THE UNIVERSITY OF HULL

Hybrid Framework for Dynamic Position Determination in Multisensor Environments

being a Thesis submitted for the Degree of

Doctor of Philosophy

in the University of Hull

by

Saana Pauliina Liimatainen, B.Sc. (hons)

May 2009

Abstract

Hybrid Framework for Dynamic Position Determination in Multisensor Environments

Information about a user's context is crucial in obtaining the goal of ubiquitous computing. This thesis introduces a new approach in for looking at a special case of context; location information. Making devices location-aware is the first step of providing context-based services. Existing technologies for position determination are ill suited in terms of interoperability and heterogeneity. Furthermore, they rely either on vast and often expensive infrastructures to perform the position estimation or alternatively the mobile device is burdened with the responsibility of localising itself. Both of the current approaches have their trade-offs. The basis of this work is to maximise the availability of positioning services allowing mobility between different environments and surroundings while minimising the vulnerabilities of existing approaches

The work presents a managed positioning environment for indoor and outdoor surroundings, in which accuracy and precision can be improved by using a mix of fixed sensors and the sensing capabilities of mobile devices in a way that it allows the transformation of proximity data into absolute coordinates. It is believed that this also improves the availability of the positioning service as partial, imprecise or incomplete data is utilised rather than discarded. The usage of wireless local area networks along with PDAs, mobile phones and similar devices, as opposed to custom sensors ensures that maintenance and administrative costs are kept to a minimum. Furthermore, a dynamic feedback system is proposed in order minimise deployment and initialisation effort by allowing refining of location information in fixed sensors.

Acknowledgements

Dr David Grey has advised and encouraged me throughout my doctoral process. I feel extremely privileged to have had a chance to work under his supervision and guidance. He never stopped having faith and always held his door open for me. He has been an inspiration, a mentor and excellent company throughout these years. For all this I am forever grateful to him.

Recognition must also go to **Dr Paul Chapman** for enabling the submission of this thesis through his hard work and **Derek Wills** & **Rob Miles** for their support and advice.

I'd also like to thank my parents, **Raija** and **Seppo**, who always encouraged me to see how far the world would take me. Regardless of what my experiences might have been they were always there to welcome me back with open arms, ready to patch me up and send me on my way again. They gave me the best possible foundation in life and have supported me in every way imaginable.

I'd like to recognise my big brother **Samu**, who instilled the passion for science in me and taught me to seek knowledge in every way possible. He has always been the one who showed me the direction, as well as the one to bail me out when I've taken a wrong turn. I am happy to see my nephews, **Konsta** and **Roope**, demonstrate the same inquisitive and endlessly curious characteristics shared by their parents.

I also owe a large debt to my grandmother, **Kerttu**, who taught me the value of unshakeable ethics, hard work and perseverance and whose example I only hope to follow one day.

This thesis is dedicated to **Kim Bale**, who is the one who dragged me through this experience in one piece. Without him by my side I would have had a very different kind of a future.

Relevant Publications

LIIMATAINEN, S. and GREY, D. (2005). 'Hybrid Approach to User Privacy in Ubiquitous Frameworks' in Proc. *3rd UK-UbiNet Workshop*. Bath, UK.

LIIMATAINEN, S. and GREY, D. (2006) 'Trust Based Security Framework for Mobile Networks' Paper Presentation in *Graduate Research Conference*. Hull, UK.

LIIMATAINEN, S. and GREY, D. (2009). 'A Framework for Dynamic Position Determination in Multisensor Environments' *6th International Conference on Mobile Technology, Applications and Systems*. Nice, France.

Contents

Page

Abstract ii

Acknowledgements iii

Relevant Publications iv

Contents v

List of Figures ix

List of Tables xi

List of Equations xiii

Page

INTRODUCTION 1

- 1.1 Overview 1
- 1.2 Context and Context-Awareness 3
  - 1.2.1 Context-Aware Environments 4
  - 1.2.2 Basic Entities 7
- 1.3 Location as a Context 9
- 1.4 Thesis Overview 11

BACKGROUND 14

- 2.1 Introduction 14
- 2.2 Mobile Distributed Systems 15
- 2.3 Positioning Systems 18
  - 2.3.1 Overview 18
    - 2.3.1.1 Scalability 18
    - 2.3.1.2 Trust 20

2.3.1.3 Authentication and Authorisation 21
2.3.1.4 Privacy 24
2.3.1.5 Heterogeneity 24
2.3.1.6 Computation 24
2.3.2 Positioning System Properties 24
2.3.2.1 Coordinates 24
2.3.2.2 Accuracy and Precision 24
2.3.2.3 Location Rate 24
2.3.3 Techniques 26
2.3.3.1 Acquisition of Location Data 24
2.3.3.2 Location Estimation 31
2.3.3.3 Positioning Techniques 35
2.4 Summary 37

RELATED WORK 38

3.1 Introduction 38
3.2 Positioning Systems 39
3.2.1 Network Centric Centralized Positioning 40
3.2.1.1 Active Badge 40
3.2.1.2 Active Bat 40
3.2.1.3 The Radar 40
3.2.2 Device Centric Localized Positioning 43
3.2.2.1 The Cricket 43
3.2.2.2 Skyhook Wireless 43
3.3 Evaluation and Performance Issues 45
3.3.1 Criteria 45
3.3.2 Discussion 47
3.4 Summary 51

DESIGN OBJECTIVES FOR POSITIONING FRAMEWORK 52

4.1 Introduction 52
4.2 Approach 53
4.3 Design Objectives 54
4.4 Design Restrictions 58

FRAMEWORK FOR POSITION DETERMINATION 60

5.1 Introduction 60

5.1.1 Location Representation 61

5.1.2 Entities 62

5.1.3 Infrastructure 67

5.2 Acquiring Location 69

5.2.1 Positioning Cycle 69

5.2.2 Creating Proximity Maps 71

5.2.3 Measuring Distance 71

5.2.4 Monitoring Changes and Detecting Movement 73

5.2.5 Calculating Confidence 75

5.2.6 Obtaining Coordinates 76

5.2.6.1 Calculating Viable Range 76

5.2.6.2 Refining Location 76

5.3 Summary 94

TESTING & VALIDATION 95

6.1 Introduction 95

6.1.1 Approach 96

6.1.2 Overview 97

6.2 Evaluation Criteria 101

6.3 Experiments Performed 102

6.3.1 Control 102

6.3.2 Insufficient Location Data & “Device Hops” 103

6.3.3 Dynamic Location Data, Moving Devices & Stored Coordinates 110

6.3.4 Inaccurate Location Data 113

6.4 Summary 120

EVALUATION 121

7.1 Introduction 121

7.2 Discussion 122

7.2.1 Multisensor Availability 122

7.2.2 Privacy 123

7.2.3 Execution of Algorithms 124

7.2.4 Supported Positioning Surroundings 126
7.2.5 Value of Location Data 127
7.2.6 Accuracy, Precision and Location Rate 128
7.2.7 Availability of Positioning 129
7.3 Open Issues & Future Research Direction 131
7.3.1 Support for Trust Management Framework 131
7.3.2 Ad-Hoc Mode for Positioning 131
7.3.3 Reducing Network Traffic 131
7.4 Summary 133

CONCLUSION 134
8.1 Contributions 134
8.2 Future Work 136
8.2.1 Modelling Signal Propagation 136
8.2.2 Mobile Application Development & Deployment 137
8.2.3 Application Support 138
8.2.4 Evaluating Usability 138
8.3 Conclusion 139

References 140

List of Figures

Figure 1.1: Example Context Classification (Schmidt et al., 1999) 4

Figure 2.1: Accuracies along with Current and Future Deployment Prospects of Sensing Technologies. (Hazas et al., 2004) 29

Figure 2.2: Taxonomy of Positioning Technologies. (Pateli et al., 2002) 30

Figure 2.3: Lateration Technique (Hightower & Borriello, 2001) 33

Figure 2.4: Angulation Technique (Hightower & Borriello, 2001) 33

Figure 3.1: Taxonomy of Location Services (Pateli et al., 2002) 40

Figure 5.1: Main Logical Components of a Positioning Environment. 61

Figure 5.2: Example data collected for proximity maps. 66

Figure 5.3: Principal Logic for Commencing a Positioning Cycle 70

Figure 5.4: Measuring Distance Utilising Signal Strength Indicators 72

Figure 5.5: Calculating Shared Coordinate Points from Intersecting Detection Ranges. 76

Figure 5.6: Calculating Viable Range for an entity with an Immediate Reference and a Device Beyond a Hop 80

Figure 5.7: Calculating Viable Range with Variable Distances 82

Figure 5.8: Example Error Margins for Sparse Positioning 84

Figure 5.9: Two Immediate Reference Devices and a Device Beyond a Hop 86

Figure 5.10: Logical Order of Choosing Reference Devices for a Refining Cycle 89

Figure 5.11: The Principle Behind Using a Single Moving Device as a Sole Reference .. 91

Figure 6.1: Example Simulation Scenario 98

Figure 6.2: Example Output Data from a set of Positioning Cycles 99

Figure 6.3: Experiment 4 - The Effect of Inter-device Distances in Number of Coordinate Points 105

Figure 6.4: Experiment 5 & 6 - The Effect of Device Arrangement in Error Margin ..108

Figure 6.5: Experiment 7 - The Effect of a Device beyond a Hop with Two Immediate References 109

Figure 6.6: Experiment 8 - Set of example speeds for getting a reliable position fix with a single moving device as a reference with error margin set to 1 metre. 111

Figure 6.7 Simplified example range of a possible bias in a third reference device when triangulating. 115

List of Tables

Table 3.1: Positioning System Classification Criteria....47

Table 6.1: Control 1-3 - Accuracy and precision for positioning of single devices with a varying number of references. 102

Table 6.2: Experiment 4 - Impact of Device Hops: Error Margins and precisions for positioning of single devices with a single device as an immediate reference and a single device beyond a hop....104

Table 6.3: Experiment 5 & 6 - Impact of "Device Hops": Error Margins and precisions for positioning of single devices with two devices as an immediate reference and a single device beyond a hop....107

Table 6.4: Experiment 7 - The Effect of Device beyond a Hop (BEOH) on Precision and Error Margins 109

Table 6.5: Experiment 8 - Average Location Rates for Positioning with a Single Moving Reference with Mean Distance. 112

Table 6.6: Experiment 10 - Positioning a Moving Device with Varying Number of References....113

Table 6.7a Control....116

Table 6.7b Effect on triangulation caused by bias from one reference device 116

Table 6.7c Effect on triangulation caused by bias from two reference devices....116

Table 6.7d Effect on triangulation caused by bias from three reference devices 117

Table 6.8a Triangulating in a dynamic environment....117

Table 6.8b Positioning with a single moving device as a sole reference device in order to obtain more accurate location information....118

Table 6.8c Positioning with a single moving device along with a stationary device as references in order to obtain more accurate location information....118

Table 6.8d Positioning with a single moving device as a sole reference device in order to obtain more accurate location information..119

Table 6.8e Triangulating in a dynamic environment..119

List of Equations

Equation (1)
Distance Measurement Calculation........72
Equation (2)
Multiplication Law........74
Equation (3)
Probability of False Movement Indication Calculation........74
Equation (4)
Euclidean Distance Calculation........77
Equation (5)
Calculating Radical Axis between Device Ranges (one)........77
Equation (6)
Calculating Radical Axis between Device Ranges (two)........77
Equation (7)
Calculating Radical Axis between Device Ranges (three)........77
Equation (8)
Calculating Radical Axis between Device Ranges (four)........77
Equation (9)
Detection Range Determined Intersection Points Calculations........78
Equation (10)
Coordinate Point Calculations for Detection Range Intersection Points (one)........78
Equation (11)
Coordinate Point Calculations for Detection Range Intersection Points (two)........78
Equation (12)
Detection Range Circumference Calculation........80
Equation (13)
Method for Angle Increment for Viable Range Calculations........81
Equation (14)
Coordinate Point Calculations for Viable Range (one)........81

Equation (15)
    Coordinate Point Calculations for Viable Range (two) ... 81
Equation (16)
    Angle Calculations for Viable Range Determination ... 81
Equtaion (17)
    Error Margin Calculation for Positioning on Sparse Mode ... 85
Equation (18)
    Calculation for Number of Possible Coordinates ... 85
Equation (19)
    Start Confidence Calculations ... 85
Equation (20)
    Viable Confidence Calculations ... 85
Equation (21)
    Start Confidence Calculations (two) ... 86
Equation (22)
    Confidence Calculation for a Device on a Persistent Mode ... 92
Equation (23): ... 93
    Confidence Calculation for a Device on a Persistent Mode (two) ... 91
Equation (24): ... 93
    Confidence Calculation for a Device on a Persistent Mode (three) ... 91

Chapter 1

INTRODUCTION

1.1 Overview

"We believe that people live through their practices and tacit knowledge so that the most powerful things are those that are effectively invisible in use. This is a challenge that affects all of computer science. Our preliminary approach: Activate the world. Provide hundreds of wireless computing devices per person per office, of all scales (from 1" displays to wall sized). This has required new work in operating systems, user interfaces, networks, wireless, displays, and many other areas. We call our work 'ubiquitous computing'. This is different from PDA's, dynabooks, or information at your fingertips. It is invisible, everywhere computing that does not live on a personal device of any sort, but is in the woodwork everywhere." Mark Weiser (Weiser, 1988)

The vision of Mark Weiser has been echoed in a whole new field of information technology: ubiquitous computing, where sensing physical attributes in an environment seamlessly enables customised and personalised control of surroundings. Ubiquitous computing aims to provide the user with a useful mobile system which captures the surrounding situational and location data and acts according to it with minimal intervention from the user. The system is not only expected to interpret the environmental situation but also the actual user context in such a way that it could deliver information to the user, which is relevant possibly only to her, there and then. Thus, ubiquitous systems are not concerned only with mobile computers but also mobile people in their current context, which is the issue that differentiates ubiquitous computing from the field of ordinary mobile computing. (Schilit, 1995)

There are multiple prototypes and systems developed in the field of ubiquitous computing enabled by the recent advances in two main technologies: portable computers and wireless communication technologies, which allow users to move with their mobile devices that have increased processing capabilities, decreased power consumption and smaller size than ever before whilst making network resources constantly available. There are several ways in which portable devices can be connected without wires. These include wireless cellular networks, wireless local area networks (WLAN) supporting IEEE 802.11 and OpenAir standards and wireless personal area networks (PAN) or body area networks (BAN) including Bluetooth and IrDA (the Infrared Data Association) standards. (Chen & Kotz, 2000)

The same technological improvements that have led to more portable computers and wireless communications technologies also facilitated the creation of specialised, wireless and even autonomous sensing nodes, which are capable of observing the surrounding environment and can be managed in a coordinated manner in order to create a ubiquitous system that responds to contextual triggers. Fundamental to creating systems, which are capable of selecting services depending on the surroundings of a user, is *location-awareness.*

It is important to consider the field of ubiquitous computing as a whole, in order to understand the challenges faced by estimating an objects position and hence, making mobile devices location-aware. Furthermore, the significance of location information is only truly revealed once it is put into a perspective of a context-aware environments, which are responsible for providing services based on the position of the user and everything that may be derived from it. Without investigating the purpose behind the need of acquiring location it is difficult to come up with a useful system that is able to make devices location-aware and provide positioning in a way that meets the needs of users. The following is an introduction to location-awareness and positioning in the light of context-aware, ubiquitous environments consisting of mobile users and their personal communication devices.

1.2 Context and Context-Awareness

There are possibly almost as many definitions of context as there are existing frameworks. The main differentiating factor is the way context is considered in relation to users and their environment. Some definitions refer to the context as being primarily focused on describing the user's surrounding whereas others consider it to be the application's computational environment. Schilit divides context into three main categories:

- "*Computing context* (i.e. communications & nearby objects)
- *User context* (profile, location, nearby people & current social situation)
- *Physical context* (i.e. lighting, noise level & temperature)" (Schilit, 1995)

Some other most obvious definitions consider context to be composed of location (absolute, relative, orientation), identities of nearby people and changes to these. (Schilit, 1995) Some other definitions include time of the day, season, temperature and such. (Chen & Kotz, 2000) The user's emotional state, focus of attention and informational state are also considered in more experimental frameworks. Figure 1.1 illustrates some of the most often-considered context classifications. (Schmidt et al., 1999)

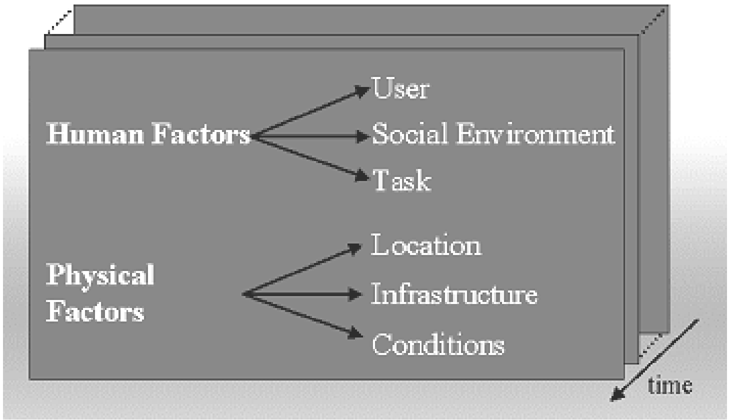


Figure 1.1: Example Context Classification (Schmidt et al., 1999)

1.2.1 Context-Aware Environments

There are several ways in which context-aware applications can use context-information effectively. Some of the first and still widely used categorisations for context-aware applications include Schilit's (Schilit, 1995) definition, which identifies classes of differently behaving applications:

1. "*Proximate Selection*: is related to user interfaces, where nearby objects are emphasised.
2. *Automatic Contextual Reconfiguring*: occurs when applications respond to context changes by adding, removing or modifying components and their connections in the system.
3. *Contextual Information and Commands*: refers to applications which behave differently according to the context.
4. *Context-Triggered Actions*: are simple rules which specify how applications should behave and the system adapt to different context triggers."

Pascoe (Pascoe, 1998) concentrates more on defining features of these applications, which include: *"Contextual sensing, Contextual resource discovery and Contextual augmentation"*.

Dey, Abowd & Salber (Abowd, 2002) propose a categorisation of application functions based on the two previous definitions:

1. "*Presenting information and services*: these applications may either use context-information for the purpose of solely presenting it to the user or providing selection of possible actions to the user.
2. *Automatically executing a service*: describes applications, which automatically respond to context changes by, for example, triggering a command or reconfiguring the system.
3. *Attaching context information for later retrieval*: includes applications, which collect data and tag them with appropriate context information to be used later."

Chen & Kotz (Chen & Kotz, 2000) have a simpler approach and similarly to Dey, Abowd & Salber categorise the applications into ones which are automatically able to adapt the behaviour according to context and ones which present the information to the user on the fly or additionally store it for later retrieval.

Dey, Abowd & Salber propose that the framework should ideally support all the possible tasks that applications may require. This way the application developer would only need to be concerned about implementing the application specific tasks and everything else would be left to the architecture. Also the dealing with vast amount of context information would be easier. According to Dey, Abowd & Salber the points to consider for the framework are:

- *"Separation of Concerns* is concerned about keeping context acquisition separate from its usage in order to provide application developers an abstraction of context.
- *Context Interpretation* should in most cases be done before applications would use the context information.
- *Transparent, Distributed communications:* neither sensors nor applications should suffer from the fact that communication was distributed.

- *Constant Availability of Context Acquisition* implies the same idea as the separation of concerns in which components that acquire the context must be independent from the applications that use the information. Furthermore, the application should be able to access the context information at any time.
- *Context Storage and History* for the purposes of future prediction.
- *Resource Discovery:* The application should be able to communicate with the sensor in order to determine what kind of information it can provide, where it is located and the communications protocols, languages and mechanisms it uses."

Campbell et al. (Cambell et al., 2002) consider requirements on a different level for the framework, which is mostly concerned with applications.

- *"Resource-Awareness:* applications must be aware of existing resources, their capabilities, availability and cardinality.
- *Context-Sensitivity:* Context alters at least data, composition and logic aspects of applications.
- *Multi-Device:* Applications should be sometimes partitioned into different devices as defined by the context and the users.
- *User-Centrism:* Applications should be bound to users and mapped to the resources, which are present.
- *Mobility:* concerning both intra-space mobility and inter-space mobility."

Again, Fox et al. (Fox et al., 2001) consider different design goals with their framework:

- *"Adaptability*: in both appliance-level and workspace-level. Contextual information should be relevant for the current workspace as well as in useful format for the current device.
- *Deployability*: And furthermore:
  1. *Flexibility of language/OS/ UI toolkit*: The language and Operating System should be a matter of preference for application developers.

2. *Spectrum of UIs/Applications*: It should also be possible at least partially to generate meaningful application to a particular context.
3. *Robustness*

- *Aggregation:* Applications should be created for different combinations of services when needed."

1.2.2 Basic Entities

In order to understand the diversity of different environmental contexts it is necessary to categorise the context information in terms of basic entities and different characteristics of the information. These classifications are unique to each examined framework or middleware and determine a large part of the functionality the framework can provide. By combining the following definitions of the entities and the context information categories it is possible to derive additional pieces of context information in order to be able to evaluate the surroundings more accurately.

Dey, Abowd & Salber (Abowd et al., 2002) base their conceptual framework on three basic entities, which have context information:

1. "*Places* (regions of geographical space)
2. *People* (co-located or distributed individuals or groups)
3. *Things* (physical objects or software) "

All these entities have context information, which can be categorised in four groups by their characteristics:

1. *"Identity*, a unique identifier in the namespace.
2. *Location*, including orientation and elevation as well as spatial relationships between entities (i.e. co-location, proximity & containment).
3. *Status* or *Activity*, identifies characteristics of the entity
4. *Time,* mostly used as time stamp or time span. "

Campbell et al. (Cambell et al., 2002) have a similar approach with their Gaia middleware. The basic entities they define are divided into two main categories:

1. "*Digital Entities* with Applications & Services
2. *Physical Entities* with Devices & Persons"

The information, which can be stored about these entities include *name, type, owner, location* and *situation*.

Fox et al. (Fox et al., 2001) have a slightly different approach to the framework's entities, which consist of:

1. *"Users*, who interact with,
2. *Services,* such as devices and applications, by using,
3. *Appliances*."

Each of the entities has their own descriptions, which can be compared according to specific rules.

A common issue in defining the context is the decision is whether the users' profiles such as interests and preferences are part of the context information. The opinion which majority seem to adopt is the goal of the context gathering. The purpose of capturing contextual information is to be able to determine what the user is trying to accomplish. The opinions differ again whether all gathered information can be counted as context information or if it is necessary to differentiate between automatically and manually gathered information.

1.3 Location as a Context

Location is particularly important piece of context information mainly because from location information much of the other types of context information such as social situation or physical conditions can be either inferred or looked up.

Acquiring a location requires a mobile positioning system, which traditionally are grouped into *indoor* and *outdoo*r systems with little interoperability or prospect of mobility between the two. For example, cellular systems such as the Global System for Mobile Communication (GSM) and Global Positioning System (GPS) address the issue of positioning by being able to position devices outdoors. GPS can very effectively record absolute co-ordinates such as latitude, longitude and altitude for an object up to the accuracy of less than a metre. Unfortunately, this can be greatly distorted due to technical challenges caused by the walls of a building due to signal attenuation and reflection effects making the prevalent GPS technology unsuitable for indoor use (GPS, 2009). Although methods such as High Sensitivity GPS, Assisted GPS (A-GPS) (Sun et al., 2005), which relies on cellular infrastructure and TV-GPS (Hazas et al., 2004) utilising broadcast television infrastructure have been developed they are not adopted for wider public use since the devices are thought to be specialist equipment due to their high specification requirements and price. (Sun et al., 2005)

In comparison indoor positioning systems generally use either wireless networks for inferring a location of a device or a sensory network to localize nodes. Traditional wireless indoor location systems are often based on a radio and require an infrastructure of fixed base stations. These systems require an initial off-line phase, where the system is calibrated and a model or a map is made to correspond to the received signal strengths in order to enable positioning of devices based on these during the online operation. The need for fixed infrastructure makes these systems expensive to deploy and manage in order to provide coverage in outdoor surroundings. (Hazas et al., 2004) There are also privacy considerations in infrastructure based systems, some of which utilise the infrastructure or specialised sniffer software to track and store information about the users' movements. (Sun et al., 2005)

To resolve this issue of cost and management, which have are associated with the scalability of infrastructure based positioning systems, a number of researchers are investigating ad-hoc location-sensing. The ad-hoc location sensing relies on the idea of ad-hoc wireless Personal Area Networking where no central controller or large infrastructure is needed to establish the connection between two objects. The devices used are often based on standards like Bluetooth RadioFrequency- (RF) based standard, PulsOn UWB-based (UltraWideBand) technology or (infrared) IrDA, which typically offer a low-cost, low-power and short range networking. (Chen & Kotz, 2000)

In ad-hoc location sensing all objects are mobile with the same sensors and capabilities, sharing sensor data to co-operate with nearby objects. These objects can be at known locations, in which case the ad-hoc location sensing can produce absolute coordinates in addition to information about nearby devices. Ad-hoc systems suffer from security issues (Stajano & Anderson, 1999) as well as problems with limited device resources.

Since context-aware applications for emergency services, medical facilities, military, office and home applications are getting increasingly popular, the need to make mobile devices location-aware in varying circumstance is the key. The basic problem of positioning a device is that there is no technology that can accurately and reliably locate an object in all situations where location-awareness is required. There is a need for a system that is able to provide uniform location information in a seamless manner by integrating technologies and techniques that are available in the reach of mobile devices and users, without the need of specialist equipment or vast infrastructure. In order to fulfil the goal of ubiquitous “everywhere computing” the technology should be readily implemented and available for location-based services to become part of the everyday life.

1.4 Thesis Overview

This thesis contends that traditional approaches to location estimation are ill suited due to the requirements posed by device limitations, environmental requirements and user preferences. In the field of ubiquitous computing a positioning technique should acquire location information for the purpose of making an object location-aware for context based applications. Current techniques are not suitable for both indoor and outdoor environments, rely on costly infrastructure or result in inaccurate or out-of-date positioning information. Furthermore, they may, in the worst case, leave the user identity exposed to the environment.

This thesis postulates that it is possible to accurately and seamlessly position devices in both indoor and outdoor environments which lack location references by sharing location information between mobile devices without the need for costly sensory infrastructures or custom devices. In order to evaluate this hypothesis, this thesis proposes a positioning mechanism for mobile devices within an environment, which is simple, honours user privacy preferences, is feasibly deployable using pre-existing technologies, cost-effective and sufficiently accurate. The proposed positioning framework aims to satisfy the requirements for location-awareness in context-based systems by being as pervasive as the purpose of acquiring location information. Several key issues are presented:

- *Hybrid approach to location tracking*. Motivated by existing location tracking techniques this thesis examines the possibility to combine the strengths and minimise weaknesses of current approaches by introducing a hybrid framework.

- *Accuracy and precision are prioritised*, by introducing confidence calculations to the process of positioning. The solution also seeks to improve these by combining multiple sensors with varying resolutions and by being able to process partial or inaccurate location data.

- *Minimal administrative and maintenance costs*. The adopted approach uses general purpose sensors and combines a number of technologies already available on mobile devices. This helps to keep the administrative and maintenance cost minimal.

- *Nominal initial set up and calibration efforts*, which are warranted by the introduced sensor feedback system, which also facilitates seamless integration into existing environments with fixed sensors.

- *Mobile devices or users are not tracked* as the approach ensures data is gathered by the devices and not stored in the infrastructure.

- *Computational burden is minimised on resource limited devices.* The solution ensures processor heavy calculations are not performed on devices with limited processing power.

- *Mobility* between indoor and outdoor surroundings. The deployment of the framework does not restrict the usage of the positioning system to either indoor or outdoor use.

- *Availability of Positioning* in environments with minimal location references.

Chapter 2 introduces issues that are specific to mobile distributed computing and explores the limitations under which a positioning framework must operate. The chapter introduces the key issues this thesis aims to resolve and some of the techniques and technologies, which can be used to acquire a location and determining an object's position. This chapter also aims to introduce taxonomy along with criteria for positioning systems, which can be used to evaluate existing frameworks discussed in Chapter 3.

Chapter 3 presents background on existing positioning systems and suggests criteria which are used to evaluate location-aware frameworks. The chapter also offers a critical appraisal of the advantages and limitations of current approaches.

Chapter 4 describes the need for further research and proposes a positioning framework. It also aims to clarify the focus and the design choices that have been made.

Chapter 5 explains the main concepts of the solution and discusses in detail the algorithms and approaches that have been developed in order to implement the solution. It also describes the system organisation and basic entities. It also illustrates interactions between different components in the architecture as well as deployment of the framework.

Chapter 6 introduces the developed simulation, which was used as a test bed to the framework. The chapter provides details of experiments conducted along with the results.

Chapter 7 evaluates the approach and assesses it against the criteria introduced in chapter 3. It also offers insight into the open issues not covered by the focus of this thesis.

Chapter 8 contains a summary and conclusion along with some discussion about the achievements of the research and recommends a direction for future work.

Chapter 2

BACKGROUND

2.1 Introduction

The purpose of this chapter is to discuss the concepts of mobile distributed systems concentrating on issues which are relevant to be considered when aiming to implement a positioning framework in order to enable location-awareness for application use. The design of a positioning framework relies largely on the same required level of abstraction as middleware for mobile computing, which aims to hide the restrictions caused by the distribution of components. For this reason it is necessary to inspect the wider field of mobile distributed systems.

Furthermore, this chapter aims to provide insight into what is required in order to achieve location-awareness and what kind of criteria are suitable for use in evaluating existing location estimation techniques by introducing a taxonomy for acquiring and processing location information.

The chapter has been divided in two distinct sections; the first one presents common issues in mobile and distributed computing. Its main concern is the areas, which have relevancy to location-aware middleware and need to be acknowledged when designing a positioning framework. The second section discusses taxonomy for acquiring location as well as describes the important aspects and necessary design considerations of positioning systems.

