Location Awareness in Wireless Networks

By

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Declaration

I, Barry Pearn certify that this thesis contains no material which has been accepted for the award of any other degree or diploma in any tertiary institution, and that, to the candidate's knowledge and belief, the thesis contains no material previously published or written by another person except where due reference is made in the text of the thesis.

Signed: .... Date: ....

Abstract

With the proliferation of wireless networks and the declining cost of wireless devices there is increasing interest in the development of location aware applications. These applications include robotics, context aware systems to collect or disseminate information, duress alarms in institutions such as hospitals and prisons and security of the wireless network.

There are many technologies that may be used to sense the location of mobile devices or personnel, including those based on infrared, ultrasonic, radio frequency tags and magnetic sensing. Most of these technologies require the deployment of devices specifically placed to support the location system. This paper focuses on a location system based on the RSSI of packets on the IEEE 802.11b wireless network. This technique has the great advantage that it may be implemented using off the shelf hardware that is generally already deployed to support the data network.

A simple wireless network was deployed in the School of Computing Building at the Newnham Campus of the University of Tasmania and used to test the location performance of a location system based on Bayesian filtering of detected signal strengths.

Acknowledgments

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Acronyms and Abbreviations

The following acronyms or abbreviations have been used in this paper:

AP	Wireless Access Point
RSSI	Received Signal Strength Indication.
WLAN	Wireless Local Area Network

1. Introduction

Recent advances in Wireless Local Area Network (WLAN) technology and falling costs of WLAN devices are expected to lead to a rapid increase in the proliferation of wireless networks. It has been predicted that there will be 39 million WLAN users worldwide by the end of 2004 and this number is predicted to grow to 120 million by 2008 (IT Facts.biz 2004). Market researchers, IDC were quoted (O'Brien 2004) to have predicted that the Australian market for LAN devices will "... double this year, growing 90 percent from $43 million in 2003."

With the rapid growth of wireless networks there is a growing interest in techniques to determine the physical location of wireless devices. In traditional wired networks, networked devices ure usually situated in fixed locations that can be determined with reference to building plans and cabling diagrams. This is not the case with wireless networks. It is possible to determine the sub network to which a mobile device is attached. However, depending on the topology of the network this may reveal very little about the physical location of the mobile device and at best will only indicate that a device is within the coverage area of one or several wireless access points.

There are two main reasons why it could be advantageous to know the physical location of mobile computing devices attached to a network. The first of these reasons has to do with locating a mobile device for security, safety, maintenance or administration purposes. The second reason is to provide location information to the mobile device as part of a location aware application.

1.1 Security, safety and maintenance applications

A location system may be used to simply record or track the location of a device, or of the person carrying the device for one or more of a range of purposes. An obvious application is that of security, and in particular the security of the wireless network itself. While it may be reasonably simple to detect the presence of an intruder in a wireless network it may not be so simple to locate the physical location of the intruder. A location system could provide this information. One issue that is closely related to the use of location detection in network security is that of *WarChalking* and

WarDriving. These terms refer to the "recreational" use of scanning and monitoring tools to locate and map the locations of (especially) unprotected wireless networks. While such activities are often motivated simply by the technical challenge, the information collected may also be used to gain unauthorised access to networks either to obtain free access to the internet or to attack the private network for other more sinister purposes. Network administrators need to be concerned about such activities whatever their intended purpose. The ability to physically locate their source could be of great value in investigating and countering them.

In many industrial situations, personnel entering hazardous areas are required to place a tag in a location to indicate their presence. Procedures are implemented to ensure that machinery is not restarted until all personnel have retrieved their tag to indicate they are no longer in the hazardous area. In some complex environments it may be difficult to locate the owner of a tag. Valuable time may be lost while searching for personnel still in the area. A location system using responder tags that can be tracked by a location system could facilitate rapid location and evacuation of remaining personnel.

The increasing deployment of handheld IP telephones is another area where a location system could be of use. Traditional wired telephones are normally attached to a known fixed point so the origin of calls is reasonably easy to obtain. Handheld IP telephones though may be quite difficult to locate. If such phones were capable of being tracked by a location system, then the physical origin of calls could be determined. Maintenance, security or any other personnel whose location is of interest could, if carrying a suitably equipped handset, be quickly summoned based on their current proximity to the site of an urgent task. Such a system could also support what are known as "enhanced 911" requirements to allow the source of emergency calls to be traceable.

1.2 Location aware applications

Another growing area of interest for location systems is that of context aware applications. There are many applications where context information, including knowledge of the location of the mobile device can be used to enhance functionality.

In data dissemination applications knowledge of the location of the mobile device can be used to modify the information it displays. An example of this type of application is a museum guiding application which can display information about exhibits in the current vicinity of the device and directions to various exhibits from the current location.. One such system, in the Marble Museum of Carrara, used PDAs and a location system based on infrared sensors placed throughout the display areas (Ciavarella and Patern 2004). Hospitals are another environment where context awareness can be of significant benefit. (Munoz et al. 2003) describes a hospital application where location and other context information are an important element of the system. A map based guidance system for locating books and collections has been implemented in the University or Oulu, Finland (University of Oulu 2003).

A location system could also be of benefit in data collection applications, especially with the in Wireless Sensor Networks where large numbers of sensors may be deployed across a target area. If these devices can determine their own location then the this can be reported with the sensor data.

Another application in which a location system could be of great benefit is that of duress alarms. The need for such a system was discussed by Christ and Godwin (1993). With location sensing incorporated in duress alarms, responding staff could be quickly directed to the correct location saving vital seconds. Location aware duress alarms could also have application in hospitals and other similar institutions

1.3 Overview

Chapter two of this paper presents a review of available research in the general area of indoor location systems, including their key properties, the choice of alternative techniques, technologies and architectures. Developments in the use of IEEE 802.11 Received Signal Strength Indication (RSSI) and techniques using Bayesian Filters are reviewed.

The implementation and testing of a system based on these techniques in the School of Computing Building at the Newnham Campus of the University of Tasmania is described in chapter three.

The detailed results and analysis of these tests is described in chapter four.

Finally, in chapter five the conclusions of this research are presented and some possibilities for further work are discussed.

2. Literature Review

This chapter presents a brief review of the properties technologies and architectures to be considered when planning a location system and discusses research and developments in the field of location systems based on RSSI.

There are several technologies that can be used to provide location information in mobile networks. However before looking at particular technologies it is important to understand the issues that arise in discussing location systems.

2.1 Location system properties

A number of properties of location systems are considered by Hightower and Borrielo (2001b, pp. 57-60) as a basis for the discussion and consideration of location systems.

A location system may provide two types of information, a *physical position* or a *symbolic location*. A physical location is usually define by a set of co-ordinates in either two or three dimensions that define a particular point in space or on a surface such as a map or plan of a building. A symbolic location is a more abstract idea which can often be defined in relation to other objects or places. It may be said that a location is in a particular room, or in the vicinity of a particular door. Physical position is more precise as each location is unique whereas a location may be within more that one symbolic location.

A position may be referred to by an *absolute* reference or *relative* reference. An absolute reference places objects within a common frame of reference. For example the GPS navigation system gives position in terms of latitude and longitude and possibly elevation relative to sea level which is common to all such systems. On the other hand, a relative location is specified on a local frame of reference relative to some particular object of interest. Of course if the absolute location of two objects is known, then the position of one object relative to the other can be determined but in cases where the absolute position of both objects is not known, it may be sufficient to determine just their relative position with respect to each other.

A location system may be based on *localised computation*. In a localized computation system, the burden of calculating a location is placed on the mobile device. Again, the GPS system is an example. The satellite system provides the reference from which positions can be calculated, but knows nothing about the location of a particular device. The alternative is an infrastructure based system where the location is calculated by the system for use by the system or may be transmitted to the device. Localised computation may be required if privacy is an issue, but an infrastructure based system may reduce the power consumption and computational power required in the mobile

Two key properties of any location system are *accuracy* and *precision*. Accuracy refers to the granularity of the measurement, while precision is a measure of how often we expect to achieve a defined level of accuracy. The two are closely related and should be considered together. A system may be described as reaching an accuracy of 1 metre with a precision of 95 percent, meaning that positions within 1 metre of the true position will be reported 95 percent of the time.

Scale refers to the scope or range of a system and the number of mobile devices it can service. A system my provide locations within a room, throughout a building, across a campus or worldwide as in the case of GPS. The number of clients a system can support may be limited by computation power or network bandwidth or may be unlimited if mobile devices calculate their own positions.

A system may also need to deal with *recognition* of the identity of mobile devices. Such information may be useful where different mobile clients require different services.

Cost is an important property of any location system and may be measured in terms of capital outlays, time and such factors as bandwidth.

It is also necessary to be aware of the environmental *limitations* of the alternative systems. For example GPS systems do not work indoors and some RFID tagging systems my not work if more than a single tag is within range at once.

2.2 Location-sensing techniques

While a wide range of technologies have been proposed for location sensing applications, all rely on one of three basic techniques, namely triangulation, proximity and scene analysis. Applications may use these techniques alone or in combination.

2.2.1 Triangulation

Triangulation is based on the geometric properties of triangles and can be further classified as lateration and angulation (Hightower and Borriello 2001a, pp. 1-5).

The term *lateration* refers to the technique used to determine a position from the intersection of distances measured from multiple known points. The basic technique is independent of the method used to measure the distances and could be equally used with physical measurements, light beams, sound waves or radio signals and may use 'time of flight' or attenuation to indicate distance. To determine an unambiguous position in two dimensions requires measurement of distance from at least three non-collinear references as illustrated in Figure 2-1.

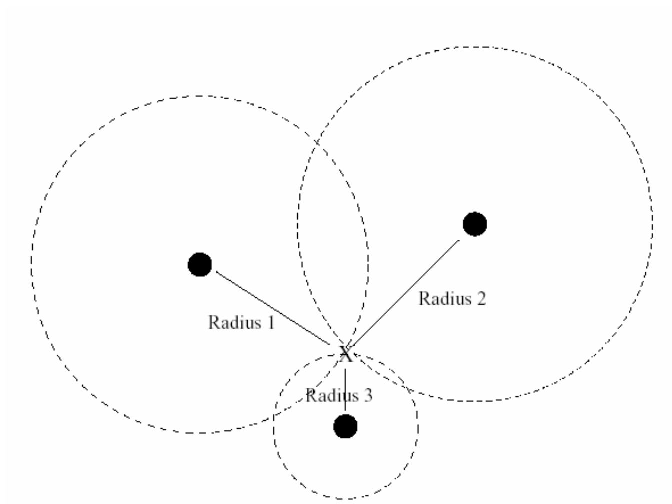


Figure 2-1 - Lateration to determine position in two dimensions.

The worldwide GPS system is perhaps the most widely known and used system based on triangulation using lateration.

Angulation on the other hand calculates a position using the angles from two points with known locations. The position is calculated from two measured angles and the known distance between the reference points as illustrated in Figure 2-2.

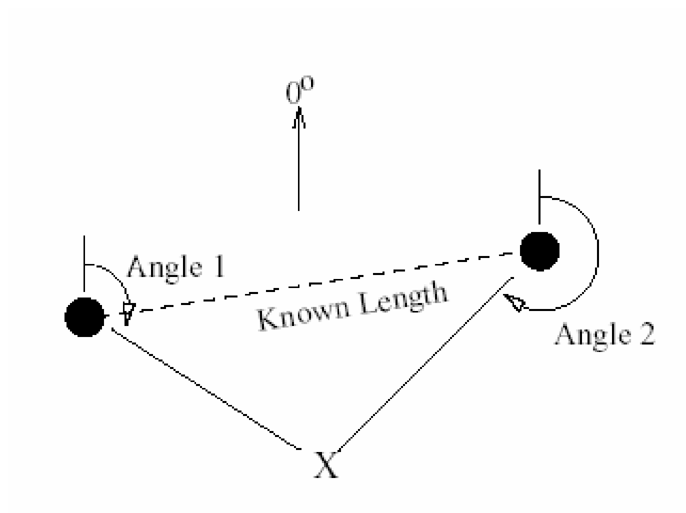


Figure 2-2 - Angulation to determine a position in two dimensions.

An example of triangulation using angulation is the VHF Omnidirectional Ranging system used for aircraft navigation.

2.2.2 Proximity

Proximity location sensing is the technique of determining the location of an object by determining when it is near a known location. Proximity can be determined by detecting physical contact with pressure sensors or capacitive field detectors. In cellular phone networks and other wireless networks, location may be indicated by which base stations or access points the target is within range of. Proximity location also includes tracking a location by means of access tags, credit card point of sale transactions etc.

2.2.3 Scene analysis

Scene analysis as a technique for location sensing makes use of features of a scene observed from a location to draw conclusions about the location of the observer or objects in the view. The location is inferred by comparing the observed features of the scene with a dataset of observations from various known points of interest. A variation to this technique is *differential* scene analysis where movement is inferred from changes in the image.

It is interesting to note that Hightower and Borriello (2001a, p. 6) expand the concept of scene analysis to include non-visual features of the scene such as the electromagnetic characteristics of the environment within this technique.

2.3 Location systems technologies

Many different technologies have been proposed to solve the problem of location determination. A survey of the field in 2001 (Hightower and Borriello 2001b) listed a number of then current technologies.

2.3.1 Infrared technology

The Active Badge (Want et al. 1992) was a personnel location system developed by the Olivetti Research Laboratory (later absorbed by AT & T). This was a cellular proximity system based on the use of diffuse infrared technology. Each badge emits a globally unique identifier every ten seconds or on demand. Data is collected by a central server from infra red sensors distributed throughout the building and made available to applications through an application programming interface.

2.3.2 Ultrasonic technologies

Later work at AT & T produced the Active Bat system (Harter et al. 1999) which is a time of flight lateration system using ultrasound waves. The system used a large number of ceiling mounted ultrasound detectors which connected by a wired, daisy-chained network. The bats transmit ultrasound pulses in response to a radio signal from a controlling base station.

The Cricket Location Support System (Priyantha et al. 2000) is also an ultrasound system, combining both proximity and time of flight lateration techniques but reverses the method used in the Active Bat system by using active beacons to disseminate location information to listeners. Each beacon transmits a short string which conveys the semantics of the location it identifies. The located device contains software to calculate its own position from the ultrasound signal it receives.

2.3.3 Radio frequency systems

RADAR (Bahl and Padmanabhan 2000b; 2000a; Bahl 2000) is a building-wide tracking system developed by a Microsoft Research group and based on the IEEE 802.11 WaveLAN wireless networking technology. The group experimented with techniques to infer the position of a mobile device from the RSSI measured by the wireless device. Firstly, and empirical method based on locating the nearest neighbour (or multiple nearest neighbours) in terms of signal strength. The second method, a signal propagation method used a mathematical model of the indoor radio propagation environment to generate a theoretical model of the signal strength expected throughout the building. They found that the empirical model was more accurate, but the propagation model was more transportable and obviated the need for detailed calibration.

2.3.4 Magnetic tracking technology

Electromagnetic sensing is a technology that offers a position tracking method capable of a very high degree of precision (Hightower and Borriello 2001b). The technology is use in products that support virtual reality and motion capture for computer. An example is the MotionStar DC magnetic tracker produced by Ascension Technology Corporation (Ascension Technology Corporation 2004).

2.3.5 Computer vision technology

Several groups have explored using computer vision technology to determine the location of people or objects. For their Easy Living demonstration of an intelligent environment, Microsoft Research developed the Easy Living Tracker, which used images captured by multiple stereo cameras to track the movement of people (Krumm et al. 2000). The system was capable of tracking up to three people in a room. Easy Living is a visual scene analysis technology where the moving objects (people in this case) are recognised by the system. Visual scene analysis can also be applied in the opposite way where the visual environment is observed by the mobile object.

2.3.6 Physical sensor technologies.

The Smart Floor (Orr and Abowd 2000) system developed at Georgia Institute of Technology is a proximity system based on physical contact with pressure sensors embedded in the floor. The system goes beyond simple location by using individual profiles of the ground reaction force of footsteps to identify individual users. One advantage claimed for the system is that it does not rely on users carrying anything or remembering anything. The trade off is the need for sensors to be incorporated in the floor of the building.

2.4 Architecture of a tracking system

The architecture of a location system affects its scalability, ease of deployment and performance. Smith et al (2004, pp. 190-191) identify two main architectures for a location system, active mobile and passive mobile.

