Positioning in Environments where Standard GPS Fails

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Key words: Ubiquitous Positioning, GPS, WiFi, cellular phone

SUMMARY

GPS or more generally GNSS (Global Navigation Satellite System) has been widely used. However, there is a major shortcoming of GNSS - it is usable everywhere where there is clear sky, and hence fails to operate where it's impossible or difficult to receive the satellite signals. In some difficult signal environments – principally where the satellite signals are weak and multipath is severe – "high sensitivity" GPS/GNSS and/or assisted-GPS/GNSS can be used to improve positioning, navigation and timing availability. Other sensors can also be integrated with GPS/GNSS to improve positioning. In environments where GPS/GNSS completely fails alternative positioning technologies based on WiFi signals or ultrasound etc. could be used. In this paper, some of the research carried out in the School of Surveying and Spatial Information Systems, University of New South Wales, into positioning in environments where standard GPS fails is described.

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1. INTRODUCTION

The development of the global navigation satellite system (GNSS) over the last three decades has revolutionised positioning, navigation and timing (PNT). The U.S. developed global positioning system (GPS) is of course the classic exemplar of this technology, being the only fully operational (since 1995) GNSS currently available. The applications of GPS can be found across almost all of a nation's economic, scientific and social activities, from spacecraft navigation and geodesy, to land surveying and mapping, to precise agriculture and vehicle fleet management, to emergency services and professional navigation, to mass market applications such as in mobile devices (cars and smartphones) and location based services (LBS). The success of GPS (and increasingly also the revitalised GLONASS) has encouraged the development of more satellite navigation systems, such as the E.U.'s Galileo and China's Compass. However, the major shortcoming of GNSS is that it is usable everywhere where there is clear sky, and hence fails to operate where it's impossible or difficult to receive the satellite signals such as inside most buildings, in urban canyon environments, in caves, tunnels and other subterranean locations, and underwater.

However, in some difficult signal environments – principally where the satellite signals are weak (<-142 dBm) and multipath is severe – so-called "high sensitivity" GPS/GNSS and/or assisted-GPS/GNSS (A-GPS/A-GNSS) can be used to improve PNT availability. Other sensors can also be integrated with GPS/GNSS to improve positioning. In environments where GPS/GNSS completely fails alternative positioning technologies based on WiFi signals or ultrasound etc. could be used. In this paper, some of the research carried out in the School of Surveying and Spatial Information Systems, University of New South Wales, into positioning in environments where standard GPS fails is described.

2. ASSISTED-GPS AND HIGH SENSITIVITY GPS

If a GPS or GNSS receiver has no prior information available, it must perform a search for satellite signals – an operating mode known as "acquisition". In the case of the visible satellites (above the receiver's horizon), the exact frequency of each satellite carrier frequency, distorted by any Doppler shift, and the alignment of the pseudo-random number (PRN) code between receiver and satellite are the search unknowns (Parkinson & Spilker, 1996). The receiver first assumes that a satellite is visible and allocates a channel for this satellite. The relative movement of the receiver and the satellite cause the Doppler frequency shift. Since the Doppler is unknown, the receiver must search across a wide range of frequency, typically 30 or more Doppler "bins". There are two types of searches: time or frequency space searches. If using time-domain acquisition, the receiver will try to align the duplicate PRN code generated by the receiver and that transmitted by the satellite. It takes around 2 seconds to search each Doppler bin (Li et al., 2009). After a satellite signal has been acquired, it can be tracked and the receiver decodes the broadcast navigation data: the time, the orbit ephemeris, the almanac, and other data. The almanac is used to identify the locations (and Doppler shifts) of the other visible satellites. However, it takes 12.5 minutes to receive the complete almanac from a single satellite signal transmission. Before being able to calculate a position, velocity and time (PVT) solution, the ephemeris of each satellite must be obtained. It takes between 18 to 30 seconds to extract the ephemeris information from the modulated navigation message, assuming there are no dropouts or loss of any data bits in the message. In a difficult signal environment it typically takes a much longer time to recover the data bits from the modulated navigation message. The signal strength may be so low that it could even be impossible to perform this decoding operation at all.

There are many techniques that can be used to improve the "sensitivity" of a GPS receiver. (Most can also be used with other GNSS receivers/signals, but the focus in this paper will be GPS.) One common way is simply to increase the time for the integration within the receiver of the received signal. In the traditional sequential search procedure a correlator is used to search many Doppler bins one after the other. The consequence is either the search is intolerably long or the search is carried out in a very imprecise manner. Increasing the number of the correlators enables the use of fast and "deep" GPS signal search capabilities. For example, the SiRF-III receiver baseband chip has more than 200,000 correlators (SiRF, 2008), while the ublox-5 chip has more than a million correlators (ublox, 2009).