2.2 Mobile Distributed Systems

According to Tanenbaum and Van Steen there are four important goals, which the design of any distributed system should meet and which differentiates it from local computing. (Tanenbaum & Van Steen, 2002) A distributed system should:

- *easily connect* users to resources
- *be transparent* and hide the fact that resources are distributed across a network
- *be open*; implementing adaptability and flexibility
- *be scalable*

In addition Mascolo et al. (2002) identify the need for:

- *Heterogeneity* allowing different components and implementations to communicate with each other seamlessly.
- *Fault-tolerance* coping with unexpected disconnect situations caused by hardware and software failures without bringing the whole system to a halt.
- *Resource sharing,* which should be managed with a form of access control that monitors the use of shared resources between users of the system.

Satayanarayanan differentiates mobile computing as a facet of distributed computing by identifying four additional distinctive constraints which are characteristic to mobile, wireless computing: (Satayanarayanan, 1996)

1. "Mobile elements are resource-poor relative to static elements."
2. "Mobility is inherently hazardous."
3. "Mobile connectivity is highly variable in performance and reliability."
4. "Mobile elements rely on a finite energy source."

According to Mascolo et al. the characteristics, which describe mobile distributed computing, can be expanded by investigating three concepts at the heart of distributed systems: . (2002)

1. *"Type of Device"*: Fixed devices have very little variations and can be characterised as being powerful machines by the means of fast processors and a large amounts of memory. Mobile devices may consist of a whole variety of different types of devices varying from Personal Digital Assistants (PDA) to smartphones and even smart cards, all with limited processor speed, small memory, low battery power and restricted screen size.

2. *"Type of Network Connection"*: Fixed devices are generally considered to have permanent, fast connections, which can be thought to be disconnected only in exceptional, unpredictable circumstances or due to administrative maintenance. On the contrary mobile devices, which use wireless communication links, are said to have intermittent connections. They may have largely varying bandwidths due to the underlying wireless network performance, unpredictable disconnections due lost connections or intentional disconnections because of the high price of staying connected to some wireless services.

3. *"Type of Execution Context"*: Context includes everything that can "influence the behaviour of an application" (Mascolo et al., 2002) such as internal device resources (memory size, screen size) or external resources (network bandwidth/quality, location). Fixed systems generally have static context whereas mobile devices' context can be extremely dynamic, for example, the location and degree of mobility may affect the bandwidth and network quality greatly.

Due to these issues it is necessary to implement mechanisms in order to find a balance between the constraints, which mobile computing depends on and the necessary independence required due to highly dynamic environments. These mechanisms can be expected to address the following basic requirements, which are also used by Mascolo et al. (2002) to characterise middleware for distributed systems:

1. *Computational Load*: Since mobile devices are considered to have restricted resources, computational load should be kept light.

2. *Communication Paradigm*: Mobile devices have an intermittent connection to the network implying that an asynchronous form of communication would be preferable to facilitate; service request, disconnect and result retrieval at reconnect -type model of execution.

3. *Context Representation*: Rather than having transparent context execution, where information about the application execution context is kept hidden a degree of application awareness is recommended to correspond to the dynamic and highly variable surroundings coupled with unreliable connection and bandwidth limitations.

According to the level of distribution two distinct stratums of mobile distributed systems can be identified, which can be used when addressing the above requirements. These are namely: nomadic and ad-hoc systems: (Mascolo et al., 2002)

- *Nomadic Distributed Systems.* Generally nomadic or infrastructure based systems comprise of a number of mobile devices which are connected to a core infrastructure with wired, static elements. The movement of mobile devices is expected while at the same time connection to a fixed wireless network is maintained. Computational load is generally kept in the infrastructure along with provided services or any required connection sequences. Some systems allow disconnection by providing services for transparent reconnections and synchronisation. Scalability can become an issue in infrastructure based systems when the number of mobile devices rises and the system is expected to have the ability to serve devices in an efficient manner.

- *Ad-Hob Mobile Distributed Systems.* Ad-hoc systems are comprised of a number of independent mobile devices, which may connect to each other through wireless links either synchronously or asynchronously. There is no need for a fixed infrastructure so unlike nomadic systems; scalability only becomes an issue if large numbers of nodes need to be coordinated. By definition ad-hoc systems tolerate disconnections very well but have security considerations associated with node-to-node communications.

2.3 Positioning Systems

2.3.1 Overview

The need for position determination of mobile devices presents special challenges for the mobile distributed system and the middleware design. Design consideration should follow closely the requirements posed by the extended field of mobile distributed computing but in addition particular attention should be paid to issues, which are directly derived from determining user's location either by tracking or estimation. Some of the principles, which are outlined in the following sections, are expected to be addressed by the context- or location-aware system whereas others are the responsibility of the positioning framework. Whichever way the mechanisms satisfy these requirements, it is necessary to consider the implications they have for the acquiring location information.

2.3.1.1 Scalability

Location acquisition requires positioning systems to scale specifically in geography, density and cost.

Geographic scaling refers to the extent of area covered and problems mainly caused by communications in wide area networks. The most obvious difficulty is faced with the speed of communications. In more traditional legacy systems, which are mostly based on Local Area Networks (LAN) and synchronous messaging it is acceptable to block the client until a reply is received to the requested message. In Wireless Local Area Networks (WLAN) the latency grows too large and asynchronous communication model is preferred. In addition to the speed of communication there is the consideration of reliability as communications may not be based on reliable methods such as broadcasting. (Tanenbaum & Van Steen, 2002)

Scaling by density refers to the number of objects that can be located in a given time scale. For example, The Global Positioning System (GPS) can handle an almost unlimited numbers of objects (GPS, 2009) whereas some electronic tag reading systems are unable to read any tags if more than one tag is within range. (Harter et al., 2002) The factors which specifically affect the scalability of a location determination system include congested signalling channels, caused by exceeding the maximum permitted number of communications resulting in latency in locating a device or inaccurate measurements.

The consideration of scalability also includes the *cost* of the infrastructure and the sensors as well as the complexity of the middleware when the system is made to span larger areas. For example, more infrastructure support, better database management and more complex calculations are often required when the area of the environment expands or more elements are introduced into the system. (Hightower & Borriello, 2001)

Most common measurements for location systems cost include time, space, weight, energy and money. Traditionally mobile devices are preferred to be as light weight and small as possible and with low energy consumption in order to have longer battery life. Infrastructure is often associated with a risen time cost in the form of installation, configuration and maintenance. In addition, spatial cost is generally also included when calculating the infrastructure costs, as the density of sensory network is often an issue that also has an effect on other areas of system cost.

2.3.1.2 Trust

Another issue in positioning system design is the notion of trust. Consideration should be given to how users are willing to interact with each other and the underlying infrastructure in order to acquire location.

When a mobile device enters an environment with location determination capabilities it is important to understand the subjective trust establishment which takes place between the users and the infrastructure. Trust implies a degree of confidence that entities behave in a predefined and approved manner in relation to one another. Therefore, a trust management system should help users cope with the uncertainty of whether or not others extend this view. Trust may have dynamic characteristics which change according to the trustee's behaviour or the current environmental or organisational situation.

Trust management frameworks attempt to allow an adequate level of trust to be established between interacting entities in order to accomplish a required action. In systems such as Kerberos (Miller et al. 1987) the trust has been established via centralised third party ticket based systems, which are intended to be contacted on demand. These authorities store trust information and therefore themselves require widespread trust from all the entities which are using the infrastructure. (Grandison & Sloman, 2002)

A large research community has realised the need for decentralised trust management such as credential-based and reputation-based trust management, which avoids a single point of control in establishing trust. Some of the research represents trust as a security policy, which explicitly permits or prohibits actions (Finin et al., 2001), without being able to support partial trust or dynamically change trust assessment. One of the widely adopted approaches to avoid the issue includes frameworks, which are based on social networks and testimonials of witnesses in order to gather a reputation for the user. (Abdul-Rahman & Hailes, 1997).

2.3.1.3 Authentication and Authorisation

Authentication and authorisation processes play a crucial part in establishing trust in infrastructure based positioning systems. Authentication has traditionally been enforced by identifying authorised users from unauthorised ones by requesting an entity's identity and asking it to prove it by using passwords or similar means. As the pervasive computing field is advancing rapidly, the number of devices used by each person multiplies and more external networks are used so a password-based authentication process is no longer a viable solution (Stajano, 2002). The identification and authentication process should not intrude upon the users' interaction but respect the goal of pervasive computing becoming invisible to the user.

Biometrics has had constantly growing interest in the field of pervasive computing. Methods such as iris recognition, voice authentication or fingerprint scanning offer fairly secure way of authenticating users (Garzonis et al., 2004), (Ariyaeeinia , 2004) Unfortunately these methods have not gained a widespread use as yet and some experiments validating the suitability of these techniques have been riddled with false negatives and false-positives (Jain & Pankati, 2006).

Frameworks which base their authentication and authorisation on testimonials of witnesses rely on portfolios which are carried by all entities and signed with their private key (Shand et al., 2003), (Ahmed & Hailes, 2004). The portfolio may include a "letter of presentation", which is signed by other entities who have interacted with the portfolio holder. In these systems it is also possible to ask around other entities about their trust level in order to interact with the portfolio holding entity. This approach tries to discourage malicious entities from forging portfolios or changing identities by complicating interactions in case the portfolio is not complete. This also applies to entities, which have previously not been communicating with other entities with good or bad intentions (Capra, 2004).

2.3.1.4 Privacy

The consideration of privacy is also a widely researched topic and one associated directly to acquiring location in ubiquitous systems. In systems where the infrastructure keeps track of, for example, user location the user's movements and identity are constantly exposed. (Patterson et al., 2003) On the other hand systems, which rely on the mobile device to do the location tracking for the user in such a way that user's identity is not made available to the existing infrastructure limit the usability of the environment. For example, locating other users is not possible in ad-hoc based localization systems.

The focus of privacy should be expanded from concentrating on users to honouring the privacy preferences of all parties involved, including the infrastructure and all the available services. This can be acquired on three levels:

- Solitude – the entity has an option of not being disturbed at any chosen time
- Secrecy – the entity's data is kept private
- Anonymity – complete anonymity in social interactions

2.3.1.5 Heterogeneity

One of the limitations in location determination systems is the incompatibility of location representation between different systems. As stated in Chapter 1 indoor and outdoor surroundings pose a challenge in terms of seamless interoperability between the environments due to incompatibilities in coordinate representations.

The way in which different locations in an environment are labelled or recognised can be referred to as symbology. The challenge in location representation is faced when a single positioning system supports multiple different location representations, which is often inevitable when a system combines a variety of different types of physical or virtual sensors along with technologies such as the Global Positioning System (GPS) or the Global System for Mobile Communications (GSM). In addition to coordinate system conflicts different sensors might have different resolutions and accuracies as well as data rates and formats.

If two location systems use dissimilar location representations, which impedes mapping locations from one system into the symbology of the other the systems are considered *independent* as opposed to *convertible* systems, which allow such mapping. An example of a concept which aims to improve interoperability by making existing location determination systems convertible by providing a common interface is the Nexus project. The Nexus research concentrates on providing an infrastructure to provide a heterogeneous communication environment between already existing positioning systems in order to support location-aware applications. (Fritsch et al., 2000)

2.3.1.6 Computation

In order to assign locations to objects in the system computation has to be performed after collecting the sensor data. The computation can either be performed by the object itself in localized ad-hoc systems or by the infrastructure in nomadic systems

As with any mobile distributed systems, the considerations of where the computation should be performed include; the sufficiency of processing power to execute sometimes intense positioning algorithms and the availability of the required data as discussed earlier in this chapter. In addition privacy may become an issue in systems where it is required a device’s identity is not exposed to the environment unless the user wants to publish the information.

The decision of whether the computation should be localised or centralised also has implications in cost factors, such as the size and weight of the mobile unit, energy consumption and channel congestion.

2.3.2 Positioning System Properties

2.3.2.1 Coordinates

The purpose of any positioning system is to provide location information, which is meaningful and usable in terms of allowing location-awareness for the application. The location information can be reported either physical or symbolic form;

- *Physical* coordinates generally define geometric position points in terms of coordinate pairs that can be converted into one of the many standard global-coverage systems. These can be global references, such as the Universal Traverse Mercator projection (Hatzopoulos, 2008) or local in terms of being valid only to the operating environment. Physical coordinate representations are most commonly used due to the fact that they often are general enough in order to provide an additional level of abstraction for recognising the relevant location labels in the environment. Furthermore co-ordinate systems have high precision and are readily convertible to more symbolic representation of the environment. (Becker & Durr, 2004)

- *Symbolic* location representation is used to define positions in terms of abstractions, which allow location reasoning "based on proximity to known objects" (Hightower & Borriello, 2001). This can mean locations being reported by establishing a containment relationship, for example, in terms of a room number or a street name. A symbolic location representation of an object can not easily be mapped to a more physical location and is thus, considered an example of an independent location system.

Furthermore, Hightower and Borriello (2001) suggest a division between absolute and relative locations by defining a type of a location that is relative to another reference point. For example, relative distance measurements may be used to get an absolute position of an object and in reverse, absolute location can be used to get a position of an object relative to the absolute point.

2.3.2.2 Accuracy and Precision

Accuracy and precision are often reported together to indicate the confidence interval of the measurements. In general terms a lower precision indicates greater variance of random errors, often modelled by a Gaussian probability distribution. The "degree to which this variation is centred on the true value is the accuracy of the system". (Tauber, 2002) Accuracy is reduced by systematic errors introducing bias to the measurements, which may be modelled by reducing the precision. An example of a non-robust measurement in a system might be the interference of sunlight and shadowing causing bias in an infrared system. To clarify the relationship between accuracy and precision further, Hightower and Borriello (2001) use the GPS system as an example: if an inexpensive receiver is able to locate a position within 10 metres for approximately 95 percent of measurements, the "grain size" or accuracy of the system would be indicated in metres with precision percentages indicating how often that accuracy could be expected.

In addition to systematic and random errors, which affect the accuracy and precision of location systems, Hightower and Borriello introduce dilution of precision as a metric of geometric based systems. The dilution of precision relates to the way in which errors in "low level geometric measurements are propagated to higher levels of abstraction". (2001)

The accuracy and precision can be improved by implementing sensor fusion. Sensor fusion is a technique which integrates sensor measurements from different types of sensors in order to form an understandable and hierarchical representation of resolution by having overlapping data from many different kinds of systems. (Hazas et al., 2004) Thus, sensor fusion in addition to improving precision by binding sensing the same distance with multiple different mechanisms can also provide properties, which are unavailable when using positioning systems individually. An example of this might be integrating several sensing systems with different error levels to increase accuracy and precision. (Hightower & Borriello, 2001)

2.3.2.3 Location Rate

The location rate refers to the rate at which locations can be calculated within the system and is often referred to as the update rate. Location lag is the delay after an object moves before being recorded by the system. Therefore, highly accurate spatial location information of an object should be matched with a high update rate to facilitate the modelling of processes of change in detail. The location rate affects the applications which the system is able to support. For example virtual reality (VR) applications require extremely fast location rates. Tauber (2002) states that people wearing VR displays can report motion sickness from as little as 10 millisecond location lag.

2.3.3 Techniques

2.3.3.1 Acquisition of Location Data

In order to estimate the location of a device it is necessary to acquire the measurements from available sensors. According to Wu et al. (2002) considerations in selecting sensors for location-aware environments include:

1. Mobile environment often means highly distributed sensors, which require highly dynamic configuration potential.
2. The price of the sensors should not be too high.
3. Inexpensive sensors might not have necessary accuracies and precisions for the required level of location estimation

When considering different technologies available for positioning an object in indoor surroundings there are mainly three separate categories: *optical, inertial and signal* technologies.

Optical systems have been implemented in the form of computer vision-based systems. The cost of these systems is relatively high limiting the deployment of optical systems to small-scale use. Furthermore, highly sophisticated scene analysis techniques are required in order to eliminate the environmental clutter from the subjects and for this reason many fail in tracking more than one subject at the time. Barcode based tags have been implemented for vision-based systems in order to make tracking more robust. (Hazas et al., 2004)

Inertial systems include, for example, accelerometers which are mounted in mobile units from a known reference point. Inertial systems have the potential of being relatively accurate providing periodic recalibration is being performed in order to avoid accumulative errors but they are not widely implemented in personal mobile devices and are thus mainly used in robotics. (Hazas & Ward, 2002)

Signal technologies suffer from propagation effects which have characteristics including the range, propagation speed, bandwidth, diffraction and reflection, interference, power constraints, safety and cost. (Tauber, 2002) The most common available signal technologies include the following:

Infrared transceivers (IR) are considered to be an inexpensive solution and are popular also due to the small power consumption. IR technology has limitations in bandwidth when it comes to other IR devices within the environment. The reliability of the technology is also affected by varying lighting levels. The signal reflects from most surfaces indoors and has a typical range of up to 5 metres.

Radio-Frequency (RF) signals have a characteristic of being able to pass through common building materials, which is often considered beneficial in location systems. When compared to IR technology, RF signals have better propagation speed, bandwidth and cost characteristics with a common indoor range of 10-30 metres.

DC Electromagnetic fields are used mainly in systems which require high precision and propagation speed. DC Electromagnetic signals are sensitive to environmental interferences and often the cost of systems using the technology rises due to the fact that the systems need constant and precise calibration. The range of DC electromagnetic fields is 1-3 metres.

Ultrasound signals have a relatively slow propagation speed but using ultrasound technology is becoming more popular due to the inexpensiveness and simplicity systems. The propagation speed may be affected by environmental effects such as humidity level or temperature.

RF signal systems are arguably the most used in indoor position determination. (Sun et al., 2005)These can be further divided into ones that utilise:

- *Wireless LAN*, such as *Bluetooth* or *WiFi.* WiFi range is generally thought to be several tens of meters whereas Bluetooth systems can provide more accurate positioning with shorter range. WLAN based systems generally depend on signal strength utilisation. (Sun et al., 2005)
- *Ultrawideband* (UWB) based systems, which have a very fine grained resolution of up to 15 centimetre accuracies are able to determine location with sophisticated calculations made possible by the short pulse duration of UWB signals.

Figure 2.1 demonstrates the granularities and current and prospective deployments of commonly used location tracking technologies. Each technology is described with a box where the horizontal span indicates the accuracy of the technology whereas the vertical boundaries predict the current deployment at the bottom and the future deployment on the top:

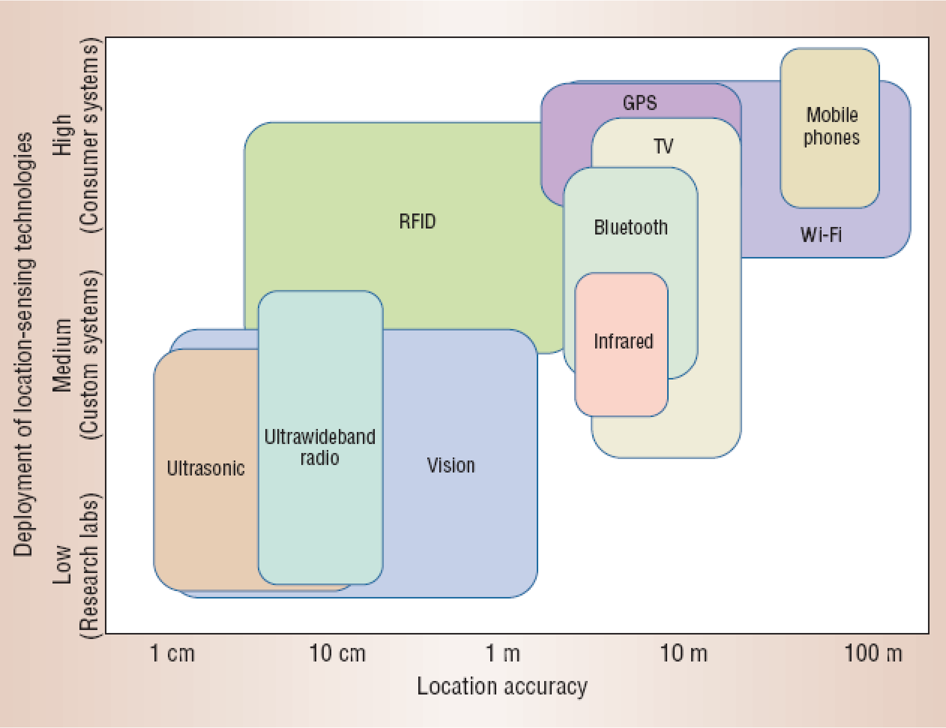


Figure 2.1: Accuracies along with Current and Future Deployment Prospects of Sensing Technologies. (Hazas et al., 2004)

The most commonly used positioning solutions which are suitable for outdoor surroundings can be roughly divided into following (Sun et al., 2005):

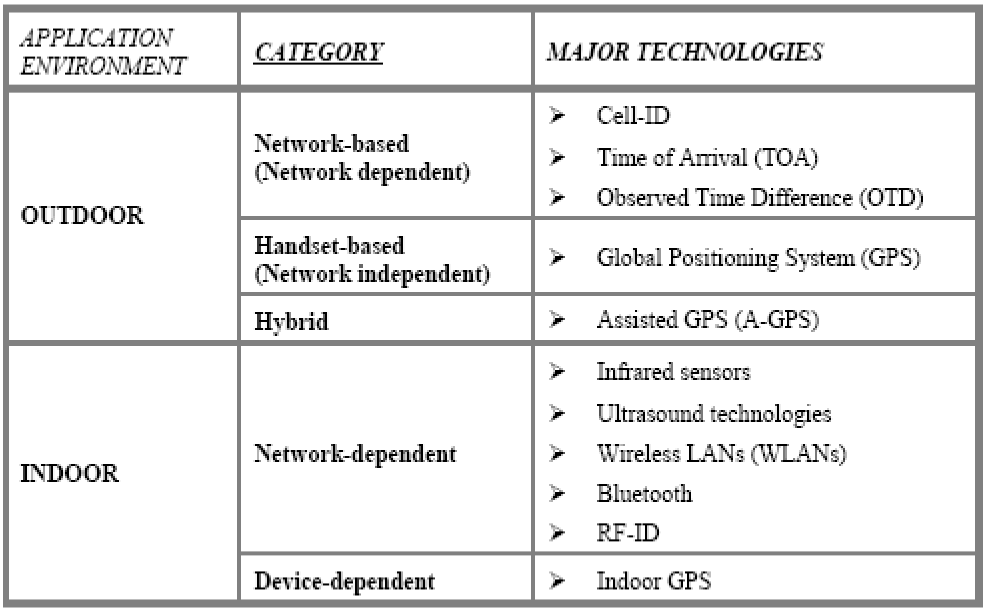
- **GPS**, which is the most common choice. The position is estimated from received satellite signals by measuring time of arrival. GPS suffers from high power consumption, long start up times (30s – 15min) and relatively high cost along with degrading performance in indoor and high-rise, dense urban areas. (GPS, 2009)

- **Assisted GPS (A-GPS)** aims to improve start up time (< 10s) and provides better accuracies than GPS both indoor and outdoor surroundings. As the technique uses terrestrial cellular networks the mobile handset is required to be equipped with a specialist A-GPS receiver. (Sun et al, 2005)

- **TV-GPS**, which relies on television broadcasting signals to intensify GPS signals. The performance of the receivers is similar to those utilising A-GPS and as with assisted GPS, TV-GPS can be also used indoors. (Hazas et al., 2004)

- **GSM** using **E-OTD** standard, which calculates the time difference of signals travelling between two different base stations. The Emergency 911 II phase requirement for United States emergency services is adopting the use of E-OTD as *de facto* standard (Sun et al., 2005) due to the capabilities of reliably positioning with accuracies of 50-125 metres with widely deployed existing hardware. (Sun et al, 2005)

The taxonomy of both indoor and outdoor positioning technologies can be seen in Figure 2.2.



APPLICATION ENVIRONMENT	*CATEGORY*	*MAJOR TECHNOLOGIES*
OUTDOOR	**Network-based (Network dependent)**	➢ Cell-ID ➢ Time of Arrival (TOA) ➢ Observed Time Difference (OTD)
	Handset-based (Network independent)	➢ Global Positioning System (GPS)
	Hybrid	➢ Assisted GPS (A-GPS)
INDOOR	**Network-dependent**	➢ Infrared sensors ➢ Ultrasound technologies ➢ Wireless LANs (WLANs) ➢ Bluetooth ➢ RF-ID
	Device-dependent	➢ Indoor GPS

Figure 2.2: Taxonomy of Positioning Technologies. (Pateli et al., 2002)

2.3.3.2 Location Estimation

After obtaining the measurements from the sensors the data is combined to deduce the location of unknown points by using one or more of the following techniques in order to locate the device: triangulation, scene analysis and proximity. (Hightower & Borriello, 2001)

1. Triangulation

Triangulation helps to calculate the position of a device by using simple triangle geometry such as the distances between known points or angles. Triangulation can be further divided into two categories, namely *lateration* and *angulation*.

- Lateration uses distance measurements as its main principle. The position of an object is measured by computing the distance of multiple reference positions. In general terms, measuring the two-dimensional position of an object requires three reference points as shown in Figure 2.3. The lateration technique can be further divided into three different techniques to measure the actual distance between reference points. Multiple different techniques exist to measure the distance of an object from a reference point whose co-ordinates are already known.

    1. One of the most common approaches is to measure the distance using *attenuation* of received signal strength (RSS) by calculating the loss of signal due to propagation. Signal propagation characteristics dictate that the signal emission decreases while the distance increases. The method utilises the signal strength measurements from the mobile devices to deduce the distance and since these measurements are a part of normal operations for RF signal systems, it is the preferred choice for most WiFi and Bluetooth based positioning systems. (Sun et al., 2005) The downside of RSS techniques is the problem with required line of sight. During line of sight operation measurements can be achieved very accurately from most sources but non-line-of-sight causes loss of information in all measurements.

(Caffery, 1999) Complex mathematical estimation techniques for expected delays exist and are surveyed by Sayed et al. (2005) and Pahlavan et al. (2002) but are outside the scope of this thesis.

2. Another method, which is widely used, is to calculate the *time-of-flight* using Time-Difference-on-Arrival (TDOA) or Time-of Arrival (TOA) of a signal in cases where the signal propagation speed is known. This implies a requirement for clock synchronisation, which is especially problematic in ad-hoc networks since this approach adds complexity, expense and in most cases weight to the mobile unit. However, cellular positioning systems have successfully utilised TDOA technique providing it is coupled with a method of broadcasting synchronization information for time difference calculations. Similarly, GPS satellites transmit a time stamp along with the signal for synchronization purposes. Also UWB based positioning systems utilise the TDOA technique combined with Angle-of-Arrival calculations (AOA) in order to determine the direction of the signal. UWB works with very short bursts of RF pulses that last only a few nanoseconds at a time, which enables an effective use of these methods in order to calculate distances very accurately. (Fontana & Gunderson, 2002) Also the time-of-flight techniques suffer from signal loss similarly to RSS and same modelling mechanism are used to calculate expected delays. (Gustafsson & Gunnarsson, 2005)

3. A *direct measurement* is also possible by using physical movement. The automation of direct measuring has been difficult to obtain due to coordination issues and hence, this type of distance measuring is only ever widely adopted in robotics. (Hightower et al., 2002)

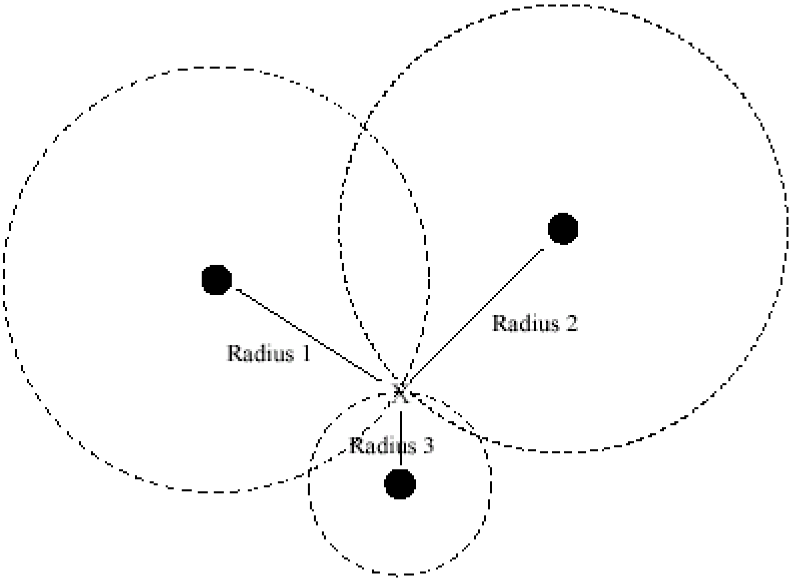


Figure 2.3: Lateration Technique (Hightower & Borriello, 2001)

- Angulation uses angles to determine the position of an object. Two dimensional measurements require two angle measurements and a length measurement as shown in Figure 2.4. (Hightower & Borriello, 2001)

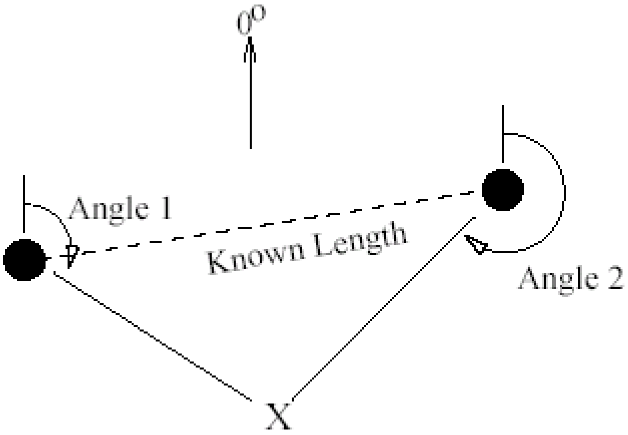


Figure 2.4: Angulation Technique (Hightower & Borriello, 2001)

2. Scene Analysis

Scene analysis or pattern matching based positioning uses distinctive features in the scene which is to be analysed from a particular point of view. Scene analysis is mainly used in outdoor positioning in urban areas to overcome severe multipath problems (Mangold & Kyriazakos, 1999) although indoor applications exist where a model is constructed based on RF signal strengths from a predefined number of locations in the target area. When a mobile device reports signal strengths during a positioning request, the model is used to compare the difference in order to deduce the position.

