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Researching the Accuracy of Indoor Positioning using NTNU's Wireless Network

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Abstract:

Indoor positioning can be based on several positioning techniques and systems. The possibilities for indoor positioning systems are endless. They can provide useful information in complex indoor environments such as hospitals, train stations and office buildings. Existing indoor positioning techniques and systems using these techniques and their corresponding accuracies were explored.

This thesis researched the accuracy of NTNU's wireless network through studying the effects of including outer and internal walls in a model and if the location estimates provided room accuracy. A test was performed to study the accuracy of the wireless network. Outer and internal walls were included in five different phases and the locations of a network of control points were estimated based on Cisco's Wireless Location Appliance system. Other indoor obstacles, such as stairwells and lift shafts, and the material of the obstacles were not included due to technical limitations.

The insertion of outer and internal walls in the model had limited effect on the accuracy and the precision of the measurements. The most accurate location estimates were of locations between triangulated access points with close proximity. These were also the only locations obtaining room accuracy. Further work should consider the inclusion of other obstacles and material type in the model and signal strength data.

Keywords:

1. indoor positioning systems
2. wireless positioning
3. location techniques
4. WLAN

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Researching the Accuracy of Indoor Positioning using NTNU's Wireless Network

BACKGROUND
Efficient infrastructures to estimate outdoor locations have been developed in the last decades, mainly by the use of satellite navigation. However, the satellites do not cover indoor environments.

An accurate network of indoor reference marks has been established in the division of Geomatics at NTNU. This network has previously been studied in order to investigate how accurate indoor positions can be achieved using NTNU's CISCO system.

In previous research, obstacles have been disregarded, such as walls made of different materials. This master's thesis will study if the accuracy can be improved when the obstacles are included in the model.

TASK DESCRIPTION
The candidate is going to investigate NTNU's system for indoor navigation provided by CISCO. Obstacles can be included in the model used for the calculation of positions. The candidate is supposed to research if inclusion of these obstacles (walls) will influence the positioning.

Specific tasks:
- Study technologies for indoor navigation
- Study the accuracies these systems achieve
- Cooperate with Trådløse Trondheim in order to include walls in the model
- Carry out measurements based on walls included in the model
- Examine how accurate different locations can be estimated

- Evaluate the results, in particular to consider the locations of control points compared to walls included in the model

ADMINISTRATIVE/GUDIANCE

The work on the Master Thesis starts on January 14th, 2014

The thesis report as described above shall be submitted digitally in DAIM at the latest at June 10, 2014

Supervisors at NTNU:

Terje Midtbø, professor in charge
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Ole Markus With, MazeMap/Trådløse Trondheim

Trondheim, January 10, 2014. (revised: 27.5.2014)

Abstract

Indoor positioning can be based on several positioning techniques and systems. The possibilities for indoor positioning systems are endless. They can provide useful information in complex indoor environments such as hospitals, train stations and office buildings. Existing indoor positioning techniques and systems using these techniques and their corresponding accuracies were explored.

This thesis researched the accuracy of NTNU's wireless network through studying the effects of including outer and internal walls in a model and if the location estimates provided room accuracy. A test was performed to study the accuracy of the wireless network. Outer and internal walls were included in five different phases and the locations of a network of control points were estimated based on Cisco's Wireless Location Appliance system. Other indoor obstacles, such as stairwells and lift shafts, and the material of the obstacles were not included due to technical limitations.

The insertion of outer and internal walls in the model had limited effect on the accuracy and the precision of the measurements. The most accurate location estimates were of locations between triangulated access points with close proximity. These were also the only locations obtaining room accuracy. Further work should consider the inclusion of other obstacles and material type in the model and signal strength data.

Keywords: Indoor positioning systems, wireless positioning, location techniques, WLAN, Cisco, room accuracy, accuracy, precision

Sammendrag

Innendørsposisjonering kan være basert på mange ulike teknikker og systemer, mulighetene for innendørs posisjoneringssystemer er svært mange. De kan gi verdifull informasjon om kompliserte innemiljø. I denne masteroppgaven ble posisjoneringsmetoder og -systemer til bruk innendørs med tilhørende nøyaktighet studert.

Nøyaktigheten på NTNUs trådløse nettverk blir her undersøkt ved å granske effekten av at utendørs- og innendørsvegger ble lagt til i en modell og om posisjonsberegningene plasserte målte lokasjoner i korrekt rom. For å kunne gjøre dette ble det gjennomført en test av det trådløse nettverket. Utendørs- og innendørsvegger ble inkludert i modellen i fem ulike faser og et nettverk av kontrollpunkter ble målt basert på Ciscos Wireless Location Appliance-system. Andre innendørshindringer, som for eksempel trapperom og heissjakter, og de ulike materialene hindringene består av ble ikke inkludert i modellen grunnet tekniske begrensninger.

Det viste seg at inkluderingen av utendørs- og innendørsvegger i modellen hadde liten effekt på nøyaktigheten og presisjonen til målingene. De mest nøyaktige målingsestimatene var posisjoner mellom triangulerte og nærliggende aksesspunkter. Dette var også de eneste lokasjonene som ble estimert til riktig rom (romnøyaktighet). Videre studier bør vurdere muligheten til å inkludere andre hindringer og materialtype i modellen og informasjon om signalstyrke.

Preface

This is a master's thesis written in the Department of Civil and Transport Engineering at the Norwegian University of Science and Technology (NTNU) in Trondheim, Norway. It is a part of the study program Engineering and ICT and was carried out in the Spring of 2014.

I would like to thank my supervisor Terje Midtbø for his contributions and guidance on this master's thesis. I would also like to thank my co-supervisors Trond Haakonsen at the division of Geomatics and Ole Markus With at Trådløse Trondheim/MazeMap for their comments and assistance. Finally, I want to thank everyone who has contributed with ideas and given valuable feedback.

Trondheim, June 10, 2014

Turid Tårland Harborg

Contents

List of Figures

List of Tables

List of Abbreviations

Abbreviation	Description
AP	Access point
AOA	Angle of arrival
CDMA	Code division multiple access
DC	Direct current
DCM	Database correlation method
Dolphin	Distributed object locating system for physical space inter networking
DSSS	Direct sequence spread spectrum
FHSS	Frequency hopped spread spectrum
GPS	Global positioning system
ILBS	Indoor location based service
INS	Inertial navigation system
IR	Infrared
KF	Kalman filter
kNN	k-nearest neighbour
LAN	Local area network
LBS	Location based service
MMSE	Minimum mean square error
RF	Radio-frequency
RFID	Radio-frequency identification
RSSI	Received signal strength information
SNMP	Simple network management protocol
TDOA	Time difference of arrival
TOA	Time of arrival
TOF	Time of flight
US	Ultra sonic
UWB	Ultra-wideband
WLAN	Wireless local area network
WPAN	Wireless personal area network

Chapter 1

Introduction

1.1 Indoor navigation

In the recent years outdoor navigation has become accessible almost everywhere due to satellite navigation. There are few areas in the world that are not covered by satellites at some time and the satellites can thus determine a user's location with high accuracy. Indoor navigation however is available in a limited amount of places, such as certain schools and shopping malls, although navigation possibilities are constantly increasing. The demand is increasing as more and more people have wi-fi access on their smart phones and personal devices and hence wireless based indoor positioning systems are particularly relevant (Köbben, 2007; Yeung and Ng, 2007).

Indoor navigation and positioning have become increasingly popular in the recent years. A lot of time is spent indoors in schools and at work and according to United States environmental protection agency (EPA) (2011) Americans spend approximately 90 % of their time indoors. Several studies have addressed different aspects of indoor positioning, such as location techniques and systems (Liu et al., 2007; Yeung and Ng, 2007; Gu et al., 2009; Ijaz and Lee, 2013) and the effects of obstacles (Bahl and Padmanabhan, 2000; Köbben, 2007; Gu et al., 2009).

Systems providing indoor positioning have grown into becoming helpful tools used for tasks such as finding one's location and the locations of friends, where the nearest room of some kind is and to get an overview in both known and unknown building environments. Several complex indoor environments can benefit from helping their users or customers orientate if they implement indoor positioning. In addition to social networking the following indoor environments could benefit people with the implementation of indoor positioning systems;

- airports
- hospitals
- train stations
- museums
- university campuses
- office buildings
- shopping malls
- emergency response
- manufacturing plants

(Ijaz and Lee, 2013; Biczók et al., 2014; Ekahau, 2014)

Indoor positioning is an interesting and wide field in constant development. An indoor positioning system based on wireless local area network (WLAN) is both an economical solution, as it uses existing WLAN frameworks, as well as being a scalable and reusable solution (Köbben, 2007, p. 287; Yeung and Ng, 2007).

1.2 Task summary and research question

The aim of this master's thesis is to research the accuracy of indoor positioning using the wireless network at the Norwegian University of Science and Technology (NTNU) in Trondheim, Norway. A network of reference marks has been accurately measured and established in the Lerkendal building at NTNU. The network was used in a previous study where Midtbø et al. (2012) accurately measured the coordinates of the reference marks and access points. Obstacles in the indoor environment were disregarded in that study. In this master's thesis the accuracy of NTNU's wireless network will be studied using the same network and measurement platform. Additionally, obstacles, in this case outer and internal walls, will be included in Trådløse Trondheim's model in this thesis.

Room accuracy is an important issue of indoor positioning. In this thesis the estimation of a location inside the correct room is therefore considered to be an important aspect of the indoor positioning based on NTNU's wireless network. The research question can be expressed with the following questions:

- How did the inclusion of walls in the model affect the measurements?
- What accuracy in terms of room accuracy can be achieved at the indoor locations?

This thesis will aim to solve these questions by studying relevant literature on indoor positioning techniques and systems. Furthermore a test of NTNU's wireless network will be carried out through five different phases where the outer and internal walls will be included and tested following a schedule. The results will be statistically studied and the accuracy and precision of the measurements will be discussed. The measurements will be plotted to indicate room accuracy. Finally, the thesis will be concluded followed by a description of future work.

In the 2012 study (Midtbø et al., 2012) the coordinates of the access points were measured with a total station which provides very high accuracy of the coordinates. Correspondingly the coordinates of the reference marks, also known as control points, were accurately measured. The network of access points and control points form a basis for the test conducted in this master's thesis. A local coordinate system is used in the Lerkendal building. In the 2012 study a JavaScript file was set up and the measurements are executed with the running of this file in a web browser. All measurements and statistics are provided in meter values with two decimal numerals, thus providing centimeter level accuracy.

1.3 Structure of the report

This master's thesis has the following structure. Chapter 2 covers the existing methods and definitions as well as technologies and systems for indoor navigation and the accuracies these systems achieve. A brief overview of the Cisco system used in the test is also included in this chapter. Chapter 3 describes the preliminary and preparatory work prior to the test. The research question, the methodology and setup of the test and the five test phases are also provided in this chapter. The results from the test and the discussion are provided in Chapter 4. The conclusion of the test and description of future work are presented in Chapter 5.

1.4 Trådløse Trondheim

Trådløse Trondheim (”Wireless Trondheim”) is a commercial wireless system. The system offers broadband services in Trondheim, Sky ID service and location based advertisement opportunities (Trådløse Trondheim, 2014b). Trådløse Trondheim cooperates with other organisations such as NTNU on different research and development projects. The Campus Guide, now MazeMap, was one of these projects and involved indoor navigation in large indoor environments (Trådløse Trondheim, 2014a). The purpose of the Campus Guide was to create a tool which allowed users, such as students, employees and visitors, to find their way around the Gløshaugen campus at NTNU (Campusguiden, 2014). The Campus Guide was launched in 2011 and later became the company MazeMap. It offers indoor environments such as universities, convention centres, hospitals and shopping malls the opportunity to provide their users, i.e. visitors or customers, with indoor navigation services (MazeMap, 2014a).

Figure 1.1 provides an overview of some of the features of MazeMap including finding the user's position and a search function for rooms. The contact person from Trådløse Trondheim/MazeMap in the testing phase and external supervisor has been Ole Markus With, Head of Development.

Figure 1.1: *MazeMap at NTNU Gløshaugen (MazeMap, 2014b)*

Chapter 2

Existing methods and technologies for indoor navigation

2.1 Methods

Three main techniques are used for indoor positioning; location fingerprinting, triangulation and trilateration. These can be combined with each other or used separately. Additional theoretical terms used in this master's thesis are also be provided in this chapter.

2.1.1 Location fingerprinting

Location fingerprinting is a technique often used with existing WLAN frameworks to provide indoor positioning. The technique joins attributes to determine a location. Received signal strength information (RSSI) is the most used attribute for this. Location fingerprinting then uses this information to estimate a location. A positioning system that will be using location fingerprinting requires a location fingerprint database or possibly a radio map (Kaemarungsi and Krishnamurthy, 2004, p. 14). For every entry in the fingerprint database a mapping is made between the position and the location fingerprint (ibid.). If a radio map is used then the RSSI is stored as vectors in a network of the locations in the indoor area.

Subhan et al. (2013, p. 3) highlight that location fingerprinting can be described as two different operational phases, an on-line phase and an off-line phase. In the off-line positioning phase the RSSI fingerprints are collected and stored in the radio map. In the on-line phase the attributes are compared with the previously stored fingerprints using a database correlation method (DCM). (Kaemarungsi and Krishnamurthy, 2004; Subhan et al., 2013)

According to Kaemarungsi and Krishnamurthy (2004, p. 14) an average of the received signal strength values at a location is usually calculated from several access points for the fingerprint database. Location fingerprinting is considered a "lighter" technique than AOA and TDOA as these techniques require precise measurement of angle and distance respectively to define the user's position. The location fingerprinting technique is considered less complicated because it does not require any specific hardware for the device, merely wireless connectivity abilities for the reuse of existing WLAN frameworks. (Kaemarungsi and Krishnamurthy, 2004; Subhan et al., 2013)

2.1.2 Triangulation

Triangulation is a technique for indoor position estimation using either lateration or angulation. Lateration is based on distance measurements and angulation is based on calculating angles from several reference points or access points (Liu et al., 2007, p. 1068). According to Feng and Liu (2012) triangulation methods consist of "mapping the signal strength as a function of distance" (Feng and Liu, 2012, p.256). Before a triangulation algorithm is performed the signal strength from a minimum of three access points must be collected. Furthermore the distances from the unknown position to the access points are estimated and the unknown position's coordinates are calculated using triangulation algorithms. However, there are different comprehensions of triangulation. From a surveying point of view triangulation is a method measuring the angles in a triangle created from "three survey control points" (ICSM, 2012). Furthermore the length of one side is estimated and the application of trigonometry is used to calculate the other sides in the triangle.

Figure 2.1 illustrates two triangulation algorithms used to determine the position of a device or a user and Figure 2.2 illustrates a typical triangulation technique from a surveyors' perspective. (Liu et al., 2007; Gu et al., 2009; Feng and Liu, 2012)

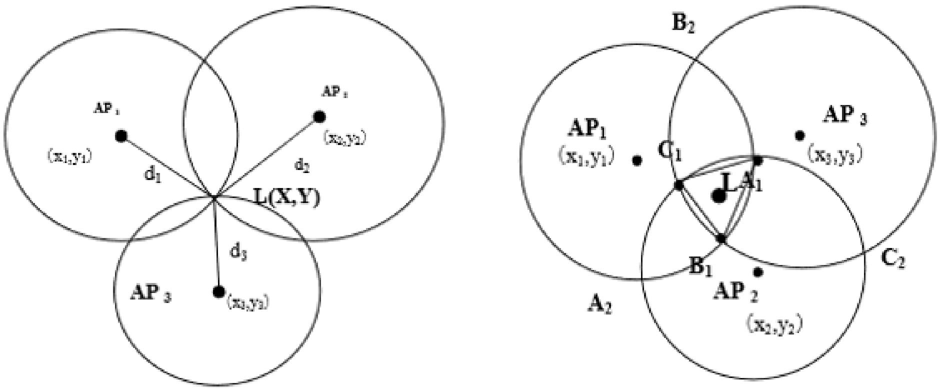


Figure 2.1: *Two different triangulation positioning algorithms in 2D (Feng and Liu, 2012, p. 259)*

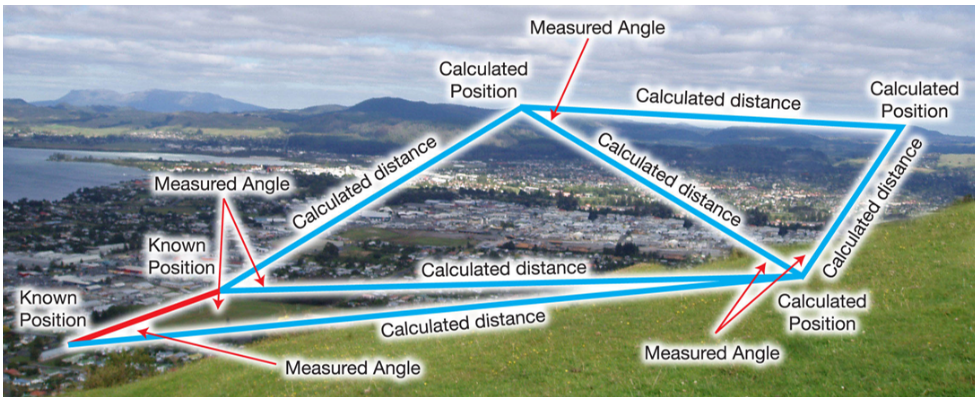


Figure 2.2: *A typical triangulation technique from a surveying point of view (edited from ICSM (2012))*

Loss of signal strength must be considered. Signal strength is reduced with increasing distance between the access point and the user. A log-distance path loss model considers signal strength of the transmitter and the receiver, distance between access points and user as well as antenna gain of the transmitter and the receiver, the signal wavelength, building layout and frequency band of the wireless network (Feng and Liu, 2012, p. 258). The distance between the three access points is measured and then circles are drawn as presented in Figure 2.1 (ibid.). The intersection of these circles is sometimes resulting in the coordinates of one location. However, the three circles might not intersect in one point as showed in the algorithm to the right in Figure 2.1. This algorithm is called a triangulation centroid algorithm (Feng and Liu, 2012, p. 259). The intersections between the circles are calculated and creates a triangle. The position of the user is then defined as the centroid of this triangle. (Gu et al., 2009; Feng and Liu, 2012)

2.1.3 Trilateration

Trilateration is a technique which uses distance measurements from three established positions to estimate the position of the object. Consequently the trilaterion technique estimates the cross-over of three established positions. According to Subhan et al. (2013, p. 2) the trilateration algorithms calculates the object's position using measurements of radio diffusion from a minimum of three ”anchor nodes” and their established positions (ibid.). The distance is gathered from the RSSI obtained at these nodes. Then a standard radio diffusion model is used to adapt the RSSI measurements ”from target nodes to distances for estimation of target position” (Subhan et al., 2013, p. 2). The technique uses minimum mean square error (MMSE) to reduce the variance of the estimation errors. Ideally the circles from the anchor nodes meet in only one point. If this is not the case, as might happen due to noise from the surroundings, MMSE is used to provide the location with the least estimation error of the location. (Subhan et al., 2013)

2.1.4 Other theoretical terms

Angle of arrival

Angle of arrival (AOA) is an angulation positioning technique. The technique is based on creating circles with the ”angle direction lines” with radius from the base station, ie. access point, to the target (Liu et al., 2007, p. 1070). The AOA technique requires merely the position of three reference elements, ie. access points (Gu et al., 2009, p. 16). The intersection of these circles is used to estimate the position of the target, such as a user or a device. According to Liu et al. (2007, p. 1070) the AOA estimation can be performed by the use of either a directional antennae or an array of antennas. There are two main advantages with the AOA technique. One advantage is that the measuring units do not require any time synchronization. The second advantage is that only three access points are necessary to estimate a 3D position and two access points for a 2D position. However, there are several disadvantages of the AOA technique. Firstly, it requires complicated and large hardware components. Additionally, the angle measurements' accuracies are reduced with increasing distance between the target and the access points. The accuracy of the AOA technique is associated with the accuracy of the angle measurements. Multipath and shadowing might reduce the accuracy of the wireless network and thus make it difficult to provide a high accuracy position (Liu et al., 2007, p. 1070). (Liu et al., 2007; Gu et al., 2009)

k-nearest neighbour

k-nearest neighbour (kNN) is an algorithm used for instance in positioning. The distances between the observed signal strength and all sample data sets are calculated (Lin and Lin, 2005, p. 1570). A previously installed database contains the sample data sets. After estimating the distance with regards to the whole set, k data samples are chosen due to their closeness to the unknown point. The coordinates for the unknown point are estimated from the average of these k data samples. According to Lin and Lin (2005, p. 1573) the complexity of the kNN algorithm is depending on the number of samples. Some sources (Lee and Yim, 2012) divide the process into two phases, the establishment of a database and the gathering of the user received RSSI data. These two phases are often called the off-line phase and the on-line phase of kNN indoor positioning respectively. (Lin and Lin, 2005; Lee and Yim, 2012)

Time difference of arrival

Time difference of arrival (TDOA) is an example of a lateration positioning technique. The technique is based on estimating the user's relative position using the time difference for the signal to reach several measuring units (Liu et al., 2007, p. 1069). According to Liu et al. (2007, p. 1069) "the transmitter must lie on a hyperboloid with a constant range difference between the two measuring units" as is illustrated in Figure 2.3. To define a 2D position two intersections of two or more measurements are necessary. If A, B and C are access points and form two hyperbolas that provide an intersection point P, then P will be the position of the target. TDOA can also be computed using cross correlation. The cross correlation is performed with signals received at two measuring units and then used in a cross correlation function (Liu et al., 2007, p. 1069). This cross correlation function considers these signals over a time period. The function requires the measuring units to be synchronised with regard to time reference and reference signals. (Liu et al., 2007)

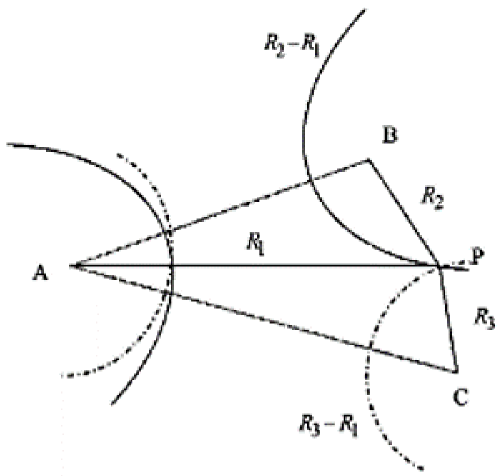


Figure 2.3: *TDOA measurements used for positioning (Liu et al., 2007, p. 1069)*

Time of arrival

Time of arrival (TOA) is another lateration positioning technique. It is based on measuring the propagation time between the target, i.e. the user or device in an unknown location, and the measuring unit (Liu et al., 2007, p. 1068). The reason for this is the fact that the propagation time is proportional with the distance. Similarly to other techniques used for triangulation, the TOA technique requires measurements from at least three access points. They are used to estimate the distance between the access points and the target. To achieve this the units must be synchronized with respect to time as well as a time stamp being attached to the transmitted signal (Liu et al., 2007, p. 1068). The TOA technique uses the intersection of the circles to determine the user's position. Gu et al. (2009, p. 16) define the TOA technique as the most accurate positioning technique due to the possibility to remove multipath effects in indoor environments. The main disadvantage with the TOA technique is the complicated implementation. (Liu et al., 2007; Gu et al., 2009)

2.2 Systems and technologies

There are several possible technologies to base indoor positioning systems on. The subsections of Section 2.2 elaborate the different systems and technologies listed below. In Section 2.3 the accuracies of these are examined in detail, as well as the range, the advantages and the disadvantages of the system. The systems described in this chapter are:

- Radio-frequency (RF)
- Ultra Sonic (US)
- Infrared (IR)
- Wireless Local Area Networks (WLAN)
- Bluetooth
- Magnetic signals
- Vision analysis
- Audible sound
- Kalman Filter
- Cellular-based triangulation

The different systems have different qualities. They can be evaluated based on several features, such as

- system cost
- reliability
- accuracy
- scalability

- energy efficiency
- complexity
- precision
- robustness
- measurement method

(Liu et al., 2007; Feng and Liu, 2012; Ijaz and Lee, 2013; Ekahau, 2014)

2.2.1 Radio-frequency (RF)

Several systems base their technology on radio-frequency. Radio signals have the advantage of the ability to travel through walls. The main principle of RF technology is the measurement of different properties of radio-frequency signals (Ijaz and Lee, 2013, p. 1147). The benefit of RF based positioning systems are that they do not require line-of-sight or contact. The RF system can be divided into several different technologies, such as radio-frequency identification (RFID), RSSI and ultra-wideband (UWB). (Gu et al., 2009; Koyuncu and Yang, 2010; Ijaz and Lee, 2013)

Radio-frequency identification (RFID)

Radio-frequency identification (RFID) is based on ”storing and retrieving data through electromagnetic transmission to an RF compatible integrated circuit” (Gu et al., 2009, p. 22). RFID technology can be combined with wireless networks as this is a low-cost method to single out each device. The basic components are RFID tags, RFID readers and the communication between them. The reader reads the data sent from the tags and can be read in all environments. RFID technology is divided into passive and active RFID, where passive RFID have tags that are the receivers. This makes the tags light and cheap, but their range is very short. In active RFID the tags are the transmitters and therefore more expensive, however the range is longer. The signal strength is reduced with the square of the distance between the tag and the reader (Koyuncu and Yang, 2010, p. 124). RFID is normally used in environments such as hospitals and offices where the indoor environments often are complicated. However, a RFID system requires many components stationed in the area where the RFID positioning system will operate. (Liu et al., 2007; Gu et al., 2009; Koyuncu and Yang, 2010)

LANDMARC is an example of a RFID based indoor positioning system (Koyuncu and Yang, 2010). In this system the RFID tags have a predefined ID so that they can be identified by the RFID readers. The readers have long range and are installed at known locations. They are then set at a specified power level that is correlated to the range of the RFID tags. Koyuncu and Yang (2010) argue that the accuracy of the LANDMARC system depends on the amount of readers and tags in subregions of the region where the system is operational. However, the accuracy can be improved by using reference tags with known locations. These reference tags are used for location calibration and can be used instead of increasing the number of RFID readers in the area. (Koyuncu and Yang, 2010)

Received Signal Strength Information (RSSI)

RF Received Signal Strength Information (RSSI) systems use the strength of the signal to estimate the position of the user. The position is determined using either trilateration, triangulation or fingerprinting to estimate the distance from the object to the transmitters. Most RSSI systems have been based on ”using existing infrastructure of WLAN, resulting in a very low cost system” (Ijaz and Lee, 2013, p. 1147). However, the performance of the RSSI-based systems is very sensitive to errors connected with signal strength, such as reflection, multipath fading, diffraction and scattering. Another disadvantage with RSSI-based systems is that obstacles such as doors and walls are made of different materials and therefore the RSSI value might change and the results might become inaccurate if this is not taken into account. (Kaemarungsi and Krishnamurthy, 2004; Koyuncu and Yang, 2010; Ijaz and

Lee, 2013, p. 1147)

The received signal can be modeled by a combination of a large-scale and a small-scale component, where the large-scale component is generally the most interesting. The large-scale component is based on the fact that the signal moves a distance and might be absorbed by walls and doors (Kaemarungsi and Krishnamurthy, 2004, p. 16). In the case of no line-of-sight component, the small-scale fading is usually modeled with a Rayleigh distribution (Kaemarungsi and Krishnamurthy, 2004, p. 16). In case of a line-of-sight component, the small-scale component is modeled by a Rician distribution. The disadvantages with these two models are that they focus on the influence of radio diffusion on the receiver design and signal coverage instead of from an indoor positioning system point of view, as might prove to be more interesting in these cases (Kaemarungsi and Krishnamurthy, 2004, p. 16).