2.1 High Sensitivity GPS Test

To test the performance of high sensitivity GPS, four test points in harsh environments at the University of New South Wales (UNSW) were selected (see Figure 1). It can be seen that hardly any line of sight (LOS) signal from the satellites can be received, and therefore the multipath-affected signals dominate in all these test environments. A PDA which has a built-in SiRF-III chipset was tested. At each test position, 100 tests were carried out. To average out the effect of the number of visible satellites and their geometric distribution, the 100x4 tests were divided to four groups; each group consisting of 25x4 tests. The GPS receiver was cold reset for each location attempt. The acquisition results – such as position, Time-To-First-Fix (TTFF), GPS time, etc. – were logged to files. Table 1 summarises the test results. Test failure is defined in two ways: a test where the receiver failed to report the position within a certain time period (130 seconds) or a test where the generated position solution was grossly in error (the horizontal distance error larger than 550m). From these tests, one obvious conclusion can be drawn: even for a high sensitivity GPS receiver it is very difficult to acquire the satellite signals and to calculate reliable position solutions. The positioning accuracy is much worse than that for tests in open sky environments (typically 5 to 10m). However, from many peoples' experience, for "cold starts", the apparent poor performance of this GPS is not so bad considering the TTFF. It is reported that a SiRF-III GPS receiver has a hard-coded almanac that can be used by the receiver even after a factory reset has occurred, which may explain the comparatively good "cold start" performance.

To further investigate the performance of a high sensitivity GPS, a ublox-5 receiver was tested at test position 1. Similar results were obtained. It was also noted that only if sufficient time (generally, more than 2 minutes) is permitted will high sensitivity GPS report a reasonable positioning result.

Figure 1. Harsh signal environments for GPS tests at UNSW (test location 1 to 4, left-to-right, top-to-bottom).

Test position	Horizontal Error (m)		Vertical Error (m)		TTFF (s)		No. of Satellites (Mean)	Failed tests (out of 100)
	Mean	STD	Mean	STD	Mean	STD		
1	36.7	0	75.7	0	115	0	3	99
2	20.6	13.6	72.9	40.0	59.6	6.6	4	95
3	99.0	75.7	68.1	4.3	104.7	21.7	3.7	97
4	20.8	22.0	50.5	49.7	53.0	17.1	4.7	26

Table 1. Summary of high sensitivity GPS test results.

2.2 A-GPS Test

To reduce the waiting time for signal acquisition the so-called A-GPS technique is useful (LaMance et al., 2002). The most useful set of assistance data for reducing acquisition time is receiver position estimation, approximate clock time and almanac (it can be replaced by the ephemeris). With this data a GPS receiver can calculate which satellites to search for and what Doppler bins/frequency to search. The ephemeris for each visible satellite is required to calculate the satellites' coordinates, and subsequently the receiver's PVT. Furthermore, if the data bit transitions are known then coherent integration can be performed over periods longer than 20ms - improving weak signal performance even further. To perform A-GPS, several things are essential: a wireless data link, a reference receiver and a processing server. Figure 2 depicts the basic procedure for an A-GPS operation.

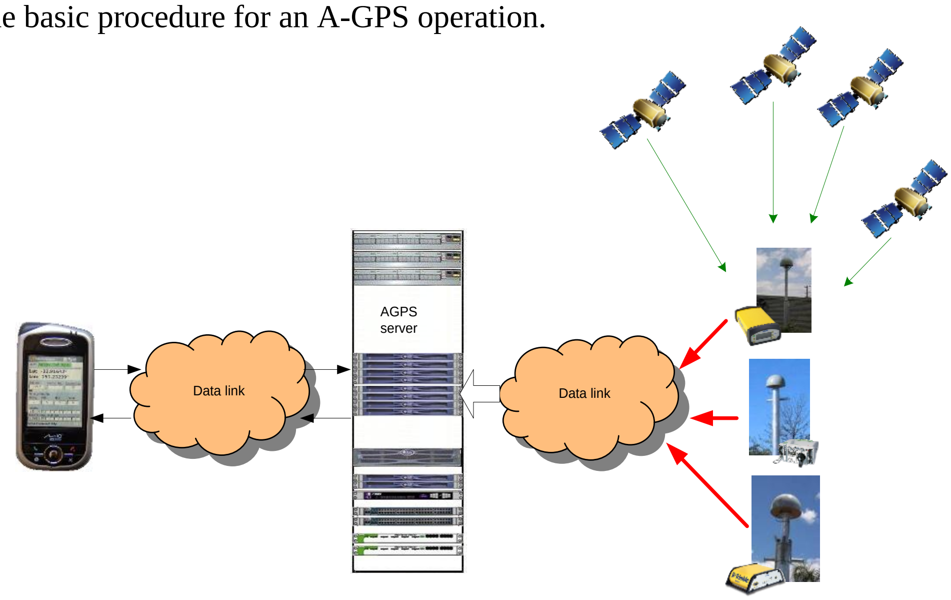

Figure 2. The general technique of A-GPS.