According to Hightower et al. (2002) scene analysis can be classified into: static scene analysis and differential scene analysis.

- *Static scene* analysis uses maps or datasets to look up features which are being analysed in the scene.
- *Differential scene* analysis tracks the differences between scenes to be able to estimate the location. The observer's position can be calculated relative to the differences in the scenes and the viewing point.

3. Proximity

The proximity location sensing technique aims to determine whether an object is near to a known location. Hightower and Borriello (2001) identify three approaches to sensing proximity.

1. *"Detecting physical contact"* with an object may include pressure sensors or touch sensors.
2. *"Monitoring wireless cellular access points"* to determine when a mobile device is in a range.
3. *"Observing automatic ID systems"* such as credit card sale terminal or computer login histories.

2.3.3.3 Positioning Techniques

As mentioned previously there are two underlying techniques, which can be used to position mobile devices. These are infrastructure based positioning and ad-hoc based localization. The underlying network topology depends on the preferred method of communication and coordination, as discussed previously in this chapter. Some of the most widely used positioning techniques, on which most current frameworks base their design, are outlined below: (Sun et al., 2005)

1. **Positioning by infrastructure in wireless LAN networks**. The positioning performed by WLANs is network centric generally utilising RF technologies such as Bluetooth and WiFi. These systems often use RSS, TOA and TDOA methods for signals obtained from wireless base stations to deduce distances and combine them with proximity or triangulation measurements to estimate a position.

    - Client Based Positioning System Design uses pattern matching (also called location fingerprinting or indoor scene analysis) (Bahl et al., 2000) technique that requires two separate phases in order to operate: the offline phase includes calibration of the system, which records signal strengths from strategic places within the environment in order to produce a model of the surroundings. The online phase allows devices to report their signal strength to the system, which compares them to the previously produced model for position estimation. (Sun et al., 2005) Obvious issues with the extent of the offline calibration phase, out-of-date environment models and area coverage arise.
    - *Client Assisted Positioning System Design* has been researched in order to address the issue of deployment and maintenance. These systems rely on simple software sniffers to monitor client signal strengths and record time stamp information from the transmission. This information is then combined with data obtained from a number of other sniffers to estimate a device position based nearest neighbour searching algorithms. (Ganu et al., 2004)

2. **Positioning in Ad-Hoc Sensor Networks**, which is generally referred to as localization, is mobile-centric often utilising temporal measurements and motion models (Gustafsson & Gunnarsson, 2005). Most localization systems use RF signals with RSS, TOA and TDOA methods for distance measurement. Technologies such as UWB can also use AOA based directional measurements to get very accurate, limited range measurements for localization. (Sayed et al., 2005) Current research in ad-hoc positioning can be roughly divided into following categories: (Sun et al., 2005)

- *Beacon Based Localization* relies on some of the nodes being equipped with special positioning equipment, such as electrical compasses or GPS receivers. Nodes which are lacking positioning equipment, localize themselves from three or more beacons by using proximity based methods and become beacons after receiving a position. (Bulusu et al, 2004) Due to simple proximity based algorithms these systems are considered energy efficient with little radio resource usage. (Sun et al., 2005)

- *Localization with Moving Beacons* is thought to reduce power consumption and cost of the system further (Sun et al., 2005). In these systems mobile beacons, which know their own position using some absolute coordinate system act as "observers". The observers move in a predictable manner and facilitate other nodes of the system to calculate their position using the trajectory of the observer combined with proximity calculations. (Sichitiu & Ramadurai, 2003)

- *Beacon Free Localization* has been investigated due to high initial and calibration cost of using technologies such as GPS to provide an infrastructure of beacons for nodes to localize with. A beacon free solution aims to facilitate localization of every node through node-to-node communication by coordinating themselves through distance calculations. The resulting map of coordinated nodes requires a translation process to convert the subjective node map into absolute coordinates. (Nagpal et al., 2003)

2.4 Summary

The diversity of technologies, which facilitate location determination means that it is necessary to have a single taxonomy to compare and contrast systems that have been developed in order to make devices location-aware. Furthermore, due to the lack of standards the multitude of available techniques for positioning needs careful consideration when choosing methods to implement. Some of the choices have to be based on good design principles, which are derived from the field of mobile distributed computing such as considerations for heterogeneity, scalability and adaptability to name a few. Others, like measuring techniques and such are more specific to the field of positioning mobile devices.

Chapter 3

RELATED WORK

3.1 Introduction

To meet the requirement of making a device location-aware a number of positioning systems and frameworks have been developed. The purpose of this chapter is to present a survey of the most impressive commercial solutions and research projects, which aim to satisfy the criteria for position determination described in the previous chapters. The positioning systems introduced have been chosen as they are considered to be good demonstrations of each technique and as such are together considered to define the current development in the field of position estimation and localization.

The chapter has been divided into two main sections: the first one outlines the basic working principle for each positioning system discussed in its own sub-category. The second section aims to use the evaluation criteria and taxonomy introduced in Chapter 2 to compare each system in order to identify the open issues that have not been solved by current techniques.

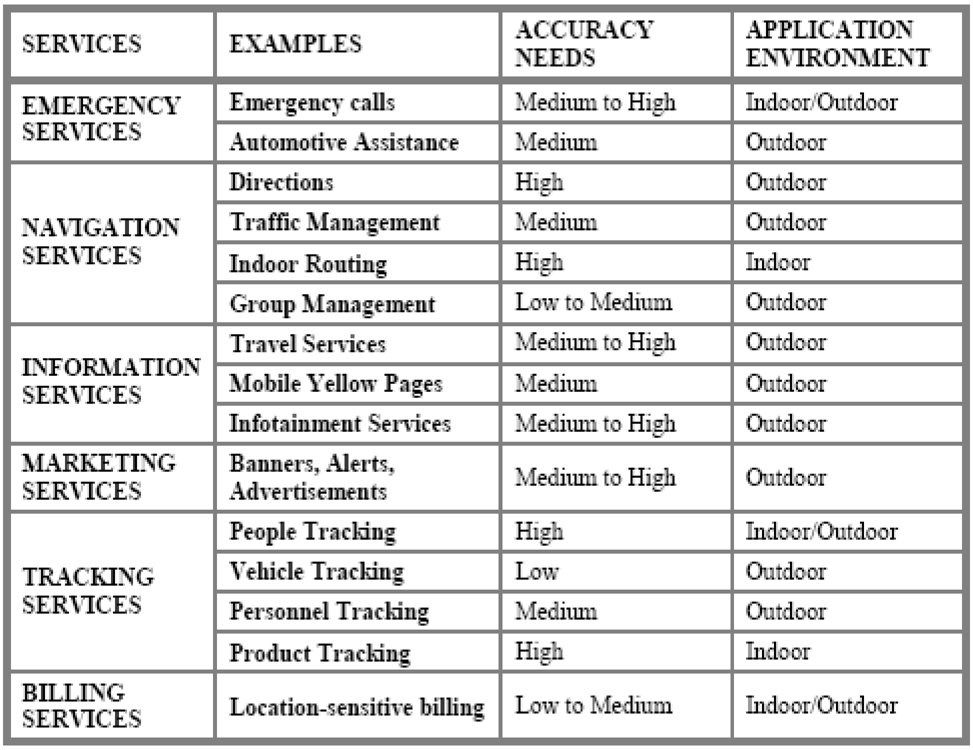
3.2 Positioning Systems

Projects such as the MotionStart Magnetic Tracker (Ascension, 2001) should be acknowledged for their positioning capabilities. The MotionStar system generates DC magnetic field pulses from an antenna at a fixed location. The system is able to compute the position and orientation of receiving antennas. The system has a very high precision and accuracy with less than one millimetre resolution. However, the implementation costs are high and the system is not scalable for large location-aware applications.

Another example of novel location determination is Microsoft Research's Easy Living (Easy Living, 2001) project which uses computer vision to determine where objects are located. The project uses real-time 3D cameras to provide stereo- vision positioning and can be expanded to use additional scene analysis features like silhouette, skin colour and face patterns to provide more accuracy. This generally increases the scene complexities and needs a lot of processing power when the frames are analysed. (Darrell et al., 1998)

Georgia Tech has developed a Smart Floor (Orr & Abowd, 2000) proximity location system which positions people by capturing footfalls with embedded pressure sensors. The approach is very unobtrusive as pedestrians can be recognised from their footprints. However, the system is not very scalable and in larger buildings the cost can be high as the floor has to be physically altered in order to install the physical sensor grids.

Although a large number of positioning systems exist and important research in the field includes these specialised frameworks, which have been developed for a specific purpose the focus of the rest of this chapter is to introduce positioning and ad-hoc localization systems, which have been implemented in order to gain wider deployment to facilitate location-based services. This includes services such as the ones shown in Figure 3.1.



SERVICES	EXAMPLES	ACCURACY NEEDS	APPLICATION ENVIRONMENT
EMERGENCY SERVICES	Emergency calls	Medium to High	Indoor/Outdoor
	Automotive Assistance	Medium	Outdoor
NAVIGATION SERVICES	Directions	High	Outdoor
	Traffic Management	Medium	Outdoor
	Indoor Routing	High	Indoor
	Group Management	Low to Medium	Outdoor
INFORMATION SERVICES	Travel Services	Medium to High	Outdoor
	Mobile Yellow Pages	Medium	Outdoor
	Infotainment Services	Medium to High	Outdoor
MARKETING SERVICES	Banners, Alerts, Advertisements	Medium to High	Outdoor
TRACKING SERVICES	People Tracking	High	Indoor/Outdoor
	Vehicle Tracking	Low	Outdoor
	Personnel Tracking	Medium	Outdoor
	Product Tracking	High	Indoor
BILLING SERVICES	Location-sensitive billing	Low to Medium	Indoor/Outdoor

Figure 3.1: Taxonomy of Location Services (Pateli et al., 2002)

3.2.1 Network Centric Centralized Positioning

3.2.1.1 Active Badge

The Active Badge location sensing system was developed at Olivetti Research Laboratory, later known as AT&T Cambridge. (Want et al., 1992) The Active Badge could generally be considered one of the first ground breaking positioning systems and is very well known in the field of position determination. The system consists of a cellular proximity system, which uses infrared technology and reaches positioning accuracies on room level, owing to the reflection characteristics of infrared signals and the fact they can be contained by walls.

Each person requiring positioning wears an active badge, which emits a Globally Unique Identifier (GUID) every 10-15 seconds or as and when needed. The data is collected by a central server by querying fixed infrared sensors around the building. The badge network is able to support up to 128 sensors, powered by the network.

The location information, which is gathered from the badges, is considered symbolic as each sensor represents a space such as a room. The Active Badge system is able to tell which badges are near to the one making the query or a specified location either at the current time or in the past. The system also provides a long lived query function, which is able to notify the user when a requested badge is being located. Due to the power consumption of the badges and limited battery size the location of each badge can be refreshed at best in 15 second intervals. There is also an approximately 1/150 chance that two signals collide when in the same room making positioning impossible for that time slice.

There are some well known problems with the Active Badge system, most of which are caused by the sensitivity of infrared technology to direct sunlight or fluorescent light. (Want et al., 1992) Infrared technology also requires a line-of-sight from the badge to the sensor. However, since the infrared signals reflect off nearly every indoor surface no directional data can be derived by the receiver.

The Active Badge system requires sensors to be placed high up in the walls or ceiling which makes the deployment of the system burdensome. The sensors and badges themselves are low cost and are connected to network with conventional twisted pair cable, which somewhat reduces the implementation costs.

3.2.1.2 Active Bat

AT&T have developed the Active Bat (Harter et al., 2002) system to follow the Active Badge. The Active Bat system uses an ultrasound time-of-flight lateration technique to resolve the location of objects. The physical location can be resolved more accurately than with the Active Badge up to an accuracy of nine centimetres with 95 percent precision. The Active Bat system is also able to determine the orientation of the objects.

As with the Active Badges the users wear Active Bat tags to respond to the short-range radio signals sent by the controller. The tags emit ultrasonic pulses to the receivers mounted in the ceiling and are identified by GUIDs. The update frequency is decided based on the monitoring of Bats and how often they tend to change location. The number of Bats in the network is determined by the number of base stations and their address spaces, which can be made almost as large as required.

The infrastructure requires a large grid of fixed sensors with precise placements, which makes the scalability of the system an issue. (Harter et al., 2002)

3.2.1.3 The Radar

The Radar tracking system developed by Microsoft Research is based on IEEE 802.11 WaveLAN wireless technology and uses no custom hardware. (Bahl et al., 2000) The Radar was one of the first systems to examine WLAN based positioning utilising generic base stations, which are stationary and continuously connected to data and power resources between wireless and wired networks.

The Radar uses a client based system design capable of calculating the 2D position of an object within a building using a location fingerprinting technique by measuring the signal strength and signal-to-noise ratio of mobile devices at the base station. In order to acquire the location of an object, an offline calibration of the Radar system is necessary, where a predefined number of signal strengths are recorded in certain locations in order to create a model of the area called signal space. This model simply consists of tuple of signal strength values and co-ordinates where they have been measured. The Radar also allows multiple models to be measured and stored, taking environmental conditions such as the signal strength variations caused by large number of people into account. The system is also capable of storing information about signal strengths through a number of walls at various distances and the power of transmitters.

Radar’s pattern matching technique can locate objects up to three meters accuracy with 50 percent precision by implementing algorithms, which are able to calculate the nearest neighbour in signal space and the probability of a user moving between two locations in successive time periods in order to predict the most likely location of the user. (Bahl & Padmanabhan, 2000)

3.2.2 Device Centric Localized Positioning

3.2.2.1 The Cricket

The Cricket system, which was developed by the The Massachusetts Institute of Technology (MIT) (Piyantha et al., 2000) shares the same ultrasonic ranging technology with the Active Bat system. The Cricket uses ultrasound emitters in the infrastructure and receivers in the objects being located, which do their own triangulation calculation in order to determine their location. In addition to using the lateration technique, the Cricket system uses proximity to detect objects nearby.

The Cricket system is completely decentralised as each component is configured independently without any synchronisation or registration by a central entity. The privacy level in Cricket is high, since the object may decide itself whether or not location information is made available to other entities.

The cricket also uses time-of-flight data but unlike with the Active Bat it does not require a large fixed grid of sensors to be mounted in the ceiling as the mobile devices perform the location calculations.

The accuracy of the Cricket system does not quite match Active Bat but is still capable of acquiring almost 95% precision. The system has relatively low level of accuracy as it is able to locate objects in approximately in four by four square foot regions. However this enables the system to be reasonably geographically scalable since it only relies on one stationary beacon for each room.

The cricket has been considered to place a burden in managing and monitoring the mobile objects and consuming too much power on already resource limited mobile devices. (Priyantha et al., 2000) Furthermore, since mobile units calculate their own position without direct communication it is possible that beacon signals interfere with each other.

3.2.2.2 Skyhook Wireless

An interesting new commercial project, which is available for multiple mobile platforms, is the Skyhook (Skyhook, 2009). Skyhook allows WLAN based positioning of a mobile device by relying on public WiFi access points, which are not controlled by any service operator associated with the positioning. Skyhook reports around one second lookup times with 10-20 meters of accuracy.

Skyhook utilises a RSS technique for measuring distance between the access points and the mobile device. This is combined with triangulation algorithm to allow the device to deduce its own position based on locations stored to a central look-up table.

The Skyhook system doesn't maintain its own WLAN structure; instead it manages a database of access point locations, which have been input along with the signal strengths and Media Access Control (MAC) addresses of the associated access points. The look up table can be queried by any mobile device that has a connection to the access point with the MAC addresses. The database is constantly updated by process called "wardriving". (Jones et al., 2007) This is done either by Skyhook "drivers" who input GPS based global coordinates to the system by visiting the sites of public access points or by devices which query the database by sending the information of all access point within the range. If the location of some of these isn't known, the system calculates the positions for these and updates the database accordingly.

3.3 Evaluation and Performance Issues

3.3.1 Criteria

Unfortunately due to the lack of existing standards it is difficult to compare error characteristics of various systems from reports that are made available about the experiment design and analysis. Some commonly accepted metrics exist, which can be used in making assumptions about the performance of the positioning systems. These are discussed in detail in Chapter 2:

- *Accuracy and precision*
- *Calibration*: Initial offline time that is needed in order to reach a functionality that responds to the real world situations.
- *Cost*: Including initial set up, deployment, maintenance and administrative cost. Also cost in power consumption and processor use is a consideration.
- *Scalability*
- *Location Rate* or Responsiveness
- *Privacy*

The assumptions that can be made include the granularity of the system, which is reported by accuracy and precision figures. For example Active Bats and the Magnetic Tracker have an error margin of up to 10 centimetres where as in Radar, Active Badge and Cricket systems the range is generally between 1 to 10 metres. For GPS the errors are typically reported in meters and public WLAN based systems tens of metres.

As discussed in Chapter 2 the sensing technologies, which have been implemented may be used as an indication of robustness. For example RF technology when used indoors has the tendency of being unpredictable due to multipath effects and signal attenuation (Pahlavan et al., 2002) due to, for example movements of large number of people in variable indoor environments. Time based measurements also remain difficult for RF as well as ultrasound, which also suffer from shadowing effects. Furthermore, IR technologies are sensitive to direct sunlight and fluorescent lighting. (Sayed et al., 2005)

When measuring update rates for current location systems it is necessary to take the numbers of units that may be located in every update into account. For example in the Cricket system each mobile unit is able to update its location each time a beacon is heard. Active Bats use polling technology where one Bat may be located in each RF range per update. Radar is able to use the either the beaconing from base stations or other mobile units.

There are number of considerations of the cost of the location systems. These include actual cost, weight and size of the mobile unit and the space the infrastructure requires. In addition one of the most crucial aspects of cost is time. This includes the installation as well as the administration overheads of each system. In Active Bat system the initial cost of set up is extremely high as the centralised model and sensory network have to be installed into a place with careful antennae measuring and positioning as well as RF signal calibration, which due to the centralised nature of Active Bat system have to have ongoing maintenance. The location database is also considered large and complex, requiring each Bat to be separately registered with the system. (Tauber, 2002)

Both the Skyhook and Radar systems have relatively small start-up cost due to the off-the-shelf requirements of the base stations. The calibration of Radar is, however, more burdensome to get accurate location predictions.

Closely related to installation cost of location systems is the system's ability to scale geographically. Generally speaking, centralised systems tend to have more scalability issues due to the fact that as the number of mobile units increase the more they have to compete for resources. For example the Active Bat system is only able to track one mobile unit in a room per one time frame. Increasing the number of units in the same space decreases the update rate for each mobile unit. This also applies to the Radar system, which in addition has greater burden placed on the location database, which has to be able to grow as the number of units increase.

Privacy is a consideration in centralized systems which gather data from mobile devices and track users. Anonymity is more likely in ad-hoc based system, where the identity of the device can be hidden behind a MAC address or a GUID.

Table 3.1 sums up the systems and technologies discussed in terms of evaluation criteria.

Name	Accuracy Precision	Scale	Unit Cost	Environment	Mode
Active Badge	Room size (~99%)	low	Low	indoor	centralized
Active Bat	9cm (95%)	low	Low	indoor	centralized
A-GPS	1m (~99%)	high	High	both	localized
Cricket	1.5m (~100%)	med	Low	indoor	localized
Easy Living	variable	low	High	indoor	centralized
GPS	1-5m (~99%)	high	Moderate	outdoor	localized
GSM	50-125m	high	Moderate	outdoor	centralized
MotionStar	1mm (~100%)	low	High	indoor	centralized
Radar	3-4m (50%)	med	Moderate	indoor	centralized
Skyhook	10-20m	high	High	outdoor	localized
UWB	15cm (~95%)	med	High	both	localized

Table 3.2: Positioning System Classification Criteria.

3.3.2 Discussion

As briefly discussed in previous chapters most technologies have not been developed in order to make devices location-aware. As a consequence the accuracies of systems implementing the technologies are measured in metres. A good example is the cellular GSM technology, which has been adopted as a positioning system due to the second phase requirement of E911, where all emergency calls in the United States have to be tracked to the accuracies of 50-100 metres. (Hazas et al. 2004). This kind of granularity is acceptable for the E911 specialist use or for very coarse positioning required by for example, simple marketing type applications. Although most of these yellow-page type services requiring positioning can manage with coarse grained location information such as the one based on cellular identities, many other applications require location-awareness on a completely different level.

One option is to combine multiple technologies such as the GPS and GSM systems to create a hybrid A-GPS position determination system. (Sun et al. 2005). The added bonus of the A-GPS is that it seems to enhance both technologies tremendously: accuracies improve along with high precision; the system is suitable for use both indoors and outdoors not to mention the significantly faster start up times to get a location fix. The only drawback of the system seems to be the availability and the support. This type of advanced technology such as A-GPS and TV-GPS is only good if it is at the fingertips of the users that require the service in the first place. The same goes to the very promising UWB technology, which would overcome many open positioning issues if only it was already accepted as a standard, already and allowed to be made widely available.

The question of supported surroundings is another one that needs careful consideration. Systems such as Active Bat and Active Badge might have mobile units that are cheap to manufacture and made available for positioning purposes. The downside is the infrastructure. Both need a significant deployment effort indoors but are not viable for use outdoors. Middleware, such as the Nexus project was developed for exactly this purpose; to enable seamless deployment of multiple different systems, such as the badges with the bat paired with GPS or compasses, under one management infrastructure. (Fritsch et al., 2000) The idea is good and definitely improves interoperability between different systems. However, it still requires users to be carrying the actual equipment which is to be seamlessly integrated. The assumption can be made, that a lot of users would prefer the choice of having a single device rather than a GPS receiver with a smartphone and with a badge or a barcode tag.

The scalability or the cost of the infrastructure isn't the only consideration when it comes to centralized, infrastructure based systems. Public WLAN based systems like the Skyhook require a mammoth effort of "wardriving" unless the system is ready to accept the risk of spoofed locations to be input in the system as demonstrated by Tippenhauer et al. (Tippenhauer et al., 2009). Client Based systems like the Radar too, require significant calibration efforts in order to achieve the required pattern matching model for positioning. Furthermore, the situation is made worse in dynamic environments where a static model just would not prove to be flexible enough. Client assisted systems aim to overcome the issue by employing sniffer software to track communications. This causes privacy concerns, which are shared throughout the whole concept of centralised positioning systems, especially the ones that track the position of the users such as the badge systems, since at least some aspects of the devices identity information must necessarily be exposed to the environment along with the location information. This implies trust from the user to the environment's access control to filter out malicious processes and vice versa.

The issue of availability of the positioning service is tightly bound to scalability, too. Most systems which aim to provide absolute location coordinates without expecting the devices to be equipped with technologies such as GPS, require three reference points to operate. This is the case with all of the WLAN based systems surveyed, although having more reference points to perform the positioning provides a basic assumption of improving the accuracy and precision of the system. Since calculations, such as triangulation algorithms provide a way of pinpointing a device from three distance measurements this is the *de facto* standard in position estimation. However, solutions which rely on having at least three location reference points knowing their position imply either an infrastructure of calibrated reference points, such as in the Radar system or an army of individual devices that can be contacted in an ad-hoc manner such as the research demonstrated by Niculescu and Nath (Niculescu and Nath , 2003) or Bulusu in his doctoral thesis (Bulusu, 2002).

Overcoming, the problem of positioning availability has been a challenge that has been attempted by using moving beacons in order to reduce the number of required reference points. Sichitiu and Ramadurai (Sichitiu and Ramadurai, 2003) propose a method of a device localising itself by using a single moving beacon on a predefined track. The device is able to estimate its own position by distance measurements and by knowing the state of the beacon's movement on the track. Although an interesting direction for future research, a robot based result such as the one introduced by Sichitiu and Ramadurai or further expanded with controllable moving beacons by Galstyan et al. (Galstyan et al., 2004) is not a viable concept to be deployed in larger public systems.

The purely ad-hoc based solution to the availability problem has been further explored by Nagpal et al. (2003) with self-organizing, self localizing community of devices that are able to deduce their own positions relative to each other. The problematic issue is how to transform the relative, proximity based information into something, which resembles an absolute position coordinate without specialist equipment indicating orientation and such.

An ad-hoc community has been seen as providing the answer to the privacy issue. A mobile unit is as anonymous as it wants to be but a problem is contacting services or other devices, which somewhat overlooks the basic idea of providing location-awareness for the use of context-based applications. Device restrictions are also an issue such as battery life and heat dissepation. Most of the positioning algorithms are complex and do require significant processing. Another problem worth noting has to do with the limitations of mobile devices and the hardware. Due to the necessarily compact characteristics of mobile devices, physical restrictions play a large part in terms of, for example, the screen size, limited battery life and processing power. In device based positioning, the already resource-poor mobile devices are forced to deal with significant computational burden in order to obtain location information from raw data and convert it to a sensible representation, as discussed in more detail in Chapter 2. Unless, of course, the application is content with using coarse-grained location information offered by technologies such as GSM or technologies lacking interoperability or such as GPS.

3.4 Summary

Although multiple position determination systems exist to satisfy the requirements for making a device location-aware each system has drawbacks which have stopped it to become widely adopted. The systems may be sufficiently accurate but expensive or the cost of the infrastructure is too high. They might have scalability issues or problems with wider deployment of the system. Or they might simply be too much work in terms of calibration and management.

There is a need for a positioning framework which is able to seamlessly determine the positions of mobile devices without the need for specialist equipment or extensive infrastructure support. The system should allow sharing of location data, such as GPS coordinates while honouring the privacy preferences and the device limitations. It should allow for the dynamic characteristics of public places and understand the uncertainty factors of wireless communications.

Chapter 4

DESIGN OBJECTIVES FOR POSITIONING FRAMEWORK

4.1 Introduction

The purpose of this chapter is to identify the need for further research in order to provide location-awareness for context-aware applications. It aims to outline the main points of weakness in the existing approaches and explores a proposed solution to address the issues raised in Chapter 3.

Section 4.2 introduces the proposed approach and while section 4.3 explores the design issues which have affected the implementation of the proposed solution. This is discussed further in subsequent chapters.

4.2 Approach

Due to the challenges faced by the current positioning approaches, it can be seen that not all the basic requirements introduced in Chapter 2 are satisfied by the existing technologies. As a consequence, the need for a framework, which takes the computational burden away from the mobile device, has been identified whilst honouring the privacy preferences of the users in terms of allowing positioning, but not tracking of the devices, as has been the case with systems like the Active Badge (Want et al., 1992). Moreover, the framework should maximise the ability to use and interact with the positioning environment and at the same time minimise the vulnerabilities of the existing solutions by combining the centralised and localised approaches into one mechanism. The framework should be able to provide a location fix with minimum location data available and yet meet some clearly defined limits for accuracy, precision and the speed of positioning.

A general approach is proposed to demonstrate the principle of positioning a mobile device in an environment with only minimum number of location references or unreliable location data available. The solution is a combination of the previously introduced positioning approaches which currently require purpose built sensory infrastructures, accurate location data or in some cases specialist equipment (Sun et al., 2005) in an attempt to meet the basic requirements for a positioning framework. The proposed solution aims to extend and enhance the existing technologies by introducing a hybrid solution, which is discussed in detail in the remaining chapters.

4.3 Design Objectives

The proposed solution has a number of properties, which make it desirable for the use as a positioning environment:

- The infrastructure has minimum administrative and maintenance costs as the technologies used are commonly available in mobile devices such as personal digital assistants (PDA), laptops or smartphones.

- The framework uses a feedback system for the purpose of initial set up as well as for easy integration into existing environments with fixed sensors. This also ensures that the accuracy and speed of positioning in more dynamic situations are improved.

- Performance heavy calculations are not performed on mobile devices but the data is sent to the infrastructure for processing and returned in the required format in order to address the issue of limited resources on the devices.

- Since the sensor data is mainly obtained from the devices, the environment is not tracking users or their movements by default. The user has an option of solitude within the positioning environment.

- The framework is able to combine multiple sensors available on mobile devices and transform generic proximity data into positioning data.

- The multiple sensor approach also ensures that accuracy can be improved by combining the best possible resolutions for available technologies.

- The issue of scalability is addressed by the minimum number of fixed sensors required, which are effectively replaced by mobile devices. In addition, the existing fixed sensors utilise broadcasting of the location data, to stop the communication channel becoming congested from data requests.

- Positioning doesn't rely on a central database as a solution for a location finding. Instead the data is current with a possibility of introducing performance enhancing solutions to the framework as further discussed in Chapter 7.

Another key point is that the proposed solution is capable of determining the position of a device with a single moving location reference. If there is a possibility that the information provided by a single reference device is incorrect the data can be stored for the future in order to determine the validity of it when more devices are within the detection range. By sharing, optimising and calculating position information as more location data becomes available, the system is able to utilise partial location data in a manner that has an important contributing role in the positioning process not only for the requesting device but also to the environment. If applicable, the acquired location information is fed back to the infrastructure and stored in the fixed sensors, where it can be further refined by future positioning requests.

In order to address the issue of accuracy as well as one of location four principles are implemented in the proposed solution. Detailed discussion on the technique is introduced in Chapter 5.

1. The positioning is performed on a demand basis, when certain conditions are met. Namely,

    - The device has no location information stored or there is a high probability that a better location value would be obtained from the available reference points.
    - The device has moved and the location information it holds is no longer accurate.
    - There is a device in the immediate proximity, which is likely to have more accurate location value.

2. The solution combines location data from multiple available sensors with different resolutions.
3. A dynamic model is implemented to determine when the required accuracy will likely to be achieved at best possible precision.
4. Partial location data is not overlooked. Instead it is utilised and used as supporting information to the absolute location data available when location calculations are performed. The weight of partial location information is determined by the confidence figure, which is associated with the final position information.