In an active mobile architecture, as illustrated in Figure 2-3, each mobile device periodically broadcasts a message on the communication channel. A number of fixed receivers are deployed throughout the area to be monitored and listen for these messages. The characteristic of the signal that is used to estimate position is then sent to a central station which analyses the result and estimates the position. Depending on the nature of the system, the derived position can be passed back to the mobile device or to intrusion detection or other monitoring application.

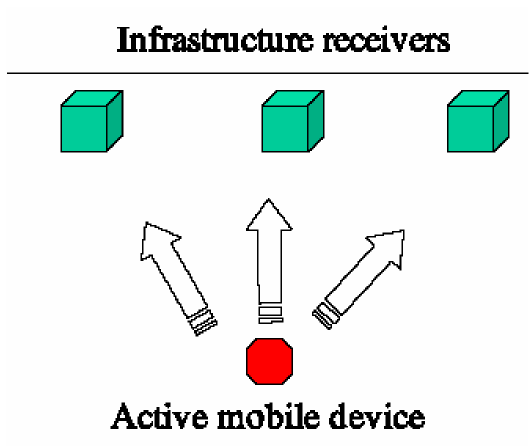


Figure 2-3 - Active Mobile Architecture (based on Smith et al. 2004, p. 191)

A passive mobile architecture uses a number of beacons deployed at known locations throughout the area. These beacons periodically transmit their position (or identity). Mobile devices that want to know their location listen to the beacons and use the characteristics of the received signal to estimate their position.

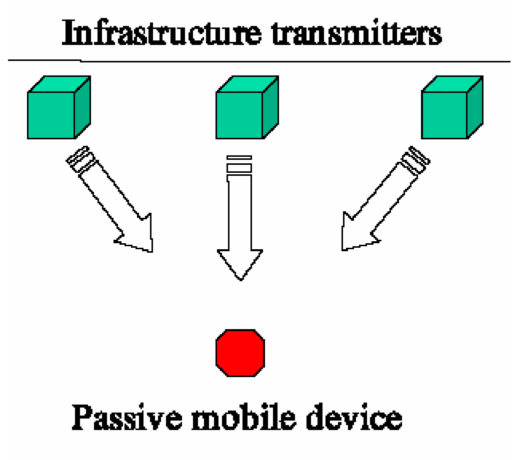


Figure 2-4 - Passive Mobile Architecture (based on Smith et al. 2004, p. 191)

It was found that although the passive mobile architecture scales better with an increasing number of devices, it suffers some loss of accuracy compared with the active mobile architecture because measurements are not made simultaneously. A hybrid architecture was proposed to preserve the scalability of the passive mobile system but provided increased precision of location (p. 201)

2.5 Choosing a location sensing technology

As has been demonstrated above, there are many different technologies to choose from when designing a location sensing system. They are each based on sensing different combinations of the properties outlined above and based on one or more of the three main sensing techniques, triangulation, proximity sensing and scene analysis. The choice of a suitable technology for any planned application depends on the characteristics of the application and the environment.

For example, Ciavarella & Patern (2004) discuss the issue of choosing a technology to add location awareness to a PDA based museum guide application at the Marble Museum of Carrara. In this case, the material to be displayed was stored in the PDA environment and there was no requirement for network connectivity, so the requirement was only to determine the location of the device. Consideration was given to three alternative technologies, WLAN, Bluetooth and Infrared to determine the location. The system adopted deployed infrared beacons which provide just an identifier so that the PDA can determine its current location and display appropriate information.

In the case of the Marble Museum, this rather course grained proximity based approach satisfied the requirements of the application. Like many of the technologies considered above, this system required the installation of infrastructure specifically to support the location system.

On the other hand, the use of radio signal strength measurements for location sensing is unique among technologies considered in that it offers the possibility of using the existing wireless infrastructure installed for other purposes to provide location information. In situations where the devices to be tracked are Wireless LAN clients then a location system may be added with little or no additional outlay for hardware. Another advantage of Wireless LAN sensing is that a system using standard devices can provide both location and identification information where other technologies can provide one or the other, but not both.

2.6 Using RSSI for location sensing

Because location sensing from observed RSSI has the key advantage that it can be achieved as a value added service using existing hardware, it is the main focus of this project. The techniques to be considered are based on the fundamental characteristics of radio signal propagation.

Wireless communication is possible because changes in the electron flow within a wire cause changes in the magnetic field surrounding the wire. Because these changes induce electron flows in other wires within the field a signal can be transmitted from one device to one or more remote devices. However only a very small fraction of the energy leaving the transmitting antenna ever arrives at the receiving antenna and this fraction becomes less as the distance between the two devices increases.

2.6.1 Limitations of RSSI measurement.

In theory it is possible to build an engineering solution to location sensing based on the properties of radio propagation by calculating the distances from a number of known access points and triangulating the position.

In practice this is difficult for a number of reasons:

- The transmitted power of the Access Points may vary over time due to changes in environmental conditions such as temperature;
- The propagation characteristics of a building are non-uniform due to structural elements and fittings and may be subject to variation caused by environmental conditions or human activity;
- As discussed later in Par. 3.1, the sensitivity of RSSI measurements reduces rapidly at increasing distances and
- The RSSI reading obtained from some devices may be of limited precision (Par 3.1.2) and may fluctuate over time.

As a result of these problems, many researchers have been led to look for alternatives to the engineering solution of triangulating estimated distances.

2.6.2 Further work on using RSSI

Some of the earliest work to investigate the use of radio signal strength to estimate location of mobile stations was conducted in the Microsoft Labs (Bahl and Padmanabhan 2000b). RADAR, the system they developed was "…based on an empirical signal strength measurements as well as a simple yet effective signal propagation model" (p. 10).

In a subsequent report (Bahl and Padmanabhan 2000a) examined some shortcomings in the basic version of RADAR and tested enhancements to improve the accuracy of continuous tracking, make the system more resilient to variations in the radio propagation environment and extend the algorithm to a three dimensional (multiple floor) space. The results obtained from the tests were encouraging. Their conclusion suggests further testing in real world environments and proposes the idea of deploying a larger number of "light" access points which would only be used for location and have no other network function. Given the subsequent reductions in the cost of Access Points a higher density deployment of fully functional access point may be considered worthwhile to increase the level of redundancy and provide additional bandwidth.

Ladd et al (2002) describe a system using RF signal strength as measured by an IEEE 802.11b wireless Ethernet card communicating with standard base stations. They used a laptop computer with a PCMCIA LinkSys wireless card to measure and record the received signal strength from wireless access points distributed throughout the building. Signal strength was determined by reading the measurement made by the card. The standard Linux kernel driver for the wireless card were modified to allow the scanning and recording of hardware MAC addresses and signal strengths in promiscuous mode. A Bayesian probabilistic model was used to predict the location of the mobile device. The system achieved one meter accuracy within one standard deviation and concluded that reliable localization can be achieved using wireless Ethernet

More recently a report by the same team (Ladd et al. 2004) apparently reporting on the same research noted that the observations reported were taken at night when the building was largely unoccupied. It was suggested that further work was needed to determine performance in more dynamic environments and suggested the need to look more closely at the placement of base stations. (Ladd et al. 2004, p. 558)

In later work by the same group in the same environment (Tao et al. 2003), an active mobile architecture was used to test modifications to the previous design aimed primarily at solving the specific problem of locating "rogue" mobiles. In particular this was aimed to increase the robustness of the location algorithm if the target mobile deliberately changed its transmit power to try and mask its location.

In this case the hardware consisted of five "snoopers" which were wireless enabled laptop computers that had custom built device drivers to read the signal strength from the receiver's automatic gain control register. These were connected to a server which was a Java application that collected the signal strength measurements from the snoopers and performed the statistical operation required to estimate the location of the target machine. The target machine was a laptop with a wireless card capable of varying it's transmitting power. The conclusion reached was that using the modified technique it was possible to estimate the location of a mobile node that varied its transmit power.

In another study (Smailagic and Kogan 2002), four different algorithms based on signal strength measurements were compared:

- <u>CMU-SC</u> which simply gathered data from the available access points and returned the position of the nearest one;

- RADAR a system developed by Microsoft (discussed previously);
- CMU-PM which matches data collected by the mobile client against pre-generated tables of signal strength vectors.
- CMU-TMI used a polynomial function to calculate from signal strength the distance to each access point, derived a position in "Signal Space" by intersecting the calculated distances and then made an adjustment from learned data determine a position in "physical space".

They concluded that the CMU-TMI algorithm offered advantages in the reduced complexity of calibration and achieved a noticeable increase in accuracy.

The use of RSSI and proximity to estimate range between devices and sensor location and how both are affected by the random nature of fading were examined by Patwari and Hero (2003). It was found that RSS provided significantly more reliable estimates of location than proximity but that a quantized RSS using only three bits (8 levels of quantization) may be sufficient. This opens the possibility of reducing the complexity of the devices required (p. 28).

Some work at Rutgers University (Ganu et al. 2004) focussed on the use of infrastructure based "sniffers" to monitor information about mobile clients and to support a server based location and security system. The purpose built sniffers operate in a passive mode and listen to the communication medium and timestamps and records the header information from the frame header of the management and control frames. The decoded information is forwarded to the centralised database for use by the location system.

2.6.3 Bayesian filtering

Two common problems with any technique that derives location estimates from measured signal strength are the dynamic nature of the RF environment and the imperfect precision of the measurement devices. This has led to the adoption of techniques to combine data of various types and to deal with the uncertainty inherent in the data. Perhaps the most widely adopted approach to this problem is the use of Bayesian filtering techniques.

The application of Bayesian techniques to the problem of location estimation is discussed in some detail by Fox et al (2003b). Bayesian filters can be used to estimate the state of a system from a set of noisy observations. It was concluded that the use of Bayesian techniques are "… an extremely promising tool for location aware computing. The detailed analysis of Bayesian theory is beyond the scope of this study. Those interested in further exploration of the application of various Bayesian techniques such as Kalman Filters, Particle Filters and others as they apply to the area of location sensing are referred to more detailed analysis by Fox et al. (2003a; 2003b) and Ladd et al.(2004)

The use of statistical modelling approach to position estimation has also been pursued at the University of Helsinki (Tonteri 2001). Teemu Roos (formerly Teemu Tonteri), in a subsequent paper, discussed the different machine learning approaches to the problem based on nearest neighbour and Bayesian algorithms. They found that "… an average location estimation error below 2 meters is easy to obtain (p. 162). The Ekahau Positioning System which is discussed later in this paper is based on the Helsinki research.

2.6.4 Self correction

Because of the high sensitivity of location estimates to small changes in signal strength, changes in environmental conditions may cause locations estimated from RSSI data to "drift" over time. This could be so whether the locations are derived by the engineering approach by triangulation, or by using a scene analysis approach using Bayesian or some other machine learning technique. Some work has been carried out to make such systems more robust in the face of variations in the signal propagation environment.

One approach is that of environmental profiling where multiple sets of data are recorded throughout the day and the base stations probe the environment periodically and pick a dataset on which to base the estimate (Bahl and Padmanabhan 2000a).

The problem has also been considered in relation to the use of wireless sensor networks and a number of solutions proposed. Some work in sensor networks use calculation based on time of arrival and direction of arrival of signal between sensors with known and unknown locations (Moses et al. 2003). Others have used objects with known positions or masters to provide a reference (Mondinelli and Zsolt M. Kovacs-Vajna 2004).

3. Methodology

This chapter begins with a brief discussion of the signal strength and how it is measured by a WLAN cards. It then discusses some software applications relevant to the area of interest. The final section describes the implementation of a location system in the School of Computing building.

3.1 Signal strength

3.1.1 Free-space path loss

The energy that is lost is called the free space path loss and can be calculated using the following formula:

$$PL = 32.4 + 20 \log(f) + 20 \log(d) \qquad (2\text{-}1)$$

Where PL is the path loss in decibels (dB), f is the frequency in MHz and d is the distance in km. (Unger 2003, p. 51) (But note that the formula as published by Unger contains an error – the first constant is printed as 92.4 and should be 32.4 and f is expressed in MHz, not GHz).

If we confine our consideration to the field of IEE 802.11 networks operating in the 2.4 GHz band then we can treat f as a constant and given the indoor environment take the distance in meters we can simplify formula (2-1) to:

$$PL = 40 + 20 \log(d) \qquad (2\text{-}2)$$

It has been suggested elsewhere (Spread Spectrum Scene 2001) that the total path loss in a typical indoor environment is more typically given by the formula:

$$PL = 40 + 35 \log(d) \qquad (2\text{-}3)$$

The effect of these two assumptions is shown in the loss curves depicted in Figure 3-1. While no attempt was made to verify which of these curves best represents the propagation characteristics of the test site, it is reasonable to assume that it would lie somewhere between them and have a similar characteristic shape.

Figure 3-1 - Estimated Indoor Free Path Loss

What the curves in Figure 3-1 clearly illustrate is that as the distance of the transmission path increases, the amount of change in signal strength for a given change of distance decreases. This decrease in sensitivity is better illustrated in Figure 3-2 which shows the sensitivity of signal strength as an indicator of distance.

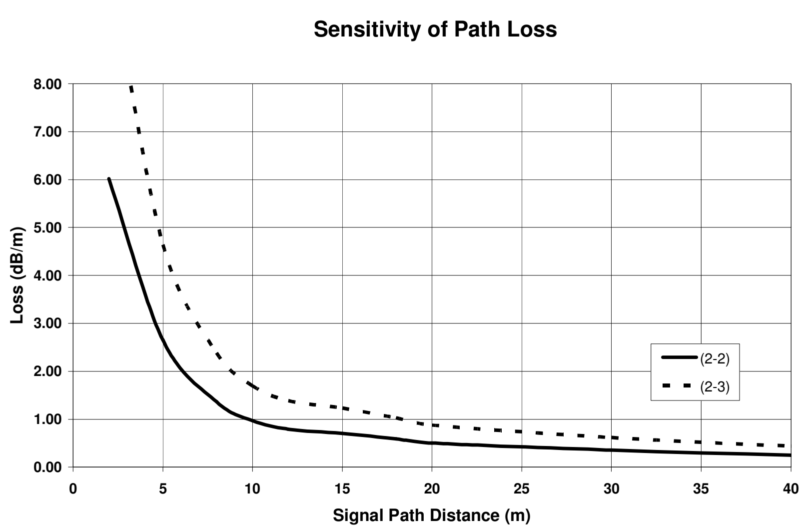


Figure 3-2 - Sensitivity of Path Loss Measurements

Clearly, even with extremely precise instruments, the accurate measurement of distance will be severely limited by the low sensitivity of the change in signal strength over greater distances. In a practical location system, signal strength will be measured by off the shelf networking components, not accurately calibrated laboratory instruments.

3.1.2 Signal strength measurements.

All IEEE 802.11 WLAN cards measure the RSSI continuously. The Physical Medium Dependent (PMD) sublayer returns a continual RSSI to the Physical Layer Convergence Procedure (PLCP) in the PMD service primitive PMD_RSSI.indicate. In the 802.11 Frequency Hopping Spread Spectrum system this is a four bit field with a range of values from 0 (weakest) to 15 (strongest) signal strength (Geier 2001, p. 133). Other 802.11 physical layer specifications (including 802.11 DSSS, 802.11a and 802.11b), use an eight bit field which allows 256 levels of signal strength (pp. 140, 149, 154). Both 802.11 Direct Sequence Spread Spectrum and 802.11b also optionally report signal quality in an eight bit primitive named PMD_SQ.indicate.

The RSSI is used by the PLCP for its clear channel assessment functions but, given suitable drivers, can be read by applications. Many adaptors are supplied with a configuration utility that includes the capability to display RSSI for the currently active channel or in some cases for all received channels. The RSSI indicator is implemented to provide necessary information for the limited internal use of the WLAN system and there is no guarantee that it will provide precise measurement to external applications.

3.2 Software

There are several software packages and utilities available to measure, log and map WLAN signal strengths. While their interest is in locating and mapping wireless access points rather than finding the position of a wireless node, Byers and Kormann (2003, pp. 43-44) discuss some hardware and software issues that are relevant to the current problem. They include standard networking utilities and packages designed to discover and map WLANs such as NetStumbler and Kismet.

3.2.1 Site survey and WLAN utility tools

NetStumbler is a tool for Windows that allows detection WLANs using IEEE 802.11b, 802.11a and 802.11g protocols. NetStumbler detects and measures the RSSI from any available access points. It works with many WLAN cards but depends on firmware and driver versions (Milner 2004). NetStumbler is a favoured tool of the warchalking sub-culture, but has uses in planning and configuring WLANs.