Secure User Plane Location (SUPL) is an emerging standard developed by the Open Mobile Alliance (OMA) (http://www.openmobilealliance.org/). The SUPL standard allows a device such as a mobile phone to connect to a location server to request its location using the TCP/IP protocol. Two modes of A-GPS are possible: the mobile station assisted (MSA) A-GPS mode, and the mobile station based (MSB) A-GPS mode (for details the reader is referred to Li et al., 2009). At the four test positions referred to earlier (Figure 1), the A-GPS testing was also carried out in the similar manner. Table 2 summarises the test results. In general there is no significant difference between the positioning accuracy obtained using A-GPS compared with using standalone high sensitivity GPS. However, the average TTFF decreased from 56s to 19s, and the average number of available satellites increased from 4.6 to 6.4. The most impressive improvement however was that all the requests for location returned successful positioning solutions.

Test position	Horizontal Error (m)		Vertical Error (m)		TTFF (s)		No. of Satellites (Mean)	Failed tests (out of 100)
	Mean	STD	Mean	STD	Mean	STD		
1	23.4	20.5	37.5	34.3	23.7	8.2	6.2	0
2	38.8	34.1	68.4	50.3	22.1	10.0	6.3	0
3	69.9	44.1	69.4	53.5	20.2	7.5	5.5	0
4	21.3	17.6	39.6	39.9	10.3	1.8	7.4	0

Table 2. Summary of A-GPS (SUPL, MSB) test results (cf with Table 1).

2.3 Dynamic Test

All the tests described above were static. The results of dynamic tests are also of interest, A difficulty is that the true position value is hard to obtain. Normally, the high precision GPS-RTK (real time kinematic) method is utilised to obtain the “true” coordinates against which the results will be compared. However, in harsh signal environments GPS-RTK can not be used. The following test scenario was employed. The researcher drove a car around the urban area again and again. The GPS-equipped PDA was placed under the windscreen and configured to operate in either the MSB A-GPS mode or in the standalone high sensitivity GPS mode. The SUPL implementation provided the assistance information. 200 requests for location were made (after a cold start) for each type of test. Figure 3 shows the test results overlain on a Google Map image. Most of the positions estimated by the receiver were reasonable – the crosses or circles are along the streets, although some of them are on top of the buildings. No large difference can be found between A-GPS and standalone high sensitivity GPS test results. But when the TTFFs are compared, big differences can be found (see Figure 4). The average difference in TTFF was 56.7s. The average number of available satellites was 7.3 and 4.6 for the A-GPS and high sensitivity tests respectively. The number of failed tests was 2 and 42 respectively.

Figure 3. A-GPS (green cross) and standalone high sensitivity GPS (red circle) positioning results.

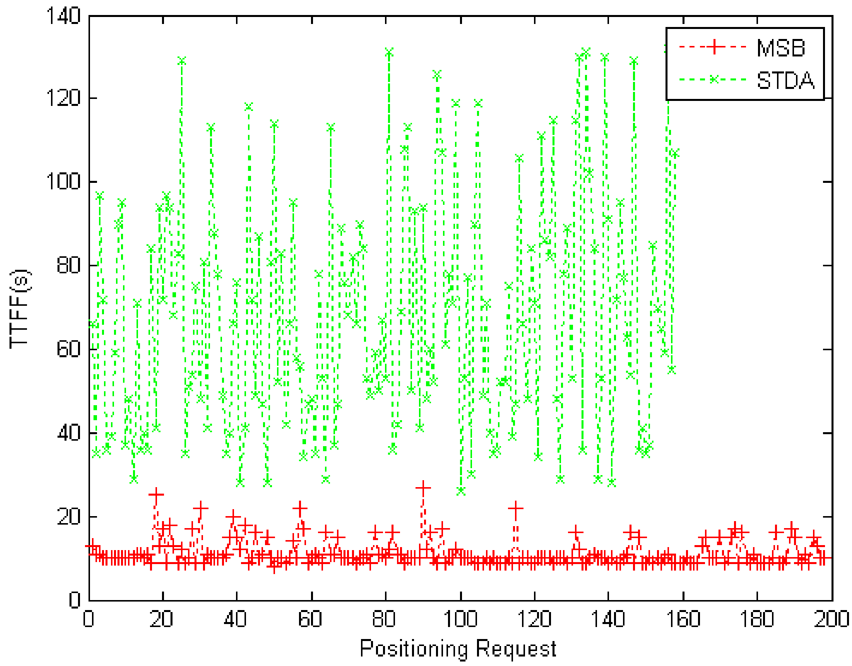

Figure 4. Comparison of TTFF for MSB A-GPS and standalone high sensitivity GPS for the dynamic tests.

Both the static and dynamic tests have shown that using only a high sensitivity GPS receiver in difficult signal environments is insufficient – the TTFF is too long and the successful rate is too low. On the other hand, A-GPS can significantly reduce the TTFF and increase the success rate of positioning.

