UNIVERSITY OF OSLO
Department of Informatics

Indoor Positioning - Technologies, Services and Architectures

Mari Saua Svalastog

Cand Scient Thesis

7th May 2007

I would like to thank Steinar Kristoffersen, Ivar Jørstad, my parents, my colleagues, and Nils Christophersen for help and motivation to finish this work.

Abstract

This thesis is about Location Based Computing Systems (LBCS), with emphasis on their underlying positioning systems. The first part of the thesis introduces a three-layered reference model for discussing LBCS, and gives background information on positioning systems in general—components, designs, properties, and techniques. It also includes an overview of existing systems for indoor positioning.

The second part of the thesis introduces a case study, which consists of two parts. One is an in-depth overview of a specific Location Based Service (LBS) called a mobile electronic tour guide, a service typically implemented on hand-held devices which are given to visitors at different exhibitions as a means for enhancing their experience of it. This results in a requirements specification. The other part of the case is a detailed description of a given museum, as an example of an indoor exhibition.

The third part of this thesis is an analysis of existing positioning solutions against the requirements specification and museum description. Based on the learning from this analysis, two proposals are provided. The first is a decision flow diagram which can help future developers to choose positioning system for a given LBS. The other is the proposal of a system wide service oriented architecture for future LBCSs, which can improve on the short-comings of existing systems' ability to accomodate various environments and services.

Contents

List of Figures

Chapter 1

Introduction

Context-aware computing is a computing paradigm in which services can discover and take advantage of contextual information. *Context* is defined in [1] as any information that can be used to characterise the situation of an entity. This means that almost any information available at the time of an interaction can be seen as context information, such as time of day, noise level, who you are with, accessible devices, and availability of resources like battery, display, network, or bandwidth. An example of contextual information is given in figure 1.1 on the following page.

Services that can extract, interpret and use contextual information are said to be context-aware. One of the most used types of context is *location*. A large range of services are based on knowing where something or somebody is—they are *location aware*, or *location based*. The latter term has recently become the more common, and will be used throughout this thesis.

Location based services (LBSs) can be divided into several categories. These are given below with examples for each category:

Navigation Car navigation with best-route suggestion or indoor navigation support in large buildings using an electronic map, e.g. in museums, plants or hospitals.

Location-sensitive information Digital distribution of content to mobile devices based on their location, like weather cast services, routing of telephone calls, mobile advertising, and electronic museum guides which allow a visitor equipped with a mobile device to get additional information about the artefacts in close proximity to him.

Tracking Tracking of people or valuable assets, like children, elderly people and expensive equipment, or tracking of large amounts of objects in supply chain management or in a warehouse.

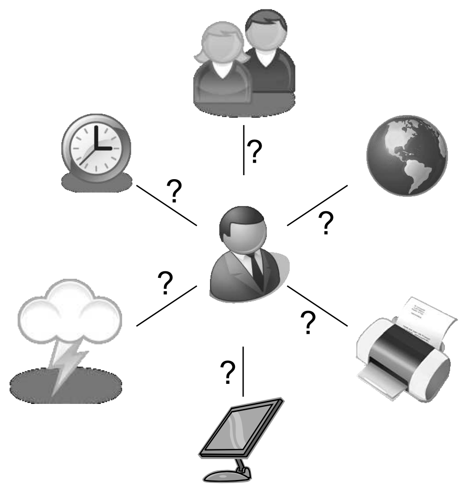

Figure 1.1: Different types of contextual information can be utilised to enhance services.

Security Monitoring and access control.

Directory services Where in this building is the nearest printer? Where is the nearest hairdresser saloon?

Emergency services A mobile user can call for assistance and at the same time automatically reveal his exact location to the emergency service called, like police, ambulance, automotive assistance, etc.

To be able to provide such location based services, we need an underlying position sensing system, henceforth only referred to as the *positioning system*. In chapter 2 (see section 2.1 on page 9) we will define and discuss the use of the words *position* and *location* in detail.

The satellite-based Global Positioning System (GPS) is the prevalent of all current positioning systems. It enables a GPS receiver anywhere on earth to determine its position free of charge with an accuracy within 15 metres. This is sufficient for a wide range of services—according to an article published in Scientific American May 2004 [2], GPS now serves more than 30 million users worldwide. The big disadvantage with GPS is that because the receiver needs line of sight to at least four satellites in the sky, it won't work inside buildings or in other cases where there are obstructions between the GPS receiver and the satellites. In addition, the accuracy is too low for most LBSs used in indoor environments.

A lot of research in the cellular telephone networks community the last few years have been focused on how these networks can be used for positioning. These systems have the advantage of functioning both indoors and outdoors, but as with GPS

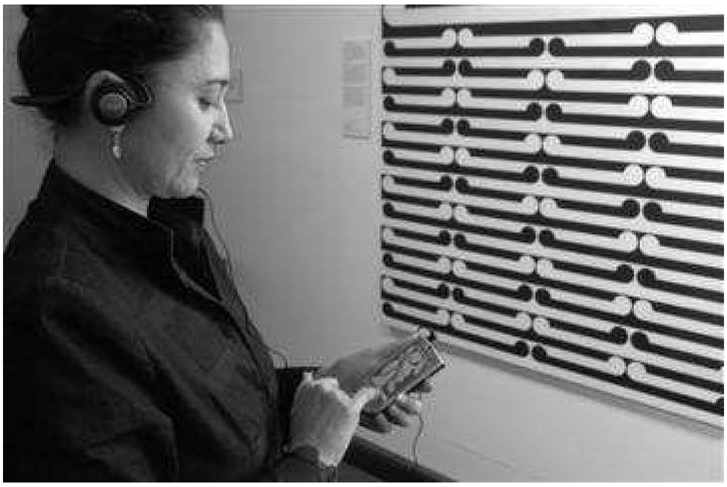

Figure 1.2: Example of an electronic museum guide.

they typically lack the accuracy needed for indoor use. One of the best solutions presented this far has an accuracy of 5 metres [3].

This thesis addresses the field of *Location Based Computing Systems* (LBCSs) for indoor environments. An LBCS consists of one or more location based services (LBSs), and the underlying technologies used to realise them. As we saw above, a large range of LBSs exist. These put different requirements on the underlying positioning technology. In this thesis, we will focus on LBSs in the domain of indoor exhibitions, like museums, galleries, fairs, and the like. In recent years, a lot of research has been performed in this domain, especially on *mobile electronic tour guides* (see figure 1.2). A mobile electronic tour guide is a means for enhancing the experience of a visitor to an exhibition, for example a museum. The visitor will be equipped with an electronic device with a screen, which can communicate to its user where he or she is on a map. It can also provide the visitor with information about the different artefacts he or she is looking at. The reason for choosing the exhibitions domain and electronic tour guides is that they face the underlying positioning system with all the typical requirements all indoor LBSs do. In addition, they have the more specific requirements needed to support a service which provides the user with information about the artefacts in his immediate surroundings, which adds an extra challenge to the positioning system. As it is likely that LBSs will be more and more advanced, we choose a complex LBS which help us reveal requirements posed to the positioning technology and the challenges faced in this area.

Many indoor positioning systems exist, representing a broad range of different positioning techniques and technologies. The problem is that current systems often are results of research that focus on solving one specific property of the positioning system, typically at the cost of sacrificing other important properties. For example, positioning systems with millimetre accuracy exist, but they are so expensive that only the military or film industry can afford them. Another example is systems that do not need any wired infrastructure. This makes them easy to install, but at the cost of time-consuming maintaining as batteries need to be replaced at all the wireless infrastructure nodes. Another problem with this field of research is that it is relatively young. A lot of solutions and early trials have been described in the literature, but few of them are very in-depth or are investigated further by other researchers.

This thesis will show that choosing which positioning solution to use for a given LBS is difficult. This will be revealed by using a simulated case, in which a complex location based electronic tour guide is to be implemented in a given museum. To better understand the challenges faced by the positioning system supporting this LBS, the first chapters will give a general introduction to positioning systems and technologies. When the case has been introduced, an extensive analysis of existing positioning solutions against the LBS requirements is performed. Finally, a tool for choosing positioning system for future LBCSs and a proposal of an improved LBCS architecture are discussed.

1.1 Problem Statements

The goal of this thesis is threefold: First, it is to give a detailed introduction to the field of indoor LBCSs and their challenges. Second, it is to provide some tools that can help others in need for a positioning system to choose among the many possible solutions that exist. Third, we will look for an architecture proposal that can be used by future positioning system developers to deal with important challenges we have identified.

The general problem statement has been the following:

> **What kind of positioning system would best fulfil the requirements of location based services used in indoor exhibitions?**

In order to answer this statement, six specific problem statements have been defined.

1. How is positioning done?
2. What technologies exist that may be used for positioning?
3. What are the requirements and challenges of positioning systems supporting LBSs in indoor exhibitions?

4. Are there any currently available positioning systems that meet these requirements and challenges?

5. Is it possible to formalise the procedure of selecting positioning system according to given requirements?

6. Are there any severe limitations of existing LBCSs?

Statement number three above implies that we have to find out what the requirements of such LBSs are. We also need to know something about the premises that houses the exhibition. Thus, we have chosen to use a case to help us with gathering such knowledge. The case used is the Norwegian *Astrup Fearnley Museum of Modern Art*. More on the use of this case will be discussed in section 1.2.

1.2 Method

The following methods have been used in this thesis to address the problem statements.

Theory Study An extensive theory study of positioning systems in general, positioning techniques, wireless technologies, existing positioning systems and location based tour guides is carried out. Many technological details are left out, the goal is to get an overall understanding of the positioning system research field, and not how the technology is realised.

In the initial phase of the work with this thesis, much emphasis and effort was put in finding state of the art literature. A recent brief search for the main topics in the thesis was performed, but revealed little new on the field. It seems like the field of indoor positioning has been “stabilised”, in that current research is mostly concerned with improvements of existing solutions.

Case Study As stated in the problem statements section, we will need extensive information about LBS requirements and the exhibition premises where it will operate, before we can evaluate if existing positioning solutions can sufficiently support this service. As a means for gathering all this information, we will use a semi-hypothetical, or semi-simulated, case. As we are not going to implement or develop a positioning solution, we don’t need a real case where the customer specifies the requirements. Rather, we use a simulated case, where we can add all the requirements we want. The main advantage of using a simulated case, is that we can include as many details as possible, and by this increase the possibility that the case will provide valuable learning for future use. A real case typically includes some specific requirements that are not relevant to others, or have too few details to be of any interest.

The case we will use is a mobile electronic tour guide in the Norwegian Astrup Fearnley Museum for Modern Art. The reason for calling the case semi-simulated, is that we will use real premises and exhibitions, but that the requirements for the tour guide will be artificial, that is, made by us and not a customer.

To get a better understanding of what is going on in the museum, *interview* and *observation* was used. A person with extensive knowledge about the museum was interviewed. She had been working as a receptionist and guide at the museum for several years. To complement the interview, two days were spent in the museum, with an exhibition change in between. How the exhibits were arranged, what kind of artefacts there were, the number of artefacts, how visitors behaved and so on were observed.

Analysis A requirements specification for a tour guide LBS based on the case is developed, and an analysis of existing positioning solutions against these requirements is performed. Also taken into account is the specific premises of the Astrup Fearnley museum. For each system we assume that it is going to be used for the LBS in the given museum, and evaluate how well the requirements are fulfilled. To make it easier to draw some general conclusions from the analysis, tables are used for representing the results in different ways.

1.3 Contributions

There are three main contributions in this thesis. First, it gives a detailed introduction to the field of indoor location based computing systems (LBCSs) in general, with emphasis on the underlying positioning systems. Then it provides an introduction to the domain of indoor exhibitions and mobile electronic tour guide LBSs used in these.

Second, this thesis provides a proposal of a tool called a *decision flow diagram*. This is supposed to help others to choose what kind of positioning system they should use, based on their LBS requirements and the premises in which it will operate.

Last, as a consequence of the problems with choosing the right positioning system, this thesis suggests a new flexible architecture for future LBCSs, based on the service oriented architecture (SOA) concept. The goal of this architecture is to make it easy to substitute one positioning system with another, with changing requirements from LBSs.

1.4 Related Work

A lot of positioning systems have been proposed, both academic and commercial. These use a variety of different positioning techniques and technologies. The Active badge system [4] from 1992 is among the first positioning systems described. It provided room scale accuracy for tracking people in an office building. Three other systems followed, with the aim of solving different challenges of the Active badge system. Active bat [5] provided a much higher accuracy at centimetre level, Cricket [6] focuses on solving privacy issues and removing wires from the infrastructure, and RADAR [7] tries to utilise already existing WLAN infrastructure for positioning, removing the need for special infrastructure completely. Since these systems, the “Classic Four”, there has been a boom of other solutions. Some positioning solutions have even been made with electronic tour guides and exhibitions in mind, like in Cyberguide [8], Torre Aquila [9] and TaggedX [10]. The shortcoming of most solutions is that they focus on only a limited set of positioning requirements, or on a specific LBS.

Taxonomies have been developed to aid developers of location based services to choose positioning system [11, 12]. This work include a list of different positioning system properties that should be evaluated. This is very useful for getting a deeper understanding of a certain positioning system, but is less valuable in cases where help for choosing which positioning system to use should be decided. This is because it does not take into account the premises in which the system is to be installed, or how the building is used. Much emphasis should also be on the specific domain the positioning system is a part of.

Architectures for LBCSs have been proposed in [13, 14, 15]. However, most of the existing systems today are proprietary.

1.5 Document Structure

In addition to this introductory chapter, this thesis consists of six more chapters.

Chapter 2 starts with introducing a reference model for discussing Location Based Computing Systems (LBCSs). It then gives an introduction to the field of positioning systems by evaluating their components, designs, properties, and how positioning can be done.

An overview of wireless technologies that can be used to implement a positioning system is provided in **chapter 3**.

In **chapter 4**, existing positioning systems are described.

In **chapter 5**, an introduction to mobile electronic tour guides and positioning technology for indoor exhibitions is provided, together with a description of the museum used in the case study. A requirements specification is developed.

Chapter 6 starts with a detailed analysis of existing positioning solutions according to the requirements specification developed in chapter 6. Then follows a discussion of the analysis results, which leads to our two proposals: a decision flow diagram that can help choosing positioning system for an LBS, and a SOA based architecture for future LBCSs.

Chapter 7 provides the conclusion of this thesis. It includes a discussion of how the thesis has managed to answer the problem statements, a list of contributions, limitations of the thesis and future work.

Chapter 2

Location Based Computing Systems

This chapter is an introduction to what we in this thesis will call Location Based Computing Systems (LBCSs). As the use of the terms position, location, positioning systems and location systems can be confusing, we will define these terms and provide a three-layered reference model which will be used throughout the thesis as a means for guiding the reader on which level in the LBCS the discussed issues are handled.

The bottom layer in our reference model is the positioning system. This is where the actual physical positioning occurs. Various issues on positioning systems will be described in detail in this chapter, to provide an understanding of the issues that are to be considered when working with such systems. Issues belonging to layer 2 and layer 3 in our model will be discussed in chapter 4 and chapter 5.

2.1 Introducing a Model for Discussing LBCSs

As mentioned in the introduction to chapter 1, the words *position* and *location* are sometimes used interchangeably. Others refer to "position" as a point in space with a specified 3D coordinate, and to "location" as a defined place or area with an assigned label [16]. Thus, any x,y,z triple in a given reference grid, for example a position on earth given by latitude, longitude and altitude, is a position. Positions are often said to be physical, while locations as defined above are said to be symbolic. A system providing physical positions can usually be augmented to provide corresponding symbolic location information. An example can be to find the nearest printer given the physical position. In this thesis we will use these distinguished definitions of position and location:

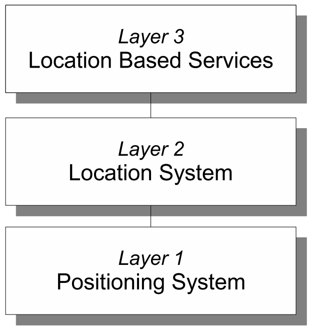

Figure 2.1: A three-layered model for discussing location based services and the technologies used to realise them

> **Position** is a point in space with a specific 2D or 3D coordinate with respect to a certain reference grid.
>
> **Location** is a defined place or area with an assigned label.

We will also assume a three-layered model for discussing location based services (LBSs) and the technologies used to realise them (see figure 2.1). There are two reasons for introducing this model:

1. It will help clarify how we distinguish a positioning system from a location system in this thesis, although they are often used interchangeably by others.
2. It emphasises the major components of an LBCS, and allows us to focus on the interfaces between these.

Together, the three layers in our model constitute what we will call a *Location Based Computing System (LBCS)*. We will refer to this model and the respective layers throughout the thesis.

Our model is similar to the Open System Interconnect (OSI) reference model for computer networks. It is a layered model, where each layer builds on the layer below. Interfaces between the layers can be used to achieve decoupling between different parts of a system, as a layer can be substituted by another without having to alter components at other layers. Similar models are also suggested by others. The six-layer *Location Stack* is a set of design abstractions for location systems for ubiquitous computing [13]. Other models are the four-layer system architectures suggested in [15, 14].

With respect to LBCSs architectures, this thesis is concerned with achieving flexible introduction of positioning systems, and flexible introduction of LBSs. Our model is therefore a simplified version of the ones referred to above, focusing primarily on flexibility between layer 1 and 2 and between layer 3 and 2. The other models consider also internal organisation of what we refer to as layer 2, but this is out of scope for this thesis.

By flexibility we mean that different positioning systems could be used in the provisioning of location information to an LBS, and that new positioning systems could be added without the need for changes in the LBS. For this we need a middle layer, which takes care of translating positions (i.e. from the positioning layer) to locations which can be used by the LBSs. Without this middle layer, each LBS would have to be designed to take advantage of positions from each positioning system.

The three layers of our model are described below, starting with the lowest layer as the other two build on this one:

Positioning System In layer 1, we find the positioning systems. This is where the actual, physical positioning occurs. Sensor hardware and low level software gather raw sensor data, compute positions based on these data, and convert them to standardised physical position representations which are accessible by layer 2. These representations could be for example x,y,z triples, or MAC address pairs of receivers and sensed entities. We will look more at the components and processes of the positioning layer in section 2.2. In chapter 3 we will look at technologies that can be used for positioning.

Location System The location systems in layer 2 are used to provide meaning to physical positions provided by layer 1. This could be to give a symbolic label to a position, like “close to object A” or “in room B”, or to plot the position on a map. The location system also maintains databases that map physical positions with symbolic locations and vice versa. This enables services on layer 3 to make use of the position information.

Location Based Services (LBSs) In layer 3 we find the location based services (LBSs), like those described in the introduction to chapter 1. In chapter 5 we will look closer at several such services, which together constitute a mobile electronic tour guide.

2.2 Fundamentals of Positioning Systems

We will now look closer at the positioning systems in layer 1 in our proposed three-layered model. First, we will look at the components of such systems, and then we will describe two different positioning system designs. Then follows an overview of positioning system properties, we introduce the concept “sensor fusion”, and finally we will look at how positioning can actually be done.

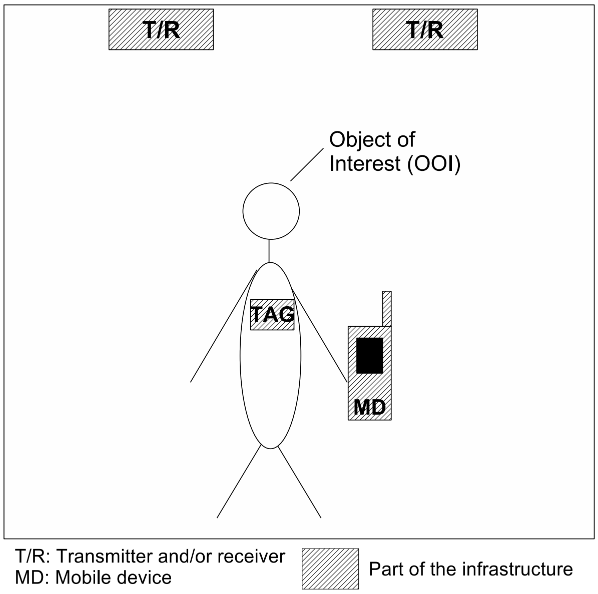

Figure 2.2: Components of a positioning system

2.2.1 Positioning System Components

A positioning system consists of the objects that we want to determine the position of, the objects of interest, and some infrastructure. An **object of interest (OOI)** could be an object that can move itself, like a human being, an animal, or a robot. It could also be a dead artefact, for example a projector in an office building, or a heart defibrillator in a hospital.

The **infrastructure** typically consists of transmitters, receivers, computing entities and network(s). These will be described in the following sections.

It is important to note that what we want to know the position of is the OOI, but what we actually position is a **mobile device** or a **tag** carried by or attached to the OOI [17]. The mobile device could be for example a hand-held computer or a mobile phone. The tag is typically a simpler and smaller device that can be attached to an OOI for the only purpose of positioning (see figure 2.2).

The mobile device or tag is normally only logically connected to the OOI. This means that when we know the position of the mobile device or tag, we can look up the corresponding OOI in a database and assume it is in the same position. However, it could be that for example two children wearing tags switch these, or throw them away, and thus fool the positioning system.

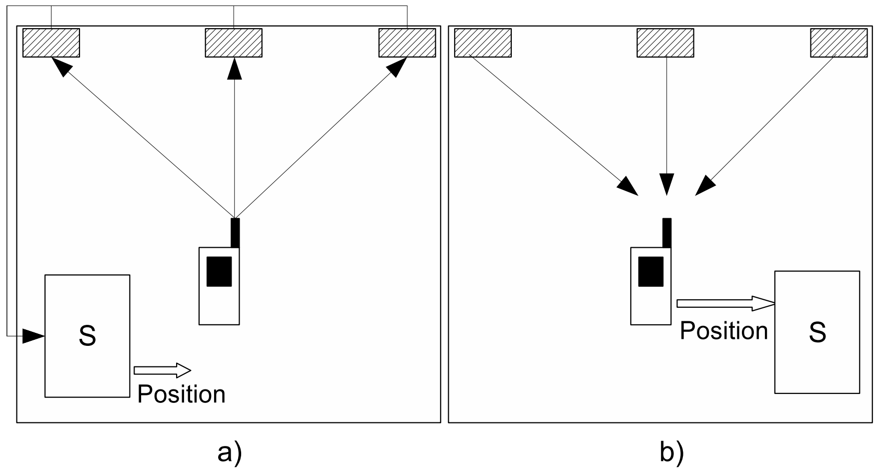

Figure 2.3: Remote-positioning vs self-positioning

2.2.2 Positioning System Designs

The objects of interest (OOIs) are associated with either the positioning infrastructure transmitters or the receivers, and this gives two different system designs [11, 12]. These are described in figure 2.3. In **remote-positioning**, a. to the left in the figure, the OOIs are associated with the transmitters, and receivers are placed in the surrounding environment. The transmitters emit signals that are detected by the receivers and sent to a central computing entity for processing and position determination. In a **self-positioning** scheme, b. to the right in the figure, the OOIs are associated with the receivers which detect signals emitted from surrounding transmitters. The computing is done by a device carried by or attached to the OOI, which the receiver is connected to or integrated in. How the positioning is done will be described in section 2.2.4 on page 17.

By using remote-positioning, the burden of the computing is laid on the infrastructure. This means that the transmitter device or tag associated with the OOI could be relatively simple, and thus typically use less power, have smaller form factor and be less expensive than a device or tag in a self-positioning scheme.

On the other hand, using self-positioning could help ensure privacy. In systems where human beings are being tracked, by positioning of a tag attached to the person or a mobile device known to be used by a certain person, privacy is an important issue. A location based computing system should not violate any privacy rights, and for a location based service to be accepted and adopted by its users it also needs to be trusted. Gathered information should not be used for other purposes than agreed upon in advance, and the user should be able to turn the tracking feature off at any time.

2.2.3 Positioning System Properties

This section will review the properties of a positioning system [11, 17]. These are necessary to understand, as a positioning system requirements specification for a location based service typically is based on them, as we will see in chapter 5, and as they are used to compare different positioning systems.

Accuracy and Related Properties

Accuracy is the most obvious property to consider when evaluating and comparing different positioning systems. Accuracy is a measure of the closeness of one or more positions to a position that is known and defined in terms of an absolute reference system [18]. "Absolute" means that it uses a shared reference grid for all the OOIs, so that two objects at precisely the same place will report equivalent positions. The known position is often referred to as the "true position". Accuracy is given in kilometres, metres, centimetres etc.

Precision, on the other hand, is a measure given in percent, and is based on a relative reference system that is unique to the device making the measurements. For example, if the OOI is a lost valuable asset with an attached transmitter, each receiver device that is searching for it reports the object's position relative to itself. Precision is a measure of repeatability, and it tells us how often we can expect to get a given accuracy. For example, if 95% of a system's position readings are within 10 cm of the true position, it would be said to have an accuracy of 10 cm 95% of the time, or 10 cm at 95% confidence.

The accuracy of position information needed vary from application to application. For example, finding a nearby printer requires less accuracy than finding a book in a large library [19]. In general, the accuracy and precision required dictate the cost and complexity of the positioning system. Positioning systems that provide high accuracy tend to require a lot of specialised infrastructure or expensive mobile devices.

Closely related to the accuracy of a positioning system is the **update rate** or position rate—how often the position of an OOI is computed. High update rate is crucial for systems which goal is to trace users or objects in real-time. Other systems can manage with lower update rates, but all systems should have an update rate which matches the accuracy to capture as many changes as possible.

Another property that is related to accuracy is **adaptive fidelity**. A positioning system with adaptive fidelity can "adjust its precision in response to dynamic situations such as partial failures or directives to conserve battery power" [11]. For example, if a mobile device in a self-positioning system needs to detect signals from four different transmitters to compute its accurate position and it only receives

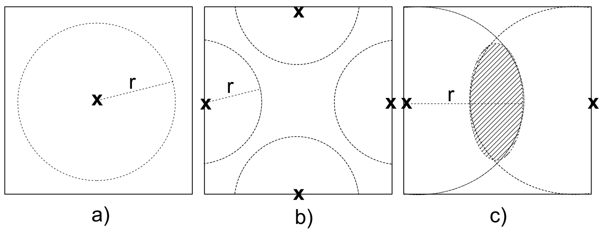

Figure 2.4: Different transmitter coverages and configurations

signals from two transmitters, it cannot compute its accurate position. However, it could still know something about its position by knowing which transmitters it receives signals from and where these are placed. Or, to conserve battery power, mobile devices in a remote-positioning system could decrease their signalling rate when they are not moving.

Research has shown that as long as users are informed about the status of the position accuracy, precision and update rate, periods with lower performance are accepted. When the user is informed he can adjust his expectations [20, 21]. Likewise, it is clever to represent the estimated inaccuracy of positions to users, to reduce confusion if for example a position showed on a map does not match the real world [22].

