Indoor Localization System based on UWB Radar and Coordinated Wireless Sensor Networks

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Preface

This Masters thesis is written for the University of Oslo at the Department of Informatics. The work was conducted over the period between Spring and Fall 2019. Supervision was provided by Professor Tor Sverre Lande, Ph. D. Kristian G. Kjelgård and Professor Dag T. Wisland, at the NANO research group.

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Abstract

This master project presents research on the subject of indoor localization systems intended for the localization of humans. Based on this research, a system is proposed and implemented. The system is based on wireless sensor network and ultra wide-band radar technology. Wireless communication is performed through Bluetooth low energy links. The implementation emphasize scaling, sensor node coordination, energy consumption and accuracy. Extension of features is also an important topic in this project, especially respiration monitoring and reliable presence sensing. Localization is performed by a scaleable multi-lateration algorithm. The system provides accurate results within a 0.5 meter radius with a precision of 86%. We conclude with a successful implementation and provide discussions on potential usages and additional features.

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Chapter 1

Introduction

The concept of Indoor Localization Systems(ILS) have seen a rise of enthusiasm the past decade. ILSs are systems that detects the presence of humans and returns their location to an application. In applications dealing with logistics, healthcare, security and safety, the location of subjects is an essential parameter to improve subjects safety, efficiency and comfort. We will refer to the person being located as a subject. We chose the term subject since it conveys a sense of passiveness towards the system. We also use the term localization for finding a subjects whereabouts, without the subject directly having to interact with the system. The location provided by the system can either be relative to the system or an absolute coordinates, like in GPS. Positioning is a term often used for similar systems, but our definition of positioning is only providing subjects coordinates. Whereas localization is a broader term which provides both coordinates and environmental information such as room number, room section and/or building. The term localization does not state whether the subject is an identified person or an anonymous person. ILSs have designated areas where they look for movement. We call this area the detection zone. One ILS may contain more than one detection zone in order to cover discrete sections of a building, like rooms or cubicles.

A major aspect of this thesis is to implement a wireless connection between the systems physical components. A wireless solution is not only easier to install, but also allow for simple scaling, cheap maintenance and flexible solutions. Combining wireless technology with the development of sophisticated sensing technology introduces many potential ILS features. Imagine not only being able to monitor the location of subjects in a detection zone, but also their well-being through respiration and movement monitoring. All while using contactless, non-intrusive sensors that can be placed out of sight from the target. A system such as this could revolutionize the way hospital patient-administration work, increase the welfare of inmates in prisons or help senior citizens live in their own homes for longer. To enable these features coordination between sensing nodes and processing units are required. Unlike many other wireless sensing systems where single sensors provide independent data used in applications, ILS systems have a strict requirement for temporal resolution. Coordination requires a high level of connectivity between sensing components and processing components.

Currently, most published ILSs requires the subject to wear some sort of hardware, like transceivers, in order to detect their location[1][2]. We call this type hardware tags. Tags makes it easier to locate more subjects in one detection zone, and provide accurate coordinates of their tags.

In this project we will emphasize the use of tag-less localizing. We will explore different possibilities of sensor technologies, wireless communication and sensor networks. Our goal in this project is to find how to create a cost-effective, coordinated sensing network able to reliably detect human presence and provide the precise location. A working proposed system will be presented, which will serve as a base for further discussion on potential functionalities and applications. This system will not use tags.

In our next chapter, chapter two, we will provide some theoretical options for designing an ILS using Wireless Sensor Networks(WSN). In this thesis we use the term WSN to describe a network of communication processing and sensing nodes. Traditionally the term WSN does not convey a notion of temporal resolution requirements. However, in this thesis it does. Note that the difference between a Wireless Sensor Network and a Coordinated Wireless Sensing Network mainly lies within the closest processing unit. Which is why most properties and challenges are inherited to coordinated WSNs.

In chapter three, we propose a system based on the theoretical possibilities we explored in chapter two. This chapter includes a description on what scenario we are aiming for, related solutions and a description on how the system was implemented.

Chapter four presents the results from testing the proposed system, calibration process and test description.

The final chapter presents a discussion for further work and potential features and applications and a conclusion to this thesis.

Chapter 2

Background

This chapter presents certain theoretical possibilities when designing a localization system. The first section, section 2.1, will be a summary of wireless communication technology and a discussion on standards suited for wireless sensor networks(WSN). Following comes section 2.2 introducing localization in wireless sensor networks, including structure types, localization methods and challenges. Section2.3 is a summary of some sensor technologies used in distance and presence monitoring. At last there will be a short discussion on what to take into account when designing a localization system.

2.1 Wireless Networks

In this project one of our main goals is to connect the internal components of our localization system wirelessly. Thus, we conducted some research on wireless communication and different ways of establishing connections between the sensor nodes and the main processing unit. In specific cases where the network consists of sensor nodes the wireless network is referred to as a wireless sensor network(WSN). WSNs usually inherit the challenges and characteristics of conventional wireless networks, which is why there will be a general introduction section and a section putting this in the context of WSNs. Additionally there will be summaries of three common wireless network standards Bluetooth, Zigbee and WiFi.

2.1.1 Wireless Communication Fundamentals

The routing of information through a wireless network can be a complicated affair, especially when working with large scale WSNs. This subsection is an introduction to the fundamentals of wireless communication on the physical level, PHY. This will not only provide a basic understanding of wireless communications, but also provide some background for radar senors.

PHY is the part of the network which is concerned with modulating and demodulating digital signals. This task is usually performed by transceivers. Modulation is a process where symbols, like 1 and 0 in binary modulation, are mapped to waveforms. A transmitter sends the modulated data, i.e waveforms, through the antenna and out into free space. When the waveforms reaches an appropriate receiver, the receiver then maps these waveform back to symbols. This is called demodulation. During the time the waveform is transmitted through free space it is subject to a number of physical phenomena that can distort the original signal. The basic phenomena are reflection, diffraction, scattering and doppler fading.

Reflection is when the signal enters another medium and the new medium is smooth such as a wooden wall, window etc. Some of the signal energy will bounce back, some will pass through and some will be absorbed. The amount of energy that are passed absorbed or reflected depends on the material.

Diffraction is the when an waveform hits a sharp edge and is propagated in a different direction.

Scattering is when the waveform hits a rough surface. It will be reflected and redirected in many directions.

Doppler fading is when the transmitter and receiver moves relative to each other resulting in a frequency shift, according to the doppler effect.

Additionally, when waveforms are sent out by an antenna, the antenna usually sends the signal in more than one direction. Some waves will reach the receiver through a direct path from the transmitter. This is called the Line of Sight(LOS) path or the direct path. Others may be affected by one of the phenomena mentioned above and reach the receiver later by the Non Line of Sight(NLOS) path, or the indirect path. The signals traveling the indirect path can interfere with the direct path signals in a constructive or destructive manner depending on the phase difference.

When channels treat all frequency components equally, this is called frequency-nonselective fading, or flat fading. In flat fading all frequency components will be faded by the same amount. If the channel discriminate frequency components it is a frequency selective channel. Whether or not a channel is frequency selective is determined by the delay spread.

Delay spread is the time between the first to the last wave hits the receiver. A channel is flat fading if the inverse of the root mean square(RMS) delay spread is larger than the full signal bandwidth. Another common source of errors caused by multi-path propagation is called inter-symbol interference(ISI). ISI occurs when the transmitter sends out symbols with high data-rates and multiple symbols from different paths overlap. Thus, the severity of ISI is completely dependent on data-rates and the RMS delay spread. This can lead to distorted data on the receiver.

The distance between transmitter(s) and receiver(s) must also be taken into account. The signal will attenuate over more and more over larger distances, this is called path loss. Under ideal conditions, Friis transmis-

sion equation2.1 can be used to calculate the power received from a transmitter at a given distance.
2.1.

$$\frac{P_r}{P_t} = (\frac{A_r A_t}{d^2 \lambda^2}) \tag{2.1}$$

Where P_r and P_t are the power received and transmitted respectively. A_r and A_t are the aperture of the receiving and transmitting antenna respectively. λ is the wavelength of the signal and d is the distance between the receiver and the transmitter.

In this section we presented some fundamental principles of wireless communications. The following sections will introduce some wireless communications standards commonly used in WSNs.

2.1.2 Bluetooth

Bluetooth protocols operates at 2.4 GHz and is commonly used to wirelessly link devices such as smartphones, laptops, headphones etc. This section will focus on the latest version of Bluetooth, which currently is Bluetooth 5[3]. The Bluetooth PHY is based on a frequency hopping spread spectrum(FHSS) scheme. FHSS is a transmitting method where the transmitter changes channel frequently using a predetermined sequence to avoid phenomena occurring on the PHY. In Bluetooth there are 79 channels(frequencies) separated by 1MHz.
Bluetooth networks are called piconets and consists of one masters and a maximum of 7 active slaves. The slaves are only allowed to communicate with one master and the master controls all communication in the piconet as well as the FHSS sequence and a clock. The symbol rate of Bluetooth is 1 megasymbol per second which correspond to a bit rate of 1 Mbps due to binary frequency modulation. In Bluetooth 5 there is a optional extension called Enhanced Data Rate (EDR) which enables a bit rate as high as 3

Mb/s. Every Bluetooth device is given a hardcoded 12-digit hexadecimal address which is unique to that device. If the device requires user interface interaction there is usually an option to set a user friendly name. Devices with shared applications(profiles) can form a physical link and will automatically connect to each other if they are within range. This is called pairing. When paired the physical link provides bidirectional packet transport between master and slaves. For two devices to connect to each other they need a shared profile. A profile is a set of additional protocols that defines what data the Bluetooth connection is transmitting. Headphones and cellphones share a profile for transmitting sound and a gaming console share a profile with its controllers for transmitting the necessary data required to play the game. This makes up the fundamentals of Bluetooth.

At the time of writing this thesis Bluetooth 5 is the latest version of Bluetooth. Bluetooth 5 comes in two forms: Bluetooth Basic Rate/ Enhanced Data Rate(BR/EDR) and Bluetooth Low Energy(LE). The main difference between BR/EDR and LE is the throughput and energy consumption. LE has lower throughput (1Mbps) but use less energy. Bluetooth BR/EDR is a continuation of the standard Bluetooth protocol. Bluetooth low energy(BLE) was launched in 2011 with the release of Bluetooth 4.0. At first BLE was marketed as Bluetooth smart and was originally designed by Nokia[4]. BLE addresses one of the main issues with conventional Bluetooth, the energy consumption. Bluetooth BR/EDR has a high energy consumption and battery driven devices are often disconnected due to low or empty battery charge. Thus the demand for lower consumption in small ad-hoc network devices have created a rapid growth in BLE usage.

BLE PHY has 40 channels separated by 2MHz each. 3 channels are used for primary advertising and 37 are used as secondary advertising and as data channels. Time units in a physical channel is known as events. Transmitted data packets are positioned in these events. BLE physical channels has four types of events: Advertising, Extended Advertising, Periodic Advertising, and Connection events. Advertising is the process where a BLE device is broadcasting advertising packets to all nearby devices. The main advertising packets are sent on the 3 primary advertising channels while other channels can be used if the device is broadcasting a lot of data, this is an extended advertising event. Periodic advertisement event allows a non-advertising device to be synchronized with the advertisements sent continuously by the broadcaster. Advertisement packets often comes in the form of an connectable advertising event, where other devices can set up a connection request on the same channel. When connected the advertisement event ends and connection event begins. The connection events are used to send data between master and slave in a bidirectional manner. More information on BLE(our chosen technology) will be provided in Chapter 3: System and Implementation.

2.1.3 Wifi(IEEE 802.11)

Wifi is a family of wireless networking technologies used to connect WiFi compatible devices. Currently WiFi is the standard way for personal computers to communicate. It can be found almost everywhere, and much like Bluetooth, it usually operates in the 2.4-GHz ISM band. In later years some WiFi devices has started operating on 5GHz due to overcrowding on the 2.4GHz band[5]. WiFi is mostly used to create WLANs(Wireless Local Area Networks) which is mostly limited to homes, workplace, shops etc. This makes Wifi a great candidate for WSNs. The infrastructure is either very easy to build or it already exists. In addition, WiFi is commonly used for precise indoor positioning when GPS on mobile devices lacks coverage.

The most recent WiFi is the WiFi 6 or the IEEE 802.11ax. WiFi 6 can support up to 10-12 Gbps data rate. WiFi 6 is not adopted by the public yet and in most devices run IEEE 802.11ac or IEEE 802.11n at the time of writing this thesis. IEEE 802.11n added additional channels at the 5GHz band reducing interference from other nearby transmitters[5]. The IEEE 802.11 PHY uses a variety of different layers depending on the current version. Newer extensions of IEEE 802.11 have replaced modulations schemes and added new mechanisms. The MAC layer has also gone through a lot of changes. Most significant changes happened with the release of IEEE 802.11n where the frames size was increased and MAC could aggregate small frames into larger ones to increase efficiency. The main focus of IEEE 802.11 developers are to increase the throughput and researcher are still finding ways to do so.

2.1.4 Zigbee

Zigbee is a low-cost, low power, two-way, wireless communications standard developed by the Zigbee Alliance. Zigbee is a very common protocol in smart home applications, medical devices and other small scale low powered applications in need of wireless communication[6]. The stack layer are shown in 2.1. The predefined standard, IEEE 802.15.4, have defined the two bottom layers, the PHY and the Data Link Layer. Additionally there are two versions of the IEEE 802.15.4 PHY layer operating at either 868/915 MHz or 2.4 GHz. 2.4 GHz is the most common PHY layer and is used worldwide. The parts of the protocol stack specific to Zigbee is the network layer and application layer. The network layer has two entities: data entity and management entity. The data entity generates the protocol data units from the application, then the data entity routes the data units to next appropriate destination(depending on network topology) and ensures authenticity and confidentiality when transmitting. The management entity provide services such as addressing, network joining, configuration of new devices, neighbour detection, routing control, network leaving and route discovery. Both of these entities communicates with the upper layer, the application layer, through two separate SAPs. The application support sublayer(APS) provides an interface to the application layer. APS is also divided into a management and data entity. In addition to providing management services the APS management entity also keeps track of managed object in the database. The APS data entity generates the application data units, binds other device addresses and provides other services to ensure a complete transmission. The application framework and Zigbee Device Object(ZDO) are part of the application layer. The application framework is an environment where the user can host their application objects on their Zigbee device.

Much like Bluetooth protocols, Zigbee application framework has several profiles that are optimized for a specific communication routine. For example home automation is a Zigbee profile optimized for small control messages from light/heating sources, binary occupancy sensors and so on. This is the profile that is most suited for ILSs.