Ultra-wideband (UWB)

Ultra-wideband (UWB) is a technology based on ultra-wideband pulses that have a short duration, normally less than 1 nanosecond. This makes it possible to filter the reflected signals from the original signal. Systems based on UWB consist of standard electronic components. UWB transmits signals on multiple bands of frequencies at the same time, from 3.1 GHz up to 10.6 GHz (Liu et al., 2007, p. 1074). The systems measure TOA of the received signals which is then sent to a central server that determines the location of the user. UWB based systems neither require line-of-sight, as the pulses pass through walls, equipment and clothing, nor do they suffer from problems with multipath biases. Therefore the UWB systems offer a higher positioning accuracy than many other indoor positioning systems. Additionally, the UWB tags are quite cheap and have less energy consumption than other systems. The cover area for the sensors are also extensible. (Liu et al., 2007; Gu et al., 2009; Koyuncu and Yang, 2010)

Ubinese is an example of a real-time UWB based indoor positioning system (Gu et al., 2009). The Ubinese system consists of tags, sensors and an Ubinese software platform. The tags transmit the UWB pulses. The sensors are placed at known locations and receive the UWB signals from the UWB tags. The Ubinese software platform then receives information about the tags from the sensors through an existing local network for the platform to interpret and determines the tags' locations (Gu et al., 2009). The tags are wireless, light weight and have a battery capacity of about a year (ibid.). However, the system is very expensive as a Ubinese package cost almost 20,000 dollars in 2009. Ubinese uses triangulation locating techniques and takes advantage of AOA and TDOA techniques to determine the user's position (Gu et al., 2009, p. 26). According to Gu et al. (2009) this provides flexibility to the positioning system and the performance of the system is therefore not exposed to complex environments and obstacles such as walls and doors. The range of the equipment is up to 400 m^2 for each cell. One cell is defined by a minimum of four sensors. (Gu et al., 2009)

2.2.2 Ultra Sonic (US)

Ultra Sonic can be used in indoor location systems. Currently two types of US systems have been developed, narrowband and wideband. The narrowband produces sound waves that travel over longer distances. The disadvantage is that the narrowband has a limitation when several users access the system due to problems in distinguishing the signals from each other. Systems using wideband can reduce the limitation with the narrowband systems and interference can also be reduced. The disadvantages with the wideband systems are the need for complex hardware and the high energy consumption. Compared to other systems, US based systems have low system costs. US is often combined with RF signals as this performs both synchronisation and coordination in the system. Together the technologies provide coverage of larger areas. (Ijaz and Lee, 2013; Gu et al., 2009)

According to Ijaz and Lee (2013) a US system delivers centimeter level accuracy on positioning at indoor locations. Another advantage with this system is that it can record several mobile nodes simultaneously and thereby be of service for many users at the same time. However, there is one important disadvantage with the system. The speed of sound depends on the temperature. The following equation describes the speed of sound, where T is the temperature in Kelvin.

$$\nu_{us} = 20.05\sqrt{T} \tag{2.1}$$

To adjust for the error in different temperatures, the US system needs a temperature sensor. The US system is also affected by environmental noise. This can be solved by filtering out the sounds with certain algorithms. (Ijaz and Lee, 2013)

In the recent years, several new US systems have been developed. The Buzz system is one of these (Ijaz and Lee, 2013). It is a narrowband US system using two systems, a synchronous and an asynchronous Buzz (Ijaz and Lee, 2013, p. 1148). Transmission patterns are used to find the position of the user. The advantages of the system are low costs, enhanced form factor and energy consumption. However, the Buzz system expects the speed of sound to be constant and this is a considerable disadvantage. (Ijaz and Lee, 2013)

Another US based system is the Cricket indoor location system (Koyuncu and Yang, 2010; Ijaz and Lee, 2013). The Cricket system consists of beacon and listener nodes, where the beacons are fixed reference nodes. The system uses RF signals to produce a reference time and then calculates the time of flight (TOF). Algorithms are implemented to prevent large errors due to constraints such as scheduling and interference (Ijaz and Lee, 2013, p. 1148). However, continuous noise causes the conduct of the Cricket system to be considerably reduced. The system can use real-time positioning with an update rate of 1 Hz according to Koyuncu and Yang (2010, p. 122). (Koyuncu and Yang, 2010; Ijaz and Lee, 2013)

The broadband system Dolphin is another example of a US system (Koyuncu and Yang, 2010; Ijaz and Lee, 2013). The Dolphin system consists of transmitters and receivers. To provide good measurements of the user's position and reduced influence of noise, the Dolphin system uses a distributing algorithm (DSSS technique).

This requires minimal manual configuration from the user of the system. (Koyuncu and Yang, 2010; Ijaz and Lee, 2013)

In 2009, an article was presented by Gonzalez and Bleakley (2009, p. 1149) defining a robust broadband US system and naming it a ”robust broadband ultrasonic location and orientation estimation” system. This was the first of its kind as the system used frequency hopped spread spectrum (FHSS) technology. It consists of fixed nodes at known locations, i.e. base stations, and mobile nodes. ”Spread spectrum modulation scheme not only provides robustness to multipath and noise, but also allows multiple access simultaneously” (Ijaz and Lee, 2013, p. 1149). This system uses RF signals for the synchronisation between the base stations and the mobile nodes. (Gonzalez and Bleakley, 2009; Ijaz and Lee, 2013)

Another quite new US system is an indoor localisation system that uses code division multiple access (CDMA) to present what Ijaz and Lee (2013, p. 1149) define as ”fine-grained location estimates”. The distance is calculated by the TOA of US signals. The location estimation is calculated based on trilateration. In noise free environments the accuracy results are very good. However, the system has not been tested in noisy environments and the accuracy will probably be severely reduced under normal circumstances and testing environments. (Ijaz and Lee, 2013)

2.2.3 Infrared (IR)

Infrared (IR) is one of the most used indoor positioning systems because IR technology is available in both wired and wireless devices (Gu et al., 2009, p. 19). These devices can be printers, TVs and mobile phones. IR systems require an unobstructed path and are therefore restricted to within a single room. However, if the room is large such as a lecturing auditorium, several transmitters or receivers in the room are required. The system costs are low and the systems are considered to be very accurate. A typical IR system has a simple architecture and rarely needs maintenance. Another advantage is that the tag emitters are small and light. There are some disadvantages with the IR systems in addition to the range. For instance, the

IR architecture do not consider the user's privacy or security. Other disadvantages are problems with interference and expensive hardware equipment. The system requires a transmitter or receiver in each room where indoor positioning will be used, as an IR emitter is limited to one room (Gu et al., 2009).

The Firefly is an example of an IR system developed for motion tracking. Firefly is a commercial product and the system consists of a camera array, tags and a tag controller as presented in Figure 2.4. The tags are small and light-weighted, but due to the wires that connect them they are not comfortable to wear on a daily basis. Additionally, optimal functioning of the system is only possible in normal lighting environments (Gu et al., 2009, p. 20).

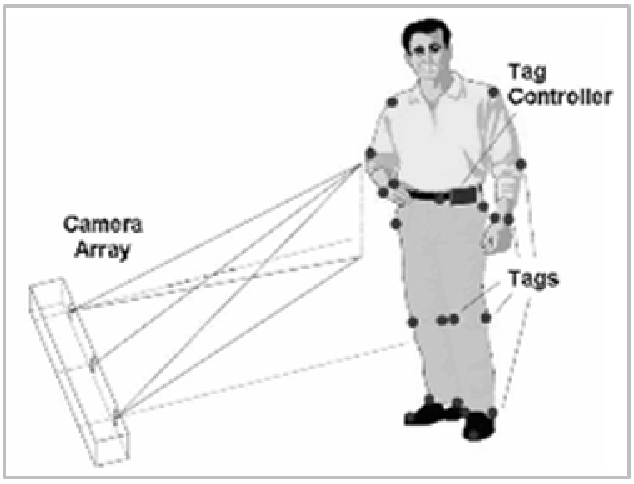


Figure 2.4: *Overview of the Firefly architecture (Gu et al., 2009, p. 22)*

Another indoor positioning system based on IR is Active Badge (Koyuncu and Yang, 2010). The system consists of tags, called beacons or badges, a central server and multiple IR sensors. The beacons are attached to a person and produce a signal four times per minute and the IR sensors observe the transmissions. The central server gathers the information from the sensors and the position of the user can be fixed by the badges' locations. (Koyuncu and Yang, 2010)

2.2.4 Wireless Local Area Networks (WLAN)

In the last years wireless local area network (WLAN) technology has become increasingly popular in public areas and work-related environments such as shopping centers, hospitals, universities and museums. Positioning systems based on WLAN technology are low-costs systems as they use existing WLAN framework to provide the users' position. Compared to other techniques such as US, RFID and Bluetooth, WLAN based positioning systems have longer ranges and the systems are both reusable and scalable (Köbben, 2007, p. 287). Nowadays most hand-held devices such as laptops, tablets and smart phones are able to handle wireless signals. The accuracy of the location estimations depends on the signal strength of the WLAN signals. This is also the most used method to determine a user's position. Other methods include measurement of AOA or TOA (Köbben, 2007) and an algorithm that collects RSSI at both access points and at the mobile devices to provide more accurate positioning (Yeung and Ng, 2007, p. 131). The disadvantage with these two methods is the requirement of additional hardware. (Liu et al., 2007; Köbben, 2007; Yeung and Ng, 2007; Gu et al., 2009; Midtbø et al., 2012)

The signal strength can be affected by components such as the user's movements and other devices that are tracked as well as walls and doors. There are two main disadvantages with positioning systems based on WLAN technology. One disadvantage is the system's location estimates using fingerprinting and stored information. These are complicated estimates and in cases where there are many users at the same time the positioning system is increasingly costly to operate. The other disadvantage is that complex indoor environments with different kinds of obstacles reduce the accuracy of the system. (Liu et al., 2007; Yeung and Ng, 2007; Gu et al., 2009; Midtbø et al., 2012)

RADAR is an example of a positioning system that uses existing WLAN technology to provide position tracking indoors (Liu et al., 2007; Gu et al., 2009). The system is developed by Microsoft (Liu et al., 2007). The RADAR system uses the kNN technique as described in Section 2.1.4 and ”signal strength and signal-to-noise ratio with triangulation location technique” to determine the position of the user or device (Gu et al., 2009, p. 27). The system is easy to establish as it reuses WLAN framework and only needs a few base stations to be able to perform the positioning of users. The disadvantages apply to equipment and privacy. The devices that are used need WLAN technology, which has become quite popular nowadays, but lighter models and models with restricted energy resources might not have the technology necessary. The RADAR system does not consider privacy questions. A user's device might be tracked with WLAN framework even if the user do not want this. Another disadvantage with the RADAR system is limitations in RSSI positioning methodology (Section 2.2.1). (Liu et al., 2007; Gu et al., 2009)

Ekahau is another example of a system using existing WLAN framework for positioning (Gu et al., 2009; Ekahau, 2014). The Ekahau system uses triangulation and RSSI to find the location of the user's device. This is a low-cost and effective way of positioning. The system requires positioning engines, WiFi location tags and a site survey as presented in Figure 2.5 (Gu et al., 2009, p. 24). The positioning engine connects the information from the tags and the site survey to calculate the position. The site survey is a software tool which uses signal strength and site calibration and thereby obtains the network's data rate, coverage area and the overlapping of the WLAN users' locations. The measured data is then sent to the positioning engine which is another software tool that provides real-time positioning for all devices such as laptops (Gu et al., 2009, p. 24). The tags are tracked from the moment they start to move. According to Gu et al. (2009, p. 24) the Ekahau system is a low-cost system due to the sharing of other WLAN networks' access points. (Gu et al., 2009; Ekahau, 2014)

Another example of an indoor location system is the COMPASS system (Gu et al., 2009). As the afore-mentioned RADAR and Ekahau systems, COMPASS reuses existing WLAN frameworks to position the user. COMPASS also uses digital compasses and together the two techniques provide a low-cost system with ”rela-

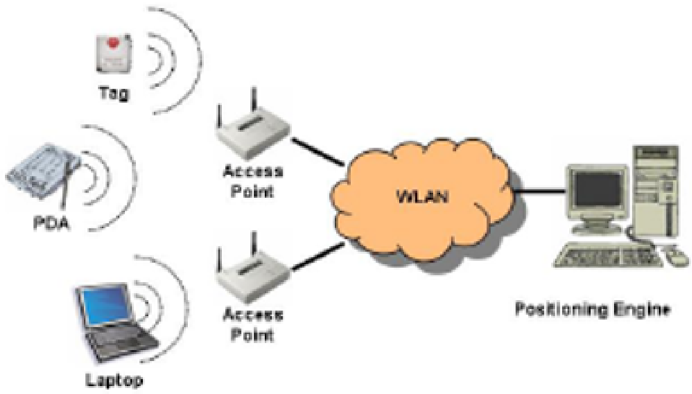


Figure 2.5: *Overview of the Ekahau system architecture (Gu et al., 2009, p. 24)*

tively high" accuracy (Gu et al., 2009, p. 24). The positions are estimated using signal strength from various access points and fingerprinting location technique and a probability algorithm to find the user's location. The digital compass sets the COMPASS system apart from other WLAN based systems, as the compass is used to find the user's orientation. The orientation is calculated by using the compass to limit how the user's body blocks the signals. The COMPASS system takes into account the effect of the amount of water in the human body has on the measurement accuracy by performing several measurements of signal strength from different angles. (Gu et al., 2009)

2.2.5 Bluetooth

Bluetooth is an IEEE 802.15.1 standard. According to the IEEE Standard Association (2014) Bluetooth is defined as "short-range radio frequency (RF)-based connectivity for portable personal devices". This definition is specified by the industry. Bluetooth is a wireless personal area network (WPAN) and some consider it a light standard compared to other WPANs (Liu et al., 2007, p. 1075). Nowadays nearly all devices are Bluetooth enabled such as mobile phones, desktops and laptops. Bluetooth tags are low-cost transceivers with a unique ID. To define a user's position the Bluetooth based positioning systems use other mobile terminals in the same cluster, i.e. in the same group of terminals. The clusters can be seen as the infrastructure in Bluetooth based positioning systems. The distance between the user's device and the tags is calculated based on the propagation loss. The propagation loss is modelled with a propagation loss model as showed in the equation below. The model considers wavelength, transmission signal power P_t, antenna gains of transmitter at a distance d from the transmitter and height of antennas. The constants α and β depend on the system and the environment respectively, where α includes the gains of antenna and the wavelength.

$$P_r = \frac{\alpha P_t}{d^\beta} \tag{2.2}$$

Bluetooth systems have some disadvantages compared to other indoor positioning systems. The major disadvantage is the accuracy. Bluetooth based positioning offers limited accuracy in addition to a delay of about 20 seconds (Gu et al., 2009, p. 25). Another disadvantage is the problems RF has with complicated indoor environments (Section 2.2.1). (Kawakubo et al., 2006; Liu et al., 2007; Gu et al., 2009; IEEE Standards Association, 2014)

The Topaz system is an example of a Bluetooth based indoor positioning system (Liu et al., 2007; Gu et al., 2009). The system merges IR technology with Bluetooth technology. As previously mentioned, IR signals cannot pass through doors and walls which indicates that the Topaz system can only find the room the device is located in, i.e. providing room accuracy. The Topaz system uses both hardware and software components to position a device with Bluetooth technology or simply the Bluetooth tags. Figure 2.6 provides an overview of the Topaz system's architecture and the different components; positioning server(s) (Bluetooth server), location server, access points, location clients and tags. Access points need to be located several places in the indoor positioning area. These access points must be both IR and Bluetooth enabled. According to Gu et al. (2009) there is normally one Bluetooth server. The server receives information about signal strength and then sends the information to the location server which determines the location of the tags. The location server, the Bluetooth server and the clients are connected through WLAN. (Liu et al., 2007; Gu et al., 2009)

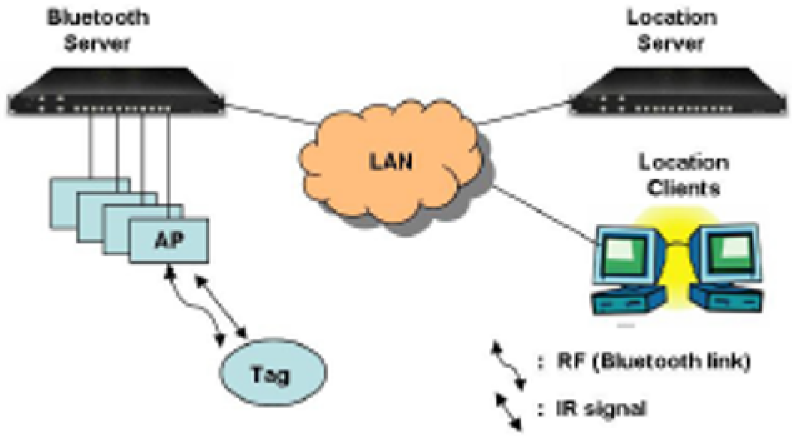


Figure 2.6: *Overview of the Topaz system's components and architecture (Gu et al., 2009, p. 25)*

An advantage of the Topaz system is the ability to track multiple users or devices at the same time. One disadvantage with the system is the limited battery operating time as the batteries need to be charged approximately once a week (Gu et al., 2009, p. 25). Additionally, the delay time is quite long, up to 20 seconds. (Gu et al., 2009)

In late 2013 Apple (2013) launched a new Bluetooth based positioning technique called iBeacon. Apple has provided limited information on iBeacon such as accuracy and range. However, it is clear that iBeacon will use Bluetooth low energy signals to estimate the location of the device. iBeacon will only be available to Apple devices with iOS7 and later operating systems. (Apple, 2013)

2.2.6 Magnetic signals

Magnetic signals is not a recently developed technique of positioning or tracking. Location systems based on magnetic signals do not require line-of-sight. The position of a user or a device is calculated as if it is an obstruction between the transmitter and the receiver. Magnetic sensors are used in magnetic positioning systems. These sensors are small, cheap and robust (Gu et al., 2009, p. 27). Magnetic positioning systems provide multi-position tracking and high accuracy simultaneously. The disadvantage with these systems is the coverage. The cover range is limited and further development and studies are required to improve this so that the system can be more functional indoors. (Gu et al., 2009)

The MotionStar Wireless system is an example of a magnetic positioning system (Gu et al., 2009). This is a newer version of the former MotionStar system (ibid.). The MotionStar Wireless system sends out pulsed direct current (DC) magnetic fields and thus locates the sensors in real-time in a 3 meter coverage area at the same time. The sensors are light and are connected with wires to a RF transmitter. The system can record multiple sensors located on a person and can therefore be functional in different tasks such as virtual reality, biomechanics and animation. The update rate is high with up to 120 measurements per second. The battery time is 1-2 hours and the range of the transmitters is only 3 meters, which is insufficient for most indoor positioning systems. (Gu et al., 2009)

2.2.7 Vision analysis

Tracking locations and identifying devices or people can be done with vision based-analysis. Vision-based analysis do not require a person to wear sensors or other devices. A relatively cheap camera can cover a large area and the user can be located using vision-based indoor positioning systems. Vision-based location systems can record data from targets from one to multiple viewpoints. There are both advantages and disadvantages with vision-based analysis. They are provided in relation to the Microsoft positioning system based on vision analysis called Easy Living. (Gu et al., 2009)

The components of Easy Living are stereo camera(s), a stereo module and a person tracker as showed in Figure 2.7. The system uses two 3D real-time cameras, i.e. using multiple perspectives, to cover the whole area of observation. The stereo cameras are fixed in the ceiling to cover the room. The Easy Living system combines the two cameras to record color and depth and then delivers position sensing and target identification services (Gu et al., 2009, p. 27). The depth and colors are recorded to reduce interference from changes in the background. The stereo module keeps track of the person's movements and the history of movements. The disadvantages with this system are the high energy consumption to process the cameras' images and the unsteady accuracy of the system due to interference of dynamic changing environments (Gu et al., 2009, p. 27).

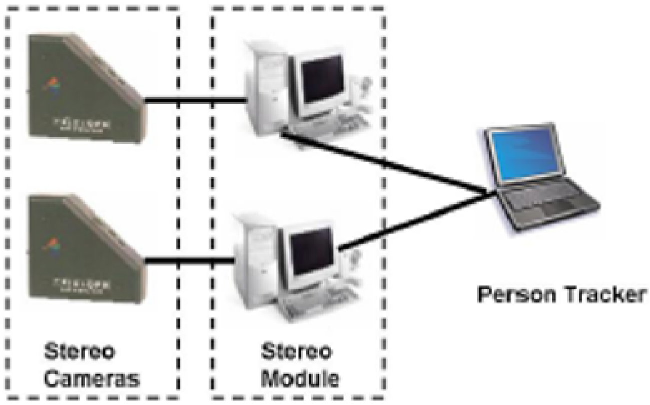


Figure 2.7: *Overview of Easy Living components (Gu et al., 2009, p. 27)*

Generally the privacy of the users of vision-based indoor location systems are not provided. A dynamic changing background causes problems with the vision data. Other factors reducing the performance and the accuracy of vision-based indoor positioning systems are changes in light and weather. The systems cannot track multiple persons at the same time in an efficient way. (Gu et al., 2009)

2.2.8 Audible sound

Nowadays nearly all mobile devices are able to send out audible sound which makes it possible to create positioning systems based on audible sound. These systems use the users' mobile devices and therefore no tags are needed for indoor positioning of the users. There is one major limitation of positioning systems based on audible sound. That is interference from other sources, such as sound noises in public environments and other constant changing environments. Due to the limited range of audible sound, these systems usually provide room accuracy. Additionally, people might find audible sounds irritating in different indoor environments. (Gu et al., 2009)

The Beep system is an example of an indoor positioning system that uses audible sound to find the position of the user (Gu et al., 2009). The system uses triangulation and a standard 3D multilateration algorithm, which is based on the measured TOA, to find the user's position (Gu et al., 2009, p. 28). The Beep system includes a central server and a roaming device. The roaming device transmits audible sound. In the indoor positioning area several acoustic sensors must be installed. The sensors obtain the audible sound and send them to the server. The server is connected to the sensors with a wireless connection. TOA and triangulation techniques are used to calculate the user's position and then the roaming device receives the position through the wireless connection. Privacy is an advantage of the Beep indoor positioning system. The users choose when they wanted to be tracked by turning on and off the transmission of audible sounds on their devices. (Gu et al., 2009)

2.2.9 Kalman Filter

Rudolf Kalman developed a standard filter called the Kalman filter to eliminate noise from data sets (Subhan et al., 2013, p. 7). A positioning system based on the Kalman filter is a technique that combines fingerprinting and trilateration techniques to improve the accuracy of an estimated position. The Kalman filter estimates the state of the process with minimum mean square error between the ideal and the real system states (Subhan et al., 2013, p. 7). The estimation is divided into two parts. The first part of the estimation process is a time update part and the second part is a measurement or correction part. (Subhan et al., 2013)

Subhan et al. (2013) experimented with an indoor Bluetooth positioning system using a Kalman filter. The experiment location was a university building and a Bluetooth USB was used on the devices. The system consisted of four anchor nodes and some mobile devices where the anchor nodes would measure the RSSI and gather these for a data collector program. (Subhan et al., 2013)

The Kalman filter was used in a combination system, integrating inertial navigation systems (INSs) and RFID systems (Koyuncu and Yang, 2010, p. 126). This combination system consisted of three stages in which Kalman filter was used in the third and final phase. According to Koyuncu and Yang (2010) the Kalman filter was used to improve the accuracy of the system by integrating the two INSs and the fingerprinting RFID techniques. The accuracy of the system was measured to just below 1 meter. (Koyuncu and Yang, 2010)

2.2.10 Cellular-based triangulation

Cellular-based triangulation is a technology that uses existing mobile cellular networks or cell towers to determine the position of a device. The technology compares signal strength readings with known positions of the cell towers to define the position of a device. The advantage with this technology is that the signals easily pass through buildings and other obstacles and it is therefore possible to use this technology in indoor positioning systems. However, the accuracy of this positioning method is generally poor as the accuracy of the distance between transmitter and receiver is low. The accuracy might be better in densely populated areas where the density of cell towers are often higher than in rural areas. (Liu et al., 2007; Midtbø et al., 2012)

2.3 Accuracies of the systems

Table 2.1 provides an overview of the accuracies of the different systems mentioned in Section 2.2. Additionally, the range, cost, major limitations and advantages are included. The cost of each system is defined as low, medium or high. The values for range and accuracy are obtained from the most recent source and define the best achieved range and accuracy, not the average values. All data sources for each system in the table are mentioned in the 'Source' column.

