Localisation Of Wireless Sensor Nodes In Confined Industrial Processes

A thesis submitted to the University of Manchester for the degree of
Doctor of Philosophy (PhD)
in the Faculty of Engineering and Physical Sciences

2012

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List of Abbreviations

2D-Two Dimensional

3D- Three Dimensional

AHLoS - Ad Hoc Localization System

APS - Ad hoc Positioning

ADC- Analogue to Digital Converter

ACL- Advanced centroid localisation

BALED-Basic Adaptive Leading Edge Detection

BCL- Basic centroid localisation

BMLS- Basic Method Least Squares

BMLSD- Basic Method Least Squares Interpolation Derivative

BMSF- Basic Method Straight Forward

DARPA - Defence Advanced Research Project Agency

DV- Distance Vector

DSO- Digital Sampling Oscilloscope

GPS- Global Positioning System

IALED- Improved Adaptive Leading Edge Detection

ISM - Industrial, Scientific and Medical

LE- Leading edge

LMS - Least Mean Square

LNA- Low Noise Amplifier

LOS- Line Of Sight

LS- Least Squares

ML- Maximum Likelihood
NLOS- Non Line Of Sight
PC- Personal Computer
RF- Radio frequency
RGLED- Range Gate Leading Edge Detection
RSS -Received Signal Strength
RTT - Round-trip-time
SMA- Sub-Miniature version A
SNR- Signal to Noise Ratio
SHM- Self-Healing Minefield
TDoA- Time Difference of Arrival
ToA- Time of Arrival
ToF – Time of Flight
UWB -Ultra Wide Band
VNA- Vector Network Analyser
WCL- Weighted Centroid Localization
WSN -Wireless Sensor Network
WSN4IP- Wireless Sensor Networks for Industrial Processes
Abstract

Work described in this thesis is concerned with localisation techniques, for determining the position, of wireless sensors whilst immersed in confined industrial processes, such as those occurring in the chemical, pharmaceutical and food processing industries.

Two different approaches to localisation were investigated. The first approach employed an existing hardware system that used ultra wide band (UWB) signals whilst the second approach used a network localisation method based on information from narrow-band received signals.

A prototype UWB-based localisation algorithm processed experimental received UWB pulses to detect their leading edges (LE) that were used to derive Time Difference of Arrival (TDoA) data. In turn TDoA data were translated into distances and used to compute the locations of the sensor nodes. Nevertheless, the process of detecting the LEs caused significant errors in the localisation process. To deal with this problem new automated adaptive LE detection methods were derived that succeeded in reducing localisation errors by half, compared to the prototype method, reaching accuracies of ±2cm.

A thorough analysis of TDoA profiles revealed that these follow specific trends depending on the positions of the sensor nodes. A number of properties of TDoA profiles are proved mathematically and incorporated into seven localisation algorithms. These algorithms were examined using experimental TDoA data and shown to achieve average localisation errors up to 3cm.

Network-based localisation was examined at a later stage of this research since complexities of large scale measurements and difficulties with equipment, delayed acquiring experimental data. The deployed network consisted of a number of nodes whose positions were known (anchors) that were used to estimate the positions of sensor nodes whose positions where considered to be unknown. Localisation was based on received signal strength (RSS) data, at every node to be localised, in anticipation that RSS could provide distance information that could be used in the localisation procedure. Nevertheless, fluctuations in RSS only allowed using localisation algorithms that associated RSS to the positions of anchors. The average localisation error in the network-based localisation algorithms was between 30cm to 100cm.
Declaration

No portion of the work referred to in this thesis has been submitted in support of an application for another degree or qualification of this or any other university or other institute of learning.

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Dedication

I dedicate my thesis to my parents and to my sister for all of their encouragement and understanding throughout my studies. Special dedication and prayers goes to my grandparents whose advices and love i will never forget.

Acknowledgement

I would like to take this opportunity to express my sincere gratitude to my supervisor Dr. Peter N. Green for his guidance and advice throughout my studies. Working together in developing experimental arrangements and above all in developing novel localisation methods was one of the most challenging and educational experiences of my life.

I am truly grateful to Dr Graham Parkinson for all of his valuable help with the RF side of my work. Working together, in setting up the experiments, transferring hundreds of kilos of grain and developing grain spillage countermeasures, made the whole experience much less tedious.

I am also thankful to Dominic Crutchley with whom I had the pleasure to work with in developing “innovating” experimental procedures for tests inside grain silos. Dominic’s exceptional programming skills were vital in setting up a successful network of sensor nodes inside a grain silo.

My acknowledgements goes to Dr Rob Sloan, Peter R. Green and Prof Trevor York for the very constructive meetings and discussions we had throughout the duration of the WSN4IP project. In addition, I would like to acknowledge Keith Khan and Vincet James, from the electronics workshops, for the constructive debates we had on several aspects of electronics and communication principles during laboratory demonstrations.

Lastly but not least i express my deepest thanks to my close friends in Manchester: Antonis Phasouliotis, Rajasmita Gossuami, Jiaping Lu and Mohamed Babahani. Without them life in Manchester wouldn’t have been as rich as it was.
List of Publications

Accepted and Published


Submitted


CHAPTER 1
INTRODUCTION

1.1 Introduction

“Where am I?”, “Where is it?” These are two fundamental question humans have always been asking. Positioning using the stars in the sky, geomorphologic fixtures, a compass and a map have been widely used to allow travel all over the planet. In one of his voyages, captain James Cook proclaimed that his aim was to go beyond anyone has ever been before, yet to go as far as it was humanly possible to go [6]. Nevertheless, the continuous desire to understand the surrounding cosmos led to the development of new technologies that allowed exploring areas that once were considered out of reach such as the outer space.