2.4 Open Source GNSS Reference Server

SUPL and the control plane-based A-GPS are "closed" commercial systems. It is very difficult for non-commercial organisations such as universities to utilise the current A-GPS receiver solutions for research purposes. The development of the Open Source GNSS Reference Server (OSGRS) provides an alternative to commercial A-GPS reference data solutions. The OSGRS is an open source Java application that provides data for Assisted-GPS/GNSS clients. It is cross-platform and provides client applications with current, relevant and specific assistance data. The client may be an A-GPS/A-GNSS handset or an application that serves a network of A-GPS/A-GNSS handsets. The OSGRS utilises the GNSS Reference Interface Protocol (GRIP). Furthermore, the OSGRS is a user plane A-GPS implementation (Yan et al., 2007). A "demonstrator" of the OSGRS client that can support three different types of A-GPS receivers has been developed by the researchers at UNSW. Figure 5 shows the interface of the software. Preliminary testing has verified that the OSGRS works. For example, under the most difficult signal environment (refer to Figure 1, test position 1), using the OSGRS to provide assistance data to a ublox EVK-5H receiver the average TTFF was found to be 42.3s. However this is worse than for the earlier SUPL tests, hence further investigation is needed.

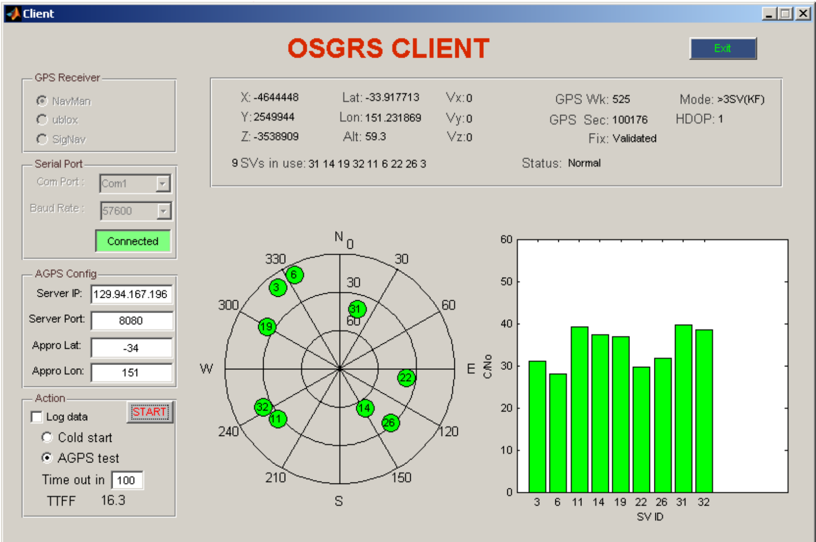

Figure 5. Display page of the OSGRS client software.

3. WIFI POSITIONING

WiFi is an attractive alternative positioning technology due to the widely deployed WiFi access points (AP) and the growing number of WiFi-enabled mobile devices on the market. Over the past five years, tens of millions of WiFi APs have been deployed around the world. The global AP shipments are forecast to exceed 70 million by 2010. Shipments of WiFi-enabled mobile phones will double in number by the end of 2010, compared to January 2008 (ABI Research, 2008).

Basically there are two types of approaches utilising WiFi signals for positioning. The first one uses a signal propagation model (plus a geometric model of the environment) to deduce distances to APs from signal strength (SS) measurements. Trilateration can then calculate the position of the user (Li et al., 2006). This technique is simple and comparatively easy to implement, but suffers from the need to develop realistic propagation models. Moreover, the exact locations of the APs are required. The second approach is known as “fingerprinting”. It has two phases: training and positioning. In the training phase, a survey of the area of interest or coverage is conducted in order to build a database of SSs at specific locations from different APs. In the positioning phase, the location of the user is obtained by measuring the SSs to all APs at their location, and comparing them with the SS data (or “fingerprints”) stored within the database (Ladd et al., 2005; Li et al., 2005a). This approach takes into account the complexity of the signal propagation environment. However, the main disadvantage of this approach is the need to create and maintain the database.

3.1 Tests of Commercial WiFi Positioning Systems

There are several companies that market WiFi-based positioning systems. Ekahau (www.ekahau.com) and Skyhook (www.skyhookwireless.com) are two of the most popular ones. The Ekahau Positioning Engine (EPE) is based on the fingerprinting technique. The database has to be built by the user, requiring the user to walk around the entire area of interest and record the SSs. Figure 6 shows the surveyed SS pattern on the 4th floor of the Electrical Engineering building at UNSW. The Skyhook Wireless Positioning System (WPS) also relies on the fingerprinting method, but doesn't require the user to make any SS survey as the database is built and maintained by Skyhook. When a user requests their location using Skyhook, the software scans the nearby APs and sends the data to Skyhook's server. The server then processes this SS data and sends back the estimated position to the user based on the "visible" APs. All the calculations are made on Skyhook's server, hence an Internet connection is required to use this system.