Kismet is an 802.11 layer two wireless network detector, sniffer and intrusion detection system. Kismet will work with any wireless card which supports raw monitoring (rfmon) mode, and can sniff IEEE 802.11b, 802.11a, and 802.11g traffic. Kismet identifies networks by passively collecting packets and detecting standard named networks, detecting (and given time, decloaking) hidden networks, and inferring the presence of non-beaconing networks via data traffic (Kismet 2004). Kismet will run on any operating system with Posix compatibility (including Windows using Cygwin).

Wireless Research API (WRAPI) a software library that allows applications running in user space on mobile end stations to query information about the IEEE 802.11 network they are attached to. WRAPI 1.0 is implemented on the Windows XP operating system and is a hardware-independent tool that works with any IEEE 802.11b wireless network hardware vendor. WRAPI has been developed as a research tool by the University of California San Diego (USCD 2002)

WRAPI provides an interface to applications requiring information about the Wireless LAN. Many network card can be read and or modified using WRAPI.

3.2.2 Location software

A number of location and tracking systems are now either commercially released or under commercial development.

The Ekahau Positioning system is a software-based positioning and site survey system which is based on research by the Complex Systems Computation Group at the University of Helsinki. It is based on "… multiple positioning and site survey patents that exploit the theoretical results behind concepts such as Bayesian networks, stochastic complexity and on-line competitive learning." (Ekahau Inc.) As a commercial product, the details of the algorithms used in Ekahau are confidential, but their published information (Ekahau Inc. 2004) indicates that the system is based on technology similar to that used in the research at Rice University (see Par. 2.6.3).

In operation, the Ekahau Site Calibration™ method is used for collecting radio network sample points from different site locations. Each sample point, containing station identification, RSSI and the related map coordinates, is stored in the Positioning Model for use in location tracking. Ekahau Positioning Engine™ (EPE) is a positioning server that receives RSSI vectors from the client software on tracked targets and makes current location information available through an API for use by location aware applications. The software works with most industry standard access points and network cards.

WhereNet's WhereLAN Location Sensor and Locating Access Point combines location sensing features in a wireless access point. The Locating Access Point configuration delivers real time location sensing coverage plus an integrated wireless LAN access point to connect mobile workers to critical information. The devices receive and detect tag signals using "… sophisticated digital signal processing." (WhereNet) The Location Sensor and Locating Access Point are able to track a large number of WhereTags simultaneously to assure location accuracy over a very large coverage area. The Location Sensor and Locating Access Point forward tag signal information to the WhereNet Visibility Server Software where information can be graphically displayed, used for report generation, or accessed through the Internet.

WLAN Tracker (Komar and Ersoy 2004a; 2004b) is an experimental, software only system developed at the Bogazici University, Istanbul, that makes use of standard IEEE 802.11 WLAN hardware to provide location information for mobile wireless devices. Signal strengths from multiple Access Points are collected by the target device and sent to WLAN Tracker workstation for analysis. The system was tested outdoors and in a three story indoor environment.

3.2.3 HostAP and Linux

The inclusion of HostAP in the Linux kernel means that extensions could be added to these systems to share and process signal info between 'pseudo' access points. HostAP is a Linux driver for wireless LAN cards based on Intersil's Prism2/2.5/3 chipset. The driver supports a so called Host AP mode, that is, it takes care of IEEE 802.11 management functions in the host computer and acts as an access point. This does not require any special firmware for the wireless LAN card. In addition to this, it has support for normal station operations in BSS and possible also in IBSS. WPA and RSN (WPA2) is supported when used with accompanied tools, wpa_supplicant (WPA/RSN Supplicant) and hostapd (WPA/RSN Authenticator).

Intersil's station firmware for Prism2 chipset supports a so called Host AP mode in which the firmware takes care of time critical tasks like beacon sending and frame acknowledging, but leaves other management tasks to host computer driver. This driver implements basic functionality needed to initialize and configure Prism2-based cards, to send and receive frames, and to gather statistics. In addition, it includes an implementation of following IEEE 802.11 functions: authentication (and deauthentication), association (reassociation, and disassociation), data transmission between two wireless stations, power saving (PS) mode signalling and frame buffering for PS stations. The driver has also various features for development debugging and for researching IEEE 802.11 environments like access to hardware configuration records, I/O registers, and frames with 802.11 headers (Malinen 2004).

HostAP opens up the possibility of constructing inexpensive access points with the capacity to listen to the network and collect signal strength information for use in estimating location of passive targets.

3.3 Implementation

3.3.1 Wireless network configuration

A test installation was established in the Main Block of the School of Computing building at the Newnham Campus of the University of Tasmania. There was no existing wireless network in the school and a preliminary survey of the wireless environment revealed only one low strength and infrequent signal from an adjacent building was detectable from inside the building.

The main block of the school building is approximately 63m. by 28m. in size. Three Apple Airport Access Points were installed in selected locations in the building (shown in Figure 3-3) and configured on channels 3, 7 and 11 respectively. These Access Points were positioned in secure rooms and connected to a private Ethernet switch to form a private network. An additional Access Point, a Belkin 6231-4, configured on channel 1, was used to provide an additional wireless signal, but was not connected to the Ethernet network.

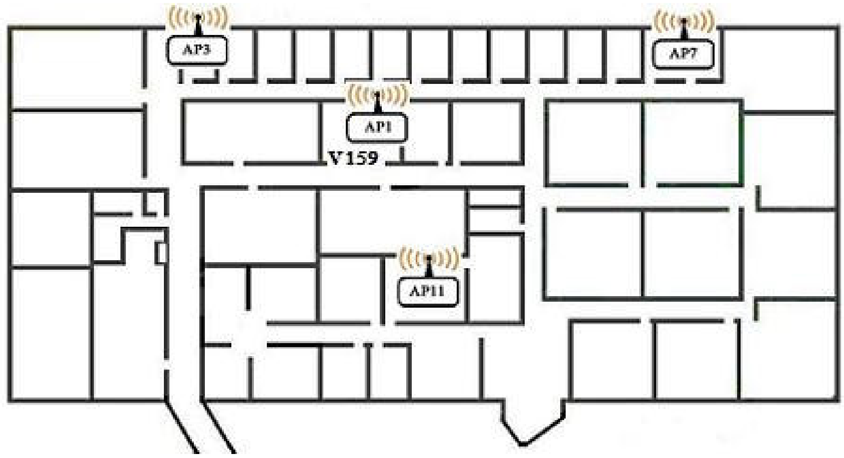


Figure 3-3 - Initial Wireless Network Configuration

In this configuration, the three Airport Access Points were positioned at the corners of a triangle with the longest side of 37.5 metres so all points in the central area were within approximately 20 metres of at least two Access Points. The Belkin Access Point was initially placed in room V159 approximately equidistant from the other access points.

Preliminary testing revealed that this configuration did not produce consistent results. The estimated locations were erratic had large errors. On reflection it seemed that the problem arose because the three outer access points were too distant and the location of AP1, being located as it was did not add sufficient additional information when the target was at the extremities of the target area.

The setup was revised to reduce the distance between the Airport access points as shown in Figure 3-4. Access Point 7 was relocated to in room V176, a position closer to the test area. Access Point 1 was also moved to a different location as shown in Figure 3-4 so that its position was further away from being co-linear with any of the other access points.

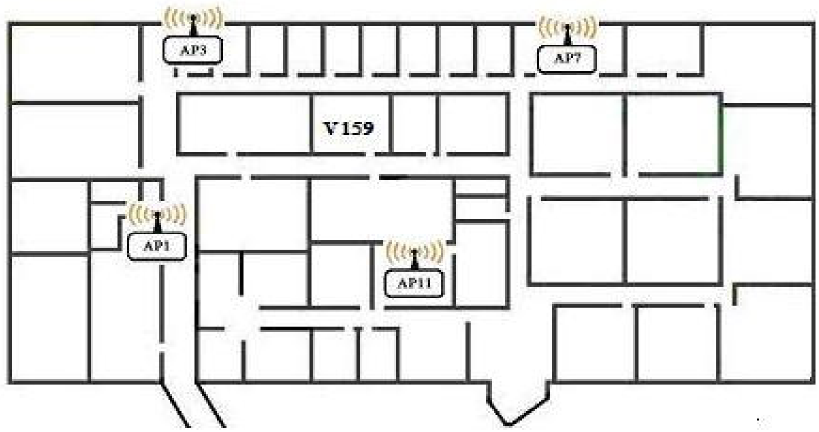


Figure 3-4 - Revised Access Point Location

A Hewlett Packard ze5730us Notebook Computer with an inbuilt Broadcom 802.11g wireless LAN adaptor was used as the mobile target. The Ekahau software, (Client, Manager and Positioning Engine) were installed on this notebook.

A desktop computer with a wireless card was also configured and placed in Room V159. The Ekahau software was also installed on this machine and the positioning engine function was moved to this unit for the later tests. As well as providing a permanent host for the Positioning Engine for the duration of the tests, it was intended to use this fixed wireless node as a reference point to monitor the stability of the location estimates over time.

However, it was found that the estimated position for this unit was quite unstable. The RSSI indicators in the Ekahau Manager indicated a rapid fluctuation in the RSSI readings so it was suspected that this instability was caused by inconsistency in the measurement of RSSI reported by the WLAN adaptor.

To test if this was the case, the notebook computer was set up at the same location and RSSI readings from the three Access Points were recorded concurrently on both machines. The RSSI readings were recorded using NetStumbler and exported to text files for further analysis. The RSSI reported by the Belkin card in the desktop machine (Figure 3-5) varied considerably more than that recorded by the adaptor in the notebook computer (Figure 3-6).

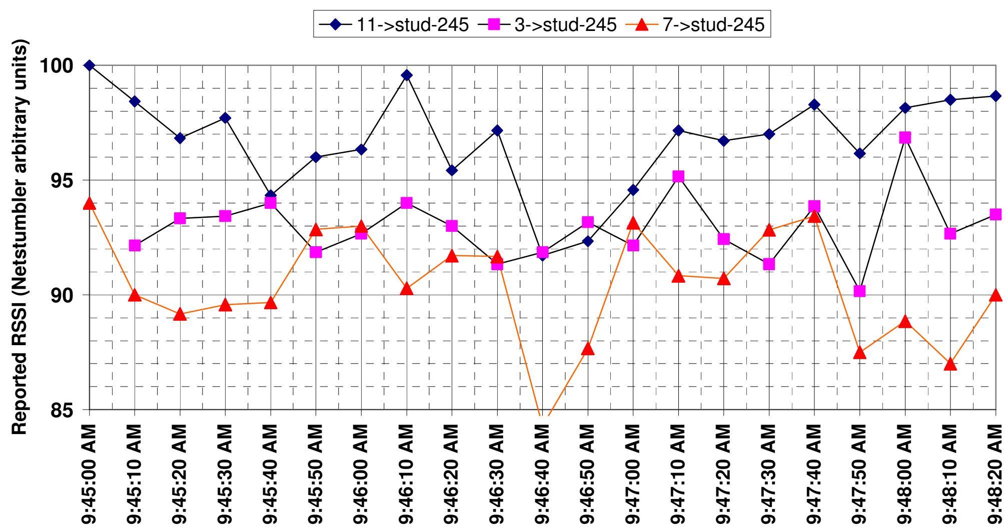


Figure 3-5 - Sample of RSSI Reported by Belkin Card

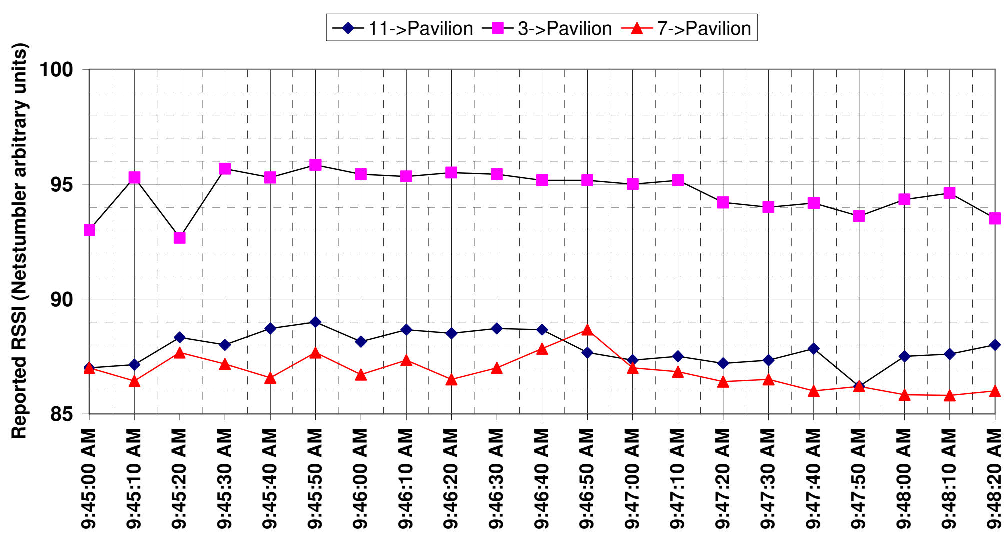


Figure 3-6 - Sample of RSSI Reported by Notebook (Broadcom card)

A more quantitative indication of this difference is obtained by calculating the standard deviation of the RSSI recorded for each signal path. As can be seen in Table 3-1, the standard deviations of the readings recorded by the desktop machine are all much higher than those recorded by the notebook computer. As both machines were recording the same signals at the same location the only possible conclusion is that the Belkin card does not produce a consistent and accurate measure of RSSI and is unlikely to produce data that can be used to derive accurate location estimates.

Table 3-1 – Comparative standard deviation of reported RSSI for Broadcom and Belkin cards in target devices

	WIRELESS CARD	
Channel	Notebook (Broadcom)	stud-245 (Belkin)
3	1.09	3.68
7	1.10	5.97
11	1.09	3.92

The Belkin card was subsequently replaced with a Netgear model WG311 PCI Adaptor. While this provided a somewhat more stable indication of the predicted location of the (stationery) terminal, examination of the RSSI reading reported by NetStumbler showed more consistent readings for Access Point 3, but very erratic readings for Access Points 7 and 11 with frequent missed readings. In the NetStumbler log file both these access points frequently recorded an RSSI of -32618 (normal readings were in the range of 75-85 for access point 11 and 90-95 for access point 7).

Because of this difficulty, it seemed unlikely that any meaningful conclusions would be reached based on data from this machine and its use for this purpose was abandoned.

3.3.2 Calibration of the positioning system

The positioning system was then calibrated using the Manager application on the Notebook computer. Calibration was performed using a plan of the site which had been imported into the Manager application. The plan was scaled by selecting two known points and entering the known real world distance to set the scale in terms of pixels per unit (metres or feet). "Tracking rails" were then drawn on to the plan to define the feasible paths within the area of interest. Calibration points were then recorded at intervals along these rails by indicating a location on the plan and rotating the device through a full circle to cancel out any directional effect of the mobile antenna. The manager records twenty samples of RSSI from each available access point.