The RFID based LANDMARC system has an accuracy of 1-2 meters and a range of 50 meters according to Koyuncu and Yang (2010). The long range is a major advantage of the system and extra reference tags at fixed locations can provide increased accuracy (ibid.).

The Ubinese indoor positioning system is based on UWB and has an accuracy of about 15 cm with short location estimation delay (Gu et al., 2009, p.29). The range of a cell is good with up to a 400 m^2 area covered and the tags are light and have long battery capacities. However, the system is so expensive that the good accuracy and range are outweighed by the price.

The US systems' accuracies depend on the latency and the update rate. The more updates the better accuracy. Among the five systems mentioned in Section 2.2 only the Cricket system has a low update rate and all of them have centimeter level accuracy (Ijaz and Lee, 2013, p. 1150). All the US based indoor positioning systems showed in Table 2.1 have accuracies of 10 cm or better. This is very good, however, the range of these systems are often limited. Buzz is a low cost system with low energy consumption. The major disadvantage with the Buzz system is that it assumes the speed of sound to be constant. As described in Section 2.2.2 this is not the case, because it depends on the temperature.

The Cricket system has an accuracy of 2 cm and a range of 10 meters according to Koyuncu and Yang (2010, p. 126). Liu et al. (2007) however claim that the accuracy is 10 cm and agree on a range of 10 meters. In any case the accuracy of the Cricket system is good and the range is quite limited. The disadvantages include high power consumption and reduced performance in noisy environments. The Dolphin system has a very high accuracy of 2-3 cm, however the range is restricted to room scale (Koyuncu and Yang, 2010, p. 126, Ijaz and Lee, 2013, p. 1150). This limits the use of the Dolphin system and it requires additional equipment to provide positioning in indoor environments not limited within a single room.

The robust broadband system has an accuracy of 1.5 cm, while the range of the system is unknown. The range of broadband US systems, such as this one, is generally shorter than for narrowband because narrowband waves have a longer reach (Ijaz and Lee, 2013, p. 1148). The US based system that uses CDMA also has an unknown range, while the accuracy is 2 cm (ibid.). However, this system has not been tested in noisy environments and the accuracy is considered to be severely reduced under such conditions.

The IR based system Firefly has an accuracy of 3 mm and a cover range of 7 meters according to Gu et al. (2009, p. 20). Similar to other IR based indoor positioning systems, the range is limited to within a room as the IR signals cannot pass through obstacles such as walls, doors and ceilings. Another limitation of the Firefly system is the fact that the tags are connected through cables, which make them uncomfortable to wear. Another IR based system is the Active Badge, which has an accuracy of 7 cm and a cover range of 5 meters. (Gu et al., 2009)

RADAR is one of the WLAN based positioning systems. WLAN based indoor positioning systems are generally low cost systems. The accuracy of the RADAR system is about 3-5 meters and the range is 4 meters. The system requires specific equipment, however, the advantages include reusing WLAN frameworks and the possibility of employing PCs as access points in the triangulation. The Ekahau system is another system based on WLAN technology. Ekahau has an accuracy of about 1 meter. The advantage of the Ekahau is the long battery capacity, the disadvantages are the calibration time and the requirement of more than three access points. The third WLAN based indoor positioning system described in the previous section was COMPASS. The accuracy of COMPASS is good, approximately 1.65 meters. The system reuses existing WLAN frameworks and the digital compass improves the system's performance. The disadvantages of COMPASS are that the human body blocks the signals and that there are no possibilities to perform real-time tracking services. (Liu et al., 2007; Gu et al., 2009)

The Bluetooth based indoor positioning system Topaz has an accuracy from 2 meters and a room scale range. The system is costly as it is indicated to have a medium to high price. The disadvantages of the Topaz system are the limitation of room range and the fact that the tags used in the Topaz system must be recharged weekly. The advantage with this system is that it does not require line-of-sight. (Liu et al., 2007; Gu et al., 2009)

The MotionStar Wireless system is a high cost positioning system based on magnetic signals. The range is about 3 meters and the accuracy 1 cm. The advantage with this system is the small, light and robust sensors. The main disadvantages are the very short range and the limited battery capacity. (Gu et al., 2009)

The Easy Living system is a low cost, vision-based analysis system. The accuracy of the system is difficult to define due to the limitations of the system. The disadvantages of the Easy Living system are problems with the vision data if the background is dynamically changing and the image processing is complicated. Additionally, the power consumption of the system is high. Apart from these disadvantages, the Easy Living system employs low cost cameras and equipment of low complexity. (Gu et al., 2009)

The audible sound-based indoor positioning system Beep operates with an accuracy of 40 centimeters. However, sound noise and obstacles reduce the accuracy of the system with 6-10 % according to Gu et al. (2009, p. 28). Sound noise is considered the main disadvantage of this system. The advantages with Beep are the low cost and the low complexity of the system as well as the possibility for personal devices such as phones and computers to be used in the positioning.

Furthermore, the privacy of the user is preserved by the Beep system as users control the transmission of audible sounds and thus the tracking of their devices. (Gu et al., 2009)

Cellular-based triangulation technology has a poor accuracy of about 50 meters. This will not provide room accuracy, it might even estimate the location of a device to be in the wrong building. The range and density of the cell towers are highly variable. It often provides better accuracy in density populated areas with buildings inside which users might need indoor positioning compared to rural areas. (Liu et al., 2007; Midtbø et al., 2012)

2.4 The Cisco system

The Cisco Wireless Location Appliance (WLA) is used in the test described in Chapter 3. Cisco's WLA is a part of Cisco Unified Wireless Network, a cost-effective system with high-resolution tracking availabilities (Cisco, 2007).

According to Cisco's web page (Cisco, 2008) the accuracy of WLA is considered to be within 10 meters 90 % of the time and within 5 meters 50 % of the time (Cisco, 2008). However, this accuracy depends on the locations of the access points. The last update of these statements were in 2008 and it remains unclear if the accuracies have changed since then.

2.4.1 Positioning technique

Cisco's WLA uses RF fingerprinting technology and RSSI information to estimate the position of a device (Cisco, 2008). Figure 2.8 illustrates how WLA will be used in indoor positioning in a system based on Cisco equipment (access points, wireless LAN controllers etc.). The equipment is required to be connected. Wireless LAN controllers collect RSSI information and transmit it to the Simple Network Management Protocol (SNMP) (Cisco, 2008). The location is then estimated by the WLA using the collected RSSI information (ibid.).

The Cisco system also has the opportunity to generate heat maps based on network maps and the access points' locations and to visually illustrate the location of the user on a floor plan of the current building (Cisco, 2008). According to Cisco (2008), the system can track the location of thousands of devices.

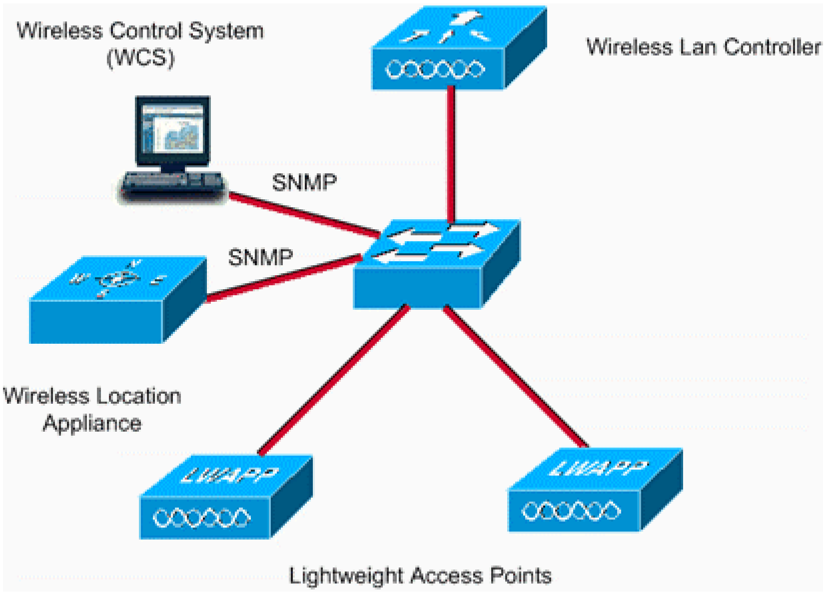


Figure 2.8: *Cisco Location Appliance used in indoor positioning (Cisco, 2008)*

Table 2.1: *Accuracy of indoor positioning technologies and systems*

Technology	System	Method	Accuracy	Range	Cost	Major limitation(s)	Advantage(s)	Source(s)
RFID	LANDMARC	RSSI, triangulation	1-2 m	50 m	Medium	Requires many components	Long range	Koyuncu and Yang, 2010
UWB	UWB	TOA	10 cm	15 m	Medium		Multiple frequencies. No range-of-sight or multipath biases.	Gu et. al., 2009, Koyuncu and Yang, 2010
	Ubinese	AOA, TDOA, triangulation	15 cm	400 m2 cover area pr cell	High	Very expensive	Light tags, long battery capacity	Gu et. al., 2009
Ultra Sonic	Buzz	TOA	4-10 cm	Unknown	Low	Expects constant speed of sound	Low energy consumption, multiple nodes simultaneously	Ijaz and Lee, 2013
	Cricket	TDOA	2 cm (10 cm)	10 m	Low	Continuous noise reduces performance, high energy consumption	Algorithms to prevent scheduling and interference	Gu et. al., 2009, Koyuncu and Yang, 2010, Ijaz and Lee, 2013
	Dolphin	TOA	2-3 cm	Room scale	Medium		Minimal user configuration	Koyuncu and Yang, 2010, Ijaz and Lee, 2013
	Robust broadband	TOA, AOA	1.5 cm	Unknown	High		Robust to multipath and noise, multiple access	Ijaz and Lee, 2013
	Using CDMA	TOA	2 cm	Unknown	Unknown	Possibly severely reduced accuracy in noisy environments	Good accuracy in noise free environments	Ijaz and Lee, 2013
Infrared	Firefly		3 mm	7 m	Medium/ high	Cables connect tags, requires normal lighting	Light tags, simple architecture	Gu et. al., 2009
	Active Badge	TOA, trilateration	7 cm	5 m	Low/ medium	Cables connect tags	Simple architecture	Koyuncu and Yang, 2010
WLAN	RADAR	kNN, triangulation	3-5 m	4 m	Low	Equipment requirements	Uses existing WLAN framework, uses PC as APs	Liu et.al., 2007, Gu et. al., 2009
	Ekahau	Triangulation	1 m	Unknown	Low	Requires more than 3 APs and calibration time	Long battery capacity	Liu et.al., 2007, Gu et. al., 2009
	COMPASS	Digital compass, fingerprinting	1.65 m	Unknown	Low	Human body blocking effect, no real-time tracking services	Uses existing WLAN framework and digital compass to improve performance	Gu et. al., 2009
Bluetooth	Topaz		2 m	Room scale	Medium/ high	Recharging of tags, room level accuracy	No requirement of line-of-sight	Liu et.al., 2007, Gu et. al., 2009
Magnetic signals	MotionStar Wireless		1 cm	3 m	High	Short range and battery capacity, expensive, wired components, heavy transmitters	Small, light sensors	Gu et. al., 2009
Vision analysis	EasyLiving		Unknown	Unknown	Low	Complex image processing, high power consumption, unreliable in dynamic changing environments	Low cost cameras, low equipment complexity	Gu et. al., 2009
Audible sound	Beep	TOA, triangulation	Up to 4 mm	Unknown	Low	Severely affected by sound noise	Possibility to position with personal devices, privacy, low cost and complexity	Gu et. al., 2009
Cellular-based		Triangulation, telephone trunk	50 m	Varying	Medium	Not necessarily cover in indoor environments, low accuracy	Passes easily through buildings and obstacles	Koyuncu and Yang, 2010

Chapter 3

Test of commercial system

3.1 Preliminary and preparatory work

The accuracy of indoor positioning measurements using the Trådløse Trondheim system was measured in the NTNU building called the Lerkendal building. The study described in the article by Midtbø et al. (2012) was the basis for the framework and the equipment used in this experiment.

3.1.1 Framework and equipment

In the Lerkendal building, also known as 'Byggteknisk', a total of 31 access points and 45 control points are located. The access points were accurately measured by the Geomatics department at NTNU and then updated for Trådløse Trondheim's model. The access points however, are not located for the primary purpose of indoor positioning, but rather for data communication at NTNU. Therefore these access points are not located to provide the best geometry for indoor positioning (Midtbø et al., 2012, p. 5). The control points were specified with red enamel paint on the floor in closed rooms such as offices and in more open areas such as corridors. These control points are placed on three different floors. They are however, mainly located on the first floor as indicated in Figure 3.1. (Midtbø et al., 2012)

31 out of the 45 control points are placed on the first floor, nine on the second floor and five on the lower floor. Some of the control points used in the 2012 study were used in this test as well. The Lerkendal building has its own local coordinate system with origin in the upper left corner of Figure 3.1 just outside the building. Up on the floor plan is defined as north in this figure. The local X axis goes directly east in this floor plan and the Y axis goes directly south. (Midtbø et al., 2012)

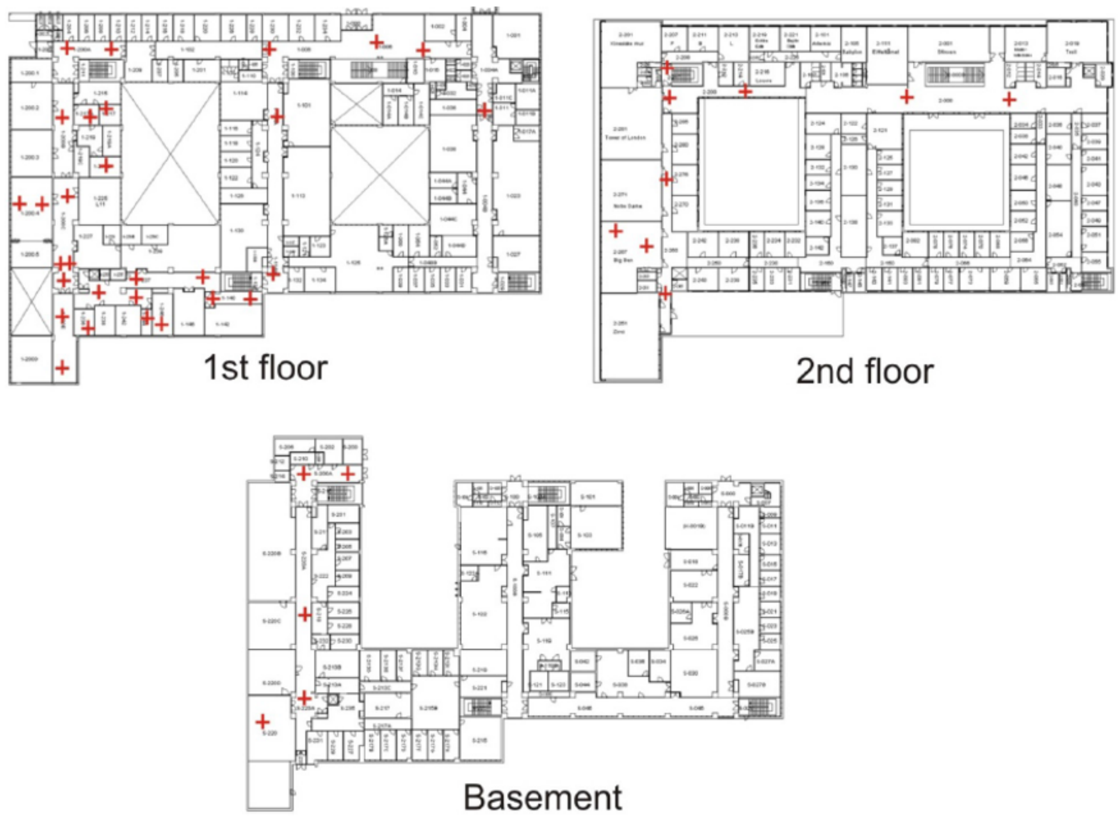


Figure 3.1: *Overview of the control points located in the Lerkendal building at NTNU (Midtbø et al., 2012, p. 6)*

The equipment used for the measurements is showed in Figure 3.2. The mobile platform is built for indoor positioning by the Geomatics department at NTNU. A HP Mini laptop was placed on the platform and connected to an external WiFi unit through a USB connection (Midtbø et al., 2012, p. 8). This was due to elimination of systematic errors as the external WiFi unit made it simple to position the platform directly over the control points and simultaneously maintain a consistent height above the floor for all measurements. A pin was installed directly beneath the external WiFi unit and close to the floor to ensure a correct position of the platform directly above the control point. The position of the pin above a control point is showed in Figure 3.4. Figure 3.3 provides an example of an access point. (Midtbø et al., 2012) The external WiFi unit had the following specifications:

- Realtek RTL8188CU Wireless LAN 802.11n USB 2.0 Network Adapter

Figure 3.2: *The measuring platform used for the measurements in the Lerkendal building (Midtbø et al., 2012, p. 8)*

A JavaScript file was used in the measurements. The file is provided in Appendix C. It is identical to the web application, which was developed as a web page, created and used in the 2012 study by Midtbø et al. (2012). The web application used Cisco Wireless Location Appliance (WLA) to gather the positions (Midtbø et al., 2012, p. 7). The server functionality did an HTML5 GeoLocation request to collect the most accurate data (ibid.).

Running the application in a web browser provided the user with certain information about the estimated position. A screen shot of the output information is

Figure 3.3: *Example of access point*

Figure 3.4: *Position of pin above a control point*

presented in Figure 3.5. The output consisted of a time stamp, a confidence number and information of the campus, the building and the floor on which the location was estimated to be. The output also defined the latitude and longitude of the estimated position in UTM, Zone 32N coordinates (Midtbø et al., 2012, p. 7) and X, Y and Z coordinates, i.e. local coordinates, of the estimated position. The Z coordinate defined the floor, i.e. a Z coordinate of '1.0' corresponded to the 1st floor. Each measurement was written on a separate line and the measurements were generated in a chosen interval. In this test an interval of 15 seconds (15.000 ms) was chosen.

Start Interval (ms): 15000

timestamp	changedOn	confidencefactor	elem	geoLatitude	geoLongitude	x	y	z
1402235988334	1402235987651	14.630400000000002	Gløshaugen|Byggteknisk|1. etasje	63.41493468115045	10.40618808762912	58.5	370.79	1.0

Figure 3.5: *The output information provided after a running of the JavaScript file*

3.1.2 Trådløse Trondheim and including walls in the model

The IT department at NTNU holds a Cisco based model for all buildings at NTNU and in their model they can draw the internal walls and the outer walls of a building. Students at NTNU can neither access or modify this model, however Trådløse Trondheim are able to. The maximum number of walls inserted in this model is a total of 50 walls. Floor plans of the Lerkendal building were collected from NTNU's map solution on the official NTNU web page (NTNU, 2014a,b,c). The floor plans were then color painted using the free graphical vector editing, software program Inkscape before it was sent to Trådløse Trondheim for them to include the walls in the model (Inkscape, 2014). Inkscape was chosen due to the simple interface and tools that suited the purpose, i.e. painting the walls to illustrate which walls were to be added to the Trådløse Trondheim's model. In certain special cases, such as the outer walls and a lift shaft, different colors were used to distinguish type of walls and obstacles from internal walls. However, this was only done to indicate the walls in the different phases and to point out the lift shaft close to several control points. Trådløse Trondheim's model did not have the possibility to add type of obstructions, such as lift shaft, stairwell or concrete wall, to the model.

3.1.3 Hypotheses

The main objective of this thesis was to research the accuracy of indoor positioning using NTNU's wireless network. As specified in the task description, obstacles would be included in the model and their effect on the measurements would be studied. Additionally, room accuracy was an important issue of indoor positioning and the estimation of a location inside the correct room was an important aspect of this test. The two main research questions to be studied in the test were: How did the inclusion of walls in the model affect the indoor measurements? What accuracy in terms of room accuracy could be achieved at the indoor locations? In order to answer these questions they were divided into the supplementary questions listed below of which the test aimed at answering.

- What effect did the outer walls have on the accuracy and the precision of the measurements?
- What differences in accuracy and precision were achieved with a complete wall model compared to an outer wall model?
- How did the removal of walls affect the accuracy and the precision of the measurements?
- How accurate were the results with regards to room accuracy?
- How did other obstacles such as lifts shaft affect the accuracy and precision of the measurements?
- What was the relationship between the confidence number and the measurements' standard deviations and variances?

3.1.4 Original schedule and changes due to errors in access points coordinates

The following phases were originally scheduled for the measurement study.

- Phase 1: Base measurements
- Phase 2: Outer walls
- Phase 3-5: Wall models

After several measurement rounds following this schedule had been performed and the analyse had started an error was discovered: The access points in the building had incorrect local coordinates. This was also visible from a heat map Trådløse Trondheim generated after insertion of all outer walls and chosen internal walls located close to the chosen control points (Section 3.2) and internal walls between control points and access points. The heat map is displayed in Figure 3.6 and shows that one access point was placed on top of another one (access point 'wlan-1200b-382-ap' had the same coordinates as access point 'wlan-1200b-382-ap2'). Additionally, other access points had incorrect locations on the heat map compared to the real world. Some access points were placed in different rooms, some in the middle of a room and some in the middle of corridors, even though all access points in the Lerkendal building were placed on walls.

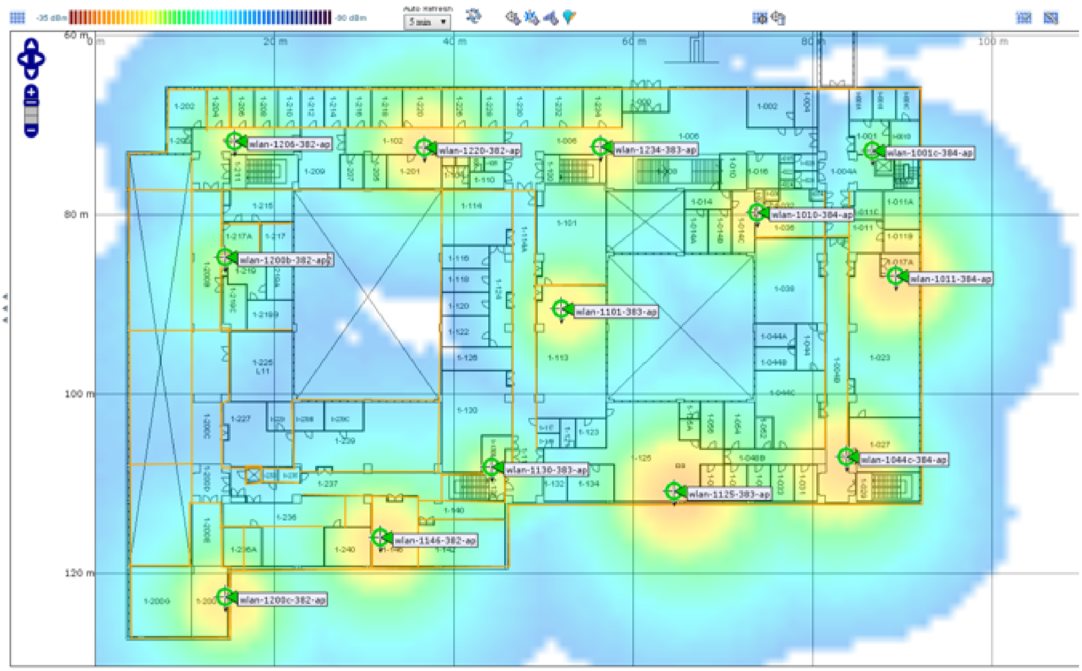


Figure 3.6: *A heat map generated by Trådløse Trondheim showing errors in access points coordinates*

To solve this, a meeting between the supervisors of this project and Trådløse Trondheim was held. It was then decided to check the coordinates of the building and this discovered that the GPS markers of the building needed to be changed as they were not up to date. The old markers did not affect the coordinates of the access points, but they were incorrect considering the floor and size of the building. The Geomatics department at NTNU had a list of the exact positions of the access points from previous measurements. All access points' coordinates in the Lerkendal building were then updated manually according to this list. The measurements already done in some of the phases in the original schedule could not be used in this study as they were incorrect and this caused a step backward in the work. A new schedule was established as presented in the next section.

3.1.5 New schedule

As the insertion, deletion and updating of the model was a cumbersome and time-consuming method, it was decided to keep the changes of walls in the model to a minimum between each phase. The outer and internals walls that are indicated in Figure 3.7 were therefore kept as they already were, as these had been inserted into the model prior to the discovery of the coordinate errors. This phase was called the complete wall model phase. As previously mentioned, the internal walls were chosen due to proximity to the control points and internal walls located between the control points and the nearest access points. The original schedule was inverted to provide only small changes in the model over time.