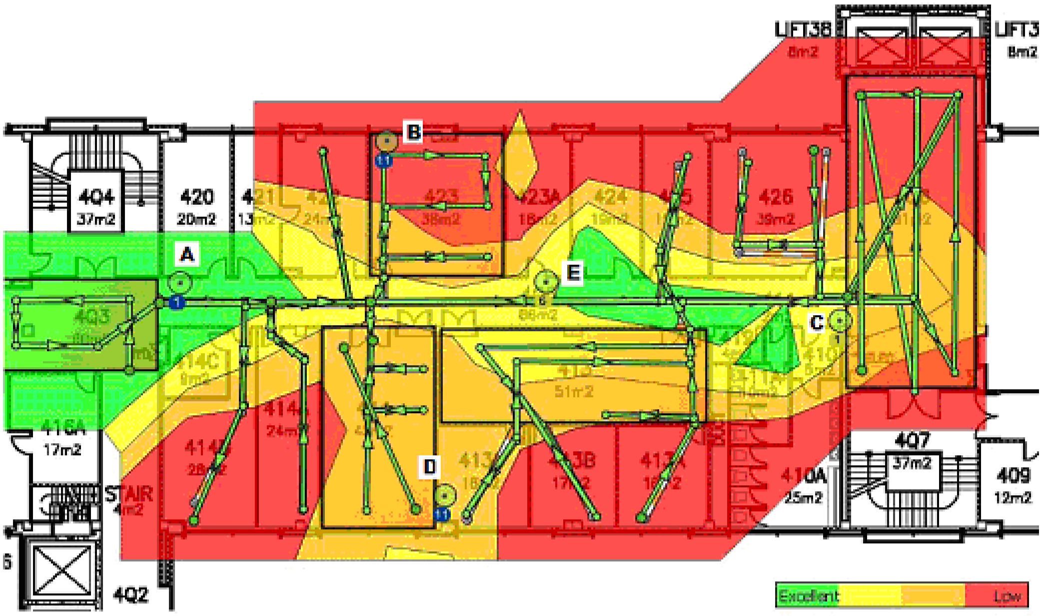

Figure 6. Site survey used in the Ekahau indoor test at UNSW.

For the Ekahua test, the client software must be installed on the devices needed to be tracked, allowing it to communicate with the EPE. For the Skyhook test, software based on Skyhook API was developed. Firstly, indoor tests were carried out. 13 test points were equally distributed along the main corridor of the floorplan shown in Figure 6, between APs A and C. Figure 7 summarises the test results of using both Ekahau and Skyhook. The Ekahau results (average error 8m) are much better than those of Skyhook (average error 41m). This is understandable because Ekahau has used a much better fingerprint database (surveyed carefully by the user), whereas Skyhook has used a very approximate, sparse database (and the test area was probably not surveyed).

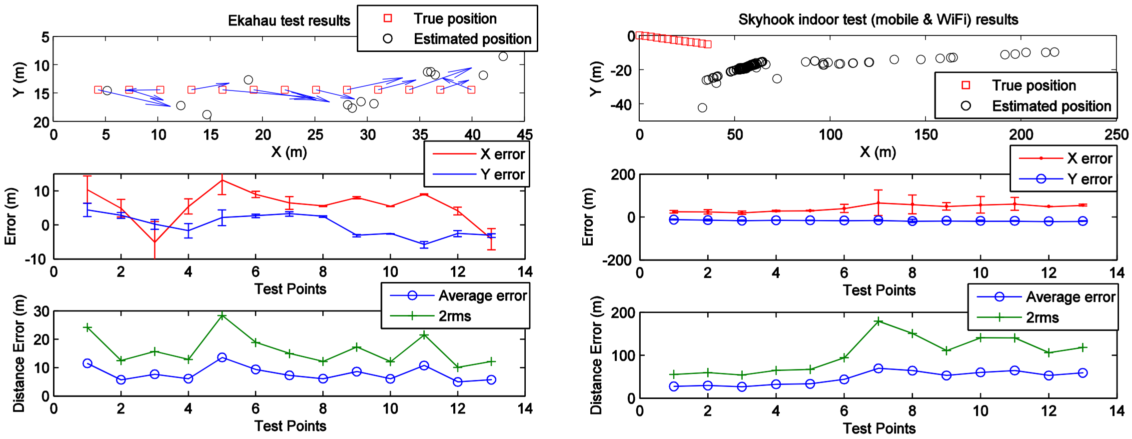

Figure 7. Ekahau (left) and Skyhook (right) indoor UNSW test results.

Tests of the EPE and WPS were also conducted outdoors, in the CBD area of Sydney (see Figure 8). An area where several survey points have been placed was chosen. For the Ekahau test, a survey of the area was made prior to testing, as in the case of the indoor tests, but this was far more difficult as the survey area was much bigger. Three test points were selected. Table 3 gives details of the test results. The outdoor test results were worse than those of the indoor tests. This can be explained by a number of factors, such as the quality of SS survey, the less dense AP distribution, and more moving objects (buses, people, etc.) disturbing the SS measurements in the outdoor case compared with indoor tests. For the Skyhook test, the test area was larger and ten test points were selected. Different handsets were tested on different dates; and a mobile network was used to communicate with the Skyhook server. Figure 9 summarises the Skyhook outdoor test results. The average range error was 73m and the failure rate was 5.8%.