The solution deploys a probability model to determine the reliability and "usefulness" of the data in terms of the whole of the positioning process, for each iteration until required accuracy has been acquired. The model defines a calculated level of precision and a range for error margins which in turn provide useful information to the calling device even in situations where no absolute location data is available. Therefore, the model is capable of producing position information based on data that would not be considered reliable in other location tracking frameworks, which generally only considerer position determination to be successful if the outcome is within the limits of set error margins.

The framework aims to address the challenge of employing a useful location representation by offering the possibility of deducing absolute position information from more vague location data consisting of containment or proximity information. The solution communicates locations in terms of internal absolute co-ordinates within the positioning environment. These co-ordinates correspond to a physical world as an x and y co-ordinate pairs, and are obtained from transforming proximity and containment data retrieved from available mobile devices.

In order to accurately position devices, the co-ordinate pairs are always associated with a confidence figure, which reflects the probability of that piece of location information being accurate and to the required precision. As an example, absolute co-ordinates, which have been obtained from a GPS device, would be converted into an internal representation of x and y values by the transformation layer of the framework and associated with a confidence figure of 99 to reflect the certainty of the correctness of the coordinates. Equally another co-ordinate system might be treated differently depending on the resolution or granularity of the technology and precision of the available information. For example, mobile phone cell co-ordinates would be transformed into absolute co-ordinates within the environment similarly to the GPS ones, but the confidence level would correspond to the nature of the technology as well as the data it produces and thus, be set to, for example, five percent due to the coarser granularity of the technology as discussed in Chapter 3. Hence, the lower the confidence figures of the devices are, the more unknown points there are in the environment. Furthermore, as demonstrated in Chapter 6, a single device with absolute co-ordinates and a high confidence figure is able to provide enough data to significantly reduce unknown locations in the environment.

The solution utilises an RF signal propagation technique in order to measure distances between devices from the attenuation of the signal strength. The distance calculations are combined with a two separate distance measurement techniques in order to determine an absolute position of a device within the environment. The technique or a combination, which is applied, is determined by the number of distance measurements available, the number of devices which may be employed as sensors and the confidence figure of these devices. As an example, the use of the triangulation technique has been adapted whenever there are sufficient numbers of devices to be used as reference points. In general terms lateration requires a minimum of three devices. In addition to triangulation, proximity information is combined from a number of different devices in order to obtain more reference points with better confidence figures. As the data is processed, the requesting device will be assigned an absolute position along with a confidence figure, which is calculated from the available reference points. How these calculations are made is discussed in detail in Chapter 5. The confidence figure may thus be seen as a “measure of usefulness” which that particular device represents to the environment.

From the transparency point of view the solution involves two mechanisms, which aim to improve availability: a dynamic model to attempt to re-establish positioning until sufficient accuracy with required precision is reached and the possible use of ad-hoc beacons when communication errors restrict exchanging of location data. In order to improve fault tolerance in full or partial failure circumstances, the confidence calculations are performed in the mobile device itself. This is to ensure that a mobile device is able to receive and use position information in terms of proximity to a beacon without a danger of the information being passed back to the environment as an accurate position for the device.

4.4 Design Restrictions

It should be noted that at present the proposed framework is currently able to support one geometry co-ordinate system like GPS with an addition of three other wireless technologies, which provide proximity information to the mobile device, such as WiFi, Bluetooth, infrared or other such signal technologies. The restriction isn’t methodological as much as a design choice, which has been adopted due to the current availability of positioning technologies.

Other design choices exist, most notably at present the framework does not produce information such as routes in a cluttered environment where physical restrictions exist within the space. Chapter 7 further discusses how the system could be initialised, customised and configured to interact with services such as route or travel distance finder in indoor environments.

It is also worth pointing out that information about device location is not stored within the infrastructure. Instead positioning is performed in an on-demand basis, where location data is stored within each device. Although techniques, such as caching of location data might prove to be beneficial for performance, the choice of not utilising, for example, a database structure for storing locations within the infrastructure reflects the belief that currency of position information is crucial for the location rate and hence, accuracy. The prospect of using caching is, however, further visited in Chapter 7.

A solution to the issue of overloading the communication channels and the mobile clients has been explored by the use of subscriptions in order to avoid devices with low bandwidth links or limited processing power getting swamped with location requests. However, similarly to the issue of caching, the implementation of the subscriptions has been left from the focus of this solution. The principle is introduced in Chapter 7.

Chapter 5

FRAMEWORK FOR POSITION DETERMINATION

5.1 Introduction

This chapter starts with an introduction to the main components of the positioning framework and aims to cover the main purpose of each. It then continues to describe their behaviour and responsibilities in order to facilitate positioning of mobile devices based in a dynamic environment. It provides details of the developed method along with the algorithms used and provides examples of situations when each one is most appropriately deployed.

The term *environment* is used to describe a collection of *entities*, which are connected to each other indirectly by an *infrastructure*. The entities may be aware of each other through overlapping sensor ranges or *detection ranges,* which are used to identify *reference devices* in order to create a *proximity map* for an entity in need of positioning.

The main logical components of the environment are shown in Figure 5.1 followed by a description in the subsequent sections of this chapter.

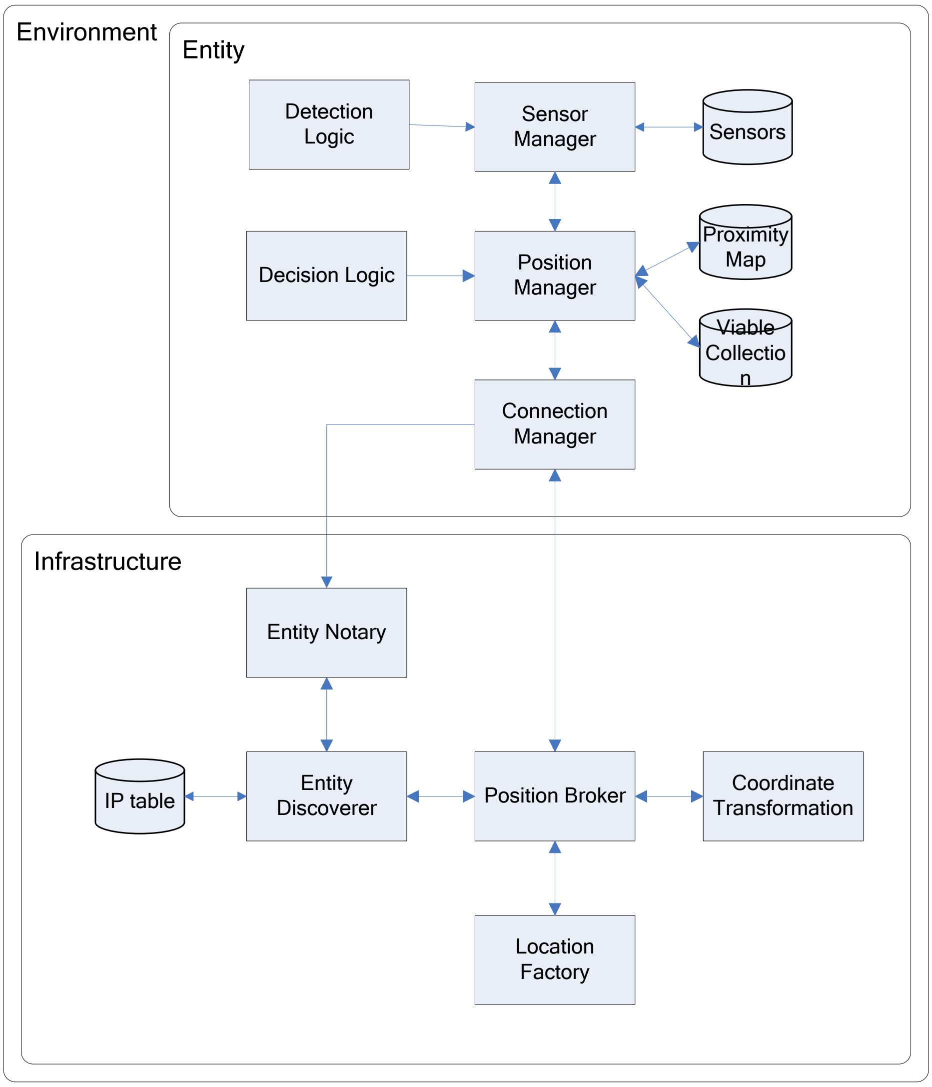


Figure 5.1: Main Logical Components of a Positioning Environment.

5.1.1 Location Representation

As briefly introduced in Chapter 4, the proposed framework defines an internal two-dimensional coordinate system (Shigeyuki et al., 2001) to symbolise locations within a positioning environment. The location information consists of a Cartesian coordinate pair (Moon & Spencer, 1988), which represents the most recent known position of the mobile device within that environment. The *x-coordinate* and *y-coordinate* of the location point is stored in the device along with a figure of certainty or a *confidence* value.

The framework aims to calculate a single coordinate pair for a mobile device by performing one of the implemented positioning algorithms. If the environment lacks sufficient position references in order to perform triangulation a number of possible coordinate points are calculated for the device based on the received signal strength indicators of nearby reference devices. By default, these viable coordinate points are spaced by one metre distance to each other. In order to achieve the required accuracy the framework aims to gradually rule out coordinates, which are not possible by recording changes in reference devices' locations within the device's proximity. The process of refining a location is referred to as positioning cycle later in this chapter.

The resulting coordinate pair does not have to be distinctive from the absolute geometrical coordinate convention such as the GPS but the values may be extracted from the device and transformed directly into a format that is uniform throughout the environment and usable by the framework. The confidence value indicates the probability that the client is located in the recorded coordinate point and not in some other absolute location some distance away.

5.1.2 Entities

The framework contains entities which may be mobile devices that are temporarily part of the environment or ones which have been set up to serve as stationary reference device, referred to as an anchored entity or a beacon. A mobile device can be anything from a smart phone to a laptop computer as long as it has a physical capability to connect to a wireless network in order to communicate with the infrastructure and allow the use of simple user interface.

Each entity within an environment may request a location or potentially be used as a reference device for the purpose of positioning another entity as long at it has a set of location coordinates. Regardless of whether an entity is anchored or moving each has a set of attributes and physical properties, which define its current status within the environment and follow implicit conventions. These are outlined below:

- ***Name***: A globally unique identifier (GUID) for each entity, which is generated by the infrastructure in order to identify and contact each entity within the environment. The name is a 128-bit integer, which is based on Media Access Control (MAC) address of each device and has a very low probability of being duplicated.

- ***Location***: An integer pair describing the device's *x* and *y* positions within the environment. Entity receives a location as a result of a completed positioning cycle, which is initialised either by movement, better availability of reference devices or a user request, which together form decision logic for initiating a cycle.

- ***Confidence***: A figure that reflects how accurate a result the current positioning cycle can be expected to return. Confidence is calculated based on the proximity map created for that cycle.

- ***Sensors***: A combination of available sensors for an entity at any given time. This consists of an array of maximum of three ranged sensors used for detecting devices nearby and one, which is capable of using an absolute geometry system such as the GPS. The minimum requirement for existing sensors is a single proximity based sensor, which can be used to communicate between the entity and the infrastructure. In addition, at least one sensor capable of peer-to-peer connection is required in order to find the RSSI value for calculating the distance measurements. In practical terms this implies an enabled WiFi adapter set on infrastructure mode along with, for example, a Bluetooth or infrared sensor reporting proximity information. Each proximity sensor has a range set uniquely depending on that sensor technology and a signal strength indicator, which reports how close the entity in question is to the sensor. The sensors are maintained by a sensor manager, which is responsible for gathering data from available sources in order to formulate when requested a list of entities' GUIDs within the detection range. The sensor manager is influenced by user preference, which dictates which sensors are visible to the environment and thus, can be used by the infrastructure for proximity maps. The user also has a choice of deciding which sensors are available in the device for the infrastructure to use at any given time. The principle idea behind the choice is to allow the user to roughly limit the number of contacts from the infrastructure for the purpose of forming a proximity map and using the device as a reference. Each entity is, however, required to have a principle wireless sensor available for networking purposes and to form a proximity map with.

- ***Detection Range***: The signal area for a sensor, which has been made available for the infrastructure and therefore, may be utilised in a positioning cycle. In case of multiple available proximity sensors, the primary detection range is always the one with finest granularity sensor or in practice, one with the shortest actual range.

- ***Proximity Map***: Collection of data compiled to describe the surroundings of an entity. This consists of GUIDs along with the possible coordinates and confidence figure of other entities within the detection range, details of the sensor technologies used and distances. A proximity map is created for an entity either because it has requested a location or because it has been identified in the map of another entity as a potential reference device. The proximity maps for different entities are combined by the infrastructure and used to perform the positioning cycles.

- ***Viable Collection***: Consists of a viable range, which is a stored set of alternative or possible coordinates for an entity.The possible coordinate points for an entity are kept in order to resume a positioning cycle in case the devices within the proximity of the entity have moved causing the proximity map to be updated. Also two sets of confidence figures are stored:

  1. A viable confidence figure calculated by combining the confidences of reference devices used.

2. A start confidence which indicates the probability of picking a correct location randomly from the viable range.

- ***Error Margin***: Indicates how much the returned location is expected to vary from the actual location of the entity. The error margin is by default one metre but depending on the user choice of positioning modes may be ***significantly hig***her.

- ***Beacon Status***: A beacon status attribute that is used to determine the level of the required positioning along with the positioning mode. The beacon status indicates whether the device is anchored and acting as a beacon, in which case the positioning cycle is launched more easily and positioning algorithms are selected, which concentrate on reducing error margins over time. The beacon status also indicates whether an entity is moving by inspecting signal strengths from the sensors.

- ***Positioning Mode***: The user has an opportunity to have impact on the decision logic when it comes to making a positioning request. Three positioning modes have been defined: *normal, persistent* and *sparse*.

The user has a possibility to set the positioning on persistent, which means the entity constantly requests its location from the infrastructure until a required confidence is reached or positioning can be initiated from the user interface on demand basis. In addition, there is the choice of normal positioning mode, which triggers the positioning cycle when certain conditions are met, as explained further in this chapter. Persistent positioning is useful in situations where the location correctness is more important than the speed of positioning or when a user requires constant refreshing of the current location. Persistent positioning is utilised by default when a device is anchored whereas on normal mode changes in the entity's detection range start the positioning cycle. There is also a choice of selecting a sparse positioning mode, which ensures a location is returned along with a start confidence whenever at least one reference device is within the detection range. The implication of sparse positioning mode is a significant rise in the error margin, which is calculated for each positioning cycle, requested using sparse positioning. Due to this fact devices, which request positioning on a sparse mode will never be used as reference devices.

Figure 5.2 demonstrates a simple arrangement of devices which may be used as the basis of forming proximity maps

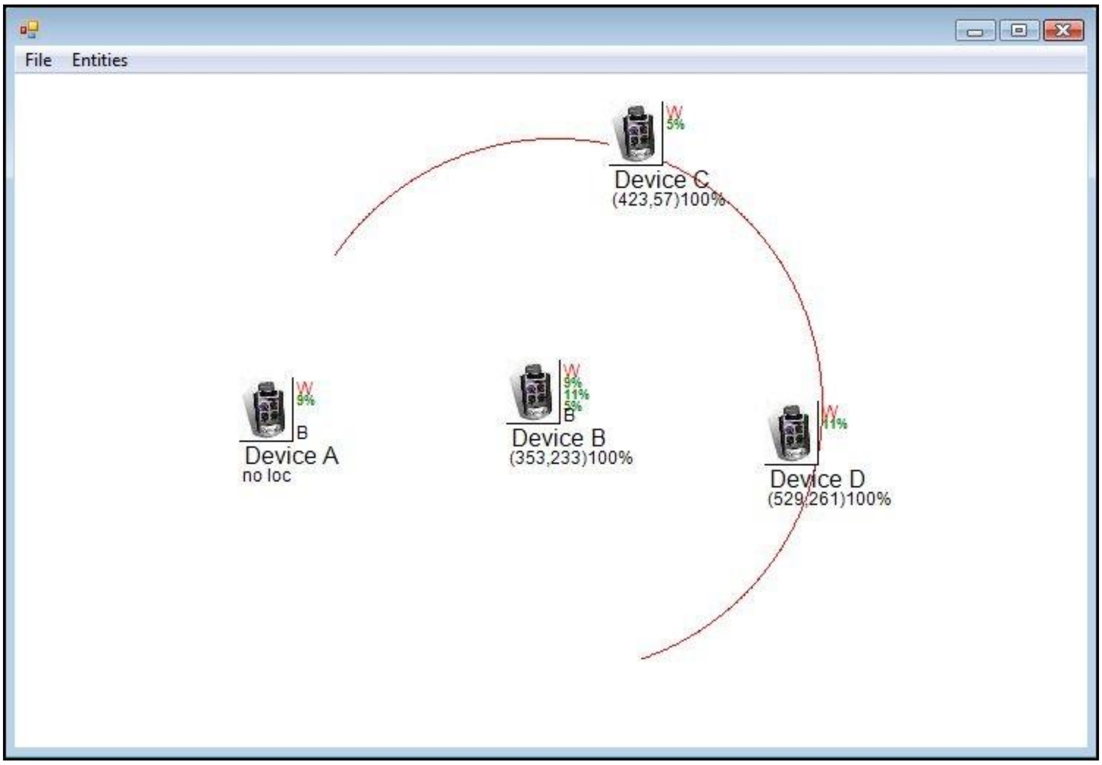


Figure 5.2: **Example data collected for proximity maps.**

.In the figure 'Device A' depicts an entity which lacks position information. When forming a proximity map for 'Device A' information about 'Device B' is recorded to include:

- GUID's to identify devices A and B
- The signal strength from device to device along with the sensor technology. These are shown as a percentage figure and a letter 'W' in Figure 5.2.

- The coordinates for 'Device B' as well as the confidence figure, which are shown *(353,233)* coordinate pair and a *100%* confidence.
- The Viable Collection for 'Device A', which consists of:
    1. The viable range for 'Device A'. In Figure 5.2 the initial viable range is calculated as a result of forming a proximity map also for 'Device B', which reveals devices C and D. These additional reference devices 'Beyond a Hop' are utilised to rule out a number of coordinates drawn as an arc in the figure. This leaves the viable range for 'Device A' to be stored in the proximity map allowing these coordinates to be used in refining positioning cycles to further rules out coordinates as described later in this chapter.
    2. The two confidence figures which indicate the combined confidence of all the reference devices used when forming the proximity map and a confidence figure which illustrates the confidence in any location picked for the device should it be on sparse mode.

5.1.3 Infrastructure

The infrastructure has a crucial part in positioning by executing most of the performance intensive calculations away from the mobile client. A number of key components may be identified:

- ***Entity Discoverer:*** In order to ensure reasonable privacy while being part of the positioning environment, entities are not able to contact other mobile clients directly. The infrastructure holds a dynamic table, which keeps track of currently available entities along with their GUIDs and how to contact them. The entity discoverer is responsible for routing and exists for infrastructure use only. Furthermore, it offers neither interface nor access for entities within the environment.

- ***Entity Notary:*** Handles registration requests and passes routing information to entity discoverer. Notary also takes care of authentication and authorisation, when necessary.

- ***Position Broker:*** Acts as an interface for entities in the environment, which request a positioning cycle. Position broker has a role in deciding, which devices are relevant for the positioning cycle, organising the gathering of device data from those entities and finally forming the proximity maps to be used for positioning.

- ***Location Factory:*** Performs position and confidence calculations based on data submitted by position broker.

- ***Coordinate Transformation:*** Acts as a layer between absolute coordinate data and the location representation used within the environment. It converts coordinates taken from a device, such as GPS receiver in GPX format and converts them into an x and y coordinate pair used for positioning an entity (GPX1.1, 2007).

5.2 Acquiring Location

5.2.1 Positioning Cycle

The process of positioning is initialised by an entity only if it doesn't have location information stored or there is a possibility that the information is incorrect or incomplete. The location information is present if the client either has absolute coordinates from, for example a GPS receiver transferred into the internal coordinate representation or a previous positioning cycle has been successful and the device has not moved since.

Whether the location information is incomplete or incorrect is judged by inspecting the confidence attribute, which indicates whether there is a possibility that a previous positioning cycle has not been executed using accurate coordinates and hence, the bias might have been transferred on to the location attribute for that entity. In this case a positioning cycle can be triggered if new or more reliable reference devices have entered the immediate detection range.

After an entity requests a positioning cycle it sends its current reported location and confidence along with the information from accessible sensors, previous viable collection and a proximity map, if available, to the position broker. After an interest has been recorded the position broker determines whether the positioning cycle is necessary or even feasible, as shown in Figure 5.3.

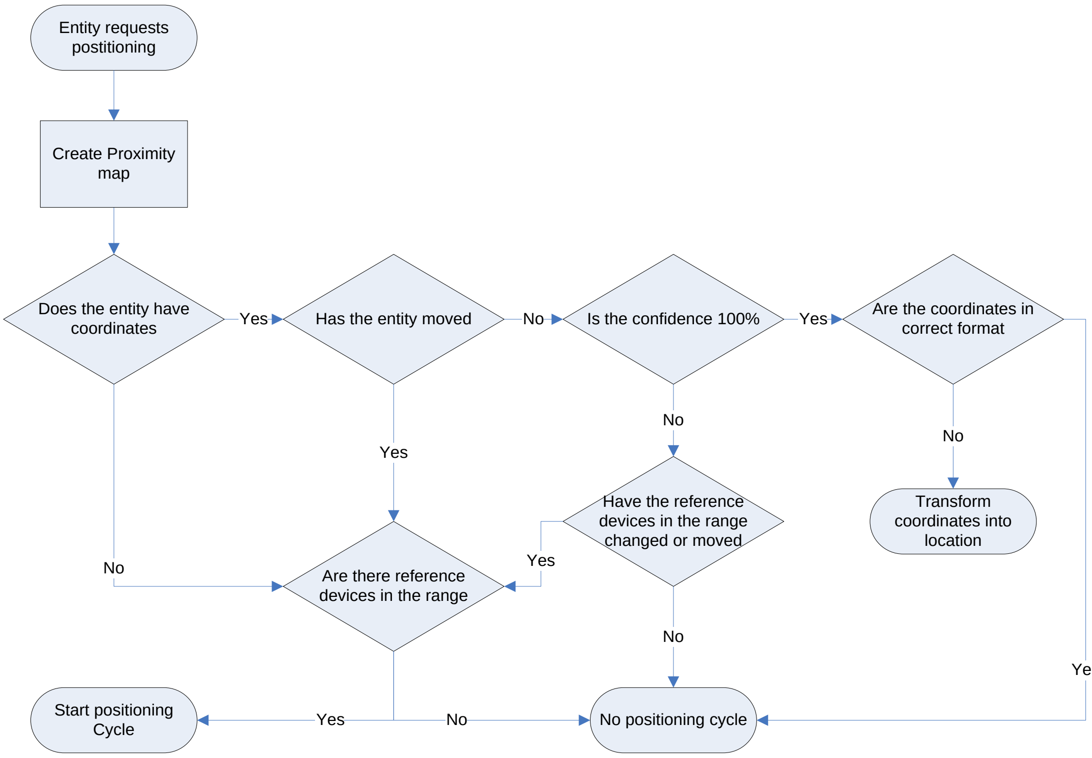


Figure 5.3: Principal Logic for Commencing a Positioning Cycle

The cycle may be successful resulting in a location that satisfies the error margins or it may be inconclusive, either resulting in no location or one or more sets of alternative potential coordinates. A positioning cycle is successful when an entity is presented with both values: a location and a confidence regardless of how high the confidence attribute for those coordinates is. If an entity has more than one set of possible coordinates a previous, inconclusive positioning cycle may be resumed by utilising the viable range providing that the entity's proximity map has changed without it having moved itself. If no reference devices are available the positioning cycle is unsuccessful. Regardless of the outcome of a positioning cycle a proximity map is still created along with a viable collection, providing at least one reference device is within detection range. This information can be later used to judge whether it is possible to complete a cycle when fresh devices enter the detection range of a device or refine a location by renewing the positioning cycle with different combinations of reference devices.

5.2.2 Creating Proximity Maps

A proximity map is created for each device involved in the positioning process either as a reference device or as an entity requesting a location. The purpose of the map is to survey the detection ranges of affected entities for potential reference devices or alternatively to detect changes in the environment. The proximity map is a collection of data compiled by the position broker based on simple questions the entity is asked to submit answers to as and when requested:

1. What is the type of sensors that are currently in use?
2. What is the detection range of each sensor?
3. What entities can be detected with each sensor?
4. What are the reported signal strengths to those entities?
5. What is the current location?
6. What is the current confidence?

Based on the answers distance measurements take place and all the data is stored into a proximity map object.

5.2.3 Measuring Distance

As stated in Chapter 2, the triangulation technique requires three reference points with absolute location coordinates and the distance of these points to the device requesting positioning.

Since the coordinates for the requesting entity are not known, the distance from one device to another is calculated by utilising signal attenuation once the range of the technology which is used by each device is known along with the received signal strength indicators (RSSI). It is worth mentioning that in order to complete theoretical calculations, ideal propagation parameters have been assumed within the space. In-building propagation characteristics as well as radiation, shadowing, spatial and temporal signal propagation have been ignored, hence leaving distance calculations relying solely on large-scale propagation, in which signal loss or weakening is determined by distance only using the inverse-square law for signal loss (Anderson et al. 1986) as described in Chapter 2. Other approaches exist and are discussed in Chapter 7.

The method for calculating distance between devices without known coordinates is based on obtaining signal strength indication for each shared sensor technology on each device in range and converting this data into a percentage for the purpose of facilitating comparison between multiple sensing technologies with varying detection ranges.

Figure 5.4 demonstrates the principle behind the signal strength based distance measurement technique.

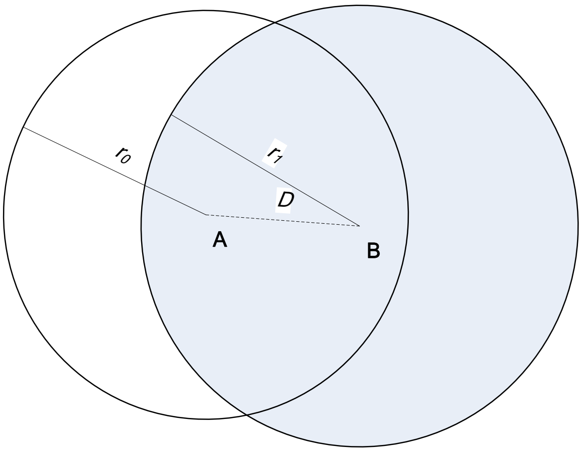


Figure 5.4: Measuring Distance Utilising Signal Strength Indicators

From observing Figure 5.4, devices A and B share a technology used for sensing each other's proximity. The technology on device B has a range of r_1 and signal strength is indicated by received signal strength indicators as *k percent of maximum 100 percent signal strength* to the device A, whereas device A has a range of r_0. The distance D is simply calculated by taking a k percent of r_1.

$$D = r_1 \frac{k}{100} \tag{1}$$

It is worth pointing out that although simple distance measurements could be performed on the mobile device without restricting performance the infrastructure is responsible for measuring distance for three main reasons:

1. It is believed that querying reference devices in order to form proximity maps for determining the position of another entity should be as unobtrusive as possible.
2. A simple check can be performed in order to decide whether there is variance between the distance measurements obtained from the RSSIs of two separate entities, which report sensing each other. In case there is variation, which is greater the accepted error margin, the used device can be discarded as reference. Otherwise an average of the two distance calculations can be used in the proximity map.
3. It is possible to integrate an existing mathematical model for signal propagation calculations into the proposed framework in order to improve the RSS model of distance measurements as described in Chapter 2 and further visited in Chapter 8.

5.2.4 Monitoring Changes and Detecting Movement

In order to determine whether a positioning cycle is worth executing it is necessary to detect changes within the environment, as shown in diagram 5.3. Mainly this means determining whether the entity, which is requesting positioning, has moved or whether reference devices within the detection range of that entity have moved or changed altogether. In order to detect changes in devices and their positioning within an entity's detection range, current proximity map and a previous one are compared. If the entity itself has stayed in the same place, each change in the range initialises another positioning cycle. The framework detects entity movement only by inspecting signal strengths. Each entity has a beacon status attribute, which indicates whether the entity is stationary, has been anchored and is acting as a beacon or whether it has moved.

The technique used to determine when an entity has changed its location without having an access to absolute tracking technology relies on briefly caching the signal strengths of the nearby devices in the client. Thus, the device is able to decide whether a value for each signal has simultaneously changed in the same proportion to avoid a situation where a number of devices have commenced moving. An entity is assumed stationary unless the sensor manager reports a coincident change in signal strengths for all devices within its detection range.

There is a possibility that each of the external devices have simultaneously changed their state from stationary to moving. The probability of this happening is the product of the probability of each device having commenced moving at the time the observation is made, assuming no preconditions are regarded, there are more than one reference devices in total and none of the devices are anchored. According to Croft and Davison (Croft & Davison, 2003) Multiplication Law can be used to determine the probability of the events: If A and B are simultaneous events with a sample space $\Omega = (\{0,1\})$ to depict 0 as a stationary device and 1 as a device that started movement at a given time, then the probability of an event P to occur is:

$$P(A \cap B) = P(B)\, P(A \mid B). \qquad (2)$$

For example, if a mobile device, which has an access to the signal strengths of four devices in the proximity, the probability that all reference devices have started moving at the same time and hence, a false positive has been recorded for location change of the requesting device is simply:

$$P = \frac{1}{2^4} = 0.0625, \text{ which equals to } 6.25\% \qquad (3)$$

Thus, resulting in a chance of at least 93.75% indicating the requesting device has initialised the recorded changes in the signal strength. It should be noted however, that the worst case scenario where all of the devices have moved instead of the entity being positioned only results in a new positioning cycle and thus, doesn't affect the reliability of the positioning cycle.