2.1.5 Communication in WSN

Now that the basic principles of wireless communication and examples of protocols have been established, we can put them in the context of wireless sensor networks. The discussion points in this section also apply for ILS WSNs.

Considerations

WSNs have some constraint that differentiate the design process from other communication networks.

One of the most important is the intention to restrict the energy consump-

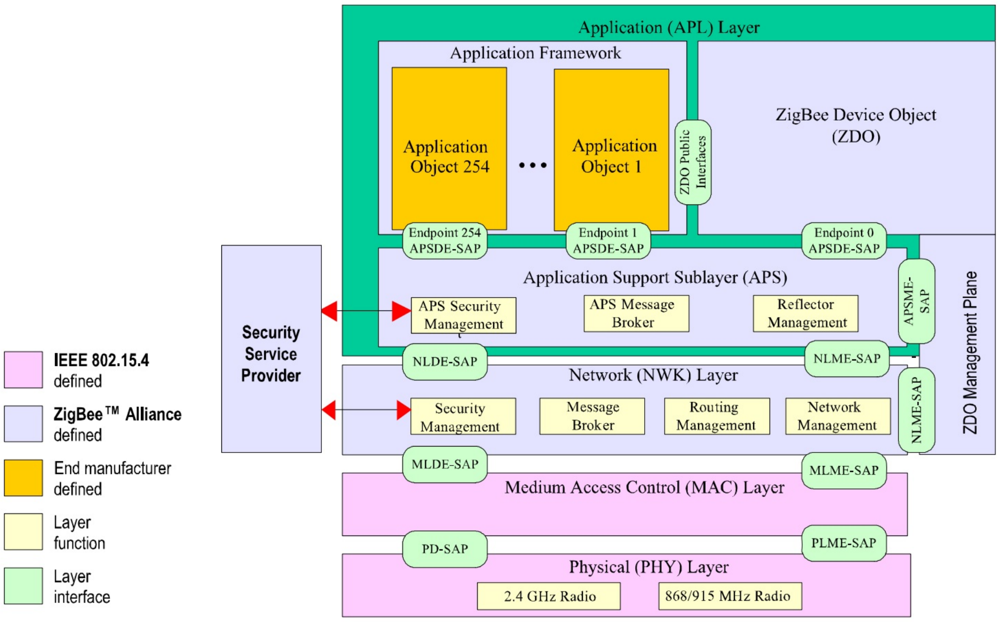

Figure 2.1: Zigbee stack Architechture[6]

tion. To achieve low energy consumption on the PHY layer transceivers and modulation schemes must be carefully considered. Low energy consumption will generally also lead to low transmit power. This is because the effective radiated power from an antenna is much lower than the power used to drive the antenna. Thus, according to Friis equation(2.1), WSN will have relatively smaller transmission ranges than that of conventional wireless networks. The small transmission range will in turn lead to a small RMS delay spread and it is reasonable to assume that most WSNs channels are experiencing flat fading 2.1.1. WSNs usually also operates with moderate data-rate which means that an assumption of low to negligible degree of ISI is reasonable.

Large scale ILSs will also need to consider the fact that sensor nodes will be placed in zones occupied by people where a lot sensor might be an issue aesthetically. So creating small compact radio devices is often desirable.

Topology and Routing

If the WSN are expected to scale much in terms of geographical coverage a multi-hop routing is preferable. Multi-hop networking allows for nodes to route information through other nodes regardless of node hierarchy. Multi-hop is mandatory in WSN structure where the detection zone is mobile. Forwarding the data from one node to another requires the network to figure out the best route for the message. This can be done in one of three ways.

1. Flooding
2. Gossiping
3. Controlled Flooding

The easiest is called flooding. This is when the node holding the message just sends it to every nearby node and eventually the message will reach the destination. This does require some mechanics to stop the message from looping and stay in the network for ever. Second method is called gossiping. Gossiping is the extreme opposite of flooding. When gossiping the node carrying the message forwards it to a random neighbouring node. In terms of latency, there is a huge random factor. It is of course possible to send more than one message when neighbouring decreasing the chance for long delays. The last method is called controlled flooding. Controlled flooding measures the suitability of a path by measuring its effectiveness by some metric, like number of hops, time etc. This is stored in each drone and require the network to have a distributed routing processes and unique stored tables for each node. Routing information a key aspect in large scale WSNs. It is also important for ILSs containing more that one detection zone to be able to efficiently route data and coordinate data. Latency in routing may cause location errors due to poor coordination. Therefore, gossiping is not a good technique for routing data in large scale ISLs.

Should a WSN scale more in number of sensors than in geographical area multi-hop routing can become problematic and more interconnectivity between nodes is desirable. Using mesh networking might solve this. The basic principle of mesh networks is that there is no node hierarchy and every node can communicate with each other. The mesh networks can be contained in clusters with gateways to the WSN base-station enabling even greater scaling potential. The computational resource requirement will increase for each node. All nodes need to gather information regarding the network topology, routes to gateway, neighbouring node roles etc. This will not only increase the computational cost, but also the energy consumption. Thus, the combination of mesh and WSN can be a complex and resource demanding task[7].

Zigbee, Bluetooth and IEEE 802.11(WiFi) In WSNs

Table 2.1 shows a summary of parameters for Bluetooth, Zigbee and WiFi. Zigbee provides a very low data-rate. In some cases where large data packets needs to be sent frequently this might not be adequate. However, if the packets are compressed before transmission it might still apply. Zig-

Table 2.1: Comparative table of Wireless Protocols[8][9]

Standard	Bluetooth	Zigbee	Wifi
Frequency Band	2.4 GHZ	2.4 GHZ;868/915MHz	2.4GHz;5GHz
Max Data Rate	3Mb/s	250kb/s	54Mb/s
Channel BW	1MHz	0.3/0.6MHz;2MHz	22MHz
Nominal Range	10m	10-100m	100m
Max Cell Nodes	8	>65 000	32 per Acc.point
Current Consumption[1]	60mA	25-35mA	400 mA

bee also offers a fairly long communication distance and very low energy consumption. This is a huge advantage in WSNs where sensor nodes are far apart and powered by batteries. There is also a huge potential for scaling the amount of sensor nodes in your network due to the limit of Zigbee nodes being huge.

While WiFi provides a very large data rate, it does come at the cost of high energy consumption. Most WSNs and localization systems does not need these larger much data rates, especially if the data is compressed of partially processed on the sensor node. A huge advantage with WiFi is the range and the ease of implementation. Almost all wireless devices can communicate via WiFi and it is therefore a simple process to make prototypes.

From table 2.1, it is clear that Bluetooth is not suited for sensor networks with large distance between nodes or systems with a large number of nodes. The data rate provided by Bluetooth is adequate for most WSN applications and with the EDR extension it can transfer more than enough data for any localization system. Another advantage is the energy consumption. While not as good as Zigbee, it is far better than WiFi.

Due to the low energy extension, Bluetooth is a solid candidate for a single-hop small scale ILS. In indoor environments, detection zones rarely exceeds $10m^2$ and the range of Bluetooth is therefore sufficient. Additionally, the range indicated in this section is only nominal and might be higher depending on the transmitter.

2.2 Indoor Localizing Systems In Wireless Sensor Networks

WSNs is an interconnected system consisting of sensor nodes and base-stations. Sensor nodes monitors the surrounding environment and wirelessly transfer the data directly or indirectly to base-station where the data is processed or funnelled to an external processing unit. A coordinated WSN is a great platform to implement an ILS. In this section we will introduce some essential terms and concepts regarding ILSs and WSNs. In this section we will use the term base-station to describe the WSN node on top of the hierarchy, meaning it is the node where all the final data ends up. Base-stations does not have to be a processing unit and can serve as a funnel to gather the data and transmit it to an application, processing unit or a database.

2.2.1 Localizing WSN Structures

Localizing WSN structures can be categorized into three groups: Tree based, Cluster based and Hybrid. [10].

The tree based category is dynamic WSN structure that consists of a sensor "field" with a root node and a base-station. When the system is operational, only sensors within range of the subject are actively sensing. The active nodes will select a leader node called the root node. This node gathers information from the other active nodes and pass it to nearby non-active nodes. Non-active nodes will serve as repeater nodes and will relay data from the root node to the closes-sink. If the subject moves away from the root node a new tree will be formed and a new root node is selected. Three based structure is visualized in figure 2.2. Creating a new tree can be quite time and energy consuming to calculation of multi-hop paths. Addi-

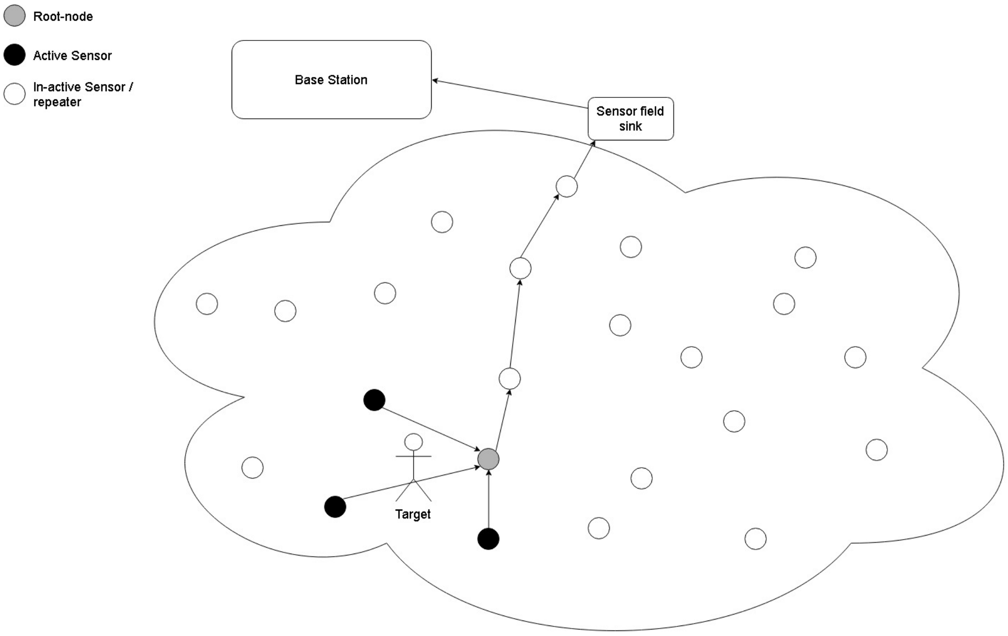

Figure 2.2: Threebased Structure

tionally, maintaining the infrastructure required is also more costly as the consumed energy increases with the number of nodes, the detection zone and the number of subjects[11].

Cluster Based architecture is the most traditional from of WSN architecture. A cluster based WSN consists one or more groups of nodes. One group has a leader called cluster head and several sensor nodes. Sensor nodes monitor the environment and sends data to the cluster head. The cluster head then routes this information to the base-station. The sensor nodes can either be fixed or dynamically implemented[12]. Dynamic nodes means that one node can relieve another node within the cluster or change cluster to relive nodes there. This includes cluster heads. Dynamic implementation greatly increasing the robustness of the system. This also makes it easy for end users to scale their system. Cluster based structures are great for scaleability. In most real ILS scenarios the detection zones are discrete locations separated by barriers. This is great for clustering since

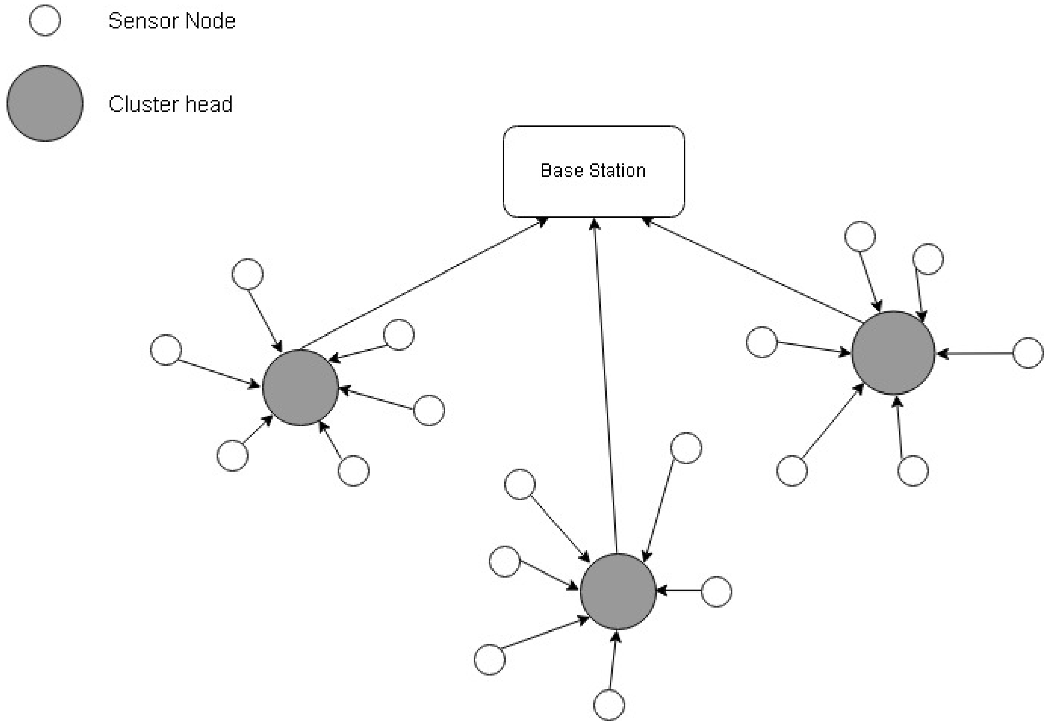

Figure 2.3: Clusterbased Structure

adding more detection zones means another cluster. Clusters ILS needs to be coordinated internally in the cluster, but externally there is no strict requirement to coordination. Cluster based structure is visualized in figure 2.3.

Last is the hybrid category. To fall into the hybrid category the structure must either combine existing architecture with a prediction method or fulfill the requirements of more than one type of ILS structure. Prediction based methods use the subjects velocity and location to predict its movement. This is a good combination with systems wielding lots of resources, due to the relatively heavy process of prediction.

2.2.2 Properties

ISLs have a set of properties that determine what their optimal application-field will be[13].