Scale and Scalability

The scale of a positioning system is another important property. Objects can be located worldwide, within a metropolitan area, throughout a building, or within a single room. A measurement unit that can be used to describe scale is the coverage area per unit of infrastructure. From figure 2.4 we can see some different coverage configurations. The crosses are transmitters with a coverage area given by the radius r. In $a)$ we can see that there is one transmitter, which does not have good enough reach to cover the whole room. OOIs in the corners would not be detected. In $b)$ there are four transmitters, but these have even smaller coverage so there are still areas that are not covered (outside the circles). In $c)$ there are two transmitters with longer reach, and we can see that the areas without coverage is smaller, and that there is one area that is covered by both transmitters (shaded).

In addition to physical reach, scale includes the system's ability to position several objects simultaneously. In an office covering several floors in a large building, hundreds of personnel and maybe thousands of items of equipment might be tracked. A measurement of this ability is the number of objects the system is able to position per unit of infrastructure per time interval.

Scalability denotes how easily a system scales, that is how easy it is to expand the system either by physical coverage or by adding more and more OOIs. Typically, a system is expanded by adding more infrastructure, which can be very cumbersome and expensive.

Easy Deployment, Integration and Configuration

A positioning system's infrastructure should be easy to deploy, to integrate into the existing environment and to configure. Deployment is made easy by small amounts of transmitters/receivers and none or little specialised cabling. As we will see in the next chapter, some positioning systems can actually take advantage of existing computer networks as a means of determining positions, thus saving a lot of work during implementation. In a system using tags attached to OOIs, these should be small, lightweight, and wireless so that motion of the objects is not hindered and that they do not disturb the wearer. Transmitters/receivers placed in the environment and power cords and network cables should be unobtrusive. When the infrastructure is in place, the configuration of the system should require as little manual work as possible.

Power Consumption

As we saw above, little specialised cabling makes deployment easier. Thus, several positioning systems have wireless transmitters and/or receivers in their infrastructure [23, 20]. However, wireless devices need a power source, typically a battery although alternative sources such as solar panels can also be used. In a large system there will be a great number of transmitters and/or receivers distributed over a large area, and maintaining batteries on all these could be a cumbersome task [4, 24]. Thus, a wired infrastructure network has the advantage of easier power feeding than a wireless infrastructure.

To minimise the task of replacing or recharging batteries on wireless infrastructure transmitters, the signal rate is a very important design issue [4]. As we saw in the discussion of accuracy and update rate (see 2.2.3 on page 14), higher signal rate may lead to better accuracy. On the other hand, with lower signal rate the batteries will last much longer, reducing the task of maintaining them. One solution to this problem could be to use an *adaptive signalling rate* (see also adaptive fidelity in section 2.2.3 on the page before). For example, in a system called Active Badge (see section 4.1.1 on page 42), the signalling units in the badges (tags) worn by personnel have a light-dependent component that make them increase the time interval between emitted signals to save power when the badge is left in a dark room or a drawer. Another issue which affects power consumption is the signal strength. More strength gives longer range and better coverage, but requires more power.

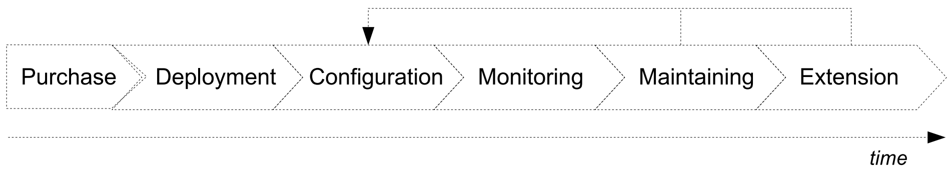

Figure 2.5: The different stages in the life cycle of a positioning system

Costs

Figure 2.5 shows the different stages in the life cycle of a positioning system: purchase, deployment, configuration, monitoring, maintaining, and reconfiguration/extension. It is important to remember that costs is not only related to initial hardware and software investments, but to all the other stages as well. The more staff required in the different stages, the more expensive the positioning system will be.

According to [11] the costs of a positioning system can be assessed in several ways, not only by the most common use of the term which is capital costs. Other types of costs can be time costs, space costs and incremental costs. In some cases, limited time or space available might be the main constraints when choosing a positioning system, not capital costs.

Limitations

All positioning systems have some limitations, which are very important to be aware of. Some systems will not function in certain environments, for example indoors, and some systems need line of sight, that is, no obstructions, between the mobile device and the transmitters/receivers for communication to occur. In general, we assess functional limitations by considering the characteristics of the underlying technologies that implement the positioning system. We will study these technologies in chapter 3.

2.2.4 Position Sensing Techniques

To be able to understand positioning systems, we need to know how positioning can be done. A great number of different positioning systems exist, but the vast majority of them are built on one of four basic techniques that can be used individually or in combination to determine the position of an object. This section will give an overview of these general techniques.

Dead Reckoning

Dead reckoning is a positioning technique that is based on the concept of direction and distance from a known starting point [25]. It was used by navigators in the days of Columbus, and is used today for example by some Garmin GPS-receivers when they temporarily lose contact with the satellites. Such a receiver will just continue to use its current heading and speed to project position [26].

When dead reckoning is used in several steps, each starting point depends on the previous estimates made. This leads to increased possibility of positioning errors. The strength of dead reckoning is that a large infrastructure is not required to locate an object, but this also means that it relies on specialised equipment for self-positioning.

Trilateration and Triangulation

Trilateration and *triangulation* are positioning techniques that use the geometric properties of triangles to compute an object's position [27]. They differ in that trilateration uses distance measurements in the computation, while triangulation uses both distances and angles. The term "triangulation" is often used about either technique, but in this thesis we will use the two different terms to clarify which technique is used.

Trilateration Trilateration computes the position of an object by measuring its distance from reference points placed in known positions. When we know the distance between an object and a reference point, we know that the object's position is somewhere on a circle with the reference point as centre and the distance as radius. If we also know the object's distance to a second reference point, we get another circle. The two circles intersect at two points, and one of these points is the position of the object. By measuring the distance to a third reference point, we get three circles which will intersect in only one point. This is the position of the object. Figure 2.6 on the facing page shows a position, the black dot, computed by measuring the distance to the three reference points A, B, and C.

What we have just described assumes that the object and the reference points are in the same plane. In three-dimensional space we have spheres instead of circles, and distance measurements to at least four reference points are required. The object's position will now be given by the intersection of the four spheres.

Domain-specific knowledge may reduce the number of required distance measurements needed in trilateration. When facing geometric ambiguity, one of the possible positions can often be eliminated by introducing some domain-specific rules. For example, if a positioning system based on trilateration is used at only one floor

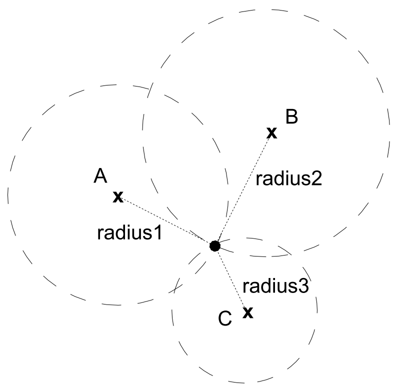

Figure 2.6: Trilateration in 2D.

in a building, three reference points can be enough for three-dimensional position. This is because one of the two possible positions given by three intersecting spheres will be on another floor of the building. This position could easily be eliminated, and the fourth distance measurement is not required.

There are two main approaches to measuring the distances required by the trilateration technique. These are by time of flight, or by attenuation.

Time of Flight Measuring distance using time of flight (TOF) means to measure the time it takes to travel between two points of interest at a known velocity[1]. One of the points may be an object moving away from the other at a known velocity for a given time interval, but the more typical case is where both points are approximately stationary and we observe the difference in transmission time and arrival time of an emitted signal. To be able to determine time of flight between a transmitter and a receiver, agreement about time is necessary. This means that they have to be synchronised.

Attenuation The intensity of an emitted signal decreases with distance from the transmitter. The decrease relative to the original intensity is the attenuation. If we know the original strength of the signal, and a function correlating attenuation and distance for this type of signal is known, we can estimate the distance between a transmitter and a receiver. The degradation of the signal is highly dependent on the surrounding environment, and empirical models for path loss have been made for many typical situations, like for different signals penetrating walls of different materials.

[1] Velocity = Known direction and speed

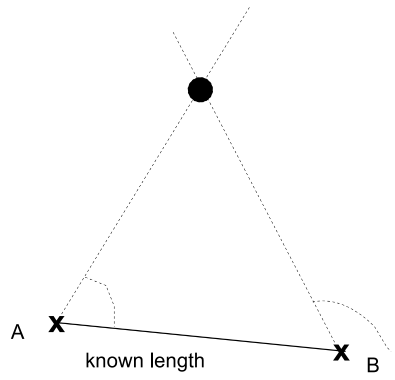

Figure 2.7: Triangulation in 2D.

A quantity called the *Position Dilution Of Precision* (PDOP) is used to describe the relative reduction in the certainty of a computed position based on trilateration. PDOP depends solely on the relative geometry of the OOI and the transmitters or receivers of the infrastructure, and thus provides a means for determining whether that geometry will result in a well-defined or more uncertain position measurement. A low value of PDOP indicates a good relative geometry, and is achieved when the transmitters or receivers are spread out in the environment [17].

Triangulation Triangulation uses angle measurements in addition to distance measurements to determine the position of an object. An example is given in figure 2.7. Two reference points (A and B) are required, and the angles between the object to be positioned and a zero degree reference vector is measured. In the figure this vector is the same as the line drawn between A and B. By knowing one length measurement, for example between the reference points, the law of sines can be used to compute the position. Two-dimensional triangulation requires two angle measurements and one length measurement. With three dimensions, an additional azimuth measurement is needed.

Proximity Sensing

A proximity based positioning technique determines when an object is "near", or in proximity to, a known position. The object's presence is sensed using a physical phenomenon with limited and known range. This could be by detecting physical contact, or by detecting wireless signals. Examples of the first could be pressure and touch sensors like floor sensors or touch screens.

When detecting wireless signals, the accuracy of the position depends on the range

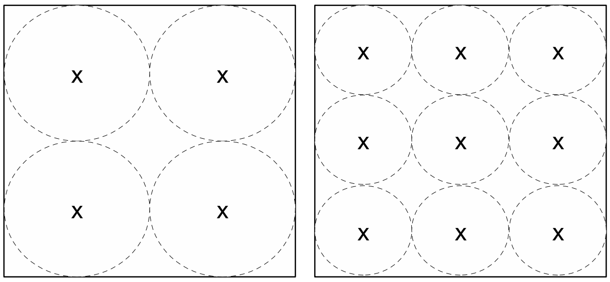

Figure 2.8: Larger vs smaller cells and coverage in a proximity system

of the device in the known position. If the range, and thus the coverage areas, of the devices in known positions are small, a large amount of devices are needed to provide coverage of the entire environment. This could be expensive and time-consuming to deploy and maintain. However, many devices with short range in known positions provide better accuracy than fewer devices with longer range (see figure 2.8). The coverage area of an infrastructure transmitter is often called a *cell*.

Scene Analysis

Visual scene analysis is a positioning technique which uses features of a scene observed from a particular point of view to draw conclusions about the position of the observer or of objects in the scene [27]. For example, observations made by a head-mounted camera can be matched to features recorded in a database with corresponding positions.

Signal strength profiling, also called fingerprinting, is another form of scene analysis. Signal strength from all transmitters in range are measured and recorded in certain positions throughout the area in which positioning is to take place. All these measurements are stored in a database, together with the associated known position. The position of a mobile device can then be determined by measuring signal strengths from the transmitters in range, and comparing these data with signal strengths in the database.

The advantage of scene analysis is that the location of objects can be inferred using passive observation and features that do not correspond to geometric angles or distances. As we will see in the next chapter, use of wireless technology could make distance and angle measurements a challenging task. The disadvantage with scene analysis is that it is based on making empirical models, which require a large amount of manual work. In addition, changes in the environment can require reconstruction of, or a completely new, data set. In fact, many environments change so often that several datasets should be made in advance. For example, a data set representing a large office may vary greatly with the time of day or day of week. On weekends there are much less people in the area, and during weekdays there are much more people coming and going at 9 am and 4 pm than during work hours. By using different datasets representing different situations, better positioning is possible.

2.3 Sensor Fusion

Sensor fusion is the use of information provided by several different sensor systems in parallell. An example of extensive use of sensor fusion is the robot industry, especially when researchers try to build robots that behave like human beings. Such robots are equipped with different specialised sensors for simulating sight, hearing, smell, touch, navigation, and so on. By using a combination of sensor technologies with different capabilities, the quality of information provided by the system can be increased. In the domain of positioning systems, sensor fusion can for example provide better accuracy.

The challenge with sensor fusion is that it requires a more complex infrastructure, is more difficult to manage, and may supply an application with contradictory position information which needs to be managed in a proper way to be useful. It would be advantageous to hide details of the positioning from the applications, so that different technologies can be used at the same time without the application need to now how to handle the different technologies, and to minimise the effects of changes [11, 17]. This means that sensor fusion is the responsibility of the location system in layer 2 of our reference model, not the positioning layer which we have described in this chapter.

2.4 Summary

In this chapter we have introduced a three-layered reference model for discussing location based computing systems (LBCSs) and the technologies used to implement them. Then we discussed components, designs, properties, and techniques for positioning systems at layer 1 in more detail. In the next chapter we will discuss challenges with wireless technology and look at the different technologies that can be used to implement indoor positioning systems. An understanding of the underlying technologies will help to understand the possibilities and limitations of actual positioning systems.

Chapter 3

Indoor Positioning Technologies

In chapter 1 we saw that the satellite based Global Positioning System (GPS) does not work well within buildings or in other areas where there are no line of sight to at least four GPS satellites. Even if we could use the GPS system as it is indoors, the accuracy of about 15 metres would not be sufficient in many applications. This is also true for mobile cellular technology (which works indoors)—the accuracy is too low for many indoor applications. Thus, researchers are seeking other ways to determine positions in indoor environments, based on wireless technology.

There are three major groups of wireless technologies commonly used for indoor positioning, depending on which type of communications medium they are based upon. The first group is positioning technologies that are based on infrared light. The second group consists of all the different technologies that are based on radio transmissions. The third group is based on ultrasound. After a brief introduction to wireless technology in general, this chapter will review wireless technologies to see how they can be used for positioning. Understanding the underlying technologies is important because it explains the physical possibilities and limitations of a positioning system. With regards to our three-layered reference model, we are still at layer 1 as showed in figure 3.1 on the next page.

3.1 General Properties of Wireless Technology

To understand wireless technology, we need to know something about waves. These are the carriers of information between transmitters and receivers in a wireless system. By encoding information onto waves, they can be used for wireless communication as in radio and mobile phones.

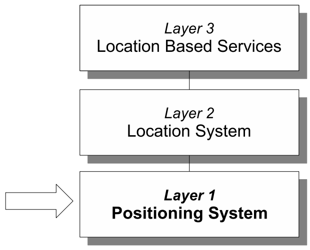

Figure 3.1: This chapter will review wireless technologies that can be used for indoor positioning. This is a part of the positioning layer.

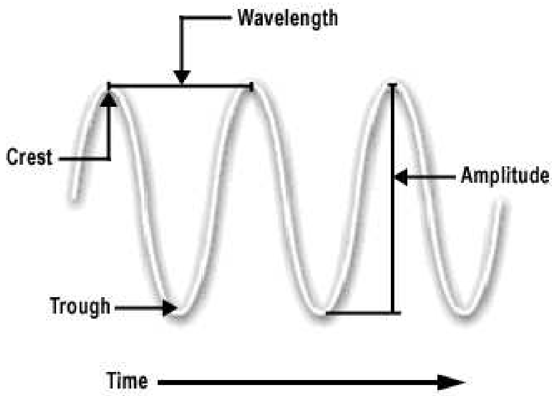

Figure 3.2: Wave properties

3.1.1 Waves

A wave can be described by its energy, wavelength, and frequency (see figure 3.2). Energy is shown by the amplitude. Wavelength is the distance between one wave crest to the next, and the frequency denotes how many wave crests that passes a given point in a second. The measurement unit for frequency is called Hertz (Hz). Depending on these properties, which are mathematically related, waves behave very differently. For example, a wave with long wavelength and thus low frequency needs less energy to travel, and is able to penetrate more materials than a wave with high frequency.

The waves that are most commonly used for communication are electromagnetic waves and soundwaves. Electromagnetic waves are related to electrical and magnetic fields, and what distinguish them from other waves is that they can travel without a medium, through a vacuum as in empty space.

The most commonly used electromagnetic waves for communication are radio waves and infrared light waves. The radio waves have wave lengths from longer than a football field to shorter than a football, and are used to carry signals for radio, television, mobile phones etc. Infrared light waves are divided in the longer far infrared wavelengths with size of a pin head, to the shorter near infrared with size like cells in our body—microscopic. The first group is actually thermal heat like the red we can see from a fire, while the near infrared cannot be felt and is what is being used for example in TV remote controls.

Sound waves differ from electromagnetic waves in that they are mechanical waves, which means that they need a medium to travel through, such as air, water, metal etc. Sound is a compression waveform, and is created by the vibration of some object, and detected when the sound wave causes a sensor to vibrate. However, sound has the standard characteristics of any waveform. The amplitude of a sound wave is the same as its loudness, and the frequency is how high or low the sound is. The speed of sound in air is approximately 344 metres/second at room temperature.

The human ear is capable of detecting sound waves of frequencies between approximately 20 Hz to 20 000 Hz. Sound with a frequency below 20 Hz is known as infrasound, and sound with frequency above 20 000 Hz is known as ultrasound. As we will see later in this thesis, ultrasound is used by many positioning systems.

3.1.2 Propagation Mechanisms

Wireless communication is more difficult than wired communications because there are so many obstacles and changes that affect the signals on their way from the transmitter to the receiver. The four basic wireless propagation mechanisms are described below:

Reflection Reflection occurs when a wave hits an object that is large compared to the wave's wavelength, and results in the wave bouncing off the surface of the object.

Refraction Refraction is the change in direction of a wave due to a change in its speed. This is most commonly seen when a wave passes from one medium to another.

Diffraction Diffraction occurs when waves are obstructed by a surface with sharp edges. The waves will bend around such obstacles, like the corner of a wall.

Scattering Scattering occurs when a wave hits objects that are small compared to the wave's wavelength.

This means that how a wave will behave when hitting an obstacle depends on its properties (energy, wavelength and frequency) compared to the obstacle's proper-

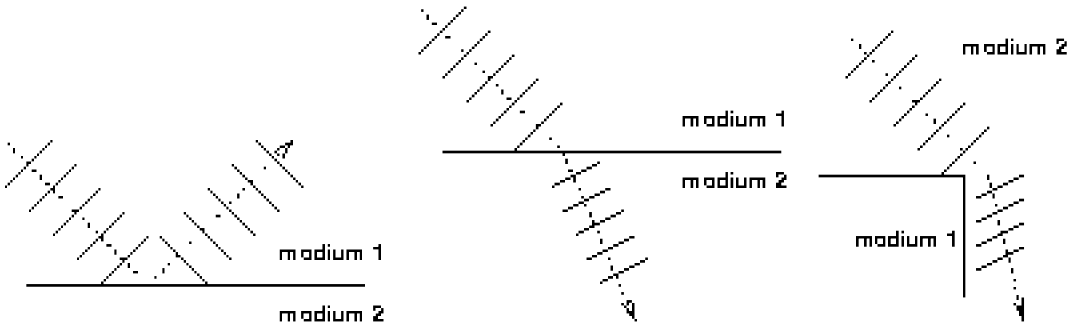

Figure 3.3: Examples of reflection, refraction, and diffraction

ties (size and material). It should be noted that in some cases we depend on these mechanisms, they are not only negative. For example, diffraction could help us reach areas which without it would have been dead-spots.

The effects of the propagation mechanisms are as follows:

Multipath Different signal components may travel by different paths from a transmitter to the receiver. The components experience different delays, hence they won't reach the receiver at the same time. This results in a distorted version of the transmitted signal at the receiver. This is a challenge for example when using time of flight, which we discussed in section 2.2.4 on page 19. Pulses traveling indirect and hence longer paths should be ignored, but this is made difficult by the fact that the direct and indirect pulses look identical. This has to be dealt with, and one solution is to statistically prune away reflected measurements by aggregating multiple receivers' measurements and observing the environment's reflective properties.

Multipath within buildings is strongly influenced by the layout of the building, the construction material used, and the number and type of objects in the building.

Shadowing Signals blocked by obstructing structures.

Attenuation The strength of waves decrease with distance between transmitter and receiver. The transmitter's power and the receiver's sensitivity determine the distance over which they can communicate. In section 2.2.4 on page 19, we saw that attenuation can be used to determine distance. However, in environments with many obstructions, measuring distance using attenuation is usually less accurate than by time of flight, due to the signal propagation mechanisms described above. These effects cause the attenuation to correlate poorly with distance.

In other words, the typical problems faced are signals that are too weak to be detected by the receiver, dead-spots, noise and interference. We will look at frequency regulations to minimise interference problems in the next section.

3.1.3 Frequency Regulations

The transmitters and receivers involved in wireless communication are tuned to operate in a given frequency range. The frequency spectrum used by wireless technology is highly regulated, and can be seen as a hindrance for the wireless industry. But, at the same time regulation is necessary for coping with interference problems.

Until 1985, vendors had to apply for frequency licenses to operate their wireless products. Then, the Federal Communications Commission (FCC) of the United States authorised the Industrial, Scientific and Medical (ISM) frequency bands at 2.4GHz for unlicensed spread spectrum and wideband communications use. This accelerated the development in the wireless industry [28].

3.2 Infrared (IR)

Infrared wireless communication makes use of the invisible spectrum of light just below red in the visible spectrum. This means that IR communication is blocked by obstacles that block light—almost everything solid. Infrared can be used in communication outdoors with Gbit/s data rates, for example to connect local area networks in different buildings. But, in such cases laser is used as the optical source, and this is not suitable for most indoor use because of the potential safety hazard and high cost. The optical source normally used indoors is light emitting diodes (LEDs), similar to those used in the remote controls of consumer electronics. Thus, IR modules can be small, low cost and consume little power. Since IR signals cannot penetrate through walls, it is suitable for sensitive communication because it won't be accessible outside the room or building. There are no restrictions for using the infrared frequencies.

IR is used in two different ways, direct IR and diffuse IR. As an example of direct IR we give an overview of the IrDA standard. Then follows an overview of diffuse IR.

3.2.1 IrDA

One method for infrared communication has been specified by the Infrared Data Association (IrDA) [29]. This method has become a recognised standard commonly called just IrDA, and is the one used by most mobile phones and notebook and hand-held computers. IrDA is a point-to-point ad-hoc data transmission standard designed for very low-power communications. It uses direct IR, which means that line of sight is required—the communicating devices must "see" each other. IrDA operates over a distance of 0 to 1 metre at speeds of up to 16 Mbps, soon to leapfrog from 100 to 500 Mbps. With its narrow 30 degree angle cone IrDA is best suited for point-and-shoot style applications, since it is usually required that the devices engaged in communication are aligned with (pointed at) each other. This implies that IrDA communication is between two devices at a time only, since a single access point cannot be shared by several users.

3.2.2 Diffuse IR

When using diffuse IR, the transmitted IR signals are stronger than those used for direct IR, and thus they have longer reach (9–12 metres) [30]. In addition, wide angle LEDs are used, which emit signals in many directions. Because the signals are easily blocked and reflected, they will bounce around the room. This means that diffuse infrared allows many-to-many connections, does not require direct line of sight, and can be uni-directional or bi-directional. Since infrared light doesn't travel through walls, diffuse IR is suitable for connecting devices which are in the same room. The effective range of diffuse IR limits cell sizes to small- or medium-sized rooms, so that in larger rooms, multiple infrared sensors must be used [11]. It should be noticed that although diffuse IR works without line of sight, the data rate decreases severely in such cases.

One problem with diffuse infrared systems is that they have difficulty in locations with fluorescent lighting or direct sunlight because the infrared emissions these light sources generate may interfere with the signals [11]. Another problem is that diffuse infrared links often create delays, since it takes time for the signals to travel to the wall or other objects that causes reflection and get back to the destination.

3.2.3 IR-based Positioning Systems

IR-based positioning systems tend to use proximity detection by monitoring wireless cellular access points. Positioning systems based on direct IR typically rely on a human user taking explicit actions for positioning to occur, due to the short range and the requirements for line of sight and device alignment. When using diffuse IR, the user can remain passive because the IR signals that bounce around the room will find any present IR receivers on their own. This also means that diffuse IR can be used where there are no human user, for example in a system which locates equipment tagged with IR receivers.

3.3 Radio Frequency (RF)

A very important characteristic of radio waves is their ability to penetrate solid, non-metal objects. This implies that there is no line of sight requirement between RF transmitters and receivers. It also implies that RF communication is not inherently secure, and that it is subject to uncontrolled interference. Special care must be taken to avoid this and to protect sensitive communication. Last, RF transmitters and receivers typically consume more power than IR devices, and most part of the radio frequency spectrum is strictly regulated, so FCC certification is required.

3.3.1 The 802.11 WLAN Family

The IEEE 802.11 Wireless Local Area Network (WLAN) standard was ratified in June 1997 [28]. The standard defines the protocol and compatible interconnection of data communication equipment via the air in a local area network (LAN) using the carrier sense multiple access protocol with collision avoidance (CSMA/CA) medium sharing mechanism.

Two configurations are specified in the 802.11 standard: ad-hoc and infrastructure. The ad-hoc mode enables mobile devices to communicate directly without the use of an access point, like a peer-to-peer network. All stations are usually independent and equivalent, and no infrastructure is needed. Such a network is closed, with no access to the Internet. In the more commonly used infrastructure mode, access points bridge mobile stations and the wired network. The radio range and the surrounding environment of an access point determines the coverage area, or cell size, for that access point. By placing the access points so that their coverage areas overlap, the mobile stations can seamlessly move between the access points without losing network contact. This is called roaming. A handoff occurs when the mobile station goes from one access point to the next. A protocol[1] has been specified which standardises this handoff information, so that access points from different vendors can communicate with each other. A single access point can support a small group of users.

The 802.11 standard can use either infrared or radio as physical medium. The type of infrared transmission used is diffuse infrared, with a typical range of 10 metres. This, and the fact that the communication quality is sensitive to the environment (e.g. the number of reflected surfaces and line of sight paths), limits the use of infrared and is the reason why vendors usually adopt radio as communication medium. The standard specifies two different radio frequency physical layers, both primarily operating at the 2.4 GHz ISM band: Direct Sequence Spread Spectrum (DSSS) and Frequency Hopping Spread Spectrum (FHSS).

[1] The Inter Access Point Protocol (IAPP) specified by the 802.11f committee

IEEE 802.11b

In September 1999, the IEEE 802.11 standard from 1997 was officially revised [28]. The new standard was called 802.11b, or 802.11 High Rate. It still operates on the 2.4 GHz frequency band, but provides a data rate up to 11 Mbps with fallback rates of 5, 2, and 1 Mbps. This standard also promises interoperability among products of different vendors, and the 802.11b networks have successfully conquered the WLAN market and are widely used in homes, cafes, airports, hotels, and at university campuses. But with such widespread use, interference problems within the 2.4 GHz ISM band become a major issue. Bluetooth devices (to be discussed in section 3.3.2 on the next page) and a lot of medical and household equipment also use this frequency band, e.g. cordless phones and microwave ovens. This interference issue and the wish for even faster speed led to the specification of an additional standard, the 802.11a described in the next section.