If there is only one device within the detection range of an entity it is impossible to say which of the devices is moving solely based on changes in signal strengths. In this case both devices are assumed to be moving and hence, requiring a new positioning cycle with no preconditions for calculating the confidence. If, however, one of these devices reports an anchored beacon status that device maintains its location attribute while the other one is concluded to have moved and hence, requires a new location.

5.2.5 Calculating Confidence

Since the confidence is a value representing the certainty in a device's absolute coordinates, it is obtained by calculating its likely position and then combining the values of the reference points, which are used to derive the location coordinates.

The confidence figure is representative in correctness of a device location at any given time; it is not aiming to indicate the precision or accuracy of the positioning system nor does it imply that one device would be a more reliable reference in all situations than a lower confidence device. The confidence attribute only has a meaning for a specific positioning cycle with an arrangement of specific devices with their current sensor and positioning configuration. The confidence value reports the certainty of the positioning cycle returning a result within a set error margin using reference devices with different sensory capabilities in specific circumstances, which lead to indicate the accuracy and precision of the positioning within the environment.

The main principle is that the confidence is initially calculated by using reference devices within the detection range and is then used to improve the location by iterations, which use different arrangements of reference devices in the proximity in order to get the best possible confidence value for that cycle, as explained further in this chapter.

The confidence is calculated by using the multiplication law as shown in equation 2, which according to Croft and Davison (2003) may be used to calculate probabilities of independent events such as a combined confidence from individual reference devices. Thus, if a positioning cycle returns a single coordinate, the confidence is calculated as a product of the confidences from the reference devices used. However, should the cycle return alternative locations for that entity, the confidence value is a product of the references divided by the number of possible coordinate points. The following sections demonstrate how this main principle is used in practice.

5.2.6 Obtaining Coordinates

The principle of calculating a position based on three devices as reference points is shown in Figure 5.5.

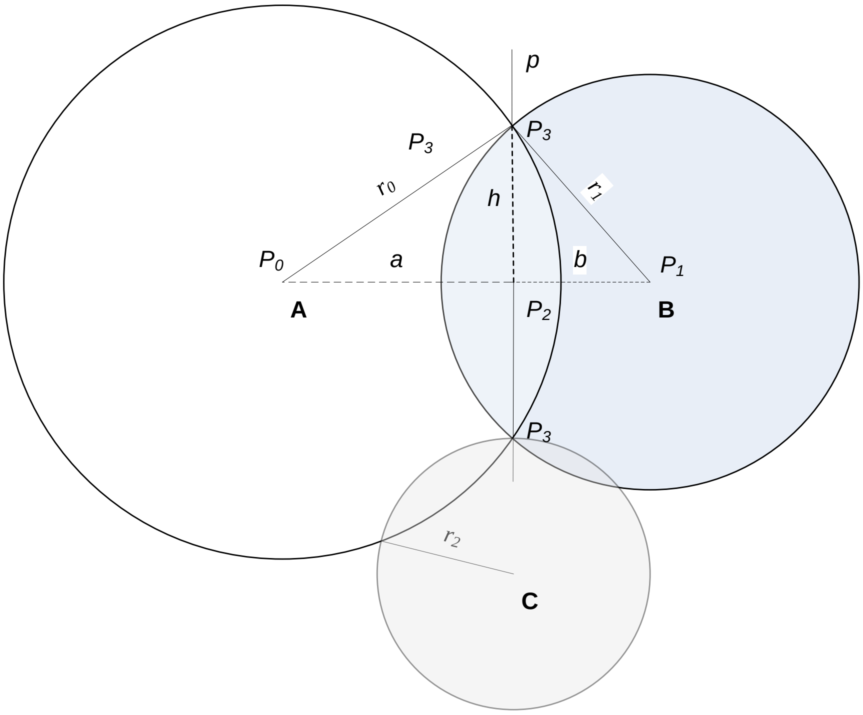


Figure 5.5: Calculating Shared Coordinate Points from Intersecting Detection Ranges

Figure 5.5 shows a radical axis *p*, which is a chord through the intersection points P_3 of the circles, which depict the detection ranges of devices A and B at coordinates P_0 and P_1. In order to determine a position of a mobile device, a radical centre is calculated, which indicates a mutual point of intersection for all three reference devices. Radical centre is obtained by initially calculating the coordinates for points P_2 and P_3 and is followed by repeating the calculations by substituting the values from a third device for the first device's equation.

The one-dimensional Euclidean distance (Nahin, 1998) between the first two devices at points P_0 and $P_{1:}$

$$d = \sqrt{(\mathrm{P}_1 - P_0)^2} = |\mathrm{P}_1 - \mathrm{P}_0| \,, \tag{4}$$

Where *d* must be smaller than the sum of the two radii;

$$d < |\mathrm{r}_0 + \mathrm{r}_1|.$$

If,

$$d > |\mathrm{r}_0 + \mathrm{r}_1|,$$

Then, the mobile devices are outside of sensing range from each other, whereas if $d = 0$, the two devices are coincident and thus, may only be counted as one reference point.

From Figure 5.5 two triangles can be formed, namely

$$\mathrm{a}^2 + \mathrm{h}^2 = \mathrm{r}_0^{\ 2} \tag{5}$$

$$\mathrm{b}^2 + \mathrm{h}^2 = \mathrm{r}_1^{\ 2}. \tag{6}$$

Using: $d = \mathrm{a} + \mathrm{b}$,

$$a = \frac{(\mathrm{r}_0^{\ 2} - \mathrm{r}_1^{\ 2} + \mathrm{d}^2)}{(2\mathrm{d})}. \tag{7}$$

Now, *a* can be substituted into the first equation in order to get,

$$h^2 = r_0^{\ 2} - a^2. \tag{8}$$

So,

$$P_2 = P_0 + a\frac{(P_1 - P_0)}{d}. \tag{9}$$

And finally coordinate pairs for points:

$P_3 = (x_3, y_3)$ in terms of $P_0 = (x_0, y_0)$, $P_1 = (x_1, y_1)$ and $P_2 = (x_2, y_2)$, is:

$$x_3 = x_2 \pm h\frac{(y_1 - y_0)}{d} \tag{10}$$

$$Y_3 = y_2 \pm h\frac{(x_1 - x_0)}{d} \tag{11}$$

In order to find an intersection point for all three detection ranges, either device A or B is substituted with device C. The resulting coordinates are compared with an error margin of one metre in order to the radical centre indicating the location, which is shared by all three reference devices.

Triangulation with three reference devices is always the first step of obtaining coordinates where sufficient reference devices exist. This is due to the fact that out of all possible positioning algorithms it is the fastest one returning a single location for an entity without alternative possible coordinates. If the entity's proximity map indicates that there are multiple possible reference devices only three are chosen based on their reported confidence values. Depending on the positioning mode of an entity, the positioning cycle may be refined further in order to obtain a higher confidence value and more accurate location coordinates.

5.2.6.1 Calculating Viable Range

The viable range is calculated if sufficient reference devices are not found within the entity's detection range either due to the outright lack of devices in the environment or in case the devices have incompatible sensors. At least one reference device is assumed with location coordinates and a confidence figure in order to calculate the viable range for an entity. If a viable range is stored for an entity, it is always paired with two sets of confidence figures. The first one is calculated as a start confidence for an entity. The start confidence is a product of the confidence values of reference devices multiplied by the ratio of viable range to all of possible coordinates for an entity. This figure indicates the probability of any arbitrarily chosen coordinate from the viable range being the device's actual location and is combined with a result from error margin calculations for devices on a sparse mode. The other confidence figure is a viable confidence, calculated as a combined product of the references' confidence figures and which can later be used to calculate the actual confidence for a final location result for an entity.

The process of calculating a viable range is initialised by forming proximity maps for all affected parties; the entity requesting positioning as well as the devices within the detection range. The purpose is to find out whether there are devices "beyond a hop" or devices, which can be used to rule out coordinates, which are not possible locations for the entity. The viable range is calculated when there are one or two immediate reference devices around the entity.

Figure 5.6 demonstrates a situation where a device beyond a hop is used to limit the viable range with only one immediate reference.

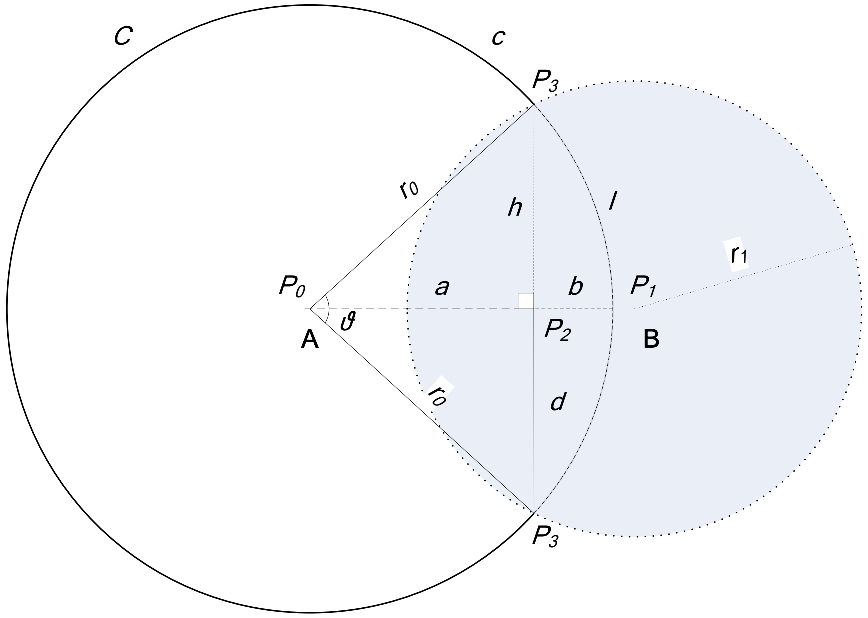


Figure 5.6: Calculating Viable Range for an entity with an Immediate Reference and a Device Beyond a Hop

The distance from the immediate reference device *A* to the requesting entity is shown as r_0. If device *A* is used as a sole reference for positioning the entity, the viable range for that entity would be the whole set of coordinates that would be r_0 metres from *A*'s coordinates. When a device *B* is introduced beyond a hop with a matching set of sensors to the entity a section of the viable range is ruled out.

It is possible to get the coordinates which are viable as a location and coordinates which fall in the detection range of the device beyond a hop by calculating the coordinate range between points P_1 and P_3, illustrated in the Figure 5.6 as the minor arc *l* and a major arc *c* making up a circumference *C*, which is formed by all the coordinates that are r_0 metres distance away from device *A*.

Coordinates for *C* are calculated in one metre intervals by utilising a circle theorem:

$$C = 2\pi r_0 \tag{12}$$

for calculating the circumference in metres for the distance range for device *A*. This is followed by calculating a circular angle increment in radians for the whole circle:

$$\delta\theta = \frac{2\pi}{C} \tag{13}$$

enabling the calculation of one pair of possible x_0 and y_0 coordinates for the entity with adding the x_1 and y_1 coordinates of the device *A* as an offset. Following a convention of defining Cartesian coordinates with the radial coordinate r_0 and the polar angle θ, which is increased by the angle increment $\delta\theta$ for each new set of coordinates on *C*:

$$x_0 = r_0 \cos\theta + x_1 \tag{14}$$

$$y_0 = r_0 \sin\theta + y_1 \tag{15}$$

The resulting set of coordinates is stored as the viable range for the entity for that positioning cycle in case no devices beyond a hop can be found. If, however, another device can be used to limit the number of possible coordinates, as shown in Figure 5.5 it is necessary to calculate the coordinates that fall on the arcs shown as *l* and *c*.

Since points P_0 and P_1 have known coordinates, P_2 and P_3 can be calculated as shown in equations 3 through to 10. Furthermore, elementary trigonometry further dictates that:

$$\vartheta = 2\sin^{-1}\frac{d}{2r_0} \tag{16}$$

Where distance *d* between points P_3 may be calculated according to equation 4.

Replacing the full circle angle increment in equation 13 with ϑ or respectively with $2\pi - \vartheta$ in radians, it is possible to calculate coordinates which fall within the detection range of device *B* as shown as an arc *l* in Figure 5.6 as well as the viable range *c*.

Figure 5.7 demonstrates how distance from the immediate reference device *A* to the entity and furthermore, the distance *ab* between *A* and device beyond a hop *B* affect the calculations of the viable range.

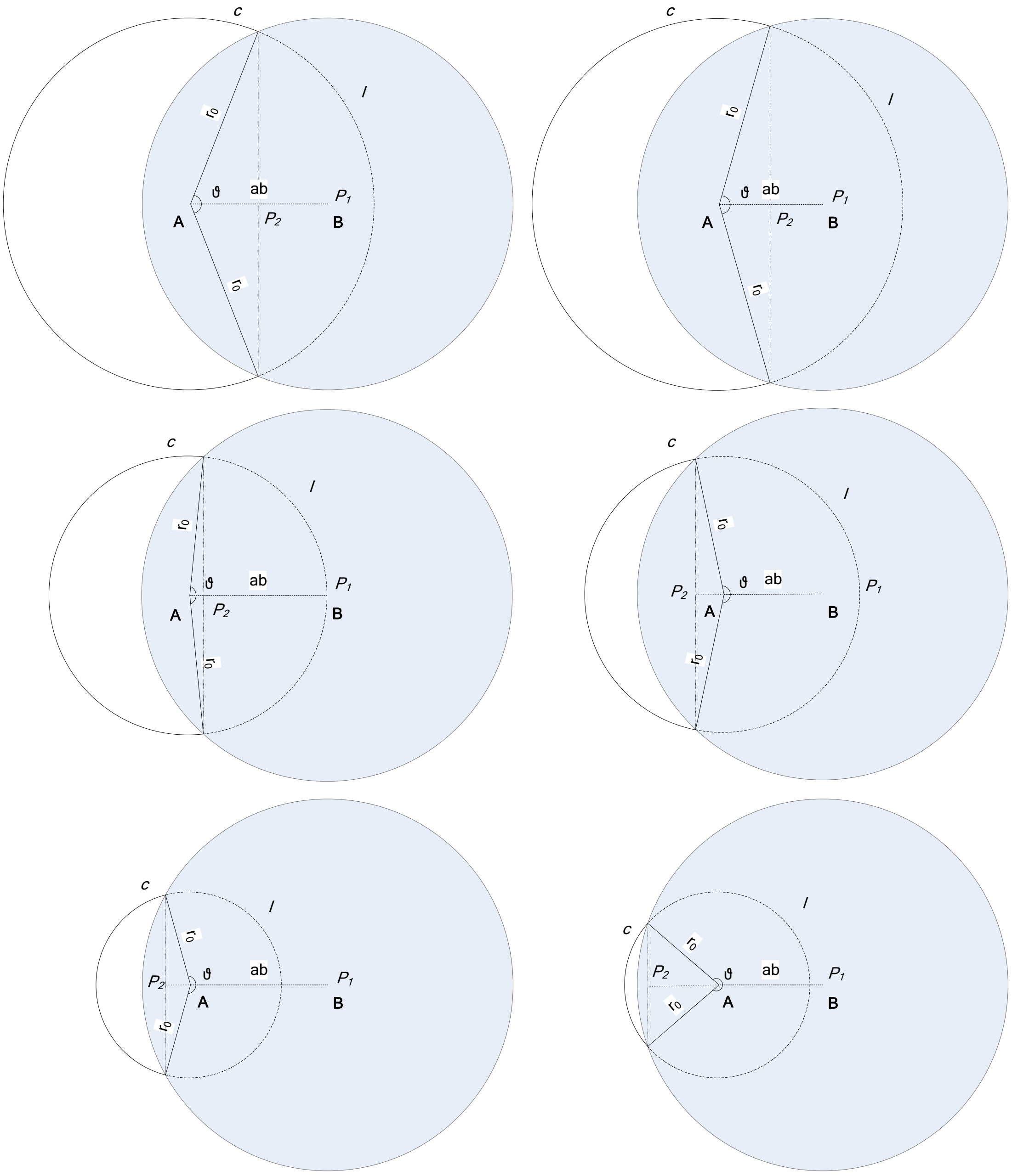


Figure 5.7: Calculating Viable Range with Variable Distances

From Figure 5.7 it can be noted that depending whether the distance between points P_2 and P_1 is longer than the distance *ab,* the coordinates calculated using equations 11 through to 14 can belong to the viable range of the entity or the detection range of device *B*. Figure 5.7 shows dashed arc *l* as coordinates, which are not possible locations for the entity since the distance between points P_2 and P_1 is longer than the distance *ab* resulting in the major arc being within the range of *B*. Solid arc *c* is shown as the viable range for an entity in an opposite situation.

It is worth noting should the user require a location based on a single immediate reference and possible alternative reference devices beyond a hop it is possible on a sparse positioning mode, although the error margin is quite significant and it is reflected on the start confidence. Figure 5.8 demonstrates a situation where device *A* detects the entity that is being positioned whereas devices B_0 and B_1 do not. The error margin is shown as dashed chord *k* in the diagram.

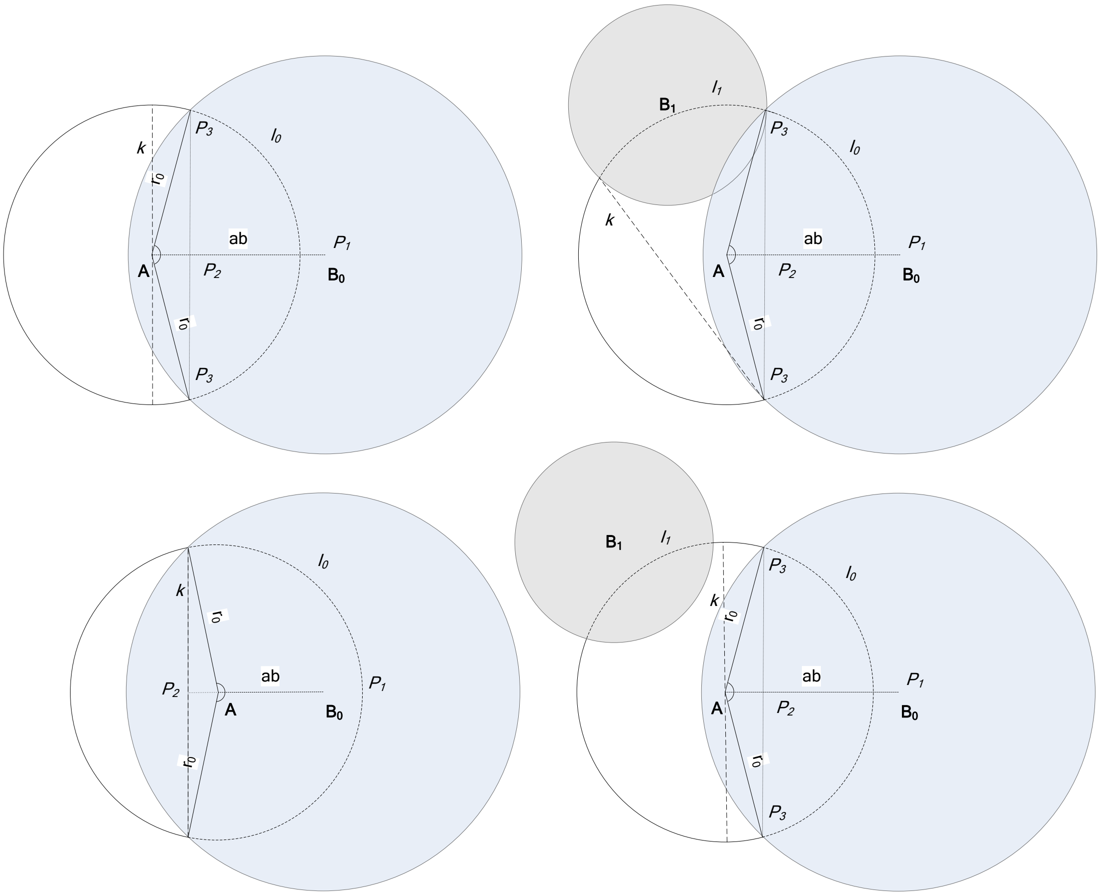


Figure 5.8: Example Error Margins for Sparse Positioning

In case there is only one device beyond a hop the error margin for picking an arbitrary point from the viable range is at the worst twice the device *A*'s detection range: $2r_0$ and at best the distance between points P_3 depending how far away from each other the two devices, *A* and B_0 are. If another reference device B_1 is added beyond a hop the error margin and start confidence are calculated using the combined coordinates, which have been ruled out as shown in equations 11 through to 15. As pointed out in Figure 5.8 the error margin is the length of the chord from the start of the viable range to the end of it if the reference devices beyond a hop can detect each other. If not, the error margin is shown as $2r_0$ as before.

The start confidence figure is derived in all cases by calculating the proportion of the viable range to the whole circumference of the immediate reference's detection range marking all possible coordinates before references beyond a hop are considered and multiplying that with the confidence figures of all devices:

Using ϑ from equation 16 the lengths of l_0 and l_1, which are shown as the dashed arcs in Figure 5.8, can be calculated simply:

$$l = r_0\vartheta \tag{17}$$

The number of coordinate points: c in the viable range, maybe obtained by using C from equation 12:

$$c = C - (l_0 + l_1) \tag{18}$$

Thus, the start confidence p for an entity may be calculated as a product of confidences for all reference devices, p_0 to p_n respectively using Multiplication Law from equation 2:

$$p = 100\left[\left(\frac{1}{c}\right)\left(\frac{p_0}{100}\right)\dots\left(\frac{p_n}{100}\right)\right] \tag{19}$$

Viable confidence would then be:

$$p = 100\left[\left(\frac{p_0}{100}\right)\dots\left(\frac{p_n}{100}\right)\right] \tag{20}$$

It may be noted that due to the significant drop in the start confidence, when an entity has requested positioning on a sparse mode and has a viable range these devices will never be used as references for other positioning cycles even if they had been anchored until they have a location with no possible alternative coordinates.

If an entity has two immediate references *A* and *B* the viable range consists of only one alternative set of coordinates, which are shown as points P_3 in Figure 5.9. Since the number of possible coordinate points: *c* would be two, the start confidence for the entity is calculated by modifying equation 19:

$$p = 100\left[\left(\frac{1}{2}\right)\left(\frac{p_0}{100}\right)\left(\frac{p_1}{100}\right)\right] \qquad (21)$$

The error margin can be obtained by calculating the distance between points P_3, as shown as a dashed line *d* in Figure 5.9.

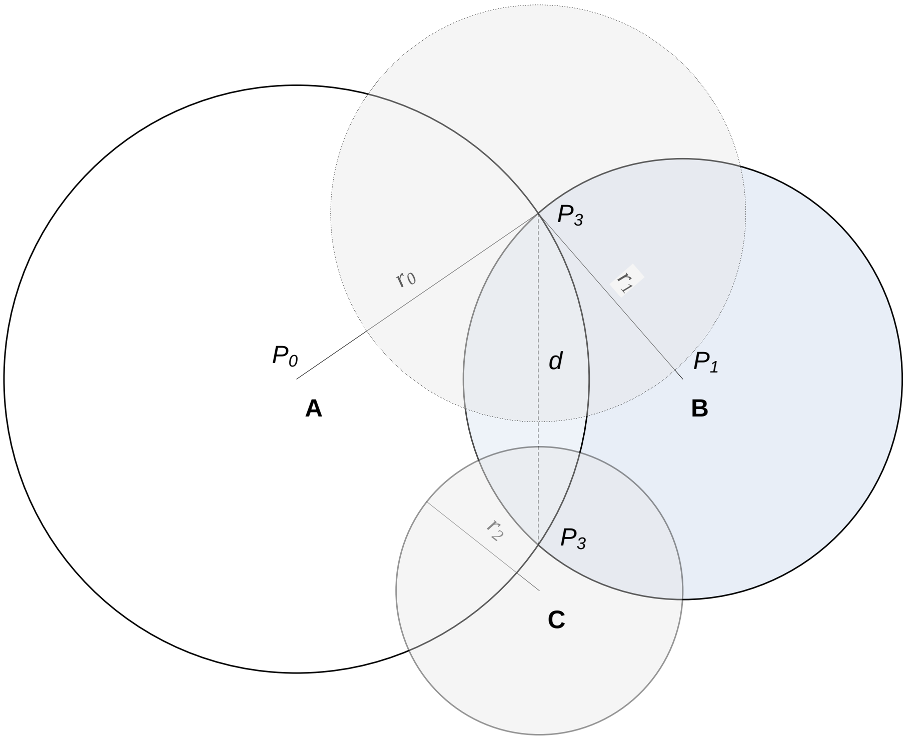


Figure 5.9: Two Immediate Reference Devices and a Device Beyond a Hop

If an alternative reference device beyond a hop *C* is found when an entity has two immediate references the detection range r_2 of the additional reference is compared to the distance from that device to points P_3. If the distance to one of the points is shorter than the range the sensor compatibility is inspected to reveal whether the device beyond a hop would detect the entity if it was positioned in the detected coordinate point. In this a single location for an entity is returned with a combined confidence from all three reference devices as shown in equation 20.

5.2.6.2 Refining Location

The location of an entity is refined by performing another positioning cycle with different combination of references in two cases: firstly, if the entity is on a persistent positioning mode either due to being anchored or by user choice or secondly, if the entity has a viable range stored but no location. In both cases the entity is expected to stay in the same position until the refining positioning cycle has been completed either by achieving the required confidence or by changing the positioning mode.

Persistent positioning is enabled for devices, which have been set to act as beacons or ones that have been anchored by the user in order to find out accurate location in cases where the environment does not have sufficient reference devices. Entities requiring persistent positioning have an option to set a required confidence, which acts as a break point for new refining positioning cycles. If the entity acts as a beacon within the environment the required confidence is generally set to 100% in order to enable constant refining of the beacon's location.

The first step of refining a location for a persistent entity is to check whether a better confidence value is possible by utilising one of two main techniques:

- Triangulation with previously stored viable range
- Using the same reference device more than once.

When attempting triangulation with a previously stored range the actual calculations are only performed after determining what the combined confidence value from the two highest confidence devices and the stored viable confidence by using equations 1 and 19. If the resulting confidence value is higher than what was obtained from triangulating with three reference devices in the first place, calculations are performed similarly to triangulation in order to obtain two possible coordinate points for the device. These are shown as points P_3 in Figure 5.9. However, instead of substituting a third reference device in the calculations a viable range is inspected for a possible match for either of the points P_3 within one metre error margin.

If triangulating is not successful with the viable range or the required confidence value is not achieved on a persistent entity the current proximity map is compared to the previously cached one in order to determine whether any of the immediate references are moving. The devices are ordered by their confidence values and positioning is attempted for each point until a single location is returned in order shown in Figure 5.10. If a single coordinate is not obtained with any of the device combinations or the confidence has not improved the result from the actual positioning cycle is detained along with the confidence value achieved from triangulating with all reference devices prior to the refining attempt.

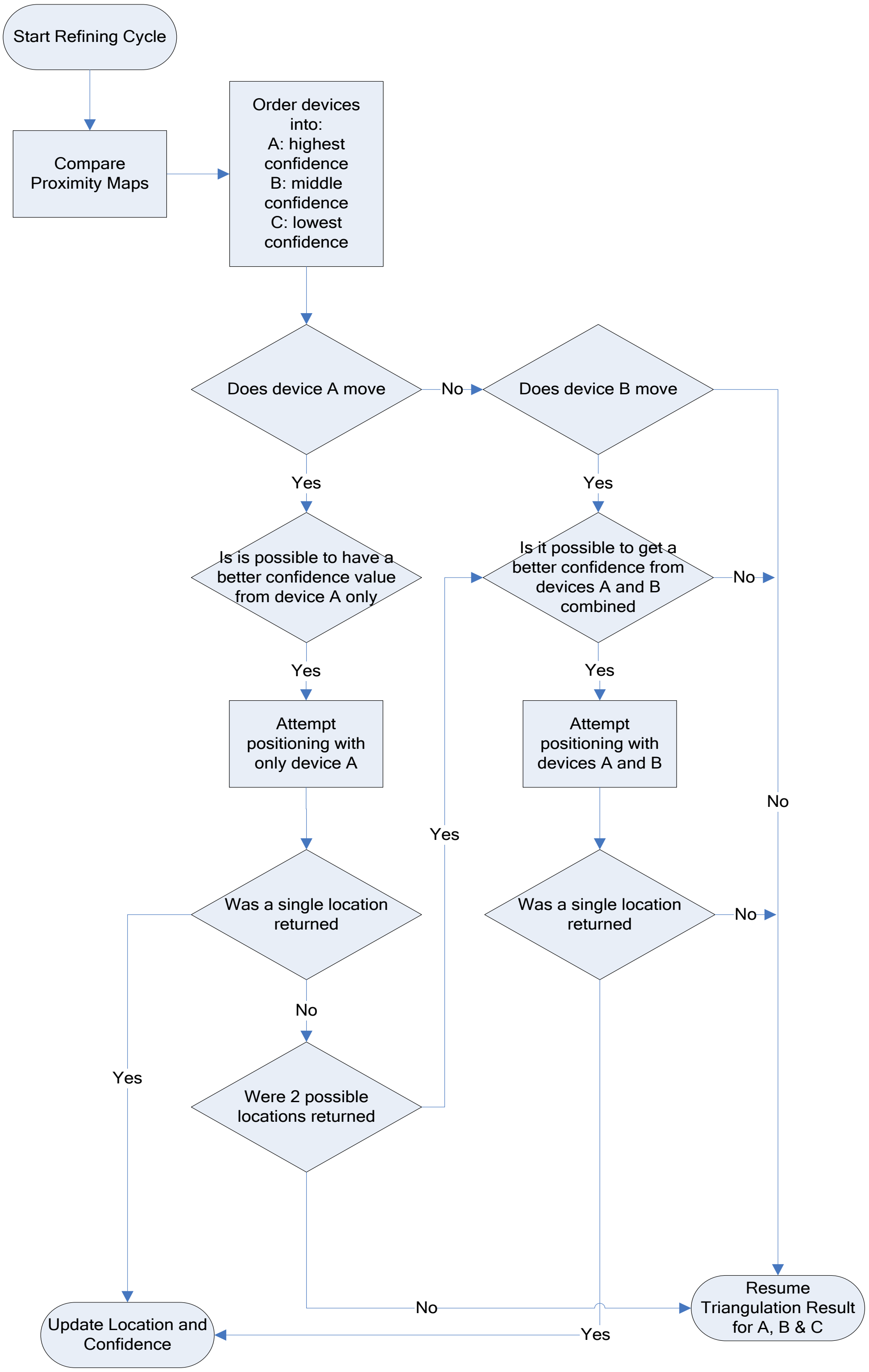


Figure 5.10: Logical Order of Choosing Reference Devices for a Refining Cycle

From Diagram 5.10 it may be noted that priority is given to a device with the highest confidence. The refining cycle attempts to store a viable range for the entity based on the single reference device according to equations 11 through to 14. After the initial calculations the reference device is requested to submit information for another proximity map in order to refresh its location data along with the confidence value and signal strength indicators. The new proximity map is then used to calculate a viable range, which is compared to the previous range with a predetermined error margin in order to find shared coordinates representing a set of possible coordinates for the entity. The process is continued until either a single coordinate is found indicating the entity's location or the reference device moves too far to detect the entity in its range.