For this project approximately sixty-six calibration points were recorded throughout the publicly accessible areas of the building as indicated in Figure 3-7

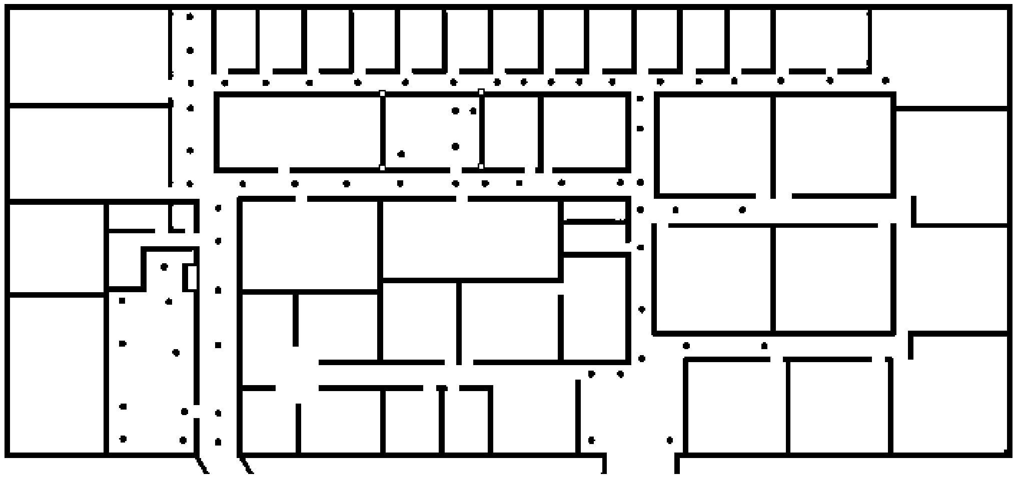


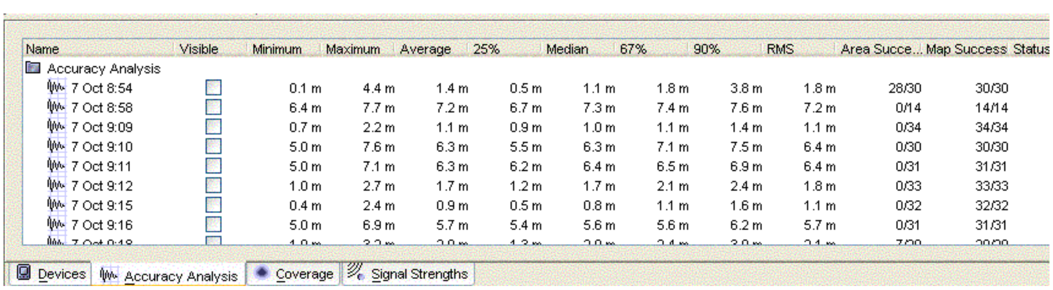
Figure 3-7 - Calibration Points

3.3.3 Testing

The Manager application's built in Accuracy Analysis function was used with this calibrated model to record a total of 2667 points for subsequent analysis.

Points were recorded by clicking the current location on the on-screen plan then moving at a steady rate along a straight line and clicking further waypoints or an endpoint. True locations are interpolated between the indicated points assuming a steady rate of travel. RSSI vectors are recorded at regular intervals between the indicated points.

For each calibration run the manager application displays selected summary statistics for the accuracy achieved (Figure 3-8) and a graphical display of the error at each point (Figure 2-1).



Name	Visible	Minimum	Maximum	Average	25%	Median	67%	90%	RMS	Area Succe...	Map Success	Status
Accuracy Analysis												
7 Oct 8:54	☐	0.1 m	4.4 m	1.4 m	0.5 m	1.1 m	1.8 m	3.8 m	1.8 m	28/30	30/30	
7 Oct 8:58	☐	6.4 m	7.7 m	7.2 m	6.7 m	7.3 m	7.4 m	7.6 m	7.2 m	0/14	14/14	
7 Oct 9:09	☐	0.7 m	2.2 m	1.1 m	0.9 m	1.0 m	1.1 m	1.4 m	1.1 m	0/34	34/34	
7 Oct 9:10	☐	5.0 m	7.6 m	6.3 m	5.5 m	6.3 m	7.1 m	7.5 m	6.4 m	0/30	30/30	
7 Oct 9:11	☐	5.0 m	7.1 m	6.3 m	6.2 m	6.4 m	6.5 m	6.9 m	6.4 m	0/31	31/31	
7 Oct 9:12	☐	1.0 m	2.7 m	1.7 m	1.2 m	1.7 m	2.1 m	2.4 m	1.8 m	0/33	33/33	
7 Oct 9:15	☐	0.4 m	2.4 m	0.9 m	0.5 m	0.8 m	1.1 m	1.6 m	1.1 m	0/32	32/32	
7 Oct 9:16	☐	5.0 m	6.9 m	5.7 m	5.4 m	5.6 m	5.6 m	6.2 m	5.7 m	0/31	31/31	

Figure 3-8 - Example Accuracy Summary

The graphical display shows each point with an arrow indicating the direction and magnitude of the error in predicting that point. The head of the arrow indicates the position that was estimated for the point.

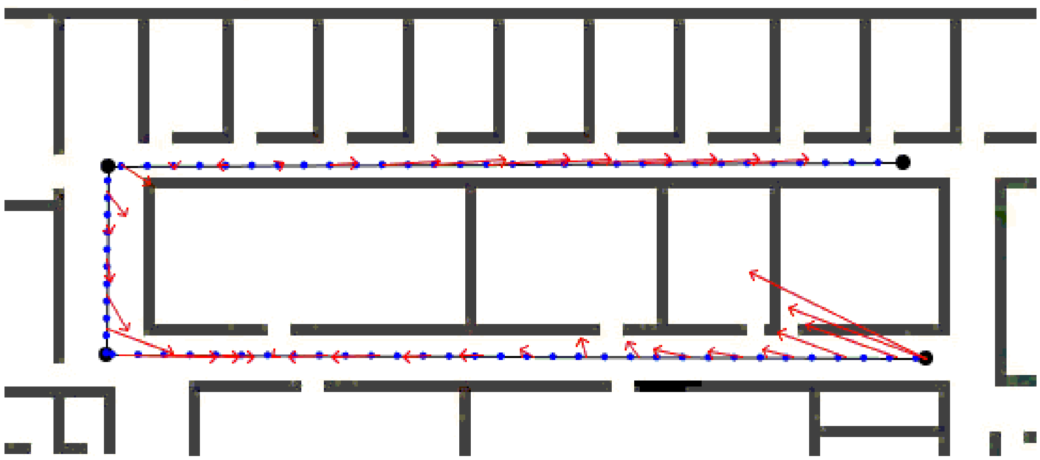


Figure 3-9 – Example Graphical Error Display

After recording this analysis with all available access points turned on it is possible to subsequently analyse the performance with different network layouts by selectively excluding one or more access points and then updating the accuracy analysis to show the location performance achieved with a subset of the full set of access points.

All of the data was recorded using the access point configuration shown in Figure 3-4. The data was collected using two different methods:

- Static Target
  This is data collected at one of several known locations over a period of approximately one minute for each session. A total of 1,624 separate observations were recorded during fifty three separate sessions. In each case, the session started and ended at the same location and comprised approximately thirty observations on the same fixed location.

- Mobile Target
  These sessions tracked a moving target travelling the same circuit in the hallways of the postgraduate and staff areas. Data was recorded in two separate sessions walking in opposite directions. The circuit is approximately fifty seven metres in length and

walking speed averaged 0.73 metres per second within a range of 0.49 – 0.97 mps. Observations are recorded at intervals of two seconds giving between thirty two and sixty observations for each session and a total of 1,043 observations.

Summaries of the Accuracy Analysis results are included in Appendix A. The detailed data was exported from the manger program to text files and imported into a spreadsheet for further analysis. Both sets of data were analysed for the full four access point configuration as shown in Figure 3-4 and for a configuration using only AP3, AP7 and AP11 with AP1 disabled. A sample of the detailed data is included in Appendix B.6.

3.4 Summary

After discussing the issues related to measuring RSSI, and some relevant software applications, this section described the implementation of a system to test the Bayesian methodology and the procedure used to collect data for further analysis. The results are described and analysed in Chapter 4.

4. Results and Discussion

This chapter contains an analysis of the data collected from the various tests undertaken and attempts to identify the configuration and environmental factors that affect the performance of the underlying method.

4.1 Measuring RSSI

Any system that uses signal strength to estimate location relies on the RSSI reading recorded by the wireless adaptor and the software used to read, display and record it. While the Ekahau manager software does display a dynamic bar chart of RSSI for all received access points, it does not have any facility to record the levels over time for external use. The Broadcom configuration utility provides a graphical display of RSSI and can log RSSI over time. NetStumbler displays signal strength in a bar chart form and store the data in memory. The stored data can be exported to a text file. The output from a sample of recorded signal with a single access point is shown in Figure 4-1. It should be noted that the Broadcom data is specified in dBm (primary y axis) units while NetStumbler uses arbitrary RSSI units (secondary y axis).

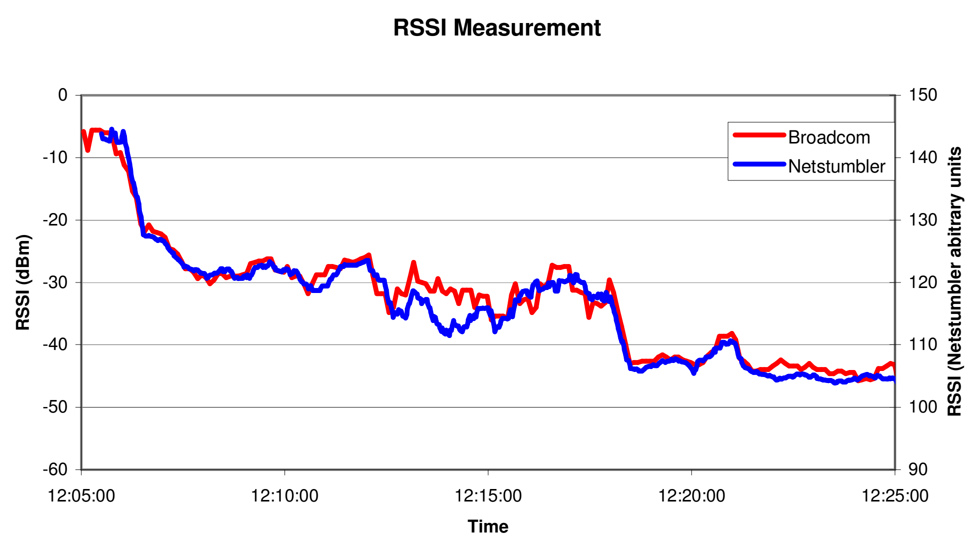


Figure 4-1 - RSSI recorded by Broadcom utility and NetStumbler

The data sets are smoothed using a moving average and the secondary y axis scaled to match the two plots. While the point data of the two series show some quite wide variation, the smoothed data is comparable and indicates the scale units are similar with a level of 100 on the NetStumbler scale equating to –50 dBm as indicated by the Broadcom utility.

The variation in the reading of these two utilities of RSSI readings of the same signals from the same wireless card illustrates just one of the potential problems in obtaining accurate location prediction using these methods.

4.2 RSSI as an indicator of distance

In order to evaluate the relationship between distance and RSSI, some simple tests were conducted with the equipment used for the main study. The Belkin access point was set up in open space at a height of 600 mm. above the ground and signal strengths recorded at various measured distances using the notebook computer positioned at a similar height. Signal levels were recorded concurrently using both NetStumbler and the logging feature of the Broadcom configuration utility. The data recorded by NetStumbler is displayed as a scatter plot in Figure 4-2.

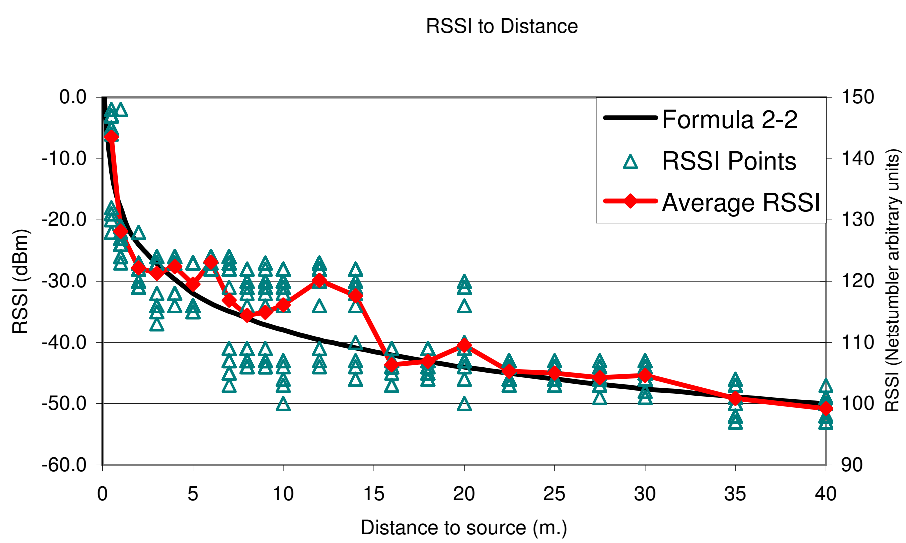


Figure 4-2 - Test of free space path loss

The plotted line in this chart is the predicted signal level using the free space path loss formula (2-2) and an arbitrary transmitted power level of +22 dBm. Signals were recorded for approximately one minute at each distance giving approximately forty samples at each location. The number of data points at each distance is not obvious because many may occupy the same position on the chart.

It can be seen that although there is a clear relationship between RSSI and distance, there is quite a large spread in the signal levels recorded at any one distance and the plot of mean levels displays significant deviations from the expected curve.

4.3 Location accuracy.

The key performance properties of a location system are *accuracy* and *precision* as outlined in Par. 2.1. Accuracy refers to the granularity of the measurement, while precision is a measure of how often we expect to achieve a defined level of accuracy. The two are closely related and should be considered together. The accuracy requirements of a location aware application can be expressed in these terms. For example a particular application may require an accuracy of 1 metre with a precision of 95 percent, meaning that positions within 1 metre of the true position are required 95 percent of the time.

Data collected from a proposed location system operating under a given set of conditions can be analysed to calculate these properties which can then be directly compared with the stated requirements of the application. The result can best be summarised in a table showing the cumulative percentage of estimated locations that are within a given distance from the true location. The result is commonly displayed in the form of a chart.

The detailed data which had been recorded was imported into an Excel worksheet and cumulative summary information extracted using the Histogram function in the Analysis Toolpak. The cumulative data was then displayed in a chart. This form of presentation has been adopted in several other studies including the developers of RADAR (Bahl et al. 2000; Bahl and Padmanabhan 2000b; 2000a) and the work at Rice University (Ladd et al. 2002; Tao et al. 2003; Ladd et al. 2004). The data for both the static and mobile data using the final configuration of 4 access points as shown in Figure 3-4 is displayed in Figure 4-3..

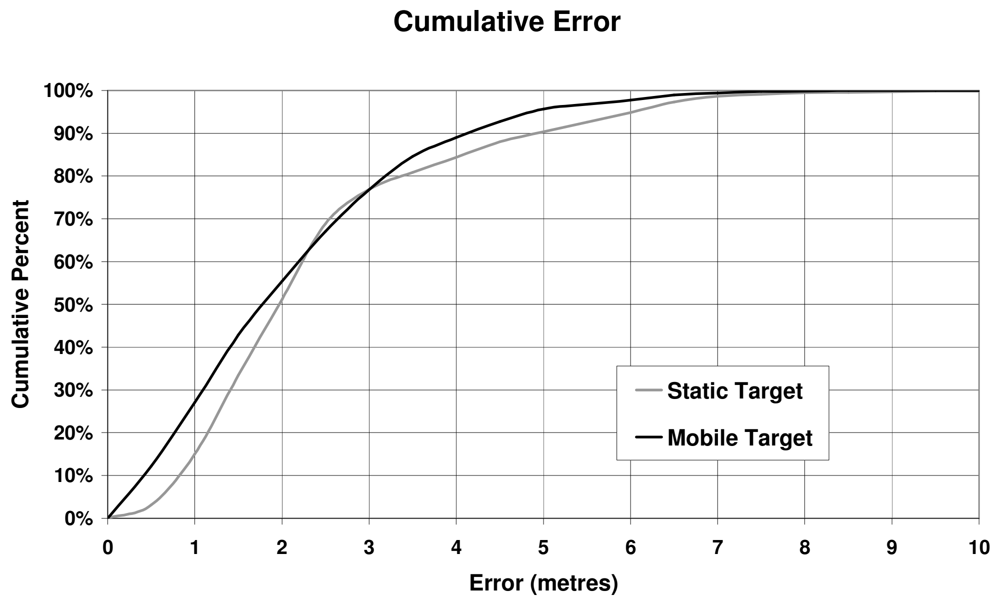


Figure 4-3 – Overall error chart for initial 4 access point configuration

It can readily be seen from this chart that, for example, approximately seventy seven percent of all estimated locations are within three metres of the true location. When tracking a mobile device, the error is less than five metres for ninety five percent of all observations. Interestingly only ninety percent of the observations of static targets are within five metres and the accuracy/precision in locating static targets is generally not as good as when tracking a moving target.

This initial assessment shows that this technique can provide potentially useful location information. However in many respects it raises more questions than it answers. These include question such as:

- What are the factors that limit the accuracy / precision of the estimates?
- Why is the accuracy / precision better when tracking a mobile target than simply locating a static one?

Some further analysis of the data was undertaken to try to find answers to some of these questions.