Performance measurements indicate that the 802.11b data rate slows down substantially the greater the distance between the access point and the mobile station. The maximum data rate of 11 Mbps is typically achievable up to 100+ feet. Between 100+ feet and 175+ feet the data rate is typically 5.5 Mbps, and from 175+ up to 225 feet the data rate is 2 Mbps. The 802.11a and g in the following sections are also subject to a such decrease in data rates with distance. In general, the data rates of all three standards are considered to be 50-100 metres.

IEEE 802.11a

The IEEE 802.11a standard was approved in September 1999 as a solution to the intereference problems in the ISM band [28]. This standard uses the 5 GHz frequency band, which means that it is not compatible with 802.11b. It uses Orthogonal Frequency Division Multiplexing (OFDM), which provides data rates up to 54 Mbps and beyond. Required speeds are 6, 12 and 24 Mbps with optional speeds up to 54 Mbps. But this high data rate is only achieved with a range less than 25 feet. The data rate then gradually decline with distance. The drawback with this standard, in addition to the incompatibility with 802.11b, is that the 5 GHz spectrum is not license-free in all countries. This led to yet another standard, the 802.11g described in the next section.

IEEE 802.11g

The 802.11g standard was ratified in June 2003 to enhance the 802.11b technology. Two optional modulations were specified, Packet Binary Convolution Code (PBCC) which supports 22 Mbps and 33 Mbps for payload data rate, and OFDM which supports at most 54 Mbps. These are both compatible with 802.11b.

WLAN as Positioning Technology

As with IrDA, the different WLAN standards were not designed to determine position of mobile devices. But still, these wireless network technologies can offer sufficient position determination to be useful in many location based services. The big advantage of using WLAN to determine positions of mobile devices in the network is that the infrastructure is often already in place, since wireless networks has become so common. In addition, the cost of the access point can't be beat; it seems like vendors are practically giving away Wi-Fi access points. On the other hand, as with any wireless LAN application, potential performance degradation should be taken into account. A location based computing system invokes the transmission of overhead packets over the wireless LAN in order to implement positioning algorithms. This additional overhead may significantly lessen throughput available to users. Thus, a solution that minimises the transmission of packets should be sought. Also, because of the large physical range, Wi-Fi technology consumes a lot of power, limiting its use in many small battery-powered mobile devices.

WLAN access points could be used for proximity sensing, but because of the wide range of WLAN access points the accuracy would be coarse-grained and not very useful for indoor location based applications. Thus, as we will see in chapter 5, most WLAN based positioning systems are based on scene analysis and signal strength profiling, or trilateration using attenuation to determine distances.

3.3.2 The 802.15 WPAN Family

IEEE 802.15 is the IEEE working group for Wireless Personal Area Networks (WPANs). This group is developing standards for short-range personal wireless networks consisting of devices such as PCs, hand-held and pocket computers, mobile phones, next-generation pagers, digital cameras, video cameras, and other devices.

Bluetooth (IEEE 802.15.1)

The IEEE 802.15.1 standard, based on Bluetooth v1.1, is a short-range wireless voice and data communications protocol which employs RF technology [31]. The Bluetooth project was begun by Ericsson in 1994, and the Bluetooth Special Interest Group (SIG) formed in May 1998 to develop an open specification for globally available short-range wireless RF communications.

Bluetooth operates in the unlicensed 2.4 GHz spectrum, and must cope with interference from IEEE 802.11 (see 3.3.1 on page 29), baby monitors, garage door openers, cordless phones, microwave ovens and other RF communications technologies which also use this frequency.

The Bluetooth network model is one of peer-to-peer communications based upon proximity networking (see 2.2.4 on page 20). When two Bluetooth enabled devices come within range of each other, they can establish a Bluetooth link, where one device acts as master and the other as slave. Any Bluetooth equipped device can assume either role. The connection establishment process can take up to 10 seconds, but it can often be accomplished in less than 5.

A master may communicate with up to 7 “active” slaves and up to 255 “parked”slaves. These devices are said to form a piconet. The use of parked mode, that the slaves maintain synchronisation but do not listen for transmissions from the master, allows the master to communicate with the whole piconet by exchanging active and parked slaves to maintain up to seven active connections. In parked mode slaves are less responsive, but it permit greater power conservation. The master-slave relationship is important for low-level communications, but in general devices operate as peers to each other.

When two or more piconets partially overlap in time and space, a scatternet is formed. This topology provides a flexible method by which devices can maintain multiple connections. This is especially useful for mobile devices which frequently move into and out of proximity to other devices.

Bluetooth is designed to be a very low power technology, with estimated nominal power at 100 mW although this is product dependent. Nominal link range for the standard 0 dBm Bluetooth radio is approximately from 10 cm to 10 metres, omnidirectional, but power amplified 20 dBm radios with range of about 100 metres are also possible. The 1.0 specification focuses on 10 metre range. The Bluetooth data rate is currently 1 Mbps.

Bluetooth as Positioning Technology The Bluetooth SIG has several working groups that focus on specific parts of the technology or on supporting services. One of these groups are the Local Positioning group, which investigates the use of Bluetooth wireless technology for positioning.

Like mentioned in the previous section, Bluetooth is based upon proximity networking. Bluetooth devices form mini-cells, and when enough such cells are installed, the position of a transmitter can be given by knowing which cell it is communicating with. However, as we will see in the next chapter, Bluetooth can also be used in trilateration and scene analysis systems.

Bluetooth has with its omni-directional characteristic problems discovering the intended recipient. A Bluetooth device must perform a timeconsuming discovery operation that will find many of the other devices in the room. Close proximity to the intended recipient will not help. The user will be forced to choose from a list of discovered devices. Choosing the proper device will often require special information from the other person (e.g. 48-bit device address or friendly name).

The advantages of Bluetooth are that in addition to positioning information it also provides some limited data communications, about 700 kbps (vs. 11Mbps in 802.11), and that two devices communicating don't need to be aligned, they don't even have to be visible to each other so they can be in different rooms.

The biggest disadvantage of Bluetooth technology is that it requires a lot of relatively expensive receiving cells. The greater the number of cells, the smaller the size of each cell and hence greater accuracy, but more cells increase the cost of purchase and installation. Another consideration is the need to have a host computer to support the Bluetooth radio to be located, so it is currently impractical to locate objects that don't have a built-in computer.

It is expected that Bluetooth hardware is likely to remain more expensive than IrDA hardware owing to the complexity of the underlying technology, although the cost difference probably will narrow over time. Current prices for an IrDA module versus a Bluetooth module is about 2 and 5 USD.

Because of the 2.4 GHz spectrum which Bluetooth is using being unlicensed, new uses for it are to be expected, and as the spectrum becomes more widely used, radio interference is more likely to occur.

IEEE 802.15.4 and ZigBee

The IEEE 802.15.4 specification defines the physical and MAC layers of a low-complexity, low-cost, low-data rate solution which makes multi-month to multi-year battery life possible. It is operating in three unlicensed frequency bands, 2.4 GHz and 915 MHz for North America, and 868 MHz for Europe. The achieved data rates for the different frequencies are 250 kbps (up to 30 metres), 40 kbps, and 20 kbps. The IEEE 802.15.4 standard was first released in 2003, and updated in 2006 [32, 33].

The ZigBee standard provides network, security, and application support services operating on top of the IEEE 802.15.4 specification. It is capable of autonomously connecting over 64 000 nodes in a network, consisting of subnetworks with 255 nodes in star, cluster, or mesh topologies. As ZigBee nodes can operate at distances ranging from 5 to 500 metres depending on the surrounding environment, very large networks are possible both regarding large number of devices and large coverage areas. Range is easily adjusted with power[34].

There are two different physical device types used for ZigBee nodes, called Full Function Device (FFD) and Reduced Function Device (RFD). Their different charactersistics are showed in figure 3.4 on the following page. In a ZigBee network, at least one FFD is required, to act as a network coordinator. Since these devices consume more power than the RFDs they are generally line powered.

Reduced Function Device (RFD)	**Full Function Device (FFD)**
Limited to star topology	Can function in any topology
Cannot become network coordinator	Capable of being network coordinator
Talks only to network coordinator	Capable of being a coordinator
Simple implementation	Can talk to any other device
Generally battery powered	Generally line powered

Figure 3.4: ZigBee physical device types

ZigBee is designed for low-duty-cycle networks, where nodes spend much of their life asleep. A typical conversation between two devices generally takes a few milliseconds, allowing the transceiver to go back to sleep quickly. Thus, nodes use very little power, and can operate for years on a pair of alkaline AA batteries without any operator intervention.

A basic ZigBee node is very small, has low complexity, low cost. It consists of a multichannel two-way radio and a microcontroller on a single piece of silicon, and could be delivered in a plastic package the size of a pinkie fingernail. Retail price of radio tranceivers compliant with the standard is rapidly approaching $1, and single-package radio/applications processor/memory products are currently about $3 and will probably continue to fall with increasing volumes. The first ZigBee products are expected in stores in 2007. Potential applications are sensors, interactive toys, smart badges, remote controls, and home automation.

Ultra Wide Band (UWB) and IEEE 802.15.3a

The term ultra wideband (UWB) was first used by DARPA in 1989. But the technology behind the name has been known since the 1960s as short-pulse technology, in which the basic concept is to develop, transmit and receive an extremely short duration burst of radio frequency (RF) energy. These bursts represent from one to only a few cycles of an RF carrier wave, and the resultant waveforms are extremely broadband. Duty cycles are very low, resulting in low average energy densities. The pulses are typically generated by impulse- or step-excited antennas and filters.

The conventional definition of UWB described above is quite unlike modern UWB variants. From 2002, the FCC came up with a new, broader definition of UWB, which defines UWB as a RF signal occupying a portion of the frequency spectrum that is greater than 20% of the center carrier frequency, or has a bandwidth greater than 500 MHz [35, 36, 37].

From the two definitions above we can see that UWB is a communication channel that spreads information out over a very wide portion of the frequency spectrum [38, 39]. This allows the UWB transmitters to consume very little transmit energy, while transmitting large amounts of data. In addition, UWB will not interfere with existing RF systems if proper designed, has high multipath immunity, will be low cost like Bluetooth components, and will enable radios to fit within small-size devices. UWB is proposed as a wireless replacement of wired USB and Firewire standards used among devices in a personal area network. Wireless connection for multimedia applications requiring in excess of 100 Mbps can be realised.

There are few technical hurdles for UWB, but it faces several regulatory hurdles in regard to interoperability. The FCC approved low power UWB with maximum radiated power of -41.3dBm/MHz to operate in an unlicensed spectrum from 3.1 GHz to 10.6 GHz in the US in February 2002. The strict power limitation is in order to limit the interference with other communication systems. There are limited adoption by other regulatory agencies around the world. Europe and Japan approval is in the process, while others are waiting to see how UWB performs in the US.

There are currently two competing UWB specifications that both hope to eventually be defined as the IEEE 802.15.3a standard (member of the WPAN family). Which one, if either, the standard group chooses is not yet known, and how widely UWB will be adopted in the future is uncertain.

The main difference between the two competing UWB specifications is the way in which they spread the data signal across the frequency spectrum. The Multi-band OFDM Alliance (MBOA) special interest group uses OFDM like 802.11a and 802.11g, while the former Motorola subsidiary Freescale Semiconductor uses direct sequence technology.

UWB as Positioning Technology UWB technology has been shown to possess a unique advantage for high accuracy positioning, even in the presence of severe multipath, by the use of short-pulse RF waveforms which permit accurate determination of the TOA and the time of flight of a burst transmission from a short-pulse transmitter to a corresponding receiver. This require special, sensitive, high speed detection circuitry at the receivers. With distances computed from the time of flight at several receivers, the position of the UWB transmitter can be determined by trilateration, as we saw in 2.2.4 on page 18.

3.3.3 Radio Frequency Identification (RFID)

Radio frequency identification (RFID) is a generic term used to describe a system that transmits the identity of an object or person wirelessly using radio waves [40]. It is grouped under the broad category of automatic identification technologies.

The RFID technology is most commonly used to automatically identify objects

	Passive RFID	Active RFID
Tag	No transmitter No power source Draws power from reader	Transmitter Own power source Broadcasts signals
Frequency	124, 125, 135 kHz 13.56 MHz 860-960 MHz 2.45 GHz and more	455 MHz 2.45 GHz 5.8 GHz
Range	Few cm – 9 m	20 – 100 m
Cost	20 cent – several dollars	$10 and up

Figure 3.5: A summary of passive vs active RFID

in large systems. RFID-tags are attached to all the objects in a system that the owners want to keep some information about, so that this information easily can be retrieved and used later. The RFID-tags consist of a microship which can typically store up to 2 kilobytes of data, and a radio antenna. A reader device is used to retrieve information from the tags, and depending on the tags used between 20 and 1,000 tags can be read each second. The best tags also work effectively even when situated within one-half inch of each other [41].

There are two broad categories of RFID systems: active and passive. These are summarised in figure 3.5. The passive RFID systems use passive RFID tags, which have no transmitter and no power source. They work by drawing power from the reader, which emits electromagnetic waves, and communicates its data by reflecting back energy to the reader. In contrast, the active tags used in active RFID systems have a transmitter and their own power source. They broadcast signals for all the readers within range to read. The range is typically between 20 to 100 metres for active tags, while the passive tags have read ranges from a few centimetres up to about 9 metres. The cost of passive tags ranges from 20 cent when bought in large volumes to several dollars with special packaging, while the active tags can be $10 to $50 or more. These tags are not mass-produced in large numbers, so they are typically used in in-house systems where the tags can be reused.

RFID systems use low, high, ultra-high, or microwave frequencies. Active tags usually operate at 455 MHz, 2.45 GHz, or 5.8 GHz, and passive tags uses 124, 125, 135 kHz, 13.56 MHz, 860-960 MHz, and 2.45 GHz and others. The different properties of these frequencies make them useful for different applications. Higher frequency gives better range but is harder to control because energy is sent over long distances and is easier reflected. The radio waves can bounce off surfaces and reach tags you did not want to read. RFID signals may be subject to interference from machinery or other RF-based systems, but fortunately not from 802.11-systems.

RFID as Positioning Technology Passive RFID tags can only be located by associating them with the reader that reads them. If high accuracy is required and the readers are not carried by a person, the system needs a lot of readers, which make the system expensive. Active tags can act as transponders which broadcast only when near a reader, or they can act as beacons which broadcast at pre-set time intervals. The beacon functionality makes it possible to use RFID in real-time systems where the precise location of objects needs to be tracked. The readers are placed in known positions, read the tags, and transmits the tag id, it's own id and a time stamp to a host computer system which can track the objects. The most common RFID applications are asset-tracking, manufacturing, supply chain management, retailing, payment systems (e.g. road tolls), and security and access control.

3.4 Ultrasound (US)

Ultrasound does not penetrate solid walls, and does not require line of sight between the tags and the detector. Ultrasound waves are mechanical waves, and do not interfere with electromagnetic waves. The ultrasound signals have relatively short communications range [42].

The disadvantages of a system using ultrasound are loss of signal due to obstruction; false signals due to reflections; and interference from high frequency sounds such as keys jangling. There are commercial systems which solve these problems with great success, but these systems are expensive, typically costing over $15,000 [43].

Ultrasound as Positioning Technology Positioning with ultrasound is suitable for both proximity sensing and multilateration. Especially for applications where room scale accuracy is sufficient, proximity sensing with ultrasound is very effective since ultrasound does not penetrate walls. Such use is suitable for personell and asset/equipment tracking in large buildings. In addition, the fact that ultrasound is relatively short range can be an advantage in such a system, because large halls or open areas can be divided in several zones, thus giving better accuracy [42]. On the other hand, it can be expensive to cover a large building with this solution.

In systems where high accuracy is required, multilateration 2.2.4 on page 18 can be used to achieve centimetre accuracy. Distances are calculated by measuring ultrasound time of flight. For very high accuracy, several fixed infrastructure stations must be used, increasing cost and complexity. The frequencies typically used are 40–75 kHz, permitting accurate transmitter-receiver distance measurements at ranges up to 10 metres [17]. The lower bound of frequencies that can be used are limited because we want to use frequencies above those that humans can hear, while the upper bound is restricted by the absorption of ultrasound in air which increases with higher frequencies.

The speed of ultrasound in air is about 340 m/s at room temperature. This is relatively slow compared to electromagnetic radiation in vacuum at almost 300 000 000 m/s, commonly called just speed of light. The slow speed has two main effects for ultrasound lateration [17]. First, ultrasound lateration systems do not need to be as complex as those using radio frequency, because timing units with microsecond resolution are sufficient for sub-centimetre accuracy. In RF lateration systems a timing error of only 1 nanosecond gives a distance measurement error of 30 cm. Second, position readings can have a time lag of tens of milliseconds, but this is still sufficient for most location based servics.

Precise distance measurements require sensitive US sensors, but such sensors react to ultrasonic[2] noise and high-energy sound pulses from for example malfunctioning fluorescent lights, people jangling keys, and slamming doors. Accurate distance estimation therefore requires good outlier rejection methods to prevent use of bad distance measurements [20].

Another advantage for indoor tracking is that it does not require line of sight, so that objects that are hidden or located in drawers or filing cabinets still can be tracked. But when there is no line of sight, distance measurements in multilateration gives reduced accuracy.

3.5 Other Positioning Technologies

3.5.1 Electromagnetic Sensing

Positioning systems based on electromagnetic sensing can provide very high accuracy and precision, on the order of less than 1 mm spatial resolution, 1 ms time resolution and 0.1 degrees orientation capability [11]. Such systems are mostly used by people working with virtual reality and motion capture for computer animation. The main reasons for not considering this technology further here are that the implementation costs are very high, the tracked object with attached sensors must be tethered to a control unit and hence is not completely mobile, and that such systems typically works in specialised, controlled environments.

[2]According to www.dictionary.com, the term “ultrasonic” is an adjective which describes something utilising ultrasound.

3.5.2 Optical Systems

Optical systems either use a set of cameras placed at static points in the environment to monitor objects in that environment, or the cameras are attached to an object so that the object's position and orientation can be determined relative to static points placed around the environment [17]. Different methods for computing positions using these schemes can be used, but they will not be discussed here. Although levels of accuracy and resolution similar to those of electromagnetic tracking can be achieved, the disadvantages of optical systems make them unsuitable for most but a few types of applications. The cameras require line of sight, need substantial amounts of processing power to analyse captured frames, tend to be expensive and mechanically complex, and are most useful in well-constrained environments.

3.5.3 Detecting Physical Contact

As we saw in section 2.2.4 on page 20, one of the methods for proximity sensing is to detect physical contact. For example, there exist systems which have embedded pressure sensors in the floor [11, 5], and by capturing footsteps or by analysing the distribution of weight across the floor, the presence of moving objects can be inferred. The major advantage with these systems is that no tags or devices are needed, but they suffer from poor scalability and high incremental costs to install the pressure sensors. In addition, they can only provide two-dimensional positioning, and it is hard to distinguish objects from each other. Other systems may use touch sensors, but these also suffer more or less from the disadvantages already mentioned.

3.6 Summary

We have now reviewed wireless technologies that can be used for indoor positioning. These are divided into three groups, based on which physical carrier they use: infrared, radio or ultrasound. An understanding of the different technologies' characteristics is necessary for understanding possibilities, challenges and limitations in positioning systems. In the next chapter, we will look closer at positioning systems used by existing location systems.

Chapter 4

Existing Indoor Location Systems

From reading the previous chapters, we have learned about the basics for understanding positioning systems. In chapter 2 we learned about their components, designs, properties, and how they actually can decide positions. In chapter 3 we studied wireless technologies and how these can be used for positioning.

In this chapter we will finally examine existing location systems that have been described in the literature or that are commercially available. With reference to our three-layered model, we are talking about layer 1 and layer 2, as shown in figure 4.1 on the next page. A location system in layer 2 includes an underlying positioning system, turns the physical positions from this system into locations, and does all the work needed before a location based service can make use of these locations.

While there are too many location systems to describe them all, an attempt is made to choose a representative collection which shows the variety of solutions. This knowledge will be applied in the next chapters, where we will look at a specific case where a museum needs a location system to support a mobile electronic tour guide, and analyse if existing technologies and systems are capable of meeting their needs.

Although we will look at both academic and commercial systems in the following, academic systems are given most emphasis. The reason is that with commercial systems it is often difficult to get behind the scenes and see the details of how the systems work. We should also keep in mind that what commercial companies claim that their systems are able to provide, is sometimes overstated or true in only very limited situations.

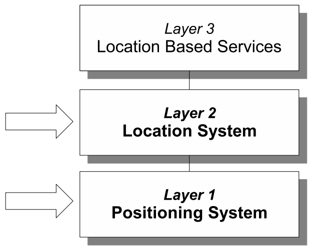

Figure 4.1: This chapter will review existing location systems and their underlying positioning systems.

4.1 The Classic Four

When reading literature on location systems, four systems quickly stand out as they are referred to almost everywhere: the *Active Badge*, *Active Bat*, *Cricket*, and *RADAR* systems. Thus, we will call them "The Classic Four". The Active Badge system from 1992 is among the first indoor LBCSs, and as we will see in the following sections, the others followed more or less directly as attempts to deal with limitations in this system in three very different ways. Later systems are often based on findings from these four different solutions. Thus, the "classic four" are described in detail in the following sections, and then follow brief descriptions of other systems, grouped after which technology they are based on.

4.1.1 Active Badge

The Active Badge system [44, 4] was developed at Olivetti Research Laboratory[1] between 1989 and 1992. The original system is able to locate individuals in a building by monitoring their presence in different rooms. This is done by equipping rooms with one or more networked sensors, which detect diffuse infrared transmissions emitted by Active Badges. The badges are worn by individuals, and they emit unique identifiers every 10 seconds [24] or on demand. In the latter case, the badge can be told to transmit by pressing a button on it. A master station is polling the sensors for information about which badges they have recently seen, and the location of the badge can be determined on the basis of this information. The range of the system is about 30 metres, and line of sight is not necessary [24]. The conventional batteries of the badges last for about one year with the time intervals between emissions set to 10 seconds [24].

In an experiment with the Active Badge system, a hybrid technology solution is used to offer more fine grained location [4]. Low-powered radio transmitters are

[1]Now AT&T Laboratories Cambridge

Figure 4.2: An Active Badge

placed where the badges should discover special zones. When a badge notices the presence of a radio frequency field, it codes a signal into the infrared signal which identifies which radio field it has moved into. The badge then immediately transmits this message. The radio transmitters are typically placed at desks, and power-adjusted to have a range of about an arm's length [24]. A further extension to the Active Badge system has been to also track equipment, by attaching slightly modified equipment badges to objects. Equipment is not as mobile as people, so the time interval between emitted signals is increased to five minutes, thus saving more power.

The largest single Active Badge system has been deployed at Cambridge University Computer Laboratory, where over 200 badges and 300 sensors were in daily use. An experiment with equipment badges and desk scale location technology is also implemented, with about 200 items of badged equipment and about 50 desks identified by using the hybrid radio/infrared scheme [24].

4.1.2 Active Bat

In the previous section we saw that the Active Badge system could provide room-scale location information. By using radio transmitters in addition to the infrared sensors, finer grain location was possible in dedicated locations. Since many applications need more fine-grained position information and sometimes also orientation information, the AT&T researchers have in more recent work developed the Active Bat location system [45]. In this system, people and objects to be located are equipped with wireless devices called Bats, and receivers connected by a wired network are installed in known, fixed positions in the ceiling. In addition, the system includes a number of base stations. A base station periodically transmits a radio message which contains a Bat identifier. Simultaneously, it sends a reset signal to the receivers in its range over the wired network. As a response to the radio message, the identified Bat transmits an ultrasonic pulse. The now synchronised receivers record the time of arrivals of the pulse, which are used to compute position by lateration (see 2.2.4 on page 18). Because all receivers are ceiling-mounted, the transmitters are always below them. Thus, position calculation can be done using only three distance measurements, rather than the four required in the general case [5]. This is an example of domain specific knowledge which makes computation easier, as mentioned in section 2.2.4 on page 18.

An ultrasonic transmission from a Bat is mainly emitted in one direction, because the wearer's body or the object shadows the ultrasonic signals. Knowing the pattern of receivers that detect the signal tells something about the object's orientation [5]. Another, better solution to determine orientation is to place several Bats at known, non-collinear positions on the same object, and calculate these Bats' positions.

The Bat system is installed in a three-floor, 1,000 m^2 office building with 750 receiver units, three radio cells, and 200 Bats. The Bats measure about 8 x 4 x 2 cm, and draw power from a single AA lithium cell which with low-power features has a lifetime of about 1 year. One of the low-power features is that each Bat has a motion detector, which helps the base stations to locate only the Bats that are moving. To simplify maintenance, telemetry can be obtained from Bats, and they can be reprogrammed in the field over wireless or wired networks. 3D positioning in Active Bat is accurate to within 3 cm about 95 percent of the time [45]. The maximum position update rate across each radio cell is 150 updates per second. Signals from simultaneously triggered Bats are encoded in a way that allows receivers to distinguish among them.

4.1.3 Cricket

Researchers from MIT started to work on the Cricket indoor location system fall 1999, and Cricket v1 got its first users by the spring of 2001 [20, 6]. In July 2004 Cricket v2—which addresses most of the shortcomings of the previous version—was ready. Cricket hardware units are commercially available, and hardware design and software are open-source [46].

Cricket is the result of the five design goals given below [6]:

User privacy Cricket was designed to avoid the user privacy problem inherent in previous tracking systems like Active Badge (4.1.1 on page 42) and Active Bat (4.1.2 on the page before), by letting devices *learn* their location rather than having the system tracking them. Thus, Cricket inverts the architecture of those earlier systems [20]; instead of having the mobile device emitting signals to be received by the infrastructure, in Cricket the infrastructure emits signals that the mobile device receive and use to infer its location. Thus, Cricket is a self-positioning system, while Active Badge and Active Bat are remote-positioning systems (discussed in 2.2.2 on page 13).

Decentralised administration There should be no need for a central entity to keep track of each component in the system, and no explicit coordination between infrastructure transmitters. This, and the choice of a self-positioning architecture, helps the system scale easily, and makes it easy to employ since the transmitters don't need to be connected to each other or to any other infrastructure [20].

Network heterogeneity Cricket should be able to provide information to devices regardless of their type of network connectivity. This is achieved by decoupling the Cricket system from other data communication mechanisms.

Low cost The Cricket devices can be made from inexpensive, commercial off-the-shelf components, resulting in a price of less than $10 for each device [6]. They are also commercially available at $225 (in low volumes) in the U.S. [47].

Portion-of-a-room granularity The system should accurately demarcate boundaries between rooms and parts of rooms. The first is easy, since ultrasound doesn't travel through walls, but it is also designed to accurately demarcate virtual parts of a room which correspond to different spaces.