The location of the outer and internal walls had not been affected by the corrections to the building and the access points' coordinates. The first phase was therefore be the complete wall model. After analysing the results from this phase, the two next phases were modifications of the internal walls in the complete wall model to study the effects of walls between the control points and the access points. The fourth phase was the measurement of the control points with only the outer walls of the building. In the fifth phase no internal or outer walls were part of the model. This phase was the base measurement phase of the study where the control points' coordinates were compared to the true values of the control points as a basis for the other phases.

The following phases were then planned in the following sequence:

- Phase 1: Complete wall model
- Phase 2: Wall model with alterations part 1
- Phase 3: Wall model with alterations part 2

Figure 3.7: *Complete wall model of the first floor of the Lerkendal building (edited from NTNU (2014b))*

- Phase 4: Outer walls
- Phase 5: Base measurements

3.2 Methodology

Previous studies in the Lerkendal building had accurately measured the positions of ten of the control points using a total station as described by Midtbø et al. (2012). These points were measured using the value feet to define the position of the control points. Since the measurements were done in 2012 the value of the measurements had been changed from feet to meter. Therefore the true value values were converted from feet to meter to simplify the comparison between the true values and the measured coordinates of the control points in the base measurements. The reason for this was to assure that the control points had not moved or that the system had not changed its origin.

The floor plan for the first floor in the Lerkendal building was used to draw the walls of the building in Inkscape. An image file in the png format was then sent to Trådløse Trondheim to employ in the model. Trådløse Trondheim drew the walls in a software program called Prime map editor.

During all measurements the orientation of the measuring platform was constant as an external WiFi unit faced the southernmost wall of the neighbouring building, the Realfag building at NTNU. All control points were measured in an arbitrary sequence. The use of two decimal numerals accuracy for the coordinates of the control points was decided in consultation with the main teaching supervisor. The second decimal numeral indicated centimeter level accuracy. For all the measurements phases the coordinates of the control points were recorded manually. One measurement round consisted of a total of five measurements of each control points. Mean X and Y values were calculated based on the five measurements' coordinates for each control point. Additionally the confidence number of each measurement, abbreviated to "conf" in the tables, and the time of measurements at each control point were registered. The confidence numbers were recorded with up to four decimal numerals accuracy. All measurements are provided in Appendix A.

The following control points on the first floor in the Lerkendal building were measured in this test:

- P1-17 *
- P1-24 *
- P1-01 *
- P1-05 *
- P1-10 *
- P1-13 *
- P1-26
- P1-31
- P1-23
- P1-12
- P1-16

These control points are indicated in Figure 3.8. They were located near possible interesting situations such as close to a lift shaft, a stairwell or an access point. The first six control points listed above were measured in the study described in the 2012 article by Midtbø et al. (2012). These control points are marked with a star symbol (*). The true and mean value results from this study are presented in Figure 3.9.

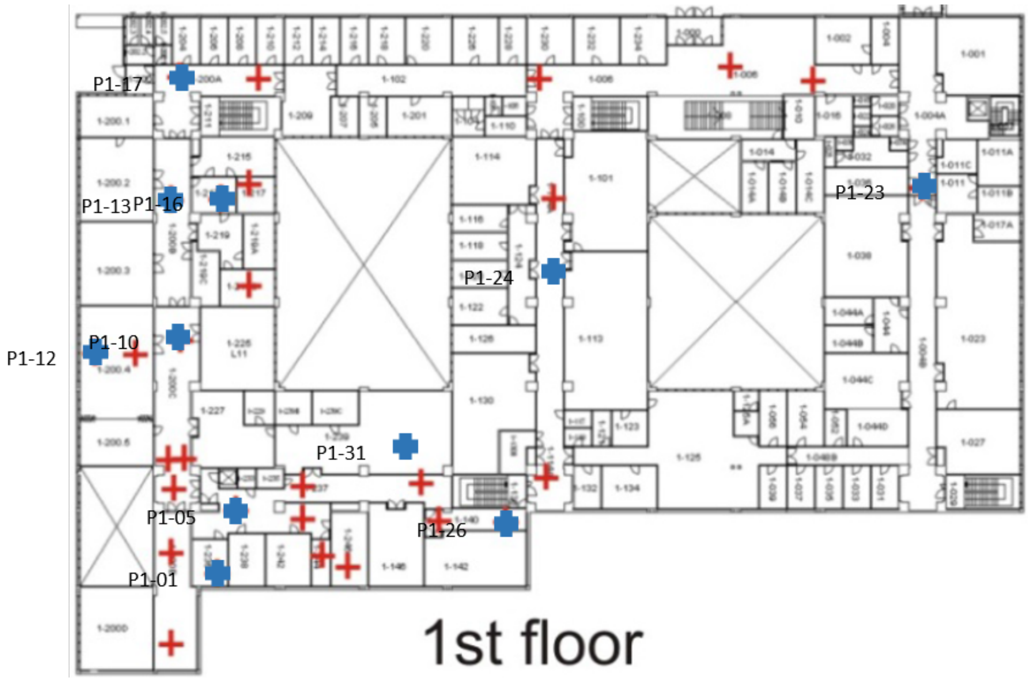


Figure 3.8: *The control points on the first floor of the Lerkendal building (edited from Midtbø et al. (2012, p. 6))*

In 2012, when that study was performed, there existed one fit, i.e. an adaptation, of the coordinates of the access point and the control points in centimeter level accuracy. From this a transformation was done and the local coordinates of both access points and control points were established. Between the 2012 study and the execution of this test a better fit had been accomplished and thereby another transformation which changed the coordinates of the access points and control points. This is called the second fit and the true value coordinates of this fit were used in the comparisons in Chapter 4 and not the values in Figure 3.9. The meter values of the chosen control points after the second fit are presented in Table 3.1 with two decimal numerals. These coordinates were provided from the Geomatics department

	True val.	Mean values			
Control point	x y	1 Old no FP	2 New no FP	3 Old with FP	4 New with FP
P-1	18 364,6	40,7 397,8	53,4 390,6	64,3 378,6	61,4 366,1
P-13	40,5 266,1	42,7 268,2	48,0 263,5	48,1 277,7	45,9 273,4
P-24	154,4 284,9	145,7 295,5	182,8 277,5	163,2 292,2	161,2 268,6
P-18	64,7 226,8	48,2 219,8	51,0 235,4	79,3 233,7	62,4 235,2
P-05	60,6 354,5	57,8 375,0	55,7 368,1	71,0 359,7	69,3 356,2
P-17	41,5 225,1	57,0 259,8	56,7 254,5	54,5 255,5	61,8 255,5
P-09	40,3 340,1	62,7 332,8	80,3 290,5	66,3 350,7	77,2 307,6
P-28	113,8 347,4	118,4 362,8	106,3 343,8	107,8 360,7	102,5 343,1
P-10	43,1 305,6	43,9 311,3	54,8 309,5	62,5 293,3	67,4 308,8
P-02	88,1 369,9	83,2 396,8	53,8 403,6	79,5 375,2	60,1 372,3

Figure 3.9: *The true and mean values of the control points measured in the Lerkendal building from the 2012 study (Midtbø et al., 2012, p. 9)*

at NTNU and in both feet and meter values (NTNU Division of Geomatics, 2014, p. 12-13).

The external WiFi unit connected to the laptop was connected to a wireless network called 'eduroam', as this network had good signal intensity at NTNU and it was a secure network. A connection to 'eduroam' requires a user name and password. The wireless connection of the laptop itself was not connected to any wireless network. The JavaScript file was run in a Google Chrome browser. For each measurement at a new control point the JavaScript file was started and then ran for four or five sequences and thereby causing a 45-60 second initialisation. The external WiFi unit was then disconnected from the 'eduroam' network and reconnected between each measurement. Due to frequent occupancy in 'Galleri 4' (room 1-200.4), the measurements of the control point P1-12 were often performed later than the other control points.

Table 3.1: *The true values of the chosen control points in 2014, another fit than in the 2012 study*

Control point	**True value [meter]**
P1-17	
X	13.34
Y	73.64
P1-24	
X	49.54
Y	92.69
P1-01	
X	18.31
Y	121.55
P1-05	
X	19.54
Y	115.03
P1-10	
X	13.91
Y	99.39
P1-13	
X	13.05
Y	86.77
P1-26	
X	45.20
Y	116.19
P1-31	
X	31.79
Y	110.08
P1-23	
X	85.48
Y	85.10
P1-12	
X	5.41
Y	99.27
P1-16	
X	16.79
Y	85.27

3.3 Phase 1: Complete wall model

As previously mentioned the complete wall model was studied in the first phase due to the coordinate errors. Figure 3.7 shows the complete wall model which was used in this phase. The lift shaft is included and drawn in blue to distinguish the square from other walls as it was a small complete rectangle. The outer walls were drawn in green and the internal walls in red. In this model there were a total of 50 walls: four for the lift shaft, ten for the outer walls and 36 for the chosen internal walls. The internal walls that are indicated in Figure 3.7 were chosen due to their proximity to either control points, access points or both. Figure 3.10 shows the model Trådløse Trondheim created from this floor plan with outer and internal walls. The figure also shows the locations of the access points after the coordinate corrections were embedded in the model.

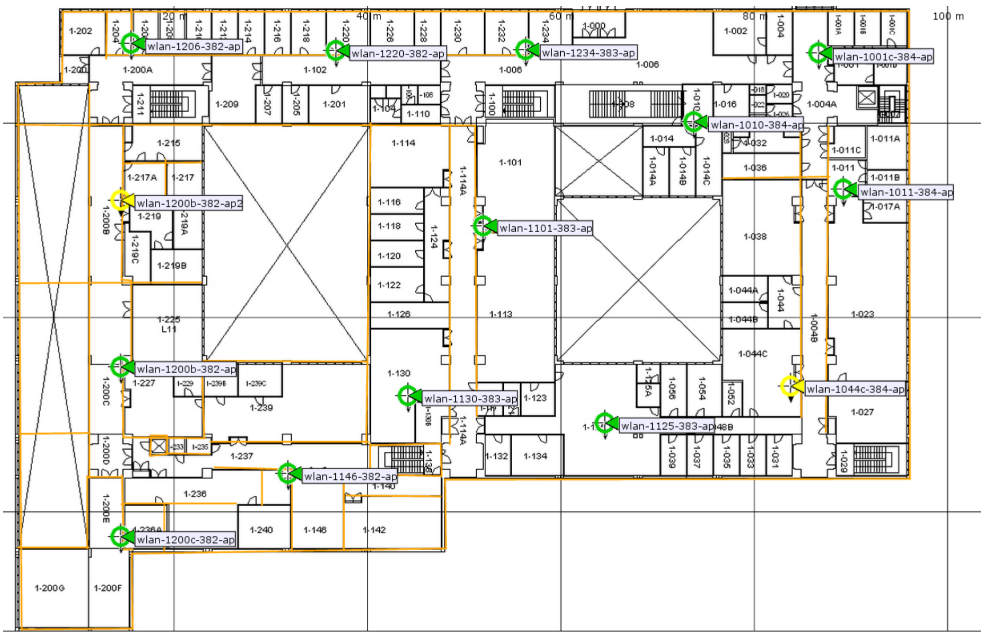


Figure 3.10: *Complete wall model: Trådløse Trondheim's model after insertion of outer and internal walls*

Two measurement rounds were performed for this phase. The first measurement round was done with time difference between the measurements of about 3 hours, i.e. the control points were measured three times and then measured again twice after about 3 hours. The second measurement round was measured without time difference, i.e. each control point was measured five times in a row. This meant that the control points were measured ten times in total. Mean X and Y coordinate values were calculated for both measurement rounds, however for the first round two mean X and Y values were calculated: one mean X and Y for measurement number 1, 2 and 3 and one mean X and Y values for measurement number 4 and 5. The measuring rounds were performed the 21st and 25th March 2014.

3.4 Alterations for phase 2 and 3

Some of the control points were used as the basis for phase 2 and phase 3. Three control points were chosen due to their location inside a triangle of access points: P1-05, P1-23 and P1-31. These control points were located inside different triangles, i.e. triangles of maximum two identical access points. Additionally, control point P1-16 was chosen because it was among the topmost four accurate coordinates when considering the difference between mean value and true value in both of the measurement rounds in phase 1.

Prior to the discovery of a second fit (Section 3.2), the differences between the measurements from phase 1 and the true values were calculated. The control points with less than 10 meters difference between the mean value and the true value in both X and Y direction were studied. These control points were interesting as the removal of internal walls between the control points and the closest access points might provide changes in the accuracy. These were the ones mentioned above and the following control points were therefore used for further inquiries:

- P1-05
- P1-31
- P1-23
- P1-16

Figure 3.11 shows the locations of the chosen control points.

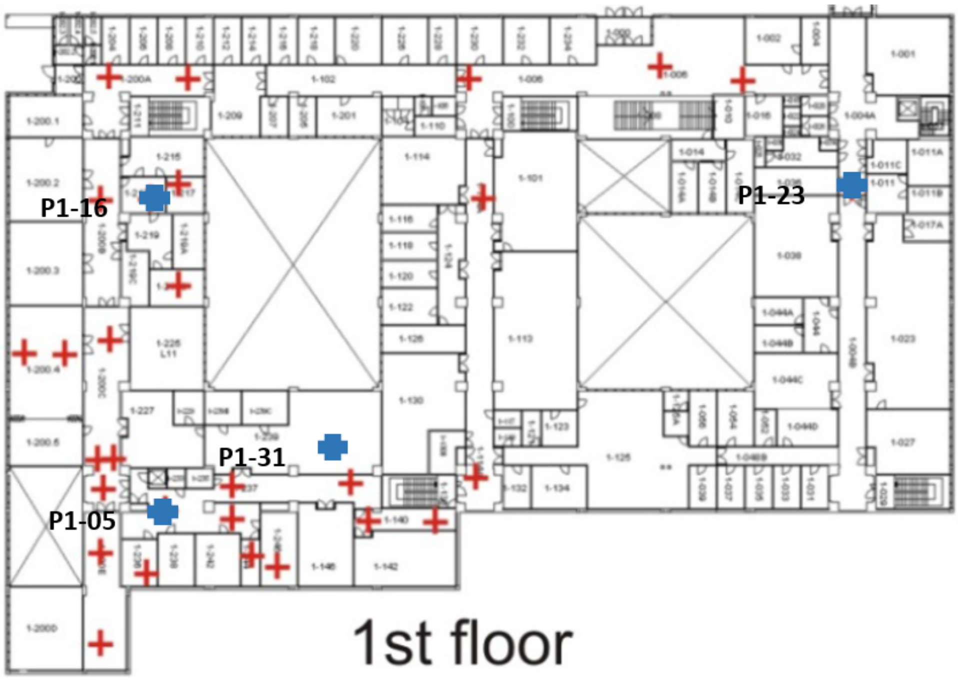


Figure 3.11: *The four chosen control points on the first floor of the Lerkendal building (edited from NTNU (2014b))*

For phase 2, the nearest walls located west (one internal wall) or east (four internal walls) – in the floor plan – of the four chosen control points and at the same time located between a control point and the nearest access point were removed. All other walls were kept as in the complete model. The reason for this was that the four chosen points all had one access point located closer than the other access points, but not the same access point. To exclude these walls from this phase made it easy to distinguish phase 2 from phase 3. This scenario is presented in Figure 3.12, where the blue walls indicate the internal walls that were removed in phase 2. In total five internal walls were removed.

In phase 3 the removed walls from phase 2 were included in the model. The internal walls removed from the model in phase 3 were walls located between the chosen control points and the access points in north-south direction in the floor plan or the second nearest access point in east or west direction. Figure 3.14 shows this scenario, where blue walls again indicate removed internal walls. In total six internal walls were removed from the model in the third phase.

3.5 Phase 2: Wall model with alterations part 1

The wall model for phase 2 is presented in Figure 3.12. The model Trådløse Trondheim created from this modified floor plan is provided in Figure 3.13.

Figure 3.12: *Wall model with alterations part 1: The internal walls kept from the complete model in red, removed internal walls in blue (edited from NTNU (2014b))*

All of the 11 control points were measured 15 times during three measurement rounds in phase 2. The first two measurement rounds were done without time difference. The third measurement round was performed with time difference between the measurements of about 2.5 hours, i.e. the control points were measured three times and then measured again twice after about 2.5 hours. The mean X and Y values were calculated for the three measurement rounds, however for the third round two mean X and Y values were calculated: one mean X and Y for measurement number 1, 2 and 3 and one mean X and Y for measurement number 4 and 5. The measuring rounds were performed the 1st and 2nd April 2014.

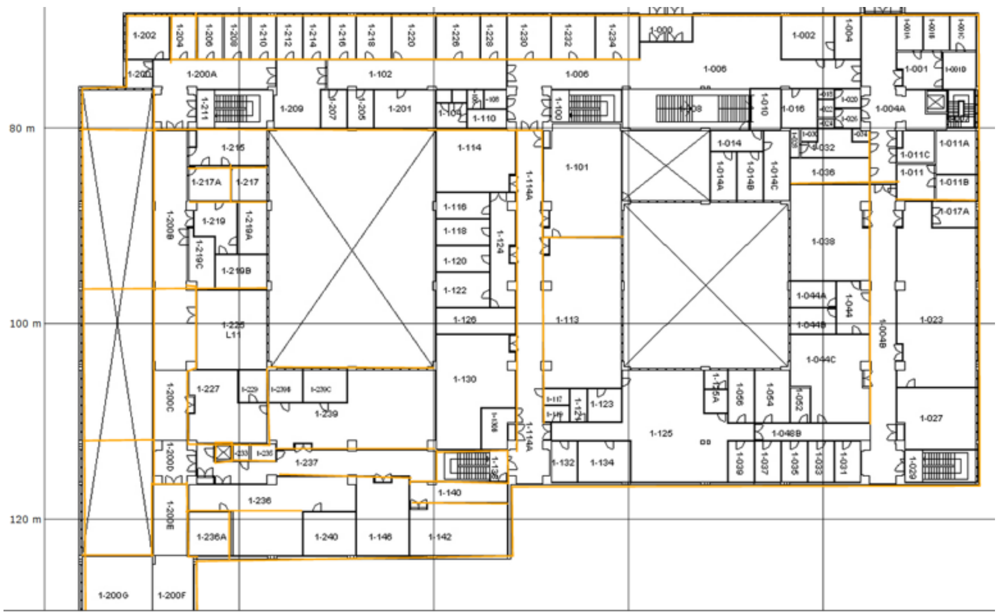


Figure 3.13: *Wall model with alterations part 1 in Trådløse Trondheim's model*

3.6 Phase 3: Wall model with alterations part 2

Figure 3.14 shows the internal and outer walls included in the wall model with alterations part 2. The model Trådløse Trondheim created from this wall model is provided in Figure 3.15.

All control points were measured 15 times during three measurement rounds of phase 3, similar to phase 2. The first measurement round was done in two groups of measurements with time difference of approximately 3.5 hours between them. The second and third measurement rounds were performed without time difference. Thereafter mean X and Y values were calculated for the three measurement rounds, similar to phase 2. The measuring rounds were carried out the 3rd and 4th April 2014.

3.7 Phase 4: Outer wall model

In the outer wall model all internal walls from previous phases were removed and only the outer walls remain, as are presented in Figure 3.16. Figure 3.17 shows the

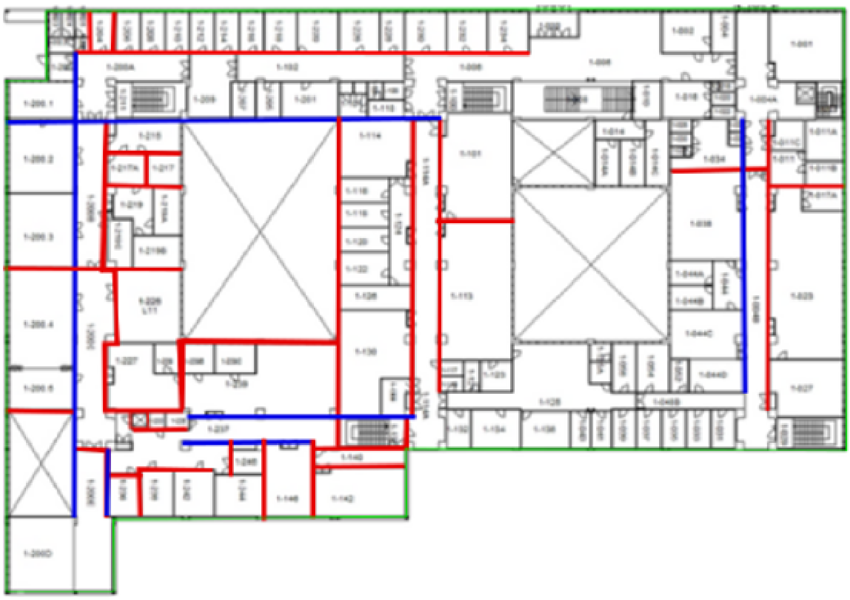


Figure 3.14: *Wall model with alterations part 2: The internal walls kept from the complete model in red, removed internal walls in blue (edited from NTNU (2014b))*

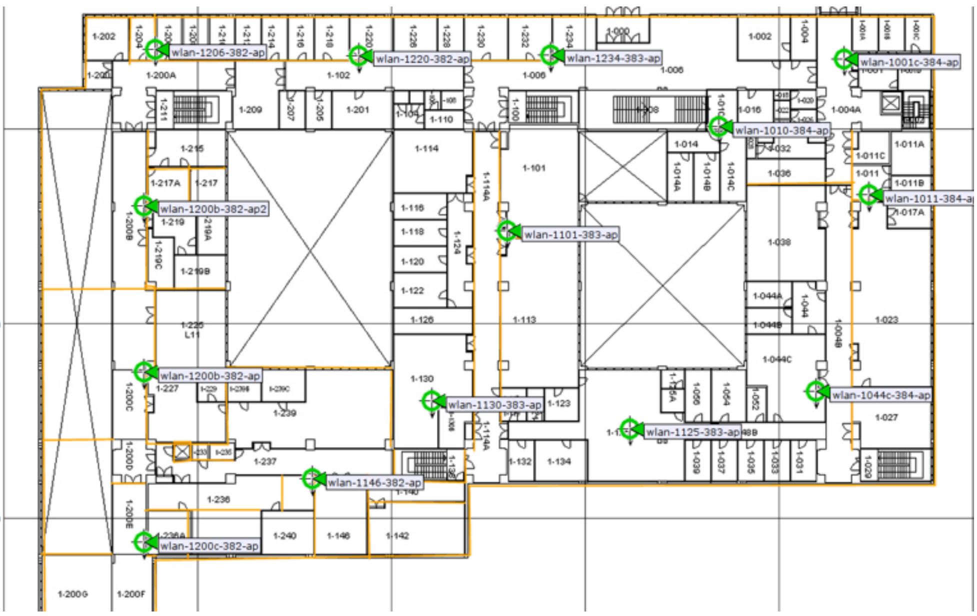


Figure 3.15: *Wall model with alterations part 2 in Trådløse Trondheim's model*

model Trådløse Trondheim created after the removal of the internal walls.

All control points were measured 15 times during three measurement rounds in phase 3, similar to phase 2. The second measurement round was executed with a time difference of approximately 3.5 hours. The first and third measurement rounds

Figure 3.16: *Outer wall model (edited from NTNU (2014b))*

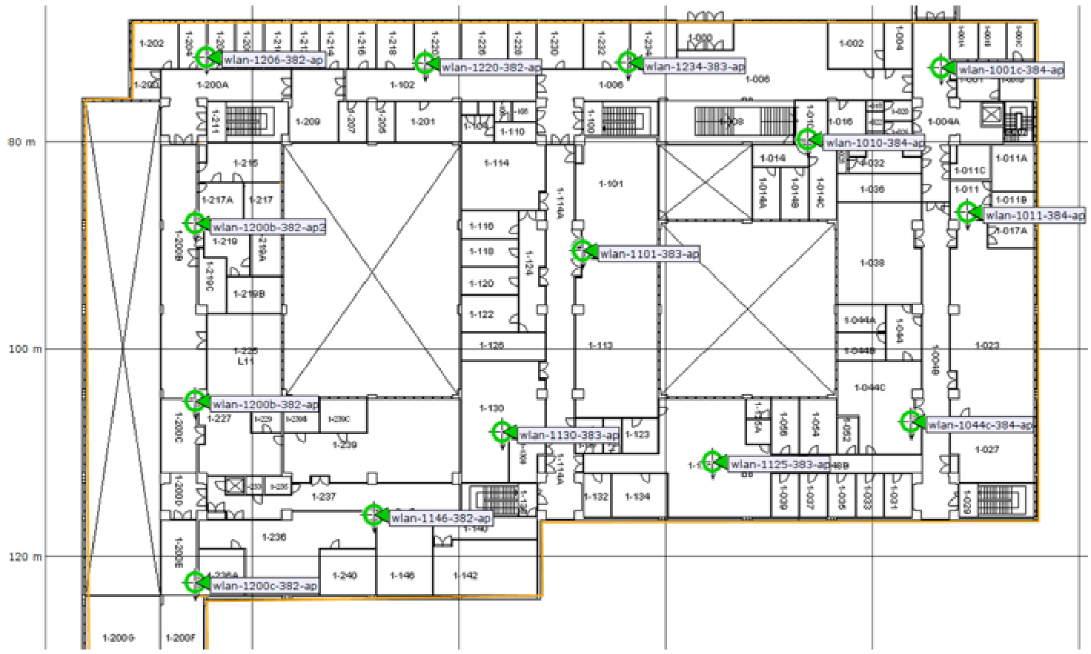


Figure 3.17: *Outer wall model in Trådløse Trondheim's model*

were performed without time difference. Thereafter mean X and Y values were calculated for the three measurement rounds, similar to phase 2. The measuring rounds were performed the 7th and 8th April 2014.