Physical versus Symbolic Location

Whether the system states a precise physical location(i.e coordinates) or a symbolic descriptive location(i.e room 12) defines a big part of what the system can be used for. Designing systems using symbolic location is very different from designing systems using physical locations. First of all, a minimal system using symbolic locations only requires a binary presence indicator. This can be done fairly cheap and is very easy to scale.
Physical localization requires more processing power and a sophisticated sensor technology. Locating the physical coordinates of subjects comes with a couple of requirement. Most importantly is coordination between sensors. In order to provide accurate coordinates the senor nodes needs to provide samples at the same time and at a interval which provides sufficient temporal resolution. Second is data processing and communication costs. There are several ways to determine physical location which we will discuss later in this chapter. All requires algorithms running for every measurement to determine the exact location of the subject. It is possible to use a combination of both. In this a sensor group can symbolize a location and measure the subjects physical location within their detection zone.

Absolute versus relative coordinates

Absolute versus relative coordinates is a question of scale. Absolute coordinates are suitable for systems with a very large coverage area. A system using absolute coordinates are most likely dependent on the use of GPS or direct connection to internet. Relative coordinates are suited for systems as small or as big as the application calls for. It is possible to combine the two. At the time of writing this thesis it is not uncommon to use GPS for outdoor absolute localizing and then WiFi for relative indoor localizing[14].

Localized versus centralized processing

Having powerful sensor nodes will allow the designer to reduce the base-stations work load. This is done by processing data locally at the sensor node, cluster heads or in passive nodes. If the data that is transmitted from sensor nodes has large overhead it might be more efficient to do distributed processing to decrease the wireless network load. If privacy is an issue, then localized processing can in addition withhold location information from the central processing unit.

Interconnection

Interconnection refers to the WSNs sensors nodes ability to communicate with each other in a dynamic and/or non-hierarchically manner. For maximum interconnection the system may employ mesh networking. If implemented right it will increase the range and robustness of the system. It does however, increase the minimum required processing power of every sensor node and the complexity of implementation. For coordinated WSNs a good level of interconnection is required. If the nodes are poorly interconnected this may lead to latency and subsequently loss of important information.

Accuracy and precision

Accuracy and precision is one of the most important performance properties in an ILS. Accuracy is measured by the distance between the estimated location and true location of a subject. Precision is the ratio in which the claimed accuracy is true averaged over the number of measurements. Thus, accuracy and precision does not really make sense if not mentioned together. Designers of localization systems can choose to sacrifice some accuracy for more precision or opposite.

Scale

The scale of an ILS are measured in three ways. The number of intended subject, the size of the detection zone and the number of detection zones. The scale of detection zone and number of detection zones is largely dependent on the wireless communication properties and the size of data transmitted. The number of intended subjects is more dependent on the sensor technology. This will be discussed further at the end of this chapter.

Cost

The cost of manufacturing a system is very important for commercial use. The maintenance of such systems might also cost money and should be considered.

Limitations

Different localization techniques and sensor technologies has inherent limitations. These should be considered by the designers when creating an ILS.

Its important to consider these properties when designing an ISL. There are often trade-offs and connections between different properties. For example, high level of interconnection requires more localized processing. These properties must be considered when designing the system and will be revisited in later chapters.

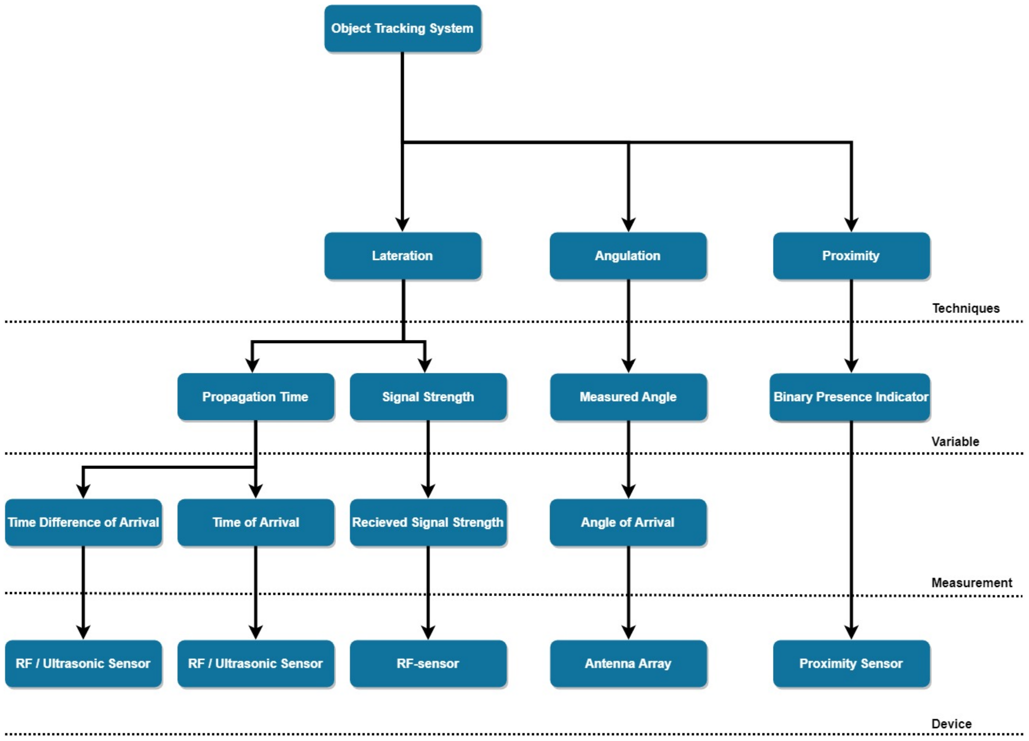

Figure 2.4: Overview

2.2.3 Localizing Techniques

Localizing through WSNs can be done in one of three ways[15].

Proximity

Proximity is arguably the easiest technique for localization. Sensor nodes outputs a binary value indicating whether there are subjects within the proximity of its detection zone. The main weakness of proximity localization is the low spatial resolution output. However, in a scenario where detection zones of several sensor nodes overlap, there is a potential for higher resolution location estimation. This will require a lot of sensor nodes however.

Scene analysis

Scene analysis is a demanding localization technique. Scene analysis techniques use environmental factors to determine subjects location. Such factors can be extracted from pictures, radio wave propagation or signal strength. This technique requires a lot of computing resources, but is very precise and by using cameras there are a lot of potential features. Features such as facial recognition or object identification.

Geometric Analysis(Trilateration and Triangulation)

Trilateration and triangulation is the most common technique for localization. In WSNs, sensor nodes have an inherent attribute: geometric relationship. Utilizing the geometric relationships of senor nodes and the sensor data, ILS designers can produce physical localizing algorithms. Trilateration are algorithms use distances as the main parameter for determining the subjects location, while triangulation uses angles.
In angulation, the geometric relationship between 2 sensor nodes and the subject is used for determining the position. The 2 sensor nodes know their distance to each other and the angle to the subject and can then simply calculate a triangle with the 2 sensors and the subject as ends. To localize a person using Trilateration one need a minimum of 3 sensor nodes. In fact the term trilateration refers to the usage of the minimum 3 sensing nodes, where as multi-lateration refers to more than 3 sensor nodes. Using only 3 nodes provides 2D localization. Intuitively explained, each node will have a circle where the radius is the distance to the subject. The subjects location is where all circles intersect with each other. Adding more sensors, or multilateration, will increase the accuracy and may extend the localization to three-dimensions.

The main advantages with geometric analysis is the scaling potential, precise physical location and flexible solutions. Geometric analysis disadvantages are cost and complexity of infrastructure and coordination requirements.

Mathematical Principles of Trilateration and Multi-lateration

Trilateration and multi-lateration is the most popular form of localization used in coordinated WSNs. There are some definitions:

1. All sensor node coordinates are known (x_i, y_i).
2. All sensor nodes know their distance to the subject r_i.
3. The subjects location is unknown (x_u, y_u).

this is true for all sensors $i = 1, 2, 3$.

According to Pythagoras theorem, we then get three equations:

$$(x_i - x_u)^2 + (y_i - y_u)^2 = r_i^2 \quad for \quad i = 1, 2, 3 \tag{2.2}$$

In order to get a linear equation set the quadratic terms x_u^2 and y_u^2 needs to be removed. This is done by subtracting the last equation from the previous two.

$$\begin{aligned} (x_1 - x_u)^2 - (x_3 - x_u)^2 + (y_1 - y_u)^2 - (y_3 - y_u)^2 &= r_1^2 - r_3^2 \\ (x_2 - x_u)^2 - (x_3 - x_u)^2 + (y_2 - y_u)^2 - (y_3 - y_u)^2 &= r_2^2 - r_3^2 \end{aligned} \tag{2.3}$$

Rearranging the terms and put them in a linear matrix equation:

$$2 \begin{bmatrix} x_3 - x_1 & y_3 - y_1 \\ x_3 - x_2 & y_3 - y_2 \end{bmatrix} \begin{bmatrix} x_u \\ y_u \end{bmatrix} = \begin{bmatrix} (r_1^2 - r_3^2) - (x_1^2 - x_3^2) - (y_1^2 - y_3^2) \\ (r_2^2 - r_3^2) - (x_2^2 - x_3^2) - (y_2^2 - y_3^2) \end{bmatrix} \tag{2.4}$$

When using three accurate sensor nodes this is a method that works fine. However, if the sensor nodes are inaccurate and are not able to find the correct distance, the most intuitive solution is to add more sensor nodes. This will render equation 2.4 overdetermined and produce several potential solutions with different mean square error. An overdetermined system is a system with more equations than answers. The goal from this point is to compute a solution that minimize the mean square error. Linear overdetermined systems can be solved setting up the normal equation. The matrix on the right side of the equation will be denoted as b and $\frac{1}{2}$ of the matrix on the left will be denoted as A from this point forward. So we can write:

$$Ax = b \tag{2.5}$$

Then we multiply by the transposed A matrix on both sides:

$$A^T Ax = A^T b \tag{2.6}$$

Equation 2.6 is called the normal equation for the linear least squares problem. It is called a normal equation because b-Ax is normal to the range of A. Note that when only dealing with two unknowns the system is only localizing in 2D. For 3D, a third unknown and sensors oriented orthogonal to the others must be added.

2.2.4 Challenges with Localization in WSN

In order to implement a reliable and accurate ILS we must first identify the challenges associated with the general idea of localization with WSNs. S. Ismail, E. Alkhader and S. Elnaffar[16] have provided a comprehensive review of the field of localization and WSNs where challenges and solutions are discussed. A summary of the relevant challenges from [16] will be presented in this section.

Scaleability

There is a lot of factors to consider when adding more sensors to ILS WSN. This problem gets even more challenging if the system contains self-organizing features. Thus the system will need to adopt efficient coordination and communication overhead management in its localizing algorithm. Furthermore the number of intended localized subjects also introduce quite a significant challenge. Localizing multiple subjects is a balancing act between energy consumption, senor node number, network throughput, processing power and sensing technology. Creating more clusters or detection zones is the easiest, since there are less demand for coordination and infrastructure.

Computation and Communication Costs

With the coordinated real-time requirement of ILS, distribution processing power of computation and especially communication is very important. Local computation is often cheaper than the cost of communication. Thus a minimal overhead is desirable. However, this comes with the challenge related to the trade off between sensor node power consumption and processing power and communication data rate. This directly affects the price and scaleability of the system.

Energy Constraints

Most WSN sensor nodes are battery powered. In order to increase the life time of a node the energy consumption must be considered. An effective way of decreasing energy consumption is to implement a sleep mode in the nodes. This allows the nodes become passive when there are no subject within the detection zone.

Data Aggregation and Compression

In WSNs we want the overhead to be as small as possible to increase scaleability potential, reduce energy consumption, save processing power etc. There are several ways to minimize overheads but the most common is to summarize important information, compress data or a both. This does however create another challenge. If the algorithm that is doing the data aggregation and compression is not efficient enough there will be network constipation and severe latency issues. Additionally compression algorithms may cause higher energy consumption.

Sensor Technology

The application of the ILS decides what sensor technology is optimal. No sensor is equally good in every environment. Several factors need to be taken into account when choosing a sensor type. Factors such as distance range, signal attenuation, resolution, bandwidth, sensor homogeneity etc. This is the topic of the next section 2.3 in this chapter.

Sampling Frequency

Finding the right sampling frequency can be complicated. To low sampling frequency will yield distorted images and loss of information. To high frequency might lead to network congestion or too much energy consumption. It therefor important to analyze the scenario and environment where the system will be placed in order to get a fair balance.

These challenges will be revisited in the next chapters in the context of a performance review, implementation considerations and discussions.

2.3 Proximity and Geometrical Analysis Sensors

Distance and proximity sensors are a vital component of any localization system using geometrical analysis or proximity based methods for determining position. In this section a summary of infrared, ultrasonic and UWB radar sensors are presented.

2.3.1 Infrared Sensor

Passive infrared(PIR) sensors are the most popular choice for presence/-movement detection. This is due to PIR sensors being compact, low-powered, cheap and durable. PIR sensors detect presence by measuring differences in infrared radiation levels. The warmer something is, the stronger the infrared radiation emitted will be. This radiation can be converted to temporary voltage when exposed on the pyroelectric detectors in a PIR sensor. Thus, PIR sensors are particularly sensitive to temperature. PIR sensors does not emit any radiation and are therefore passive, hence the name. To cover a larger area, radiation is focused through a Fresnel-lens on top of the sensor. The infrared detectors behind the lens are internally divided into two differential detectors. This is because motion is not detected by measuring the level of IR-radiation, but rather the change. Infrared wavelengths(700nm – 1mm) are less than that of microwaves(1mm – 1m). PIR sensors are not really suited for geometrical analysis due to their binary output. PIR sensors are great for proximity based localization, but is susceptible to false triggers. The degree of which is greatly dependent on the quality of the sensor.

2.3.2 Ultrasonic Sensors

Ultrasonic sensors are a cost effective and reliable alternative for detecting objects and measuring distance to reflective objects. This makes ultrasonic sensor a popular sensor in short to medium range applications such as distance/object sensing, fluid level measurements or conveyor belt monitoring. Ultrasonic sensors are equipped with transducers that transmit and receives ultrasonic pulses. The pulses are typically in the range of 40 to 70 kHz, just above the frequency humans can hear(20 kHz), and travels at the speed of sound(343 m/s). Due to the low operation frequency ultrasonic waves gives good spatial resolution. The distance information is

determined by the time it takes for a pulse to hit the subject and reflect back at the transducer, time of flight. Besides the reliability and cost of ultrasonic sensors, one of its major benefits is that, unlike optical and camera sensors, it is independent of visual obscuring phenomenons such as smoke, dust or light. This is also true for transparent materials, such as thin glass. Soft and sponge-like materials however, will absorb ultrasonic pulses and block measurements. This can include highly absorbent clothing, carpets, curtains etc.
In the context of ILS, it is common to use ultrasonic sensors homogeneously. It is usually in combination with other sensor technologies[17] or with the use of tags[18][19]. An important limitation/feature of ultrasonic waves is that it can not penetrate walls, which means that any emitter communicating with the network is always in the same room. With the theory provided in this subsection it is clear that Ultra Sonic Sensors are a viable candidate for a positioning system, especially in combination with positioning technology that have higher range resolution and or in applications dealing with areas divided in small discrete rooms.