Cricket can provide two forms of location information, names associated with rooms or parts of rooms—called *space identifiers*—and position coordinates. The most common way to use Cricket is to place Cricket *beacons* on walls and/or ceilings, and attach Cricket *listeners* to host devices whose location needs to be obtained. The beacon and listener hardware are identical, the difference is in the running software [46]. This makes the Cricket infrastructure quite flexible, in that you can also run the beacon on a moving device, or configure all Cricket devices to simultaneously function as both a beacon and a listener [46].

The Cricket system works by having the beacons periodically broadcast their position information—space identifier and/or position coordinates[2]— on a radio frequency (RF) channel. Simultaneously, they also broadcast an ultrasonic pulse. Listeners that are in the radio range of a beacon, have line of sight to it, and are in the ultrasonic range from it, will thus receive both an RF signal and an ultrasonic signal. Because RF travels about 10^6 times faster than ultrasound, the listener can then use the time difference of arrival between the start of the RF signal and the corresponding ultrasonic pulse to infer its distance from the beacon. This is how Cricket solve the problem with synchronising the beacons and the listeners. The listener provides the location information of the beacon and the associated distance to the host device through an API, and the listener or host device infers its position from such information from multiple beacons.

[2]Actually, in v2, the beacons send their unique ID's, and the applications download a database which maps beacon ID's and space/coordinate information [20].

There are also disadvantages with the Cricket architecture [20]. Since the Cricket beacons broadcast their location information, this has to be given to them in advance when deploying the system. Configuring spatial information in the beacons is easy, while configuring accurate position coordinates is cumbersome. Continous tracking of objects is harder because a listener hears only one beacon at a time, and updating the position thus takes longer time and is more complex. Cricket also needs a distributed beacon scheduling scheme to avoid RF and ultrasound collisions at the listeners. Finally, the power consumption of the Cricket units is high, and the batteries have to be replaced pretty often. Attempting to solve this problem an adaptor was made for plugging the beacons directly in the wall outlets, but this is laying constraints on where beacons could be placed. Another solution is to use solar cells which use energy from the fluorescent lighting system often used in office buildings. This works fairly well and may be the future solution, although some problems still exist for example in dim lighting or when the lights are turned off. Regarding the latest Cricket listeners, they interface to a host using a compact flash interface. Thus, they can draw power from the host, eliminating the need for a battery.

Cricket can be as accurate as between 1 and 3 cm in real deployments [46]. The radios run at a frequency of 433 Mhz, with the default transmit power level and antennas providing a range of about 30 metres indoors when there are no obstacles. The maximum ultrasound range is 10.5 metres when the listener and the beacon are facing each other and there are no obstacles between them.

4.1.4 RADAR

RADAR is a radio-frequency (RF) based system for locating and tracking users inside buildings. The system was developed by researchers from Microsoft Research, and their work was published in two articles early 2000 [7, 19]. The goal was to overcome an important limitation of earlier systems: the need for specialised infrastructure implemented solely for locating users. The approach was to make use of existing RF wireless local area networks (WLANs) to provide accurate user location and tracking capabilities. In this way the costs of the positioning system can be dramatically lowered because no additional hardware is required. It should be noted that RADAR's goal is the opposite of the network heterogeneity design goal of Cricket in the previous section. Cricket provides location information to devices regardless of their type of network connectivity at the cost of requiring additional infrastructure, while RADAR eliminates the need for such extra infrastructure at the cost of providing location information of WLAN-devices only.

The base stations in a RADAR-enhanced WLAN system are positioned to provide overlapping coverage, and broadcast beacons periodically. Mobile WLAN-equipped receivers record beacon signal strengths, which can be used to infer distance for use in trilateration (see 2.2.4 on page 19 and 2.2.4 on page 18). To determine locations, RADAR uses a radio map—a database that maps measured signal strengths to position coordinates. The major part of the work in deploying RADAR is to construct this Radio Map, which can be built using two different approaches. In the first, empirical approach, a mobile user is walking around the building and explicitly measure and record base station signal strengths at different known locations. In the second approach, a mathematical model of indoor RF signal propagation is used. The first approach is superior in terms of accuracy, while the latter makes deployment easier.

To improve accuracy RADAR uses *continous user tracking*, which means to use information from the past to make better guesses of user location. This is based on physical constraints, in that the user is very likely to be near a previous location. The *aliasing problem*, that two locations that are physically far apart is close to each other in signal strength, can be solved using this technique. The aliasing problem may arise if for example there is an obstruction between a receiver and a base stations that are close to each other, while there is no obstruction between the base station and a receiver that is farther away. By knowing the user's previous position, measurements with large deviations can be discarded. Another technique used by RADAR to improve accuracy is *environment profiling*, which is to use multiple Radio Maps representing different environmental conditions, for example how crowded a place is. Human bodies consist of a lot of water, and water absorbs RF signals. Thus, a Radio Map created after work hours with very few people in the building will not reflect the environment at a different time, like lunch hour, very well.

RADAR has been deployed in an area of 980 square metres with over 50 rooms, covered by three base stations. The accuracy is about 2-3 metres—about the size of a typical office room—50% of the time with the empirical radio map approach. With the radio propagation model the accuracy is about 4.3 metres 50% of the time.

4.2 Infrared-based Location Systems

4.2.1 PARCTAB

The PARCTAB system [48, 49] was a research prototype developed at Xerox PARC between 1992 and 1995. This system is similar to the Active Badge system in that it provides room scale positioning accuracy by utilising a networked infrastructure that listens for diffuse infrared transmissions from the users' devices. These, the PARCTABs, are personal digital assistants (PDAs) with several IR diodes spaced around the case and they also have a multi directional receiver. The IR diodes used are wide angle LEDs to ensure diffuse infrared emissions.

The networked tranceivers have 24 IR emitters spaced with 15 degree intervals for complete coverage in all directions, and two detectors that provide 360 degrees viewing angle. The range is about 6 metres, and when placed in the ceiling in the middle of a room it provides very good coverage. The diffuse emissions make LOS not necessary, because tranceivers and PARCTABs can sense infrared light reflected from surfaces. The researchers report that if there already are a networked computer in the room it would only take about 15 minutes to install a tranceiver.

4.2.2 Locust Swarm

Locust Swarm [23] is another infrared system. It differs from the Active Badge and PARCTAB systems in that the infrastructure nodes, the Locusts, are wireless and that they broadcast their location information for the user's device to listen to to ensure user privacy. The Locusts are measuring about 3 x 8 cm, and are connected to a small solar cell panel measuring about 15 x 15 cm. They are placed in the grills beneath overhead fluorescent lights, and draw all their power in this way and don't need batteries. One Locust covers an area of about 6 metres in diameter, depending on the distance to the floor. In 1999 one Locust could be made for under $20. The user device could be any device with a proper infrared receiver.

4.2.3 IRIS-LPS

IRIS-LPS (Infrared Indoor Scout) is an optical infrared local positioning system developed at the Darmstadt University of Technology in Germany, and published in 2003 [50]. The system consists of a number of IR emitting tags and a stationary mounted stereo camera. All hardware is made of cheap off-the-shelf components.

The stereo camera consists of two USB cameras with 120 degree lenses mounted 20 cm from each other. The cameras measure angle of arrival of light emitted from the tags, and this is used to triangulate the tags. The light results in a bright spot in the image, and the size and the density of the spot is used to determine distance. The stereo camera is connected to a PC which decompress the images and performs the real-time image processing. There could be up to 100 tags.

To determine the accuracy of the system it was installed in a lecture hall. The camera was mounted in front of the blackboard, three metres above the floor. It covered almost the entire room, which measures 15 x 9 metres. The tag itself is smaller than the battery, and consists of one LED with a narrow angle of 20 degrees and range over 10 metres. An exposure time of 1/500 second is enough for the camera to detect the signal. The accuracy decrease with increasing distance and angle from the camera and was about 8 cm in near range and 16 cm when covering a room of about 100 m^2.

Figure 4.3: A prototype headset used in IRIS-LPS.

In an application using the positioning system the users wore headsets with eight IR diodes mounted on top of it, each covering 45 degrees. This was done to get a greater total coverage, because smaller angle gives better range. By letting the diodes point in different directions very good coverage is achieved. By placing the emitting diodes on the head, the problem with IR requiring line of sight was solved.

4.3 Radio-based Location Systems

4.3.1 WLAN Based Systems

Ekahau

Ekahau [51] is a Finnish company that offers real time, multi-floor location tracking of WiFi-devices or WiFi-tags in any standard Wi-Fi network (802.11 a/b/g). Average accuracy up to 1 metre in less than a second is achieved indoors by use of 5–7 access points, or 2–3 metres average accuracy by use of 3–5 access points. The patented Ekahau location-sensing system is a software-only solution that works with any off-the-shelf Wi-Fi access point. No proprietary infrastructure is needed. Both zone based tracking, to report the device location by zone name, and continuous real-time positioning of precise x, y, floor, heading, speed, etc. location coordinates are supported. The system is able to locate over 100 devices per second on a typical desktop PC, and more with more powerful hardware.

Ekahau uses a *probabilistic approach* to location sensing [52]. Signal strength data from various known locations infer a model that can be used to make predictions about the location associated with a set of new signal strength data. Building such a model involves the construction of a probability function which estimates the probability that a particular measurement corresponds to a particular position. This can be seen as a special case of the scene analysis technique used in RADAR. The first big advantage with Ekahau's approach is that the time needed for site calibration (a walk-through in the environment to collect sample points for building the model) is much shorter than for building a radio map as used by RADAR. Approximate time needed is only 1 hour per 1,200 m^2. The second big advantage is that minor environment changes like number of people or furniture arrangement do not require re-calibration of the positioning model. Partial re-calibration is only required when access points are moved or heavy structures are modified in the coverage area.

Cordis RadioEye

The Cordis RadioEye System (CRE) is a Norwegian price winning technology[3] for indoor positioning which is able to provide the physical coordinates of 802.11b WiFi devices. The system consists of a roof mounted unit—a RadioEye—measuring 25x25x7 cm with advanced antenna technology that can be compared to the facet eye of a fly. By analysing the signal spectrum of microwaves emitted from the mobile devices, the system can determine their coordinates as long as there is line of sight between the RadioEye and the devices. This positioning technique is unique and patented by Radionor [53].

CRE is able to provide accuracy up to 50 cm, *or* it could provide coverage of 2000 square metres per RadioEye. Devices can be monitored with a coverage angle of 110 degrees, and a tradeoff between coverage and accuracy is required since accuracy decreases when the coverage area gets bigger. The system is able to compute 1000 positions per second [54].

A Norwegian company has tried both the Radionor and Ekahau solutions. They report that EPE has longer latency in delivering location than the RadioEye, which means that this system may not be as real-time as they claim. A user moving rapidly may have moved far between two position updates.

4.3.2 Bluetooth Based Systems

An Indoor Bluetooth-based Positioning System

A team from Hanover has implemented a Bluetooth-based indoor positioning system [55]. The system is based on self-positioning, where the position estimation occurs in the mobile device without the need of changes in the already fixed installed Bluetooth network. Positioning is done by trilateration using received signal strength (RSSI). Achieved positioning error for the system is given by a deviation of 2 metres on average.

For precise position estimation, the correlation between distance and RSSI has to

[3] The 2004 European IST-Prize, The Rosing Prize for IT Product of the Year 2003, and The Rosing Creativity Prize 2003

be determined (see 2.2.4 on page 19). Because of the radio propagation effects and potentially no LOS, caused by for example the person holding the Bluetooth device, the equation for signal propagation in free-fields is not suited for the indoor area. To approximate the correlation between signal strength and distance that fits the environmental conditions an empirical approach is taken. This is described in the training phase below.

The implemented system consists of three Bluetooth access points and one Bluetooth enabled PDA. The room is $46m^2$ and virtually divided in 1 x 1 metre sections. The work with splitting the premises in sections and placing the access points is called the *preparatory phase*. To obtain a good approximation function between the RSSI and the access point distances, several measurements are recorded in each of a number of randomly chosen sections. This is called the *training phase*. The mean of all measurements belonging to one section and access point forms the reference value of the RSSI in the section. The third phase is called the *location phase*. Here the distances to the access points are determined based on RSSI measurements, and the trilateration method is employed to find the position of the PDA.

The Bluetooth specification does not provide any means for extracting the RSSI value directly, so that this value has to be computed from another value. It turns out that this limits the maximal distance between an access point and the mobile device to 8 metres, and thus restricts the coverage of the positioning system. In addition, the accuracy of the value which the computed RSSI is inferred from is also not standardised, and depends on the Bluetooth hardware manufacturer.

BIPS

BIPS [56] is another Bluetooth-based indoor positioning system, which is similar to the IR-based Active Badge system. Both systems are designed for tracking people with room-scale accuracy by cellular proximity sensing throughout a building. BIPS uses this to offer a service that allows a mobile user to visualise on his portable, Bluetooth-enabled device the shortest path he has to follow in order to reach another mobile user inside the same building. To do this, the system keeps location information about all users in a central database.

BIPS defines a room as a space that can fit into a circle of 10 metres radius, since this is the maximum coverage area of a Bluetooth device. The system consists of a set of Bluetooth cells, one for every significant room of the building. The Bluetooth access points are interconnected via an Ethernet LAN with a central server machine containing the location database. The database is updated whenever an access point detects a new device in its coverage area.

As we saw in the section about the Bluetooth standard (3.3.2 on page 31), a potentially time-consuming process is required to establish a connection between a master and a slave. This is the major concern of BIPS. The masters (the access points) must dedicate a certain percentage of their working time to device discovery and the remaining time to serve the slaves (the mobile devices). BIPS has done experiments for defining the scheduling policy of a master, and found that if the master spends 3.84 seconds on device discovery, then 95% of the slaves will be discovered on average. This is satisfactory for BIPS, and it means that the average load of tracking service is about 24% of the operational cycle.

Bluetooth Indoor Localisation System (BILS)

This system is able to determine the position of any Bluetooth-enabled mobile device with an intended accuracy of about 1 metre in indoor environments. The major advantage of the system besides the good accuracy is that additional hardware is needed only on the stationary base stations. No hardware or software need to be added or changed on the mobile Bluetooth-devices to be located [57].

One of the four base stations needed to determine location in three dimensions is also master station, and it broadcasts a data packet containing a correlation code. When the other base stations receive this signal, they start internal time measurement counters. When the mobile device receives the signal, it replies by broadcasting the same data packet again, which upon arrival at the base stations stops the time measurements. The four base stations measure the TDOAs for the signal traveling from the mobile to the base stations using specialised correlation hardware. The measurements are then collected at a host PC, where the position of the mobile will be calculated and evaluated by DTDOA taking the local coordinates of the base stations into account. The big advantage with this scheme is that the base stations don't need to be synchronised with each other or with the mobile devices, since it is time differences that are measured and not time of arrivals. It is the specialised correlation hardware at the base stations that make it possible to determine the exact receive time, but because of the very high accuracy requirements it is mainly limited to line of sight conditions, because obstructions will introduce propagation delays which will make the time measurements mirror wrong distances. Thus, the base stations should be placed in the upper corners of a room.

4.3.3 PAL650 UWB System

An example of an UWB positioning system is the PAL650 system, an FCC approved, commercial precision asset location system which is being used for tracking of high valued assets in hospitals, factories, and military facilities. The system consists of a set of active UWB tags, one of which is used as calibration or reference tag, UWB receivers, and a central processing hub. Three or more receivers are placed at known positions within or around the area to be monitored. At startup the system is calibrated by monitoring data from the reference tag which is placed at a known location. The tags produce bursts of short-pulse RF emissions once every second, and the time difference of arrival (TDOA) of the bursts are measured at the various receivers and sent back to the central hub for processing. The tags are powered by one 3.0-V 1A-h Lithium cell battery, which lasts for approximately 4 years. The range of a tag in indoor environments is typically 60 metres, between several walls, and an absolute tag positioning accuracy better than 30 cm is routinely achieved [36].

4.4 Ultrasound-based Location Systems

4.4.1 DOLPHIN

The Active Bat and Cricket systems described in the previous sections are able to provide very precise indoor positioning. But, deploying these systems in large-scale environments require manual configuration of a large number of infrastructure sensor nodes, because these are required to have inherent knowledge of their positions[4]. DOLPHIN[5] is an ultrasonic positioning system developed to reduce such configuration costs [58, 59].

DOLPHIN is similar to Active Bat and Cricket in that a reference node broadcast an RF signal and an ultrasonic signal simultaneously so that surrounding nodes can measure the TDOA used for distance measurement. With three such measurements position can be computed by trilateration. The difference in DOLPHIN is that by using a distributed positioning algorithm only a few nodes have to be pre-configured with their exact position. For example, if reference nodes A-C are used by node D to determine its position, node E can determine its position based on nodes B-D and so on. With this approach even nodes outside the coverage area of the reference nodes can be positioned.

The disadvantage of DOLPHIN's approach is that a positioning error in a node affects all later positioning determinations based on this node, direct or indirect. In the test implementation of the system, which consists of only 3 reference nodes and four other nodes, the positioning accuracy at a node using only reference points for positioning was less than 5 cm, degrading to 10-15 cm in nodes that used this first node for positioning. This error propagation problem is unavoidable, but can be minimised by proper placement and number of reference nodes. It should also be noted that the current test implementations of DOLPHIN assumes that all devices

[4] The researchers behind the Cricket system are working on automatic BeaconConfig algorithms, but these are not working satisfactory yet.

[5] Distributed Object Locating System for Physical-space Internetworking

are static. Handling moving devices and techniques for improving the accuracy are the current focus of the researchers behind DOLPHIN.

4.4.2 Bristol Indoor Positioning System

The Bristol indoor positioning system (Bristol) is another ultrasonic system that tries to cope with one of the disadvantages of the Active Bat and Cricket systems. The goal is to reduce costs by using only minimal infrastructure and readily available components. A simple system covering a room of about 4 x 7 metres and providing accuracies of 10–15 centimetres can be implemented for only $150 [43]. As in the Active Bat system, a radio signal is used for synchronising transmitters and receivers, and distances are computed by measuring time of flight of ultrasonic signals. The system is self-positioning and uses four ceiling-mounted transmitters connected to a transmitter module containing the ultrasonic drivers, the microcontroller and the radio transmitter. The receiver is attached to a host computer or to the shoulder of a person. Line of sight is required. A rechargeable 9 v battery in the receiver module will last only for one day. However, the system is easy to install and requires no calibration after the initial installation. But for large scale use the costs will increase.

Bristol is tested with several configurations. Four US transmitters can also cover a 8 x 8 m room with an accuracy of 15 cm, or a 8 x 16 m room with 20 cm accuracy. A larger configuration of 6 US transmitters at a height of seven metres covers a 10 x 18 m room, with accuracy better than 25 cm.

4.4.3 Ultrasonic 3D Position Estimation Using a Single Base Station

In the previous section we saw that reducing the amount of infrastructure is a way to reduce costs. A novel experiment is described in [60, 61], where only one base station is needed to determine the position of objects in a room using ultrasound. In a box-shaped, empty room with LOS conditions, accuracies were usually better than 20 centimetres. However, in a non-empty room and/or in a case of no LOS, the accuracy degrades to 2.5–3 metres 95% of the time.

The idea behind the method is to use reflections from walls, floor and ceiling as virtual sources of ultrasonic signals into the room instead of real ones in the form of transmitting base stations. An ultrasonic signal consists of amplitude peaks caused by acoustic reflections, and makes up a pattern that depends on the receiver position and orientation. This pattern is called a *signature*, and it can be predicted by an acoustic room model. Position determination is done by a method called *signature matching*, where the signature for many given positions are first predicted. Then any measured signature in the mobile device can be compared to the predicted signatures to find the one with the closest match. The approach is similar to that of RADAR, in that it uses scene analysis that requires preparations to be done in advance to build the data set measurements are to be compared with. If this method could be done with nearly automatically preparations and realistic environments in the future, it could be a very attractive solution.

In addition to the acoustic reflections method described above, an experiment is conducted which uses an array of ultrasonic transducers at the base station. This makes it possible to determine the direction of arrival of received signals, or to steer transmitted signals in certain directions. Then TDOA measurements can be used to compute positions. In a non-empty room with LOS the accuracy with this approach was below 1.4 metres 95%, degrading to 3.2 metres when no LOS.

It should be noted that the experiments conducted so far have shown many challenges that have to be solved before these approaches can be used in real-life environments, but such solutions may prove suitable for special applications.

4.5 Summary

In this chapter, we have reviewed a total of 17 existing location systems. Four systems are based on infrared technology, eight are based on different radio technologies, and five are based on ultrasound. In addition to using different wireless technologies, these systems show how the different positioning techniques and designs described in chapter 2 can be used. Thus, we should by now have a good understanding of how positioning and location systems work, and their challenges. We can now procede with the location based services at layer 3 in our reference model, which builds on the positioning systems in layer 1 and the location systems i layer 2. Location based services will thus be the focus of the next chapter.

Chapter 5

Location Based Services for Indoor Exhibitions

This chapter will be about location based services (LBSs). These reside in layer 3 of our reference model, see figure 5.1. As stated in the introduction to chapter 1, a location based service is based on knowing where something or somebody is. The underlying layers provide the LBSs with such information.

There are two goals of this chapter. One is to come up with a description of "the domain of indoor exhibitions". The other is to come up with a requirements specification for "an LBS operating in this domain". However, as we saw in the introduction to chapter 1, a broad range of different LBSs exist. Likewise, an exhibition could be everything from a museum or a gallery to a shopping mall or an indoor zoo. If we were to take into consideration only generic issues with LBSs and exhibitions, a lot of interesting problems and challenges might be left out. Thus, our solution is to use a simulated case in this work, in which we can include as many details as we want. The case consists of two parts, an LBS and a given physical existing exhibition. The LBS we have chosen is a *mobile electronic tour guide* for indoor exhibitions, and the exhibition is the Norwegian *Astrup Fearnley Museum*

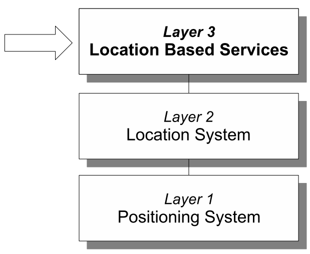

Figure 5.1: This chapter will review location based services on layer 3.

of Modern Art. The reason for calling the case “simulated” is that we have come up with requirements ourselves—they are not coming from a real client. The reason for this is the same as for not using a generic description. However, the selected museum is real.

The result of this chapter is a requirements specification for our chosen LBS and a description of the museum. These will be used in chapter 6, where we will analyse the location systems from chapter 4 to see whether any of these are able to fulfil the requirements.

5.1 Problem Area

Before we introduce our specific case, we will look at exhibitions and mobile electronic tour guides in general. First, based on what we have learned about challenges with indoor positioning so far in this thesis, we will try to come up with a list of characteristics of indoor exhibitions that may influence an indoor positioning system. Then, we will learn about electronic tour guides. This is an important part of this thesis, as it is what we will base our requirements specification on.

5.1.1 Characteristics of Indoor Exhibitions

In chapter 2 we learned how positioning can be done. In chapter 3 we learned that wireless communication, and thus positioning, in indoor environments is challenging, and in chapter 4 we saw how different positioning systems have been implemented. Based on this learning, we have come up with a list of characteristics below that should be taken into consideration when working with positioning systems for indoor exhibitions:

- Layout of the premises where the positioning system will be installed. This includes for example the number, size and shape of rooms, storeys and partitioning walls.
- Construction materials of walls, ceilings, floors, windows and so on.
- Furniture, partitioning walls, etc. that the premises are fitted out with.
- The placement and number of artefacts in the exhibition.
- How often the exhibition is changed.
- The number of visitors and how they are typically distributed around the exhibition, both physically and timewise.

Figure 5.2: Traditional museum guide using a megaphone so that everyone in the group can hear him.

Actually, these characteristics could be valuable to look at for any indoor location based computing system.

5.1.2 Mobile Electronic Tour Guides

Our LBS example will be a mobile electronic tour guide. We will define such a guide as a mobile physical device that could replace a human guide in an exhibition. This means that it is possible to store information on the device or use the device to retrieve information stored on a server over a communications medium. In addition, the device has at least one output channel, so that the stored or retrieved information can be revealed to its user. The information is supposed to guide the visitor while he is at the exhibition. The main reason for replacing human guides with electronic guides is that each visitor then can have his own personal guide. This offers the visitor with much more freedom, because he can choose what he would like to see, when he wants to see it, and for how long he wants to see it. Because the visitor only needs to focus on those parts of the exhibition he finds most interesting, he can spend more time at these and thus get more in-depth information about them.

In the definition provided above it was stated that the electronic guide could replace a human guide. It should be mentioned here that the electronic guide also could replace any other means of guiding in an exhibition, like posters with text, illustrations or pictures, touch screens, static mounted head-phones and so on. The big advantage with the mobile, personal electronic guide over such static guiding tools is that the visitor will avoid spending time in queues for access to the additional information.

As we have now seen, electronic guides can serve as substitutes for human guides and static guiding tools for their users. The first such guides appeared in the 1950s and 60s, and the devices used were portable reel-to-reel players and cassette players. They allowed the users to listen to pre-recorded information about the different artefacts in their own pace, without having to follow a human guide in a group. While audio-only guides still are much in use today, in more modern forms such as MP3-players for example, a new generation of guides has arrived with the development of the hand-held computers, especially the personal digital assistants (PDAs). These devices are able to provide the user with full multimedia content, that is information in the form of text, sound, images and video.

The development of new technology and increasing research interest in the field of enhancing exhibition experiences have led to a broad range of suggestions to what a modern electronic tour guide should be able to provide. A summary is given below, where the suggestions are divided into four groups which differ in type of use of the tour guide.

Enhance the visitor experience The most basic idea of enhancing the user experience in an exhibition is to provide the user with additional information about the different artefacts he is watching. For example, a visitor that stands in front of a painting can be provided with information about the work itself, the painter, the artistic style of the era, and so on.

Ease the visitor experience A tour guide implemented on a mobile device with a screen can provide the user with a map of the premises. The map can be used for navigation, to guide the user along different pre-defined routes or a route generated automatically from the visitor's preferences, or it can help clarifying where the user has already been. The map can also contain information about where the toilets, emergency exits, cafeteria and so on is situated. If the user comes to the exhibition as part of a group, he could see where the others are on the map. The map could also report about congestions and queues so that the visitor could avoid these.

Management tool Many tour guides have the ability to record the visitor's actions while at the exhibition, like the order in which he watched the different artefacts, which ways he walked between them, how much time he spent at the objects, and what information he requested on the device. The exhibition owners can use this information to make statistical data about the behaviour of the visitors, which can be analysed and used to improve the system. For example, the visitors' navigation patterns may reveal congestion spots within the museum that the management could solve by re-organising the exhibition. In a real-time system the management could even use such data to make quick decisions regarding employee allocation to sections where additional needs emerge.