3.8 Phase 5: Base measurements

In the fifth phase all walls were removed from the model, both outer and internal walls. There were two main reasons for this. One reason was that this formed a basis for the other phases. Secondly it made it possible to compare the control points' true values coordinates from previous studies with measurements from this phase.

The model consisted of no walls and it was as plain as the floor plan in Figure 3.1. The model would be as it is illustrated in Figure 3.18. However, there was an error in the location of the access point 'wlan-1146-382-ap' (room 1-146). The location on the model was incorrect, but the coordinates of the access point were correct according to the Geomatics department's list of access points coordinates in the Lerkendal building.

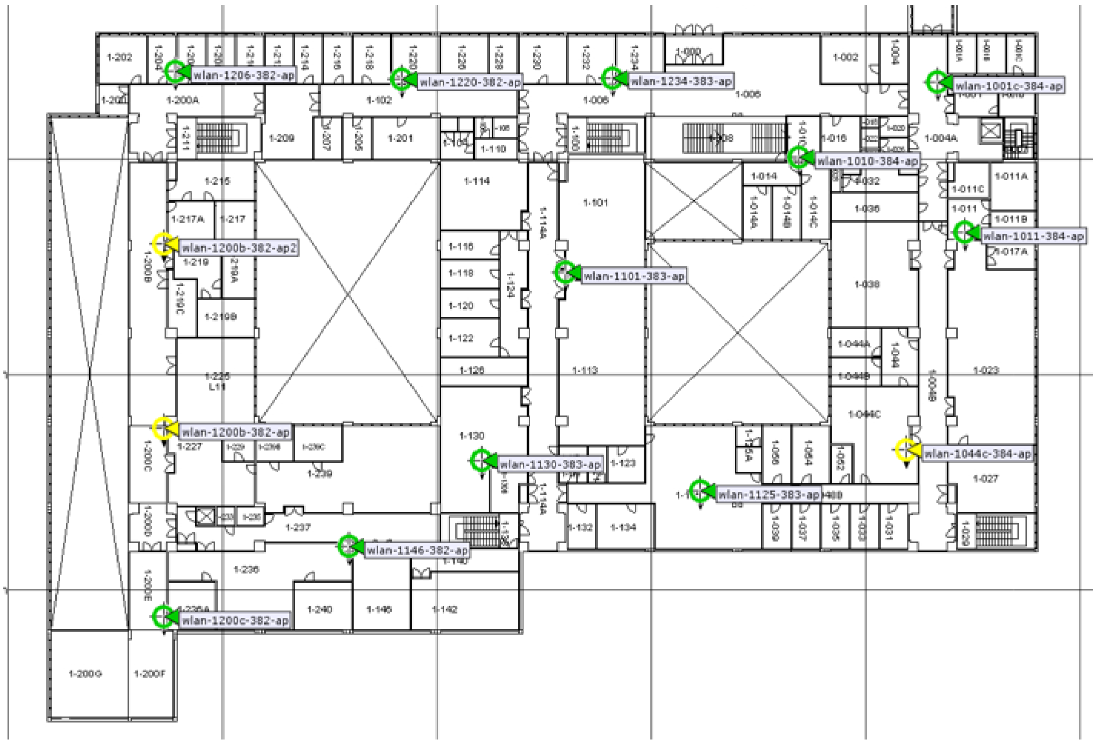


Figure 3.18: *Model for the base measurements in Trådløse Trondheim's model*

The fifth phase was carried out the 9th and 10th April 2014 in three measurement rounds. The first two measurement rounds were performed without time difference and the third measurement round with a time difference of about 4.5-5 hours.

3.9 Generation of plots

Plots of the different measurement rounds in the three first phases were made to indicate the differences in accuracies and precision between the true values of the control points and the measured values. This was done to indicate the effect of walls in the model and to indicate room accuracy.

Ideally all measurements would have been plotted, but 10 or 15 measurements of each control point would be impossible to present clearly in a figure. Therefore the average coordinate values of each measurement round, i.e. of five measurements, are presented. To separate the measurement rounds they were colour coded. The colour codes were as follows:

- Blue = measurement round 1
- Orange = measurement round 2
- Brown = measurement round 3

Additionally, the green coloured circles defined the access points and the red triangles the control points that were measured in the test. An old floor plan was used as the map base because this was the same base map that Trådløse Trondheim used as the floor map in their model. This base map had a higher resolution than the floor plans used to provide an overview of the walls included in the model, such as indicated in Figure 3.16. The base map was then georeferenced according to the coordinates of the Lerkendal building. In the following chapter the plots were rotated. The local coordinate axes however remain as they were. The average coordinate

```
05 P1-17 23.21 87.87
05 P1-24 42.07 102.39
05 P1-01 20.54 114.57
05 P1-05 24.81 112.62
05 P1-10 16.71 100.42
05 P1-13 16.71 91.74
05 P1-26 36.63 112.01
05 P1-31 30.01 111.30
05 P1-23 84.88 82.64
05 P1-12 15.44 102.93
05 P1-16 15.06 87.71
```

Figure 3.19: *The kof format of measurement rounds used in the plots*

values of the measurement rounds were created as kof format files as illustrated in Figure 3.19 where the outer wall model measurement round 1 is presented. These files indicated the average value of each measured control point in the X and the Y coordinate in the two last columns.

Chapter 4

Results and discussion

The results are presented in the order of which they were in the original schedule:

- Base measurements (phase 5)
- Outer walls (phase 4)
- Wall models (phase 1, 2 and 3)

The reason for the reverse order was that the comparison of the base measurements and the true values had to come first. It was followed by the base measurements results as these created a basis for the other phases. The phase number in the new schedule are written in brackets.

The results are presented with two decimal numerals in all of the tables and the data is in meter values. As the five measurements in measurement rounds with time difference were part of the same round even though there was a difference in time between the measurements, they were not divided into smaller rounds. All of the measurement rounds contained five measurements of each control point in all test phases. This was also done to reduce the number of columns in the tables and the number of plots in the figures. Each measurement round with time difference was used as one measurement round in the calculations of standard deviation and variance. The main purpose of the statistics and the plot figures were to demonstrate the accuracy and the precision of the measurements and to illustrate the effect of walls in the model by comparing the difference between the phases and the measurement rounds.

4.1 Statistical equations

Four statistical equations were necessary to analyse the accuracy and precision of the measurements performed in the previous chapter. The corrected sample standard deviation is symbolised by s and the unbiased sample variance by s_N^2 and N is the number of measurements. Hence, the corrected sample standard deviation and the unbiased sample variance are simplified to 'standard deviation' and 'variance'. To analyse the accuracy, the standard deviation and the variance were calculated based on the true value of the measurements. For the precision of the measurements the mean value of the measurements of each control point was used, i.e. the measurements were compared with each other using the mean value and not the true value. Due to the small amount of observations (10 or 15 measurements per phase), N-1 measurements were used as the degrees of freedom (in the following equations: beneath the bracket line) instead of N. The standard deviations and variances have the same unit as the data they are based on, i.e. they are meter values. The data management and the statistics were performed in Microsoft Excel 2013. (Wolfram MathWorld, 2014)

Accuracy: Standard deviation and variance

$$s = \sqrt{\frac{1}{N-1}\sum_{i=1}^{N}(x_i - \mu)^2} \tag{4.1}$$

$$s_N^2 = \frac{1}{N-1}\sum_{i=1}^{N}(x_i - \mu)^2 \tag{4.2}$$

Precision: Standard deviation and variance

$$s = \sqrt{\frac{1}{N-1}\sum_{i=1}^{N}(x_i - \overline{x})^2} \tag{4.3}$$

$$s_N^2 = \frac{1}{N-1}\sum_{i=1}^{N}(x_i - \overline{x})^2 \tag{4.4}$$

where μ is the true value and $\overline{x}$ is the mean value of the measurements of the same control point coordinate:

$$\overline{x} = \frac{1}{N}\sum_{i=1}^{N} x_i. \tag{4.5}$$

4.2 Base measurements compared with true values

The results from phase 1 are presented as mean values in Table 4.1. The mean value of each control point in each measurement round is displayed in the second, third and fourth column. The values in the 'Mean value' column were calculated from all of the 15 measurements in the base measurement phase. The difference between the mean value and the true value is presented in the last column marked as 'Mean-true value'.

The differences between the mean value and the true value for each control point, i.e. the X and Y coordinate pair, were varying. From the three measurement rounds the most accurate and least accurate measured coordinate pair were similar, about some decimeters and up to around 18 meters respectively. From each of the measurement rounds five or six coordinates, i.e. control points' coordinates, had a less than 10 meter difference between the true value and the mean value. There were no large biases that indicated a systematic error such as that some of the control points had been moved or that the origin of the coordinate system had changed.

Table 4.1: *Base measurements: Difference between mean value and true value of the control points*

	Mean m1	**Mean m2**	**Mean m3**	**Mean value**	**True value**	**Mean-true value**
P1-17						
X	22.31	19.35	22.30	21.32	12.65	8.67
Y	88.03	87.64	84.40	86.69	68.62	18.08
P1-24						
X	43.52	47.13	44.07	44.91	47.06	-2.16
Y	99.41	94.16	101.94	98.50	86.84	11.66
P1-01						
X	23.28	20.19	21.19	21.55	5.47	16.08
Y	114.61	116.06	111.92	114.20	111.13	3.07
P1-05						
X	21.93	23.90	21.90	22.57	18.46	4.12
Y	110.39	111.57	110.70	110.88	108.04	2.85
P1-10						
X	17.46	17.86	17.35	17.55	13.13	4.42
Y	104.31	96.60	102.47	101.13	93.13	7.99
P1-13						
X	13.74	15.47	17.66	15.62	12.34	3.28
Y	96.85	96.65	99.90	97.80	81.11	16.69
P1-26						
X	35.87	36.98	39.41	37.42	42.88	-5.45
Y	113.42	112.92	109.81	112.05	109.20	2.85
P1-31						
X	30.75	31.54	29.47	30.59	30.13	0.46
Y	112.33	112.34	108.60	111.09	103.35	7.75
P1-23						
X	80.43	85.74	77.27	81.14	81.30	-0.16
Y	85.81	83.05	85.76	84.87	79.69	5.18
P1-12						
X	15.91	16.32	16.36	16.20	5.04	11.16
Y	103.23	100.26	106.17	103.22	93.00	10.22
P1-16						
X	17.21	14.61	15.22	15.68	15.91	-0.23
Y	84.42	91.31	92.58	89.44	79.69	9.75

4.3 Accuracy

4.3.1 Base measurements

The accuracy of the base measurements with regards to standard deviation and variance is presented in Table 4.2. This is reflected by the base measurements' average results that are plotted in Figure 4.1. The accuracy of the measurements were varying, from the best accuracy at control point P1-31 and the least accurate control point P1-17. For instance had both control points P1-17 and P1-12 poor accuracy, as not one of their measurement rounds estimated the location nearby. Control point P1-31 had good accuracy according to the standard deviation and this was clear in the plots as well. P1-31 was estimated in the same room during all three measurements rounds. The results from this phase were used as 'before' measurements for the other phases comparable results.

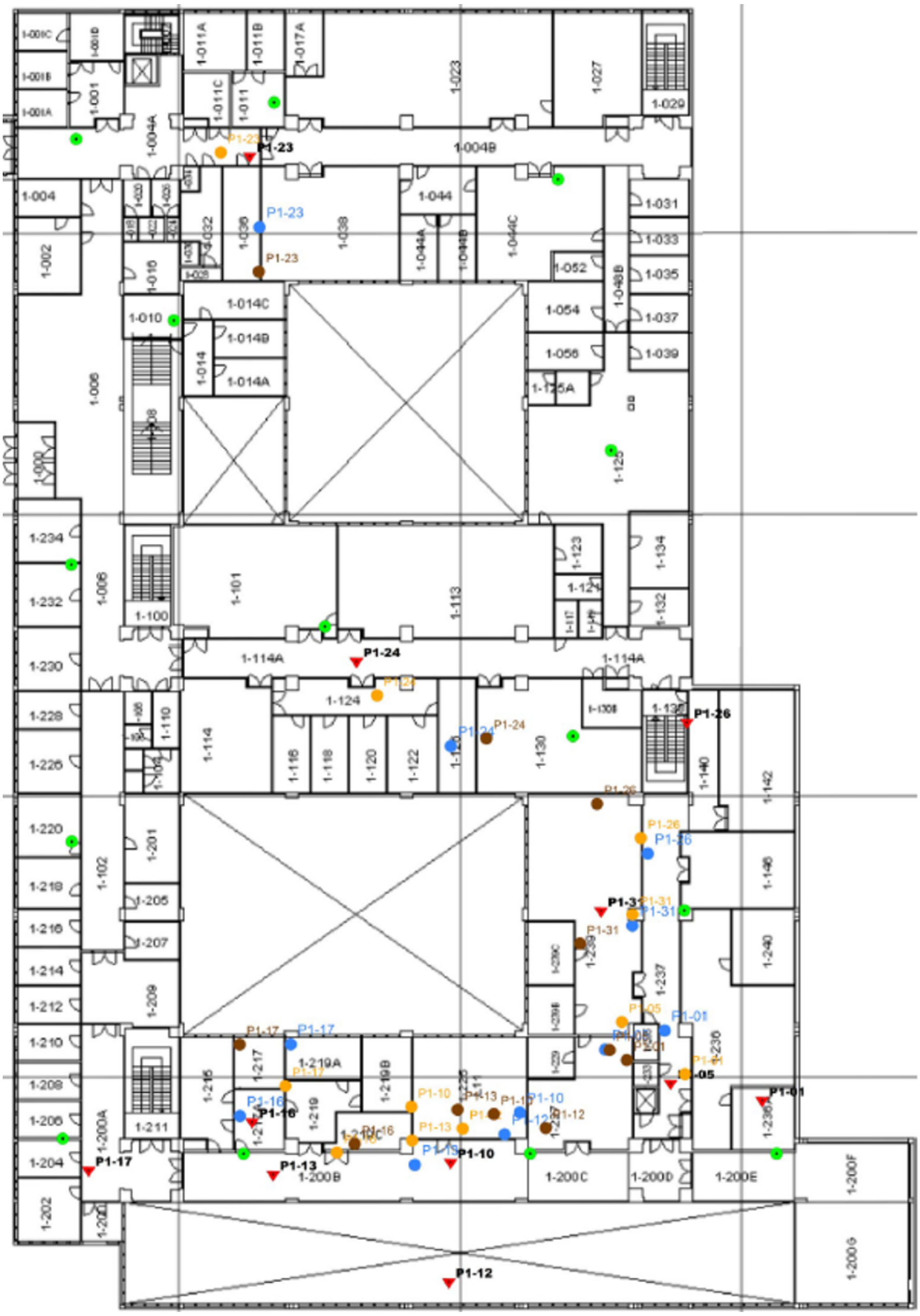
4.3.2 Outer wall model

Table 4.3 shows the accuracy of the outer wall model measurements with standard deviation and variance. Some control points had considerably better accuracy in this phase compared with the base measurements, but mostly either in the X coordinate or the Y coordinate. For instance the Y coordinate of P1-13 which had 5 meters better accuracy according to the standard deviation than the corresponding results in the base measurements' phase. The Y coordinate of P1-17 was even less accurate than in the previous phase, while the X coordinate was more accurate. The standard deviation was only 1 meter less accurate in Y direction of the P1-17 control points, but the variance was larger compared to the base measurements. This was also the case of control points P1-05 and P1-23. The X coordinates were less accurate and the Y coordinates were more accurate than in phase 5.

Table 4.2: *Accuracy: The standard deviation and the variance of the base measurements*

	True value	**Mean value**	**Standard deviation**	**Variance**
P1-17				
X	13,34	21,32	8,51	72,43
Y	73,64	86,69	13,70	187,81
P1-24				
X	49,54	44,91	6,22	38,70
Y	92,69	98,50	7,79	60,61
P1-01				
X	18,31	21,55	3,83	14,66
Y	121,55	114,20	8,04	64,63
P1-05				
X	19,54	22,57	3,69	13,62
Y	115,03	110,88	4,64	21,51
P1-10				
X	13,91	17,55	3,94	15,55
Y	99,39	101,13	4,49	20,18
P1-13				
X	13,05	15,62	3,21	10,29
Y	86,77	97,80	11,58	134,02
P1-26				
X	45,20	37,42	8,26	68,25
Y	116,19	112,05	4,67	21,81
P1-31				
X	31,79	30,59	2,52	6,36
Y	110,08	111,09	2,66	7,10
P1-23				
X	85,48	81,14	8,68	75,28
Y	85,10	84,87	2,95	8,69
P1-12				
X	5,41	16,20	11,18	125,06
Y	99,27	103,22	4,98	24,80
P1-16				
X	16,79	15,68	2,43	5,92
Y	85,27	89,44	6,35	40,29

Figure 4.1: *Plots of base measurement rounds*



Some control points were less accurate in both the X and the Y coordinate, these were the control points P1-24 and P1-10. However, there were actually five exceptions. The following control points were nearly unaffected of the changes in the model: P1-01, P1-26, P1-31, P1-12 and P1-16. Not all of the five control points were located near the outer walls.

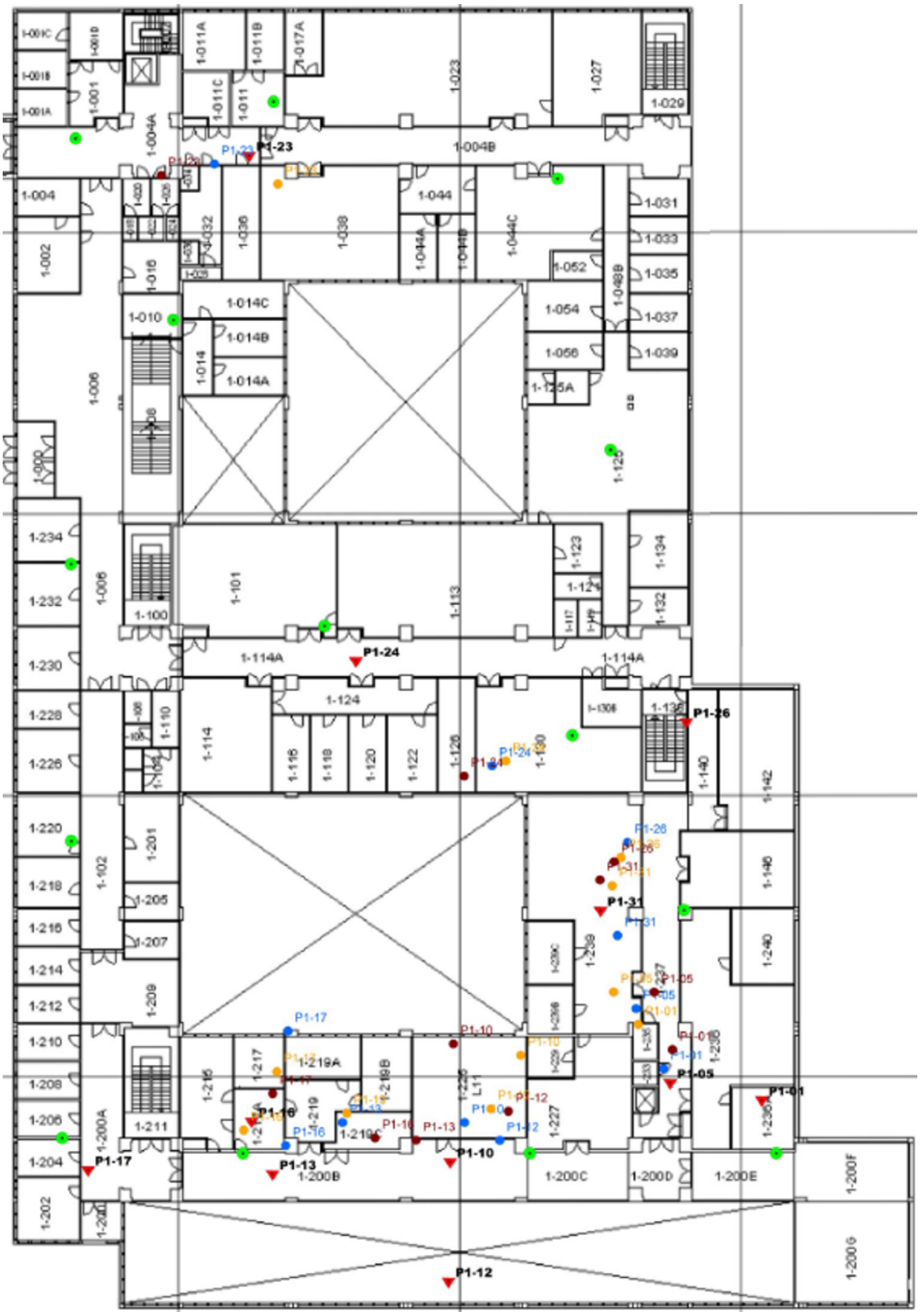
Comparing the control points with each other in this phase P1-31 had the best accuracy, followed by P1-23 and P1-16 when studying the coordinate pair results. Except for the Y coordinate of P1-16 (5.66 meters) the standard deviation accuracy of these three control points were below 5 meters. The other control points had mainly a standard deviation accuracy of 8 meters or better, as 15 out of the 22 X and Y coordinates were equal to or better than 8 meters accurate. The mean coordinates of the measurement round (Appendix A) were compared with the true value. Compared with the accuracies of the systems in Table 2.1, the tested wireless network had equivalent accuracy (i.e. best accuracy, not average accuracy) with Ekahau and COMPASS and better accuracy than RADAR in some of the control point measurements. These control points were for instance P1-31 and P1-16 with about 1 meter accuracy, which was estimated from the difference between mean value and true value.

From the standard deviation and the variance a particular conclusion cannot be drawn. However, it can be noted that the insertion of outer walls seemed to have limited effect on the accuracy of the control point measurements.

Table 4.3: *Accuracy: The standard deviation and the variance of the outer wall model measurements*

	True value	Mean value	Standard deviation	Variance
P1-17				
X	13,34	20,77	8,00	64,04
Y	73,64	87,24	14,49	210,03
P1-24				
X	49,54	41,95	8,14	66,18
Y	92,69	102,04	10,14	102,87
P1-01				
X	18,31	22,04	4,27	18,24
Y	121,55	114,18	8,07	65,12
P1-05				
X	19,54	25,60	6,67	44,44
Y	115,03	112,52	3,03	9,18
P1-10				
X	13,91	20,17	7,16	51,27
Y	99,39	101,49	3,54	12,54
P1-13				
X	13,05	16,51	3,95	15,58
Y	86,77	93,59	8,09	65,48
P1-26				
X	45,20	35,81	9,79	95,89
Y	116,19	111,54	4,89	23,86
P1-31				
X	31,79	32,50	3,08	9,47
Y	110,08	110,76	1,26	1,60
P1-23				
X	85,48	84,13	4,15	17,21
Y	85,10	82,88	4,50	20,29
P1-12				
X	5,41	16,88	11,96	142,93
Y	99,27	102,92	4,02	16,16
P1-16				
X	16,79	15,61	2,34	5,48
Y	85,27	88,83	5,66	32,05

Figure 4.2: *Plots of outer walls measurement rounds*



The plots of the measurement rounds for this phase are presented in Figure 4.2. Some of the measurement rounds of control points located close to outer walls, such as P1-01 and P1-26, had slightly improved accuracy compared to the base measurement rounds' plots. However, the comparison of the standard deviations indicated very small differences between the two phases. Other control points also had improved accuracy in some of the measurement rounds, such as P1-13 and P1-23. As stated above some control points achieved poorer accuracy in this phase compared to the base measurements phase. These control points were P1-10 and P1-24 and the differences are visible when comparing the plots in Figure 4.1 and Figure 4.2.

4.3.3 Wall models

Table 4.4, Table 4.5 and Table 4.6 present the accuracy, using standard deviation and variance, of the complete wall model and the wall model with alterations part 1 and part 2 respectively. The results from the complete wall model were compared with the base measurements and the outer wall model measurements. The results from the two wall models with alterations were compared with the results from the three previous phases.

Complete wall model

When comparing the results from the complete wall model with the base measurements in Table 4.2, there were no unambiguous conclusion. Some control points had slightly better accuracy, such as P1-24 and P1-01. Other control points had slightly poorer accuracy, such as the control points P1-26 and P1-31. In both cases the difference in standard deviation accuracy from the base measurements were mainly between 1 and 3 meters and all of the control points mentioned above were not located near outer walls. Neither were all of them located close to the internal walls inserted in the model. However, the result was neither better nor poorer accuracy. Some of the control points achieved better accuracy in either the X or the Y coordinate, while the other half of the coordinate pair had less accurate results or vice versa. Similar to the outer walls measurements, some control points had the same accuracy in both phases, such as P1-12 which was located close to both an outer wall and an inserted, internal wall. Overall the differences between these two phases were mainly minor changes in accuracy.

