a 20 m radius area with the accuracy threshold set to 5 m.

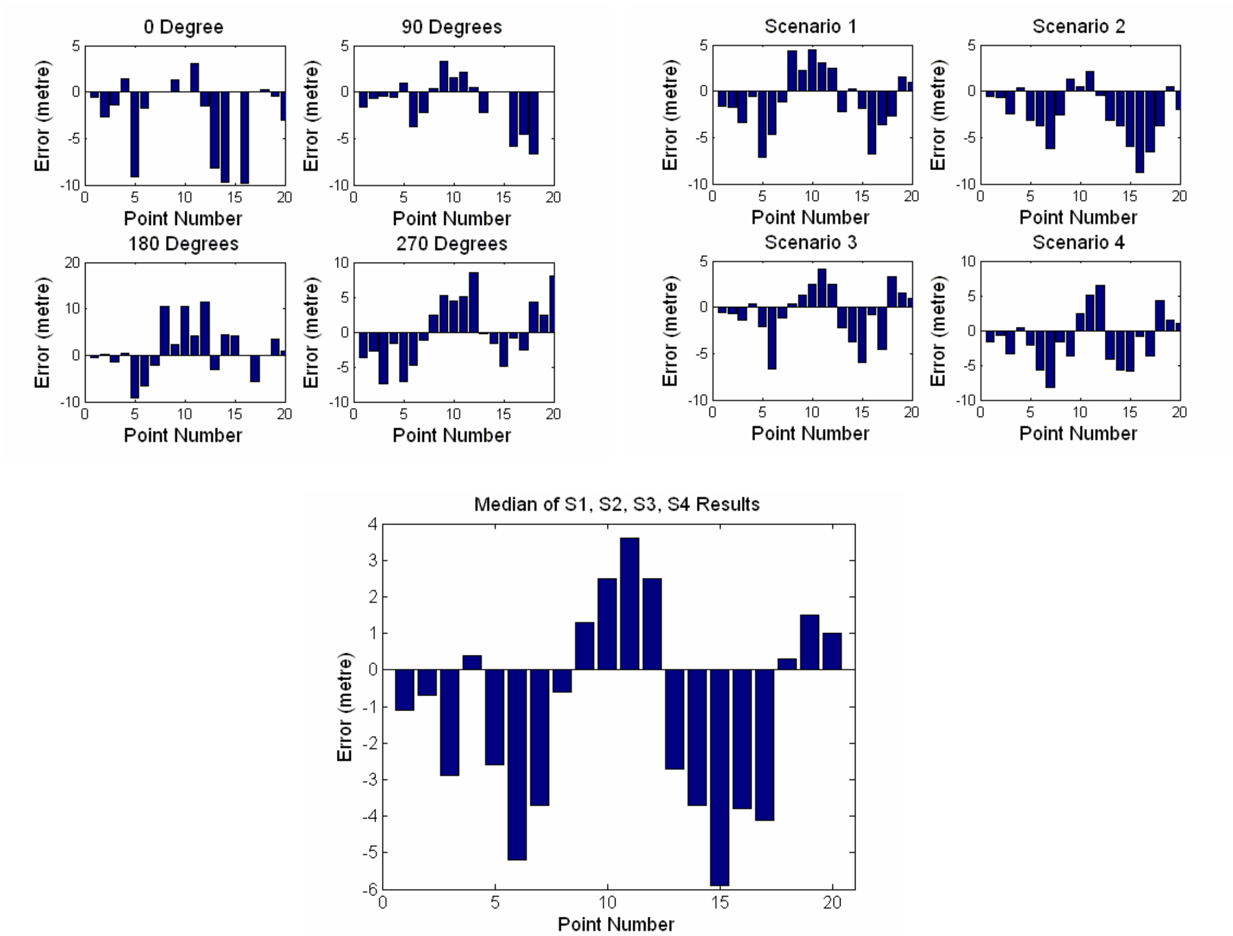


**Figure 8:** Graphical representation of the errors in distance estimation using different data set for interval searching

Although the algorithm used is successful using one calibration baseline in our test, it should be noted that some other site conditions may have different signal strength propagation characteristics which would require more than one calibration baseline. Therefore further investigation will be caried out and presented elsewhere.

## ACKNOWLEDGEMENTS

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## BIOGRAPHICAL NOTES

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Prof. Dr. Linyuan Xia is currently working on State Key Laboratory for Information Engineering on Surveying, Mapping and Remote Sensing (LIESMARS), Wuhan University, China. Over years he has been focusing on GPS course teaching, theoretical research and its applications including some research work involved in state projects and collaborations with oversea institutes. He is international editorial board member for Survey Review (UK) and member of ICCT by International Association of Geodesy(IAG).

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