Extending the museum experience to before and after the visit In addition to provide the visitor with additional information while at the exhibition, the visitor could be offered to prepare his excursion at home. By logging on to the exhibition's web site through the Internet, he could browse the different content of the exhibition and selecting those he is most interested in. Upon arrival at the exhibition at a later point, the visitor is provided with an electronic guide that can give a guided tour based on the visitor's pre-selection.

In those cases where the visitor either makes his own route in advance as mentioned above, and/or the system at the exhibition records the visitor's actions while at the exhibition, it is easy to automatically generate a CD or personal web site for the visitor which contains information about all artefacts he has shown an interest in during the visit. In this way the learning could be improved because it is easy for the visitor to go back and review all that he has seen.

Mobile Electronic Tour Guides and Positioning Systems

To be able to provide the services described in the previous section, a positioning system is required. We saw that the most basic idea of enhancing the experience from an exhibition visit is to let the guide provide the visitor with additional information about the artefacts he is watching. For the guide to do this, it has to know which artefact the visitor is currently watching. The simplest way to do this is to mark each artefact with a number, and then let the visitor enter the number belonging to the artefact in question on his device. The corresponding information is then revealed on the device [62].

There are two main reasons that this very simple and low-cost solution will not hold in many tour guide applications. First, this solution will not provide navigation support, and second, the user will have to take an active part. Whether the users should be actively involved in the positioning process, or whether they should remain passive, is a very important issue developers of LBSs have to consider, as it put very different requirements on the underlying positioning system. An *active user* has to perform some action for the system to do the positioning. For example, the user can be equipped with a hand-held device. When the user sees an interesting artefact, he can point his device at a sensor attached to the artefact, and by this tell the system that he is present. He will then receive some information about this artefact. On the other hand, a *passive user* does not have to perform any specific action for the positioning to occur. He could wear a tag on his jacket that is automatically positioned by a surrounding infrastructure without the user being aware of it. In general, providing positioning capability to systems with passive users is much more challenging than to systems with active users.

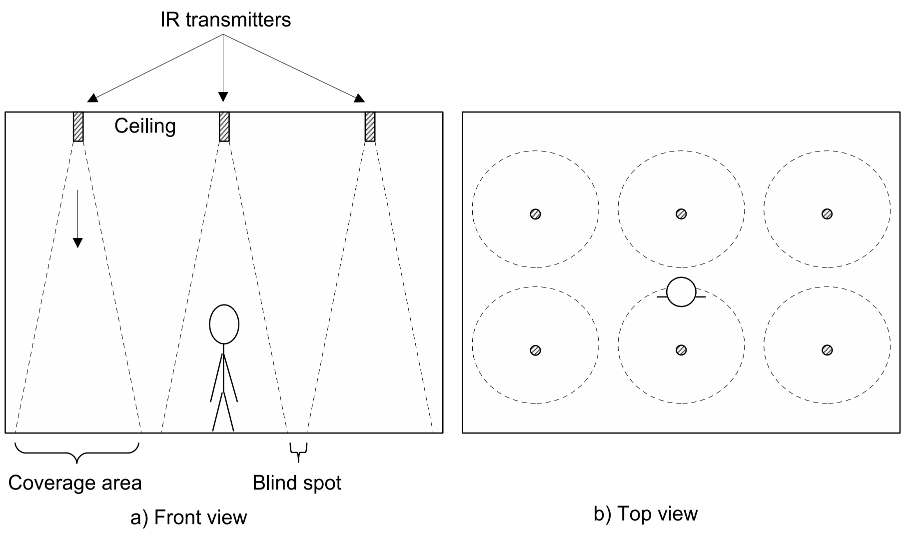

Figure 5.3: The Cyberguide system

Existing Location Based Tour Guides

We will now look at examples of how positioning technology has already been used in electronic tour guides. Only indoor systems are included.

Cyberguide The Cyberguide project [8] took place at Georgia Institute of Technology during a one year period in 1996/97. Project researchers and students developed prototypes of a location based tour guide that could support a visitor to one of the labs during monthly open houses. The visitor was provided with a PDA[1] with a map of the lab, with symbols representing the different projects demonstrated at different places in the lab. When the visitor clicks on a symbol, information about the project is displayed on the screen. All information is stored on the PDA.

The positioning capability of Cyberguide was used to automatically scroll the map so that the user and his immediate surroundings would always be in the picture. Positioning information was based on proximity sensing, by having a special IR receiver connected to the PDA listening for infrared signals (beacons) emitted from TV remote control units hanging from the ceiling. Each unit made up a small cell, and position was updated when the user moved into a new cell. Figure 5.3 illustrates this.

[1]From the Apple MessagePad series, running Newton OS. In sale from 1995–98.

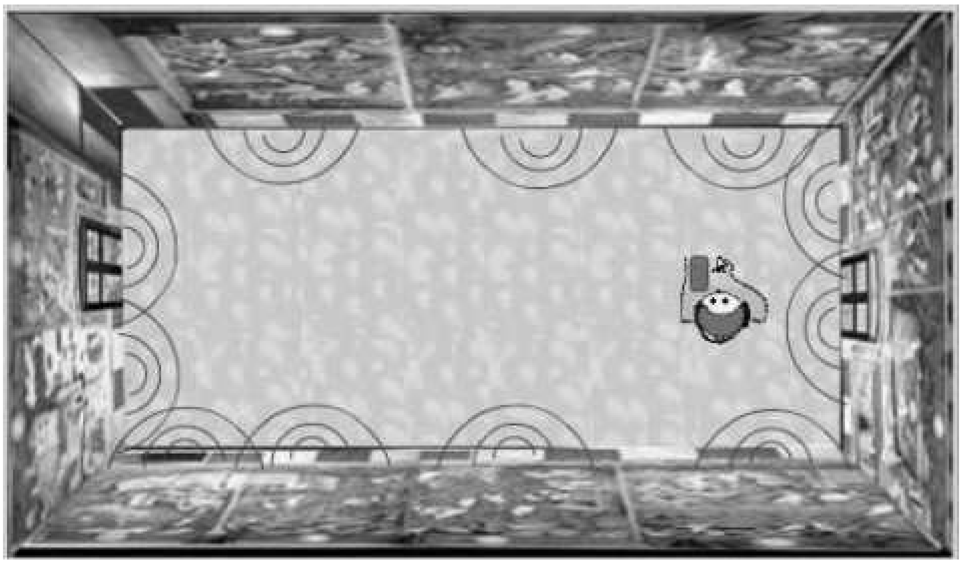

Figure 5.4: Infrared transmitters in the fresco room in Torre Aquila.

Torre Aquila Torre Aquila is a tower at the Buonconsiglio Castle in Trento, Italy. In this tower there is a room with a large fresco, which covers all four walls with a total of eleven different panels (see figure). Researchers from The Trentino Cultural Institute have developed a prototype of a multimedia museum guide, which is supposed to enhance an audio presentation of the fresco by showing the visitor pictures of the parts of the panel which is currently spoken of on a PDA [9]. The idea is that this will make it easier for the visitor to identify details in large, complex paintings while simultaneously listening to an audio commentary.

As in the Cyberguide project, an infrared based proximity technique is used for positioning. IR transmitters are installed in front of each of the eleven panels, and the PDA has an infrared receiver. When the system detects a visitor in front of a panel, a picture of that panel is displayed on the PDA. If the user does not move, the panel will be highlighted on the screen and the visitor can click on it to start a presentation about the panel.

Pilot tests of the prototype, conducted in 2003, showed that most of the test users pointed directly at the infrared transmitters with the PDA to speed up the positioning.

TaggedX TaggedX (Tagged Exhibition) is a location based museum guide project that was implemented at the Natural History Museum of Aarhus in Denmark in 2003 and 2004 [10]. The museum has both a permanent exhibition and several temporary exhibitions. The technical set-up of the TaggedX system is given in fig-

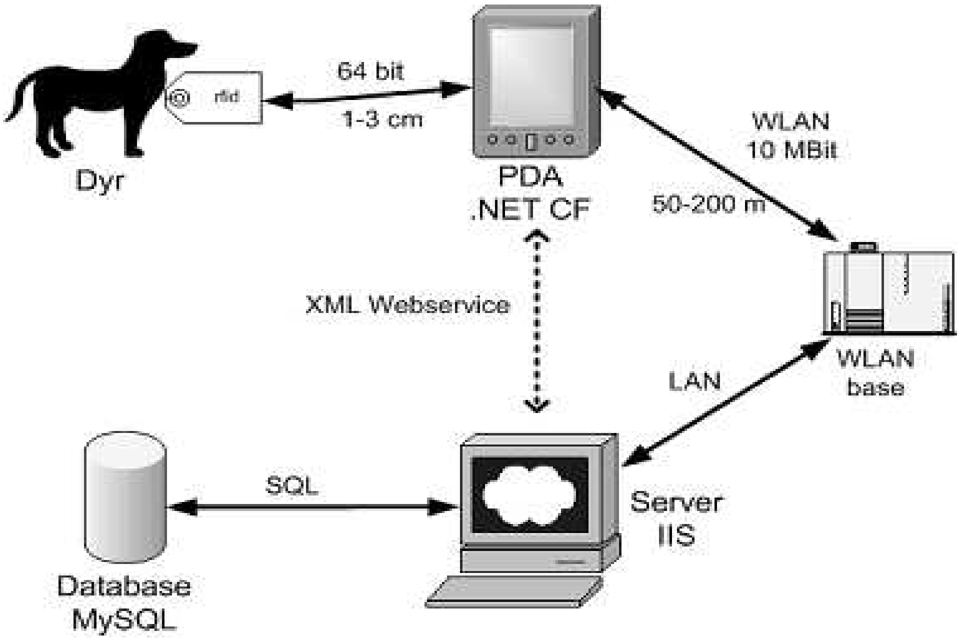

Figure 5.5: TaggedX technical set-up

ure 5.5. The artefacts that the visitors are going to get additional information about in this case are stuffed animals. These are tagged with passive RFID tags, and each visitor PDA is equipped with a Compact Flash (CF) RFID reader by using an extension sleeve. When the visitor moves his PDA within 3 cm of an animal, the CF reader reads the unique ID and provides it to the PDA. The PDA then sends a request to a central server using WLAN, asking for information that corresponds to this ID. The information is retrieved from a database and sent back to the PDA. The battery life of the PDA is two hours when constantly in use.

The MUSE Project The MUSE project [63, 64, 65] is an industrial research project in the domain of cultural heritage and tourism. The first report on the project was published in 2000, and articles on the evaluation of pilot tests were published in 2004.

The MUSE project has developed a general framework for implementing context-aware applications that can deliver multimedia content and services on several different devices—from powerful, stationary computers with large wall-mounted screens to mobile devices. For mobile use, a proprietary wearable terminal called WHYRE has been built. This device plays the role as a personal context-aware multimedia guide for use in museums and architectural sites. WHYRE can detect position and orientation by several different sensors and WLAN. The sensors can provide position, azimuth, roll, and pitch information, and there are also a digital compass, two acceleroscopes, and a gyroscope included in WHYRE. In the pilot tests, users' approximate positions were detected by a positioning algorithm based on signals received by WLAN access points. Orientation is tracked by a combination of inertial and geomagnetic sensors. The WHYRE device is very expensive, and weighs nearly three pounds.

Nidaros The work with an electronic tour guide for visitors to Norway's most famous cathedral Nidaros, was published in 2004 [66]. These tour guides are WLAN-equipped iPAQ PDAs, and positioning information is provided by the commercially available Cordis RadioEye system described in section 4.3.1 on page 50. This system claims that it is able to determine the position of all WLAN-equipped devices in its range with an accuracy of up to 50 cm. However, in the tour guide prototype, the RadioEye was found not to be accurate enough. The virtual zones the cathedral was divided into were relatively small, and required an accuracy of about 1 metre. Tests showed that this was not achieved.

The RadioEye was placed above an entrance, 15 metres above the floor. The accuracy is influenced by obstacles between the mobile device and the RadioEye, and by the angle between them. Thus, the placement of RadioEyes is very important to get maximum accuracy. However, with large angle and some obstructions, the accuracy is still as good as about 2 metres.

Shared Mixed Reality in the Lighthouse The goal of this research (from 2003) was to make a mixed reality system, where physical and digital users can share a museum visit together in real time [**?**]. This is done by using a virtual reality (VR) version of the museum. In this way, social experiences could be supported at a distance, letting the visitors collaborate and discuss the exhibitions like if they were at the museum together. Location awareness is a powerful resource for such a shared experience, which in this project was produced using PDAs, an ultrasonic tracking system, a 3D representation of the gallery, 2D maps, and mixed reality exhibitions. Two other resources are a common audio channel through the use of an Internet voice conference system and a common information space.

Awareness of the other users locations and orientations are used to indicate what they are looking at and what they are doing. The physical users are equipped with a PDA, which has a sensor package that is part of the ultrasonic location system described in section 4.4.2 on page 54. The sensor package also includes an electronic compass for orientation information. The location and orientation are displayed on a map, along with the locations and orientations of the other visitors. The VR user sees the other users as avatars on his screen.

5.2 Case: The Astrup Fearnley Museum of Modern Art

The Astrup Fearnley Museum of Modern Art in Oslo, Norway, is a private contemporary art museum that produces temporary exhibitions of international art [67]. It was chosen because it is a popular museum, it is privately held by people with money (which they may spend on new technology), and they have shown an interest in electronic museum guiding. The museum has already implemented some form of enhanced visiting by providing their visitors with additional information about the artefacts. Their concept is called “Artists on the Mobile Phone”. The visitor is given a list of number-artist pairs, and can call a telephone number with their own mobile phone and then select a number code from the list. The audio content varies between the artists themselves talking about their art works, and guides from the museum talking about the art works. The cost of this service is NOK 30,-, in addition to local rate. The customer is charged the cost via SMS and on receipt of the SMS you may use the service repeatedly for two hours.

5.2.1 Detailed Description

Here follows a detailed description of the Astrup Fearnley museum. It tries to cover the list of exhibition characteristics given in section 5.1.1 on page 58.

The Astrup Fearnley museum is part of a bigger building. It is about 2500m2, with exhibition areas on two different floors. The distance from floor to ceiling varies in the different halls, from 3.5 metres to 10.5 metres. Figure 5.2.1 on the next page shows the layout and measures of the two floors. It should be noted that some of the walls in the figure are temporary walls. Between each exhibition a joiner comes in and takes down and builds up new walls so that the premises will fit the requirements of the next exhibition.

The large curved wall is made of concrete. The stairs are steel with steps of oak. The floor is Portugeese sandstone called Cascais Azul. There are a few windows, but they are all covered with plastic blinds.

In 2005 the museum hosted three exhibitions between January 22 and December 11. The first and the second exhibition lasted for about four months each, while the last exhibition lasted for two months. Between exhibitions the museum is closed for visitors while the old exhibition is replaced by a new one. In 2005 this took two and three weeks, respectively. Except these periods, the museum is open to the public for free, six days a week.

In 2005 there were about 117 000 visitors to the museum. By using the information above to make an estimate of how many days that year the museum was open we get about 250 days. This means that there were an average of 468 visitors each day, but there are typically more in the beginning of an exhibition. By using this

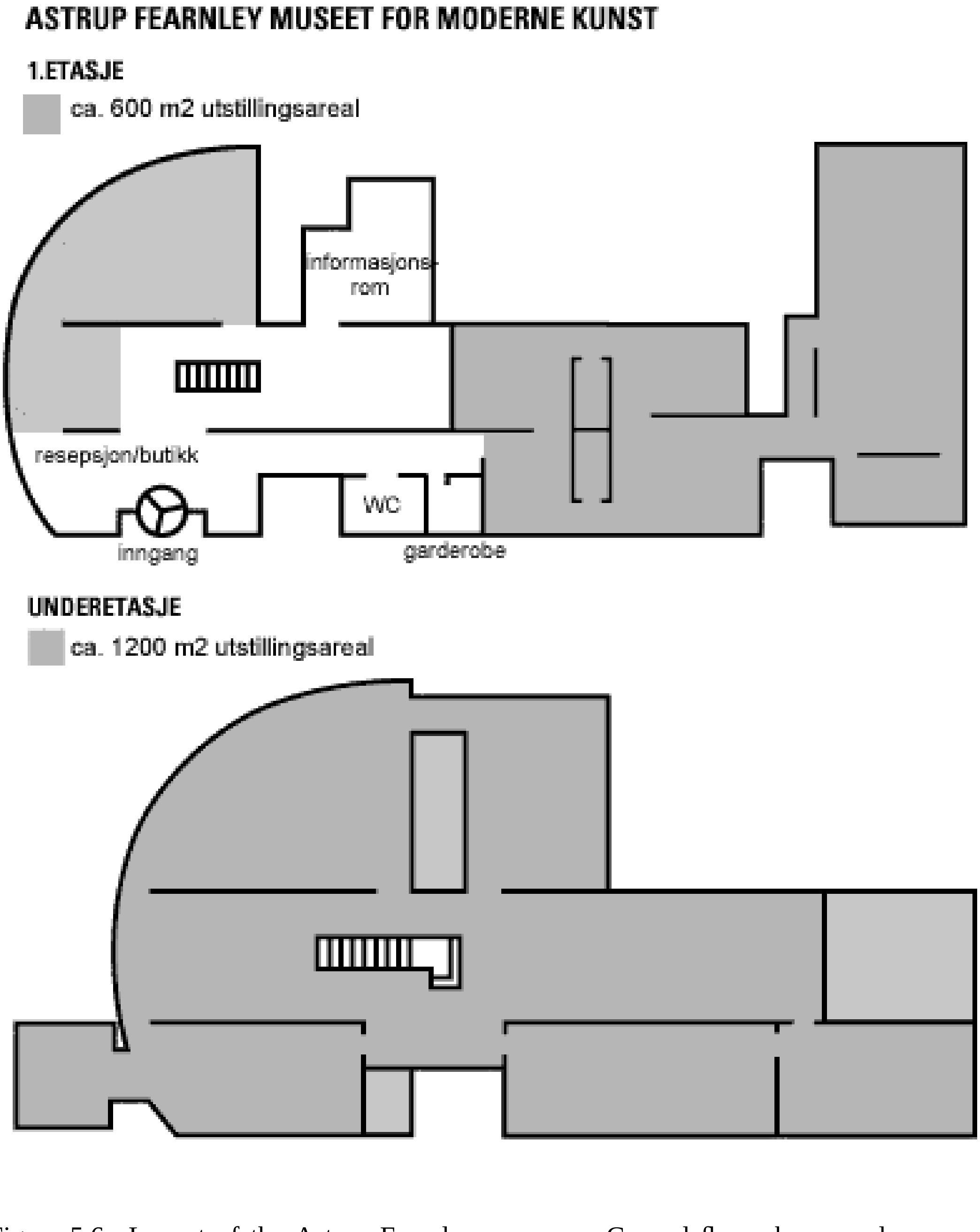

Figure 5.6: Layout of the Astrup Fearnley museum. Ground floor above, and lower ground floor below. The gray areas are the exhibition areas. The white areas include restrooms, shop, information center etc.

number and divide it by opening hours, which is six hours on average through the week, there are approximately 78 visitors at any time in the museum. These are normally evenly spread out.

Weekdays from 11am to 2pm there are guided tours for school classes, one at a time and with a maximium of 30 students per class. There is also possible to order guided tours at any time for groups of maximum 30 people.

Visitor numbers varies a lot from time to time, but the estimates can still give us an idea of how crowded the museum is by taking some logical assumptions. The first days of an exhibition it is very crowded, and there are less people at other times. Weekdays have more groups than weekends etc.

I did my on-site research of the museum on December 7 og 9 2005 in the afternoon. There were between 20 and 40 visitors in the museum at that time. The exhibition I watched is called “Uncertain States of America - American Art in the 3rd Millennium”. The exhibition consists of a variety of different kinds of artwork, which is typical for a contemporary art exhibition (see also figure 5.7 on the facing page):

Paintings and pictures There were traditional paintings hanging on the walls, and there were canvases or panels in varying sizes leaning to the walls.

Stand-alone artefacts With stand-alone I mean artefacts, typically sculptures or models of any kind that is standing or lying on the floor. In this particular exhibition there were many artefacts on the floor. The size of these artefacts were typically about half the size of a human body or same size as a human body, but there were also a few very large installations.

Showcase artefacts This means that the artefact is placed inside a showcase of glass, which is typically placed on a pedestal.

Television and projector installations It is more and more common that the artworks are video or film. In these cases the installation consists of a television or projector and a screen, canvas or just the wall, and in some cases a coach or several chairs. One of the rooms were actually completely empty, with only a projector in one of the upper corners that made funny patterns on the floor and that was it.

Because of the trend with increasing number of video installations, the museum have to split the exhibition areas into several smaller rooms because it is supposed to be dark or quiet.

5.2.2 Museum Application Requirements

We will now establish a requirements specification for a mobile electronic tour guide which is to be used by the Astrup Fearnley museum. What they want is

Figure 5.7: Pictures from the case study exhibition

an electronic guide that provides all the services and features described in the end of section 5.1.2 on page 60. In this section these services and features are turned into more formal requirements which will be used throughout the analysis which follows in section 6.1 on page 77.

Functional Requirements

The functional requirements specify the services or functions of the system—what the system must accomplish.

FR1 *The electronic museum guide should present the user with multimedia content corresponding to the artefact(s) he is most likely to be interested in at any time.*

FR2 *The electronic museum guide should offer the user with a map of the museum. The map should be automatically updated to show the area in which the user currently is (e.g. which floor), and where in this area he is (e.g. which room).*

FR3 *The user should be able to get information about where in the museum his co-visitors and representatives from the staff are.*

FR4 *The management should be able to get information about where in the museum visitors and staff are.*

FR5 *The system should record the user's actions while in the museum.*

This implies that the museum application will consist of at least six components: a mobile hand-held device, a map, a positioning mechanism, rich multimedia content, databases for location information and multimedia content, and communication channels. The device used for the electronic guide and the communication channels are described in more detail below, because these components impose some important constraints on the system design. The positioning mechanism is the most important component in our case, and will be further described in the next section called non-functional requirements.

It should be noted that it is very important to address privacy issues in a system like this, which is actually monitoring its users, both staff and visitors (refer to the privacy discussion in section 2.2.2 on page 13). However, in most cases this can be solved by explaining the person to be monitored the reasons for doing it, and by providing him with the opportunity to switch the positioning mechanism off whenever he wants to.

Device Requirements and Constraints To be able to show multimedia content, the mobile end-user device needs a screen and an audio output channel. It should also have some input channels, like buttons or a touch screen, and it must be easy to carry around. The commercially available devices today that best suits these characteristics, are the personal digital assistants (PDAs). The drawback with these devices is that they have limited processing power and limited memory and battery capacity. One of the implications from this is that most of the multimedia content that the PDA should present have to be stored on a server, and that it must be decided what data to store on the device, and what data to be streamed upon request. Regular textual content could be stored on the PDA.

As mobile phone technology improves, these are promising for use as tour guides instead of the PDAs. Mobile phone screens get larger, battery capacity improves, and they are equipped with several means for communication. For example, the Nokia N95 mobile phone has a large screen, GPS, WLAN, Bluetooth and IR. The big advantage of using visitors' own mobile phones as tour guides, is that the museum does not have to invest in user devices. The disadvantage is that mobile phone screens will probably always be smaller than PDA screens, that visitor's have to dowload an application upon arrival at the museum, and the huge variety of phones that would have to be supported. In the following, we use a PDA as the user device in the Astrup Fearnley museum.

A tour guide prototype for mobile phones was made for the Nobel Peace Center in Oslo, Norway, in 2005. In this prototype, a new means for positioning was also developed, in cooperation with Radionor, the provider of the Cordis RadioEye system described in this thesis. A new SIM card for mobile phones was developed, so that the phone could be positioned using WLAN and Cordis RadioEye.

Communication The mobile device needs to communicate with a central system for a lot of different reasons. It will request for content, its locally stored content would need to be updated, messages may be sent between visitors and between the visitor and staff or the central system. In addition, position information must be exchanged between the device and the system. As we have seen in earlier chapters, some communications systems such as WLAN can also be used for positioning. An important issue regarding the underlying positioning system is thus whether it should be coupled with the communication system or not. In the following, we assume that a WLAN network is installed in the Astrup Fearnley museum for communication purposes like those mentioned above.

Non-functional Requirements: The Positioning System Requirements

By reviewing the functional requirements in section 5.2.2 on the facing page, we can see that they all depend on an underlying positioning system, which should cover the 1800 m^2 of exhibition areas. The electronic museum guide application's requirements of this positioning system is given below. They are based on the location system properties outlined in section 2.2.3 on page 14.

User involvement

PR1: The user should be passive.

This first requirement could equally well be called semi-passive or semi-active. What it means is that the user should be told that his position relative to the different artefacts in the museum determines which artefacts the PDA automatically will provide information about, but the user should not have to be required to perform certain actions for the positioning to occur. This means that the user will have to walk about and be near the artefacts he is interested in information about, but he should not have to walk very close to the artefact, point to it, read instructions posters, etc.

Accuracy, precision, and update rate

PR2: The system should know in which room the visitor is at any time, with a confidence level of 95%.

This requirement will cover functioanl requirements FR2-FR4. For FR2, the user will be presented with a map of the building or a part of the building, and the room the user is currently in will be highlighted. For the user this room-scale accuracy is good enough, since there is no added value in knowing exactly where in a room he is in this kind of application. He is most likely to see that for himself.

One advantage by room-scale accuracy is that the positioning update rate can be lower than in a case with continous real-time tracking of a small dot representing the user, thus potentially saving power or reducing the amount of infrastructure. But, it is important that the system is designed so that it quickly detects when a user enters a new room.

Since the system knows where a visitor is at any time, it knows where all visitors are. By storing the positioning information about all visitors centrally, a user can get information about other visitors he came to the museum with (as long as these have agreed to it) upon request to the system (FR3). As response small symbols for each co-visitor could be displayed in the different rooms on the map, and/or the user could be presented with a list of name-room pairs textually. Information about staff members can be stored in the same way, and the management could get information about both visitors and staff (FR4).

PR3: The system should know which artefact the user is most likely to want additional information about at any time, based on where he is. An accuracy of 2 *metres is sufficient.*

This requirement is based on two assumptions. The first is that there is very unlikely that there are so many artefacts within a radius of two metres from the user that the PDA will show too many “hits” or miss out some “hits”. The second is that 2 metres is the longest distance when the user still feels that he is “near” an artefact.

Scale and scalability

PR4: The system should be able to handle 200 concurrent users, and crowds of up to 40 users packed closely together.

PR5: The positioning system should scale well regarding both physical reach and handling larger amounts of MOs.

Scalability is not very important in our particular case, but for the solution to be used in other museums as well this is very important. It is also possible that the museum will expand its exhibition areas in the future, and it is clever to be aware if this would be a problem with the existing positioning system.

Deployment and integration

PR6: The system infrastructure should be easy to install and configure.

PR7: The system infrastructure should not disturb its users.

PR8: The system infrastructure should be easy to reconfigure with new exhibitions.

This includes both replacement of hardware components in the infrastructure and reconfiguration of the system.

Power consuption

PR9: The user should be able to stay in the museum a whole day (six hours) without having to worry about recharging any batteries.