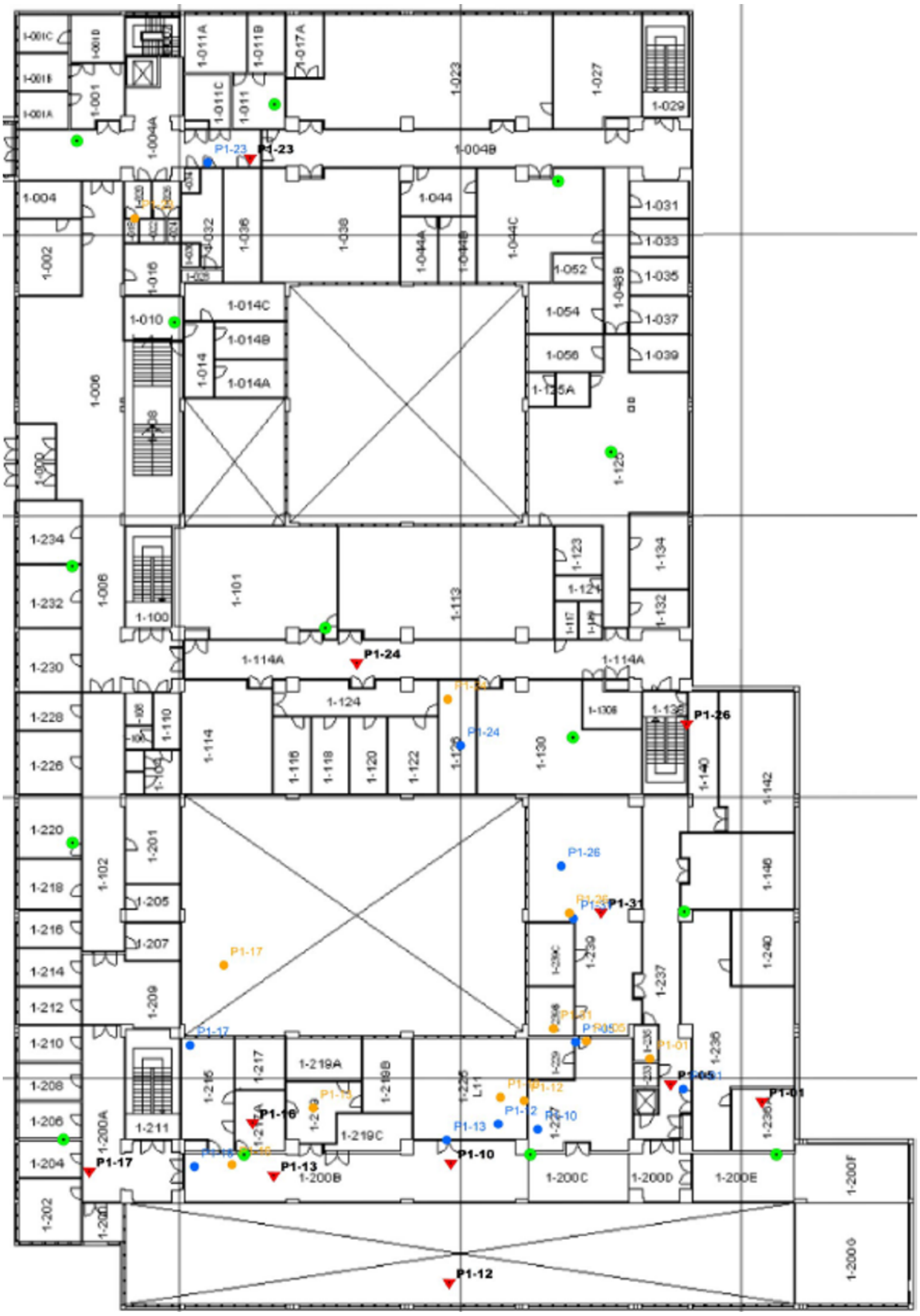
Figure 4.3 illustrates the fact that some control points had improved accuracy, such as P1-01, compared to the results in the base measurement phase. There are visible differences in accuracy in control point P1-26 between the two phases when comparing Figure 4.1 and Figure 4.3. As previously stated the differences in accuracies were small. However, notice that some control points in one measurement round in the complete wall model was more accurate than in the other round. This was particularly the case of the control points P1-13 and P1-31, even though both measurement rounds estimated P1-31 to be in the correct room. The other control points did not have similar large differences between the two measurement rounds' accuracies.

The results from the complete wall model were also compared to the outer walls results in Section 4.3.2 and Table 4.3. Nine out of the 22 X and Y coordinates had better or slightly better standard deviation accuracy than the corresponding results in the outer wall model phase. The remaining 13 X and Y coordinates were less accurate or slightly less accurate than their corresponding outer wall model results. This did not provide any proof for the suggestion that insertion of internal walls in the model makes a significant difference to the accuracy of the measurements, neither did it prove the opposite.

Table 4.4: *Accuracy: The standard deviation and the variance of the complete wall model measurements*

	True value	**Mean value**	**Standard deviation**	**Variance**
P1-17				
X	13,34	25,16	13,40	179,62
Y	73,64	82,03	9,72	94,40
P1-24				
X	49,54	45,29	5,07	25,65
Y	92,69	99,64	7,70	59,24
P1-01				
X	18,31	20,27	2,95	8,67
Y	121,55	114,76	7,43	55,24
P1-05				
X	19,54	22,57	3,43	11,74
Y	115,03	108,66	6,83	46,65
P1-10				
X	13,91	17,46	3,98	15,81
Y	99,39	104,26	6,69	44,70
P1-13				
X	13,05	16,71	4,30	18,46
Y	86,77	94,35	9,66	93,34
P1-26				
X	45,20	33,40	13,20	174,24
Y	116,19	107,55	9,18	84,27
P1-31				
X	31,79	27,41	7,20	51,80
Y	110,08	107,41	3,80	14,47
P1-23				
X	85,48	83,18	3,52	12,40
Y	85,10	79,49	7,12	50,69
P1-12				
X	5,41	17,53	12,85	165,21
Y	99,27	103,69	5,11	26,16
P1-16				
X	16,79	13,74	3,26	10,60
Y	85,27	82,47	4,28	18,31

Figure 4.3: *Plots of complete wall model measurement rounds*



A comparison with the plots from the outer wall measurements in Figure 4.2 and the plots from the complete wall model measurements in Figure 4.3 showed that some control points, such as P1-24, had improved accuracy after including the internal walls in the model. Other control points had the same or poorer accuracy, such as P1-12 or P1-26.

Wall model with alterations part 1

The standard deviation and variance results of the first of the two altered wall models were compared to the results from the base measurements to examine the accuracy of the former phase. There were minor differences in the accuracy. When studying the accuracy of the four chosen control points by means of the standard deviation, both of control point P1-05's coordinates, the Y coordinate of P1-23 and the X coordinate of P1-16 were very similar to the results in the base measurements. The X coordinate of P1-23 was actually slightly more accurate than in the base measurements. However, the four coordinates mentioned above were less or slightly less accurate than their corresponding base measurements according to the standard deviation and variance results. Control points P1-31 and P1-16 were located far from any of the outer walls and only close to internal walls. This could indicate that a wall model without walls might have provided better accuracy for some locations far inside a building, than using a wall model with internal walls where some of the closest walls were removed.

Table 4.5: *Accuracy: The standard deviation and the variance of the wall model part 1 measurements*

	True value	**Mean value**	**Standard deviation**	**Variance**
P1-17				
X	13,34	25,14	12,74	162,30
Y	73,64	83,22	10,41	108,37
P1-24				
X	49,54	45,12	4,94	24,38
Y	92,69	98,31	6,52	42,56
P1-01				
X	18,31	19,96	2,09	4,36
Y	121,55	116,13	5,91	34,98
P1-05				
X	19,54	22,60	3,72	13,86
Y	115,03	110,70	4,93	24,30
P1-10				
X	13,91	18,26	4,84	23,45
Y	99,39	99,01	2,05	4,20
P1-13				
X	13,05	14,26	1,53	2,34
Y	86,77	96,42	10,34	106,96
P1-26				
X	45,20	38,26	8,06	64,95
Y	116,19	109,20	7,33	53,72
P1-31				
X	31,79	30,11	3,82	14,57
Y	110,08	107,89	4,39	19,30
P1-23				
X	85,48	82,96	3,95	15,58
Y	85,10	84,42	2,86	8,17
P1-12				
X	5,41	15,82	10,79	116,33
Y	99,27	101,79	2,75	7,55
P1-16				
X	16,79	15,00	2,83	8,02
Y	85,27	91,66	9,06	82,03

Figure 4.4: *Plots of wall model part 1 measurement rounds*

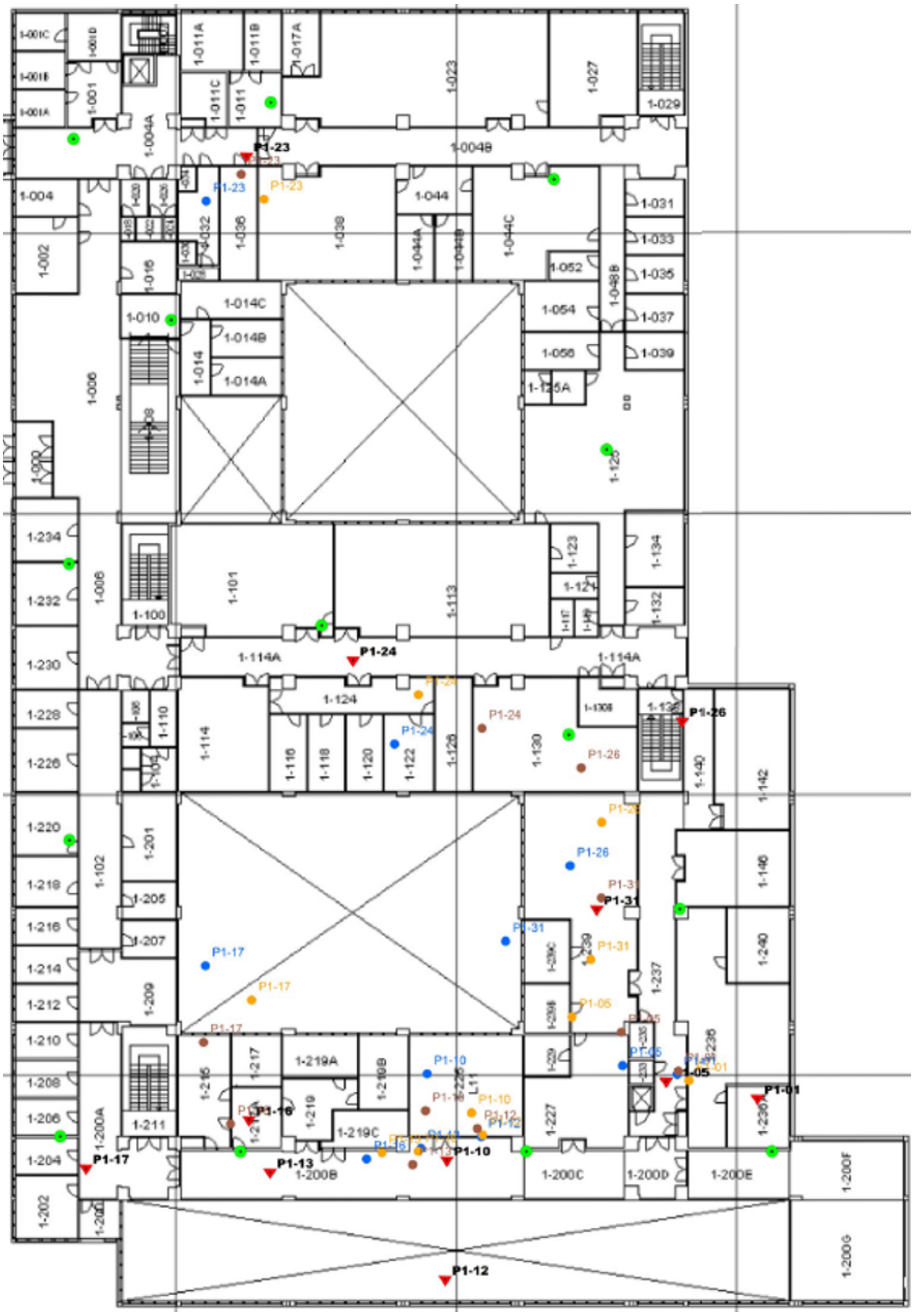


Figure 4.6 presents a close-up of the plots of the control points P1-05 and P1-21 in the first three phases. Figure 4.8 shows a close-up of the plots of control point P1-16 and Figure 4.7 shows a close-up of the plots of P1-23 in the same phases. The comparison of Table 4.4 and Table 4.5 indicated some differences in accuracies between the chosen control points in phase 1 and phase 2. Control point P1-05 had similar X coordinate accuracies in both phases, the Y coordinates however, had slightly better accuracy in phase 2. Figure 4.6 indicates the same observations.

For control point P1-31 the tables as well as Figure 4.6 indicate that the X coordinate had better accuracy in phase 2 than in phase 1, while the Y coordinate had slightly poorer accuracy in phase 2. These indications were compared with the walls that were removed for this phase and there was not clear that the walls had an effect on the accuracy as both control points' coordinates slightly improved or remained very similar in the direction towards the removed wall(s). However, in both cases the removed walls were not between each control point and the closest access point which in P1-05's case was 'wlan-1146-382-ap' and the closest access point for P1-31 was 'wlan-1200c-382-ap'. The walls between these two control points and their closest access points were removed in phase 3.

Control point P1-23 had similar X coordinate accuracies in phase 1 and phase 2, even though the Y coordinate was more accurate in phase 2 compared to phase 1 when comparing Table 4.5 and Table 4.4. This was also supported by the close-up plots in Figure 4.7. Compared to the removed walls in this phase, there was no clear indication to why the Y coordinate was more accurate when no walls were removed in this direction.

The control point P1-16 had an X coordinate of slightly better accuracy in phase 2 than phase 1, while the Y coordinate were less accurate in phase 2. Figure 4.8 illustrates the situation. The wall located between control point P1-16 and the closest access point was removed, however it was located in the opposite direction of the Y coordinate with less accuracy. The closest access point, 'wlan-1200-382-ap2', was located on the internal wall which was removed. This suggested that the removal of the wall had limited effect due to the access point was located on the wall.

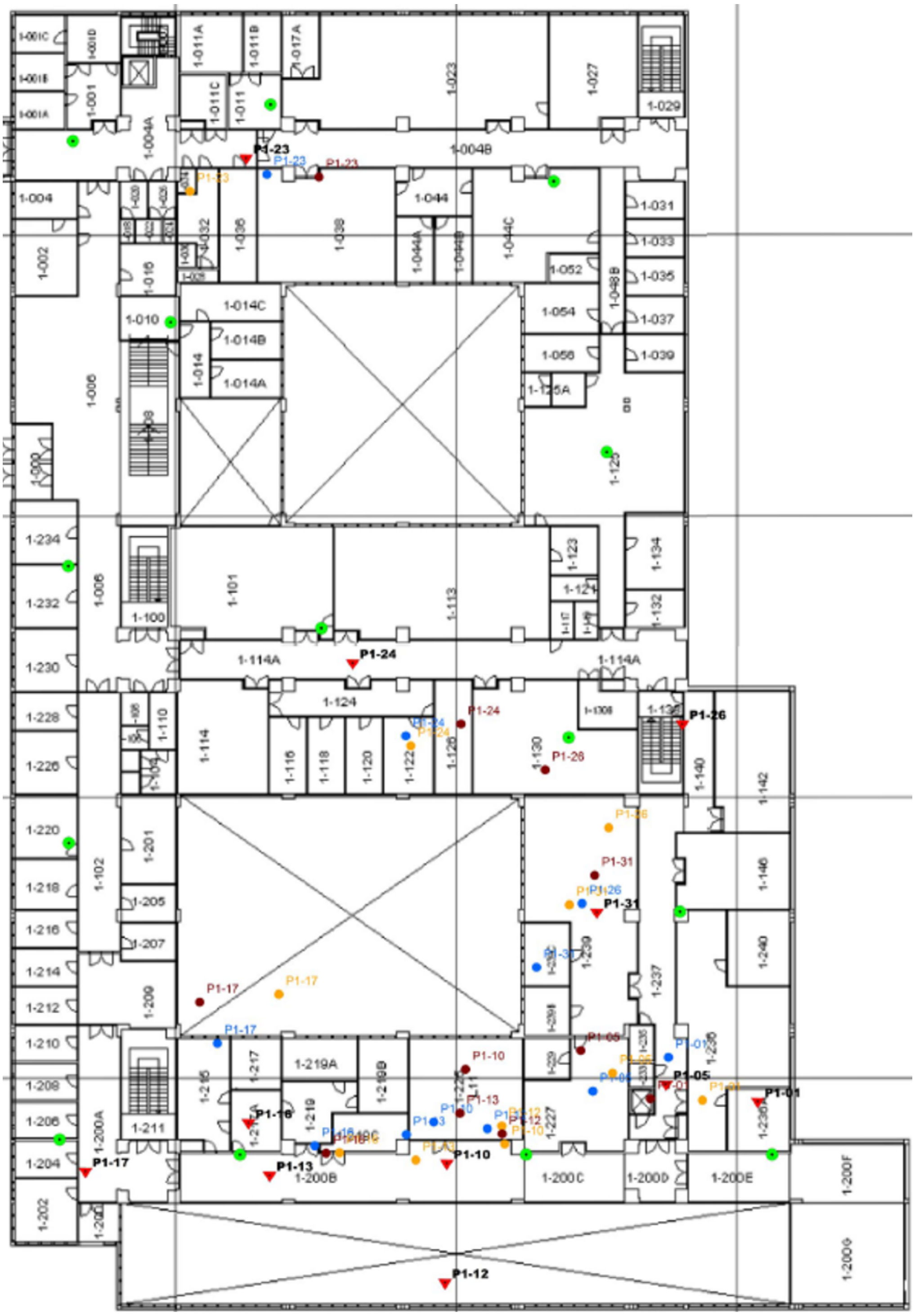
Wall model with alterations part 2

Figure 4.5 illustrates the plots of the measurement rounds in the wall model with alterations part 2 phase. The standard deviation and variance results showing the accuracies from this phase are presented in Table 4.6. The results of the four chosen control points were compared to the results in the base measurement phase in Table 4.2. Generally there were only small differences in the accuracies. The X coordinate of control point P1-05 was slightly more accurate in phase 3 and the Y coordinate was slightly less accurate in phase 3 than in phase 5. For control point P1-31 both the X and the Y coordinate were slightly less accurate in phase 3. In control point P1-23 the X coordinate was more accurate and the Y coordinate slightly less accurate in phase 3 than in phase 5. Control point P1-16 had a slightly less accurate X coordinate and about the same accuracy in the Y coordinate. These observations are also reflected in the plots in Figure 4.5. The comparison of the standard deviations and the figure plots suggested that there might not have existed a clear difference between the accuracy of the results when some walls, both internal walls and outer walls, were included in the model or not.

Table 4.6: *Accuracy: The standard deviation and the variance of the wall model part 2 measurements*

	True value	**Mean value**	**Standard deviation**	**Variance**
P1-17				
X	13,34	24,59	11,89	141,27
Y	73,64	84,09	11,41	130,29
P1-24				
X	49,54	44,39	5,59	31,25
Y	92,69	97,91	6,41	41,10
P1-01				
X	18,31	19,46	2,21	4,87
Y	121,55	115,58	6,66	44,41
P1-05				
X	19,54	20,44	2,17	4,73
Y	115,03	109,99	5,92	35,05
P1-10				
X	13,91	17,58	4,58	20,99
Y	99,39	100,91	3,38	11,39
P1-13				
X	13,05	15,86	3,50	12,25
Y	86,77	98,02	12,04	144,96
P1-26				
X	45,20	37,39	9,76	95,24
Y	116,19	108,80	8,35	69,76
P1-31				
X	31,79	31,54	4,01	16,09
Y	110,08	107,96	3,34	11,15
P1-23				
X	85,48	83,86	3,57	12,75
Y	85,10	86,00	4,17	17,36
P1-12				
X	5,41	16,32	11,33	128,43
Y	99,27	102,98	3,99	15,93
P1-16				
X	16,79	14,82	3,25	10,54
Y	85,27	90,85	6,66	44,36

Figure 4.5: *Plots of wall model part 2 measurement rounds*



A comparison of the standard deviation and variance results regarding accuracy was performed on the wall model with alterations part 2 in phase 3 and the complete wall model results in phase 1. Control point P1-05 had slightly better accuracies in both coordinates in phase 3 compared to phase 1. This is illustrated in the close-up plots of these phases in Figure 4.6. As suggested in the comparison of phase 1 and phase 2, the removal of walls in between the control point and the closest access point might have affected the accuracies. This seemed not to be the case of control point P1-05 as there were no clear indications of this in either the statistics or the plots. The control point was located inside a triangle of close access points. The other three chosen control points were located inside similar triangles. This might indicate that RSSI was providing a relatively good accuracy. The accuracy of the measurements was not the best. Still an accuracy between 2 meters and 6.8 meters is considered to be acceptable. However, in all the measurement rounds, P1-05 was never estimated inside the correct room, i.e. the corridor and thus providing room accuracy, but rather into the nearest rooms 1-227 and 1-239.

The Y coordinate of control point P1-31 had about the same accuracy in phase 3 as in phase 1, while the X coordinate was more accurate in phase 3. Figure 4.6 illustrates this as well and among the five measurement rounds in the two phases only four of the control points were estimated in the correct room. It might seem like two additional rounds estimated incorrectly as well, though this was not the case. It appears like this in Figure 4.6 due to the old floor plan used as the base map. The two small rooms have been removed since the floor plan was updated.

The control point P1-23 had approximately the same X coordinate accuracy in phase 2 and phase 3, while the Y coordinate was more accurate in phase 3. The standard deviation and variance comparison is also supported by the close-up plots in Figure 4.7 as it is visible that the second measurement round (orange measurement) in phase 1 was slightly less accurate than the other measurement rounds. In this case the wall that had been removed from the model close to control point P1-23 was not located between P1-23 and the closest access point. As the X coordinate remained virtually unchanged this supports the suggestion that the removal of internal walls that were not located between the control point and the closest access point had a minor effect on the accuracy of the measurements.

In the case of control point P1-16 the X coordinate had the same accuracy and the Y coordinate was slightly more accurate in phase 3 compared to the results in phase 1. Figure 4.8 reflects the small differences in accuracies. It was noteworthy to see the changes in Y direction in Figure 4.8 where the estimations in phase 2 are located much closer to the origin than the estimations in phase 3.

Among the control points which were not among the top four most accurate, it was interesting to note that P1-26 was most accurately measured in the base measurement and the outer wall model phases and least accurate in the complete wall model. Control point P1-26 was located close to outer walls and in all five phases the accuracy of the estimated location was low. This was interesting due to the fact that the stairwell between the control point and the nearest access point was not included in any of the wall models. Due to technical limitations in including stairwells in Trådløse Trondheim's model, none were inserted in the model and thus a possible major limitation was not taken into account. The generally low accuracy of control point P1-26 might therefore be explained by the stairwell providing considerable penetration loss and the fact that P1-26 was not located inside a triangle of access points.

Gu et al. (2009, p. 23) and Bahl and Padmanabhan (2000, p. 777) define walls, doors, human bodies, movement, nearby electronics, signal strength and overlapping access points as factors affecting the accuracy of indoor positioning. Wang et al.

(2003) argue that major obstacles such as brick walls affect the accuracy of indoor positioning due to the considerable penetration loss. The control point P1-05 was located very close to a prominent obstacle, a lift shaft, which was located between the control point and one of the three closest access points. The close-up plots in Figure 4.6 illustrate that all wall model phases' measurements of the control point P1-05 was estimated closer to the origin in Y direction than the actual location of the control point. A comparison with Figure 4.2 also suggested that the insertion of the lift shaft might have had an effect on the accuracy as the outer wall plots had higher X coordinate value accuracies than in the wall model plots (Figure 4.6). Additionally the standard deviation provided evidence that the outer wall model measurements appeared to be less accurate in X coordinates of control point P1-05 than phase 1, 2 and 3.

Comparison of the altered wall models

The standard deviation and variance results of phase 3 was also compared to the results of phase 2 to study possible differences in accuracy between the two altered wall models. In control point P1-05 the X coordinate was most accurate in phase 3, while the Y coordinate was most accurate in phase 2. Figure 4.6 reflects this as well. In both phases the removed walls located close to control point P1-05 had constant X values, i.e. they were located in the Y direction. The X coordinates and the Y coordinates only differed with 1 meter from phase 2 to phase 3, indicating minor differences in accuracies and similarity to other control points in these phases, such as P1-24 and P1-26.