Figure 5.10 introduces some of the movement patterns, which may be expected. The dashed arrow indicates the path and the movement direction of the reference device whereas possible points for the entity are shown as circle intersections *a* and *b*. The solid circles model the distance radius from the reference device to the entity at different intervals: namely different times as well as at different locations. Accordingly, the surrounding halo mimics the detection range of the reference device for the movement intervals.

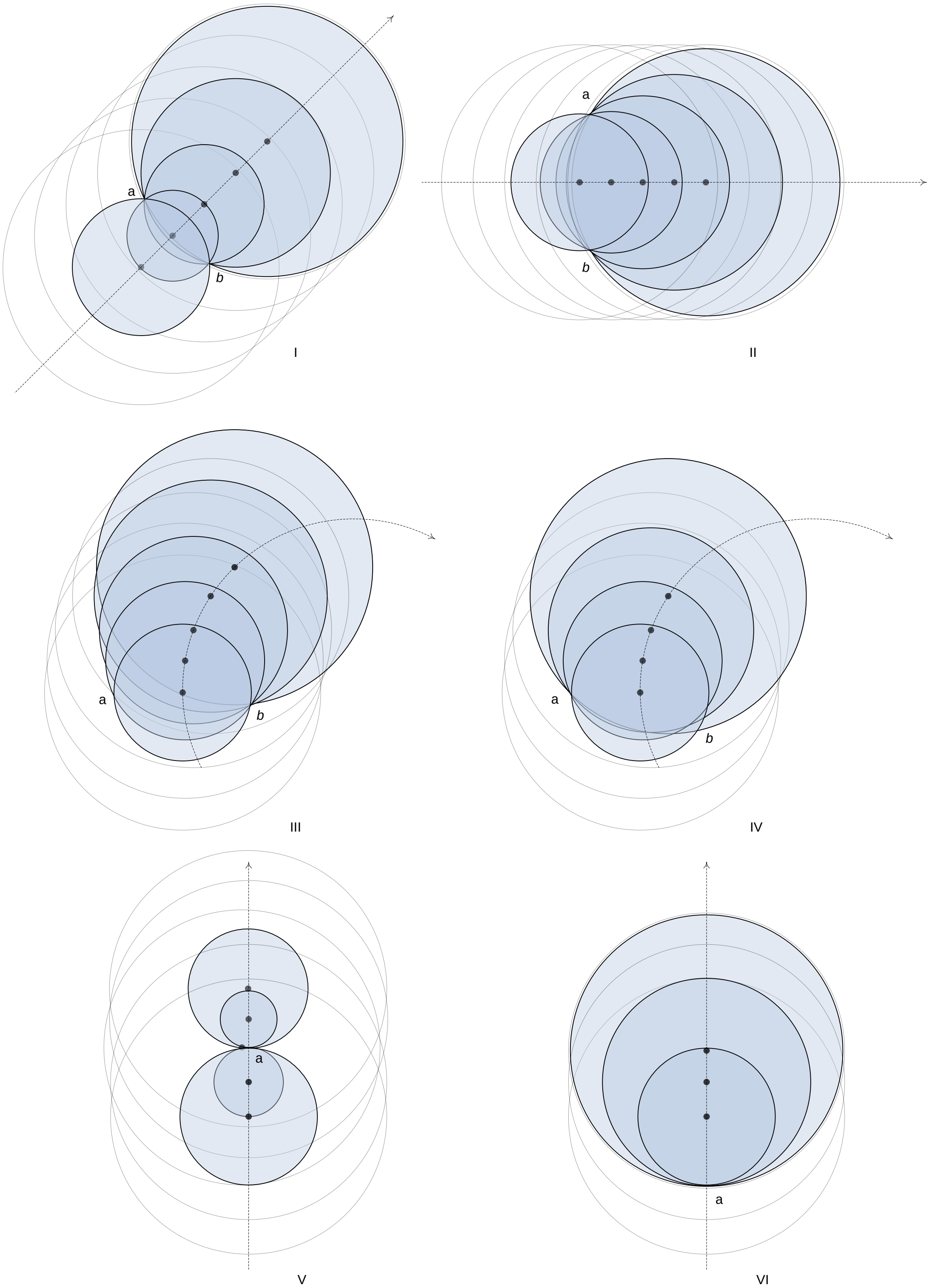


Figure 5.11: The Principle behind Using a Single Moving Device as a Sole Reference

Figure 5.10 aims to point out a number of factors, which have an effect on the outcome of the attempted positioning with a single moving reference device:

- *Sensing Technology:* The detection range for that technology has to be large enough to accommodate movement away from the entity.
- *Speed:* If the pace of the movement is too fast it is not possible to form a sufficient number of proximity maps and calculate a possible location based on these before the reference device moves out of the sensing range.
- *Direction:* If the device has no variation in the direction of movement a single location is not possible as shown in cases I and II of Figure 5.10. An exception to this would be if the device moves directly away from the entity or directly towards it as cases V and VI demonstrate.
- *Start Position:* As with movement speed, if the reference device is too far on the edge of the detection range it is not possible to calculate sufficient amount of proximity maps before the reference device moves out of the range.
- *Continuation:* The movement has to carry on until the viable range has been refined enough.

These device specific issues, which are necessary to be considered when attempting positioning with a single reference, mean that it is impossible to predict whether a refining of the location is achievable with that particular device. If the cycle succeeds the confidence figure p is calculated for the entity based on the single reference device's confidence p_0:

$$p = 100\left[\left(\frac{p_0}{100}\right)^3\right] \tag{22}$$

From Diagram 5.10 it may be noted that in case of the refining cycle doesn't produce a single location with the primary reference it is still possible to resume the cycle with the secondary device. If the primary reference indicated two possible locations for the entity as shown as points a and b in cases I and II (Figure 5.10) the secondary device may be used as a reference for calculating a viable range for the entity and substituting that to the positioning algorithm as explained earlier. The confidence *p* would then be calculated using both of the devices' confidences p_0 and $p_1$respectively as follows:

$$p = 100\left[\left(\frac{p_1}{100}\right)\left(\frac{p_0}{100}\right)^2\right] \tag{23}$$

Should the primary device be altogether unsuccessful as a reference the secondary reference would be used to calculate two possible coordinate points, from which it was possible to pick the correct one by using a solid location from the primary reference device. The confidence *p* would then be:

$$p = 100\left[\left(\frac{p_0}{100}\right)\left(\frac{p_1}{100}\right)^2\right] \tag{24}$$

As may be noted from Figure 5.9 further iterations for the refining cycle are not executed if location cannot be obtained by using either the primary or secondary devices. In the case of unsuccessful refining cycle the initial location obtained from triangulation is resumed with the appropriate confidence figure.

5.3 Summary

This chapter has explained the method of positioning a device using just reference devices within an environment. It demonstrated how different algorithms form a positioning framework, which is not dependent on certain arrangements of sensors or devices in order to be able to calculate a location for a device with a confidence value that reflects the certainty of that location being correct. It also showed that it is not necessary to have a minimum configuration for a sensory network or a number of pre-set beacons in order to have an environment for positioning. Instead the method utilises a number of existing technologies in each mobile device in order to use each other for acquiring a location.

The following chapters concentrate in the experiments that have been conducted in order to validate the positioning framework and aim to evaluate the findings in the light of practical deployment.

Chapter 6

TESTING & VALIDATION

6.1 Introduction

This chapter introduces performance evaluation issues and demonstrates how the correctness of the framework has been ensured. The chapter presents a discrete event simulation of the environment which also aims to verify the reliability and validity of the work done by introducing a series of metrics and assumptions as well as presenting some open issues, which have been unearthed by the evaluation process. The aim of the chapter is to validate the hypothesis as well as the design choices which have been introduced in earlier chapters of this thesis.

The next section looks at the different layers of the positioning algorithms used for dynamic environments and discusses the implications of each to the overall framework. Following this is an examination of the consequences of the adopted design choices.

6.1.1 Approach

Rather than deploying a full-scale wireless mobile distributed system infrastructure a simulated environment has been implemented to evaluate and demonstrate the correctness of the developed algorithms as well as the overall system configuration for the proposed positioning framework. This approach has been chosen for number of reasons. Firstly, since it is inevitable that system load in evaluation of the performance of positioning environments is mainly affected by user activities and movement it is not an easy task to reproduce the behaviour of people and the circumstances. A discrete event simulation provides a more reliable and repeatable evaluation environment with an additional benefit of being able to capture each state of the events. This is especially important when the system measurements are required to execute for extended periods of time in order to capture infrequently occurring high load conditions, which are necessary to record and evaluate accurate performance. Another deciding factor is the way in which it is possible to separate hardware and other deployment factors readily from other performance issues. (Banks et al., 2005)

The simulation concentrates on validating the protocol for the communication between the clients and the environment such that the principle may be considered separately from the deployment issues. It greatly accelerates the process of finding out future behaviour of entities within the environment. The discrete event simulation also provides a flexible enough test-bed to support the verification and validation of the framework, which would not have been possible to develop with a hardware only based implementation of the system. (Pooch & Wall, 1992)

The simulation has been designed to serve a specific purpose in demonstrating the functionality of a hybrid positioning environment. Although it aims to mimic the operation of a real world system it should not be considered as an entirely accurate representation of a fully deployed mobile distributed system since it does not aim to model physical characteristics of signal propagation and such. It provides a means to analyse and control key processes as well as prove correct the points used to evaluate the positioning system, which are introduced in Chapters 4 and 5 and of interest to this research. The validity and verification of the simulation has been ensured by a number of controlled inputs with known outputs and hence, may be treated as an adequate representation of a positioning environment for performance evaluation purposes.

6.1.2 Overview

The environment simulation consist of activities, which are autonomous processes creating events at either random or pre-defined time intervals causing the system state to change. In the simulation the entities are tracked while they pass through the environment based on "canned" user activity obtained by recording sightings in actual real world situations. These are then either multiplied or simplified according to the stress level required by each individual experiment and turned into entity data before being played back to the simulation in order to be able to provide state changing activities as close to real world example as possible.

The simulation is intended to model the developed positioning framework and is able to generate artificial entities in differing environments, which can be made to mimic real world sightings of people with mobile devices. The entities in the simulation may be either stationary, following a path, or randomly moving at different speeds within the simulated environment. Each entity consists of a choice of technologies, representing different types of sensors available in client devices. These correspond to one absolute coordinate system, such as a GPS capable device and a mix of short, medium and medium-long range technologies. For each sensor a range has been input according to either an accurate depiction of the capabilities of that device or alternatively an average figure to represent unavailable data in real life situations. A simple scenario can be seen in Figure 6.1 where devices are depicted with absolute coordinates along with coordinate figures, signal strength indicators, available sensors as well as GUIDs for the basis of forming proximity map for positioning an entity without a location. It may be noted that the arc shown around the immediate reference indicates a range of coordinates that are not included in the viable range due to the device beyond a hop.

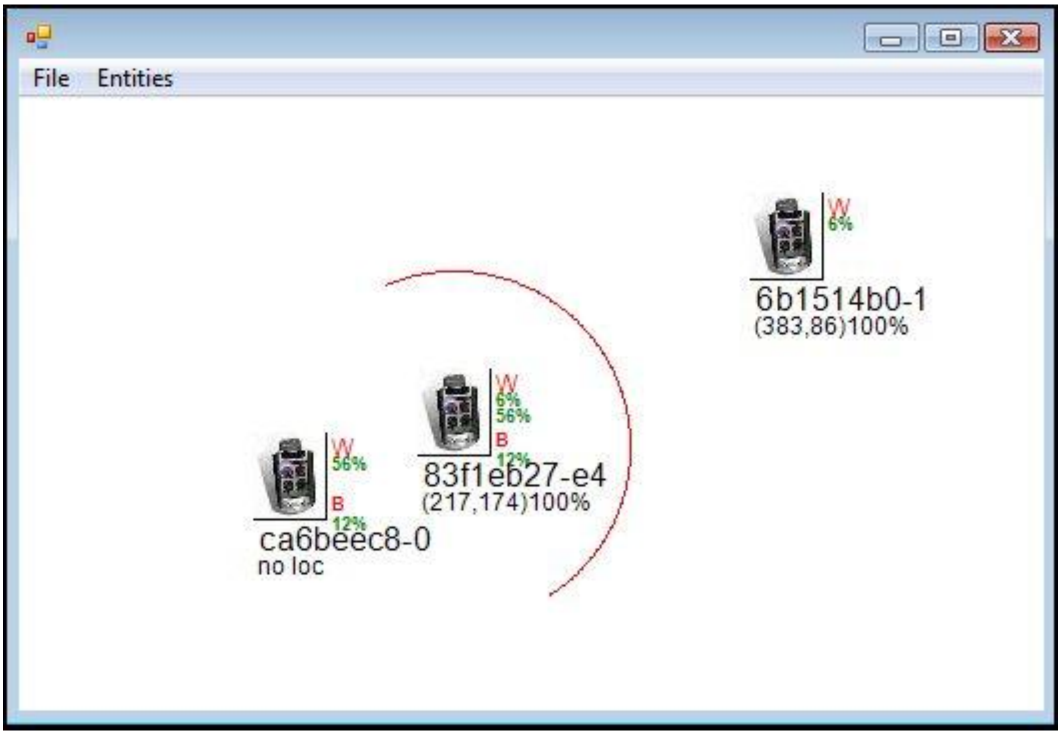
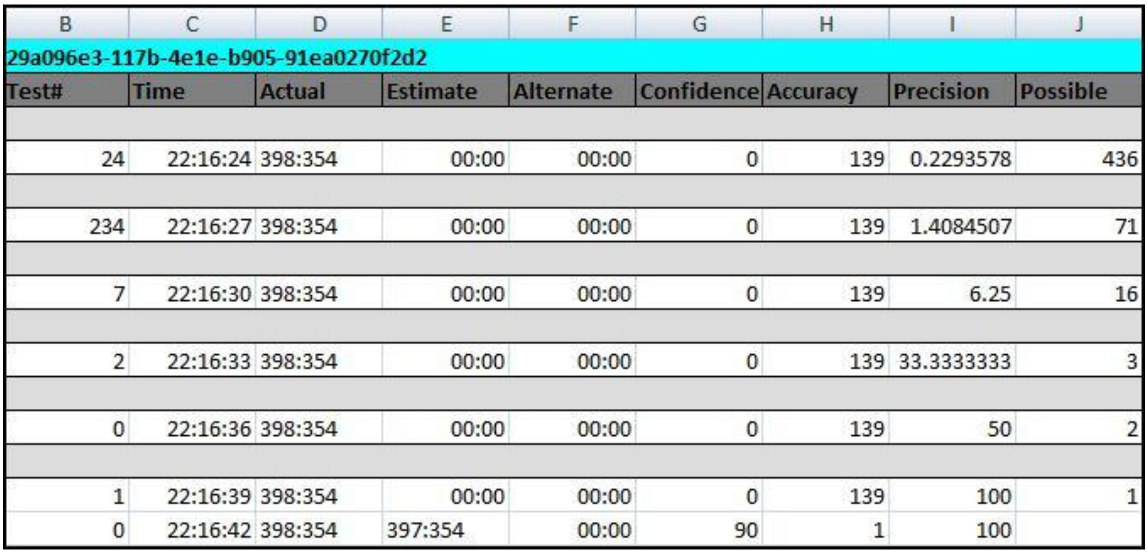


Figure 6.1: Example Simulation Scenario

For the purpose of this thesis the simulation has been set to constitute a space of 700 by 700 metres with no barriers to impede signal propagation, so no signal propagation modelling is required. In the simulation a polling approach has been adopted to demonstrate how entities are detected entering and leaving sensor ranges. A three second polling has been assumed for the experiments in order to mimic the how mobile devices wireless adapters record changes in the detection range.

The simulation output consists of the actual location coordinates of the device as well as the outcome for the positioning cycle. In addition, accuracy and precision for each set of events as well as a confidence figure, number of possible coordinate points and an improvement when compared to the control set of events. The simulation also records internal time in order to measure how long it takes to change the state in milliseconds as well as a number of iterations, which represent the intermediate state changes from start of the sequence to completing it. Figure 6.2 demonstrates an example raw output obtained from a refining positioning cycles using a single moving reference with 95% confidence:



B	C	D	E	F	G	H	I	J
29a096e3-117b-4e1e-b905-91ea0270f2d2								
Test#	Time	Actual	Estimate	Alternate	Confidence	Accuracy	Precision	Possible
24	22:16:24	398:354	00:00	00:00	0	139	0.2293578	436
234	22:16:27	398:354	00:00	00:00	0	139	1.4084507	71
7	22:16:30	398:354	00:00	00:00	0	139	6.25	16
2	22:16:33	398:354	00:00	00:00	0	139	33.3333333	3
0	22:16:36	398:354	00:00	00:00	0	139	50	2
1	22:16:39	398:354	00:00	00:00	0	139	100	1
0	22:16:42	398:354	397:354	00:00	90	1	100	

Figure 6.2: Example Output Data from a set of Positioning Cycles

The first column "B" records time in milliseconds how long each refining positioning cycle has taken to execute the algorithms along with the actual system time in column "C". Columns "D" and "E" demonstrate the actual coordinates of an entity and estimated coordinates respectively. Column "E" records altenative coordinates if a positioning cycle is inconclusive. Columns "G", "H" and "I" indicate confidence figure, accuracy and precision for each cycle and column "J" stores the number of possible coordinates calculated for each iteration.

The simulation aims to produce required outputs by repeating a number of activities by using controlled as well as more pseudo-random inputs. Thus, the experiments consist of predefined arrangement of entities and events followed by pseudo-randomly generated state changes which perform within the parameters of each experiment. These parameters include predefined set of inputs, such as start and end coordinates for each entity, possible movement path and speed, as well as bias, which has been introduced in order to mimic a drop in confidence and errors in the location representation for the reference devices. The purpose of the location bias has been simply to facilitate experiments which require sampling with incomplete and incorrect data. The following sections discuss these experiments in further detail.

6.2 Evaluation Criteria

The environment simulation was built in order to investigate two separate cases: what types of situations the positioning framework should be expected to cope with and more importantly, how well it does this. In order to find out whether the positioning of a device is achieved within appropriate requirements a number of commonly established metrics were used along with some other system specific criteria:

1. *Accuracy:* The worst possible error margin for a specific location fix
2. *Precision:* The average probability of acquiring the required accuracy for the system, expressed as a percentage.
3. *Confidence:* A measurement indicating a single device's certainty in the correctness of the location data subject to the current state of the environment and the client entity.
4. *Time/number of iterations:* Time in seconds how long it takes to reach the required accuracy and precision in varying environment states not taking into account network traffic or conditions.
5. *Number of possible location coordinates:* For each state and iteration a number of possible locations are recorded in order to see the effect of adopted algorithms have in reduction of overall possible coordinates.

Since the test-bed was developed as a simulation, the performance evaluation concentrates on the criteria outlined above and does not include consideration of network traffic or other delays which would be experienced in a full implementation of the positioning framework. This also includes tests which would indicate scalability factors, actual query loads and consequent delays as the number of clients would rise. Assumptions about these factors have been discussed based on the design of the system in the following sections.

6.3 Experiments Performed

6.3.1 Control

Control experiments were conducted in the simulated environment to provide points of comparison when the effects of the variables, such as number of devices, sensors and references were examined. The control experiments also provided error margins for the positioning framework by defining the granularity of the system. The positioning of the control devices is chosen to reflect the detection ranges commonly reported by medium range wireless adapters. These vary from 100 metres to 1 metre throughout the experiments and although wider detection ranges are possible the trend of how distance effects the positioning is demonstrated from the used range.

From the first set of control experiments shown in Table 6.1 it is possible to deduce the effect which a number of stationary reference points with a known absolute positions have on the determination of the position of a single stationary device. From these experiments it may also be noted how distance between the devices affects precision.

Test	Distance 1	Distance 2	Distance 3	Possible Points	Error Margin(m)	Precision (%)
1	100	n/a	n/a	628	200	0.159
1	75	n/a	n/a	471	200	0.212
1	50	n/a	n/a	314	200	0.318
2	100	100	n/a	2	142	50
2	75	75	n/a	2	53	50
2	50	50	n/a	2	35	50
3	100	100	100	1	1	100

Table 6.1: Control 1-3 - Accuracy and precision for positioning of single devices with a varying number of references.

The first control experiment shows a single reference device at the distances of 100, 75 and 50 metres from the device being positioned. In an event where neither of the devices is in motion and there is 100 metres between the devices, 628 possible coordinate points have been calculated with one metre between them. This gives a precision of 0.159% for the successful positioning cycle with an accuracy of 1 metre. This transfer into an error margin of 200 metres for any point picked within the coordinate range with 100% precision. When distance between the devices is reduced by 25% the number of possible coordinate point is reduced accordingly with the comparable precision increase of 25%.

When a second reference device is introduced to the experiment the possible number of coordinate points is reduced to two with a precision of 50%. A third device will further increase precision to 100% and pinpoint the location coordinates to one possibility.

6.3.2 Insufficient Location Data & "Device Hops"

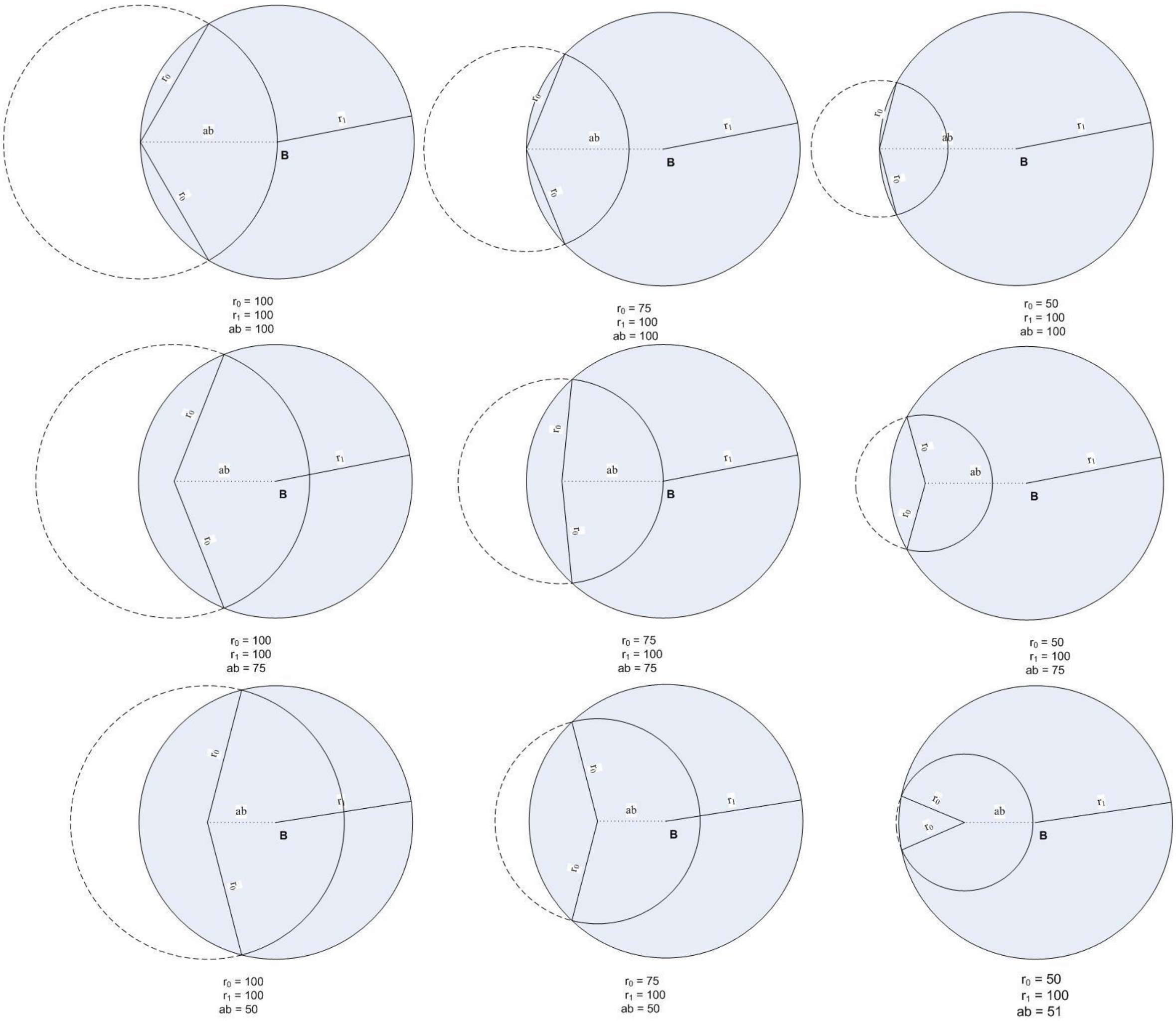
As described in Chapter 5 a "device hop" is a technique for utilising devices as positioning references outside the immediate detection range of the original device. The aim is to improve precision along with decreased error margin by allowing devices, which are detected by immediate references but not the original device, to be part of the decision making about possible coordinates for the original device.

Table 6.2 shows the impact of a "device hop" in a positioning cycle. As with the control experiments the table shows that precision is very slightly improved when the distance between all the three devices is reduced. Furthermore, as expected, the experiment shows that the number of possible coordinate points is reduced most when the two reference devices are as close to each other as possible and the error margin reduced in proportion to the distance between the immediate reference and the device to be positioned.

TEST	Distance 1 (r_0)	Distance 2 (ab_1)	Number of Points	Error Margin (metres)	Precision (%)
1 (control)	100	n/a	628	200	0.159
1 (control)	75	n/a	471	200	0.212
1 (control)	50	n/a	314	200	0.318
4 (a)	100	100	418	200	0.239
4 (b)	75	100	292	150	0.342
4 (c)	50	100	181	100	0.551
4 (d)	100	75	390	200	0.256
4 (e)	75	75	252	150	0.396
4 (f)	50	75	131	96	0.761
4 (g)	100	50	364	200	0.274
4 (h)	75	50	196	144	0.509
4 (i)	50	51	19	19	5.130

Table 6.2: Experiment 4 - Impact of Device Hops: Error Margins and precisions for positioning of single devices with a single device as an immediate reference and a single device beyond a hop.

Although reduction in possible coordinate points is evident along with improvement in precision and error margin when an additional device beyond the immediate reference is taken into consideration, the improvement is only recordable when the overall distances between all three devices are as close to the detection range of the original device as possible. Figure 6.3 offers an explanation by illustrating the viable coordinate range for the entity. The distance between the immediate reference ‘A’ and the entity being positioned is shown with a variable $r_{0.}$ The detection range r_1 of the reference device beyond a hop ‘B’ is drawn as a solid circle with a distance ‘ab’ to the reference device ‘A’. Possible coordinates are shown in the figure as a dashed arc outside the detection range of device ‘B’.



$r_0 = 100$
$r_1 = 100$
$ab = 100$

$r_0 = 75$
$r_1 = 100$
$ab = 100$

$r_0 = 50$
$r_1 = 100$
$ab = 100$

$r_0 = 100$
$r_1 = 100$
$ab = 75$

$r_0 = 75$
$r_1 = 100$
$ab = 75$

$r_0 = 50$
$r_1 = 100$
$ab = 75$

$r_0 = 100$
$r_1 = 100$
$ab = 50$

$r_0 = 75$
$r_1 = 100$
$ab = 50$

$r_0 = 50$
$r_1 = 100$
$ab = 51$

Figure 6.3: Experiment 4 - The Effect of Inter-device Distances in Number of Coordinate Points

Table 6.2 along with Figure 6.3 shows that positioning with a single stationary device, which utilises a proximity map in order to indentify further devices "beyond a hop", is not a sufficient method to be used solely for position determination when a device is on a normal or persistent positioning mode. This is due to the fact that these two positioning modes prioritise accuracy and precision over the location rate. The benefit of identifying additional references beyond a hop becomes obvious in three situations:

1. The device is on a *persistent* positioning mode either due to a user choice or because it is part of the infrastructure acting as a beacon which is the case of, for example, WLAN base stations. Persistent positioning mode implies that the device is anchored at least until a single location is returned from a positioning cycle and a confidence figure that satisfies the criteria is achieved. As shown in Table 6.2 and Figure 6.3, depending on the distances between the devices the reduction in the viable coordinate range can be dramatic, resulting in fewer refining position cycles when attempting to estimate a position of an anchored device based on a single moving reference device as described in Chapter 5 and illustrated in Figure 5.11.

2. The device is on a *sparse* positioning mode, prioritising location rate and the speed of position estimation over accuracy and precision. In this case the improvement in precision is modest but it may be noted that the error margin is reduced according to the distance between the devices and has an impact in the correctness of the location estimate.