PR10: The museum staff should spend a minimum of time and effort recharging or replacing any batteries.

Cost

PR11: The costs should be as low as possible.

Priority	Requirement	Description
1	PR2	Room scale accuracy
2	PR3	Proximity 2 m
3	PR1	Passive user
4	PR11	Cost
5	PR10	Power IF
6	PR8	IF reconfigurable
7	PR6	Easy install
8	PR9	Power device
9	PR7	IF not disturbing
10	PR4	Many users
11	PR5	Scalability

Figure 5.8: Requirements prioritised

Deciding Requirement Priority

To give priorities to the requirements is not an easy task. They are all important to us, that is why they are chosen as our requirements. Still, some are more important than others, and it is important to clearify this before starting the analysis work because it makes it possible to compare different solutions to each other in a structured way.

The result of deciding requirement priority is given in figure 5.8. Below follow some of the arguments for ending up with this result.

The top three requirements in figure 5.8 makes sure that the positioning system is able to do what we want it to do. The fourth requirement ensures that the museum could afford it. Requirements 5–7 says something about how much extra work is put on the museum staff (or on hired extra personnel). They are internally ranged as they are because number five represents continuos work, number six represents a work process that will happen about four times a year (with each new exhibition), and number seven will typically be a one time only happening.

Requirement number eight and nine are very important for the user experience. However, together with requirement number ten it may be possible to adjust our requirements only a little if these are not fullfilled. For example, if the battery on the PDA only lasts for four hours and not the required six, the visitors could be made aware of this and it would not be a big deal. It might be rare anyway that a visitor spends the whole day in the museum. Or if the user device includes a headset that is somewhat bulky, it is still likely that many of the visitors interesting in using a PDA in the museum would not care about this. If the positioning system does not manage to support as many as 200 concurrent users, the museum could reduce this number by only providing PDAs to 100 visitors at a time. This is actually not unlikely, because buying and managing 200 PDAs is maybe over the top for most museums.

The “least important” requirement is scalability. The reason for this is that scalability is not necessary for an initial set-up of the system to work. One could say that scalability has a big influence at the system from the start because the “effectivity” of the infrastructure plays a big role—that is how much more space is covered or how many new users can be supported by adding one piece of infrastructure. Although this is true this is covered by other requirements here, such as how easy the system is to install and whether the hardware costs are low (which both mean more scalable infrastructure). However, scalability is important if the system is to be expanded at a later time, and it often also say something about how well the particular system would suit other buildings with different environments.

5.3 Summary

In this chapter, we have looked at a selected location based service, a *mobile electronic tour guide*, for use in indoor exhibitions. First, we gave a list of important characteristics with indoor exhibitions. Then, we described electronic tour guides in detail. This formed the basis for a requirements specification for our tour guide.

In addition, we gave a detailed description of a selected exhibition, a modern art museum. In the next chapter, we will analyse location systems from chapter 4 against the requirements specification and museum description, to see if any of these systems can be used to provide location information to our tour guide in a sufficient way.

Chapter 6

Analysis

In the previous chapter, a requirements specification for the positioning system to be used in the Astrup Fearnley museum was developed. In this chapter, a thorough analysis of whether any of the already existing positioning solutions described in chapter 4 or 5 will fulfil the museum's needs, is performed. Each solution is reviewed in a structured manner in section 6.1. Then follows a discussion of findings in section 6.2 on page 91. Finally, in section 6.3 on page 99, we will try to make some important lessons learned in this thesis more general and easily available for use by others. However, as will be shown, this is very challenging. Thus, we will also propose a new architecture for future LBCSs, which can reduce the risk of choosing a solution that does not work as intended.

6.1 Structured Analysis

The positioning system requirements PR1 to PR11 were sorted in prioritised order in figure 5.8 on page 74. These requirements will be reviewed for most of the systems from chapter 4 and chapter 5, and the results will be summarised in a table like the one in figure 6.1 on the following page. The requirement with highest priority is on the leftmost side, and the least important one is at the rightmost side. If a requirement is marked with an "X", it means that it is not fulfilled. If it is marked with a "/", it means that the requirement is only partly fulfilled. No mark means that the requirement is fulfilled. The reason for doing it this way instead of the opposite, with marks for requirements that are fulfilled, is that it makes the table easier to read. What we are interested in are the requirements that are not fulfilled, and this is made more explicit by marking only these and leave the others empty. There are more requirements that are fulfilled than are not fulfilled. Systems that are not analysed and the reasons for this are given in section 6.1.4 on page 90.

	Room scale accuracy	Proximity 2 m	Passive user	Cost	Power IF	IF reconfigurable	Easy install/config.	Power device	IF not disturbing	Many users	Scalabilit
	PR2	PR3	PR1	PR11	PR10	PR8	PR6	PR9	PR7	PR4	PR5
System 1											
System 2											
Etc...											

Figure 6.1: Summary table for structured analysis

The analysis will start by reviewing existing location based tour guide systems described in section 5.1.2 on page 62. This group of systems will be called **Category 1 systems**. It is natural to start with these systems, because they have been implemented in the same domain as we are interested in. Then follow the **Category 2 systems**. These are similar to those in the first group, but used for other LBSs and in other domains. The third group, the **Category 3 systems**, consists of the rest of the systems described in chapter 4.

The analysis of a system will be based on a scenario where the system is to be installed in the Astrup Fearnley museum, which was described in section 5.2.1 on page 66. Assumptions are made when necessary, for example because information on some aspects of a solution is not available. All requirements are reviewed, but only those requiring explicit explanations are discussed in the text. A brief conclusion of each system's suitability for use is given, and a summary of the whole analysis is shown in figure 6.4 on page 91.

6.1.1 Category 1 Systems

The Category 1 systems are the location systems used by the different tour guides described in chapter 5. These are Cyberguide, Torre Aquila, TaggedX, Cordis RadioEye (used in the Nidaros project) and Bristol (used in the Shared Mixed Reality project).

Cyberguide

Cyberguide, described in section 5.1.2 on page 62, uses TV remote control units hanging from the ceiling as infrastructure transmitters (*beacons*). The IR range of such units vary, and can be as good as 5 metres. By using a unit with several LEDs, a coverage area of 2 metres radius at waist height is possible.

In the original set-up, the Cyberguide system required special IR receivers connected to the PDA. Today, there exist a lot of plug-in programs which can turn the IrDA port on a mobile device into a receiver that can receive signals from remote controls.

Room scale accuracy using Cyberguide technology is possible by placing beacons just inside the entrance of all rooms. Because most rooms in the Astrup Fearnley museum have more than one possible entrance, the number of such beacons would be about 18 for the ground floor. To support 2 metre proximity sensing to artefacts, beacons would also have to be placed above each artefact, or group of artefacts if these are placed very close to each other relative to the coverage area of the beacon. For the exhibition on display during our site survey in the museum, this would mean adding 27 more beacons for the ground floor, making the total amount of beacons 45.

It should be noted that in some cases it might be necessary to have several beacons per artefact. For example, if an artefact is very large and wide and placed in the middle of a room, it might be necessary to have beacons on several sides of the artefact. If only one beacon is used and it is placed right above the artefact, the range of it might not reach outside the artefact itself. If the beacon is placed on the outer edge of the artefact it won't cover visitors coming from all directions.

The prices of remote controls range from $10 to several hundred dollars, depending on their functionality and IR hardware. A $40 remote with IR capabilities that would cover our needs was found, but as all remotes it has a lot of functionality and a housing with buttons that we don't need for it to function as a Cyberguide beacon. It would not be difficult to make simpler beacons at lower costs. However, if $40 remotes are used, the total beacon costs would be $1800, which is not a very high cost for a complete sensor infrastructure. With more research, it is also likely that a cheaper remote that does the job could be found.

The Cyberguide beacons have to be ceiling mounted. Although no wires are needed, it would be a time-consuming task to mount 45 beacons for one floor (and the other floor is twice as large). In the two areas of the museum where the ceiling–floor distance is above 7 and 10 metres, the beacons would have to be hanging from the ceiling down to normal ceiling height due to limited range. One of the biggest disadvantages with the Cyberguide system is that the cumbersome installation process would have to be repeated with each new exhibition. Because the new artefacts may be arranged in a completely different way, many or all of the beacons have to be moved accordingly. One could think that it would be better to mount as many beacons as is needed to cover the whole floor during the first installation, and just map new artefacts to the appropriate beacons. Then it would not be necessary to move any beacons. However, this would require a tremendous installation effort, a huge amount of beacons and a more difficult beacon/artefact mapping process. The challenging indoor environment is also likely to cause problems with non-intended beacon signals reaching receivers which normally are outside their reach.

The biggest problem with using Cyberguide in the Astrup Fearnley museum would be to change beacon batteries. For this to not be a problem, the batteries would have to last for at least four months, because then they could be replaced while remounting the beacons between two exhibitions. As the beacons continuously emit their IDs at short time intervals, and because they have several LEDs and provide relatively long range, batteries would need to be replaced too often.

Conclusion *The disadvantages with the Cyberguide solution is that it would be time-consuming and cumbersome to install, to reconfigure, and to maintain beacon batteries.*

Torre Aquila

The Torre Aquila system, described in section 5.1.2 on page 62, operates with only 1 metre IR range. This means that our requirement of 2 metres proximity sensing can not be fulfilled. It also means that the user would have to take an active part for room scale positioning to occur, for example by pointing his device at a special “Entering new room” transmitter by the room entrance. The reason for this is that some of the openings between rooms are wider than 2 metres, so even if transmitters were placed all around the entrance, their signals may not reach the receiver at the PDA.

If we were to use the Torre Aquila system although it does not support 2 metres accuracy, a new problem may arise. Because of the limited range, the visitors would have to get very close to an artefact for positioning to occur. The result could be queues at the most popular artefacts. The Torre Aquila system would also be cumbersome to install, as the transmitters are wired, and one transmitter is needed for every artefact.

Conclusion *The biggest problem with the Torre Aquila solution is that the range is too limited. 2 metres proximity sensing can not be achieved, and room scale accuracy would require an active user. This makes Torre Aquila a bad candidate for use in the Astrup Fearnley museum.*

TaggedX and Passive RFID in General

The TaggedX system, described in section 5.1.2 on page 63, could not be used in the Astrup Fearnley museum because the tag/reader range is only a few centimetres. As in the Torre Aquila case, limited range violates the requirements for 2 metres proximity sensing and a passive user. Room scale accuracy is difficult, and queueing problems are likely to occur. The user would have to be very active—walking really close to the artefacts, and then hold his PDA next to the artefact's tag. This solution could be replaced by a much simpler and cheaper solution, where the user enters given numbers for the artefacts he is interested in.

As just described, the TaggedX solution violates our three most important requirements due to its limited range. However, it does fulfil all the other requirements. Thus, it is interesting to look closer at passive RFID in general, to see how it can solve all these other requirements. RFID technology was described in section 3.3.3 on page 35.

When a new exhibition is about to be set up, a lot of new artefacts arrive at the museum. Before each artefact is placed in its proper location in the exhibition areas, a member of the staff could attach a passive RFID tag to it. The tag's ID is read with a hand-held reader and stored in a database, together with an artefact-ID and a room-ID. This work does not add much time or effort to the regular working process. The advantages with using passive RFID tags are that they are cheap, and they do not need their own power source. No battery maintaining or wiring is necessary.

The museum visitors are equipped with PDAs with RFID-readers. When a reader comes within range of an artefact-tag as the visitor walks about in the museum, it reads the artefact-ID and transmits it to a central server through WLAN. The central server looks up the tag-ID in the database, and finds out which artefact the user is close to and sends the correct content to the PDA through WLAN. It also checks on the room-ID, and if this is different from the last reading it sends an updated map to the PDA. Depending on how much storage capacity the PDA has, some of this work may happen on the PDA without needing data from the central server. For example, information about the most popular artefacts could be pre-stored on the PDA, together with these artefacts' IDs. When the RFID reader detects these IDs, it can show the right content without contacting the central server.

In some exhibitions the distribution of artefacts might be scarce. In this case, we propose to introduce tags which we will call *tracking tags*. These are similar to the artefact tags, except they are not associated with an artefact-ID, only a room-ID. These tags can be placed where appropriate, for example just inside room entrances where artefacts are placed far into the room. During set up, after all artefacts of an exhibition is placed around the areas, a staff member could take a walk through the museum and look for places where tracking-tags are needed. In this way the visitor will always have an updated map.

We will now look at the possibility for having a passive RFID solution with better range, preferably about 2 metres. The problem is that current RFID-readers that are small enough to be used in combination with a PDA, for example readers with a Compact Flash (CF) or Secure Digital (SD) interface, have very low range, max-

	Tradewind	Wireless Dynamics	Syscan	Pro Active
Interface	SD	SD	CF	CF
Read/write	Yes	Yes	Yes	Yes
Frequency	13.56 MHz	13.56 MHz	13.56 MHz/125 kHz	13.56 MHz
Range	7 cm	Few cm	Max 10 cm	0-4 cm
Price	$200		$150 (in 2003)	

Figure 6.2: Examples of RFID SD/CF readers

	Reader1	Reader2	Reader3	Reader4	Reader5
Frequency	13.56 MHz	125 kHz	13.56 MHz	869.4 – 928 MHz	865 – 928 MHz
Range	15 cm	60 cm	1.2 m	3 m	5 m
Price	$154	$380	$2648	$3746	$4762

Figure 6.3: Examples of RFID reader costs

imum 10 cm (see figure 6.2). This means that the users will have to be very active and move close to the tags for reading to occur. This will be very disturbing for the user, and it may also cause congestions at popular artefacts because all the users have to walk very close up to it for reading to occur, before they can get information about it. Furthermore, figure 6.3 shows that RFID readers get very expensive with increasing range. For use in a proximity solution as we have described, we would need a range of about 2 metres. This will give a reader cost of $3000, which is very expensive (prices from spring 2006).

Conclusion *TaggedX or other passive RFID solutions would be easier to install than the Torre Aquila solution, as the infrastructure RFID tags are wireless. Except for this, it faces the same problems as the Torre Aquila solution, as the tag/reader range is very limited. The cost of readers that could give longer range is very high. However, technology is always improving and prices are likely to drop, so passive RFID may be a very promising solution in the future.*

The Cordis RadioEye

The Cordis RadioEye (CRE) system used in the Nidaros project requires line of sight for accurate positioning (see section 5.1.2 on page 65). This means that we would need one RadioEye in every room in the Astrup Fearnley museum, eight on the ground floor and nine at the lower ground floor. Since the PDAs used by visitors, management and staff can have built-in WLAN support, no additional hardware is needed at the client side.

With CRE, there are no extra hardware that draws battery power from the PDA.

However, the WLAN connection is always on, and this draws much power. With todays technology, the PDA battery would not last for the required six hours.

The accuracy of the CRE system is typically 1–2 metres or better. This suits our proximity requirement of 2 metres very well. It was reported in the Nidaros project that such accuracy was not achieved, but the reason for this is probably that the RadioEye was placed 15 metres above the floor at one side of a room. In the Astrup Fearnley museum, the RadioEye would be placed in the middle of the room at heights of about 3, 4, 7 and 10 metres, and the rooms are smaller than the cathedral gallery. This should provide much better coverage and accuracy.

The RadioEyes have to be mounted in the ceiling and connected to a power outlet, and then they have to be configured. After this initial installation, the system does not have to be reconfigured, unless a new room is set up. In this case a new RadioEye would have to be installed.

The CRE system is a commercial product, and the cost of each RadioEye is almost $8000. The Astrup Fearnley museum would need 17 RadioEyes to cover all rooms, making the total sensor infrastructure costs $136000. The CRE system will thus be a much more cost-effective solution in buildings with larger and fewer rooms than in our case.

Conclusion *Because one RadioEye is needed in every room, and the Astrup Fearnley museum consists of many rooms, the CRE solution will be expensive. Otherwise, it fulfils most of our requirements.*

The Bristol US Positioning System

The Bristol positioning system was used in the Shared Mixed Reality project described in section 5.1.2 on page 65. To implement this system in the Astrup Fearnley museum, four networked ultrasonic transmitters would have to be mounted in the ceiling in every room. An RF transmitter in each room is also required. A special receiver would have to be connected to each PDA. Preferably, it should be placed on the users' head or shoulder, since line of sight is required.

At the ground floor, there are five rooms that could be covered with a four US transmitters configuration. The largest room would probably need at least ten transmitters to be covered. In the two smallest rooms there might be only one transmitter to detect the presence of a person in the room. The total amount of US transmitters needed is thus 32, on the ground floor only. In addition, there are the radio transmitters, and they all have to be connected with wires.

Bristol positioning hardware could be made for about $150 per room. In our case the total hardware costs for the ground floor would be about $1050, which is affordable. Costs of wiring and receiver costs must be added.

The Bristol positioning system requires line of sight for accurate measurements to occur. Thus, the receiver should be placed on the visitors' head or shoulder.

Conclusion *The main disadvantage with the Bristol positioning system is that it is very cumbersome to install.*

6.1.2 Category 2 Systems

The category 1 systems that have been analysed this far are all used for positioning in electronic tour guides. Now, we will analyse positioning systems that are similar to these, but implemented in other domains.

Locust Swarm

The Locust Swarm system, described in section 4.2.2 on page 48, is very similar to the Cyberguide system. Wireless IR transmitters called *Locusts* broadcast their IDs, for receivers at the user devices to listen to. A Locust can cover an area of 6 metres in diameter, depending on the distance above the floor. By reducing the signal strength, the coverage area can be reduced. The system description and analysis are almost identical to that of the Cyberguide system, and will not be repeated.

The difference between the Cyberguide and the Locust Swarm systems is that the latter tries to solve the problem of changing batteries in the infrastructure nodes by equipping them with solar cells and place them in fluorescent lamps. In the Astrup Fearnley museum, there are three problems with this solution. The first is that this place restrictions on where Locusts can be placed, because there has to be a lamp there. The second is that it is not unusual that some of the exhibition rooms are kept dark, for example when showing light installations or video presentations. The last problem is the places where the ceiling–floor distance is very high. The Locusts' range would then be too short to reach down to the mobile devices.

Conclusion *The Locust Swarm system is very similar to the Cyberguide system and has the same disadvantages. It suggests to use solar cells instead of batteries at the infrastructure nodes, but in the Astrup Fearnley museum, most nodes will still require batteries.*

IRIS-LPS

For using the IRIS system, described in section 4.2.3 on page 48, a stereo camera would have to be mounted in each room. If the room is larger than 15 x 9 metres, an additional camera would be needed. In the Astrup Fearnley museum, this would result in 9 cameras at the ground floor.

The visitors will have to wear headsets, with a transmitting IR tag made of 4 LEDs and a battery mounted on top of it. A LED with a transmitting angle of 20 degrees had a range of more than 10 metres. By choosing LEDs with wider angles and shorter range, we can get the range and coverage area we need. A tag battery supporting 4 LEDs can last for a minimum of six hours.

The first problem with IRIS is that it is cumbersome to install. Cameras have to be mounted in every room, and they have to be connected with a central computer. The second problem is that the headsets will be somewhat bulky, so a proper design is important.

Conclusion *The IRIS system may be a little cumbersome to install, and it requires a bulky headset.*

Active RFID

Passive RFID was discussed in 6.1.1 on page 80. Its biggest advantages are that the tags do not need their own power source, and their low cost. In the case of active RFID (described in section 3.3.3 on page 35), the tags are much more expensive, they will need their own power source and the readers are at least as expensive as those in figure 6.3 on page 82. Thus, we will not analyse this approach any further.

Conclusion *By using active RFID we will solve the passive RFID range problem, but at the cost of much more expensive tags that need their own power source, and still very high reader costs. Active RFID is thus not a good solution at this time.*

BILS

BILS, described in section 4.3.2 on page 52, is similar to the Bristol system. The main difference is that it uses Bluetooth instead of ultrasound and radio waves. Four Bluetooth base stations with additional special hardware are required in every room. The Bluetooth range is 10 metres, so the biggest room at ground level in the Astrup Fearnley museum would require more than four base stations. The total amount of base stations would be about 36, only at the ground level.

Each base station has to be placed in a fixed known location, because its coordinates are used in the position calculation. They must also be connected to a host computer, which performs the position calculations. As BILS requires line of sight, the base stations should be placed in the upper corners of a room.

The Bluetooth module on the mobile device will draw much power from the PDA.

Conclusion *BILS would be cumbersome to install in the Astrup Fearnley museum. It also has a strict line of sight requirement, and the use of Bluetooth will draw much power from the mobile device.*

PAL650 (UWB)

The PAL650 system (see section 4.3.3 on page 52) is similar to Bristol and BILS, as it needs four receivers, or actually three receivers and a reference tag, in fixed known positions. But the range is six times longer than with BILS, so it is better at covering large rooms. This means that less infrastructure is needed. One advantage of PAL650 over BILS, is that the museum visitors wear tags that are only logically connected to the PDA. Thus, it does not draw power from the PDA. The lifetime of a tag battery is as long as four years. The other advantage with PAL650 is that it does not require line of sight.

Conclusion *The disadvantage of the PAL650 system is that it is cumbersome to install, like Bristol and BILS.*

Active Bat

The Active Bat system from section 4.1.2 on page 43, is tested with 750 receivers covering an area of 1000 m^2. In the Astrup Fearnley museum, this would mean that about 1350 receivers would be needed to cover the exhibition areas on the two floors. All the 1350 receivers have to be mounted in the ceiling in known fixed locations. This would be a tremendous work, and makes the Active Bat system a bad candidate for the Astrup Fearnley museum—and any other indoor location based computing system covering several large rooms. The only case where this huge installation effort could be defended, is when centimetre accuracy is required in a limited area.

Conclusion *The tremendous effort of installing the infrastructure makes Active Bat a bad candidate for all location based computing systems spanning large areas or several rooms.*

Cricket

Cricket was described in section 4.1.3 on page 44. The ultrasonic range of the Cricket beacons decide how many such beacons are required in an area. The range is 10.5 metres when there is line of sight, but this is not always the case. Thus, an assumption is made that the range is minimum 5 metres in the worst case scenario. By having nine beacons in each of the similar sized rooms at the ground floor in the museum, and some more and some less in the much bigger and smaller rooms, the total amount of beacons at this floor will be about 84. The amount of beacons that make up the Cricket infrastructure is high, but they are completely wireless, and thus much easier to install than wired sensors. However, they are dependent on their own power source, so battery maintaining might be a burden. Another major problem is that the beacons need to be configured with their exact position. This may be solved by auto beacon configuration algorithms in the near future, but the power problem will still exist. The Cricket listeners are attached to the PDAs through the CF slot, and draw power from the PDA.

Conclusion *The Cricket solution is not suitable for the Astrup Fearnley museum. The large amount of beacons require a very good auto configuration algorithm and a better battery solution first.*

6.1.3 Category 3 Systems

In this category, we find the rest of the systems described in this thesis that are not belonging to category 1 or category 2.

Active Badge

The Active Badge system (see section 4.1.1 on page 42) could be used for room scale accuracy only, or it could also be used for small scale proximity sensing by using a hybrid IR/radio scheme. For the room scale only solution, one networked IR sensor would be mounted in each room. 8 sensors would thus be required at the ground floor. The visitors wear badges which transmit IDs that are associated with their PDAs. The central server gets information about where everybody is, and can send the proper information to the different PDAs. In the hybrid scheme, there are radios placed at each artefact in addition to the infrared sensor network. The radio transmitters could be wired for power, or they could use batteries. Their range can be adjusted with power.

If our goal is room scale accuracy only, the Active Badge system is a good candidate. Its only disadvantage is that the sensors have to be wired, so that some work has to be done during installation. But, in our case only one sensor would be required in each room, so this should not be too difficult.

In the hybrid scheme the two different cases have different problems. If the radios are power-adjusted to about 2 metres range, their batteries would have to be replaced pretty often. If the radios are wired, installation and reconfiguration would be cumbersome, and the wires may be disturbing. For example, in cases where the artefact is placed in the middle of a room, the wire would have to cross the floor or be hanging from the ceiling.

Conclusion *The original Active Badge system is a good solution for providing room scale accuracy, but it does not support 2 metres proximity. A hybrid scheme with radios can be used to solve this problem, but then other problems arise. Wired radios cause a lot of problems, and are thus not interesting. Wireless radios impose a problem of changing their batteries.*

BIPS

BIPS (see section 4.3.2 on page 51) is very similar to the original Active Badge system, and could be used in the same way. The only difference is that instead of using diffuse infrared, the sensors use Bluetooth. This means that the sensors' range is 10 metres, and that there are some problems with handling many users because of the slow device discovery process. Thus, the Active Badge would be a better choice if room scale accuracy is the only goal. In our case, however, we would have to place wireless sensors at all artefacts for reaching 2 metres proximity. Because of their range, power consumption and device discovery problems, using Bluetooth in this way would not be a good choice.

Conclusion *BIPS is similar to the original room-scale Active badge system. It is not suitable for 2 metres proximity sensing, due to the Bluetooth characteristics such as power consumption and slow device discovery.*

RADAR

RADAR (see section 4.1.4 on page 46) has been deployed in an area of 980 square metres with over 50 rooms, covered by three base stations. This means that three base stations are enough to cover the ground floor (600 m^2) of the Astrup Fearnley museum, and that three or four base stations are enough to cover the lower ground floor (1200 m^2). The PDAs are equipped with WLAN, so no other hardware is needed.

A radio map must be built to map measured signal strengths to position coordinates. Using the radio propagation model, only 4.3 metres accuracy was achieved. Thus, we would have to use the empirical approach, which provides accuracy of 2-3 metres 50% of the time. Constructing the radio map takes time, and the museum would need help from experts to do it. For better accuracy, maps for different situations should be made, and all these maps would have to be made again with each new exhibition introducing larger changes. Thus, although the hardware costs are very low, the configuration process will cost both time and money.

More and more buildings are equipped with WLAN today. If this is already in place, no additional hardware would be necessary, or the only thing required is to add a base station or two, or to place the base stations in other locations. However, existing WLANs may be more usual in office buildings, learning institutions and cafes than in museums. Still, installing three WLAN base stations is not very difficult or time-consuming, and the prices are very low.

Conclusion *The accuracy/precision combination of RADAR is not sufficient for our tour guide, and the radio map construction process(es) would have been both time-consuming and expensive.*

Ekahau

Ekahau (see section 4.3.1 on page 49) is very similar to RADAR, in that it uses (existing) WLAN infrastructure for positioning. Accuracy of 1 metre is possible by using 5–7 access points, and the probabilistic approach reduces the time needed for site calibration to about 1 hour per 1200 m^2. The site calibration of the Astrup Fearnley museum would then take about 90 minutes only. The second big advantage with Ekahau compared to RADAR, is that minor environment changes do not require re-calibration of the positioning model. Partial re-calibration is only required when base stations are moved, or heavy structures are modified.