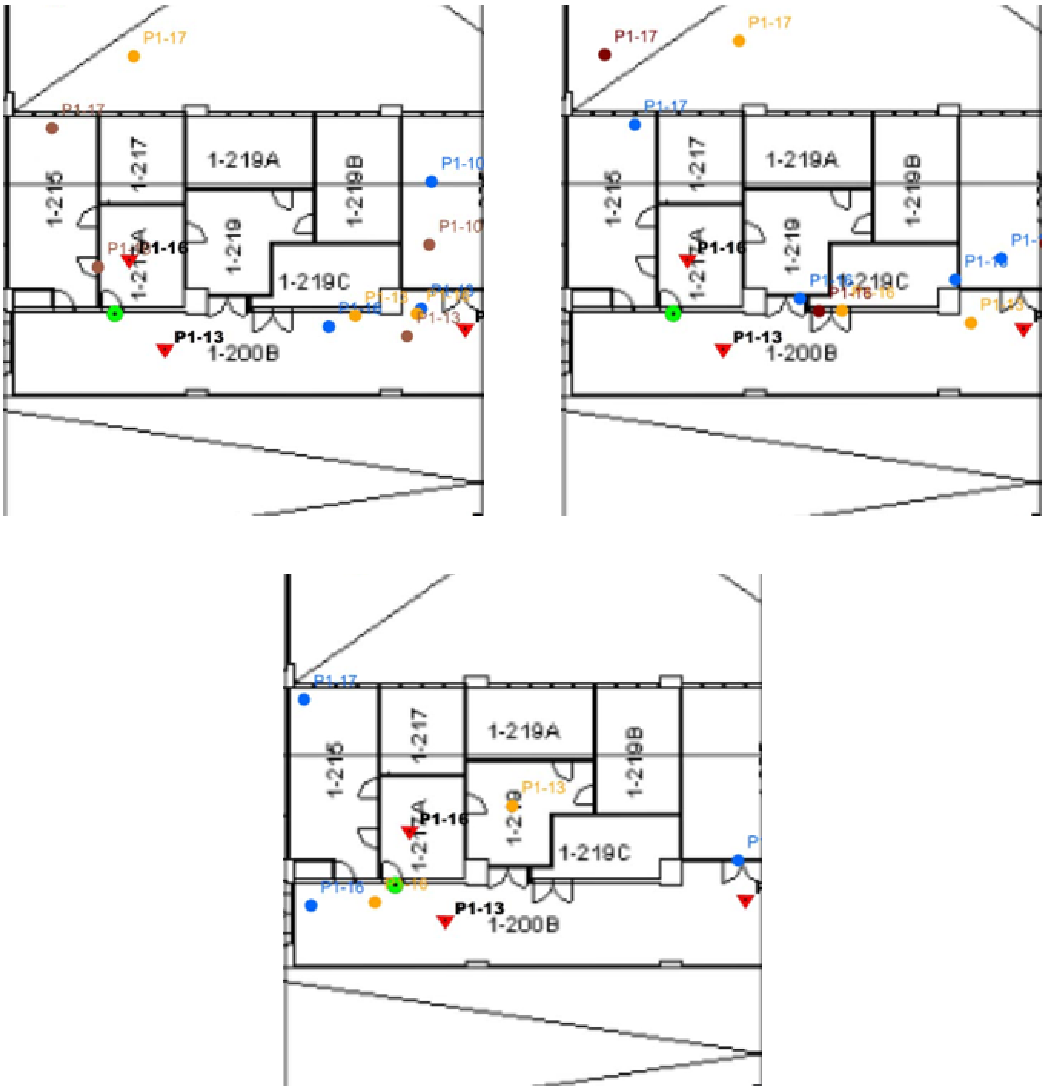
The control point P1-31 had only minor differences in accuracies between phase 2 and 3. The X coordinate was very similar and the Y coordinate was only slightly more accurate in phase 3. The same occurred in the case of control point P1-23, only the Y coordinates were very similar and the X coordinate had slightly better accuracy in phase 2. Both cases are visible in their respective close-up plots in Figure 4.6 and Figure 4.7. It was previously suggested that the removal of internal walls not located between a control point and the closest access point had limited effect on the accuracy of the estimates. The comparison of the control points P1-31 and P1-23 and their observations in phase 2 and phase 3 made no clear indication that the removal of internals walls had an effect on the accuracy.

The chosen control point P1-16 stood out from the other chosen control points. The comparison of the standard deviation and variance accuracies of control point P1-16 showed that the X coordinate accuracies were very similar. The Y coordinate accuracy however, showed that the accuracy was about 2.5 meters better in phase 3 than in phase 2. This was supported by the close-by plots in Figure 4.8. Additionally, all of the measurement rounds regarding P1-16 in phase 3 compared to in phase 1, in which both phases the estimated locations were closely collected, the Y coordinate was considerably further away from the origin. It seemed as though the removal of the two internal walls close to control point P1-16 affected the accuracy of all the measurement rounds of this control point in phase 3. Figure 4.8 shows that the control point was not estimated to be located inside the correct room (1-217A) in any of the first three phases' measurement rounds. This room was very small and that might have been the reason why room accuracy was not provided in this case. Still all of the measurement rounds estimated the location of the control point to be close by, mostly in one of the adjacent rooms and thus providing acceptable accuracy. This suggestion was supported by the tables of the standard deviations and the variances of all five phases.

Figure 4.6: *Plots of control points P1-05 and P1-31: Top left phase 2, top right phase 3, bottom phase 1*

Figure 4.7: *Plots of control point P1-23: Top left phase 2, top right phase 3, bottom phase 1*

Figure 4.8: *Plots of control point P1-16: Top left phase 2, top right phase 3, bottom phase 1*



4.4 Precision

4.4.1 Base measurements

The precision of the control points in the base measurements phase using standard deviation and variance are provided in Table 4.7. Out of the 22 X and Y coordinates, 18 had a standard deviation of less than 4 meters and correspondingly low variance values. The best precision was achieved at control point P1-05 and P1-13, although the X coordinate of P1-12 had a very high precision of 64 centimeters. The least precise measurement was the X coordinate of control points P1-23 which sat apart from the other control points with a standard deviation precision of 7.43 meters. The cases of control points P1-05 and P1-13 as well as the X coordinates of both P1-12 and P1-23 are all visible on the plots in Figure 4.1.

4.4.2 Outer wall model

The precision of the control points in the outer wall model phase by means of standard deviation and variance are presented in Table 4.8. In this phase the precision was very high at all control points. The least precise control point was P1-16 where the Y coordinate had a standard deviation of 4.30 meters. The best precision was achieved at control point P1-26 with standard deviation of both the X and Y coordinate below 1.25 meters followed by P1-12 and P1-05, both below 2.30 meters. Twelve out of the 22 X and Y coordinates had standard deviation precision better than 2.50 meters. As indicated by the standard deviations and variances, the precision of the measurements were generally higher than in the base measurement rounds. This is also visible in the plots of the average values of the outer wall measurement rounds in Figure 4.2.

Table 4.7: *Precision: The standard deviation and the variance of the base measurements*

Precision	Standard deviation	Variance
P1-17		
X	2.03	4.14
Y	2.29	5.27
P1-24		
X	3.96	15.71
Y	4.94	24.41
P1-01		
X	1.84	3.39
Y	2.59	6.72
P1-05		
X	1.94	3.76
Y	1.76	3.10
P1-10		
X	1.15	1.32
Y	4.12	16.95
P1-13		
X	1.79	3.19
Y	1.91	3.64
P1-26		
X	1.85	3.42
Y	1.86	3.45
P1-31		
X	2.19	4.81
Y	2.45	6.00
P1-23		
X	7.43	55.14
Y	2.94	8.63
P1-12		
X	0.64	0.41
Y	2.84	8.09
P1-16		
X	2.15	4.60
Y	4.65	21.67

Table 4.8: *Precision: The standard deviation and the variance of the outer walls measurements*

	Standard deviation	**Variance**
P1-17		
X	2.20	4.84
Y	3.43	11.74
P1-24		
X	2.10	4.40
Y	3.03	9.20
P1-01		
X	1.84	3.37
Y	2.63	6.92
P1-05		
X	2.27	5.15
Y	1.55	2.41
P1-10		
X	3.04	9.26
Y	2.80	7.82
P1-13		
X	1.66	2.76
Y	3.96	15.66
P1-26		
X	1.21	1.47
Y	0.83	0.69
P1-31		
X	2.99	8.92
Y	1.05	1.10
P1-23		
X	3.91	15.26
Y	3.88	15.04
P1-12		
X	1.40	1.95
Y	1.36	1.86
P1-16		
X	2.00	4.00
Y	4.30	18.47

4.4.3 Wall models

The precision of the complete wall model measurements, wall model part 1 and wall model part 2 by means of standard deviation and variance are presented in Table 4.9, Table 4.10 and Table 4.11 respectively.

Complete wall model

The precision of the complete wall model estimated by the standard deviation and variance showed that the measurements had marginally lower precision than the outer wall model results. Twelve out of the 22 X and Y coordinates had a precision better than 2.50 meters which was similar to the outer wall model results. However, the least precise standard deviation measurements were about 1 meter less precise than in the previous phase (i.e. phase 4). The Y coordinate of control point P1-31 and P1-13 had a precision of 5.52 meters and 5.43 meters respectively. Apart from these the precisions of the two phases were fairly similar.

The most precise measurement of a control point was P1-05 with a precision of about 1.25 meters in both directions. The single best precision in standard deviation was measured in the X coordinate of control point P1-16 with a precision of 53 centimeters. This control point was located very close in X direction to an access point ('wlan-1200b-382-ap2') on the other side of the wall. These findings are also visible in Figure 4.2 and Figure 4.3. It is apparent that some control points, such as P1-24 and P1-26, had better precision in the outer wall model than in the complete wall model.

Table 4.9: *Precision: The standard deviation and the variance of the complete wall model measurements*

	Standard deviation	**Variance**
P1-17		
X	4.94	24.38
Y	4.03	16.26
P1-24		
X	2.37	5.60
Y	2.35	5.54
P1-01		
X	2.10	4.41
Y	2.00	4.00
P1-05		
X	1.26	1.58
Y	1.24	1.54
P1-10		
X	1.34	1.79
Y	4.29	18.37
P1-13		
X	1.90	3.60
Y	5.43	29.53
P1-26		
X	4.41	19.45
Y	1.16	1.35
P1-31		
X	5.52	30.45
Y	2.56	6.56
P1-23		
X	2.55	6.50
Y	3.96	15.67
P1-12		
X	1.42	2.02
Y	2.11	4.47
P1-16		
X	0.53	0.28
Y	3.10	9.60

Wall model with alterations part 1

The precision of the measurements performed on the wall model with alterations part 1 using standard deviation (Table 4.10) was similar to the precisions in phase 1 and phase 4. Twelve out of the 22 X and Y coordinates had a precision better than 2.50 meters in phase 3. Similar to the complete wall model results, the least precise measurement was the Y coordinate of P1-16 with a precision of 6.19 meters. The resemblance to the complete wall model results was natural due to the fact that only a few wall model alterations had been made.

The most interesting control points were the four chosen control points around which five walls were removed from the model in this phase. All of them had a constant X value and only changed in the Y direction as indicated with blue lines in Figure 3.12. For control point P1-05 the precision was 70-80 centimeters less for both coordinates than in the complete wall model measurements when considering the standard deviation. At control point P1-31 the X coordinate was actually 2 meters more precise than in the previous phase, while the Y coordinate was about 1 meter less precise. Close-up plots showing the small precision differences are provided in Figure 4.6.

The precisions using standard deviation in control points P1-23 was similar to the measurements in the complete wall model phase. The X coordinate was about 40 centimeters less precise, while the Y coordinate had a precision about 80 centimeters better than in the previous phase. The close-up plots in Figure 4.7 suggest small differences in precision in this phase. Control point P1-16 had a precision of approximately 1.6 meters and 3 meters less than in the complete model for the X and Y coordinate respectively. The plots in Figure 4.4 and the close-up plots in Figure 4.8 illustrate this difference in precision. The third measurement round was considerably more accurate than the first two measurement rounds and thus indicated a somewhat poorer precision of P1-16 in this phase.

In six out of the eight chosen control points' coordinates, the X and Y coordinates' precision were somewhat poorer after the removal of the five internal walls in this phase. Of these six coordinates three were X coordinates and three were Y coordinates. The differences between the standard deviation precisions in these six coordinates compared with the complete wall model results were below 1 meter, except for the coordinates of control point P1-16. This was the control point closest to an access points and in between them a wall had been removed. Figure 4.8 reflects this and indicates that the removal of walls located close to both control point locations and one or more access points had an effect on some of the measurement precisions.

It was interesting to observe that the control point P1-13, which was located close to the same access point as P1-16, had better precision after the walls were removed. The reason for this slightly opposite behaviour might have been related to the fact that P1-13 and the access point were located in the same room. Also notable was the fact that control point P1-12 had the most precise measurements in the wall model part 1, although it was the among the least accurate control points in the same phase (Table 4.5). This is reflected in the plots in Figure 4.4. When comparing the plots from all five phases however, it was evident that control point P1-12 never was estimated to be located inside the correct room.

Table 4.10: *Precision: The standard deviation and the variance of the wall model part 1 measurements*

	Standard deviation	**Variance**
P1-17		
X	3.63	13.18
Y	3.17	10.03
P1-24		
X	1.85	3.41
Y	2.95	8.72
P1-01		
X	1.21	1.46
Y	1.89	3.56
P1-05		
X	1.96	3.83
Y	2.06	4.22
P1-10		
X	1.79	3.19
Y	2.01	4.05
P1-13		
X	0.88	0.77
Y	2.67	7.15
P1-26		
X	3.64	13.28
Y	1.16	1.36
P1-31		
X	3.40	11.55
Y	3.76	14.16
P1-23		
X	2.96	8.76
Y	2.77	7.68
P1-12		
X	0.48	0.23
Y	0.86	0.74
P1-16		
X	2.14	4.60
Y	6.19	38.28

When comparing the precision of the four chosen control points in phase 2 to the outer wall model results in phase 4, the X and Y coordinate of control point P1-05 were both more precise. The opposite occurred in the coordinates of control point P1-31 where the precision was poorer. However, this might have been due to the control point not being located close to any outer walls. Control point P1-23 had better precision than in the outer wall model results. The same occurred in the Y coordinate of control point P1-16. The precision of the X coordinate was approximately the same as in the outer wall model results. In other words, there was no clear connection between poorer accuracy and internal walls being removed in the model.

Wall model with alterations part 2

The results of the wall model with alterations part 2 (phase 3) are presented in Table 4.11. Eight out of the 22 X and Y coordinates had a precision better than 2.50 meters. This was four less than in the wall model with alterations part 1. In phase 3 six internal walls were removed from the wall model, three walls went in the X direction and three in the Y direction as illustrated in Figure 3.14. The most precise measurement was the X coordinate of control point P1-12 with a precision of 92 centimeters and the least precise was the X coordinate of control point P1-26 with 5.46 meters.

When the precisions of the four chosen control points using standard deviations were compared with the corresponding results in the complete wall model phase, six out of the eight X and Y coordinates were less precise. Both coordinates for control point P1-05 were less precise. The X coordinate of control point P1-31 had better precision, while the Y coordinate remained the same. For both control point P1-23 and P1-16 the X coordinates were less precise and the Y coordinates were slightly less precise than in the complete wall model results. The close-up plots in Figure 4.6, Figure 4.7 and Figure 4.8 illustrate the minor differences in precision between phase 1 and phase 3.

Compared to the outer walls measurements, five out of the eight chosen control points' X and Y coordinates in the wall model with alterations part 2 had poorer precision. These were both Y coordinates of control point P1-31, the X coordinate of P1-16 and the Y coordinate of both P1-05 and P1-23. The poorer precisions corresponded to some extent to the removal of the internal walls. In phase 3 only six internal walls were removed compared to the complete wall model. However, the standard deviation and variance of the precision suggested that the internal walls not necessarily improved the precision of the measurements of control points close to outer walls such as control point P1-05. As both coordinates of control point P1-31 were less precise in the wall model with alterations part 2 than the outer wall model, this indicated that outer walls had limited impact on locations far inside a building. Accordingly were locations close to outer walls little affected of the insertion of internal walls in the wall model when the outer walls were already included.

As previously mentioned, control point P1-05 was located very close to a lift shaft which might have affected the accuracy of the positioning. A comparison of the precisions of P1-05 in the first four phases using standard deviation and variance showed that the best precision was achieved in the complete wall model. The outer wall model measurements had the least precise X coordinate while the two altered wall models had the least precise Y coordinate. This provided additional evidence that both the precision and the accuracy of indoor locations were affected by major obstacles such as lift shafts which were located near them.

Table 4.11: *The standard deviation and the variance of the wall model part 2 measurements*

	Standard deviation	**Variance**
P1-17		
X	2.36	5.58
Y	3.63	13.21
P1-24		
X	1.69	2.86
Y	3.45	11.90
P1-01		
X	1.86	3.46
Y	2.48	6.16
P1-05		
X	1.97	3.86
Y	2.80	7.82
P1-10		
X	2.57	6.59
Y	2.99	8.91
P1-13		
X	1.95	3.80
Y	3.06	9.39
P1-26		
X	5.46	29.81
Y	3.36	11.27
P1-31		
X	4.00	16.02
Y	2.51	6.32
P1-23		
X	3.15	9.94
Y	4.06	16.50
P1-12		
X	0.92	0.85
Y	1.08	1.16
P1-16		
X	2.52	6.36
Y	3.31	10.95

Control point P1-26 was not among the four chosen control points due to the generally low accuracy of the measurements. In the complete wall model and the last two phases however the precision was generally good. With the exception of the X coordinate in the complete wall model, all measurements had a precision below 2 meters and the best precision was 83 centimeters in the outer wall model's Y coordinate. Similarly to control point P1-12, control point P1-26 was never estimated to be located inside the correct room and only a few measurement rounds located the control point in one of the adjacent rooms. Both of these control points were located close to outer walls.

Comparison of the altered wall models

A comparison of the two altered wall models' precision results showed that all four chosen control points had a precision of 4 meters or better with the exception of the Y coordinate of P1-16 which had a precision of 6.19 meters. In the cases of the control point P1-05 and P1-23 the X coordinates' precisions were very similar in the two phases, while the Y coordinates' precisions were slightly better in phase 2 than phase 3. The close-up plots in Figure 4.6 and Figure 4.7 indicate this as well.

For control point P1-31 the X coordinate precision was slightly better in phase 3 than in phase 2, although the Y coordinate had best precision in phase 2. This was in exactly the opposite X and Y directions of the closest removed walls. Figure 4.6 indicates the differences between the phases. In the case of control point P1-16 the X coordinates had similar precisions, while the Y coordinate was more precise in phase 3 than phase 2. This is clearly visible in Figure 4.8 where the measurement rounds of phase 3 are very closely collected.

4.5 Confidence number

The confidence numbers measured for each measurement are provided in feet in Appendix A. According to Cisco (2009) the confidence number (called 'confidence factor' by Cisco) is used to indicate the 95 % confidence region.

The majority of the measurements had a confidence number in the interval between 7 and 25 feet, i.e. an interval between 2.13 meters and 7.62 meters. Therefore values outside the interval stood out and were defined as unusual confidence number values. Of the 770 measurements that were performed only 26 had a confidence number above 25 feet. They were evenly spread out among the test phases. The first four phases had either five or six confidence number measurements outside the chosen interval and the fifth phase, the base measurements, had three measurements outside the interval.

There was an uneven distribution of confidence numbers outside the interval among the control points. Control point P1-17 and P1-10 had seven, P1-13 had six, P1-16 had three, P1-12 had two occurrences and P1-23 had one occurrence of high confidence numbers each. Each point was measured a total of 70 times. The other control points did not have any confidence number observations outside the interval. The fact that P1-23 and P1-16 were among these indicated that the chosen control points had both high and low confidence number values. Other control points with lower accuracy and with high or low precision had high confidence numbers as well. Therefore there was no indication of a connection between accuracy and confidence number or precision and confidence number.

Comparisons of the standard deviations and variances for each control point in both the accuracy section and the precision section did not suggest any coherence between these and the measured confidence number. Some measurement rounds had several measurements and others had some measurements with confidence numbers outside the interval. These measurements did not occur at certain times of the day, i.e. there was no coherence to times of the day when many people uses the wireless network.

4.6 Limitations

There were some limitations considering the test of NTNU's wireless network. The major limitations were as follows:

- Wall material and type of obstacle, such as lift shafts, were not included in the model
- Stairwells were not possible to include in the model

As described in Section 2.2.4 several sources including Liu et al. (2007), Yeung and Ng (2007) and Gu et al. (2009) highlight the accuracy of indoor positioning to be dependant on the signal strength and claim that obstacles reduce the accuracy of positioning. Several support services of larger corporations, such as Apple (2014) and Zen Internet (2014), define different wall and obstacle materials to affect signals from wireless networks indoors differently. For instance are brick walls, concrete walls and obstacles of any type of metal considered highly probable to interfere and reduce the signals from nearby access points.

No wall or obstacle materials were included in the model during the testing due to technical limitations. The obstacle types and materials inside the Lerkendal building include glass doors and windows, metal obstacles such as lift shafts and concrete walls. The fact that obstacle type and material were not included in the model was a major limitation in the measurements.

As highlighted by Wang et al. (2003) and stated above, brick walls are examples of obstacles likely to reduce the accuracy of indoor positioning due to the penetration loss. Stairwells were not included in any of the wall models due to the lack of a possibility to include them in Trådløse Trondheim's model. Stairwells can naturally be made of different types of materials. The ones in the Lerkendal building are mainly made of metal. According to several studies ((Liu et al., 2007; Gu et al., 2009; Apple, 2014; Zen Internet, 2014) they therefore have an impact on the indoor positioning accuracies. To achieve more accurate measurement results, the stairwells close to the measured control points can advantageously be inserted into the model. At this point this is not possible within technical limitations.

Chapter 5

Conclusion and future work

5.1 Concluding remarks

Wall models

The insertion of outer walls in Trådløse Trondheim's model had a limited effect on the accuracy of the measurements conducted indoors in the Lerkendal building in the testing phase. It was observed that some locations close by the outer walls seemed to have obtained higher accuracy when the outer walls were included in the model compared to when no outer or internal walls were included. This was however not statistically proven. Other locations had similar accuracies in the outer wall model and the complete wall model and others again obtained lower accuracies when outer and internal walls were inserted.

The highest accuracies were achieved at locations placed within triangles created by closely located access points. This is indicated in the tables regarding accuracy and the plots of the five phases and the most accurate locations. The best achieved accuracies were about 1 meter and thus equivalent to the WLAN based COMPASS and Ekahau systems (Liu et al., 2007; Gu et al., 2009). Wang et al. (2003) argued that major obstacles reduce the penetration of the signals and thereby reduce the accuracy in estimations of indoor locations. The accuracies of the locations in the test seemed to be influenced by major obstacles located close by, such as stairwells and lift shafts.

It was observed that the precision of the indoor locations seemed to be improved after the outer walls of the building had been included in the model. The inclusion of internal walls in addition to the outer walls had not significant enough impact to imply that the precision of the measurements improved. Nor was there a relation between reduced precision in all indoor locations and the removal of internal walls. Only in some cases the precision of the measurements were reduced when their immediate walls were removed. These were typically locations far from outer walls.

Room accuracy

Room accuracy was only achieved at certain indoor locations with high accuracy, such as within triangles of access points. Some locations had a few measurement estimates within the correct room, while others never obtained room accuracy due to certain limitations. These limitations were locations inside small rooms which required very high accuracy to obtain room accuracy, major obstacles such as stairwells reducing or blocking the signals and locations outside triangles of access points. There was no clear connection between improved room accuracy and inclusion of either outer walls or both outer and internal walls in the model.

Confidence number

There were no indications that the confidence number indicated any particular behaviour in the measurements' accuracies or precisions. In other words there was no implication of a consistence between the confidence number and the standard deviation and variance in the measurements. Similarly, there were no suggestions of a correspondence between the confidence number and certain test phases or certain times of the day. It seemed to have been a connection between the very high confidence number values and certain control points, however there were no further connection to reduced or improved accuracy or precision.

5.2 Future work

There are several issues with the test that can be used as a basis for future work within the field. One of these issues is the possibility to include wall and obstacle type and material in the model. As different types and materials of obstacles interfere with the signals it can be useful to estimate the penetration loss. For instance can a factor system be used, i.e. defining the penetration loss based on material types and grouping materials with similar behaviour, such as what Apple (2014) has done. The inclusion of stairwells are probably a more technical issue as stairs are different in design and material type.

It can be useful to apply and test NTNU's wireless network and other networks in other buildings to compare the results. However that requires several preparatory tasks. Similar to what is done in the Lerkendal building, the access points and control points must be accurately measured.

Another issue is the RSSI at the measured locations. To include signal strength data in the measurement output and information about which access points are actually used in the estimations can provide valuable information on how the access points are used in the indoor positioning.