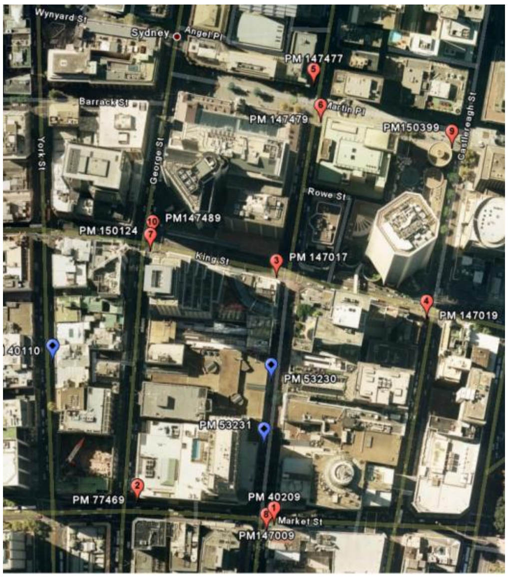

Figure 8. The outdoor test area in the Sydney CBD.

	Test point 1	Test point 2	Test point 3
Average distance error (m)	14.3	20.5	40.3
Standard deviation (m)	2.3	23.5	33.5

Table 3. Ekahau outdoor test results for the Sydney CBD.

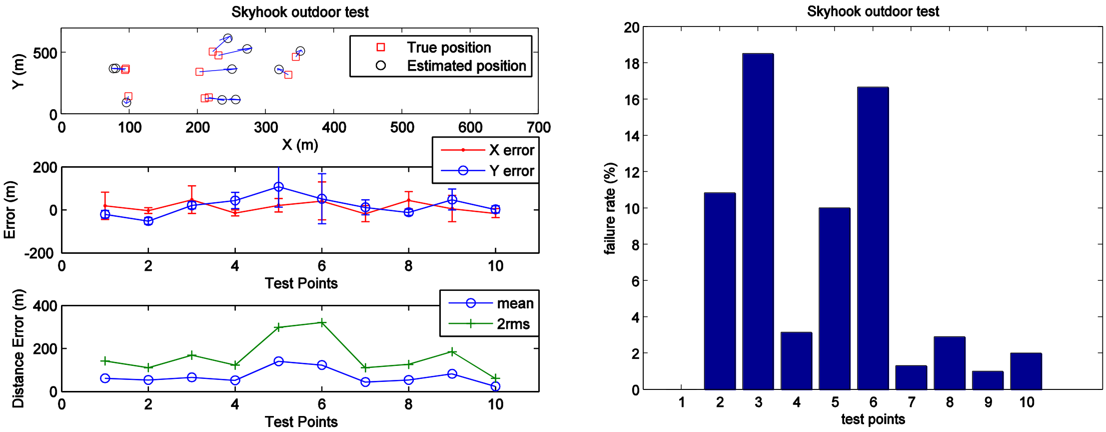

Figure 9. Skyhook outdoor test results for the Sydney CBD.

3.2 WiFi Positioning Research at UNSW

The UNSW researchers started WiFi positioning research in 2002. A WiFi-based positioning system was developed and the first results were published in 2003 (Wang et al., 2003). The researchers investigated the core aspects of the trilateration approach and fingerprinting approach of a WiFi Positioning System (Li et al., 2005b; Li et al., 2006), using both deterministic and probabilistic methods. The fingerprint approach was also tested for outdoor positioning. In addition, the directional information derived from WiFi was investigated for indoor and outdoor positioning (Li et al., 2007a; 2007b). 1-2m accuracy in indoor environments and 20-30m accuracy outdoors was achieved. A novel method to generate the fingerprint database can greatly reduce the burden of effort in the training phase (Li et al., 2005a). The researchers developed a hybrid WiFi positioning method based on the fact that although the RF signal propagation is very complicated for indoor environments, locally, such as in a room, the propagation model is reasonably well behaved. This method combines the fingerprinting and trilateration approaches (Li et al., 2005c). The theoretical underpinning of the fingerprinting technique was also investigated, including the WiFi signal propagation model, the relationship between mean distance error and different signal distance, and the short baseline propagation characteristics of the deterministic fingerprinting approach (Dempster et al., 2009, Li, 2006). Furthermore, to support the WiFi (and mobile phone) positioning research, software for PDAs which run the Windows Mobile OS, called ‘fLogger’, was developed to collect WiFi (and cellular base station) information in an efficient manner. Figure 10 shows how fLogger was used to log the WiFi information inside the Electrical Engineering building at UNSW.