Conclusion *As with RADAR, constructing the positioning model in Ekahau takes time, but much less time. A few more base stations are required, but these are low cost and easy to install and provide better accuracy. Reconfiguration is also easier. Ekahau is a commercially available software product, but experts are required to do the walk through. The software and service costs may be high.*

Hanover

The Hanover system is also similar to RADAR, but instead of using existing WLAN infrastructure, it relies on an existing Bluetooth infrastructure. Because the Bluetooth range is much lower than the WLAN range, a minimum of three base stations are necessary in every room. Another disadvantage with the Hanover over RADAR is that using Bluetooth draws more power from the PDA.

Conclusion *The Hanover system is most interesting in cases where a Bluetooth network is already in place, or where there is no WLAN network.*

6.1.4 Technologies or Systems Not Analysed

Some of the systems included in chapter 4 and 5 are not analysed further. The reasons for this are given below.

The MUSE project (see section 5.1.2 on page 64) provides little detailed information on the positioning solution used, except that it uses WLAN. This is alreday covered by other systems.

The only difference between the analysed Active Badge system and the PARCTAB system (see section 4.2.1 on page 47), is the use of a badge versus a special PDA. Since this is the only major difference and we would like to use existing commercially available PDAs, only the Active Badge system was analysed.

DOLPHIN (see section 4.4.1 on page 53) is currently only handling positioning of static devices, and is thus not interesting to us. However, it should be noted that its auto configuration algorithms may be used by Cricket and Active Bat systems in the future.

The ultrasound system which requires only one base station (see section 4.4.3 on page 54) is very interesting research, as it would be similar to the IRIS-LPS and the Cordis RadioEye systems in that only one unit of positioning hardware is required in each room. However, even though experiments show an accuracy of 2–3 metres, this is in ideal situations in a lab, and not in a changing and dynamic environment like a museum.

ZigBee technology was described in section 3.3.2 on page 33. In section 6.1.1 on page 80, we analysed solutions based on passive RFID, and found that a proximity solution with tagged artefacts is a very promising solution. However, limited range makes it difficult to realise. It would be interesting to see if ZigBee technology could be used instead of passive RFID in such a solution. However, this will need a lot of testing, and is suggested as future work.

	Room scale accuracy	Proximity 2 m	Passive user	Cost	Power IF	IF reconfigurable	Easy install/config.	Power device	IF not disturbing	Many users	Scalability
	PR2	**PR3**	**PR1**	**PR11**	**PR10**	**PR8**	**PR6**	**PR9**	**PR7**	**PR4**	**PR5**
Category 1 Systems											
Cyberguide					X	X	X		/		X
Torre Aquila passive	X	X			/						X
Torre Aquila active		X	X		/					/	X
TaggedX	X	X	X							/	X
Cordis Radio Eye/Nidaros				X			/	/		/	
Bristol/Shared Mixed Reality							X		/	/	
Category 2 Systems											
Locust Swarm					/	X	X		/		X
IRIS-LPS							/		/		
Passive RFID 2m prox.				X				X			X
Active RFID				X	X			X			X
ZigBee (passive RFID)					X			X		X	X
BILS							X	/		/	
PAL650 (UWB)				?			X				
Active Bat				?			X		/		
Cricket				?	X		X				
Category 3 Systems											
Active badge/PARCTAB		X					/				
-with wireless radios					X		/				X
-with wired radios						X	X		X		X
BIPS		X					/	/		X	X
RADAR		/				X	X	/			
Ekahau				?		/	X	/			
Hanover						X	X	X			

Figure 6.4: Summary of analysis

6.2 Discussion

The results of the analysis in the previous section are summarised in figure 6.4. At a first glance, it is difficult to see if some systems prevail the others. In the following subsections, we will thus try three different approaches which may help clarifying the analysis results. In the first, we will try to simplify the table in figure 6.4 by removing solutions that for some reason are clearly not candidates for use in the Astrup Fearnley museum. We will then introduce a scheme for giving scores to the different solutions. Based on these scores, the solutions can be rated.

In the second approach, we will alter the summary table by grouping the solutions according to the positioning technique they are using. In the third approach, we will also take into consideration the wireless technology that is used. The hope is that this may reveal some general information that can help choosing a positioning system, or give clues to future positioning system developers.

6.2.1 Simplifying and Rating the Analysis Results

Our first approach in trying to make it easier to extract useful information from the analysis results, is to remove systems that are clearly not candidates for use in the Astrup Fearnley museum. First, we remove the solutions which has an “X” for one or more of the three leftmost columns (PR2, PR3, or PR1). As stated in section 5.2.2 on page 74, these requirements ensure that the solution is able to do what we want. Systems with an “X” here fail to do so. Thus, they are not interesting to discuss any further, and can be left out so that the table gets easier to read. When these systems are removed, the three columns can be removed altogether, as they are now empty.

The fourth requirement from the left before we remove any columns is PR11—*Cost*. Because this is a requirement with a lot of uncertainty, we will remove this one also, but take it into consideration again in later discussions.

We then remove the rows with grey backgrounds. As we saw in the conclusion of each of these systems during the analysis, their unfulfillment of at least one of the requirements but the four leftmost is so severe that it eliminates the solution for use in the Astrup Fearnley museum altogether.

To make it easier to sort the systems from “most suitable” to “least suitable”, we will use a simple weighting scheme. There are seven requirements left, with the most important one still on the leftmost side and the least important on the rightmost side. We start on the leftmost side and give this requirement weight seven, the next requirement six and so on. Thus, if a requirement has an “/”, it is given a score of it’s weight. If it has an “X”, it is given a score of it’s weight times 2, as this is a more severe case. Finally, all the scores a system gets are summarised in a total score. Low score means better suitability. The result of this process is given in figure 6.5 on the next page, with the most suitable systems at the top and the least suitable at the bottom.

Findings from Simplifying and Rating the Analysis Results

As we can see in figure 6.5 on the facing page, IRIS-LPS seems to be the best choice for use in the Astrup Fearnley museum. It actually fulfills all our requirements to some extent. One or two cameras has to be mounted in each room, depending on room size, but this work should not be too much to overcome. Users of the museum guide will have to wear the transmitter tag in the form of a headset, but this should not be a major problem as the same headset should be used for sound and most users are used to this.

The Cordis RadioEye system is also a very good candidate, but it might be expensive. This solution is very good for museums or other indoor environments with

	Power IF PR10	IF reconfigurable PR8	Easy install/config. PR6	Power device PR9	IF not disturbing PR7	Many users PR4	Scalability PR5	Score
IRIS-LPS			/		/			8
PAL650 (UWB)			X					10
Cordis Radio Eye/Nidaros			/	/		/		11
Bristol/Shared Mixed Reality			X		/	/		15
BILS			X	/		/		16
Abad with wireless radios	X		/				X	20
Ekahau		/	X	/				20
Cricket	X		X					24
RADAR		X	X	/				26
ZigBee (passive RFID)	X			X		X	X	28
Hanover		X	X	X				30
Locust Swarm	/	X	X		/		X	34
Cyberguide	X	X	X		/		X	41
Weight for X	14	12	10	8	6	4	2	
Weight for /	7	6	5	4	3	2	1	

Figure 6.5: Revised and sorted summary table from the analysis

few and/or large rooms, because then only a small number of the relatively expensive RadioEyes are needed. One solution for the Astrup Fearnley museum to keep the costs down could be to install RadioEye's in most rooms except the smallest. Because very small rooms are likely to have fewer artefacts, it would be sufficient to know that the user has entered a specific room. This could be inferred from knowledge about the different RadioEyes' placements and which RadioEye saw the user last before he disappeared out of view.

6.2.2 Analysis Results vs Positioning Techniques

In chapter 2, the different positioning techniques triangulation, proximity sensing, and scene analysis were described. The second approach to interpret the analysis result in figure 6.5, is to group the systems according to the positioning technique they are based upon. The hypothesis is that we will see some general differences.

Findings from Analysis Results vs Positioning Techniques

The first part of figure 6.6 on the following page shows the systems that are based on the triangulation method. As we can clearly see, they are all able to do what we want. Their main problem is that they are cumbersome to install and/or configure.

	Room scale accuracy	Proximity 2 m	Passive user	Cost	Power IF	IF reconfigurable	Easy install/config.	Power device	IF not disturbing	Many users	Scalability
	PR2	**PR3**	**PR1**	**PR11**	**PR10**	**PR8**	**PR6**	**PR9**	**PR7**	**PR4**	**PR5**
Triangulation systems											
Cordis Radio Eye/Nidaros				X			/	/		/	
Bristol/Shared Mixed Reality							X		/	/	
IRIS-LPS							/		/		
BILS							X	/		/	
PAL650 (UWB)				?			X				
Active Bat				?			X		/		
Cricket				?	X		X				
Scene analysis systems											
RADAR		/				X	X	/			
Ekahau				?		/	X	/			
Hanover						X	X	X			

Figure 6.6: Summary table of triangulation and scene analysis systems

	Room scale accuracy	Proximity 2 m	Passive user	Cost	Power IF	IF reconfigurable	Easy install/config.	Power device	IF not disturbing	Many users	Scalabilit
	PR2	**PR3**	**PR1**	**PR11**	**PR10**	**PR8**	**PR6**	**PR9**	**PR7**	**PR4**	**PR5**
Cyberguide					X	X	X		/		X
Torre Aquila passive	X	X			/	X	X		/		X
Torre Aquila active		X	X		/					/	X
TaggedX	X	X	X							/	X
Passive RFID 2m prox.				X				X			X
Active RFID				X	X			X			X
Locust Swarm					/	X	X		/		X
ZigBee (passive RFID)					X			X		X	X
Active badge/PARCTAB		X					/				
-with wireless radios					X		/				X
-with wired radios						X	X		X		X
BIPS		X					/	/		X	X

Figure 6.7: Summary table of proximity systems

This is because their infrastructure is wired, and all except Cordis and IRIS need a lot of infratructure installed in each room. But, once in place, they are doing a very good job.

The scene analysis systems are given in figure 6.6 on the preceding page below the triangulation systems. These systems take time to configure, and thus violate the requirements for initial set-up, as do the triangulation systems. In addition, these systems also take time to reconfigure if changes in room or artefact layout in a new exhibition are substantial.

By comparing figure 6.6 on the facing page with the summary table for the proximity systems in figure 6.7 on the preceding page, it is easy to notice that there are much more diversity between the proximity systems. While using a proximity solution can solve the installation/configuration hurdle faced by most triangulation systems, it introduces other problems. For example, we can see that many proximity systems fail to fulfill requirement PR10, which is typically not a problem with triangulation systems. The main problem with proximity systems is that they put very demanding requirements on the infrastructure nodes. To be able to fulfill all our requirements such nodes have to be small, lightweight, and low cost. Their range should be 2 metres, they should use very little power, and handle many simultaneous users. None of the solutions we have analysed have nodes with a hardware/software combination to do all this. There are two main problems that have to be overcome, cost and battery life, both on transmitter and receiver device.

We have now seen that triangulation systems seem to be better than proximity systems and scene analysis systems. Their main problem is that installation and configuration is cumbersome. The Astrup Fearnley museum consists of 18 rooms, and equipping all of these with minimum four wired base stations in precise known positions is a big task. But if the number of rooms had been smaller, this work might be worthwile.

Having stated this, it would be interesting to look closer at the case with a proximity solution when the number of rooms is high, like in the Astrup Fearnley museum. We did already say that this could solve the initial set-up problems. What is the main reason that current solutions will not work in Astrup Fearnley? The answer is the high number of artefacts on display in the museum. If the number of artefacts were smaller, more of our requirements would be fulfilled. For example, the job with replacing batteries on infrastructure nodes (PR10) would be a smaller one.

The discussion above is summarised in figure 6.8 on page 97. The X-axis is the number of rooms in the museum, and the Y-axis is the number of artefacts. We have seen that the triangulation systems fulfill many of our requirements except that they are difficult to install. This means that if the number of rooms is small it could be worth doing the job. However, at some point (r) we reach a number of rooms where it is no longer cost effective to use a triangulation method. Instead, we could use a proximity solution with wireless infrastructure nodes, because there is no wiring or other time-consuming installing involved. However, such a solution typically performs worse with increasing number of artefacts, because they need battery replacements.

"Many" rooms or artefacts is not a very accurate measurement. The values for r and a depend on many different factors, such as the the special premises, time, money available in the analysed case. A rule of thumb may be that r is somewhere between 5–10, and a about 20, depending on battery life time of the infrastructure nodes and number of staff to change the batteries.

The different solutions we have analysed are plotted in the figure. It shows that several systems could be used if the museum had fewer rooms and fewer artefacts. We can also see that several systems can handle many artefacts *or* many rooms. The Astrup Fearnley museum has both many rooms and a high number of artefacts. This places it in the upper right quadrant. As we have seen earlier, the IRIS-LPS system and the Cordis RadioEye system are the only systems that could be used. However, if prices drop and battery technology improves, proximity solutions based on passive or active RFID technology could also be used.

6.2.3 Analysis Results vs Positioning Techniques and Technology

We have now found the existing solutions that would be most suitable to use for positioning in the Astrup Fearnley museum. We have also seen that the number of rooms and the number of artefacts in a museum are important properties that influence the type of positioning system that should be chosen. We will now include the technology used by the positioning system in the discussion, to see if this could reveal some complementary information. Figure 6.9 on page 98 shows the new extended table.

Findings from Analysis Results vs Positioning Techniques and Technology

There are mainly three findings from figure 6.9 on page 98.

1. Few systems use the scene analysis positioning technique compared to triangulation and proximity sensing. The main reason is that for such a system to work well, a lot of work is required beforehand to build maps or databases. These also have to be continously updated.

2. IR-based systems are typically proximity systems. The reason is the limited range of IR-signals, and the fact that they are so easily blocked. Although diffuse IR helps increase range, the signals are altered every time they hit something on their way and it is difficult to interpret the signals correctly at

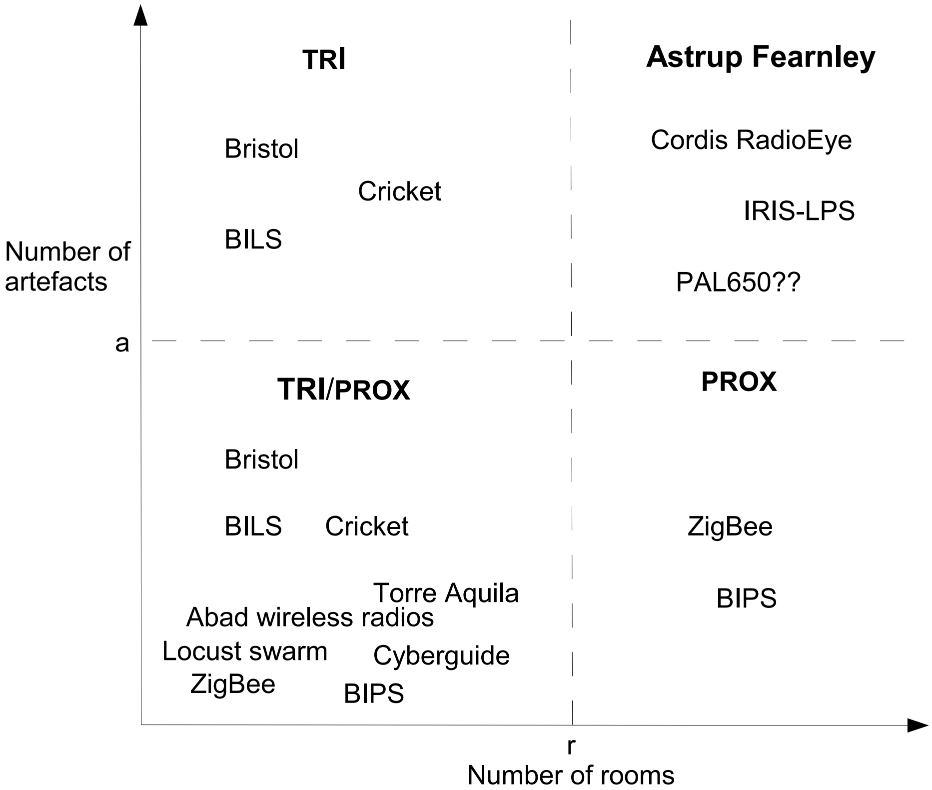

Figure 6.8: Number of rooms vs number of artefacts, and possible system choices.

	Triangulation	Proximity	Scene Analysis
IR-based			
Active Badge		X	
PARCTAB		X	
Locust Swarm		X	
IRIS-LPS	X		
Cyberguide		X	
Torre Aquila		X	
RF-based			
RADAR (WLAN)			X
Ekahau (WLAN)			X
Cordis Radio Eye (WLAN)	X		
Hanover (BT)	X		
BIPS (BT)		X	
BILS (BT)	X		
Mitsubishi (ZigBee)	X		
PAL650 (UWB)	X		
TaggedX (RFID)		X	
US-based			
Active Bat (+RF)	X		
Cricket (+RF)	X		
DOLPHIN (+RF)	X		
Bristol (+RF)	X		
One base station			X

Figure 6.9: Summary table of systems with regards to positioning technique and technology

the receiver. A proximity solution does only need to detect a signal, it is not using it for further computation of position.

3. Systems using triangulation for positioning are typically based on radio and/or ultrasound technology. As described above, IR-signals are too easily distorted and can not be used for the precision computing in triangulation. Thus, the more robust radio or ultrasound signals are used. As we have seen, many solutions use both to get even better accuracy.

6.2.4 Better Solutions with Sensor Fusion?

As we saw in section 2.3 on page 22, sensor fusion—using more than one sensor system—could help improve a technology solution. Could we use a combination of solutions we have analysed to get a solution that would fulfill all our requirements better than IRIS-LPS or Cordis RadioEye? Unfortunately, when it comes to the proximity systems none of them would be wise to combine, as the hardware and/or cost constraints are not overcome by having more of what causes the problem. The same is true for combining triangulation solutions. Combining a proximity solution with a triangulation system or a scene analysis system is no good either, as this will add the problem of installing/reconfiguring and by this removing this potential advantage with a proximity system. Thus, sensor fusion will not help in our case. The electronic museum guide application that our particular positioning system is going to support, have too many conflicting requirements.

6.3 Results and Suggestions

While none of the systems we have analysed fulfil all our requirements, there are two candidates that stick out. The best solution seems to be to use the IRIS-LPS system. The second best solution would be Cordis RadioEye with no RadioEyes in the smallest rooms. However, it is important to remember that while Cordis is a commercially available system, IRIS-LPS is a research project only. Thus, all hardware infrastructure and software have to made based on the prototypes from the project. This means that choosing Cordis is a much easier and safer solution, although more expensive.

We have seen that our electronic tour guide put many and conflicting requirements on the underlying positioning system. Although we reached a result for our specific LBS here, it would be valuable to extract important learning from the process and use this to provide a generic tool which can be used by others that are to choose a positioning system for supporting an indoor LBS. This will be the focus of the next section.

Because it is so hard to choose positioning system, the consequences of making a bad choice should be minimised, and it should be easy to switch to or add new positioning technologies as they become available. Thus, we will propose a flexible architecture for LBCSs based on the service oriented architecture (SOA) concept, which can help realise this. This will be the focus of section 6.3.2 on page 102.

6.3.1 Decision Flow Diagram for Choosing Positioning System

Our work has shown that a thorough investigation of the domain the positioning system is going to be a part of, is necessary. For example, we have seen that other properties than those in our requirements specification were crucial, especially the number of rooms and number of artefacts at the exhibition. The method we have used to find a positioning system is summarised below:

1. Perform a domain analysis and a specific analysis of client premises
2. Decide functional requirements
3. Decide non-functional requirements
4. Prioritise the non-functional requirements

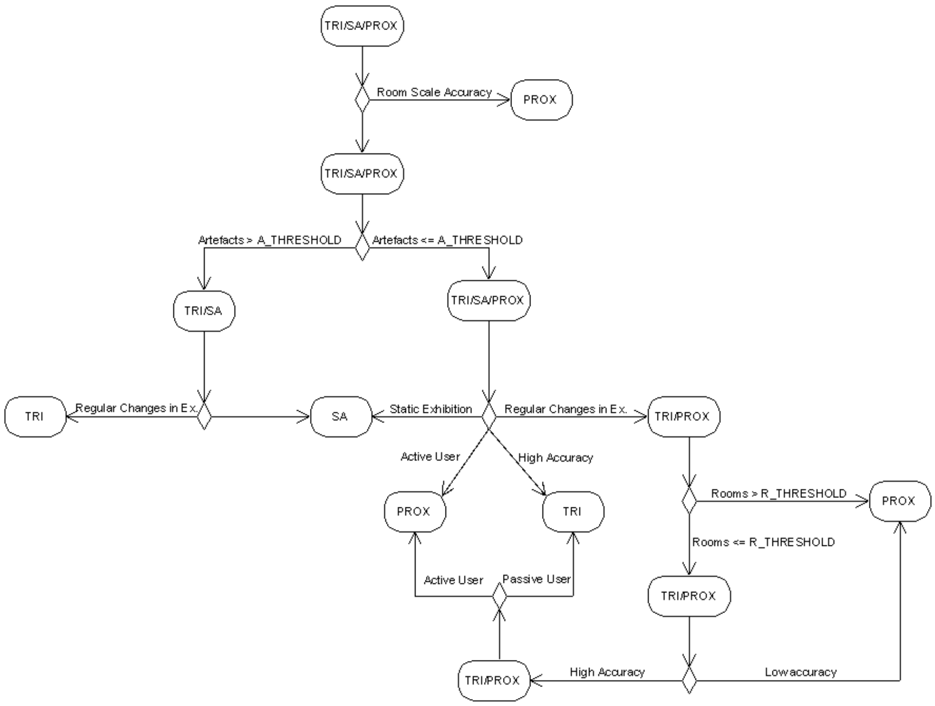

Figure 6.10: Decision Flow Diagram

5. Introduce some kind of weighting scheme for the requirements

6. Perform a structured analysis of alternative solutions according to the requirements

While this method can be used, it is very specific and time-consuming. Thus, we have tried to come up with a more general tool, which is able to give its user help in the initial decision process of choosing a positioning system. This tool still requires at least step 1 and 2 of the method above, maybe more, but by using the provided tool before step 6, the number of solutions to analyse could be greatly reduced, maybe down to two or three systems that all look promising. This will be a much more practical method to use.

Figure 6.10 shows a decision flow diagram that could be used to decide which kind of positioning system that would be most suitable in an indoor exhibition domain when it comes to positioning technique. As we have seen, systems based on different techniques often have some characteristics that make them advantageous and some that make them disadavantageous in different cases.

The diagram is the result of many rounds of trial and error. It may not cover all possible scenarios, but could still be a very useful tool to get a quick overview of possible solutions and their advantages and drawbacks in given premises. It should be noted that the diagram can be used in general, not only by tour guides that is similar to the one we described in chapter 5. However, there are two requirements that should be present: The user should be provided with information about the artefact he is most likely to be interested in at any time, and the user should be provided with a map showing where he is.

At the beginning of the decision process we have three possible outcomes: a trilateration or triangulation based solution (TRI), a scene analysis based solution (SA), or a proximity based solution (PROX). The first question to ask is whether the LBS will suffice with room scale accuracy or not. If it does, a proximity solution would be the best choice, as it could do with very limited infrastructure.

If better accuracy is required, we have found that the most important issue to consider is wether there are "many" or "few" artefacts in the exhibition. As these are subjective measures, we suggest to introduce an artefact threshold value called A_THRESHOLD. This value has to be determined in each case, and is dependent on the combined hardware/software costs of an artefact sensor used in a proximity solution with one sensor per artefact, and management and deployment time of these, compared to available resources (for example manpower and budget). A specification of this value is suggested for future work. If the number of artefacts exceeds A_THRESHOLD, a proximity solution could be excluded as a candidate solution.

To determine whether to use a TRI or a SA solution in a system with many artefacts, we could ask if the exhibition is static or if there are regular exhibit changes (with substantial changes so that reconfiguration is necessary). If the exhibit is mainly static, an SA solution is preferred as this will in general require less infrastructure than a TRI solution. However, if there are frequent changes a TRI solution is a better choice. The initial set-up may be very time-consuming, but once in place it will work regardless of changes in the exhibit. With an SA solution time-consuming reconfiguration is required with each exhibit.

If the number of artefacts is below the A_THRESHOLD value, we are still left with all three solutions. This is an easier case to solve. We then use the question of static vs non-static exhibit changes again as we did above, to decide if SA is the right solution or should be eliminated.

As we can see in the figure, there are two questions that can be asked initially after decided that the system has few artefacts. If the system needs sub-metre accuracy and the user is passive, the only possible solution is TRI. If the user can be active, PROX is preferred.

If we have a system with few artefacts and frequent exhibition changes, the number of rooms could help decide whether to use TRI or PROX. Again, we could use a threshold value inferred from the actual case to decide the limit. The value depends on the deployment time and costs for the TRI solution. If the number of rooms is high (exceeds R_THRESHOLD), PROX is preferred. If the number of rooms is below R_THRESHOLD, the required accuracy level can decide whether to use PROX or TRI. If high accuracy is required, the requirement for an active user or the lack of such a requirement finally settles whether to use PROX or TRI.

As with A_THRESHOLD, R_THRESHOLD, and maybe also a value for high vs low accuracy, should be discussed further and are suggested for future work. Some of the decisions here rely on a cost analysis, which is out of scope of this thesis. Our work has mainly been concerned with technological aspects with regards to LBCS requirements.

6.3.2 Applying Service Oriented Architectures (SOA) for Location Based Computing Systems

Many traditional Location Based Computing Systems (LBCS) are completely proprietary. By this, we mean that their interfaces and interconnections between components of the systems are closed and not accessible by other systems. The LBCSs might have an internal layering and modularisation, but not one which can be exploited easily by other systems. We suggest that future LBCSs adapt a *system wide Service Oriented Architecture*. This will be described in the following, after a brief introduction to the SOA concept.

The SOA Concept

Service-orientation has become a very popular concept in recent years, and is used in a broad variety of applications. A definition of Service Oriented Architecture (SOA) is given in [68]:

> Service oriented architecture (SOA) is a paradigm for organising and utilising distributed capabilities that may be under the control of different ownership domains.

Entities like people, organisations, and applications create capabilities to solve or support problems and needs, and these can be used by other entities. A *service* in SOA is the mechanism which enables access to one or more capabilities. This is done through a pre-described *service interface*, which includes specific protocols, commands and other means for supporting information exchange. For interaction to occur, services must be visible to each other, which means that entities must be made aware that the service exists. This is often effected by discovery mechanisms. Interaction can then occur through exchange of messages, and the result is typically a response to a request.

SOAP	Messaging/method invocations
WSDL	Service endpoint descriptions
UDDI	Service registration and discovery mechanisms

Figure 6.11: The main technologies of XML Web Services, which can be used to realise a service oriented architecture.

XML Web Services technologies are commonly used to realise a SOA. This is a set of standards and protocols based on XML, which covers the requirements of a SOA. The main technologies of XML Web Services are SOAP[1], WSDL[2], and UDDI[3] (see figure 6.11). Communication between services can be performed using SOAP, a simple XML based protocol to let applications exchange information over HTTP, or simply put, a protocol for accessing a Web Service. WSDL is an XML based language for describing Web Services and how to access them. UDDI is a directory service where entities can register and search for Web services, and is used for service discovery purposes [69].