2.3.3 UWB Radar

The word radar was officially adopted by the Allies during world war two. It is an acronym for radio detection and ranging. There are two basic principles that lay the foundation for radar technology:

1. If the transmitted electromagnetic pulse from a radar hits a electrically leading surface, the parts of the pulse will be reflected back to the antenna.

2. Electromagnetic waves travels at approximately the speed of light, $c = 3 * 10^8$.

As an addition to item two, in radars these electromagnetic pulses are transmitted through a radar antenna that focuses the energy in a given direction. The electromagnetic waves will always spread out from its source to a certain degree. Which, in the case of radars, is a desirable trait in order to cover more area. The spread of the transmitted pulse is determined by the antenna.

These principles allows radar operators to calculate the direction, height and distance to any reflecting object, even in conditions where visual confirmation is impossible. In order to reach objects far away the radar transmitter must create a pulse with high power. This can be measured by using Friis transmission equation 2.1. Note that electromagnetic waves from radars are susceptible to the same physical phenomena as physical layers of wireless communication, mentioned in section 2.1.1.

When the pulse hits the object the energy will scatter and only a fraction the transmitted energy will be reflected back at the radar. Therefore, a sensitive receiver is required. The pulse repetition frequency(PRF) is the number of pulses transmitted per second. For bandwidth restricted transmissions, each pulse is transmitted with a reference frequency called the carrier frequency. A typical radar consists of one antenna. The antenna switches between transmitting and receiving. After transmitting a wave the radar goes into listen time and waits for certain amount of time before transmitting another pulse. In addition to distance and direction, some radars can also measure the speed of the object. In older radar systems this is done by measuring the Doppler frequency shift. Newer systems transmits electromagnetic waves with higher propagation speed and the Doppler frequency shift is not noticeable. In such cases the radars use phase information to determine speed. More on this in section 3.2.3.

The receiver bandwidth is the range of frequencies the radar accepts. At any frequency there will be noise. Therefore, wider the receiver bandwidth results in more noise. A design goal of conventional long range radars are to keep the bandwidth as narrow to the signal bandwidth possible to avoid noise.

The "conventional" narrowband radar systems are still highly effective in many modern applications, but the feature potentialities of such systems are practically exhausted. The increasing need for higher resolution and lower energy consumption has spawned a commercial interest for wider frequency range radar systems. There are more than one definition on what classifies as an UWB signal. The most common definition was formulated by the Federal Communications Commission(FCC). FCC stated in a report regarding UWB emission and regulation to define an UWB transmitters as such[20]:

> Ultra-wideband (UWB) transmitter. An intentional radiator that, at any point in time, has a fractional bandwidth equal to or greater than 0.20 or has a UWB bandwidth equal to or greater than 500 MHz, regardless of the fractional bandwidth.

The European Telecommunications Standards Institute(ETSI) has confirmed this definition in a technical report 101 994-1[21]. However, the IEEE Standard for Radar Definitions[22] declares “A radar is UWB if the fractional bandwidth, B_f, of the radiated far field exceeds 0.25.”
where:

$$B_f = \frac{f_h - f_l}{\frac{1}{2}(f_h - f_l)} = \frac{BW}{f_c} \tag{2.7}$$

f_h and f_l is the frequencies of -10dB attenuation from the peak and BW is the signal frequency bandwidth($f_h - f_l$). Center frequency f_c is the frequency at 0.5BW.

UWB radars are a quite different from "conventional" narrowband radars. One advantage wide bandwidth provides is the range resolution. Range resolution is the radars ability to detect objects separately when they are located at a distance, Δr, relative to each other. Generally, wider bandwidth gives better range resolution.

$$\Delta r = \frac{C_0 * \tau}{2} \tag{2.8}$$

Where C_0 is speed of light and τ is the pulse duration. We estimate the -3dB bandwidth to be approximately the inverse of the pulse duration. This gives us the relation:

$$\Delta r = \frac{C_0}{2BW} \tag{2.9}$$

Which means a range resolution of 5 cm requires a bandwidth of 3GHz.

2.3.4 Summary

In this section we have introduced 3 sensor technologies that can be used for tag-less ILS. PIR and Ultrasonic sensors are both attractive choices for their cheap price and simple principles. Both sensor technologies are already used in ILS applications and research on implementation is quite available. However, in our research goal we stated that we wish to create a coordinated sensing system to create the potential for advanced features. With binary sensors like PIR there are few potential features outside symbolic localization that are of interest. An example of an interesting potential feature using PIR sensors location prediction. This requires a high level of coordination. In section 3.1 we take a look at one such system. Ultrasonic sensors are another alternative used by several localization systems. The limiting penetration abilities of these sensors makes them robust against interference from motion outside the detection zone if the detection zone is a closed environment. This also implies that static objects in the detection zone will create blind spots if not considered while installing the ILS. Another disadvantage is absorption that can be caused by clothing or other soft material. For example, if the subject is sleeping under a duvet an ultrasonic sensor is unable to detect movement and can therefore not provide reliable human presence indication.

The last sensor technology we introduce can however. UWB radars are able to detect tiny motions such as breathing even by subjects clad in thick clothing or lying under duvets. UWB radars are therefore a sensor technology with huge potential for advanced features.

2.4 ILS Scenarios

Due to the massive amount of adjustable parameters, there is no unique solution that would provide an optimal ILS. Using the background provided in this chapter we are able to create a discussion and predict challenges with different localization applications.

2.4.1 Localization Scenarios: Subject Density

One of the arguably most important parameters is the density of subjects that are being localized. This will define a big part of the system. This subsection will be split into 3 scenarios. Subjects in dense crowds, scattered crowds or a single subject. There is a blurry line between what can be defined as scattered or dense crown, in this

Dense Crowds

If the subject is within a dense crowd of people, many sensor technologies would not be sufficient. The most used method for localizing subjects in dense crowds is using cameras and scene analysis. This does require some infrastructure and complicated image processing, but can be done with great accuracy like in [23]. In [23] the algorithm was trained to recognize the head region of humans and takes into account the camera viewpoint resulting in precise localization. Sadly, there are many applications where cameras are not a good alternative. People may not be comfortable with being filmed or the scene might be poorly lit or covered in smoke. In cases like these geometric analysis compatible sensors are better suited. Localizing individuals in dense crowds of moving people using tag-less distance sensors requires very high spatial resolution and sampling rate, and is a very difficult process. Most tag-less non-intrusive distance sensors are not able to differentiate, or even see, the individuals in dense crowds due to the human body blocking signals creating big blind spots. To be able to find individuals in dense crowds without the use of cameras, the ILS can use tags. Tags usually have an unique ID and is therefore easily separated from the rest of the surrounding crowd. This does not necessarily require more infrastructure because it can easily be implemented in smart-phones or other personal devices. This is already a common practice, WiFi and Bluetooth RSSI localizing can be found in many phone apps. The major drawback of using tags when localizing people in large crowds is the amount of interference as a consequence of many transceivers. Personal gadget, routers, IoT devices, phones, computers etc. are all using the same 2.4-GHz ISM band for communication. The 2.4-GHz ISM band, sometimes referred to as the garbage band, is occupied by overlapping channels of Bluetooth, ZigBee, 802.11(WiFi), etc. Interference between channels in such standards is inevitable when large quantities of wireless devices are populating a small area[24][25]. This is important to take into consideration when implementing tags in ISLs where dense population of tags can be expected.

Scattered Crowds

If the subjects are within a scattered crowd of people more possibilities for use of tag-less geometric analysis localization opens up. Tag-less distance sensors are more suited in applications involving scattered subjects. With scattered subjects it is easier to separate individuals in the sensor data and with certain sensors it is even possible to create identity based on additional data the sensor can provide. This additional data can be date like radar cross-section(RCS) or vital signs. The people being localized will still create blind-spots, but this can easily be solved with more sensors.

Single Subject

Localizing a single individual is the simplest scenario. This requires the least amount of processing and infrastructure. Using singe subjects is often the easiest way of prototyping an algorithm or a whole system. This is because all error causing factors mentioned above is not present.

2.4.2 Localizing Scenarios: Environment

The surrounding environment of a ILS can greatly affect its performance. It is important to consider how well the sensor is suited for the area it is deployed. ILS are frequently deployed in environments like offices, apartments, halls or hospitals. Such environments are usually furnished and may contain objects that move, like fans. Most sensor technologies will struggle to differentiate between a moving object and a moving human without an algorithm to filter them out. Unwanted movement might also come from outside the desired detection zone. If the detection zone is within a confined space by walls like in a room or a cubicle, movement from people outside this space may trigger a false positive by sensors with wall penetrating capabilities. This is something the system designer needs to take into account in order to make a robust system. If the system is designed to penetrate walls it is also important to consider the material of the wall. Certain frequencies are less suited for wall penetration than others and certain materials are extremely hard to penetrate. ILS may also experience communication difficulties on the physical level, due to walls and floors. This can either be solved by adding more routing nodes, wired gateways etc. Using suitable attenuation models the designer can position the nodes in a manner that yields the least amount of path loss.

Chapter 3

System and Implementation

Based on the background presented in the last chapter we should be able to choose the right sensor and sensor setup for a localization system. In this chapter we will attempt to define and justify a scenario for a localization system and provide properties, specifications and hardware descriptions of a proposed system for said scenario. The goal of this project is to create a simple localization system in a coordinated single-hop WSN using UWB radar sensors. Detailed system specifications and scenario description will be provided in the proposed system section3.2 the related work section 3.1.

3.1 Related Work

In this section we will present two systems that are a representative on recent research done on ILS.

FindingHuMo[26] is a indoor multi-hop localization system that consists of binary PIR motion detectors and a powerful back-end system. Each node feeds binary presence data to the back-end system which applies localization algorithms. The localization algorithm is an Adaptive-Hidden Marcov Model(AHMM) and a path ambiguity correction algorithm, applied in that order. AHMM takes the binary sensor data and outputs a decoded state sequence for each subject. This state sequence is essentially the chain of sensor nodes activating as the subject passes them. In order to correct any ambiguity due to overlap a path ambiguity correction algorithm is applied. The localization system is made to locate and track human motion in a 'smart' environment. The system is designed to provide relative symbolic coordinates for moving subjects. The required infrastructure is fairly small scale, enabling the system to be installed in most building. Although PIR sensor performance is quite dependent on environment for its performance, 'smart' environment are probably one of the best for such sensors. Furthermore, while binary sensors are cheap and durable, their binary information output limits systems features by quite a lot.

In 2015, W. Yan, Z. Jing and Z. Nailong[27] presented an indoor localization system using the PulsON Impulse Radio Ultra Wide-Band (IR-UWB) sensors. PulsON UWB sensor is a series of sensors developed by Time Domaim from USA. The PulsON sensor has the ability to communicate with other PulseON sensors and in this project they utilized this to implement a self-organizing feature. The range between the tag and the sensor nodes are measured by two-way time of flight. A request packet is transmitted by the UWB sensor to the tag, and time it takes for response packet to return determines the distance. The distance is then plugged into a localization algorithm which is not shown in this paper, although one can safely assume that it is some form of geometric analysis method i.e multilateration. The system accuracy was approximately 20 cm, even with walls in the detection zone. This is a relatively high accuracy for localization systems.

There currently is a lot of research on localization WSN systems. The two systems presented above is fairly representative on how localization systems are implemented[1][2]. That is, systems using tags and binary motion sensors. However, by using tags and binary sensors the system are not able to detect "True presence". True presence means that there is no possibility for false negatives, i.e no person can occupy the detection zone without triggering a presence indicator. The true presence feature will require sensors sensitive enough to detect humans vital signs. Binary sensors like the ones used in FindingHuMO[26] cannot provide data that can differentiate between moving objects and moving humans. Additionally, if a human where to sit completely still most PIR sensors are not sensitive enough to be able to detect true presence. In tagged localization systems, like in [27], one can argue that the tag being in the detection zone provides true presence. However, in most cases the tag is not physically attached to the subject. If the subject where to forget the tag in the detection zone, this would trigger a false positive. Additionally, if the tag where to be completely still the system are not able to determine if the tag has been removed from the subject or if the subject is being still. This can pose a big problem, especially when applied in services such as elderly care where people often forget to wear their tag.

3.2 Proposed system

Humans have several tiny bodily functions that are detectable by UWB radar sensors. Even when standing completely still, people still move slightly by breathing. This is something we will utilize in our localization system. The proposed ILS is a single-hop WSN consisting of ultra wideband(UWB) radar sensor nodes connected via a BLE link. We chose to use BLE because of its sufficient data-rate, range, and low power consumption. An overview of the proposed system is presented in figure 3.1. The system is based on a single cluster structure, which has great potential for scaling. The sensors are XeThru X4 UWB radar modules made by Novelda[28]. The X4 modules are connected to Nordic Semiconducters nRF52 BLE Development Kit boards through SPI[29].