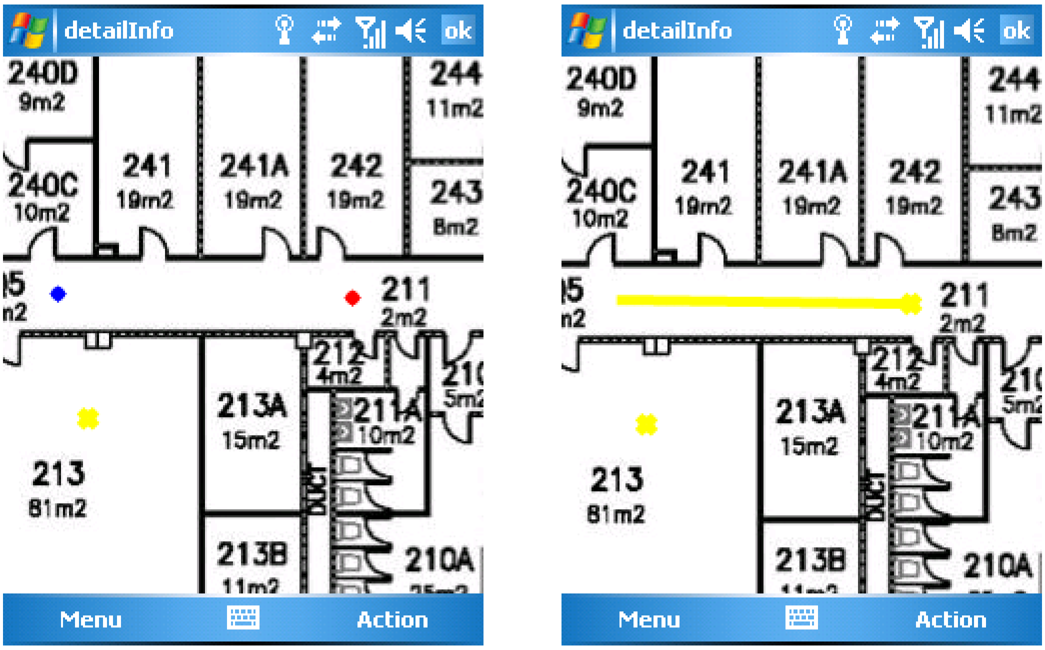

Figure 10. Using fLogger to gather WiFi SS information: by point or by line.

4. MOBILE PHONE POSITIONING

Using the mobile or cellular network for positioning has been widely used for location based services in many countries. The U.S.'s "Enhanced 911" (E911) requirement is one of the major drivers for improving mobile phone positioning (see www.fcc.gov/911/enhanced/). The most common techniques are based on Cell ID, Time Advance (TA), Time of Arrival (TOA), Time Difference of Arrival (TDOA), Angle of Arrival, and Fingerprinting. Most of these techniques suffer from non-line-of-sight (NLOS) error. The error can be up to thousands of metres (in range measurement) or 180 degree (in angle measurement), and consequently position estimation can be very inaccurate.

The fingerprinting approach can take advantage of the NLOS error. In a manner similar to WiFi fingerprinting, the received SS can be used to create the "fingerprints". In a mobile network, more measurements can be obtained such as TOA, TDOA, all of these information can, in principle, be used. However, the problem identified in WiFi fingerprinting also exists in mobile fingerprinting. From the results of tests, approximately 70% of the users were positioned with 50m or less distance error using the probabilistic approach (Li et al., 2005b).

To eliminate the NLOS error when using TOA, TDOA or AOA measurements for positioning, the wireless signal map matching approach was proposed by UNSW researchers (Lee et al., 2008a). The key aspect of this method is that a large amount of wireless signals are map-matched by statistical characteristics. Then the reference points can be obtained and the NLOS error can be extracted. Once the NLOS error map is generated, the NLOS error correction can be applied to improve the positioning accuracy. Figure 11 shows the cumulative distance error distribution before and after using the NLOS correction map (Li et al., 2006). The improvement in performance is significant. In this experiment TDOA measurements were used to calculate the user's position. However, this approach is not limited to TDOA, and other measurements such as the downlink pilot strength measurement can also be used (Lee et al., 2008b).

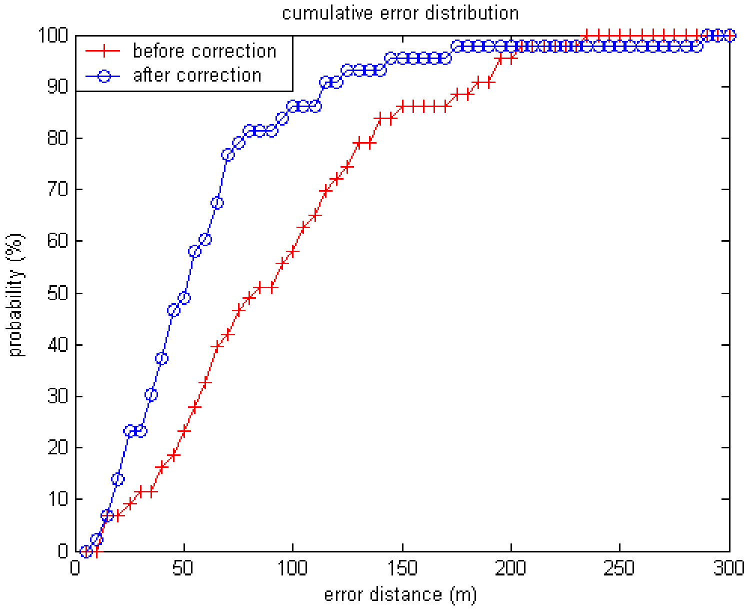

Figure 11. Cumulative error distribution before and after applying wireless signal map matching.