4.3.1 RSSI and distance

The known properties of radio frequency propagation allow the propagation loss in free space to be calculated. However propagation characteristics inside buildings are more complex. The walls and other structural element of the building, people and other objects all cause changes to the propagation of radio signal.

In order to further investigate the propagation characteristics of test environment, several samples of RSSI readings were collected. These were recorded using the logging function of the Broadcom Wireless Configuration Utility on the notebook computer. Several log files were recorded concurrently with the accuracy testing of the location system. These RSSI readings were then correlated by time in an Excel worksheet with the corresponding information exported from the accuracy analysis function in the Ekahau manager. Approximately 400 RSSI readings from the mobile tracking tests were matched up with the actual locations and plotted against the calculated distance to the relevant AP. The scatter plot is shown in shown in Figure 4-4.

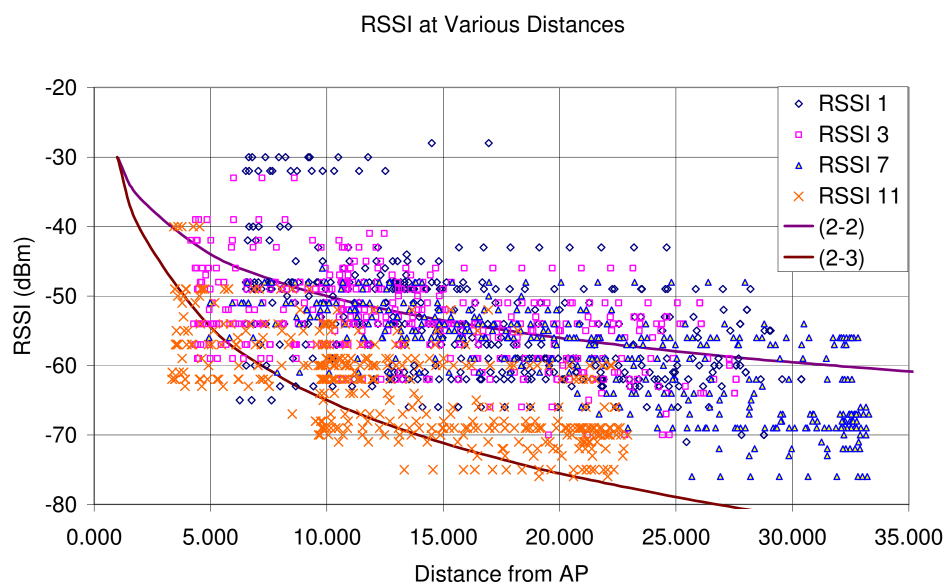


Figure 4-4 - Scatter plot of RSSI against distance to the AP.

The curve 2-2 represents a theoretical signal strength based on the free space path loss formula discussed in Par. 3.1 using an assumed transmitter output of +20dBm

(100 mw). The curve 2-3 represents the modified formula proposed as an approximation of the theoretical loss inside buildings.

A number of conclusions can be drawn from Figure 4-4:

- There is a loose correlation between RSSI and distance to the transmitting AP but only within a broad band. Even for a single access point, the spread of recorded levels is generally wider than that recorded in the open (Figure 4-2). This is most likely a result of the effect of variation of attenuation caused by walls and other obstructions.

- This majority of plotted points conform roughly with the theoretical formulas with the upper limit generally at about the free path loss;

- The alternative formula (3-3) is a reasonable representation of the lower bound of the collected data and

- AP11 generally recorded a pattern of points clearly below the other units in RSSI at any given distance. As this access point was an identical model to AP3 and AP7 it seems likely that this difference is due to higher attenuation of intervening walls. No testing was undertaken to determine if this was so.

4.3.2 Number and spacing of access points

An obvious factor that would be expected to affect the operation of a location system is the density and location of the access points that are available to provide RSSI information. While the opportunity to change the location of the access points was limited it was possible to do some testing of this factor. In particular the location of AP1 was chosen so that it gave additional coverage of one end of the site but the area was reasonably well covered without it. The recorded test data for both the static and mobile tests were retested without AP1 in order to judge how much it contributed to the result.

This was done using the same collected information but by regenerating the position analysis with AP1 disabled. Therefore the recorded signal information from the other three access points is identical to that used in the original analysis and is not subject to any change in environmental conditions. In fact the result when tracking the mobile client was almost identical so the overall accuracy was not affected by the presence or absence of the additional access point. On the other hand, the accuracy for location of a static target was affected as can be seen in Figure 4-5.

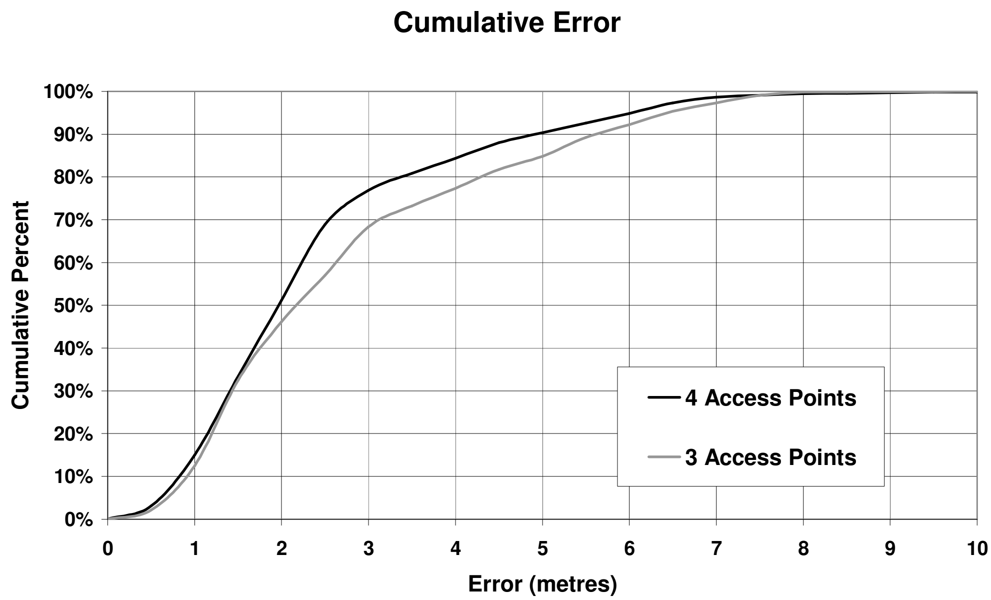


Figure 4-5 - Effect of removing one access point when locating a static target.

There is a reduction in accuracy of about 1 metre around the eighty percent precision level and a reduction of almost ten percent in the precision at an accuracy of three metres.

4.3.3 Zones of effectiveness.

Because AP1 is located at one end of the target area, it would be expected to have the most effect in that section. Also given the location of the other access points there would be expected to be better signal information in the centre of the target area where all access points are within reasonable distance. This can be seen on the signal strength map (Figure 4-6) which depicts the signal strength pattern for the third strongest signal at any location. This map was chosen because it is necessary to have signals from at least three non co-linear stations to derive an unambiguous signal pattern.

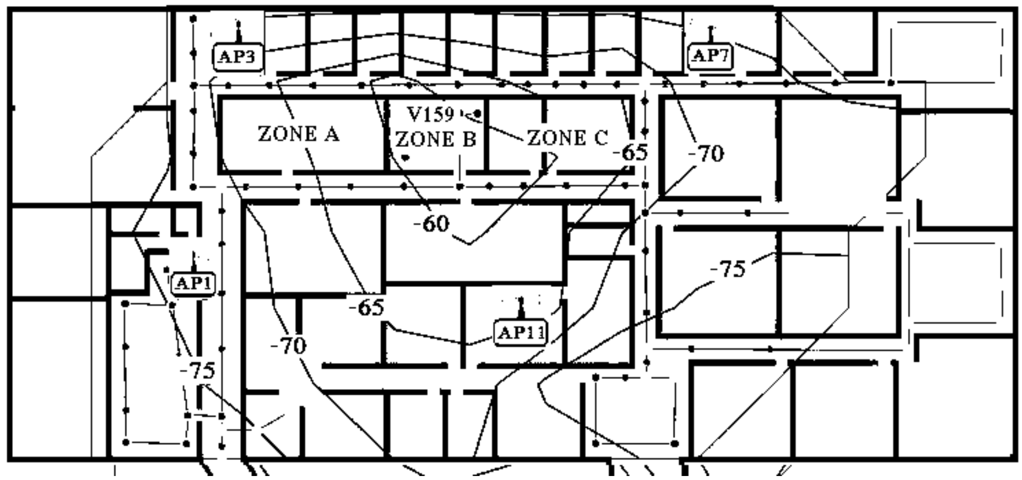


Figure 4-6 - Plan of signal strength zones.

The signal strength plan clearly shows an area of superior coverage (minimum -60 dBm) in the centre of the target area with the signal pattern tapering off at both ends as one of the access points becomes more distant. To further investigate the effect of access point placement, the target area was arbitrarily divided into three signal strength zones as follows:

- Zone A is the area west of room V159 and is bounded by a line approximating the -60 dBm signal contour. This area would be expected to be most affected by the presence of AP1.

- Zone B is room V159 and the adjacent hallways and approximates the area with greater than -60 dBm RSSI.

- Zone C is the area east of Zone B.

For simplicity, the zone boundaries were created as straight lines running north south (vertically on the plan) so the data could be partitioned using the X co-ordinate of the true location of each point. The data for each zone was then analysed separately.

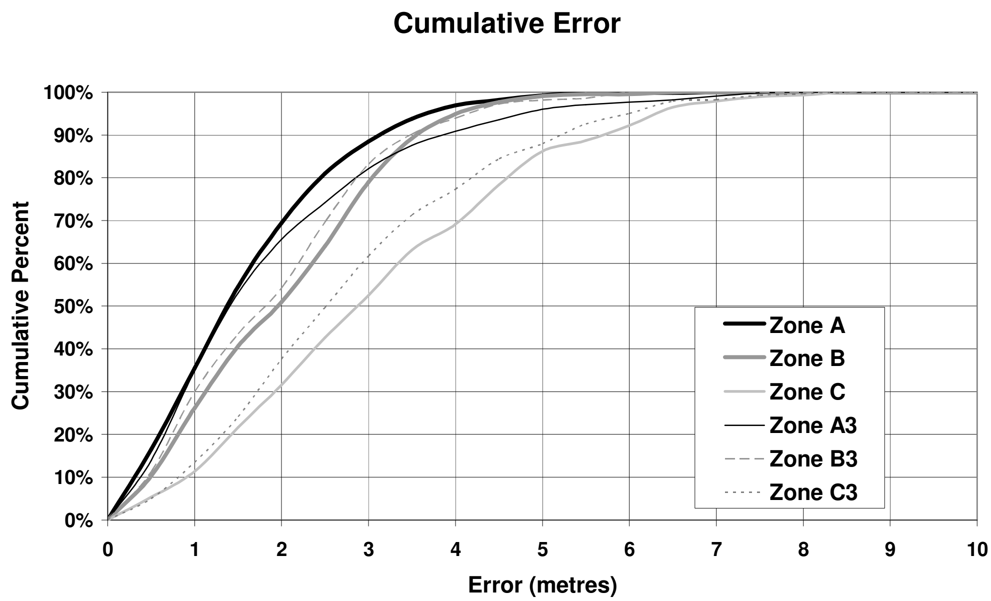


Figure 4-7 - Zone performance for mobile target

The zoned cumulative error chart for tracking of a mobile device (Figure 4-7) shows the performance in each of the three defined zones compared with the overall performance.

The performance in zone A shows a significant improvement compared to the overall result. This probably reflects the influence of the presence of access point 1 which ensures that most points in this area have reliable signals of reasonable strength from at least three well dispersed sources. Performance in zone B is closer to the overall result but still exhibits better performance at the higher end of the curve.

As would be expected the performance in zone C is considerably less accurate and this is clearly having a detrimental effect on the overall result. This may reflect the fact that access points one and seven are quite distant and access points seven and eleven are close to being co-linear at this end of the area and so do not provide much differentiation between locations.

The static location data was also partitioned into the zones defined above. The performance for each of the zones is shown in Figure 2-1.

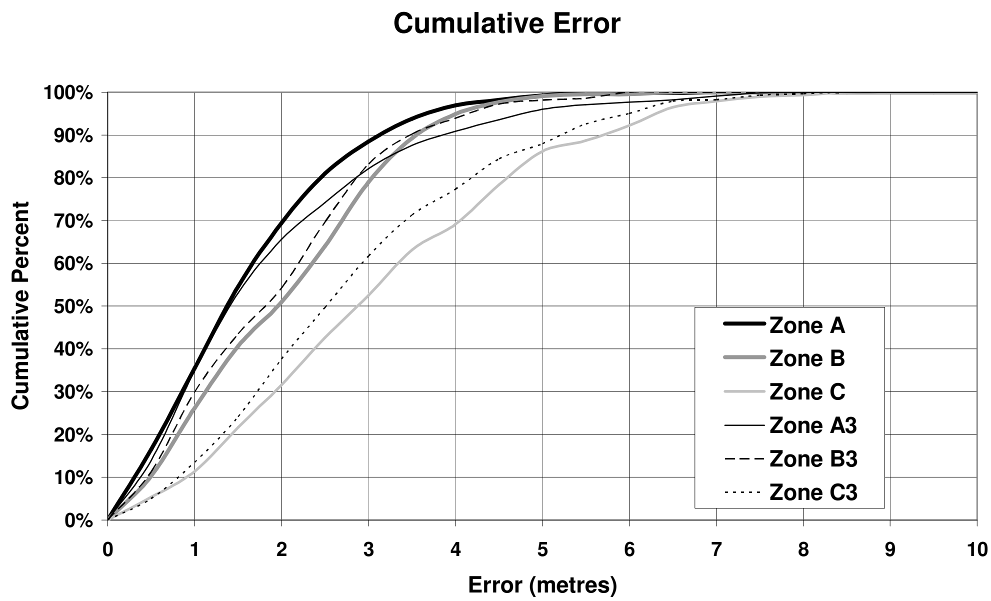


Figure 4-8 - Zone performance for static targets

In Zone A the performance was almost identical to the overall result with all 4 access points active, but removal of the fourth access point had a significant impact. In Zone B, the performance was considerably better than the overall performance, with locations within 2.5 m. above 90% of cases. The impact of removing the fourth access point was noticeable, but had only a marginal effect on the performance curve. In Zone C the performance is again much worse and surprisingly having AP1 active resulted in a slight decline in performance.

4.3.4 Time to Converge

It is perhaps also worthy of note that the visual error display for many of these sessions exhibit large errors on the first few points recorded. This is illustrated in the Figure 4-9 which shows the errors typically found on the first few point on a session.