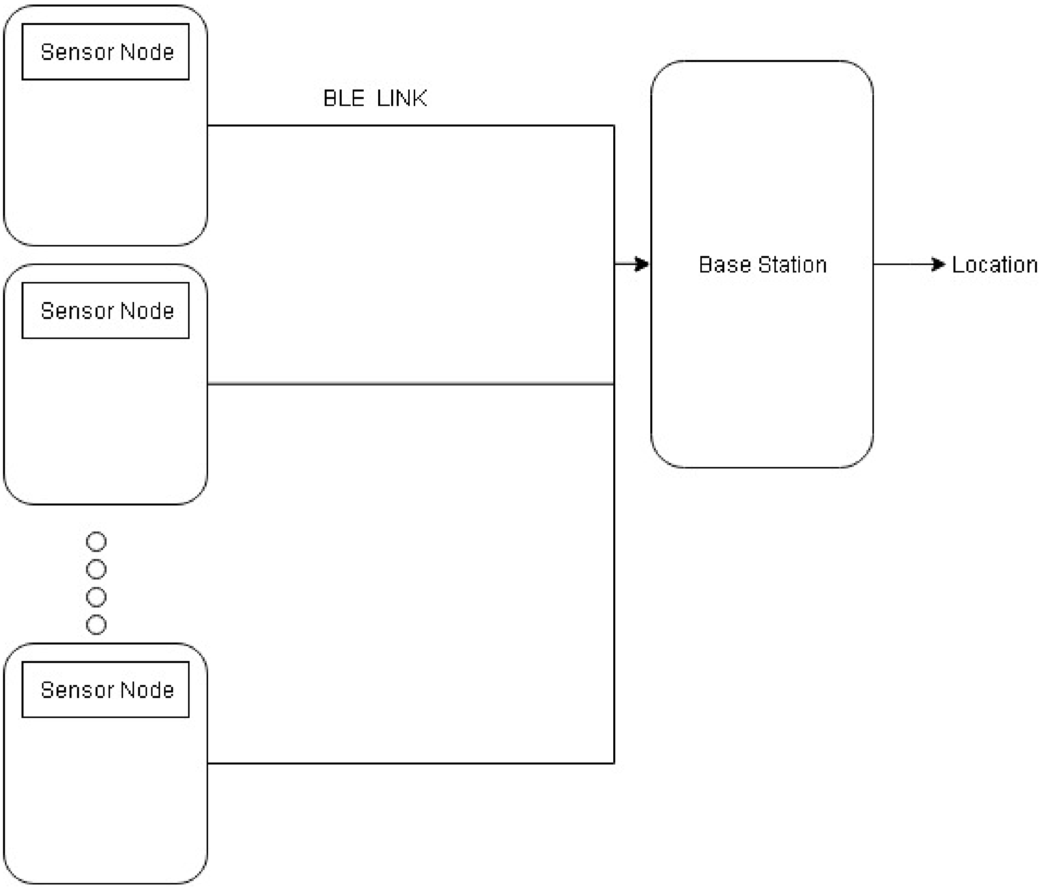

Figure 3.1: System Visualization

Radar data is streamed to a base-station computer, where the subjects location is determined by a scaleable planar multi-lateration algorithm written in Python. The location is given by physical relative coordinates. Absolute and symbolic location can be implemented if the system is scaled with more clusters.

3.2.1 Scenario

This project will focus on finding precise relative location of people within a detection zone without the use of tags. This means that the system will need to separate human reflections from object reflection. The system will also be able to separate static objects introduced after the system started running. This is done through a process called adaptive cluttermapping which will be discussed more in the following sections. The X4 UWB radar is a great tool for detecting breathing motion due to its sensitivity. This is the reason Novelda can claim to detect true presence. Thus, we can assume a high reliability in presence detection features.

Using UWB radars may generate some challenges. Many reflective surfaces may cause many multi-paths and distort the data. Multi-paths share the same concept as indirect paths and flat fading in wireless communications, but in this context the extra signal component will distort the actual sensor readings not the communication quality. For our sensors to work properly there needs to be relatively few such reflective surfaces occupying the detection zone.

The detection zone size is limited by the range of the sensor, which is 9.45 m [28], but the longer the range the lower the signal quality. This may result in loss of advanced features, such as respiration monitoring and true presence at longer distances. Additionally, the nominal range of BLE devices are 10 meters[8] so long range(>10) interconnection might not an option. In order to create a scaleable system a custom BLE service will be implemented. This will allow for easy addition of features in future work, such as self-organization tools, energy saving, adjustable settings and so on. The base-station/cluster head will also be implemented with respect to scaleability. It should be easy to add and remove sensor nodes to the system without having to add software. It should also take into account that an installation service or self-organizing feature may be added in the future.

3.2.2 System Properties

This section will present and discuss the properties of the proposed system based on the background provided in section 2.2.2. The system will provide relative 2D coordinates for the physical location of subjects. Location is determined by tag-less geometric analysis, more specifically 2D multi-lateration. The base-station of the WSN has access to GPS and WiFi which means that implementing absolute coordinates and symbolic locations is easy. If the system is implemented at a facility the users might want to cover more than just one room. To cover several rooms, more clusters needs to be added and communication between clusters needs to be established. This is a easily implemented due to the cluster head having a lot of processing power and access to more than one network option. Furthermore, one room might be very big or have walls shading parts of the room, requiring more sensor nodes to provide good coverage. Adding more sensor nodes are very simple. The cluster head/base-station software is implemented so that only the coordinates of the new node needs to be provided to add it to the network. The most demanding form of scaling in this system is increasing the number of subjects. If a sensor node returns more than one reflection the location of the subject becomes ambiguous since the sensor have no way of identifying what distance belongs to which equation other than testing every combination and picking the one that returns the least R^2 value from equation 2.6. This will in turn lead to a lot of equations that will need to be processed by the cluster head.

In summation the localization system can scale in three ways:
1: The number of localized subjects can be increased. The potential of increasing the number of subjects being localized while still maintaining precision and accuracy. Dense crowds are not compatible with these systems due to signal body blocking.
2: The number of sensor nodes in one system can be increased. Increasing the number of sensor nodes will provide higher accuracy due to higher orders of multi-lateration and add the possibility to extend the localization in three dimension if desirable. However, this will increase the workload of the base-station. Additionally, the conventional Bluetooth slave capa-

city is maxed at 7 active nodes, but the s132 Bluetooth stack from Nordic supports 20 active nodes.
3: The number of systems can be increased. Increasing the number of systems on different locations will create a cluster structure WSN. This requires another layer of software controlling each cluster head. In theory, there is no limit to how this could scale.

Signal processing is mostly centralized at the base-station, or if scaled, distributed among cluster-heads. Base stations will have more than enough processing power to deal with incoming data from the sensor node.
The system is quite expensive. At the time of writing this thesis, one XeThru X4M05 module costs around 250 USD depending on the distributor. Nordics nRF52 development kit(DK) can be purchased for around 40 USD(also depending on distributor). However, the nRF52 DK can be replaced by a cheaper alternative. For large scale production, companies usually go by bulk purchase prices which can be negotiated with provider. System limitations and accuracy/precision will be reviewed in chapter 4.

3.2.3 System Hardware

This section presents basic information on components used in this project. We will be using the XeThru UWB radar sensor for distance measurement. XeThru UWB radar sensors are developed by a Norwegian company named Novelda. The sensors are radio-impulse ultra wide-band radar modules with sophisticated on-chip signal processing and a high degree of development potential.
The X4 SoC is Noveldas latest radar transceiver.The X4 transceiver operates at a center frequency of 7.29 or 8.748 GHz and with a transmitter bandwidth of 1.4-1.5 GHZ, these numbers depend on what electromagnetic radiation regulations are in effect in the area of usage. In figure3.2 the basic

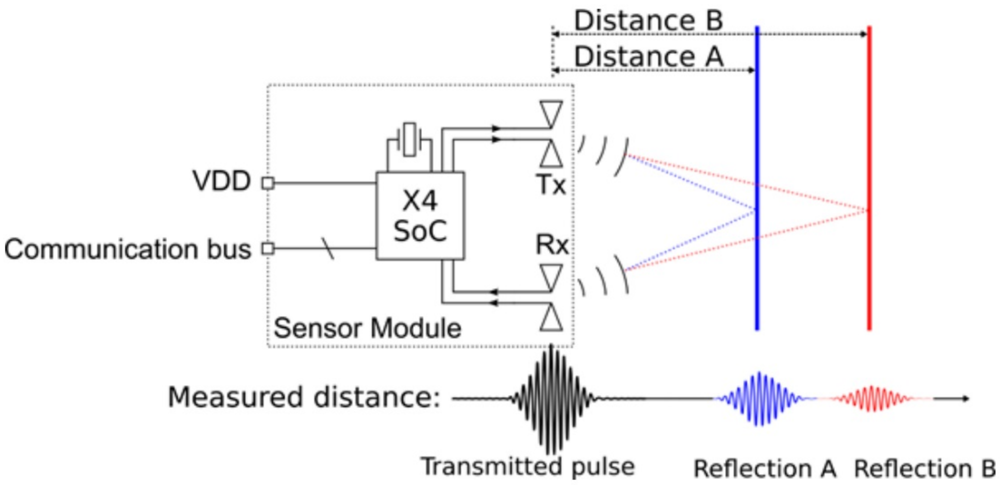

Figure 3.2: X4 Sensor module

principle of range measurement using X4 sensors is visualized. X4 radar modules are highly sensitive to movement. A key factor in the high SNR acheived by X4 is the concept of coherent radar processing. Coherence in pulse radar technology describes the relationship between phase of an outgoing pulse and an incoming pulse. In non-coherent radars, the transmitter is called Power Oscillator Transmitter(POT). POT generates pulses with random phase shifts between them. In recent radar development POTs are replaced with Power-Amplifier-Transmitters(PAT). PATs allows for fully coherent radars. This means that phase-shifts between each transmitted pulse is consistent. Having access to phase information provides X4 radars with the potential to detect tiny motion, such as breathing and heart rate.

X4 SoC communication is handled through X4driver. X4driver is an open-source software module that provides direct access to all X4 features. We embed x4driver in a nrf52 development kit is made by the Norwegian company Nordic semiconductor. nRF52 support multiple wireless protocols with a focus on BLE.

3.2.4 System Communications

The system communications will be performed by nRF52 DKs using BLE links between the nodes and the base-station. The X4 radar modules and nRF52 DK are connected through SPI.

3.2.5 Data Throughput and Overhead

In order to avoid congestion and system communication errors it is important to analyze the amount of data transmitted between the system components. A data packet containing the signal power of all range-bins will be referred to as a radar frame. Required data throughput for each module depends on the frame-rate (FPS) and the size of each radar frame. The size of each radar frame is determined by the range of sensor. Longer range and higher frame rate calls for higher throughput. In this section we will calculate the size of radar data packet overhead in order to make informed decisions on what radar settings we can use. Bluetooth 5 low energy supports a maximum of 2Mbps datarate. SPI communication on nRF52 DK supports a maximum data rate of 8 Mbps. Using the X4 datasheet[28] we can calculate the distance the bins represent when the radar is sampling rf data 3.1.

$$\begin{aligned} range_{max} &= \frac{((N_{bins}-1)*c)}{F_s} * \frac{1}{2} \\ range_{max} &= 9.8632849586m \end{aligned} \tag{3.1}$$

Where Sampling speed: $F_s = 23.328GHz$. Speed of Light: $c = 299792458$. N_{bins} is the number of sampling points(bins) in full frame: $N_{bin} = 1536$
X4 radar sensors can also stream complex baseband data. This decimates the bins by 8, makes the maximum bin amount 188, and the physical length of one bin approximately 5.14 cm. Baseband messages comes as complex IQ vectors. The message consists of[30]:
(PacketLength(INT-32), RESERVED(Byte), XTS-SPR-DATA(Byte), XTS-

SPRD-FLOAT(Byte), ContentId(INT-32), Info(INT-32), Length(INT-32), DataItems(FLOAT-32 ARRAY))

The message consists of single bytes, 32-bit integers and a 32-bit float array. A lot of these variables are irrelevant the most important is the float array. The float array contains the data for each range bin and is split in two. First half are the "I" components and second half are the "Q" components. This means that the float array is twice the size of the number of range bins. 32 bits integers and floats are 4 bytes big. This gives us the equation:

$$\begin{aligned} Size_{bytes} &= (int + int + byte + byte + byte + int + int + int + (float * 2 * bins)) \\ &= 4 + 4 + 1 + 1 + 1 + 4 + 4 + 4 + (4 * 2 * N_bins) \\ &= 23 + (8 * N_{bins}) \end{aligned} \tag{3.2}$$

Equation 3.2 describes the amount of bytes a single IQ baseband message is. This is important for SPI communication. For the BLE link, only the float array will be transmitted. This makes the equations slightly easier:

$$\begin{aligned} Size_{bytes} &= (float * 2 * bins) \\ &= (4 * 2 * N_bins) \\ &= (8 * N_{bins}) \end{aligned} \tag{3.3}$$

This means that for a sample rate of 1 FPS the range can be:

$$\begin{aligned} DataRate_{max} &= 2Mbps \\ float &= 32b \\ 2Mbps &= (32 * 2 * N_{binsMax}) \\ N_{binsMax} &= \frac{2Mbps}{64} \\ N_{binsMax} &= 31250 \end{aligned} \tag{3.4}$$

Which means we can scale the FPS up quite a lot and still be within a reasonable range. Calculating the maximum frame rate for a given range is can be with 3.5:

$$DataRate_{max} = FPS * (8\frac{Range(m)}{0.0514}) \tag{3.5}$$

If we assume that the subject can move at a maximum speed of 2 m/s, we can find a ΔD_m the subject can move for a given FPS:

$$\Delta D_m = \frac{2\frac{m}{s}}{FPS} \tag{3.6}$$

If the minimum ΔD_m is set to 0.5 m then the a FPS will need to be 4.
Now that an overview of what overhead capacities are available, we can make informed decisions regarding radar frame rate and range in our testing.

3.2.6 Embedded System

We use a software development platform called nRF5 SDK as the base for the embedded software created in this project. There are two components to the software: Radar and BLE. In this section, we present key aspect of the two components.

Radar

A hardware abstraction layer(HAL) is created to emulate the X4Driver's specific details and to provide access to X4 resources. Through the HAL we are able to read radar data and set radar parameters. The parameters include DAC sweep range, iterations, detection range, downconversion, pulses per step and finally FPS. Table 3.1 shows the parameters sent to the x4driver. The downconversion parameter enables a decimation and downconversion feature. The feature shifts the sampled RF signal to DC, filters out of band energy and decimates the frame by a factor of 8 in order to reduce the overhead while still including all relevant information. The result is a complex IQ baseband frame which can be

Table 3.1: Radar Parameters

Parameter	Value
Dac min	900
Dac max	1150
Iterations	16
Pulses per step	26
Downconversion	True
Frame area	0.4m to 5m
FPS	5

converted to an amplitude values by calculating its absolute values for each bin and phase information by calculating the arctan2 values of the complex[31]. A radar signal before downconversion after converted to amplitude baseband is visualized in figure3.3. After FPS has been set the

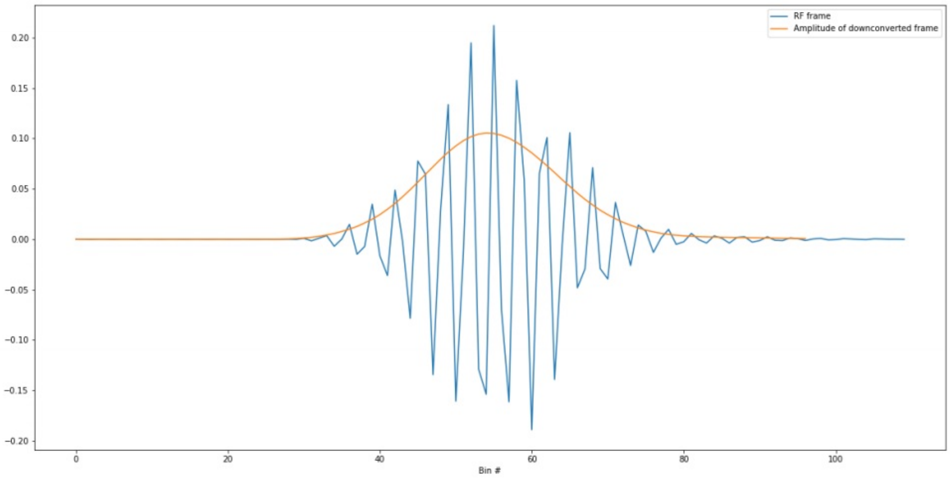

Figure 3.3: RF-pulse and Amplitude baseband pulse

radar will start streaming data.