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Appendix A

Measurement results

Table A.1: *Phase 1: Complete wall model measurements*

P1-17	Measurement round 1					Measurement round 2				
X	22,17	23,93	30	14,86	20,57	24,27	29,19	28,83	28,7	29,08
Y	79,82	84,28	87,37	76,89	75,79	88,19	83,600000	82,16	81,46	80,7
conf	17,0688	163,3728	14,6304	160,9344	17,0688	17,0688	12,1920	12,1920	121,9200	12,1920
P1-24										
X	42,55	43,87	44,92	42,12	44,76	44	45,86	47,25	48,64	48,95
Y	101,41	98,22	95,65	104,12	101,12	100,51	99,96	99,14	98,83	97,46
conf	19,5072	21,9456	14,6304	17,0688	14,6304	12,1920	14,6304	12,1920	12,1920	12,1920
P1-01										
X	20,74	19,1	18,64	20,2	17,23	20,87	22,91	23,02	22,35	17,62
Y	112,96	115,4	116,08	116,44	118,89	113,72	113,12	113,14	112,72	115,12
conf	12,192	12,192	12,192	12,192	9,7536	14,6304	14,6304	12,1920	17,0688	12,1920
P1-05										
X	20,46	21,96	22,93	25,25	22,06	23,52	22,89	22,06	21,85	22,67
Y	106,97	107,12	108,45	109,05	109,8	109,15	107,34	108,51	109,39	110,8
conf	14,6304	12,192	9,7536	12,192	12,192	12,1920	12,1920	12,1920	14,6304	12,1920
P1-10										
X	16,56	16,18	17,19	15,64	16,06	19,62	18,89	18,38	18,14	17,97
Y	110,9	110,45	108,17	99,73	98,67	105,28	102,48	102,57	102,18	102,15
conf	17,0688	12,192	17,0688	9,7536	14,6304	14,6304	12,1920	9,7536	12,1920	168,2496
P1-13										
X	15,42	15,28	15,22	15,74	16,14	21,31	18,18	16,54	15,67	17,57
Y	101,72	100,66	99,65	97,79	95,65	86,07	89,39	90,89	91,06	90,6
conf	9,7536	12,192	104,8512	17,0688	21,9456	17,0688	14,6304	12,1920	131,6736	12,1920
P1-26										
X	31,28	30,58	34,74	39,09	39,68	24,01	33	33,83	33,77	33,99
Y	105,95	105,94	107,89	108,64	107,89	105,88	108,13	108,17	108,19	108,83
conf	21,9456	21,9456	17,0688	12,192	12,192	21,9456	14,6304	17,0688	19,5072	14,6304
P1-31										
X	27,13	28,22	26,96	35,98	38,31	21,79	24,3	24,15	23,78	23,44
Y	105,34	110,04	110,48	105,77	108,98	101,76	107,62	107,95	108,33	107,85
conf	12,192	14,6304	12,192	12,192	9,7536	14,6304	12,1920	9,7536	9,7536	9,7536
P1-23										
X	84,88	86,13	84,73	85,08	85	77,73	80,67	82,16	82,84	82,53
Y	79,36	77,44	83,01	85,61	85,04	80,31	78,26	75,97	75,08	74,78
conf	12,6304	12,192	14,6304	12,192	12,192	17,0688	14,0688	12,1920	12,1920	14,6304
P1-12										
X	18,14	17,9	17,25	15,31	14,89	17,99	17,4	18,3	18,73	19,38
Y	101,42	101,71	102,91	104,31	103,48	107,97	106,14	104,51	102,83	101,6
conf	12,192	12,192	12,192	9,7536	9,7536	12,1920	12,1920	14,6304	12,1920	12,1920
P1-16										
X	14,77	13,37	12,76	13,8	13,65	14,28	13,91	13,66	13,63	13,59
Y	79,45	79,04	76,89	85,52	84,73	86,11	84,47	83,88	82,88	81,73
conf	12,192	17,0688	12,192	14,6304	14,6304	12,1920	9,7536	12,1920	12,1920	12,1920

Table A.2: *Phase 2: Wall model with alterations part 1 measurements*

P1-17	Measurement round 1					Measurement round 2					Measurement round 3				
X	19,85	29,92	32,28	27,27	29,53	23,24	24,36	25,31	25,41	28,32	21,04	22,19	24,03	22,16	22,16
Y	87,65	82,43	81,03	80,50	79,19	89,62	85,94	84,32	83,47	84,02	80,99	79,74	79,43	86,35	83,63
conf	165,8112	124,3584	17,0688	160,9344	17,0688	14,6304	14,6304	12,192	156,0576	17,0688	12,192	12,192	17,0688	14,6304	14,6304
P1-24															
X	41,67	42,61	44,03	44,61	44,88	45,89	46,70	47,28	47,74	47,82	43,61	44,01	44,01	45,82	46,05
Y	97,57	96,12	95,22	94,71	94,66	99,11	98,29	97,20	96,59	95,66	103,14	101,54	100,84	102,90	101,11
conf	17,0688	14,6304	17,0688	12,192	12,192	12,192	12,192	12,192	12,192	14,6304	12,192	12,1922	14,6304	17,0688	19,5072
P1-01															
X	20,43	19,89	19,82	20,02	19,94	19,20	19,57	19,94	19,54	19,67	21,63	21,95	21,93	18,02	17,77
Y	114,40	115,20	115,95	116,66	116,95	114,80	117,38	117,40	116,61	117,11	113,87	113,68	113,66	117,93	120,41
conf	12,192	12,192	12,192	12,192	12,192	9,7536	9,7536	9,7536	12,192	9,7536	12,192	12,192	12,192	12,192	9,7536
P1-05															
X	21,39	20,03	20,17	20,92	20,74	23,63	24,44	24,04	24,26	24,19	21,74	22,24	22,10	27,08	22,01
Y	113,00	112,50	111,67	111,45	111,07	110,42	108,00	108,41	108,13	106,63	112,26	113,07	112,54	111,64	109,73
conf	9,7536	9,7536	9,7536	9,7536	9,7536	12,192	12,192	9,7536	14,6304	12,192	9,7536	9,7536	12,192	12,192	12,192
P1-10															
X	18,31	19,07	19,25	21,81	21,89	16,46	17,57	17,32	17,39	17,64	16,47	18,03	19,67	16,61	16,37
Y	98,89	98,22	98,63	97,26	96,90	101,94	100,51	101,19	101,01	101,17	99,72	98,93	98,05	98,40	94,29
conf	17,0688	14,6304	156,0576	14,6304	14,6304	9,7536	12,192	12,192	9,7536	12,192	14,6304	17,0688	17,0688	12,192	9,7536
P1-13															
X	16,05	14,90	14,09	13,83	14,85	15,66	14,97	14,10	13,85	13,68	13,47	13,95	14,38	13,05	13,08
Y	97,93	98,13	97,77	97,70	96,19	101,34	93,71	92,93	92,81	93,08	94,83	97,91	99,12	94,05	98,83
conf	14,6304	12,192	12,192	141,4272	12,192	12,192	14,6304	12,192	9,7536	9,7536	12,192	9,7536	12,192	14,6304	12,192
P1-26															
X	33,78	34,28	34,74	35,57	36,10	32,42	36,33	39,48	40,00	41,75	40,71	42,65	42,73	40,38	42,90
Y	108,47	109,08	108,47	107,36	107,52	109,67	110,51	110,76	110,44	110,83	109,90	109,55	109,26	108,27	107,90
conf	14,6304	17,0688	19,5072	19,5072	14,6304	12,192	19,5072	17,0688	17,0688	17,0688	12,192	12,192	14,6304	17,0688	14,6304
P1-31															
X	28,63	31,11	29,28	28,40	30,15	27,64	30,21	30,32	26,91	26,02	36,19	36,27	35,70	26,73	28,08
Y	99,77	102,44	105,47	105,45	104,78	111,56	110,10	110,09	108,60	108,00	108,26	108,30	109,29	113,66	112,56
conf	19,5072	14,6304	14,6304	12,192	14,6304	12,192	14,6304	12,192	9,7536	9,7536	12,192	12,192	12,192	12,192	17,0688
P1-23															
X	73,66	83,10	84,38	85,24	84,97	82,28	84,23	81,99	81,64	81,90	81,94	84,58	86,55	83,47	84,39
Y	86,78	79,43	79,46	80,83	84,56	88,50	87,47	86,08	85,36	84,32	86,87	85,59	84,35	82,96	83,80
conf	21,9456	14,6304	17,0688	17,0688	14,6304	14,6304	12,192	14,6304	14,6304	12,192	12,192	9,7536	9,7536	12,192	12,192
P1-12															
X	16,14	15,31	15,33	15,41	15,71	16,17	15,62	15,65	15,61	15,52	15,81	15,68	15,70	17,09	16,54
Y	102,92	101,90	101,22	101,55	101,69	103,62	102,56	101,89	101,12	100,56	101,02	101,68	102,91	101,03	101,19
conf	9,7536	9,7536	9,7536	12,192	9,7536	9,7536	14,6304	9,7536	9,7536	9,7536	12,192	9,7536	9,7536	9,7536	9,7536
P1-16															
X	13,97	13,13	14,26	14,33	14,27	13,96	14,43	14,68	14,94	14,65	21,56	16,34	13,77	17,62	13,14
Y	96,21	95,98	93,21	91,89	91,03	95,17	96,86	97,96	98,40	98,42	81,68	85,48	86,85	80,81	84,96
conf	14,6304	19,5072	17,0688	17,0688	17,0688	17,0688	12,192	12,192	12,192	17,0688	21,9456	19,5072	14,6304	17,0688	14,6304

Table A.3: *Phase 3: Wall model with alterations part 2 measurements*

P1-17	Measurement round 1					Measurement round 2					Measurement round 3				
X	18,30	23,77	25,80	22,02	22,36	26,67	26,24	25,44	25,84	25,56	22,80	25,72	27,49	25,20	25,69
Y	85,42	83,64	84,22	81,81	80,16	94,66	87,67	84,18	84,73	85,96	83,98	81,70	81,25	80,31	81,71
conf	14,6304	17,0688	17,0688	12,192	12,192	19,5072	17,0688	14,6304	19,5072	14,6304	12,192	12,192	12,192	12,192	14,6304
P1-24															
X	45,99	45,55	45,27	41,11	43,80	40,97	42,38	44,32	44,95	45,59	43,94	44,58	45,34	45,85	46,25
Y	96,64	94,02	93,14	101,60	96,99	102,16	99,02	95,24	94,47	93,31	103,80	101,66	99,72	99,04	97,86
conf	17,0688	14,6304	14,6304	17,0688	14,6304	19,6304	17,0688	17,0688	14,6304	17,0688	12,192	12,192	14,6304	17,0688	14,6304
P1-01															
X	20,32	21,42	20,88	24,61	20,03	17,56	17,32	18,60	19,07	19,51	19,19	19,03	18,44	18,09	17,79
Y	114,46	116,06	116,30	111,42	117,76	117,53	117,98	117,76	117,49	117,35	109,44	113,73	115,42	115,42	115,52
conf	12,192	12,192	12,192	12,192	12,192	12,192	9,7536	9,7536	9,7536	9,7536	14,6304	14,6304	9,7536	9,7536	12,192
P1-05															
X	19,36	20,20	19,64	16,11	19,88	18,64	19,10	20,93	21,23	21,80	23,77	23,85	21,90	20,44	19,69
Y	110,48	109,45	110,10	105,04	113,99	115,49	112,67	110,11	109,58	108,22	105,14	108,71	110,89	110,88	109,06
conf	14,6304	9,7536	12,192	17,0688	9,7536	9,7536	12,192	17,0688	12,192	12,192	12,192	12,192	12,192	12,192	9,7536
P1-10															
X	15,43	16,82	17,43	16,92	17,59	14,57	14,90	15,33	15,73	15,92	17,43	20,90	21,10	21,35	22,21
Y	99,43	99,83	100,79	95,34	96,97	100,89	103,71	104,05	104,48	104,47	105,36	101,14	100,12	98,49	98,59
conf	14,6304	14,6304	14,6304	12,192	12,192	9,7536	7,3152	9,7536	12,192	9,7536	112,1664	131,6736	12,192	134,112	14,6304
P1-13															
X	18,88	17,51	15,84	13,31	14,19	13,97	14,05	14,20	14,24	14,23	18,59	17,86	18,14	16,58	16,24
Y	100,56	99,08	98,51	90,89	93,59	93,58	96,05	98,22	98,94	99,17	100,56	100,68	100,03	100,48	99,96
conf	14,6304	17,0688	14,6304	14,6304	9,7536	12,192	14,6304	12,192	12,192	12,192	14,6304	12,192	14,6304	17,0688	14,6304
P1-26															
X	35,32	37,86	38,21	23,65	26,99	39,49	37,50	37,10	37,49	37,50	39,69	41,68	42,49	43,17	42,64
Y	105,30	105,56	105,39	115,61	113,35	109,95	110,86	111,15	111,35	111,42	105,96	105,65	105,96	106,57	107,94
conf	19,5072	19,5072	24,384	19,5072	19,5072	12,192	12,192	14,6304	14,6304	12,192	14,6304	14,6304	17,0688	14,6304	12,192
P1-31															
X	30,37	31,06	31,33	21,95	24,62	36,19	32,44	30,83	31,01	31,14	31,08	33,76	35,03	35,97	36,28
Y	102,96	103,44	105,62	109,33	107,63	107,16	108,87	109,57	108,81	106,30	112,09	110,63	109,65	108,92	108,39
conf	12,192	12,192	12,192	14,6304	14,6304	17,0688	12,192	12,192	12,192	12,192	12,192	9,7536	9,7536	9,7536	9,7536
P1-23															
X	82,78	87,14	87,16	79,77	84,81	75,18	83,66	85,73	85,77	85,25	82,15	82,04	85,39	85,59	85,48
Y	87,21	85,92	85,11	87,80	86,89	82,73	80,84	80,27	80,19	81,52	89,44	92,91	89,54	89,62	89,93
conf	12,192	12,192	12,192	14,6304	9,7536	19,5072	14,6304	12,192	9,7536	12,192	14,6304	14,6304	14,6304	14,6304	12,192
P1-12															
X	18,56	15,86	14,83	17,01	15,65	17,42	16,76	16,29	16,55	15,86	16,97	16,05	15,46	15,68	15,88
Y	103,53	101,07	100,43	102,49	103,94	102,48	103,56	103,71	103,62	103,21	102,52	102,68	103,38	103,71	104,41
conf	12,192	9,7536	12,192	12,192	9,7536	17,0688	12,192	12,192	14,6304	12,192	9,7536	9,7536	9,7536	9,7536	9,7536
P1-16															
X	12,41	12,87	13,89	21,33	15,29	19,57	14,43	13,14	12,95	13,23	14,37	13,84	16,25	14,98	13,70
Y	95,81	91,35	91,35	83,74	87,74	87,52	91,37	92,84	93,69	93,39	95,58	91,99	87,73	88,93	89,78
conf	14,6304	14,6304	17,0688	21,9456	14,6304	17,0688	12,192	12,192	14,6304	14,6304	277,9776	12,192	9,7536	17,0688	241,4016

Table A.4: *Phase 4: Outer wall model measurements*

P1-17	Measurement round 1					Measurement round 2					Measurement round 3				
X	21,50	23,88	24,61	23,02	23,07	19,22	19,60	19,23	22,19	21,42	20,41	19,02	18,21	18,29	17,93
Y	94,70	88,82	85,43	85,01	85,40	86,37	86,44	86,53	90,67	85,41	93,62	88,54	85,00	83,09	83,63
conf	19,5072	14,6304	17,0688	14,6304	14,6304	12,192	14,6304	12,192	19,5072	14,6304	19,5072	14,6304	12,192	12,192	9,7536
P1-24															
X	38,74	41,23	42,57	43,41	44,43	38,79	42,17	44,50	41,69	44,89	38,63	40,38	41,56	42,63	43,59
Y	106,74	103,17	101,44	100,86	99,73	108,46	103,02	100,17	104,39	100,69	104,52	101,68	99,93	98,29	97,51
conf	14,6304	14,6304	14,6304	12,192	12,192	19,5072	14,6304	14,6304	17,0688	14,6304	19,5072	17,0688	14,6304	14,6304	14,6304
P1-01															
X	17,96	20,76	21,64	21,01	21,32	24,16	23,22	20,94	25,80	24,27	22,62	21,97	21,54	21,95	21,36
Y	108,75	113,46	116,00	117,32	117,31	108,80	114,15	115,12	112,00	113,79	113,60	115,02	115,41	115,74	116,23
conf	17,0688	12,192	12,192	9,7536	9,7536	14,6304	12,192	9,7536	12,192	9,7536	12,192	9,7536	12,192	9,7536	9,7536
P1-05															
X	25,29	25,55	23,92	23,71	25,58	23,83	22,74	23,63	32,28	27,48	25,30	26,53	26,68	25,78	25,64
Y	112,62	113,46	112,90	112,57	111,58	111,18	108,99	109,87	112,20	112,86	114,58	114,05	113,82	113,51	113,55
conf	12,192	12,192	12,192	9,7536	12,192	9,7536	9,7536	9,7536	12,192	12,192	9,7536	12,192	9,7536	12,192	9,7536
P1-10															
X	15,77	16,67	17,20	17,02	16,90	19,36	21,85	23,24	21,92	21,15	18,40	21,12	22,49	24,63	24,89
Y	100,62	98,35	99,97	101,07	102,12	102,67	103,03	102,70	108,31	105,41	102,06	100,45	99,30	98,32	97,95
conf	14,6304	9,7536	12,192	9,7536	9,7536	12,192	112,1664	14,6304	17,0688	12,192	17,0688	12,192	14,6304	17,0688	14,6304
P1-13															
X	15,52	16,66	16,95	16,92	17,48	18,27	20,62	18,53	14,79	14,63	15,69	15,69	15,46	15,20	15,22
Y	88,40	91,00	91,85	92,61	94,82	96,56	95,71	94,77	87,97	85,26	95,54	95,74	97,08	97,82	98,69
conf	14,6304	12,192	12,192	195,072	12,192	124,3584	17,0688	14,6304	9,7536	12,192	12,192	12,192	12,192	9,7536	87,7824
P1-26															
X	34,62	36,49	37,09	37,45	37,50	33,73	35,50	36,06	36,47	36,03	33,45	35,23	35,23	36,07	36,28
Y	112,35	112,50	112,19	111,59	111,42	112,05	112,25	112,26	110,27	110,87	112,36	111,55	110,55	110,19	110,68
conf	7,3152	9,7536	9,7536	9,7536	9,7536	9,7536	12,192	12,192	9,7536	12,192	12,192	12,192	12,192	12,192	12,192
P1-31															
X	28,51	29,07	28,20	32,18	32,11	29,20	31,52	32,04	38,36	36,60	35,47	34,73	33,17	33,22	33,19
Y	112,98	112,14	111,15	110,34	109,89	112,25	111,34	111,24	109,77	110,07	109,53	109,76	110,01	110,38	110,58
conf	9,7536	9,7536	9,7536	12,192	9,7536	14,6304	9,7536	9,7536	9,7536	9,7536	9,7536	9,7536	9,7536	9,7536	9,7536
P1-23															
X	74,65	85,19	87,25	88,72	88,59	77,30	86,46	86,88	81,57	85,03	84,96	85,05	84,52	83,21	82,56
Y	83,84	81,75	81,91	82,09	83,60	87,63	84,38	84,47	90,69	88,60	80,09	79,73	78,70	77,62	78,15
conf	21,9456	12,192	9,7536	9,7536	9,7536	19,5072	9,7536	9,7536	14,6304	14,6304	9,7536	9,7536	12,192	12,192	12,192
P1-12															
X	15,56	15,58	15,58	15,33	15,17	18,33	16,61	16,04	18,97	18,50	19,21	17,50	17,83	16,46	16,54
Y	103,51	102,80	102,31	102,54	103,51	102,40	101,22	101,71	102,71	103,46	107,09	102,19	101,81	102,84	103,74
conf	7,3152	7,3152	9,7536	7,3152	7,3152	12,192	9,7536	9,7536	9,7536	9,7536	134,112	9,7536	12,192	9,7536	9,7536
P1-16															
X	19,59	14,44	13,62	13,83	13,82	14,73	14,86	14,48	19,19	17,60	15,26	13,14	16,76	16,20	16,67
Y	89,06	87,83	87,13	86,95	87,57	86,12	86,22	86,52	81,09	83,63	93,99	95,98	92,50	93,82	94,02
conf	17,0688	14,6304	9,7536	12,192	12,192	19,5072	17,0688	17,0688	19,5072	195,072	17,0688	14,6304	14,6304	12,192	17,0688

Table A.5: *Phase 5: Base measurements*

P1-17	Measurement round 1					Measurement round 2					Measurement round 3				
X	20,10	21,60	22,66	22,84	24,36	17,69	18,61	19,35	20,34	20,78	22,63	23,23	23,88	19,29	22,48
Y	91,89	89,08	86,56	85,93	86,71	89,31	87,96	87,45	87,40	86,09	85,81	85,06	84,10	83,22	83,81
conf	24,384	14,6304	12,192	17,0688	17,0688	17,0688	12,192	9,7536	12,192	12,192	17,0688	12,192	12,192	17,0688	17,0688
P1-24															
X	37,26	42,92	44,70	45,87	46,88	55,81	49,18	44,26	43,33	43,07	42,53	43,50	44,13	44,38	45,80
Y	110,10	100,29	96,92	95,30	94,41	91,69	92,96	94,29	95,58	96,29	103,27	101,57	101,21	103,32	100,35
conf	17,0688	17,0688	14,6304	12,192	12,192	19,5072	14,6304	12,192	12,192	12,192	14,6304	12,192	12,192	14,6304	14,6304
P1-01															
X	24,76	24,33	24,00	23,52	19,81	21,41	20,73	19,73	19,24	19,82	21,64	20,79	19,99	22,51	21,03
Y	112,45	113,44	114,32	115,08	117,77	114,57	115,59	116,35	116,47	117,33	107,35	113,13	113,80	111,58	113,74
conf	12,192	9,7536	9,7536	9,7536	9,7536	9,7536	9,7536	12,192	9,7536	12,192	14,6304	14,6304	9,7536	12,192	12,192
P1-05															
X	20,04	21,21	23,68	20,98	23,72	25,37	23,99	23,92	23,28	22,94	20,01	18,90	21,85	24,31	24,41
Y	108,99	110,15	110,48	112,06	110,26	112,04	112,03	110,90	111,54	111,33	114,77	112,14	110,70	108,07	107,81
conf	9,7536	9,7536	12,192	9,7536	9,7536	9,7536	9,7536	9,7536	9,7536	9,7536	12,192	12,192	12,192	12,192	12,192
P1-10															
X	14,70	16,40	17,86	18,55	19,77	17,81	18,36	17,78	17,63	17,70	16,87	17,72	18,30	16,49	17,39
Y	99,88	103,04	105,97	106,44	106,20	97,34	97,19	96,51	95,75	96,23	102,61	99,53	98,95	105,05	106,20
conf	12,192	14,6304	12,192	12,192	12,192	12,192	17,0688	9,7536	12,192	41,6304	12,192	12,192	12,192	14,6304	17,0688
P1-13															
X	13,61	13,35	13,80	13,90	14,05	16,18	15,77	15,43	15,09	14,89	17,96	16,97	16,18	18,93	18,26
Y	94,01	97,34	98,12	98,08	96,72	97,61	96,25	96,58	96,35	96,47	100,15	99,47	98,71	101,74	99,42
conf	14,6304	12,192	9,7536	9,7536	9,7536	12,192	19,5072	12,192	12,192	12,192	12,192	12,192	12,192	19,5072	14,6304
P1-26															
X	33,63	36,40	37,29	36,09	35,94	37,12	36,55	36,80	37,06	37,37	38,82	40,46	38,79	37,87	41,13
Y	112,54	113,06	113,06	114,05	114,37	111,67	113,29	113,53	113,26	112,88	108,83	109,68	110,92	111,13	108,50
conf	9,7536	9,7536	12,192	9,7536	9,7536	12,192	9,7536	12,192	9,7536	12,192	17,0688	14,6304	17,0688	14,6304	12,192
P1-31															
X	30,18	30,77	30,83	31,08	30,90	35,59	34,21	28,67	29,36	29,87	26,18	29,68	30,31	31,71	29,49
Y	111,89	110,51	117,00	111,01	111,24	111,86	112,15	111,67	112,46	113,54	110,46	109,10	108,64	106,81	108,00
conf	9,7536	12,192	9,7536	12,192	9,7536	12,192	9,7536	12,192	9,7536	9,7536	14,6304	12,192	12,192	12,192	9,7536
P1-23															
X	65,86	82,41	84,44	84,76	84,67	85,49	85,66	85,80	85,92	85,82	63,39	74,71	78,64	83,24	86,37
Y	91,77	84,96	82,18	84,20	85,93	83,81	82,47	82,94	82,93	83,10	90,78	83,55	82,37	86,85	85,26
conf	24,384	14,6304	14,6304	14,6304	12,192	14,6304	12,192	12,192	14,6304	12,192	29,2608	19,5072	17,0688	9,7536	12,192
P1-12															
X	17,33	16,10	15,25	15,34	15,53	16,54	16,44	16,58	15,96	16,07	17,38	16,19	15,49	16,43	16,31
Y	102,83	102,07	102,79	103,65	104,81	100,98	100,23	100,76	100,09	99,23	104,89	104,32	104,74	109,49	107,40
conf	9,7536	9,7536	9,7536	282,854	9,7536	9,7536	12,192	12,192	12,192	12,192	9,7536	9,7536	9,7536	9,7536	14,6304
P1-16															
X	22,33	18,64	15,62	15,62	13,82	14,76	14,81	14,42	14,54	14,50	14,76	14,94	15,77	15,76	14,90
Y	84,18	83,37	83,73	83,73	87,08	95,41	93,10	90,64	89,46	87,96	94,88	88,55	87,80	96,28	95,41
conf	24,384	19,5072	270,662	12,192	17,0688	17,0688	17,0688	19,5072	21,9456	19,5072	19,5072	19,5072	9,7536	14,6304	17,0688

Appendix B

Test computer specifications

Model HP Mini 5102

CPU Intel Atom N450 Processor

RAM 2 GB

GPU Intel Graphics Media Accelerator 3150

Storage 215 GB

Operating system 32-bit Microsoft Windows 7 Home Premium

Appendix C

JavaScript file

The JavaScript file used in the test.

```
var positioningURL = 'https://ntnu-pos.mazemap.com/position?callback=?';

var logging = false;

$(document).ready(function() {
	$.get("getIP.php", function(data) {
		$("#notifications").append("<b>IP-address: " + data.ip + "</b><br>");

	});

	$("#start").click(function() {
		if(logging != false) {
			clearInterval(logging);
			logging = false;
			$("#start").val("Start");
		} else {
			getCampusGuideLocation();
			logging = setInterval(getCampusGuideLocation,$("#interval").val());
			$("#start").val("Stop");
		}
	});
});

var writtenHeader = false;
function writeHeaders(object) {
	$("#notifications").append("timestamp\t");
	for(var key in object) {
		$("#notifications").append(key + "\t");
	}
	$("#notifications").append("\n---------------------------------------------------------
	-------------------------------------------------------------------------------------- \n");
	writtenHeader = true;
}


function getCampusGuideLocation() {
	$.getJSON(positioningURL, function(data) {
			if(writtenHeader == false) {
				writeHeaders(data);
			}
			var d = new Date();
			$("#notifications").append(d.getTime() + "\t");
			for(var key in data) {
				$("#notifications").append(data[key] + "\t");
			}
			$("#notifications").append("\n");
			//console.log(data);
	});
}
```