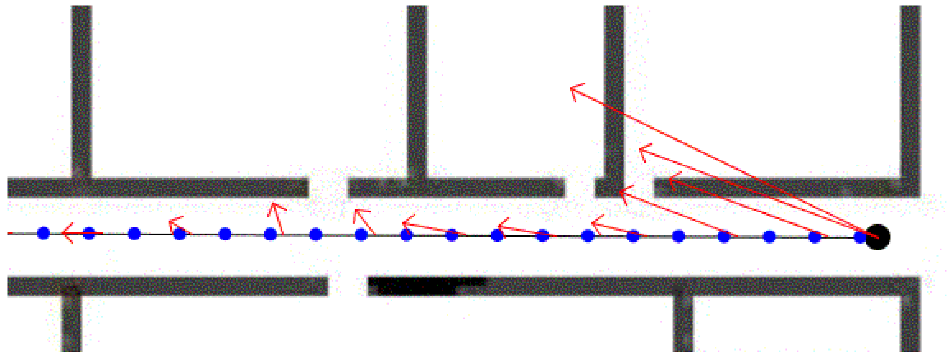


Figure 4-9 - Typical error display for initial points in a mobile scan

It is not clear whether in fact this results from the poor coverage in this area or from a delay in convergence at the start of a session. Certainly the recorded performance is significantly improved if the first five points in each session are omitted from the analysis (Figure 4-10). But as the first points were always at the extreme end of the zone, it seems likely that what is seen is just the fall of in accuracy at the worst end of the worst zone most distant from two APs

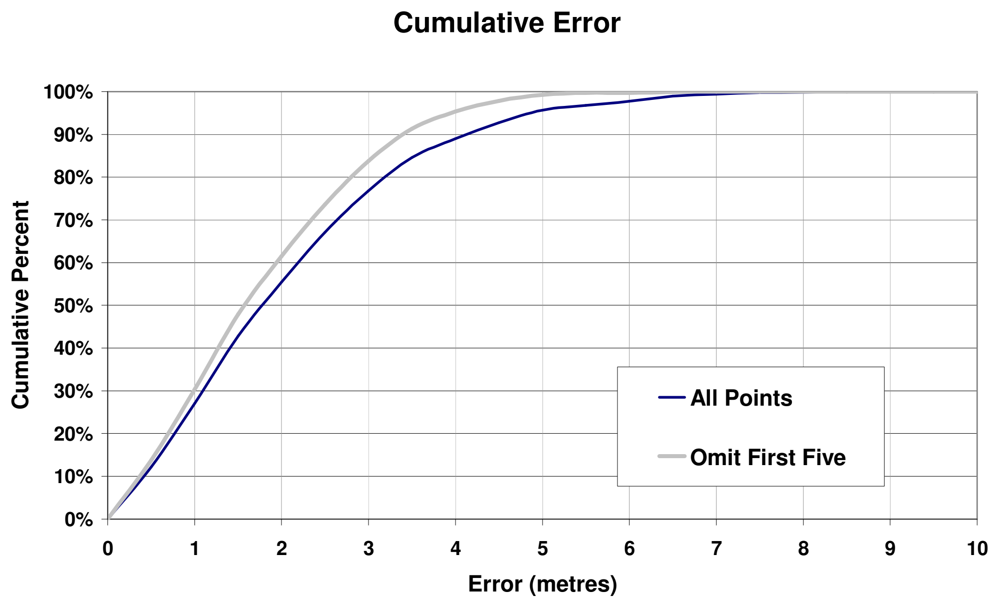


Figure 4-10 - Effect of dropping first five points

Dropping the first five estimates is equivalent to a delay of approximately ten seconds in obtaining a valid location. This would not generally be noticed in the case of a visual display of located objects but requires specific consideration if the location is being used by an application. Of course in a production system, location tracking would be continuous and this delay would only be a consideration when a tracked device is first located. This short delay in converging at the start of tracking a mobile device gives rise to the question of the time taken to converge on a static location.

4.3.5 Convergence on a fixed point

All the test data for static locations was recorded by occupying a position and immediately commencing the recording of data which generally continued for a period of one minute. The graphical display for some sessions indicated this possibility (see for example Figure 4-11). By plotting the exported data from this sample, we can see the pattern of convergence on the point (Figure 4-12)

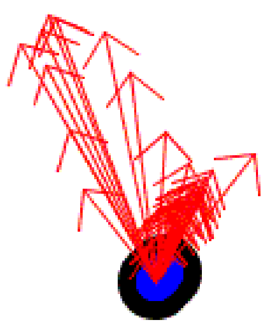


Figure 4-11 - Errors on a static location

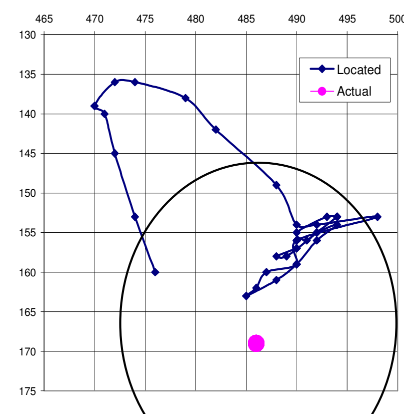


Figure 4-12 - Convergence Pattern

While a pattern of convergence on a fixed location similar to that shown above can be observed in some cases, a closer examination of the data shows that this is not necessarily representative of the general case. By averaging the errors for each sequential location across all the sequences for static locations we can see that the pattern of convergence on fixed locations is much less pronounced than shown in the case shown above.

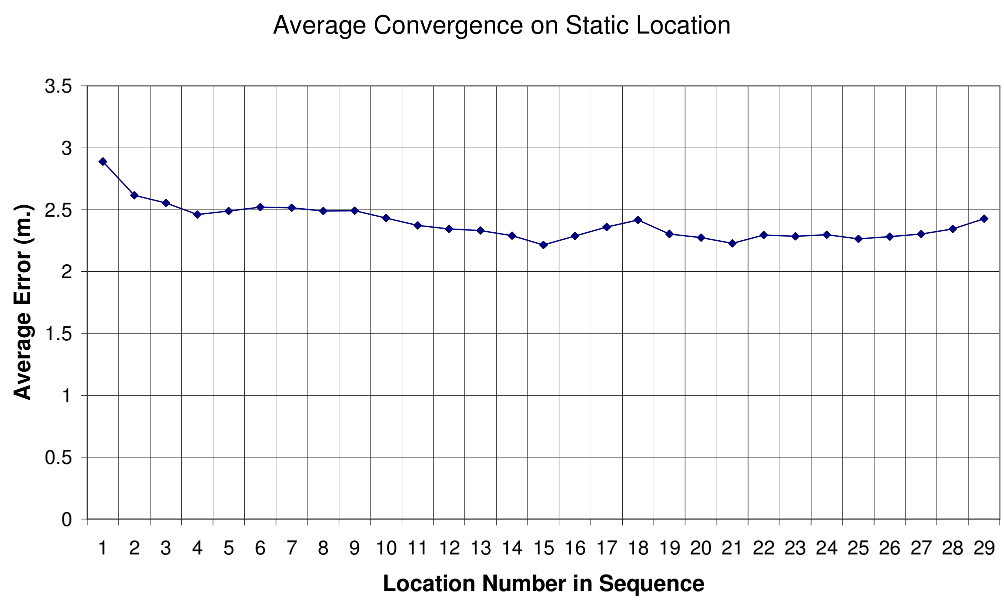


Figure 4-13 - Average pattern of convergence on fixed locations

4.3.6 Drift in location estimate over time

An examination of the error displays for tests on a given point on different days or at different times, shows that the mean indicated location changes over time. This can be clearly seen in the series of error displays shown in Figure 4-14 which were all recorded at the same true location and under the same conditions but at different times.

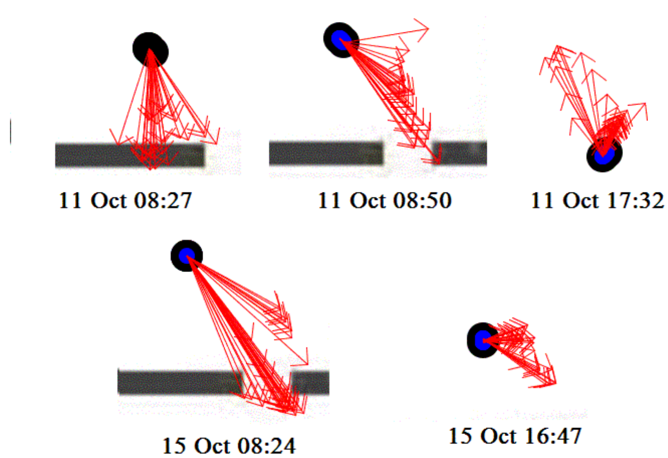


Figure 4-14 - Drift in indicated location at different times

It can be seen that in each of these cases the predicted locations are clustered around some point within about 2 m. of the true location. However the direction and offset to the midpoint of the predicted locations is different on each occasion. This is further illustrated in Figure 4-15 which shows the predicted location over a one minute period. The average of the predicted locations is approximately 2.2 metres from the true location and all the points are in the same general direction.

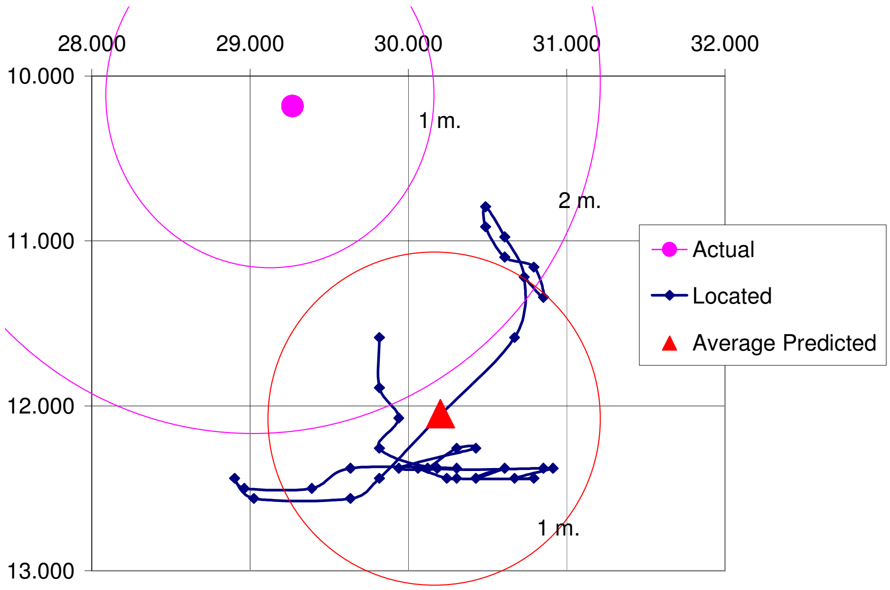


Figure 4-15 - Pattern of predicted locations at 15 Oct 8:24

It could be postulated that this “drift” in indicated location is either an artefact of the location algorithm or it is caused by some change in the signal propagation environment. An examination of the RSSI levels recorded during this time period revealed that the signal from AP7 fluctuated significantly but all the other three APs remained constant within a small range. It is also clear from Figure 4-15that variation in the indicated location is primarily in an axis aligned to the position of AP7. The distance from the indicated location to AP7 over the period was plotted against the corresponding RSSI (Figure 4-16). This makes it possible to relate the change in RSSI to the change in location.

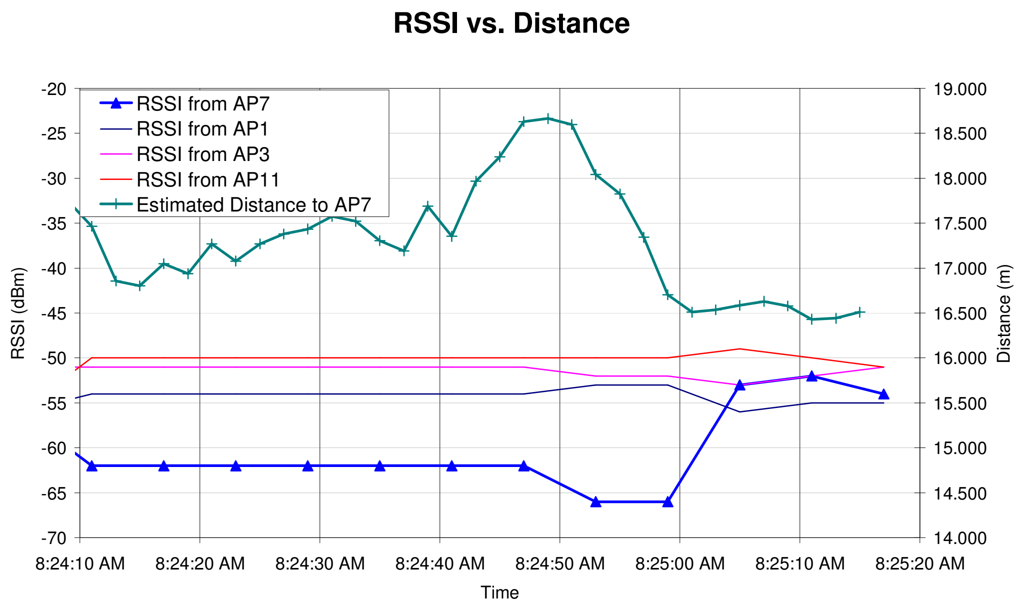


Figure 4-16 - Correlation of estimated distance with RSSI

The predicted location (distance from AP7) initially fluctuates within a range of about 1 metre, but then an initial drop in RSSI corresponds a larger shift in the indicated position away from AP7. The subsequent increase in RSSI is associated with a move in the indicated location towards the AP7. While not conclusive, it does appear that this variation in indicated location is a result of changes in RSSI rather than an artefact of the location algorithm.

4.4 Other factors influencing accuracy

4.4.1 Target orientation

While most mobile devices would be expected to have omni directional antennae, their compact design is likely to result in some variable directional characteristics. The target laptop has a built in card with an internal antenna. To test if it varied from a true omni directional receiver, a number of observations were recorded with the target machine rotated through eight different directional orientations at each of four different distances from the transmitter. The recorded data is summarised in Table 4-1, which shows the average results in the arbitrary units reported by NetStumbler.

Table 4-1 - Directional signal data (NetStumbler arbitrary units)

Direction	5.00	10.00	15.00	20.00
0	118.08	107.55	123.00	105.38
45	118.00	108.50	108.93	102.23
90	103.00	104.50	105.28	100.50
135	119.30	109.45	112.86	101.92
180	118.45	106.40	103.92	103.75
225	117.20	102.67	105.00	111.50
270	104.25	105.64	104.31	103.56
315	118.77	100.73	105.86	101.56

As can be seen in the table and in the radar chart of this data (Figure 4-17) the inbuilt antenna appears to exhibit different characteristics at different distances. For example the five meter plot is symmetrical in the front to back direction but has almost 20 dB less gain at the sides. On the other hand, at fifteen metres there is a pronounced gain at the front.

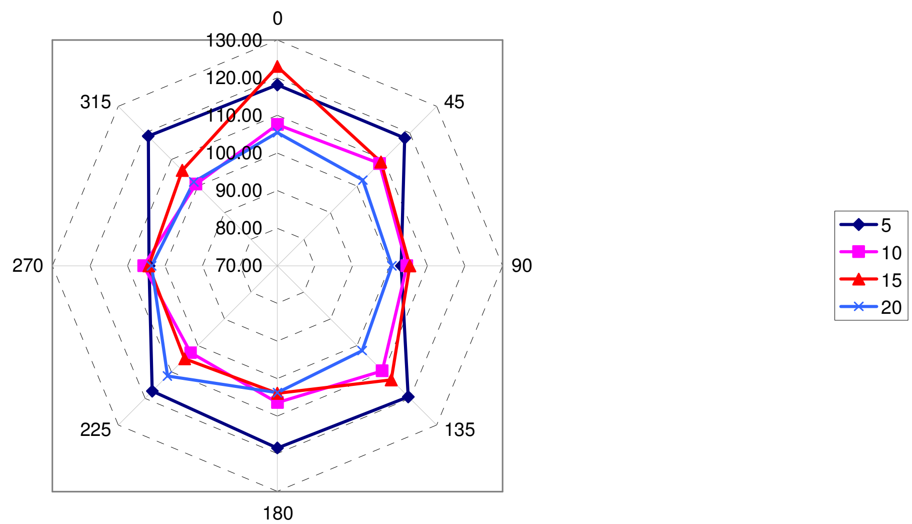


Figure 4-17 - Directional properties of notebook computer

Some of the other tests indicated significant random variations in RSSI over short periods. It is possible that some of the differences seen in this test are the result of such general fluctuations. It was not practical to investigate this further with the available equipment. Regardless of the source of this variation, it does further illustrate another source of uncertainty in the process of estimating locations from RSSI.

The possibility of directional effects is accounted for when calibrating a location model by rotating the target device through a full circle while recording each calibration point. However no attempt was made to take account of or cancel directional effects when testing the accuracy of the model. While the directional effect should be considered, it would not generally be practical to effectively eliminate them in a practical location application. Ideally target devices should, as far as possible, be omni-directional. However, that will often not be possible, especially if the device is hand held.

4.4.2 Effect of human bodies in the signal path

Another possible source of variation in the signal propagation is the movement of people within the signal path. To test for this effect, the notebook was set up at a distance of twenty metres from the access point and the RSSI monitored with a man positioned at various point along the signal path. Figure 4-18 shows the signal pattern over a period with a man in the signal path for short periods at different distances.