BLE

To understand how BLE was implemented it is useful to know what "Attribute Protocol"(ATT) and "Generic Attribute Profile"(GATT) are. Bluetooth core specifications state that[32]:

> The Attribute protocol defines two roles; a server role and a client role. It allows a server to expose a set of attributes to a client that are accessible using the Attribute protocol. An attribute is a discrete value that has the following three properties associated with it:
>
> 1. attribute type, defined by a UUID(Universally Unique Identifier)
> 2. attribute handle
> 3. a set of permissions that are defined by each higher layer specification that utilizes the attribute; these permissions cannot be accessed using the Attribute protocol.
>
> The attribute type specifies what the attribute represents. Bluetooth SIG defined attribute types are defined in Assigned Numbers and used by an associated higher layer specification. Non-Bluetooth SIG attribute types may also be defined.

An attribute is a term for information stored on either the client or the server device. Attribute information can be the state of a LED, position data, sensor values etc. This information is associated with some property and is organized in a table. Attributes handles identifies an attribute on a server device, giving client devices the ability to refer to it. It can be thought of as the non-sequential index of a list. UUID or attribute types is an abbreviation for Universally Unique Identifier and is a 16 of 128-bit value used to describe what type of attribute it represent. UUID can be declared by a system designer for custom services, if the system uses Bluetooth Special Interest Groups(SIG) predefined services UUID are already created. Attribute Permissions encapsulates the terms authorization permissions, encryption permissions, authentication permissions and access permissions. These are security parameters. To summarize, ATT is a protocol that provides communication between clients and servers through the use of attributes. GATT is a profile extending ATT. GATT uses ATT to transport the data using commands, requests, responses, indications, notifications and confirmations between devices. GATT can either be used by an application alone or by another profile and is not bound by master/slave roles. GATT can contain one or more service. A service is data and definitions that are associated with a specific application. There are many predefined services, like for example Insulin Delivery or Environmental Sensing that have predicted behaviors suited for their specific application. A profile contains several characteristics. Characteristics are attributes with values used by services to encapsulate information. Characteristics have their own UUID, properties, values etc. For example, in the Insulin Delivery service there are characteristics such as "Insulin Delivery Device(IDD) Status Reader Control Point", which tells the server relevant information about the status of the medical device. Or the "IDD Command Control Point" which provides procedures to operate the insulin therapy remotely. Figure 3.4 visualize the hierarchy of a profile[33]. Unfortunately there are no predefined service for radar data. To efficiently transmit radar data between devices, we attempted to create a custom service for X4 radar data. The custom service is quite simple and is designed with the intention of expansion. At the time of testing, the service contains only one characteristic: Amplitude Baseband data. This data is an array of float values describing the signal power indexed at range bins like in figure3.3. Adding a characteristic for the phase data, which is an Array of float values of the signal phase, is a simple process only requiring a few lines of code. In this project, we will not be using phase information, thus

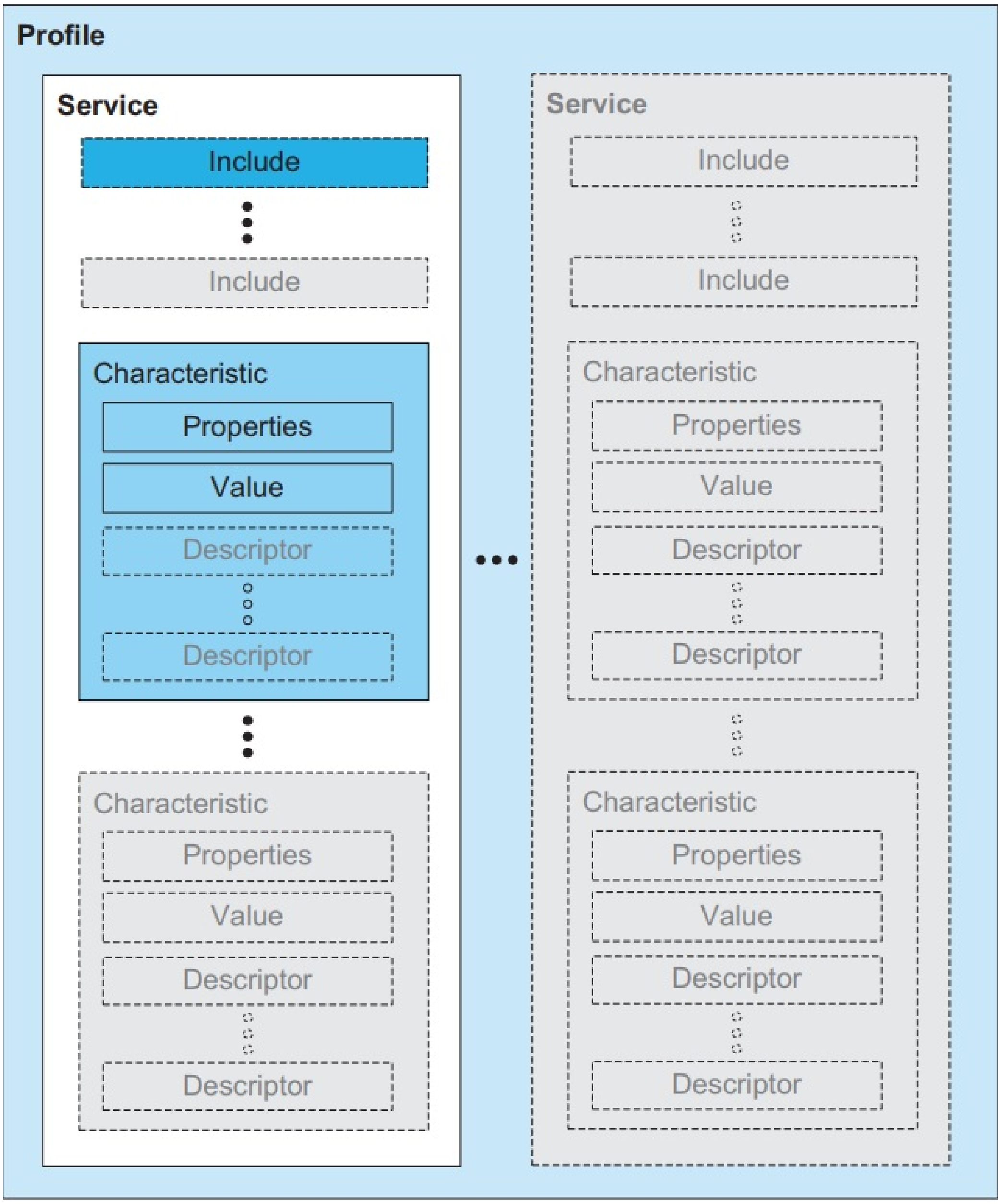

Figure 3.4: Profile Hierarchy

we will only be sending the signal power.

When notification is enabled from the host, the characteristic value updates continuously with the same frequency as the FPS. The radar characteristic has the read and notify properties and can only be influenced by X4.

3.2.7 Host Programming

The localization algorithm and radar data processing is written in Python. Nordic have released an unofficial driver for PCs that has a Python API which is used for this project. After connection have been established, the radar data are stored on a buffer. Radar data is sent as bytes and needs to be converted to float values before being stored. There is one buffer for each connection. A simple adaptive cluttermap is applied to remove static clutter. Adaptive cluttermap can also filter out static objects that is added after system boot. After applying cluttermap, the last step is to add frames to a FIFO buffer and sum them to increase the reflection amplitude in the frame. The number of frames that are added together will vary with the FPS in order to satisfy a minimum ΔD.

A threshold peak-detection function is applied to the resulting frame to find distance to subjects. The distances are then returned into the equations 2.4 and 2.6. The coordinates of the subject is then plotted to a user interface.

Chapter 4

Results

In this chapter test results and test-setup from our working example will be presented. We will use the term subject presence, which refers to the presence of a subject that can be located. Subject presence error is a term used to a no subject presence detection, while the subject is in the detection zone. Note that subject presence is not the same as true presence detection. True presence detection requires only one sensor, and different radar and calibration settings. This will further be discussed Chapter 5 5.1.

4.1 Test Setup

In this section we will present how the main tests where conducted and justify the setup.

Unfortunately, at the time of testing we did not have access to a large room with minimal noise sources. However, this created the opportunity to test in a realistic environment. The tests where conducted in a medium sized classroom, furnished with desks and chairs. The room did not contain moving objects, but the ventilation system had large metal tubes that we believe could cause some multi-path components. Each sensor node was mounted on a tripod. This is so that the system can easily be transported to the test location. A more realistic way of testing the system would be

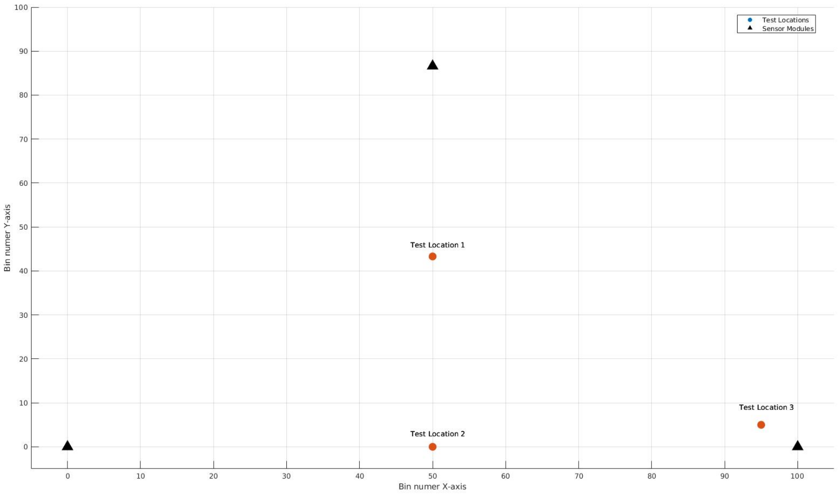

Figure 4.1: Test setup

to mount the nodes in the ceiling or high up on the wall, but this was not possible in our test environment. Each sensor node was powered by a rechargeable power-bank connected to nRF52 boards through USB. The nodes where placed in an equilateral triangle with the sensor antennas pointing to the center. Three test locations are marked on the floor for reference. The test setup is visualized in figure 4.1. The black points forming a big triangle is the sensor node while the small points forming a small triangle are the test locations. A test subject would wait outside the detection zone for 5 seconds to check for false subject presence triggers, then enter the detection and walk to the designated test location. The subject would then stand at the test location for 25 seconds before leaving. We tested using 5 FPS in a detection zone of 4 m^2. The reason we chose 5 FPS will be discussed in the performance section in the next chapter 5.1. Tests are considered a success if:

1. Subject presence is not triggered before the subject enters the detection zone.

2. There are no periods longer than 3 seconds of subject presence error

while subject occupies detection zone.

3. The mean distance between actual location and measured location is less than 0.5 m.
4. Subject presence is not triggered after the subject has left the detection zone.

Item 1 and 4 in list 4.1 are set to make sure the system does not trigger false alarms. Item 2 are set because we expect a few subject presence errors when subject is standing still due to variation in signal quality. Item 3 is set as a performance goal. The reason we chose exactly 0.5m is because this is approximately the width of a human body across the shoulders.

In order to get successful test results we spent some time calibrating the system.

4.2 Calibration

Before being able to determine distance the system must be calibrated. First the radars signal power are plotted and analyzed in order to set the right parameter values. A reflector is placed in the middle of the detection zone as a reference point. The reflector is a metal ball rotating slightly off its axis. This is meant to emulate the movement of a chest when breathing. We apply the cluttermap to the incoming radar frame and start tuning parameters. Ideally, the power by distance plot should look like figure 4.2 for each radar. In this plot, it is easy to determine the distance by finding the peak. The parameters are: cluttermap strength, area offsets, detection threshold and buffer size.

Cluttermap strength is an indicator of how much static clutter is filtered by each frame. Cluttermap strength is the percentage of how much is removed from the cluttermap for each frame.

Area offset is a distance in front of the sensor that is cut off due to noise

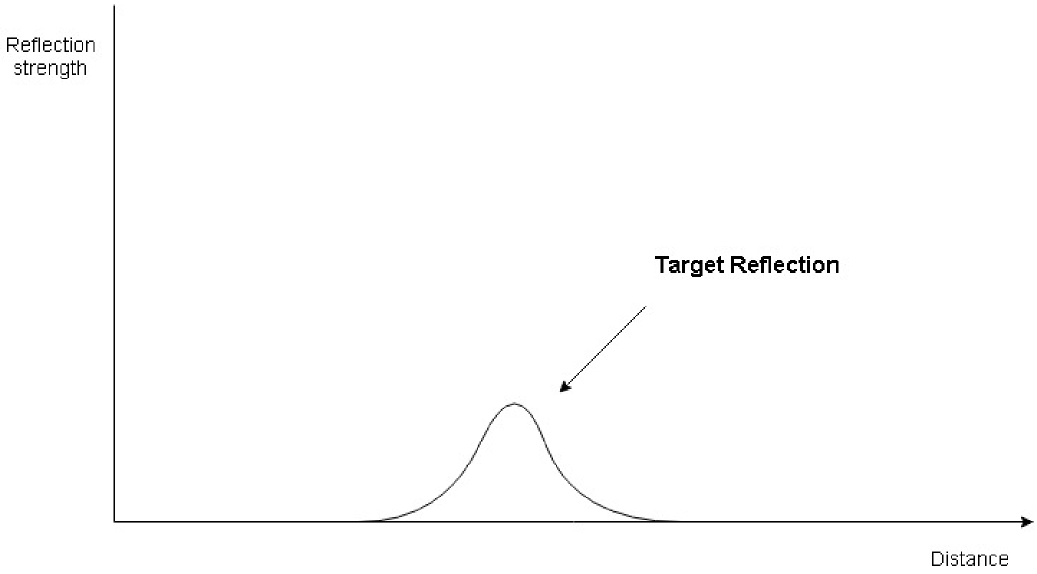

Figure 4.2: Ideal Reflection Plot

generated by the direct path between Rx and Tx.