5. INTEGRATE WIFI POSITIONING WITH OTHER TECHNOLOGIES

All current positioning technologies have their own pros and cons. No technology appears to be a clear "winner" for ubiquitous positioning and navigation. Integrating several technologies can go some way to addressing the problem. For example, the integration of WiFi and GPS is an obvious one.

In open sky conditions there is no doubt that using GPS is the best choice. In indoor environments, using WiFi can deliver much better performance. Wayn et al. (2008) discussed a FPGA-embedded approach to integrating GPS and WiFi. The strategy was simple: when GPS is good, use GPS; when GPS is not available but WiFi signals are present, use WiFi. Otherwise use the combination of GPS and WiFi results, with the weights decided by the DOP value and number of GPS satellites available.

In some environments such as urban canyons, it is not unusual that less than four GPS satellites can be tracked. Furthermore, the signals from these satellites may suffer from multipath. Tan et al. (2009) investigated GPS positioning for scenarios of fewer than four satellites, including when there are only two available satellites. The technique uses the TDOA measurement generated by two pseudoranges of two satellites to yield a hyperboloid. This hyperboloid is then intersected with the earth spheroid to produce a curve on which the receiver should lie. If the user's approximate location can be determined using another technology, e.g. the mobile network Cell ID, using the TDOA curve as a constraint, an improved positioning result can be generated. The technique suggests a better way to integrate WiFi and GPS. Gallagher et al. (2009) describes a simple algorithm based on the two satellites approach which can significantly improve the WiFi positioning accuracy. Figure 12 illustrates the principle of the algorithm. Further studies suggest that in urban canyon areas WiFi positioning can locate the user on the correct street. The two satellites hyperbolic-spheroid intersection curve cross the street in most of the cases. Hence the geometric information (direction and location) of the street can help integrate WiFi and GPS positioning.

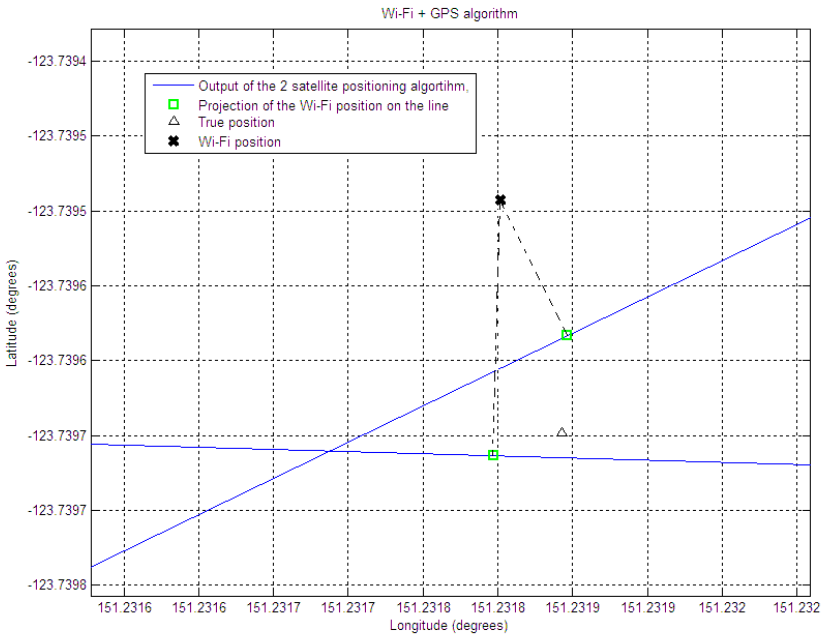

Figure 12. WiFi/GPS integration, the two lines correspond to two different pairs of satellites used.

In similar approach as loosely-coupled GPS/INS integration, WiFi can also be integrated with an inertial navigation system (INS). WiFi can provide location information to constrain the drift of the INS. This integration can increase the accuracy and reliability of indoor navigation. Other sensors, such as barometer or digital compass can also be integrated into a single system. RFID (Radio-frequency identification) technology can also be used for indoor positioning. A short-range RFID tag is basically a location indicator of important infrastructure or entrances, e.g. the door to a building, etc. On the other hand, the principle of the long-range RFID positioning system is similar to that of the WiFi positioning system (Retscher & Fu, 2009), and it can be easily integrated with WiFi system if necessary. Such integrated systems are under active development by UNSW researchers.

6. CONCLUDING REMARKS

"Ubiquitous positioning" is the "holy grail", that will finally enable location based services and many other applications in all environments, indoors and outdoors. In GPS/GNSS friendly environments, the GPS/GNSS receiver can meet almost all the positioning requirements for mass market as well as specialist applications. However, in GPS/GNSS unfriendly environments, an augmentation, or even alternative, technology is required. This paper describes some of the recent research work undertaken in this area at UNSW. There is no single "winner", and integration of several technologies is the current research focus.

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