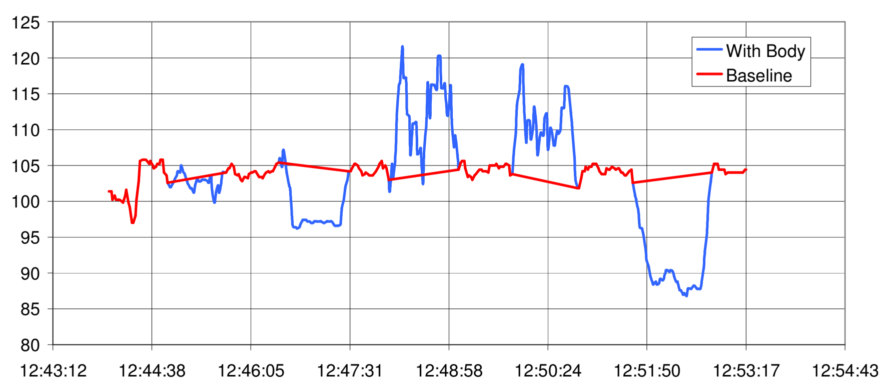


Figure 4-18 - Effect of a body in the signal path

No significant effect was observed with the person only one metre from the access point. Noticeable reductions of RSSI resulted when the body was five metres from the AP (-7.5 dB) and at 19 metres from the AP or 1 metre from the target (-15 dB). Interestingly, with a body in the direct path at ten and fifteen metres, an increase in RSSI was observed. While this strange pattern is unexplained, it is clear that the presence of human bodies in the signal path can have significant effects on the propagation environment. Because many tracking targets are likely to be handheld devices, this is likely to have a significant impact in many installations

4.4.3 Intrusion detection

The Ekahau Positioning System, in its current form, can only track targets that have its client program installed it is only suitable for tracking "willing" targets. This makes it unsuitable for use in tracking intruders in wireless networks. However there seems to be no reason why the underlying algorithm would not be suitable if a method was devised to detect and forward the relevant RSSI data. Suitably equipped access points or dedicated "sniffer" devices could be configured to monitor the communication channels for appropriate control packets from mobile devices. The RSSI information would then be passed to the server which would assemble the data and pass it to the location algorithm.

4.5 Summary

This chapter began by examining the problems of measuring RSSI using standard wireless network cards. Some simple tests were conducted to verify the relationship between RSSI and distance. The tests undertaken demonstrated that systems using the Bayesian machine learning approach can generate useable location estimates from inherently noisy RSSI data. The effect of some changes in configuration and various environmental factors on the system were also evaluated.

5. Conclusions and Further Work

There is a growing interest in location aware applications and location systems can be based on several technologies. Most of the available technologies require the installation of specialised hardware. Location systems based on the strength of the WLAN signal have the distinct advantage that they can be implemented using the existing hardware infrastructure of a wireless network.

The wireless propagation environment inside a typical building is non-uniform because of the variable attenuation of signals passing through walls and other elements of the building, changing environmental conditions and the movement of people in the signal path. This makes it difficult to directly infer distances by engineering calculations from measured signal strength. The measurements of RSSI by typical wireless cards may also lack the precision to support accurate calculations.

In an attempt to overcome the level of uncertainty inherent in RSSI measurements because of these factors, researchers have turned to machine learning techniques such as Bayesian filters to infer locations by searching for patterns of RSSI information. This approach was tested in the environment of the School of Computing by conducting a series of experiments using the implementation of the method in the Ekahau Positioning System.

It was found that, despite these difficulties, a location system based on the Bayesian technique can provide location estimates with a useful level of accuracy. Over a series of trials, the system achieved an average accuracy within two metres while tracking a mobile target or locating a static device. Estimated locations for the mobile target were within four metres for ninety percent of the observations. Ninety percent of static locations were within five metres. This overall level of accuracy is comparable with some of the previous studies based on similar systems in other locations.

The level of accuracy required of a location system depends on the application for which the location is required. This level of accuracy would be useful for locating personnel or equipment and many other applications, but to quote Jim Geier "… you certainly wouldn't want to use the system for positioning robots drilling holes into parts with this level of accuracy …"(Geier 2002).

A comparison of overall performance with only three access points enabled resulted in an increase of the error at ninety percent precision to five and a half metres for the static targets but little change for the mobile target.

The target area was partitioned into three zones in an attempt to identify factors that might provide a more accurate result. It was found that the best performance for tracking a mobile target was achieved in zone A where and average error of 1.4 metres was achieved and ninety percent of predicted locations were within three metres with all APs active. When AP1 was excluded, the average error was unchanged but the error rate increased to almost four metres at ninety percent precision.

The performance on tracking a static device was best in zone B which was the central area that had best signal coverage from all access points. With four access points active, the average error was about one and a half metres and ninety percent of locations were within two and a half metres. Excluding AP1 increased the error rate only slightly at the higher precision level. Interestingly, the performance in zone A was considerably lower with all APs active and declined significantly when AP1 was excluded.

While these results do not provide a recipe for higher performance they do suggest that better performance can be achieved by better placement of the access points. The improved performance in zone B and the significant effect of AP1 in zone A suggest that overall performance would be enhanced if access points were placed to ensure that all locations in the area received a signal level of at least -65 dBm from at least three non co-linear sources.

It was noted that repeated samples on fixed locations resulted in different predicted locations on different occasion. This suggested that in addition to the usually small short term variation in location there was a larger "drift" in the estimated location over time. It was intended to test whether two adjacent targets experienced the same direction and magnitude in this drift. However due to problems with equipment this was not possible and was eventually abandoned. If it was found that there was a general drift in the predicted location in a given area it may be possible to locate a fixed target in a sensitive area and use its data to estimate the drift in the estimated location. This estimated drift could then be used to compensate for the drift when predicting the location of tracked targets. This could possibly be achieved by adjusting the parameters of the model, scaling the RSSI vectors or adjusting the predicted location in the location aware client application.

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Appendix A – Data Files

A.1 Description of workbook Two Clients 23 Sept.xls

Name	**Description**
NetStumbler Data	Data exported by NetStumbler
Pivot Table	Summarised Data
Chart	Excel chart used for Figure 3-5 and Figure 3-6
Comparison Table	Figure 3-1 - Estimated Indoor Free Path Loss

A.2 Description of workbook RSSI Tests.xls

Name	Description
Distance	Time log for distance test
Direction	Time log for signal direction test
Body	Time log for test of body attenuation
Ns1 Nov	NetStumbler data export
RSSI 1 Nov	RSSI log from Broadcom utility
Chart	RSSI vectors from Date 15 Oct
Mobile4P	Correlated data for mobile scan with 4 APs
Static4AP	Correlated data for static scan with 4 APs
Sig Comp	Figure 4-1 - RSSI recorded by Broadcom utility and
Body Effect	Figure 3-5 - Sample of RSSI Reported by Belkin Card
RSSI v Dist	Figure 4-2 - Test of free space path loss
Direction PT	Pivot Table used as Table 4-1
Direction Chart	Figure 4-17 - Directional properties of notebook computer
Params	Sundry constants etc.

A.3 Description of workbook RSSI Analysis.xls

Name	Description
Data 1 Oct	Signal strength data collected 1 Oct
RSSI 1 Oct	RSSI vectors from Date 1 Oct
Data 7 Oct	Signal strength data collected 7 Oct
RSSI 7 Oct	RSSI vectors from Date 7 Oct
Data 15 Oct	Signal strength data collected 15 Oct
RSSI 15 Oct	RSSI vectors from Date 15 Oct
Mobile4P	Correlated data for mobile scan with 4 APs
Static4AP	Correlated data for static scan with 4 APs
Mobile Chart	Figure 4-4 - Scatter plot of RSSI against distance to the AP.

A.4 Description of workbook 11 Oct 1732.xls

Name	Description
11 Oct 1732	Data exported form Ekahau
Chart 4	Figure 4-12 - Convergence Pattern

A.5 Description of workbook Static Convergance.xls

Name	Description
Converg Rate	Pivot table (based on detail.xls)
Conv Chart	Figure 4-13 - Average pattern of convergence on fixed locations

A.6 Description of workbook 15 Oct 08242.xls

Name	Description
Data	Data table (based on data exported from Ekahau)
Chart 4	Figure 4-15 - Pattern of predicted locations at 15 Oct 8:24
RSSI Table	RSSI vectors
RSSI Chart	Figure 4-16 - Correlation of estimated distance with RSSI
Chart2	Not used

Appendix B Accuracy Analysis Data

Predicted locations were recorded for both static location and tracking a mobile client and each was analysed for configurations using three access points and with the addition of a fourth access point. This appendix contains summary information captured from the Accuracy Analysis function in the Ekahau Manager for each data set, a sample of the exported detail data and a description of the Excel Workbook containing the full data

B.1 Description of workbook detail.xls

Name	Description
Mobile3AP	Detail data for mobile targets with 3 active APs
Mobile4AP	Detail data for mobile targets with 4 active APs
Static3AP	Detail data for static targets with 3 active APs
Static4AP	Detail data for static targets with 4 active APs
Mobile Sum	Cumulative error summary for mobile data
Static Sum	Cumulative error summary for static data
Converge Sum	Cumulative error summary for convergence
Initial Chart	Figure 4-3
3 vs. 4 AP	Figure 4-5
Mobile Zones	Figure 4-7
Static Zone	Figure 4-8 - Zone performance for static targets
Mobile -5	Figure 4-10 - Effect of dropping first five points
Params	Misc constants etc.

B.2 Summary of static data with three access points

Name	Min.	Max.	Mean	25%	Median	67%	90%	RMS	Area	Map
7/10/2004 8:54	0.1	4.4	1.4	0.5	1.1	1.8	3.8	1.8	28/30	30/30
7/10/2004 8:58	6.4	7.7	7.2	6.7	7.3	7.4	7.6	7.2	0/14	14/14
7/10/2004 9:09	0.7	2.2	1.1	0.9	1.0	1.1	1.4	1.1	0/34	34/34
7/10/2004 9:10	5.0	7.6	6.3	5.5	6.3	7.1	7.5	6.4	0/30	30/30
7/10/2004 9:11	5.0	7.1	6.3	6.2	6.4	6.5	6.9	6.4	0/31	31/31
7/10/2004 9:12	1.0	2.7	1.7	1.2	1.7	2.1	2.4	1.8	0/33	33/33
7/10/2004 9:15	0.4	2.4	0.9	0.5	0.8	1.1	1.6	1.1	0/32	32/32
7/10/2004 9:16	5.0	6.9	5.7	5.4	5.6	5.6	6.2	5.7	0/31	31/31
7/10/2004 9:18	1.0	3.2	2.0	1.3	2.0	2.4	3.0	2.1	7/29	29/29
7/10/2004 9:20	0.5	3.2	1.4	1.1	1.4	1.5	1.8	1.5	30/30	30/30
7/10/2004 9:23	0.5	1.4	0.8	0.5	0.8	0.9	1.1	0.8	31/31	31/31
7/10/2004 16:32	4.0	9.6	5.6	4.5	5.2	5.9	7.4	5.7	0/30	30/30
7/10/2004 16:36	2.4	3.5	2.7	2.5	2.6	2.8	3.4	2.8	0/29	29/29
7/10/2004 16:41	0.9	3.4	1.4	1.1	1.4	1.5	1.8	1.5	0/30	30/30
7/10/2004 16:42	1.8	3.7	2.7	2.1	2.7	3.1	3.6	2.8	0/30	30/30
7/10/2004 16:52	3.6	5.5	4.6	4.4	4.4	4.7	5.2	4.6	2/29	29/29
7/10/2004 16:54	1.0	1.5	1.2	1.1	1.2	1.2	1.3	1.2	29/29	29/29
11/10/2004 8:15	0.4	3.7	1.9	0.9	2.0	2.5	3.1	2.1	0/28	28/28
11/10/2004 8:19	1.0	3.0	2.1	1.7	2.1	2.6	3.0	2.2	0/30	30/30
11/10/2004 8:23	1.3	2.3	1.5	1.4	1.4	1.5	1.8	1.6	0/31	31/31
11/10/2004 8:24	2.0	3.9	2.6	2.3	2.5	2.7	2.9	2.6	0/30	30/30
11/10/2004 8:26	0.7	2.0	1.4	1.2	1.6	1.7	1.8	1.5	0/29	29/29
11/10/2004 8:27	0.9	1.8	1.5	1.4	1.5	1.6	1.8	1.5	28/28	28/28
11/10/2004 8:33	3.3	7.4	5.4	4.6	5.6	5.9	6.6	5.5	0/29	29/29
11/10/2004 8:36	2.8	6.1	3.6	3.0	3.3	3.5	5.1	3.7	0/29	29/29
11/10/2004 8:46	2.3	4.3	3.4	2.6	3.5	3.8	4.2	3.4	0/29	29/29
11/10/2004 8:47	3.3	5.0	4.0	3.7	4.0	4.1	4.6	4.0	0/32	32/32
11/10/2004 8:48	0.6	1.7	1.0	0.8	0.8	1.0	1.4	1.0	0/31	31/31
11/10/2004 8:50	1.0	2.4	1.5	1.2	1.4	1.8	2.1	1.6	27/29	29/29
11/10/2004 17:22	1.5	4.0	2.3	1.8	2.2	2.4	3.7	2.4	0/30	30/30
11/10/2004 17:25	1.3	5.4	4.0	2.8	4.8	5.0	5.3	4.2	0/30	30/30
11/10/2004 17:28	1.7	3.1	2.4	2.3	2.5	2.5	2.8	2.5	0/30	30/30
11/10/2004 17:29	2.4	3.1	2.6	2.5	2.7	2.7	2.8	2.6	0/28	28/28
11/10/2004 17:30	1.1	2.4	1.5	1.2	1.5	1.7	1.8	1.5	0/29	29/29
11/10/2004 17:32	0.7	3.1	1.7	1.2	1.5	2.0	2.9	1.9	36/36	36/36
12/10/2004 12:59	2.7	4.7	3.7	3.2	3.8	3.9	4.5	3.7	0/30	30/30
12/10/2004 13:02	1.5	2.4	1.9	1.7	1.9	2.1	2.2	1.9	0/31	31/31
12/10/2004 13:05	0.7	1.9	1.4	1.1	1.4	1.5	1.8	1.4	0/30	30/30
12/10/2004 13:07	1.1	2.4	1.8	1.6	1.8	1.9	2.2	1.8	0/30	30/30
12/10/2004 13:08	0.5	2.4	1.2	0.6	1.1	1.1	2.1	1.3	0/30	30/30
12/10/2004 13:10	1.8	3.5	2.5	2.3	2.5	2.6	3.0	2.5	4/30	30/30
15/10/2004 8:16	1.2	4.8	3.1	2.1	3.4	3.8	4.3	3.3	0/37	37/37
15/10/2004 8:19	1.3	6.5	2.2	1.6	1.7	1.8	3.6	2.6	0/31	31/31
15/10/2004 8:21	2.0	7.3	5.8	5.3	6.5	6.7	7.2	6.0	0/33	33/33
15/10/2004 8:23	0.6	2.5	1.3	0.8	0.9	1.4	2.4	1.4	0/30	30/30
15/10/2004 8:24	1.6	3.0	2.5	2.1	2.6	2.8	2.9	2.5	13/37	37/37
15/10/2004 8:29	0.4	4.8	2.6	2.2	2.3	2.6	3.7	2.8	4/52	52/52
15/10/2004 16:37	1.2	3.7	2.5	1.8	2.4	3.1	3.5	2.6	0/32	32/32
15/10/2004 16:41	0.5	3.2	2.0	1.6	1.9	2.5	3.1	2.2	0/29	29/29
15/10/2004 16:44	4.3	6.7	5.7	5.2	5.6	6.1	6.5	5.7	0/33	33/33
15/10/2004 16:45	4.1	5.3	4.7	4.5	4.8	4.9	5.1	4.7	0/29	29/29
15/10/2004 16:46	0.8	2.6	1.5	0.9	1.4	2.0	2.3	1.6	0/30	30/30
15/10/2004 16:47	0.2	1.3	0.7	0.4	0.7	0.8	1.3	0.8	30/30	30/30