Architecture Proposal for Future LBCSs

Based on the three-layered model of an LBCS used throughout this thesis, including a positioning layer, location layer, and an application (LBSs) layer, a SOA for LBCSs is now introduced. The goal of this approach is to make it easy for different systems to interact and collaborate. For example, it would be advantageous if the lower layer positioning mechanism could be substituted for another one (see figure 6.12 on the next page), without having to worry about the upper layers. This could for example be due to LBS requirements changes. This way, a mobile device which should be positioned could be provided with several means for positioning, and the appropriate technology could be chosen based on the requirements specified by the application. Recent cellular phones can be positioned by either GPS or GSM, and the Location API (JSR-179) defined by the Java Community Process abstracts the details from the application developer by providing him with the same interface for using both positioning technologies. However, this architecture is still rather static, as it is not possible to add other positioning technologies than the predefined ones.

An LBCS can be built according to the SOA concept by mapping each of the layers in our three-layered model into a service on their own, see figure 6.13 on the following page. In addition to these services (represented by S_n in the figure), the SOA must also include a discovery-mechanism (represented by D in the fig-

[1]Previously Simple Object Access Protocol, but now only called SOAP
[2]Web Services Description Language
[3]Universal Description, Discovery and Integration

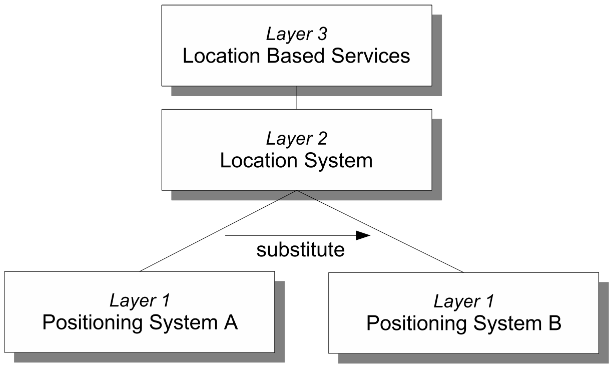

Figure 6.12: Substituting one positioning system for another without requiring changes in the layers above.

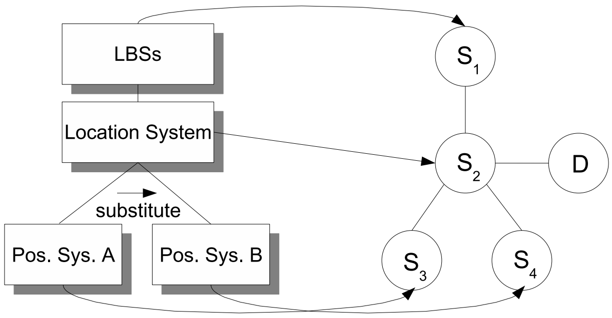

Figure 6.13: Mapping the layers of our reference model to services in a SOA.

ure). When a new positioning technology is introduced on the mobile device, for example by equipping a PDA with an RFID reader, it will contact UDDI and register itself. The location layer can then query the UDDI for the most appropriate positioning technology according to requirements specified by the LBS.

Figure 6.14 on the next page shows how most LBCSs are implemented today, with proprietary interfaces between all components on the mobile device side, proprietary interfaces between the mobile device and the server system in the network, and proprietary interfaces between the components on the server side. Figure 6.15 on page 106 shows how some LBCS architectures have been proposed today, where parts of a SOA concept or just XML messaging have been used to introduce flexibility between the mobile device and the components on the server side in the system[10, 13, 70]. However, it is also possible to employ the SOA concept for the entire architecture of an LBCS, see figure 6.16 on page 106. It is possible to expose the internal components running on the mobile device and the components running on the LBCS server as services as well, with the interfaces

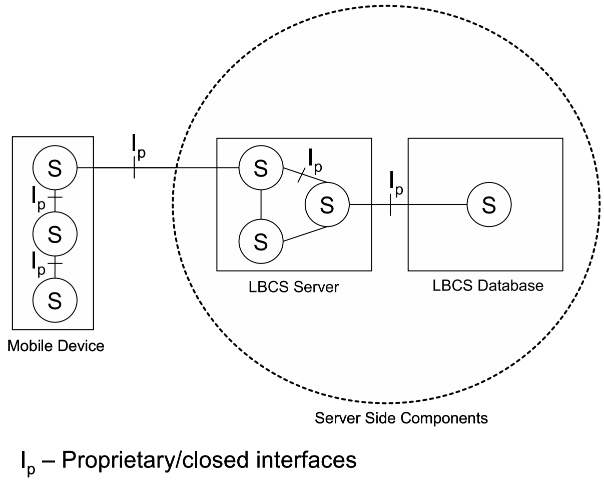

Figure 6.14: The architecture of most LBCSs today.

between them defined through e.g. WSDL if the XML Web Services platform is used. With this approach, the reorganisation of the services is simple (e.g. move some functionality from the mobile device side to the server side if appropriate), but more importantly, it makes it easy to attach new positioning technologies (layer 1) and deploy new services (layer 3). To add a new positioning technology on layer 1, the developer of the system only has to take the appropriate interface definition into consideration (e.g. the WSDL), and generate skeleton code based on this. To add a new service on layer 3, the developer of the service also only has to take the appropriate interface definition into consideration, and generate client stubs based on this.

Advantages and Challenges

In general, the main advantages of using the SOA concept in computing systems are reuse and interoperability. Because service interfaces are open and the services are published as available for use by others, they can easily be reused, either to solve the same problems or needs, or in a completely new way not intended by the service provider. Service providers can build on existing services without having to start from scratch for each new system development.

Our proposed SOA architecture for future LBCSs has two specific advantages based on the general advantages of using SOA. Different positioning systems could be used by the same LBS for different purposes, and the same positioning solutions could be used by several LBSs. New positioning systems and LBSs can be added to the LBCS in runtime. In addition, our proposed architecture is able to support all different architecture distributions, so that components of the architecture can

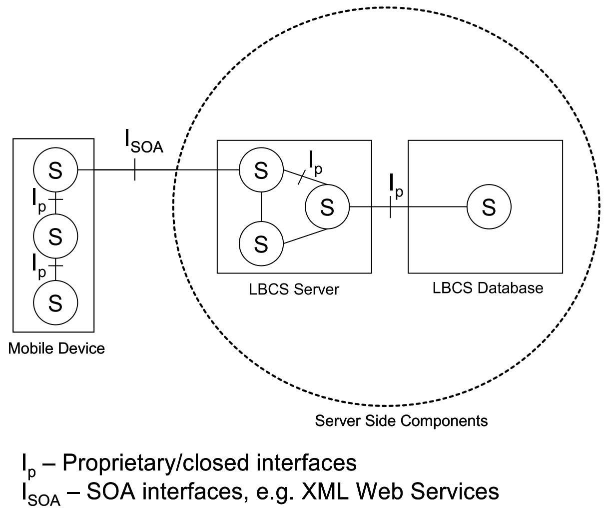

Figure 6.15: SOA concept applied for LBCS.

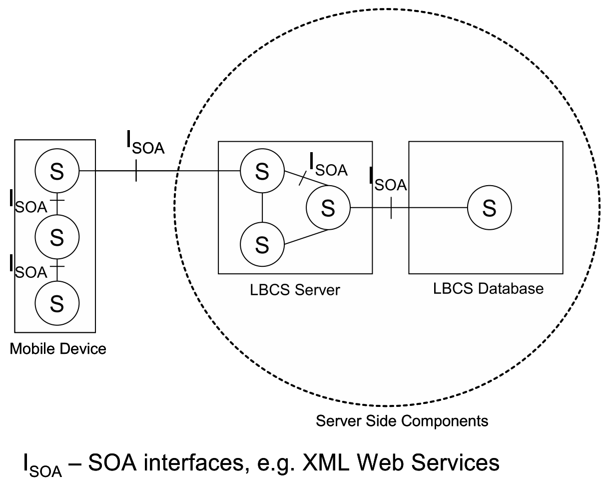

Figure 6.16: Using SOA system wide for increased flexibility.

be placed where it is most appropriate with regards to the specific LBCS. For example, in some LBCSs the layers from our reference model will be implemented solely on the mobile device, while in others some layer components will be implemented on the mobile device and some at the server side. Some systems may even have most components at the server side, and only a thin client on the mobile device.

The main challenge for our proposed system wide SOA to be successful, is that a general agreement is reached with regards to a common semantics or ontology for LBCSs, as standard XML Web Services do not consider the semantics of interfaces.

6.4 Summary

In this chapter we have applied all the knowledge gathered in the previous chapters. First, we analysed a range of different location systems from chapter 4 against a complex requirements specification made in chapter 5. We found that two solutions, called IRIS-LPS and Cordis RadioEye, seemed to be able to cover our needs. However, we realised that this specific result might not be very useful for others. Thus, we tried to extract some general knowledge from the work with the thesis, and turn it into a tool that more easily could be used by others. The result was a decision flow diagram which may help emphasising important characteristics with indoor positioning, and the choice of positioning solution. In addition, we also proposed a new architecture for future LBCSs, based on the concept of Service Oriented Architectures (SOA), which will ensure increased flexibility.

Chapter 7

Conclusion

In this final chapter we will discuss how this thesis managed to answer the problem statements given in section 1.1 on page 4. We will also summarise our contributions, and discuss limitations of the thesis and future work.

7.1 Achievements and Results

This thesis is trying to find the answer to the question *"What kind of positioning system would best fulfil the requirements of location based services used in indoor exhibitions?"* The first answer found is that this is highly dependent on three things:

1. The location based service that is to be supported by the positioning system.
2. The premises in which the system is to be implemented.
3. The exhibition(s) on display.

Thus, we suggest that thorough research and preparations are performed in these areas before choosing a positioning system. Then, it would be valuable to make use of a framework which could take specific parameters describing your LBS, your premises and typical exhibitions as input, and give the best suitable positioning system as output. However, as there are so many different and conflicting parameters, this proved rather difficult. But, by going up one level, from the existing positioning system implementations to a categorisation of positioning techniques, a useful decision flow diagram was made, which hopefully can guide future developers and owners in the decision process.

The second answer to the problem statement is that because there is substantial uncertainty about different positioning systems suitability as support for different

LBSs, future LBCS should be built using a very flexible architecture that allows for easy changes of positioning mechanisms. A selected positioning system might not work as well as intended, or new positioning technology becomes available that seems to be a better solution than the current. Thus, positioning solutions should be developed according to a flexible LBCS architecture, which makes it easy to substitute one positioning mechanism with another one, without having to replace the entire LBCS, for example middleware, databases and services.

Although not directly, we will claim that the general problem statement is successfully answered. We can also see from the summarised list of contributions below that the specific problem statements were successfully answered.

- An overview of the field of positioning systems in general, and positioning techniques and technologies in particular.
- A detailed description of the domain of indoor exhibitions and location based mobile electronic tour guides.
- An overview and an extensive analysis of existing positioning systems against requirements from a complex tour guide.
- A decision flow diagram which may help clarify consequences of choosing different positioning systems, and by this also help in this selection process.
- Suggestion of a new flexible architecture for LBCSs based on a service oriented architecture (SOA) concept.

7.2 Critical review and Future Work

As there are so many different parameters to take into consideration when choosing positioning system in an LBCS, it is not likely that our general decision flow diagram covers all different scenarios. Thus, it is important that this tool is not used as a rule for choosing type of positioning system, but as helping guidelines to get a quick initial overview over different positioning system possibilities and consequences of using them. Future work with the idea of such a decision flow diagram could result in a more inclusive and powerful tool. It could be extended to cover more parameters, be restructured in more effective ways, and maybe also be used for both indoor and outdoor cases, regardless of domain. The threshold values should be further examined.

With regards to the proposed system wide SOA architecture for future LBCSs, it should be noted that this is very early work. A minimum set of methods a positioning system should support must be developed, and standardisation issues discussed. Test implementation should be carried out, especially to see how well mobile devices can handle the overhead (network and processing) introduced by existing technologies for SOA realisation. However, future mobile devices will have even better processing capacity than today, so this should not be a problem in the near future.

Bibliography

[1] Anind K. Dey and Gregory D. Abowd. Towards a better understanding of context and context-awareness. Workshop on The What, Who, Where, When, and How of Context-Awareness, 2000 Conference on Human Factors in Computing Systems (CHI 2000), apr 2000. Available online at: ftp://ftp.cc.gatech.edu/pub/gvu/tr/1999/99-22.pdf.

[2] Per Enge. Retooling the Global Positioning System. *Scientific American*, pages 90–97, May 2004.

[3] Veljo Otsason. Accurate indoor localization using wide GSM fingerprinting. Master's thesis, University of Tartu, 2005.

[4] Roy Want, Andy Hopper, Veronica Falc ao, and Jonathan Gibbons. The Active Badge location system. *ACM Trans. Inf. Syst.*, 10(1):91–102, 1992. Available online at: http://www-lce.eng.cam.ac.uk/ publications/files/tr.92.1.pdf.

[5] Andy Ward, Alan Jones, and Andy Hopper. A new location technique for the active office. *IEEE Personal Communications*, 4(5):42–47, October 1997. Available online at: http://www-lce.eng.cam.ac.uk/ publications/files/tr.97.10.pdf.

[6] Nissanka B. Priyantha, Anit Chakraborty, and Hari Balakrishnan. The Cricket location-support system. In *Mobile Computing and Networking*, pages 32–43, 2000. Available online at: http://nms.lcs.mit.edu/papers/ cricket.pdf.

[7] Paramvir Bahl and Venkata N. Padmanabhan. RADAR: An in-building RF-based user location and tracking system. In *IEEE INFOCOM*, pages 775–784, March 2000.

[8] Gregory D. Abowd, Christopher G. Atkeson, Jason Hong, Sue Long, Rob Kooper, and Mike Pinkerton. Cyberguide: A mobile context-aware tour guide. *Baltzer/ACM Wireless Networks*, 3:421–433, 1997.

[9] Massimo Zancanaro, Oliviero Stock, and Ivana Alfaro. Using cinematic techniques in a multimedia museum guide. In *Museums and the Web 2003: Selected Papers*. Archives & Museum Informatics, March 2003. Available online at: http://peach.itc.it/papers/maw2003.pdf.

[10] Taggedx. http://www.taggedx.dk. 06.04.2006.

[11] Jeffrey Hightower and Gaetano Borriello. Location systems for ubiquitous computing. *IEEE Computer*, 34(8):57–66, August 2001. Available online at: http://citeseer.ist.psu.edu/article/rey01location.html.

[12] Vasileios Zeimpekis, George M. Giaglis, and George Lekakos. A taxonomy of indoor and outdoor positioning techniques for mobile location services. *SIGecom Exch.*, 3(4):19–27, 2003.

[13] Jeffrey Hightower, Dieter Fox, and Gaetano Borriello. The location stack. Technical report, University of Washington, Department of Computer Science and Engineering, July 2003.

[14] Patrick Röder, Mario Hoffmann, and Matthias Ritscher. A distributed framework for location sensing systems. http://www.patrick-roeder.de/projects/locserver.pdf.

[15] Mike Hazas, Christian Kray, Hans Gellersen, Henoc Agbota, Gerd Kortuem, and Albert Krohn. A relative positioning system for co-located mobile devices. 2005.

[16] Cliff Randell and Henk Muller. Digital hopscotch: Exploring the relationship between positioning accuracy and location size. Sixth International Conference on Ubiquitous Computing - Workshop: Playing with Sensors, September 2004. Available online at: http://www.cs.bris.ac.uk/Publications/Papers/2000432.pdf.

[17] Andrew Martin Robert Ward. *Sensor-driven Computing*. PhD thesis, University of Cambridge, August 1998. Available online at: http://www.uk.research.att.com/bat/ sdc.pdf.

[18] Andrew Harrington. What's the difference between accuracy and precision? Online: http://www.geoplace.com/gw/2000/1000/1000gps.asp.

[19] Paramvir Bahl, Venkata N. Padmanabhan, and Anand Balachandran. Enhancements to the RADAR user location and tracking system. Technical Report MSR-TR-2000-12, Microsoft Research, February 2000.

[20] Hari Balakrishnan, Roshan Baliga, Dorothy Curtis, Michel Goraczko, Allen Miu, Bodhi Priyantha, Adam Smith, Ken Steele, Seth Teller, and Kevin Wang. Lessons from developing and deploying the cricket indoor location system. Available online at: http://nms.lcs.mit.edu/projects/cricket/V1Exp.pdf, November 2003.

[21] Keith Cheverst, Nigel Davies, Keith Mitchell, and Adrian Friday. The role of connectivity in supporting context-sensitive applications. In *Proceedings of the 1st International Symposium on Handheld and Ubiquitous Computing*, pages 193–207. Springer-Verlag, 1999. Available online at: http://www.guide.lancs.ac.uk/ RoleOfConnectivity.pdf.

[22] B.Brown, I.McColl, M.Chalmers, A.Galani, C.Randell, and A.Steed. Lessons from the lighthouse: Collaboration in a shared mixed reality system. In *Proceedings of the CHI 2003 Conference on Human Factors in Computing Systems*, pages 577–584. ACM Press, April 2003.

[23] T. Starner, D. Kirsch, and S. Assefa. The locust swarm: An environmentally-powered, networkless location and messaging system. In *Proceedings of the 1 st International Symposium on Wearable Computers*, pages 169–170, October 1997.

[24] Andy Harter and Andy Hopper. A distributed location system for the active office. *IEEE Network*, 8(1), January 1994. Available online at: http://www-lce.eng.cam.ac.uk/ publications/files/tr.94.1.pdf.

[25] Shun yuan Yeh, Keng hao Chang, Chon in Wu, Hao hua Chu, and Jane Yung jen Hsu. GETA sandals: a footstep location tracking system. *Springer Personal and Ubiquitous Computing Journal (PUC), special issue for Location-and Context-Awareness*, February 2007.

[26] Dale DePriest. Getting a fix with your Garmin. http://www.gpsinformation.org/dale/gpsfix.htm.

[27] Jeffrey Hightower and Gaetano Borriello. Location sensing techniques. UW CSE 01-07-01, University of Washington, Computer Science and Engineering, Seattle, WA, July 2001. Technical report, companion to [11].

[28] Jui-Hung Yeh, Jyh-Cheng Chen, and Chi-Chen Lee. WLAN standards. *IEEE Potentials*, 22(4):16–22, 2003.

[29] What is infrared and where is it used? http://irda.org/displaycommon.cfm?an=1&subarticlenbr=14.

[30] James J. Carter. Light wireless: Infrared as a practical alternative to radio frequency communication systems. Available online: http://users.cafwap.net/s̃dcp/members/carter_wp.html. 12.05.2005.

[31] Brent A. Miller and Chatschik Bisdikian. *Bluetooth Revealed: The Insider's Guide to an Open Specification for Global Wireless Communications*. Prentice Hall PTR, 2001.

[32] William C. Craig. Zigbee: Wireless control that simply works. Technical report, ZMD America, Inc. and ZigBee Alliance, 2004.

[33] Jon Adams and Bob Heile. Busy as a ZigBee. *IEEE SPECTRUM*, October 2006.

[34] What is ZigBee. http://www.palowireless.com/zigbee/whatis.asp.

[35] Robert J. Fontana. Recent developments in short pulse electromagnetics or uwb the old fashioned way. Presentation held for Microwave Theory and Techniques Society and Northern VA Communications Society, March 2004. Available online at: http://www.multispectral.com/pdf/IEEE030904.pdf.

[36] Robert J. Fontana. Recent system applications of short-pulse ultra-wideband (UWB) technology. *IEEE Microwave Theory and Tech.*, 52(9), September 2004.

[37] Inc. Multispectral Solutions. Uwb frequently asked questions. http://www.multispectral.com.

[38] Jim Geier. Ultra-wideband: Fast, short-range wireless, January 2005. Available online at: http://www.mobilepipeline.com/specwatch/011205_specwatch.jhtml.

[39] Ketan Mandke, Haewoon Nam, Lasya Yerramneni, Christian Zuniga, and Ted Rappaport. The evolution of ultra wide band radio for wireless personal area networks. Technical report, University of Texas at Austin, September 2003. Available online at: http://www.ece.utexas.edu/ wireless/TP%2039,%20High%20Frequency%20Electronics,%20Sept%2003.pdf.

[40] Inc. RFID Journal. A guide to understanding rfid. http://www.rfidjournal.com/article/gettingstarted/. Source valid May 25.

[41] Inc Symbol Technologies. Rfid and the mainstream supply chain - seven steps to rfid sanity. http://www.symbol.com/products/whitepapers/ rfid_mainstream_sc.html. March 30, 2006.

[42] Sonitor Technologies AS. The ultrasound advantage. http://www.sonitor.com/technology/. Source valid May 26.

[43] Cliff Randell and Henk Muller. Low cost indoor positioning system. In *Proceedings of the 3rd international conference on Ubiquitous Computing*, pages 42–48. Springer-Verlag, September 2001. Available online at: http://www.cs.bris.ac.uk/Publications/ Papers/1000573.pdf.

[44] AT&T Laboratories Cambridge. The Active Badge system. Online: http://www.uk.research.att.com/ab.html.

[45] Mike Addlesee, Rupert Curwen, Steve Hodges, Joe Newman, Pete Steggles, Andy Ward, and Andy Hopper. Implementing a sentient computing system. *IEEE Computer Magazine*, 34(8):50–56, August 2001.

[46] MIT Computer Science and Artificial Intelligence Lab. *Cricket v2 User Manual*, July 2004. Available online at: http://nms.lcs.mit.edu/projects/cricket/v2man.html.

[47] Crossbow Technology Inc. MCS Cricket Series (MCS410). http://www.xbow.com/Products/productsdetails.aspx?sid=116. Source valid June 19.

[48] Norman Adams, Rich Gold, Bill N. Schilit, Michael Tso, and Roy Want. An infrared network for mobile computers. In *Proceedings USENIX Symposium on Mobile & Location-independent Computing*, pages 41–52, August 1993.

[49] Roy Want, Bill Schilit, Norman Adams, Rich Gold, Karin Petersen, John Ellis, David Goldberg, and Mark Weiser. The PARCTAB ubiquitous computing experiment. Technical report, Xerox Palo Alto Research Center, mar 1995. Available online at: http://sandbox.parc.xerox.com/parctab/csl9501.ps.Z.

[50] Erwin Aitenbichler and Max Mühlhäuser. An ir local positioning system for smart items and devices. In *Proceedings of the 23rd IEEE International Conference on Distributed Computing Systems Workshops (IWSAWC03)*, pages 334–339. IEEE Computer Society, May 2003.

[51] http://www.ekahau.com/products/. Source valid June 17.

[52] George Roussos. Location sensing technologies and applications. JISC Techwatch Report TSW 02–08, School of Computer Science and Information Systems, Birkbeck College, University of London, November 2002. Available online at: http://www.jisc.ac.uk/uploaded_documents/tsw_02-08.pdf.

[53] Odd R. Valmot. Radioøyet ser deg. *Teknisk Ukeblad*, (31):10–11, September 2003.

[54] Radionor Communications AS. Cordis radioeye localisation technology. http://www.radionor.no/Downloads/radionor_white_paper.pdf. Source valid June 9.

[55] Silke Feldmann, Kyandoghere Kyamakya, Ana Zapater, and Zighuo Lue. An indoor bluetooth-based positioning system: Concept, implementation and experimental evaluation. In *Proceedings of the International Conference on Wireless Networks*, pages 109–113, June 2003.

[56] G. Anastasi, R. Bandelloni, M. Conti, F. Delmastro, E. Gregori, and G. Mainetto. Experimenting an indoor bluetooth-based positioning service. In *ICDCSW '03: Proceedings of the 23rd International Conference on Distributed Computing Systems*. IEEE Computer Society, 2003.

[57] Gunter Fischer, Burkhart Dietrich, and Frank Winkler. Bluetooth indoor localization system. In *1st Workshop on Positioning, Navigation and Communication 2004 (WPNC'04)*, pages 147–156. Shaker Verlag, 2004.

[58] Hiroyuki MORIKAWA Yasuhiro FUKUJU, Masateru MINAMI and Tomonori AOYAMA. DOLPHIN: An autonomous indoor positioning system in ubiquitous computing environment. *IEEE ISORC*, 2003. Available online at: http://www.mlab.t.u-tokyo.ac.jp/publications/2003/ fukuju-isorc03.pdf.

[59] Hiroyuki Morikawa Masateru Minami, Kazuki Hirasawa and Tomonori Aoyama. Implementation and evaluation of a distributed ultrasonic positioning system. In *Proceedings of First International Workshop on Networked Sensing Systems*, pages 75–78, June 2004. Available online at: http://www.mlab.t.u-tokyo.ac.jp/ publications/2004/minami-inss-04.pdf.

[60] Esko O. Dijk, Kees van Berkel, Ronald M. Aarts, and Evert J. van Loenen. Ultrasonic position estimation using a single base station. In *European Symposium on Ambient Intelligence (EUSAI 2003)*, pages 143–148, November 2003.

[61] Esko O. Dijk. *Indoor Ultrasonic Position Estimation using a Single Base Station*. PhD thesis, Eindhoven University of Technology, September 2004. Available online at: http://alexandria.tue.nl/extra2/200412423.pdf.

[62] The home of mobile multimedia guides. http://www.lapavalley.com/.

[63] Franca Garzotto, Tullio Salmon Cinotti, and Massimiliano Pigozzi. Designing multi-channel web frameworks for cultural tourism applications: the MUSE case study. In *Museums and the Web 2003: Selected Papers*. Archives & Museum Informatics, 2003. Available online at: http://www.archimuse.com/mw2003/papers/ garzotto/garzotto.html.

[64] Tullio Salmon Cinotti, Giuseppe Raffa, Luca Roffia, Franca Garzotto, Rossana Muzii, Viviana Varlese, Maurizio Malavasi, and Stefania Galasso. Evaluating context-aware mobile applications in museums: Experiences from the muse project. In *Museums and the Web 2004: Selected Papers*. Archives & Museum Informatics, 2004. Available online at: http://www.archimuse.com/mw2004/papers/ salmon/salmon.html.

[65] Tullio Salmon Cinotti, Raviprakash Nagaraj, Giuseppe Mincolelli, Giuseppe Raffa, Luca Roffia, and Fabio Sforza. WHYRE: a context-aware wearable computer for museums and archaeological sites. In *Proceedings of the Eighth International Symposium on Wearable Computers (ISWC'04)*, pages 174–175, November 2004. Available online at: http://csdl.computer.org/comp/ proceedings/iswc/2004/2186/00/21860174.pdf.

[66] Sigurd Gimre and Hege Servold. Generic framework for development of location-aware applications. Master's thesis, Norwegian University of Science and Technology, 2004.

[67] Astrup Fearnley museum of modern art. http://www.afmuseet.no/, December 2005.

[68] The OASIS consortium. *Reference model for Service Oriented Architecture 1.0*, August 2006.

[69] Web building tutorials. http://www.w3schools.com/.

[70] Ulf Rerrer. Location-aware web service architecture using wlan positioning. OTM Workshops, 2005.