Detection Threshold is the minimum power of a reflection for it to be characterized as a subject. Due to the attenuating signal, this threshold is lower at longer ranges and will be adjusted through testing. This threshold will also serve as a simple indicator for subject presence.

Buffer size the buffer size determines how many input frames are summed in one output frame. Every incoming frame from the sensor nodes goes through a FIFO buffer. The sum of all the frames in this FIFO buffer is used to determine the distance to the target. The size of the buffer will increase the amplitude and stability of reflections, but at the cost of more noise from multi-paths and longer start-up sequence.

After calibration we ended up with the parameters shown in table 4.1. The detection threshold parameter is set with respect to the path loss attenuation through free space. We measured the peak signal power of a subject standing close to the sensor versus standing at the edge of the detection zone at 4 m. Close to the sensor the peak signal power was approximately

Table 4.1: Calibration Parameters

Parameter	Value
Cluttermap strength	1%
Area offset	0.4 m
Detection Threshold	$0.0025 - 0.000045 * n$
Buffer size	5

0.005 when standing still while at 4 m it was 0.0007. The attenuation can be modelled by a forth power term, r^4, but due to short range and simple tests we are using a linear term. The threshold is set to approximately half of the measured peak values.
After calibration was complete we begin testing.

4.3 Test Results

In this section, the results from our main tests are presented.

4.3.1 Test 1

In test 1 the subject where to walk into the detection zone and stand in the middle with the same distance to all sensors. No subject presence where detected before the subject entered the detection zone. After 5 seconds the subject entered and the system started localizing. During the time the subject where stationary in the center only 9 frames returned with no locations. The measurement shape can be seen in figure 4.3. The true location is represented by the circle with the center and the small points are the measured values. Figure 4.4 shows the distribution of the distance from the true value of each measurement or the error. The mean error of measured locations was 29.6 cm and 41/125 of the detections were further

than 0.5m away from the test location. After leaving the detection zone no location output where detected.
Thus, according to our test criteria 4.1 test 1 is considered a success.

4.3.2 Test 2

In test 2, the subject followed the same procedure as in test 1, except this time the test location is located between two of the tree sensors. No subject presence was detected before entering the detection zone. In test 2, we expected more subject presence error. This due to the subject being located far away from one sensor. Out of 125 frames, 46 frames returned with no subject presence. This corresponds to a total of 9.2 seconds. The measured locations from test 2 is plotted in figure 4.5. Figure 4.6 shows the distribution error in test 2. The mean value of error was 13.25 cm and 0/79 of the detections were outside the 0.5m radius. There was no subject presence after subject had left detection zone. While there where a total of 46 frames with subject presence error, the longest period where 12 frames, which is 2.24 seconds.
Thus, according to our test criteria 4.1 test 2 can be considered a success.

4.3.3 Test 3

In test 3, the subject entered the detection zone and stood in front of one of the sensors. No subject presence was detected before entering the detection zone. We expected approximately the same subject presence error as in test 2, but found only 10 frames with subject presence error. The measured locations from test 3 is plotted in figure 4.7. The mean value of error was 15.60 cm and 3/115 of the detections were outside the 0.5m radius. Figure 4.8 shows the distribution error in test 3. There was no subject presence after subject left the detection zone.
According to our test criteria 4.1, test 3 can be considered a success.

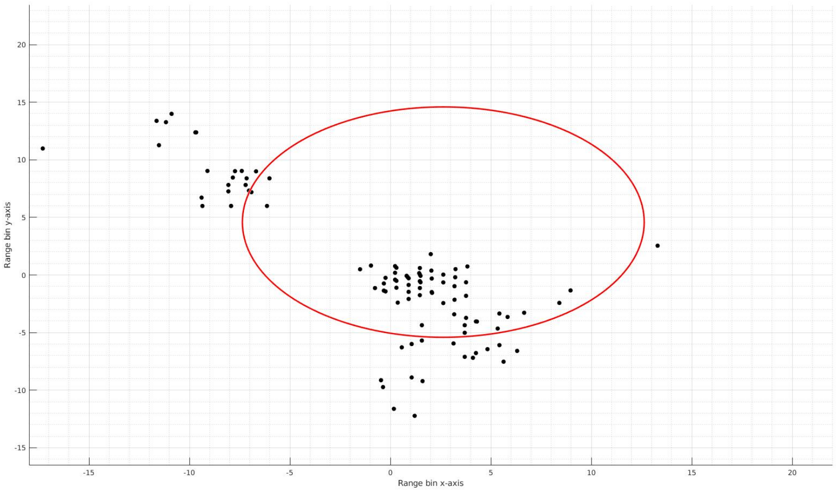

Figure 4.3: Scatter plot of normalized measured locations for test 1

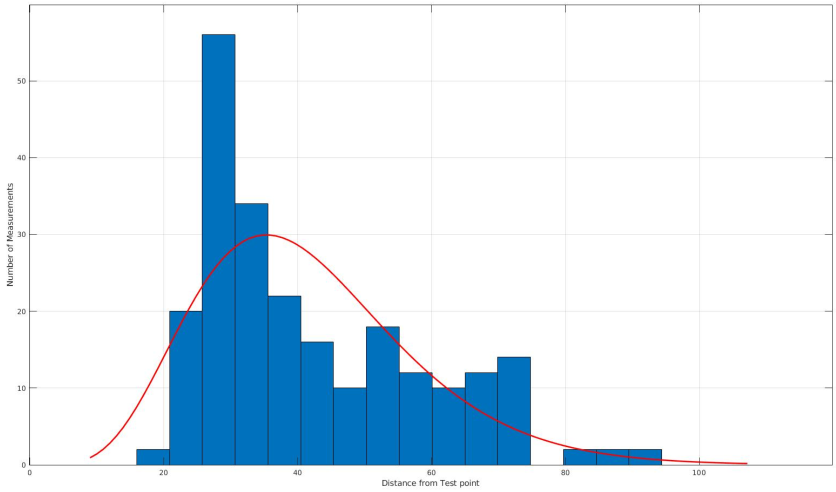

Figure 4.4: Distribution of error test 1

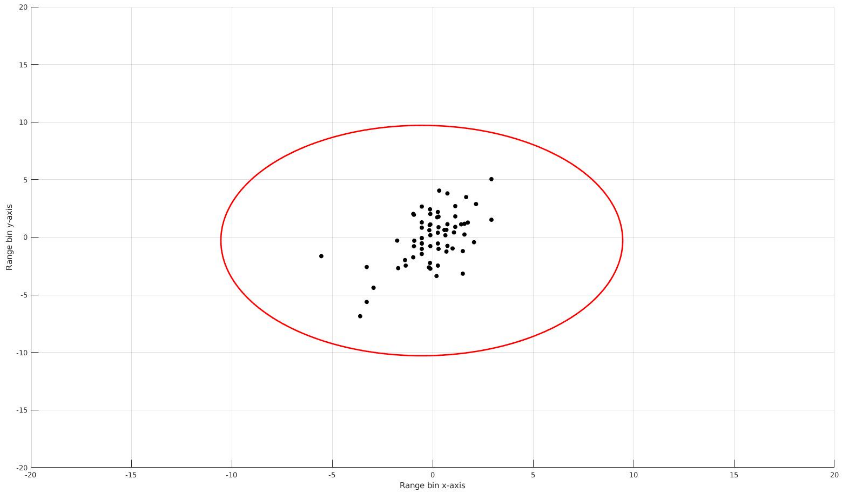

Figure 4.5: Scatter plot of normalized measured locations for test 2

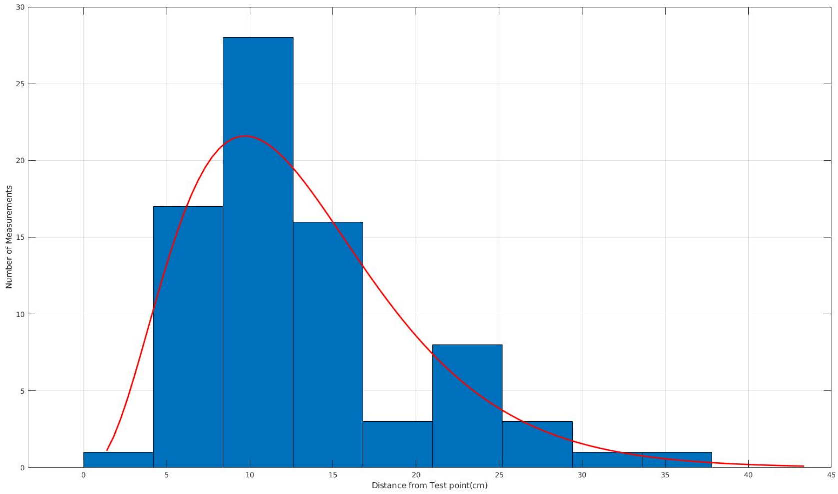

Figure 4.6: Distribution of error test 2

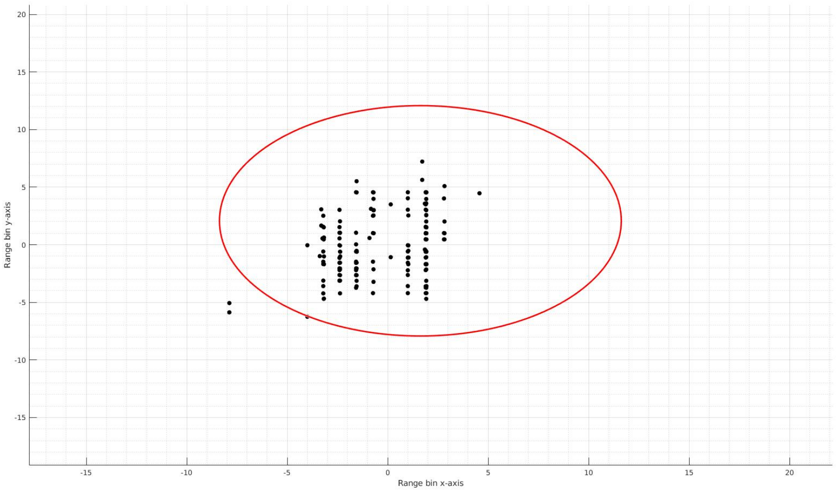

Figure 4.7: Scatter plot of normalized measured locations for test 3

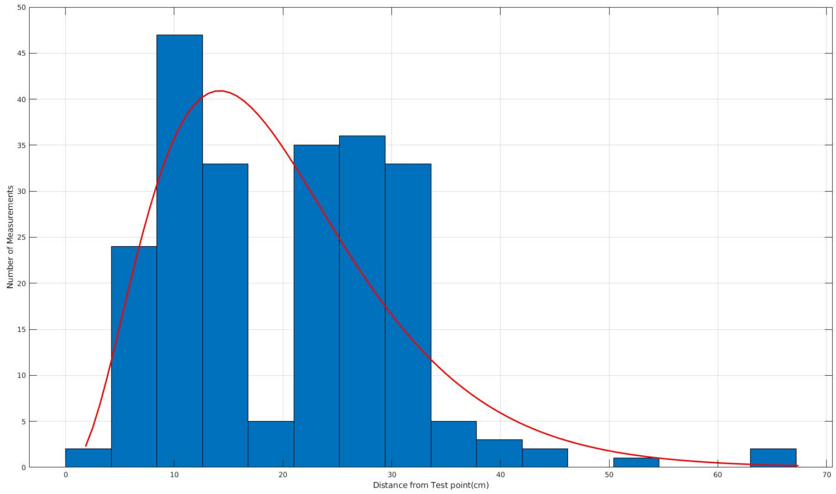

Figure 4.8: Distribution of error test 3

4.3.4 Other tests

We did a quick test on the BLE range. Test yielded quite surprising results. We expected the data-rate and signal quality to degrade drastically carrying the receiver out of the testing room. However, we left the room and walked to the end of the hallway, about 40 m from the room, and still did not detect any degradation in signal quality or data-rate. In order to verify that the data was complete, we counted frames and ran localization while the base-station was carried away. The amount of frames was identical with what we calculated and the localization performed seemingly the same as in our previous tests.
The last test we conducted was an attempt to visualize the difficulties of localizing more than one subject on a sensing level. First we recorded data of one subject occupying the detection zone. Then another subject entered and positioned himself in front of one of the sensors approximately 1.5 meters from the first subject. In figure4.9 we clearly see the first subject. The circle has a 0.5 m radius with a center in the exact coordinates of the subject. Sensors are are located at the two bottom corners and the upper middle point. The figure looks much like what we can expect after examining figure4.3. When the second subject enters the detection zone the image change. The new subjects positions in front of the bottom left sensor. In figure4.10 we see that the power of the previous subjects reflection is barely noticeable. From the perspective of the bottom right sensor the previous subject is practically invisible. For this reason it is very difficult to conduct tag-less trilateration with more than one subject. We have to add more sensor modules, i.e multi-lateration, in order to localize more subjects and add adaptive multi-lateration methods that are able to localize subjects without having to use all sensor nodes.