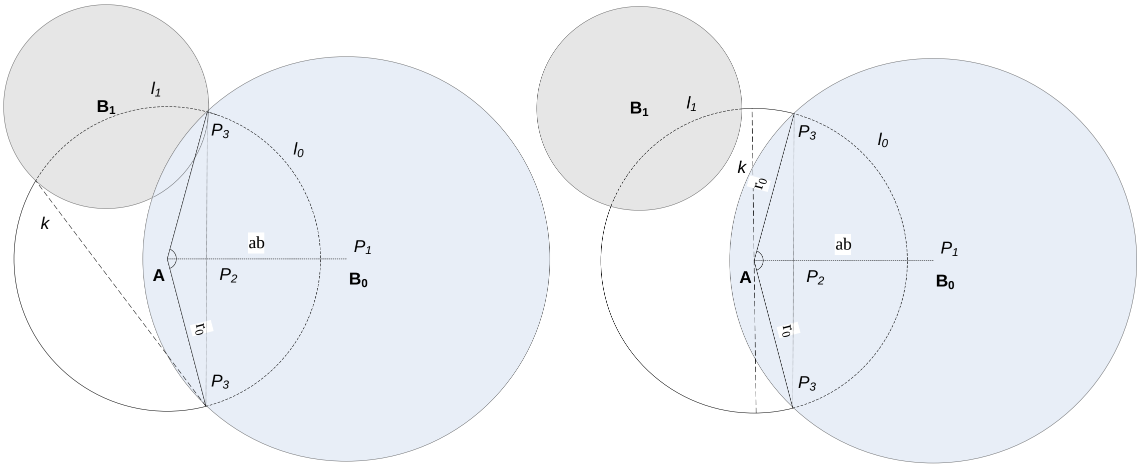
3. The device is on a *normal* positioning mode, where positioning is attempted until the device is moved. In this case the reference device "beyond a hop" reduces the number of refining positioning cycles making it more likely to obtain a location fix before the user changes place.

While adding another device beyond a hop very slightly improves precision, Table 6.3 shows little improvement in error margin when the two devices are adjacent to each other. This is shown as an experiment 5. Furthermore, when the secondary reference devices beyond a hop are not adjacent in a way in which their detection ranges would overlap it may be noted that error margin is at the same level with the control, as shown by experiment 6 in Table 6.3.

Test	Distance 1	Distance 2	Distance 3	Points	Error Margin	Precision
1 (control)	100	n/a	n/a	628	200	0.159
1 (control)	75	n/a	n/a	471	200	0.212
1 (control)	50	n/a	n/a	314	200	0.318
4 (a)	100	100	n/a	418	200	0.239
4 (b)	75	100	n/a	292	150	0.342
4 (c)	50	100	n/a	181	100	0.551
5 (a)	100	100	100	313	199	0.319
5 (b)	75	100	100	214	148	0.467
5 (c)	50	100	100	129	96	0.775
6 (a)	100	100	100	313	200	0.319
6 (b)	75	100	100	214	200	0.467
6 (c)	50	100	100	129	200	0.775

Table 6.3: Experiment 5 & 6 - Impact of "Device Hops": Error Margins and precisions for positioning of single devices with two devices as an immediate reference and a single device beyond a hop.

The results shown in Table 6.3 can be explained upon inspecting Figure 6.4 where a line k demonstrates the error margin obtained when using device A as an immediate reference and devices B_0 and B_1 as references "beyond a hop".



Test 5

Test 6

Figure 6.4: Experiment 5 & 6 - The Effect of Device Arrangement in Error Margin

The benefit is mostly seen when a device has two immediate references and therefore two possible coordinate points are returned from the positioning cycle as illustrated in Figure 6.5 as points P_2 and P_3. A device beyond a hop *C* may be used to determine which one of the two location points is the correct one, providing either point is within the detection range of the additional reference device. In this case, the accuracy for that positioning cycle reaches 1 metre with a precision of 100%.

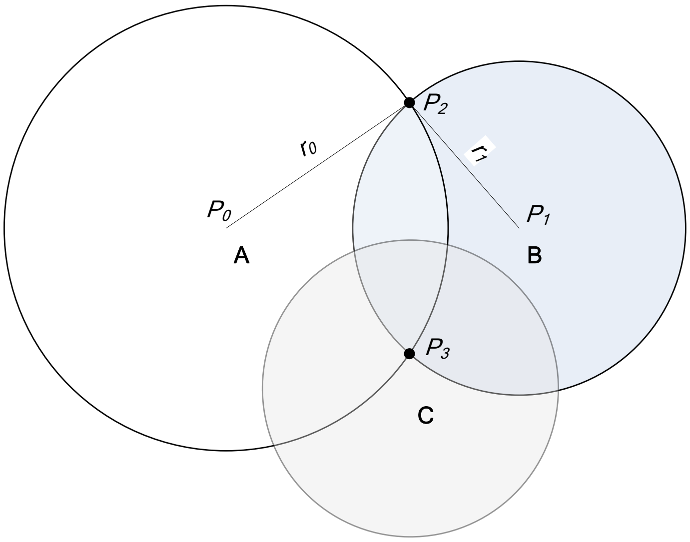


Figure 6.5: Experiment 7 - The Effect of a Device beyond a Hop with Two Immediate References.

Table 6.4 further demonstrates the purpose of implementing "device hops". Test number 7 implements a scenario shown in Figure 6.5 with 100 metres between each of the two immediate reference devices to the entity to be positioned. As described earlier the same distances are used in the experiments 1 to 5, which are provided as a comparison. It can be noted that in experiment 7 the device "beyond a hop" is used with the same results as achieved from triangulation with three immediate reference devices in control test 3.

Test	No.of References	No. of Dev. BEOH	Possible Points	Error Margin(m)	Precision (%)
1 (control)	1	n/a	628	200	0.159
2 (control)	2	n/a	2	142	50
3 (control)	3	n/a	1	1	100
4 (a)	1	1	418	200	0.239
5 (a)	1	2	313	199	0.319
7	2	1	1	1	100

Table 6.4: Experiment 7 - The Effect of Device beyond a Hop (BEOH) on Precision and Error Margins

An experiment was conducted in order to find out whether it would be beneficial to detect devices beyond multiple hops. The results showed that unless an additional "hop" was performed due to devices sensors not being compatible no benefits were recorded. This was due to the fact that in the case of two reference devices, the device beyond a hop had to have one of the possible points within its detection range as stated above. This directly implies that at least one coordinate point was shared between the ranges of the devices in the first hop.

6.3.3 Dynamic Location Data, Moving Devices & Stored Coordinates

As shown in previous experiments it is possible that there are not enough reference devices in the environment at any one time to perform a successful positioning. In these situations a range of possible coordinates is stored for each device from that position cycle whether it was successful or not. The viable range of coordinates is kept until the device's location has changed or a position fix is obtained within the set confidence limits. An example of such a circumstance would include a moving reference device, which would calculate a new set of coordinates for the original, stationary device on a persistent positioning mode as long as the reference devices was within the detection range and hence would be able to perform positioning with past data as discusses in Chapter 5 and illustrated in Figure 5.8

A set of experiments was conducted with one stationary device being positioned on a persistent mode and one moving reference device as shown in Figure 6.6. In all cases the trajectory of the moving reference device was chosen to enable positioning as stated earlier. The acceptable error margin was set to one metre with a requirement of getting a single location as a result from the positioning cycles.

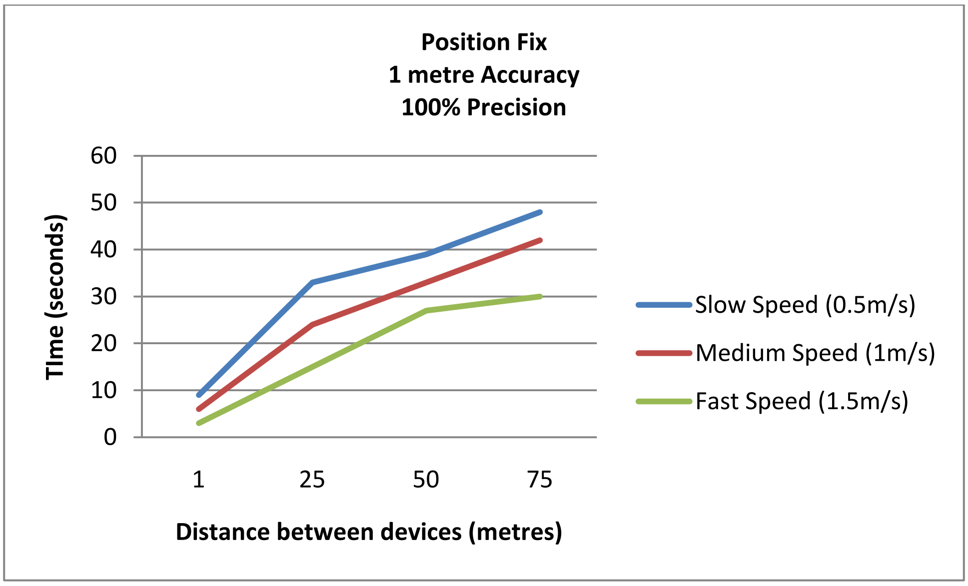


Figure 6.6: Experiment 8 - Set of example speeds for getting a reliable position fix with a single moving device as a reference with error margin set to 1 metre.

The accuracy of one metre was achieved with 100% precision as shown by test set 8 in Table 6.5, regardless of the movement speed of the reference device, which varied between 1.5 metre per second to half a metre per second. The time it took to position a device was dependant on movement speed as well as the distance between devices. The most efficient positioning took place with a fast movement speed as close to the original device as possible without a contact and the worst with a slow movement speed at the very edge of the detection range

Test	Number of References	Distance to References	Positioning Time	Possible Points	Error Margin(m)	Precision (%)
1 (control)	1	50	1	314	200	0.318
2 (control)	2	50	1	2	35	50
3 (control)	3	50	1	1	1	100
4 (i)	1	50	1	19	19	5.130
5 (c)	1	50	1	129	96	0.775
7	2	50	1	1	1	100
8 (slow)	1	50	39	1	1	100
8 (med)	1	50	33	1	1	100
8 (fast)	1	50	27	1	1	100

Table 6.5: Experiment 8 - Average Location Rates for Positioning with a Single Moving Reference with Mean Distance.

As shown in Table 6.6 experiment 9 indicates that adding a second reference device to the range accelerated the positioning process in all cases, achieving only a three second delay, which was largely due to the polling interval mimicking the mean time interval of 3 seconds for the device to notice a change in the detection range. Location coordinates were correct between half a metre and one metre accuracy and 100% precision. It is also worth pointing out that it made no difference whether the second reference device was moving or not.

Another set of experiments was executed in order to find out how the framework would perform when positioning a moving device with a varying number of references. A moving device with a single reference shown as test 10(a) in Table 6.6 was unable to get a position fix and there was no reduction in number of possible coordinate points resulting in an outcome similar to that shown in experiment 1 in Table 6.1. When a moving device detected two stationary reference devices in experiment 10(b), 2 possible location points were obtained for each polling interval providing the device had changed position similarly to experiment 2 in Table 6.1. The situation stayed unchanged when one or both of the reference devices were moving as well. When a third device was introduced in experiment 10(c) to the mix triangulation could take place as shown with experiment 3 in Table 6.1, again for each iteration in the positioning cycle. The same result was achieved regardless whether the reference devices were moving or not.

Test	No. of References	Distance to References	Positioning Time	Possible Points	Error Margin(m)	Precision (%)
1 (control)	1	50	n/a	314	200	0.318
2 (control)	2	50	n/a	2	35	50
3 (control)	3	50	1	1	1	100
4 (i)	1	50	n/a	19	19	5.130
5 (c)	1	50	n/a	129	96	0.775
7	2	50	1	1	1	100
8 (slow)	1	50	39	1	1	100
8 (med)	1	50	33	1	1	100
8 (fast)	1	50	27	1	1	100
9	2	50	3	1	1	100
10 (a)	1	50	n/a	314	200	0.318
10 (b)	2	50	n/a	2	35	50
10 (c)	3	50	1	1	1	100

Table 6.6: Experiment 10 - Positioning a Moving Device with Varying Number of References.

6.3.4 Inaccurate Location Data

The confidence figure reflects the certainty of a device being at the location it reports at any given time. As explained in Chapter 5, a number of factors contribute to a device's confidence figure for the purpose of effectively depicting the possibility of bias when using that device as a reference.

Introducing the confidence figure has significance for number of reasons: firstly it aims to make it possible to correct the reported position for a fixed or anchored device by recognising that new positioning cycles may improve accuracy when fresh reference data becomes available. Secondly, the concept attempts to prevent a bad location value from polluting a positioning cycle by indicating a possibility that a device may report an inaccurate position. The confidence figure also acts as an indication of maximum error range and the worst possible precision when a device with a potentially inaccurate location coordinate is used as a reference. This gives the framework an opportunity to use devices with inaccurate data as references, giving the environment a chance to evolve into a more accurate positioning system with minimum maintenance and initial setup.

Experiments were conducted in order to see the effects of inaccurate location data in reference devices and how it was reported by introducing a known degree of inaccuracy to the reference devices' location coordinates.

A set of experiments was performed with two stationary, immediate references; one reporting a biased location and 70% confidence while the other one held correct location information. In cases where the two reference devices did not have their detection ranges overlapping in a way that it would have been possible to calculate one or two possible location points, the results were similar to those shown in experiment 1 in Table 6.1. Hence, the outcome was a number of potential coordinate points calculated by using only the more reliable device as a reference. When the location bias was adjusted in a way that the detection ranges from the reported device positions shared at least one coordinate, the worst possible error margin corresponded to the range of the more reliable device with a confidence figure of 35% for the positioning cycle. In a case where both of the reference devices reported a biased location with 70% confidence similar results were obtained with the resulting confidence figure decreasing to 17%.

Similarly, as another stationary reference device was added to the environment the detection ranges of all the references had to overlap. The resulting confidence was calculated by assessing the combined probability of the reference devices having incorrect location information. For example, in case of two reliable reference devices and one reporting possibly incorrect data with 70% confidence, the bias on the location of the third device had to be restricted to an area where the detection ranges of all three devices had a single common coordinate, as demonstrated in figure 6.7 where A and B indicate the ranges of the two reliable reference devices and the dashed circle diameters depict the possible detection ranges of the third device. This resulted in confidence of 70% for the positioning cycle. If the deviation in the reported location would not correspond to the specified range, positioning was done with two reference devices, as described earlier in this section.

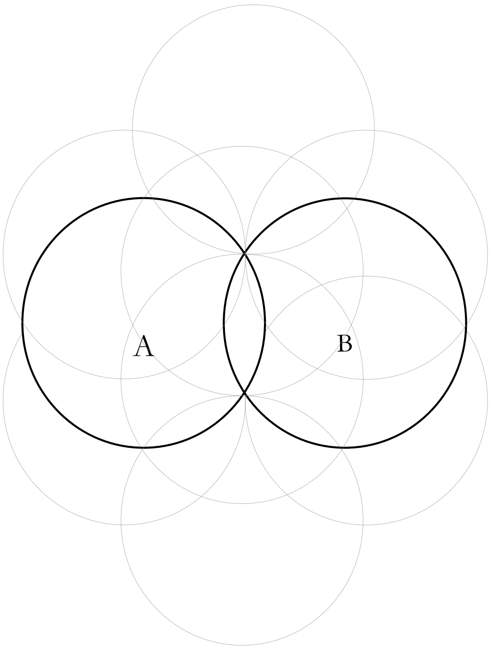


Figure 6.7 Simplified example range of a possible bias in a third reference device when triangulating.

When a bias was introduced to two of the three reference devices the area of the possible position of reference devices expanded to nearly double the area with the confidence figure of 48% reflecting this. When a bias was also extended to the third device confidence for the positioning cycle dropped to 34%. The results can be seen in tables 6.7a through to 6.7d along with the time it took to complete the positioning cycle. In case of triangulation the three second positioning is largely due to the polling interval of the simulation.

It is worth pointing out that lower confidence was not indicative of a certain bias in the location information in all of the cases. If bias was present in the reported position of one of the three reference devices also the resulting positioning cycle had an incorrect outcome, which varied between 1 metre and the size of the full detection range of the most reliable device, in this case 200 metres. Furthermore, since the confidence figure does not indicate how incorrect the location data for each device is the following tables do not record this information. Furthermore, a section for possible bias is included in the subsequent tables purely to demonstrate the possibility of a "bad" location value being passed from device to device through the use of different combinations of reference devices and is not used as a selection criteria for references.

Device	Confidence	Poss. Bias	Moving
A	100	no	no
B	100	no	no
C	100	no	no
Result (3s)	100	no	

Table 6.7a Control

Device	Confidence	Poss. Bias	Moving
A	100	no	no
B	100	no	no
C	70	yes	no
Result (3s)	70	yes	

Table 6.7b Effect on triangulation caused by bias from one reference device

Device	Confidence	Poss. Bias	Moving
A	100	no	no
B	70	yes	no
C	70	yes	no
Result (3s)	49	yes	

Table 6.7c Effect on triangulation caused by bias from two reference devices

Device	Confidence	Poss. Bias	Moving
A	70	yes	no
B	70	yes	no
C	70	yes	no
Result (3s)	34	yes	

Table 6.7d Effect on triangulation caused by bias from three reference devices

In order to examine the effects of one or more of the reference devices moving, a slightly different set of rules was observed for devices on normal or persistent positioning modes, as demonstrated in tables 6.8a through to 6.8d. Table 6.8a shows a situation where one of the lower confidence devices is moving with triangulation taking place on the first iteration. The positioning cycle was successful as long as it was possible to get a location "fix" due to the requirement of having all reference devices' detection ranges sharing at least one coordinate point. If this was not the case in the first interval positioning was performed with the two remaining devices, as explained earlier in this section.

Device	Confidence	Poss. Bias	Moving
A	80	no	no
B	70	no	no
C	70	yes	yes
Result (1s)	39	yes	

Table 6.8a Triangulating in a dynamic environment

Table 6.8b demonstrates a situation where the highest confidence device was moving. The positioning cycle consisted of two parts: the first location was obtained by triangulating with all three reference devices. The result was as shown in Table 6.8a with a confidence of 39%. As device 'A' started movement the location information was updated for devices on persistent positioning mode by utilising only a single reference device. This resulted in 51% confidence instead of the previous 39% although the improved positioning took 14 seconds longer to execute.

Device	Confidence	Poss. Bias	Moving
A	80	no	yes
B	70	yes	no
C	70	no	no
Result (15s)	51	no	

Table 6.8b Positioning with a single moving device as a sole reference device in order to obtain more accurate location information.

In Table 6.8c device 'C' with the highest confidence was stationary while device 'A' was moving. For persistent mode the positioning was performed by using both of these devices as references, after the initial triangulation as in the previous experiment. The result was a confidence of 50% initially, followed by an improved confidence of 57% after subsequent 11 seconds.

Device	Confidence	Poss. Bias	Moving
A	80	no	yes
B	70	yes	yes
C	90	no	no
Result (11s)	57	no	

Table 6.8c Positioning with a single moving device along with a stationary device as references in order to obtain more accurate location information.

Table 6.8d shows a situation where the highest confidence device 'C' is moving along with the other two reference devices. As with previous experiments, the first location and confidence figure of 50% for the positioning cycle are obtained within the first three seconds. The following 15 seconds are used for improving both figures by using device 'C' as the sole reference. This results in confidence of 72%.

Device	Confidence	Poss. Bias	Moving
A	80	no	yes
B	70	yes	yes
C	90	no	yes
Result (15s)	72	no	

Table 6.8d Positioning with a single moving device as a sole reference device in order to obtain more accurate location information.

Table 6.8e demonstrates how movement of the lowest confidence device is not a deciding factor as two of the higher confidence devices are stationary. The positioning is performed by utilising the triangulation algorithm with a confidence of 50%.

Device	Confidence	Poss. Bias	Moving
A	80	no	no
B	70	yes	yes
C	90	no	no
Result (3s)	50	yes	

Table 6.8e Triangulating in a dynamic environment

Although the confidence figure can not be used to indicate certain correctness or incorrectness of position information it can be utilised in the process of deciding which devices to be used as references purely on the basis of probability. For example, a reference device, which has a GPS receiver, is more likely to report a less incorrect location to a device, which has received a position as a result of a sparse positioning cycle. Due to this, the higher confidence devices have been selected as references where the device to be positioned has indicated a priority for lower error margin rather than location rate by selecting a persistent positioning mode. In most cases,the selection process has led to slower positioning but better confidence value. It may be noted that in all cases if a primary reference device became unavailable the positioning cycle was re-evaluated in a way that the existing devices were utilised as reference devices to perform triangulation as a secondary option with reduced confidence, regardless of the positioning mode as explained previously.

6.4 Summary

This chapter described how a positioning framework can be evaluated by using a simulated environment based on user activity. This was important in order to provide a flexible test-bed with a capability to reproduce device movement and validate the viability of the developed positioning techniques and algorithms.

The chapter continued by describing experiments, which showed that it is possible to reduce error margin for a positioning cycle by utilising devices outside the immediate detection range of the original device. Error margin could be reduced with only one reference device, although the techniques proved to be mostly valuable in situations where two immediate reference devices existed resulting in two possible coordinate points. In this case additional devices beyond a hop could be used in order to get a position fix. The experiments also demonstrated how it was not necessary to pursue devices after the first hop due to clashing detection ranges, which meant no benefits were recorded.

In addition, this chapter discussed the implications of dynamic references in the form of moving devices. It was concluded that moving devices can be used for positioning in a manner that allows fewer reference devices to be used. The obvious advantage of this was in situations where sufficient reference devices were not available to perform triangulation or alternatively in conditions where bias was thought to be present in the position information. Hence, the confidence in the reported location was better implying that the error margin too was improved by selecting devices as references with most confidence in their own location. It should be noted that the selection of higher confidence devices as references was performed only if the device to be positioned was on persistent positioning mode due to the lower location rate when using moving devices as references.

Chapter 7

EVALUATION

7.1 Introduction

This chapter looks at how well the proposed framework performs positioning based on experiments and evaluation criteria discussed in earlier chapters. The first part of this chapter concentrates on evaluation issues, which have arisen from as a result of experiments explained in Chapter 6. It aims to relate the design choices to the taxonomy introduces in Chapter 4 and concentrate on how well the requirements for a positioning framework have been fulfilled. The second part discusses topics that were not described by this thesis and explores the open issues, followed by recommending a direction for further research.

7.2 Discussion

7.2.1 Multisensor Availability

The purpose of the multisensory approach is to maximize availability of each device as a reference and by definition the more sensor technologies there are available, the better the chances of finding references in order to be positioned. However, it is evident that different technologies have their technological constraints limiting the usefulness of each one to the framework.

It can be said that usable wireless technologies, which are able to provide device-to-device proximity information for the positioning purposes in the proposed framework and which are widely available on mobile devices are currently limited to the WiFi, Bluetooth and infrared technologies. New technologies are, however, currently being developed and standards accepted so that options such as ultra-wideband are expected to be widely implemented in the future.

In order to collect information for proximity maps and perform positioning calculations the system assumes at least one sensor capable of a peer-to-peer connection in order to find a RSSI value for distance measurements as well as network connectivity. In practical terms this implies that any device, which is temporarily within the environment, has a WiFi adapter, which is set to infrastructure mode along with a Bluetooth or infrared adapter reporting proximity information. Furthermore, the usefulness of the infrared technology is debatable due to its need for line of sight and very short range. In many cases this would mean that the devices' WiFi adapters would need to be set to ad-hoc mode or the Bluetooth technology would be the only viable entity proximity measurement. The obvious implications of this would be the need for supporting a number of permanent nodes within the environment, which would act as centralised stations for connecting mobile devices to the infrastructure but would hinder the capability of using the network for other purposes. Due to this reason it is reasonable to assume most users would prefer their WiFi adapters in infrastructure mode for most environments where network connectivity is desirable. This would mean limiting the proximity information available from the WiFi adapter to the vicinity of the wireless access point rather than using the adapters on ad-hoc mode enabling the recording of device-to-device proximity information. Integrating access points themselves to the framework as possible reference devices is discussed further in this chapter.

7.2.2 Privacy

Due to the ever growing privacy awareness of the users one of the considerations in the positioning framework has been privacy and trust. In its present form the framework requires an implicit trust between the infrastructure and the entities within the environment. In order to be positioned the entity is required to provide identity information in the form of a MAC address to the infrastructure. This is used to establish a way to contact each entity, either because they are used as reference devices or they require a positioning. Hence, as with any infrastructure based positioning frameworks anonymity is not an option. The user also agrees to disclose data from the device's proximity sensors as an exchange to positioning.

The proposed infrastructure based positioning framework can, however, be considered as the more private option when compared to equivalent ad-hoc systems in dynamic environments, which are not guaranteed to have fixed beacons. The entities are not directly aware of each other any more than what their sensor technologies RSSI's would normally report in the surroundings. Furthermore, they are not required to have neither communication nor have they got a way of contacting each other; instead the entity discoverer holds the information in the infrastructure side. If an ad-hoc based positioning system was to be implemented with similar requirements the entities would need a public handle to each other in order to exchange location and proximity information.

It is also necessary to consider the trust issue from the infrastructure's angle. The entities with equipment such as GPS are expected to report actual data back without malicious intentions to interfere with the GPX data obtained from the receiver.

Furthermore, the infrastructure has no other means of validating the coordinates, which are received from entities than performing the positioning algorithms, which will return a location based on the reported coordinates unless they are sufficiently incorrect. This means that in the worst case the maximum allowed error in the reported location would be as high as four times the size of the detection range from the corrupted reference device before it would be detected, providing the positioning was done with at least another reference with correct coordinates. In case of the device being the sole reference the error margin cannot be defined until another reference would appear in the detection range.

7.2.3 Execution of Algorithms

The positioning algorithms are currently performed by the infrastructure for two reasons; firstly due to privacy preferences of most users, as discussed earlier and secondly due to the heavy processing that is involved in determining the position.

When analysing the positioning algorithms from the performance point of view it can be noted that the algorithms get more expensive the less reference devices there are available. For example, if three reference devices are used to calculate a location for the entity according to equation 4 through to 11 the number of coordinate points returned is just four implying the required number of coordinate comparisons is set*,* since a maximum of two coordinates will be compared in turn to see if they match to either of the remaining two coordinates. In the case of two reference devices the situation is linear and according to Weiss (1996) may be depicted as an order notation *O(N)* as the initial algorithms return two possible coordinate points, which in the worst case scenario both have to be in turn compared to the whole distance range of viable coordinates in order to get a reliable location. The issue is significantly worse if the entity requires persistent positioning with a single reference having the complexity of $O(N^2)$. The viable range of possible coordinates is reduced by comparing a full distance ranges to others until either the number of possible coordinates has reduced to one or the reference device is no longer available. From previous experiments shown in Figure 6.6 if the reference device which is furthest away from the entity with the slowest speed was used as a sole reference to reduce the number of possible coordinate points the coordinate comparison would require on average nine intervals when the comparison algorithm would have to be executed. When considering the time of 119 milliseconds it took for the first interval to execute on the test machine with 2.4GHz dual-core processor 3 GB of RAM it becomes obvious that a mobile device with limited processing power (typically as low as 400MHz single-core CPU) would struggle with the whole set of algorithms, which are necessary for the on-demand positioning calculations. Furthermore, since each device within the environment is expected to return queries about other devices they have in their detection ranges the processing requirements would very quickly exceed the capabilities of most light weight mobile devices currently on the market. Also, for lower specification devices it might be required to limit the number of queries it is expected to return as a reference device. For example caching a proximity map of a device for a period of time instead making a fresh query every time entities surroundings have changed would not only make a difference to the reference devices but also the network traffic burden would eased.

Although mobile devices are often required to have the capabilities to run software as complicated as the software on desktop computers, they still have considerably reduced speed as a comparison (Raghavan et al, 2004). Even though faster devices with significantly greater processing power are being developed, battery life and heat dissipation will always be issues resulting from higher power consumption of new generation of faster devices. Due to this fact it is unreasonable to assume mobile devices would be suitable to continuously execute the proposed positioning algorithms while being used for their actual purpose of being personal communications devices. Because of the requirements for on-demand positioning along with a high connectivity, in order to provide “normal” expected network availability to the users infrastructure based execution of the positioning algorithms seems to be the only viable alternative.

7.2.4 Supported Positioning Surroundings

The proposed framework has two very different surroundings where positioning is required to take place: indoor and outdoor environments. As discussed in earlier chapters normal GPS based positioning is not an option indoors due to various shadowing and signal distortion effects. Furthermore, specialised GPS technologies such as A-GPS and TV-GPS are not widely used. For this reason most indoor positioning systems are operating purely on either ad-hoc mode or require significant static sensory structure, which generally isn't readily deployed in other environments without significant effort. In outdoor environments an absolute coordinate receiver, such as GPS is capable of very accurate positioning but without a device with a GPS capability the user is again relying solely on static positioning systems performing triangulation based on pre-stored location data of wireless base stations.

The proposed framework challenges these restrictions by providing positioning in both indoor and outdoor environments providing there is a network access that facilitates sending proximity data collected from the sensors for the infrastructure to process along with some initial configuration. Because the solution doesn't rely on sensory infrastructure to gather the readings about entities' locations within the environment the concept can be readily transferred into outdoor surroundings. Furthermore, due to the positioning techniques used the solution doesn't rely on the environment to consist of static structure but instead utilises the dynamic movement of reference devices in order to improve geographic scalability.

In indoor environments the challenge is to provide the first reference devices for the environment. Although specialised absolute coordinate technologies such as A-GPS and TV-GPS exist as discussed in earlier chapters it is recommended that initial setup would take place in environments where it unlikely that devices with these capabilities are available for references. The configuration would mean that the environment would have a minimum of three proximity sensors with overlapping detection ranges, which would know their absolute coordinates either by:

- Intentional set-up configuration. In practice this would mean that, for example wireless base stations would need to be set up in known and stored locations.