B.3 Summary of static data with four access points

Name	Min.	Max.	Mean	25%	Median	67%	90%			
7/10/2004 8:54	0.1	4.8	1.8	1.0	1.5	2.0	4.2	2.1	27/30	30/30
7/10/2004 8:58	6.7	9.4	7.2	6.8	6.9	7.0	8.3	7.3	0/14	14/14
7/10/2004 9:09	0.6	2.4	1.6	1.3	1.7	1.9	2.2	1.7	0/34	34/34
7/10/2004 9:10	3.5	6.3	4.7	4.1	4.5	5.3	6.1	4.8	0/30	30/30
7/10/2004 9:11	1.6	5.3	3.2	2.0	2.5	3.9	5.0	3.4	0/31	31/31
7/10/2004 9:12	0.8	2.5	1.7	1.5	1.8	1.9	2.0	1.7	0/33	33/33
7/10/2004 9:15	0.4	2.3	1.4	0.9	1.4	1.8	2.1	1.5	0/32	32/32
7/10/2004 9:16	5.5	8.0	6.3	6.0	6.2	6.4	6.8	6.3	0/31	31/31
7/10/2004 9:18	0.2	1.7	0.9	0.5	1.0	1.2	1.5	1.0	4/29	29/29
7/10/2004 9:20	0.5	1.9	1.2	1.0	1.4	1.5	1.6	1.3	30/30	30/30
7/10/2004 9:23	0.2	2.1	1.1	0.6	1.0	1.2	1.8	1.2	26/31	31/31
7/10/2004 16:32	5.9	11.0	7.3	6.3	6.9	7.5	10.3	7.5	0/30	30/30
7/10/2004 16:36	2.6	6.2	4.2	3.5	4.3	4.5	5.9	4.3	0/29	29/29
7/10/2004 16:41	1.0	2.8	1.9	1.5	2.0	2.1	2.6	2.0	0/30	30/30
7/10/2004 16:42	1.7	3.2	2.3	2.0	2.3	2.4	2.8	2.3	0/30	30/30
7/10/2004 16:52	3.6	4.5	4.2	4.0	4.2	4.3	4.4	4.2	13/29	29/29
7/10/2004 16:54	1.2	2.1	1.5	1.4	1.5	1.6	1.8	1.5	29/29	29/29
11/10/2004 8:15	1.2	4.2	2.7	2.5	2.8	3.1	3.6	2.8	0/28	28/28
11/10/2004 8:19	2.0	3.9	2.8	2.4	3.0	3.1	3.6	2.9	0/30	30/30
11/10/2004 8:23	1.2	2.5	1.6	1.4	1.5	1.6	2.0	1.6	0/31	31/31
11/10/2004 8:24	1.8	3.5	2.3	2.1	2.3	2.4	2.6	2.3	0/30	30/30
11/10/2004 8:26	0.7	1.9	1.3	1.1	1.5	1.6	1.8	1.4	0/29	29/29
11/10/2004 8:27	0.8	1.8	1.4	1.3	1.5	1.6	1.7	1.4	28/28	28/28
11/10/2004 8:33	3.2	8.0	5.2	4.4	5.3	5.8	6.7	5.3	0/29	29/29
11/10/2004 8:36	0.1	5.3	1.6	0.7	1.4	1.6	3.3	2.0	0/29	29/29
11/10/2004 8:46	2.0	5.5	3.3	2.8	3.2	3.3	4.6	3.4	0/29	29/29
11/10/2004 8:47	1.0	3.0	1.8	1.2	1.7	2.4	2.7	1.9	0/32	32/32
11/10/2004 8:48	0.4	1.6	0.8	0.6	0.8	0.9	1.1	0.9	0/31	31/31
11/10/2004 8:50	0.8	2.4	1.5	1.2	1.4	1.7	2.1	1.5	27/29	29/29
11/10/2004 17:22	1.9	4.2	2.8	2.5	2.6	2.8	3.5	2.8	0/30	30/30
11/10/2004 17:25	1.7	6.0	4.9	4.8	5.4	5.5	5.7	5.0	0/30	30/30
11/10/2004 17:28	1.4	3.5	2.1	1.7	2.0	2.3	3.4	2.2	0/30	30/30
11/10/2004 17:29	0.6	2.4	1.4	0.9	1.4	1.6	2.2	1.4	0/28	28/28
11/10/2004 17:30	0.7	2.2	1.4	1.1	1.4	1.6	1.8	1.4	0/29	29/29
11/10/2004 17:32	0.2	1.8	0.8	0.5	0.6	0.8	1.8	0.9	36/36	36/36
12/10/2004 12:59	2.6	4.7	3.3	2.8	3.4	3.6	3.9	3.4	0/30	30/30
12/10/2004 13:02	0.7	2.1	1.4	1.1	1.4	1.6	1.9	1.5	0/31	31/31
12/10/2004 13:05	1.1	2.5	1.5	1.2	1.4	1.6	2.4	1.6	0/30	30/30
12/10/2004 13:07	0.4	2.0	1.2	0.8	1.2	1.4	1.7	1.2	0/30	30/30
12/10/2004 13:08	0.5	2.3	1.2	0.7	1.0	1.3	2.1	1.3	0/30	30/30
12/10/2004 13:10	1.7	2.6	2.3	2.2	2.4	2.5	2.5	2.3	4/30	30/30
15/10/2004 8:16	1.1	4.1	2.2	1.4	2.2	2.4	3.3	2.3	0/37	37/37
15/10/2004 8:19	1.2	3.2	1.6	1.4	1.5	1.6	2.0	1.6	0/31	31/31
15/10/2004 8:21	0.6	6.1	3.0	1.2	2.9	4.0	5.3	3.5	0/33	33/33
15/10/2004 8:23	0.4	2.7	1.2	0.6	0.7	1.4	2.4	1.4	0/30	30/30
15/10/2004 8:24	1.4	2.8	2.2	2.0	2.4	2.4	2.7	2.3	14/37	37/37
15/10/2004 8:29	0.5	2.8	2.2	2.2	2.2	2.3	2.6	2.3	3/52	52/52
15/10/2004 16:37	1.6	4.5	2.6	2.0	2.7	3.0	3.6	2.7	0/32	32/32
15/10/2004 16:41	1.0	2.8	2.1	1.8	2.1	2.4	2.6	2.1	0/29	29/29
15/10/2004 16:44	3.6	6.5	5.1	4.5	5.0	5.5	6.0	5.1	0/33	33/33
15/10/2004 16:45	0.9	3.9	2.3	2.1	2.3	2.4	2.7	2.3	0/29	29/29
15/10/2004 16:46	0.7	2.4	1.5	0.9	1.4	1.9	2.3	1.6	0/30	30/30
15/10/2004 16:47	0.4	1.3	0.8	0.5	0.7	0.8	1.2	0.8	30/30	30/30

B.4 Summary of mobile data with three access points

Name	Min.	Max.	Mean	25%	Median	67%	90%	RMS	Area	Map
1/10/2004 13:30	0.1	4.3	1.9	1.0	2.0	2.3	3.5	2.2	0/53	53/53
1/10/2004 17:38	0.2	7.1	2.6	1.4	2.7	3.1	4.5	3.0	0/60	60/60
1/10/2004 18:12	0.5	6.5	2.3	1.3	1.8	2.2	4.4	2.7	0/50	50/50
1/10/2004 18:16	0.1	7.6	1.7	0.8	1.4	1.9	3.1	2.3	0/54	54/54
5/10/2004 13:02	0.1	5.0	1.4	0.7	1.2	1.8	2.7	1.7	0/39	39/39
5/10/2004 13:03	0.3	6.3	2.0	1.3	1.7	2.2	3.2	2.3	0/47	47/47
5/10/2004 18:25	0.1	4.2	1.2	0.5	0.9	1.2	3.2	1.6	0/39	39/39
5/10/2004 18:27	0.2	6.0	2.2	1.0	2.0	2.6	4.0	2.5	0/49	49/49
7/10/2004 8:36	0.1	4.9	1.6	0.9	1.4	2.1	3.0	2.0	0/48	48/48
7/10/2004 8:38	0.2	8.2	2.3	0.9	1.7	2.6	4.5	2.9	0/48	48/48
7/10/2004 9:00	0.2	7.3	1.5	0.5	1.0	1.5	3.0	2.1	0/37	37/37
7/10/2004 16:34	0.1	6.6	2.1	0.9	1.9	2.9	3.7	2.6	0/39	39/39
7/10/2004 16:39	0.1	5.6	2.5	1.1	2.3	3.0	4.8	2.9	0/41	41/41
11/10/2004 8:18	0.1	5.2	2.1	1.1	1.8	2.7	4.2	2.5	0/46	46/46
11/10/2004 8:22	0.1	6.2	2.1	0.6	1.8	2.9	4.3	2.6	0/37	37/37
11/10/2004 8:35	0.3	5.3	1.8	1.0	1.7	2.1	2.7	2.1	0/43	43/43
11/10/2004 8:44	0.4	6.6	2.7	1.5	2.2	3.0	5.3	3.2	0/37	37/37
11/10/2004 17:23	0.0	4.6	1.2	0.5	0.9	1.2	2.0	1.6	0/33	33/33
11/10/2004 17:27	0.1	4.9	2.0	0.9	2.4	2.6	3.6	2.4	0/32	32/32
12/10/2004 13:01	0.1	4.5	1.5	0.8	1.2	2.0	2.7	1.8	0/35	35/35
12/10/2004 13:04	0.1	7.8	2.9	1.6	2.4	3.2	6.1	3.5	0/40	40/40
15/10/2004 8:14	1.3	5.2	3.3	2.5	3.1	4.0	4.8	3.5	0/21	21/21
15/10/2004 8:18	0.1	7.2	3.5	2.2	3.2	4.4	6.7	4.1	0/45	45/45
15/10/2004 16:40	0.2	5.5	1.9	1.2	1.5	2.1	3.4	2.2	0/36	36/36
15/10/2004 16:43	0.4	5.3	2.5	1.0	2.7	3.4	4.2	2.9	0/33	33/33

B.5 Summary of mobile data with four access points

Name	Min.	Max.	Mean	25%	Median	67%	90%			
1/10/2004 13:30	0.2	3.7	1.9	1.0	1.9	2.5	3.3	2.1	0/53	53/53
1/10/2004 17:38	0.2	6.0	2.6	1.7	2.7	3.3	4.7	3.0	0/60	60/60
1/10/2004 18:12	0.2	5.1	2.0	0.8	1.6	2.3	4.3	2.4	0/50	50/50
1/10/2004 18:16	0.2	6.3	1.8	0.8	1.3	2.3	3.4	2.3	0/54	54/54
5/10/2004 13:02	0.1	6.3	1.3	0.6	1.1	1.4	2.4	1.7	0/39	39/39
5/10/2004 13:03	0.2	4.8	1.8	1.0	1.7	2.2	3.3	2.1	0/47	47/47
5/10/2004 18:25	0.1	6.0	1.5	0.6	1.3	1.9	3.1	2.0	0/39	39/39
5/10/2004 18:27	0.2	4.6	2.1	1.1	2.0	2.8	4.1	2.5	0/49	49/49
7/10/2004 8:36	0.3	6.5	1.7	0.8	1.2	2.0	3.2	2.2	0/48	48/48
7/10/2004 8:38	0.4	8.1	2.3	1.2	1.9	2.6	4.1	2.8	0/48	48/48
7/10/2004 9:00	0.0	8.2	1.7	0.8	1.2	1.3	3.4	2.4	0/37	37/37
7/10/2004 16:34	0.1	7.9	2.1	0.6	1.6	3.0	3.8	2.7	0/39	39/39
7/10/2004 16:39	0.4	5.0	2.5	1.5	2.1	2.7	4.6	2.8	0/41	41/41
11/10/2004 8:18	0.0	7.0	1.9	0.7	1.5	2.1	3.9	2.5	0/46	46/46
11/10/2004 8:22	0.1	6.0	2.2	1.2	1.9	2.4	4.3	2.6	0/37	37/37
11/10/2004 8:35	0.2	6.1	1.9	0.9	1.8	2.3	3.3	2.3	0/43	43/43
11/10/2004 8:44	0.1	6.6	2.5	1.9	2.4	2.9	5.0	2.9	0/37	37/37
11/10/2004 17:23	0.1	4.7	1.4	0.7	1.2	1.5	2.5	1.7	0/33	33/33
11/10/2004 17:27	0.2	5.1	2.0	1.2	1.9	2.5	3.1	2.3	0/32	32/32
12/10/2004 13:01	0.0	4.8	1.6	0.7	1.5	2.1	3.1	2.0	0/35	35/35
12/10/2004 13:04	0.1	5.3	2.2	0.8	2.3	3.0	4.5	2.7	0/40	40/40
15/10/2004 8:14	2.3	6.6	3.9	3.0	3.7	4.6	6.1	4.1	0/21	21/21
15/10/2004 8:18	0.1	7.2	3.0	2.0	2.9	3.5	5.2	3.4	0/45	45/45
15/10/2004 16:40	0.1	6.3	1.6	0.7	1.2	2.2	3.1	2.1	0/36	36/36
15/10/2004 16:43	0.2	6.0	2.5	1.1	2.6	3.2	4.7	3.0	0/33	33/33

B.6 Sample of detailed data

Number	Time	CorrectX	CorrectY	LocatedX	LocatedY	Error	Expected Error
1	1/10/2004 14:29.59	675	107	604	118	4.35	4.7
2	1/10/2004 14:29.59	675	107	614	110	3.69	3.25
3	1/10/2004 14:30.00	663	107	617	108	2.85	2.91
4	1/10/2004 14:30.02	644	107	615	108	1.77	2.53
5	1/10/2004 14:30.04	624	107	603	108	1.29	2.66
6	1/10/2004 14:30.06	605	107	571	108	2.06	2.82
7	1/10/2004 14:30.08	585	107	553	108	1.95	2.79
8	1/10/2004 14:30.10	565	107	521	108	2.73	3.03
9	1/10/2004 14:30.12	546	107	505	108	2.47	2.99
10	1/10/2004 14:30.14	526	107	479	108	2.85	3.2
11	1/10/2004 14:30.16	507	107	467	108	2.41	2.95
12	1/10/2004 14:30.18	487	107	453	108	2.04	2.52
13	1/10/2004 14:30.20	467	107	431	108	2.2	2.39
14	1/10/2004 14:30.22	448	107	416	108	1.95	2.17
15	1/10/2004 14:30.24	428	107	382	108	2.82	2.11
16	1/10/2004 14:30.26	409	107	357	109	3.13	2.11
17	1/10/2004 14:30.28	389	108	331	109	3.55	2.22
18	1/10/2004 14:30.30	369	108	314	109	3.37	2.34
19	1/10/2004 14:30.32	350	108	290	109	3.67	2.5
20	1/10/2004 14:30.34	330	108	265	110	3.97	2.24
21	1/10/2004 14:30.36	311	108	252	111	3.56	2.21
22	1/10/2004 14:30.38	291	108	247	114	2.69	2.32
23	1/10/2004 14:30.40	271	108	236	108	2.16	2.27
24	1/10/2004 14:30.42	252	108	232	102	1.28	2.37
25	1/10/2004 14:30.44	232	108	230	104	0.29	2.49
26	1/10/2004 14:30.46	230	122	230	111	0.66	2.6
27	1/10/2004 14:30.48	230	137	229	111	1.62	2.58
28	1/10/2004 14:30.50	229	152	230	119	2.04	2.72
29	1/10/2004 14:30.52	228	168	231	130	2.3	2.75
30	1/10/2004 14:30.54	228	183	234	157	1.64	2.93
31	1/10/2004 14:30.56	227	198	243	183	1.34	2.77
32	1/10/2004 14:30.58	227	212	254	194	1.98	2.87
33	1/10/2004 14:31.00	246	212	270	201	1.61	3.05
34	1/10/2004 14:31.02	265	212	273	204	0.71	2.93
35	1/10/2004 14:31.04	283	212	279	207	0.43	2.86
36	1/10/2004 14:31.06	302	212	289	209	0.82	2.98
37	1/10/2004 14:31.08	321	211	299	210	1.33	2.91
38	1/10/2004 14:31.10	340	211	324	211	0.97	2.65
39	1/10/2004 14:31.12	358	211	354	212	0.26	2.42
40	1/10/2004 14:31.14	377	211	392	212	0.9	2.09
41	1/10/2004 14:31.16	396	211	415	212	1.21	2.12
42	1/10/2004 14:31.18	414	211	447	210	2.02	2.14
43	1/10/2004 14:31.20	433	210	474	203	2.57	2.4
44	1/10/2004 14:31.22	452	210	484	192	2.26	2.3
45	1/10/2004 14:31.24	470	210	497	192	1.98	2.07
46	1/10/2004 14:31.26	489	210	510	199	1.45	1.94
47	1/10/2004 14:31.28	508	210	517	203	0.67	1.71
48	1/10/2004 14:31.30	527	210	528	208	0.12	1.63
49	1/10/2004 14:31.32	545	209	531	208	0.88	1.85
50	1/10/2004 14:31.34	564	209	552	211	0.72	1.93
51	1/10/2004 14:31.36	583	209	573	212	0.62	1.57
52	1/10/2004 14:31.38	601	209	611	212	0.62	1.63
53	1/10/2004 14:31.40	620	209	650	211	1.84	2.08