The test results and system performance will be discussed in the next

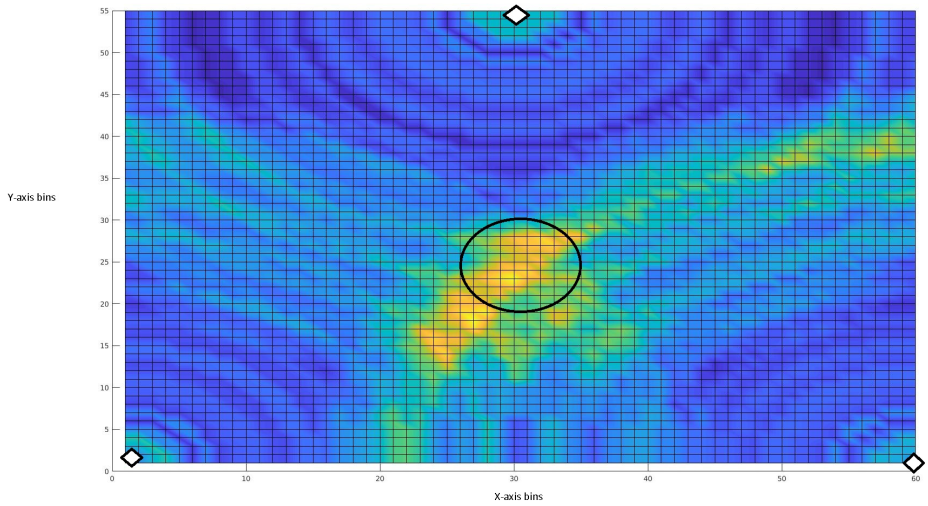

Figure 4.9: Heatmap of one subject Occupying zone

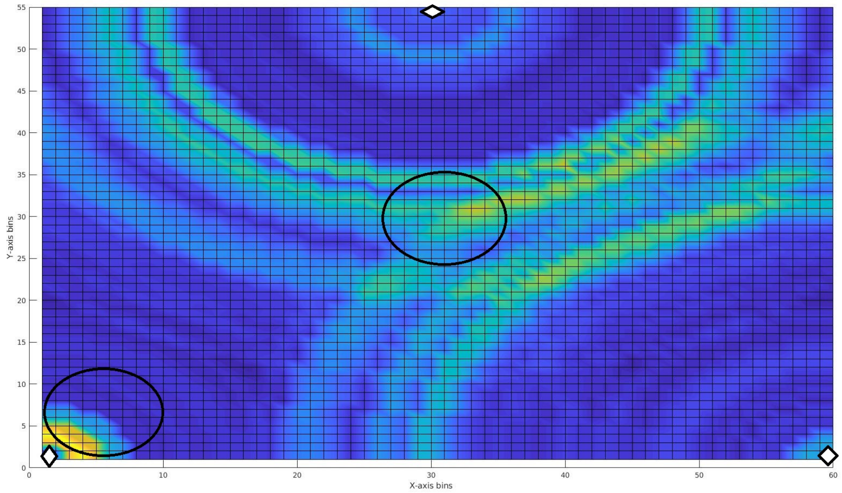

Figure 4.10: Heatmap of two subjects Occupying zone

chapter.

4.4 Disclaimer

Unfortunately, due to several technical difficulties this system was finished quite late in the project period and we where not able to test it properly due to time constraint. If we could test the system further, a movement accuracy test would also be conducted. This would have provided a stronger indication of performance. While the system was operational we where able to see that the system could follow our movement pretty accurately, but there was no time to test it properly. We where also not able to thoroughly test the Bluetooth connection, but we did not experience any latencies or distortion.

Chapter 5

Discussion and Conclusion

In this chapter we will discuss the learnings from the research, the suggested conclusion, what could have been done better, and potential extensions and applications of the technology we have used in our research.

5.1 System Performance

At the start of this thesis we stated that our main goal in this project is to find how to create a cost-effective, coordinated sensing network able to reliably detect human presence and provide the precise location. This required us to gather the necessary knowledge and tools, and create a working prototype to prove that the tools we chose are viable.
Unfortunately, we were not able to do test the system as much as we wanted . The technical difficulties we encountered affected the results by not having time to do several iterations. More iterations would only marginally improve the results by setting better calibration settings. Thus, we can confidently state that the results provides a valid indication of performance

From the results presented in chapter 4 we will suggest that UWB radar sensors are a viable tool in human localization systems: With an accuracy of 50cm we achieved a total precision of 71% when considering subject presence error(s). If subject presence error(s) are not taken into account the precision is 86% We will argue that the latter measurement are the most relevant because if the system encounters subject presence error it can use the previous location until the subject is detected again, unless the error continues for too long. When the signal power is under the threshold it is usually due to the subject standing still. The longest subject presence error we encountered was 2.2 seconds long. An interesting observation is that the precision is lowest in the middle. This is counter to what we expected. However, even thought the results were less accurate in the middle they where still above our minimum criteria 4.1. This may be due to stronger reflective surfaces located above test location 1. Another reason might be the calibration settings. The settings where set in order to provide accurate readings for an relatively small reference reflector with a maximum width of approximately 5 cm. While a human subject will have a maximum width of at least 0.4 meters. This can be solved by doing calibration using a bigger reference reflection.

We chose to use 5 FPS in our localization testing to see if the system could provide sufficient coordination and data-rate for frame rates higher than necessary. When tracking humans it is not necessary to sample more than once or twice per second unless the subject is running. However, if the a designer where to implement a respiration monitoring feature, the sampling rate will have to be drastically increased.
From our testing of BLE range we see that no frames where lost during transmission with 5 FPS. 5 FPS corresponds so a required data-rate of 3.1KBps per module. 3.1 KBps is is quite low and we can thus safely add the maximum number of nodes in a cluster(using this or a higher FPS) giving us the ability to increase the range of our system. The maximum

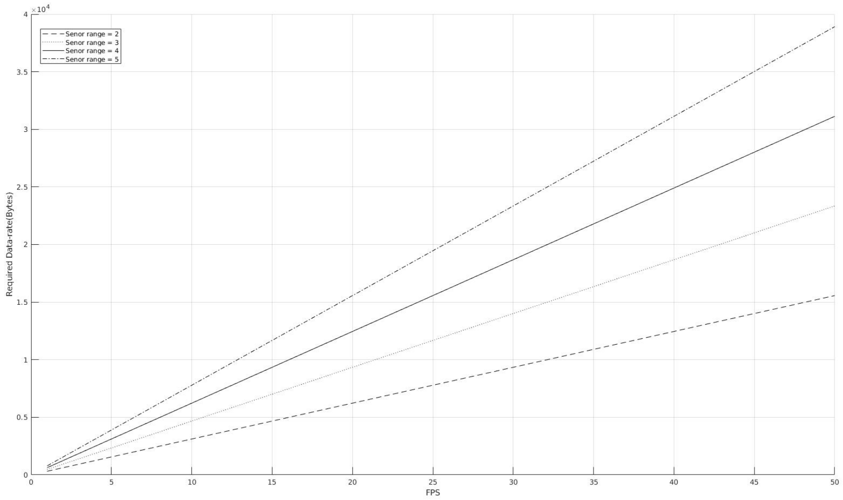

Figure 5.1: Required data rate

FPS supported on a range of 4 m with 7 nodes is approximately 400 FPS, which is well above the required amount for ILSs. In figure 5.1 we see a plot of FPS versus required data-rate with different ranges. In figure 5.2 we see the same plot but for more nodes at a range of 5 meters. As reference, XeThru respiration sensor is set to a 17FPS[34] and claim to able to monitor respiration rate reliably. We can therefore safely state that the BLE network data-rate can support several additional features.

5.2 Suggested Improvements

Ideally radar data should be processed locally. This would make BLE communications less complicated and allow for more flexible solutions. The sensor node should have a fast and slow movement buffer where it gathers radar data over a short and long period respectively. The user should be able to choose radar parameters, filter techniques and modes from the base station. The only localized processing in our system was converting raw radar data into phase and power arrays. In retrospect this is not an

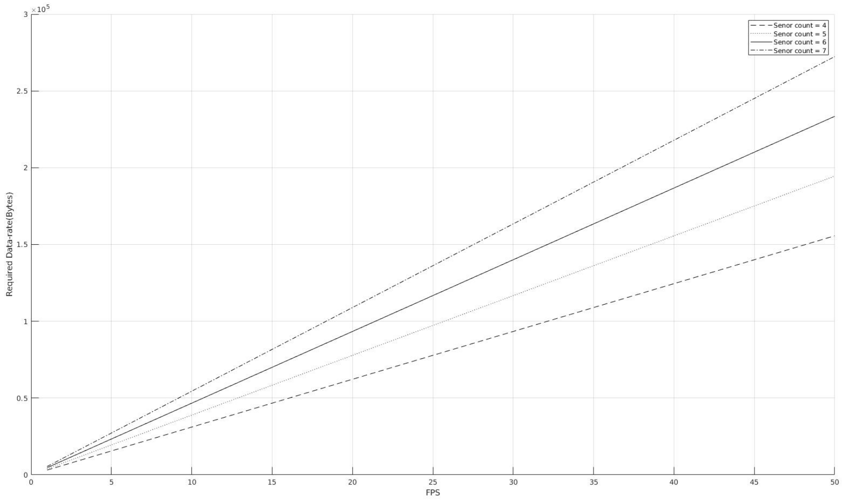

Figure 5.2: Required data rate for more nodes at 5m

optimal solution, but at the time of creating BLE our embedded programming skills where limited and processing radar data on a computer was a quicker way to prototype the system.

Overall, the system performed quite well under testing and would have performed slightly better with more testing and calibration time. The biggest limitation of the current working example is the noise susceptibility. Without algorithms able to detect and filter multi-paths components, the system performance is very dependent on the environment. This is not only true for the precision and accuracy of the localization, but also for the reliability of subject presence.

If the system where to scale we would recommend a cluster based structure with a controlled flooding routing scheme. This provides for short latency routing and easy scaling. The systems should use BLE within clusters and a longer range communication standard for inter-cluster communication, like WiFi.

The BLE performance was nearly flawless with only one exception, although it has nothing to do with the usage of BLE. The driver used on the base-station for communication with sensor nodes was riddled with bugs and poorly maintained by the developers. This made the implementation process quite tedious, and a few times during calibration inexplicable errors would occur. This took quite a lot of time from our testing and calibration phase.

Thus, for future research it is therefore recommended to use a controller unit that can run several network standards as a base-station/cluster head and transfer data to a computer through a more suited standard for computers, such as WiFi.

5.3 Adding Features and Tools

In this section, there will be a discussion on how more features, tools, and services can be added and what the potential of these are.

Scaleability and extension of features has been emphasized from the beginning of this project. This is due to time constraints and set by the format of the Master thesis. Most of the features discussed in this section are relatively simple to implement.

Respiration monitoring is in fact already a feature provided by Novelda. However, implementing this into our localization system is currently not possible due to protected source code. Respiration monitoring requires long iteration period before being able to lock on the frequency of a moving chest. This also requires the target to be relatively still in order to be able get a consistent reading of chest movements. The system could create modes for certain positions within the detection zone. If the person is moving to a location marked as a bed, the system could switch one or two sensor nodes over to a predefined sleep mode, running longer iteration periods and gathering sleep data. Furthermore, it could also be possible to switch over to a vital sign monitoring mode when the person was staying in one spot over a longer period of time. Modes could simply run on the nodes themselves and return relevant data to the closest cluster head. This would in turn require the addition of characteristics and possible new BLE services.

Fall detection is a also a possible feature. Many elderly citizens live alone and can severely injure themselves by falling in their homes. XeThru sensors are already being used in systems with the fall detection feature[35]. Falling is a quite quick process so a relatively high sampling rate is required in order not to miss it.

An installation procedure must be in place to install a system like this. It would not work to simply use the same setting and setup as we did in the testing phase. However, this process can be minimized by adding some tools to each sensor node. One such tool could be the ability to change radar parameters, like in table 3.1, without having to reprogram the node MCU.

Another tool could be an configuration mode for installing the system. This is done by the sensor node and is based on a reference reflection placed by the installation crew. The installation crew will give the sensor a suitable approximated coordinate based on physical measurements and then boot the node in calibration mode where the sensor can adjust its coordinates. The adjustments would be according to a reference reflection placed at a known location by the installation crew. The reference reflector must be a slightly moving object with enough reflective surface to be visible to the sensors. Another way of cross checking location configurations is to use BLE RSSI. BLE RSSI can give the relative distance between nodes and confirm or adjust the initial coordinates. If three nodes exists within a cluster and more sensors are to be added, their position can be found using BLE RSSI as well. This will make installing large clusters easier for each node added.

The physical installation will need to be done with respect to the room layout, strongly reflective furnishings, and potential noise sources. XeThru sensors can penetrate walls of certain materials, but the signal will attenuate. [36] describes a series of tests done to examine the penetrative capabilities of the previous XeThru sensor, X2. Although X2 have slightly different penetration properties than X4, the results are still relevant. A 110mm thick brick wall will reduce the range to the sensor by 52% and the signal strength by 12.7dB, while a 11 mm thick drywall only reduce the range by 3% and signal strength by 0.5dB. Thus, knowing what the walls are made of and how thick they are may result in fewer necessary sensor nodes.

In summation, UWB radar sensors unlocks several features. Most notably is the respiration monitoring feature allowing for true presence detection.

5.4 Applications

This section will discuss possible application for this ILS.

A UWB radar based ILS can be a feature of Smart Homes. Smart Home systems is a popular subject in the tech industry, and a human tracking feature could greatly increase the potential of automation in smart homes. The sensor nodes would be non-invasive and can be mounted out of sight for residents. The true presence detection feature is especially attractive, as this could give a reliable indicator to powered devices around the house. The most intuitive example of this would probably be lighting as this is already installed in many homes using PIR sensors, which are quite unreliable. The ILS could also be used as an evacuating resource. As XeThru sensors are able to see through smoke and barriers, this could help the relevant authority localize victims of natural disasters, fires, terror instance and so on. It could also provide direct help to the victim by targeting aimed sprinkler systems[37] or smoke vents in case of fires.

Using the system as a security system is also a viable option. The true presence feature would mean that no false alarm would be sent to the security firm, which would save a lot of money. According to a report from the Center for Problem-Oriented Policing in 2007[38], US police responded to nearly 36 million alarms in 2002, mostly originating from anti burglary systems. This corresponded in an estimated annual cost of \$1.8 billion. A shocking 94-98% of these alarms where falsely triggered. At the time of the data was gathered alarms had a success rate of 2-6%. In summation a true presence alarm system would not only save security firms and tax payers a lot of money, but also eliminate a huge public safety issue.

The localization system could be placed in the homes of senior or disabled citizens whom are not able to take care of themselves. This would provide carers and nurses with movement history and localization of patient, without physical contact. XeThru sensors can also detect vital information of stationary people. If the person where sitting or lying down, the closest sensor could lock on the respiration or heartbeat frequency and relay information to a central if something is out of the ordinary. Theoretically, it is also a possibility to distinguish one person from the other by looking at the vital signs. A patient suffering from physical trauma will in most cases have a different heartbeat variation and breathing pattern than a healthy person. Feature rich localization systems could also be used as a resource in prisons to keep track of inmate movement without using cameras. If repetitive movement like or lack of movement occurs this can be a sign of degrading mental or physical health.

5.5 Conclusion

This thesis has presented research on how to design a cost effective indoor localization system based on coordinated WSNs and UWB sensors. Our research focused on the detection and localization on human subjects. We also showcased a working example using Xethru X4 UWB radar sensors and BLE links. Our system can find the precise locations of subjects, by using multi-lateration and time of flight distance measurements. We also found that by using BLE we can support a maximum Bluetooth cluster of 7. We are also able to increase the FPS enough to support XeThru respiration monitoring features. UWB radar sensors capable of detecting breath movement provides a huge potential for advanced features, including an extremely reliable presence indicator. This project will serve as a base for future research in high precision localization systems with ultra sensitive sensor technology.

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