- Utilising the feedback mechanism by purposefully using one of the indoor GPS systems mentioned to record a location for the base stations. This option requires minimal user input but would involve an off-line configuration sequence where an administrative user would train the locations into the system.
- By getting two or more separate users to indicate their location from a map when directly next to the sensor. The location could not be finalised until at least two locations matched to the accuracy of the error margin, set to one metre by default. The challenge would be to create an accurate map that would be able to pinpoint the selections into locations. More research into trust management mechanism would need to be done in order to find out the effect on confidence to reflect the danger of users indicating a wrong position either by intention or due to inability.

After the initial setup indoor surroundings, which suffer from sparseness of reference devices can be used to implement the proposed framework as discussed in Chapter 5.

Outdoor surroundings do not generally suffer a similar lack of GPS or other absolute coordinate devices. Therefore, it is not completely necessary to go through a configuration sequence for wireless stations. Instead, the framework allows these devices to be treated as anchored entities and therefore normal positioning can take place as soon as sufficient reference devices are within the detection range as described in Chapters 5 and 6.

7.2.5 Value of Location Data

Most positioning systems report accuracy and precision to the user as a single figure, indicating the likelihood of a device being positioned within the error margin when possible bias in measurements has been taken into account as described in Chapter 2. Although the importance of judging the value of positioning with these metrics is unarguable it can be noted that they are insufficient in indicating the true reliability of the location in a way that it can be weighed whether a location is sufficiently correct in order to be used as a reference in dynamic environments.

Since the proposed framework allows the use of multiple device sensors, which affect the capabilities of that device to act as a reference device and can change from one positioning cycle to another it is difficult to give an accuracy and precision to the system based on dynamic reference devices. Furthermore, reporting a simple accuracy and precision figure doesn't take into account the positioning modes, which have been implemented to improve the availability of location data and allow the evolution of the location by using refining positioning cycles.

The confidence figure aims to provide an additional measurement indicating the value of the location for an individual entity for each positioning cycle. It can be used as an internal indication as to when the location is as sufficiently correct as required by the user as well as the usage. The confidence has proved to be an invaluable indication of the weight of which a dynamically changing location value can be applied to the environment at any given time. Furthermore, the confidence value can be extended to include, for example how much the entity trusts the reference devices or how a confidence could indicate a currency of cached location after an entity has moved as described in the Future Work section of this chapter.

7.2.6 Accuracy, Precision and Location Rate

As with any WLAN based position determination method the granularity of the sensors dictate the base accuracy of the system. This is reduced by introducing bias to the environment, which could be in the form of a high-rise building causing shadowing to the GPS signal or structures such as walls disturbing the RF signal of WiFi access points causing distance measurements to be corrupt by tens of meters. The accuracy and precision may be improved by combining readings from multiple sensors, which are made available on the device.

Since the proposed method expects ideal surroundings for undisturbed signal propagation the accuracy of the system is determined by the error margin set for performing the positioning calculations. For normal and persistent positioning mode this error margin is set to one metre with an expected precision of 100% in order to compare viable coordinates to the current calculations, as explained in Chapter 6. The location coordinate is expected to be reported with one metre accuracy of the actual position regardless of whether the sensor used would be capable of finer granularities. If a device has been set to a sparse positioning mode the error margin can be significantly larger with accuracies reported as twice the size of the detection range, as explained in Chapters 5 and 6. Similarly, due to the ideal theoretical operating environment, assumptions of the precision can be only made based on precision calculations such as those shown in Tables from 6.1 to 6.3. The community has realised the need for signal propagation modelling and some of the research dedicated to the subject have been pointed out later in this chapter.

Similarly location rate can be affected by for example, network lag or processing constraints on mobile devices getting proximity information, which hasn't been fully modelled in the simulation. However, assumptions can be made about the degree of variations in location rate according to the positioning mode and the surroundings of an entity. From Tables 6.8a to 6.8e it may be seen that in situations where a single device is used as a reference for an entity, which is in persistent positioning mode in a dynamic environment, the location rate is expected to be around 15 seconds as opposed to triangulation performed in milliseconds when sufficient reference devices and ideal network conditions allow it.

7.2.7 Availability of Positioning

One of the main objectives of proposed positioning framework was to improve the availability of positioning without the need for ad-hoc localization or sensory infrastructure, which would hinder scalability and heterogeneity as well as make the deployment of the framework more burdensome. Due to these constraints the proposed method creates a stored viable range, which can be used in refining positioning cycles making it possible to determine entity's position based on "past" location data. This ensures that anchored devices or devices that have not moved have a chance of obtaining a position that is as accurate as possible over time.

Furthermore, the decision was made to facilitate positioning based on a single moving reference device. Although the concept has been previously visited by, for example, Sichitiu & Ramadurai (Sichitiu & Ramadurai, 2003) and Galstyan et al. (Galstyan et al., 2004) in the form of ad-hoc localization with moving beacons, the proposed positioning method differs since it does not need a pre-programmed robot to base the positioning calculations on. By allowing a single mobile device act as a sole reference in sparsely populated dynamic environments the devices are able to share position information without the need for ad-hoc communications, minimal distance between the devices or three references in order to perform triangulation.

7.3 Open Issues & Future Research Direction

7.3.1 Support for Trust Management Framework

A supported trust management framework such as one of those surveyed by Fernandez-Cago et al. (Fernandez-Cago et al., 2007) would ensure that the confidence value of an entity would not only be calculated based on the confidences of the reference values but also their reputations. If confidence calculations would be performed by weighing the trust in the reference as well more research would need to be made into deciding how much weight trust would have in the calculations and modelling how far bad trust would travel before the level of bias in the location value would stop positioning.

7.3.2 Ad-Hoc Mode for Positioning

An interesting future direction would involve investigating whether simplified and optimised light-weight versions of the positioning algorithms would be feasible to run on mobile devices in order to provide an ad-hoc positioning for entities in environments with limited connectivity. This would also require integrating the trust management framework into the concept and would best be developed as an optional feature in order to be able to share locations between entities when no infrastructure support was available.

7.3.3 Reducing Network Traffic

Modelling user movement speed by observing signal strength indicators could facilitate caching of the proximity maps in order to avoid having to create a new map for the detection range every time the surroundings change. The currency of the position information could be determined by calculating the movement speed and determining when the threshold for requesting new proximity maps had been reached by comparing the distance moved to the defined error margin. The same technique would be useful for positioning with a single moving device as a viable range would only be calculated based on sufficient distance to the previous reference device location as discussed in Chapter 5 and illustrated in Figure 5.11. Furthermore, caching the viable map would ensure that the entity would not be required to send the stored information for every refining positioning cycle for the infrastructure to process.

The caching potential would also ease some of the burden for mobile devices since it wouldn't be necessary to request sensor information from a reference device as frequently. A simple subscription model could be implemented for resource poor devices or ones with low bandwidth communication links in addition to the current approach of repeated polling queries for sending sensor data when a device is used as a reference. The subscription scenario would enable an entity to determine whether it could be contacted for positioning requests, for example, as a sole reference device, as part of a set of references or as a device beyond a hop. The subscription scenario should perhaps be accompanied with sanctions in terms of usability of the positioning service to the device itself, thus making the option less tempting by promoting solidarity amongst the users.

7.4 Summary

This chapter discussed how the position of a device can be estimated based on the minimum number of reference devices in dynamic environments. It based the discussion on evaluation criteria described in earlier chapters of this thesis and the data obtained from the experiments using a simulated environment.

The chapter concludes that sharing location information between devices within the environment is viable by using the techniques described in the previous chapters. In simulated circumstances it is possible to get accuracies of one metre with a single reference device. Furthermore, it was concluded that the multisensor approach could be further used to improve accuracy and precision in addition to enhancing the availability of the positioning service.

It was confirmed that privacy was improved by adopting an infrastructure based model of position determination rather than relying on ad-hoc localization, which would also place an unnecessary burden on the mobile device due to the intensive calculations required to estimate a device's position.

In addition matters, such as scalability and heterogeneity were discussed in relation to supported positioning surroundings. It was concluded that although minimal configuration would be advisable in order to facilitate the instant deployment of the proposed framework, initial offline time would not be a requirement.

This chapter also explored issues, which have not been addressed by this thesis and discussed further research directions in order to enhance the performance and usability of the framework.

Chapter 8

CONCLUSION

The last chapter of this thesis aims to provide a summary of the contributions of the research and briefly describes future work which would be necessary in order to fully deploy the position determination framework.

8.1 Contributions

The purpose of this research has been to propose a novel concept of position determination in dynamic environments in order to facilitate mobile device location-awareness for context-based computing. The goals of the research can be divided into the main areas outlined below.

The first goal is to use sensors, which are already found on most mobile devices rather than implement a middleware solution to allow a number of different sensor technologies from independent sources to be integrated. This ensures a single device, such as any personal communications devices with a WLAN capability can be used for a position determination instead of having to equip multiple positioning technologies on a number of devices which is the case with management middleware such as the Nexus project.

The available sensors are used to measure distances between devices and to provide information about nearby devices in order to create proximity maps. The proximity maps allow a mobile device's position to be determined based on reference devices, which are in the immediate detection range or one "hop" beyond it in order to transform simple containment based location information into absolute coordinates. Furthermore, combining proximity maps with the introduced positioning modes, it is possible to provide position estimation in environments where location references are sparse. This allows positioning with less than three references if necessary, which is an improvement to systems such as the Skyhook and other triangulation based WLAN systems.

The multisensor approach also allows combining readings from different sensors in order to improve the accuracy and precision of the positioning in addition to allowing sharing of position information between devices without the need for ad-hoc localization or custom built sensors such as the ones used in the Cricket or the badge systems.

The off-the-shelf approach to sensors was extended to the idea of improving geographic scalability, interoperability and heterogeneity by erasing the need for fixed sensory infrastructure, thus facilitating the mobility between indoor and outdoor surroundings, which is not the case in most of the surveyed methods. This also ensured that set-up costs would be kept to a minimum.

Another goal was to improve availability of the positioning service by including location information from reference devices which might not be able to provide accurate data due to lack of devices such as a GPS receiver. This potential incorrect data was classified by introducing a confidence figure, which facilitated the reasoning of which reference devices to use and when, based on user preference and the current positioning mode. The availability was also improved by implementing a viable range of coordinates, which were stored in case sufficient reference devices were unavailable and the positioning cycle could not be finished by the time the devices in the detection range had moved or changed. The viable coordinates were reduced by creating proximity maps for the reference devices, which indicated the devices beyond a hop potentially ruling out a directional range of coordinates without the need of custom antennas such as the ones used for beacon based AoA localization. The idea of viable coordinates enabled the ongoing training of devices, such as stationary mobile devices or environmental WiFi base stations in order to reduce the initial configuration effort and offline calibration period that hindered fingerprinting systems such as the Radar. This made certain that administrative and maintenance costs were kept to a minimum. Furthermore, the introduction of the viable range facilitated positioning with a single moving reference device without the need for a programmed beacon on a pre-defined track. Alternatively the viable range provided a choice of position estimation in situations where sufficient reference devices were not available and location rate was a priority over accuracy and precision.

A technique, which was utilised in order to ease the computational burden placed on a mobile device, was to allow infrastructure to contact devices in order to gather sensor data and perform the calculations. This also made it possible to allow devices to stay anonymous from each other in a way that would not have been possible in ad-hoc localization systems.

8.2 Future Work

8.2.1 Modelling Signal Propagation

An important direction for future work would be implementation of an accurate signal propagation model in order to ensure distance measurements could be performed as accurately as possible. A wide research field has concentrated on mathematically modelling the characteristics of signal propagation and attenuation effects. Whilst the topic is outside of the scope of this thesis the usefulness and potential of integrating one of the propagation models to the existing framework is recognised. An accurate model, such as one that has been assessed by Sayed et al. (2005) or Pahlavan et al. (2002) would improve the position estimation due to more accurate distance measurements in scattered urban environments, which suffer from non-line-of-sight effects due to walls and other structures as well as are affected by shadowing and distortion of signal.

8.2.2 Mobile Application Development & Deployment

Full scale deployment of the positioning framework would need careful consideration of aspects such as mobile device and application platforms. It is obvious that the choice of development architecture should allow cross platform deployment with a wide range of devices and operating systems that support it. Based on the hardware and software support of currently marketed mobile devices, according to Canalys (Canalys, 2007) the most common device platforms seem to be the ones supporting .NET compact framework and Java Micro Edition (Java ME).

Although Java ME has a very impressive record of being readily deployable on multiple platforms the .NET compact framework has the added bonus of having an efficient common language runtime for limited resources, memory and power. Unlike Java ME on most supported platforms the .NET compact framework provides crucial, readily accessible and very well documented APIs for accessing and using all the devices' sensor capabilities, such as GPS, WiFi and Bluetooth. Furthermore, using the .NET compact framework enables the use of techniques such Web Services, which would be the natural choice to delegate the computation-intensive position determination to the infrastructure side in order to fully deploy the positioning framework already developed taking advantage of the features in .NET framework.

While platforms such as .NET compact framework provide means of device-to-device and device-to-infrastructure communications device independent characteristics of, for example, the Bluetooth stack are an important consideration. Although interfacing standards exists, implementing a single algorithm for multiple makes of sensors may prove to be a challenge due to varying adaptations of the protocols. As a consequence the range of supported makes of devices might have to be limited to a selected few supporting the same standard.

8.2.3 Application Support

Future work should include a rigorous evaluation on what type of location-aware applications this type of position determination framework would best support. An interesting prospect would be to consider creating application support for services such as an integrated route finder or relative coordinate transformation for locating services within the environment. It is not yet clear whether the signal propagation modelling would improve distance measurements to the extent that accuracy and precision of the positioning could be matched to the requirements of some of the more fine grained applications.

8.2.4 Evaluating Usability

Another issue that should be addressed is usability of the system. The concept is not only interested in physical capabilities of mobile devices but naturally also the perceived usability. This includes gathering user experiences of the positioning framework in terms of availability, effectiveness of the algorithms in environments with limited references, time it takes to get a location and whether reference requests interfere or disturb the normal usage of the device. Duh et al. (2006), Kjeldskov and Stage (2004) and Garzonis (2005) offer some insight into the field.

8.3 Conclusion

This thesis has described a framework for dynamic position determination implementing a widely available infrastructure of wireless local area networks by allowing mobile devices share position information without a need of ad-hoc localization. The solution has concentrated on prioritising availability of positioning service in situation where incorrect location data or insufficient reference devices are present. Furthermore the framework has enabled maximum possible accuracy and precision by combining data from a mix of sensors, already available on mobile devices. The described approach allows mobility and heterogeneity between indoor and outdoor positioning methods and technologies as well as minimising the need for off-line calibration and deployment efforts.

References

ABDUL-RAHMAN, A. and HAILES, S. (1997) 'Using Recommendations for Managing Trust in Distributed Systems'. in *Proc. of IEEE Malaysia International Conference on Communication (MICC'97*). Kuala Lumpur Malaysia.

ABOWD, G. and DEY, A., (2002). 'A Conceptual Framework and a Toolkit for Supporting the Rapid Prototyping of Context-Aware Applications', Georgia Institute of Technology, [Online] Available: http://www.cc.gatech.edu/fce/contexttoolkit (Accessed 12 May 2009)

AHMED, M. and HAILES, S. (2004) 'Modelling Interactions in Ubiquitous Environments'. in *2nd UK-UbiNet Workshop*. Cambridge

ANDERSON, J. AULIN, T. and SUNDBERG, C. *Digital Phase Modulation* 1st Edition, Springer.

ARIYAEEINIA, A. SOTUDEH, R. BAILEY, C. and RODIN, F. (2004) 'User Voice Identification (Urvin)'. in *2nd UK-UbiNet Workshop*, Cambridge

ASCENSION "Anon" Ascension Technology Corporation, (2001) [Online] Available: http://www.ascension-tech.com/ (Accessed 20 March 2009)

BAHL, P. and PADMANABHAN, V. (2000). 'Radar: An in-building RF-based user location and tracking system', in *Proc. IEEE Infocom 2000*, pp.775-784. Israel

BANKS, J. CARSON, J. NELSON, B. and NICOL, D. (2005). Discrete-Event System Simulation, 4th Edition, Pearson/Prentice Hall.

BECKER, C. and DURR, F. (2005) ‘On Location Models for Ubiquitous Computing’. *Personal and Ubiquitous Computing*. 9 (January issue 1) pp. 20-31

BOUKERCHE, A. (2006) Handbook of algorithms for wireless networking and mobile computing. CRC Press. USA.

BULUSU, N. HEIDEMANN, J. ESTRIN, D. and T. TRAN, (2004) ‘Self-configuring localization systems: Design and experimental evaluation’. ACM Trans. *Embedded Computer.Systems*. 3 (May no. 1). pp. 24–60.

CAFFERY, J. (1999). Wireless Location in CDMA Cellular Radio Systems. Norwell, MA:Kluwer

CAMPBELL, R. et al. (2002), ‘A Middleware Infrastructure for Active Spaces’. *IEEE Pervasive Computing*, 1536-1268/02

CAPRA, L., “Towards Human Trust Model for Ad-Hoc Networks”. In 2nd UK-UbiNet Workshop, Cambridge, May 2004.

CHEN, G. & KOTZ, D. (2000). A Survey of Context-Aware Mobile Computing Research, Technical report TR2000-381, Dartmounth College

DARRELL, T. GORDON, G. HARVILLE, M and WOODFILL, J. (1998). ‘Integrated person tracking using stereo, color and pattern detection’, in *Computer vision and pattern recognition*. IEEE CS press California pp. 601-608

DRAYTON, P. ALBAHARI, B. and NEWARD, T. (2002) C# in a Nutshell. O’Reilly. California, USA.

DUH, H. TAN, G. and CHEN, V. (2006). 'Usability evaluation for mobile device: a comparison of laboratory and field tests'. in *ACM International Conference Proceeding Series, Proceedings of the 8th conference on Human-computer interaction with mobile devices and services*. 159. Helsinki, Finland

EASY LIVING "Anon" Microsoft Research (2001) [Online] Available at: http://www.research.microsoft.com/easyliving/ (Accessed: 10 September 2003)

FERNANDEZ-GAGO, M. ROMAN, R. and LOPEZ, J. (2007) 'A Survey on the Applicability of Trust Management Systems for Wireless Sensor Networks'. in: *Security, Privacy and Trust in Pervasive and Ubiquitous Computing*, IEEE press 19 (Issue 19). pp 25 – 30

FERRARA, A. and MACDONALD, M. (2002). Programming .NET Web Services. O'Reilley Media

FININ, T. JOSHI, A. RATSIMOR, O. and KOROLEV, V. (2001) 'Information Agents for Mobile and Embedded devices'. in: *Fifth International Workshop Cooperative Information Agents*. 2182. pp. 264-286

FONTANA, R. and GUNDERSON, S. (2002) 'Ultra wideband precision asset location system'. in: *IEEE Conf. Ultra Wideband Systems and Technologies*. (May). pp. 147–150.

FOX, A. PONNEKANTI, S. LEE, B. HANRAHAN, A. and WINOGRAD, T. (2001). 'ICrafter: A Service Framework for Ubiquitous Computing Environments'. in: *Proceedings of the 3rd international conference on Ubiquitous Computing*. Atlanta. pp. 56 - 75

GARZONIS, S. KOSTAKOS, V. KAENAMPORNPAN, M. and WARR, A. (2004). 'A Novel Approach for Identification and Authentication of Users in a Pervasive Environment'. in: *2nd UK-UbiNet Workshop*, Cambridge

GANU, S. KRISHNAKUMAR, S. and KRISHNAN, P. (2004) 'Infrastructure-based location estimation in WLAN networks'. in Proc. *IEEE Wireless Communications and Networking Conf.* pp. 465–470.

GERBER, R. (2005) The Software Optimization Cookbook. 2nd Edition. Intel Print

GPS "Anon" National Space-Base Positioning. (2009) 'Navigation and Timing Coordinate Office, Global Positioning System: Serving the World'. [Online] Alexandria: U.S. Coast Guard Navigation Center, U.S. Government. Available at: http://www.gps.gov/index.html (Accessed 20 March 2009)

GPX 1.1 Schema Documentation [Online] Available at: http://www.topografix.com/GPX/1/1/ (Accessed 12 November 2008)

GRANDISON, T. and SLOMAN, M. (2002) 'Specifying and Analysing Trust for Internet Applications'. In Proc. *Of 2nd IFIP Conference on e-Commerce, e-Business, e-Government.* Lisbon Portugal.

GRIMALDI, R. (1999). Discrete and Combinatorial Mathematics, 4th Edition. Addison-Wesley. USA

GUSTAFSSON, F. and GUNNARSSON, F. (2005) 'Mobile positioning using wireless networks'. IEEE Signal Processing Magazine. 22 (July no. 4). pp. 41–53.

HARRIS, S. and ROSS, J. (2006) Beginning algorithms. John Wiley and Sons.

HARTER, A. HOPEER, A. STEGGLES, P. WARD, A. and WEBSTER, P. (2002). 'The Anatomy of a context-aware application'. in Wireless Networks. 8 (March no:s 2-3). Springer Netherlands. pp. 187-197

HAZAS, M. SCOTT, J. and KRUMM, J. (2004). 'Location-aware computing comes of age'. in Computer Magazine, IEEE. 37 (February issue 2). pp. 95-97

HAZAS, M. and WARD, A. (2002) 'A Novel Broadband Ultrasonic System'. in Proc. *4th International Conf. UbiComp 2002: Ubiquitous Computing*, Göteborg, Sweden

HATZOPOULOS, J. (2008). 'Topographic Mapping: Covering the Wider Field of Geospatial Science & Technology'. Florida: Universal Publishers.

HIGHTOWER, J. and BORRIELLO, G. (2001), 'Location Systems for Ubiquitous Computing', Computer, 33 (no. 8). pp. 57-66

HIGHTOWER, J. BRUMITT, B and BORRIELLO, G. (2002), 'The Location Stack: A Layered Model for Location in Ubiquitous Computing'. in Proc. 4th IEEE Workshop on Mobile Computing.

HILYARD, J. and TEILHET, S. (2004) C# Cookbook, O'Reilly, California, USA.

ILYAS, M. and MAHGOUB, I. (2004) Mobile computing handbook. CRC Press.

JAIN, A. and PANKATI, S. (2006). 'A touch of money [biometric authentication systems]' Spectrum, IEEE. 43 (July issue 7). pp. 22-27

JEWELL, T. CHAPPELL, D. and LOUKIDES, K. (2002). "Java Web Services", O'Reilly & Associates, Sebastopol, CA.

JONES, K. LING. L. and ALIZADEH-SHABDIZ, F. (2007). 'Improving Wireless Positioning with Look-ahead Map-Matching' in Proc. *Mobile and Ubiquitous Systems: Networking & Services (MobiQuitous 2007).* 6-10 (Aug) pp. 1-8

ISO "Anon" (1995). 'Open Distributed Processing Reference Model', International Standard ISO/IEC IS10746.

KARZONIS, S. (2005). 'Usability Evaluation of Context-Aware Mobile Systems: A Review' in Proc. *3rd UK-UbiNet Workshop*. Bath, UK.

KINDBERG, T. SELLEN, A. and GEELHOED, E. (2004) 'Security and Trust in Mobile Interactions: A Study of Users' Perceptions and Reasoning'. in Proc. *2nd UK-UbiNet Workshop*, Cambridge, UK.

MANGOLD, S. and KYRIAZAKOS, S. (1999) 'Applying pattern recognition techniques based on hidden Markov models for vehicular position location in cellular networks'. in Proc. *50th IEEE Vehicular Technology Conf.* Amsterdam, The Netherlands, pp. 780–784.

MASCOLO, C. CAPRA, L. and EMMERICH, W. (2002). 'Middleware for Mobile Computing'. Tutorial paper in. *International Conf. on Networking*

MCCONNELL, S. (1993) Code Complete, Microsoft Press. Washington, USA.

MILLER, S. NEUMAN, B. SCHILLER, J. and SALTZER, J. (1987) 'Kerberos authentication and authorization system'. Technical report. MIT.

MOON, P. and SPENCER, D. (1988). 'Field Theory Handbook, Including Coordinate Systems, Differential Equations, and Their Solutions'. 3rd ed. New York: Springer-Verlag, pp. 9–11

NAGPAL, R. SHROBE, H. and BACHRACH, J. (2003). 'Organizing a global coordinate system from local information on an ad hoc sensor network'. in Proc. *2nd Int. Workshop Information Processing in Sensor Networks (IPSN '03).* pp. 333–348.

NAHIN P. (1998). "An Imaginary Tale: The Story of √-1", 3rd print ed. Princeton University Press

NICULESCU, D. and NATH, B. (2003). 'Ad hoc positioning system (APS) using AoA'. in Proc. *IEEE INFOCOM.* San Francisco, CA. vol. 3, pp. 1734–1743.

ORR, R. and ABOWD, G. (2000). 'The Smart Floor: Mechanism for natural user identification and tracking', in Proc. *Human factors in computing systems*. ACM Press, New York

PAHLAVAN, K. XINRONG, L. and MÄKELÄ, J-P. (2002) 'Indoor geolocation science and technology' IEEE Communication Magazine. 40 (February issue 2) pp. 112–118.

PASCOE, J. (1998). 'Adding Generic Contextual Capabilities to Wearable Computers' in Proc. *Second International Symposium of Wearable Computers*. Pittsburgh, Pennsylvania. IEEE Computer Society Press.

PATELI, A., GIAGLIS, G.M, FOUSKAS, K., KOUROUTHANASSIS P. and TSAMAKOS A. (2002) 'On the Potential Use of Mobile Positioning Technologies in Indoor Environments'. in Proc *15th Bled Electronic Commerce Conference -e-Reality: Constructing the e-Economy*. Bled, Sloveni

PATTERSON, C. and MUNTZ, R. (2003). 'Challenges in Location-Aware Computing'. IEEE Pervasive Computing. April-June, pp. 80-89

PRESSMAN, R. (1997) Software Engineering a Practitioner's Approach. McGraw-Hill. Malta

PRIYANTHA, N. CHAKRABORTY, A and BALAKRISHNAN, H. (2000). 'The Cricket location-support system'. in Proc. *6th annual int'l conf. Mobile computing and networking (MobiComp00.,* ACM Press New York, pp.32-43

POOCH, U. and WALL, J. (1992). Discrete Event Simulation: a Practical Approach. CRC Press New York

RAGHAVAN, G. SALOMAKI, A. & RAIMONDS, L. (2004). 'Model based estimation and verification of mobile device performance'. in Proc. *4th ACM International Conference on Embedded Software*

SATAYANARAYANAN, M., (1996). 'Fundamental challenges of mobile computing'. in Proc. *15th ACM Symp. Principles of distributed computing*, ACM press, pp. 1-7

SAYED, H. TARIGHAT, A. and KHAJEHNOURI, N. (2005) 'Network-based wireless location'. IEEE Signal Processing Magazine. 22 (July issue 4). pp. 24–40.

SCHILIT, W. (1995). 'A System Architecture for Context-Aware Mobile Computing'. PhD thesis, Columbia University

SCHMIDT, A. BEIGL, M. and GELLERSEN, H. (1999). 'There is more to Context than Location'. Computer & Graphics. 23 (December issue 6). pp. 893-901

SHAND, B. DIMMOCK, N. and BACON, J. (2003) 'Trust for transparent, Ubiquitous Collaboration'. in Proc. *First IEEE Annual Conference on Pervasive Computing and Communications (PerCom 2003*). Dallas-Ft, TX, USA. pp. 153-160.

MORITA, S. NAGASE, T. and NOMIZU, K. (2001). Geometry of Differential Forms. American Mathematical Society Bookstore.

SICHITIU, M. and RAMADURAI, (2003) 'Localization of wireless sensor networks with a mobile beacon' Center for Advances in Computing and Communications (CACC), Raleigh, NC, Tech. Rep. TR-03/06 (July)

SMARTDUST "Anon" SmartDust Community. (2002) [Online] Available at: http://www.darpa.mil/ito/research/sensit (Accessed 24.08.2003)

STAJANO, F. and ANDERSON, R. (1999) 'The Resurrecting Duckling: Security Issues for Ad-Hoc Wireless Networks'. in Proc. Seventh International Workshop on Security Protocols.

STAJANO, F. (2002). 'Security for Whom? The Shifting Security Assumptions of Pervasive Computing' in Proc. *International Security Symposium*, Tokyo, Japan.

SUN, G. CHEN, J and LIU, K. (2005). 'Signal processing techniques in network-aided positioning: a survey of state-of-the-art positioning designs'. Signal Processing Magazine, IEEE. 22 (July issue 4). pp. 12-23.

TANENBAUM, A. and VAN STEEN, M. (2002). 'Distributed Systems: Principles and Paradigms'. Prentice Hall. New Jersey, USA.

TAUBER, J. (2002) 'Indoor Location Systems for Pervasive Computing'. Technical Report, MIT. Massachusetts, USA.

TEUTSCH, C. (2007). 'Model-based Analysis and Evaluation of Point Sets from Optical 3D Laser Scanners'. PhD dissertation, Germany

TIPPENHAUER, N. RASMUSSEN, K. POPPER, C. and CAPKUN, S. (2009) Technical Report. ETH Zurich, Switzerland.

UDDI "Anon" The UDDI Project. (2006) [Online] Available at: http://www.uddi.org/ (Accessed 15.12.2006)

WANT, R. HOPPER, A. FALCAO, V. and GIBBONS, J. (1992). 'The Active Badge Location System'. in Proc. *ACM trans. Information Systems*. pp. 99-102

WARD, A. (1998). 'Sensor-Driven Computing' PhD Dissertation. Corpus Christi College, Cambridge University

WEISER, M. (1993), ‘Hot topics-ubiquitous computing’. [Online] Available at: http://www.ubiq.com/hypertext/weiser/UbiHome.html (Accessed 26.08.2003)

WEISS, M. (1996). Algorithms, Data Structures, and Problem Solving with C++. Addison-Wesley, California, USA.

WU, H. SIEGEL, M. and ABLAY, S. (2002). ‘Sensor Fusion for context understanding’, in Proc. *IEEE Instrumentation and Measurement technology conference.*