Over the past 40 to 50 years a variety of advanced electronic positioning systems have been developed, typically driven by the needs of the military and the civil aviation and maritime sectors, culminating in the satellite-based Global Positioning System (GPS) [1, 4, 20,21]. However, the ability to determine position is important in other contexts than navigation. With the advent of wireless sensors (discussed in more detail in Section 1.2), it has become possible to obtain measurements of parameters of interest over an area by simply distributing the sensors over the region. A key motivating factor for the use of wireless sensors is ease of deployment over potentially rough terrain or inaccessible locations. A consequence of this kind if deployment is that the position of a node i.e. the position at which its measurements are taken is typically known. However, it is often important for position to be associated with a sensor measurement and hence there is considerable interest in the issue of positioning wireless sensors.

The work reported in this thesis is concerned with localisation of sensor nodes that monitor industrial processes inside confined spaces. A representative application from the food industry was considered where sensors are used to monitor grain stored inside silos. To this extent, localisation methods and practises presented in this thesis are concerned, but not limited, to sensors embedded inside grain storage silos.
1.2 Overview of Wireless Sensor Networks

A Wireless Sensor Network (WSN) consists of numerous sensor nodes, scattered over an area of concern with the aim of monitoring conditions that can improve analysis and further understanding of that area [1]. A characteristic example of a WSN was the deployment of wireless sensor nodes to investigate the nesting behaviour of seabirds, on a remote island, were continuous human presence was undesirable [2]. Data from the sensor nodes were transmitted over the internet through a base station that had the capability of satellite communications thus allowed researchers to process real-time readings remotely [2].

Each node in a WSN is equipped with a radio transceiver, a power source, usually a battery, as well as several sensors and a microprocessor that allows gathering and processing data locally [1].

The nodes in a WSN cooperate to create and maintain the network without any supporting infrastructure such as base stations, switching centres or any other wired equipment; instead nodes once deployed can establish communication links among them and act as routers to forwarded information from one node to the next along an established route as seen in figure 1 [1, 3-5]. Nodes form links with neighbours that are in radio range and set inter-node connections that define the network topology. Instantaneous network formation without any preplanning is known as ad hoc topology.

![Figure 1. WSN architecture](image)

*Figure 1. WSN architecture*
Most WSNs include one or more base stations or gateways that provide a sink for the data gathered by the network and an interface between the WSN and other systems, typically the Internet as seen in figure 1. If the network has a single base station and all nodes have a direct link to it, then the network has a star topology and is an example of a single-hop network (figure 1) where the term hop means a direct radio link. However, in many WSNs, nodes might be out of range of the base station and so if they wish to transmit data to it, it must be sent via a number of intermediate nodes. Such a network is called a multi-hop network (figure 1) and the task of finding a path between a node and the base station is known as multi-hop routing [1, 3-5].

The infrastructure-less characteristics of ad hoc networks reduces the cost and increases the flexibility of the network to adapt in different application scenarios [5].

In general, the design of WSNs is governed by constraints such as small size and low cost [1]. However the most challenging constraint by far is sustainable low power consumption in order to prolong the life-span of the nodes for as long as possible. This is especially important in case were sensor are deployed to monitor environments that are not easily accessible [1, 2] and so batteries cannot be replaced.

Data collection and processing as well as the employed communication methods determine, to a great extent, the operational period of the nodes and as such various method have been developed to deal with these issues. To further relax node’s data processing constraints nodes in a network can pass their information from node to node and finally to a base station with higher processing capability which is able to broadcast information to users far away [1].

1.3 WSN applications

WSNs find applications in areas such as the military, the environment, health, space exploration, and in industry. Some of these application areas are discussed next.

1.3.1 Environmental monitoring

Environmental monitoring has been a popular application for WSNs. Research in this area includes deploying sensor networks in a remote island to monitor habitat patterns of seabirds [2], to monitor underwater life [7], and even monitoring the harsh environment of Icelandic glaciers [8-10].
The deployment of WSN to study glaciers (figure 2) in Iceland was an initiative by a research team as part of the Glacsweb project [8-10]. This research is a good example of a practical deployment of a WSN and so will be presented in some detail next.

The objective of this project was to provide a better understanding of the effect of environmental changes at the base of the glaciers and how this affects glacial displacement [9-11]. A number of sensor nodes were placed inside the glacier and one base station outside on the top of the glacier to collect all the data, as shown in figure 2.

![Figure 2. GlacsWeb sensor network deployment](image)

The nodes were equipped with a number of sensors to observed parameters such as conductivity, heat, temperature, pressure and light variations. Further, information on the tilt and roll of the sensor was derived using 3-axis (x, y, z) tilt sensors. The node electronics were enclosed within a polyester hull and placed inside ice using hot water drills.

Communication among nodes and the base station was achieved using transceivers operating at 173MHz; since communication at higher frequencies usually used in WSNs\(^2\) results in high levels of signal attenuation that degrades the process of data collection from the sensors. The antennas used for communication were quarter wavelength helical antennas. However, it was found necessary to ‘tune’ the antennas (reducing their length) to obtain satisfactory performance, since the signals propagated through ice and not air.

\(^2\)Frequencies in the unlicensed Industrial, Scientific and Medical (ISM) band are often used in WSNs. These include 433, 868 and 2400 MHz.
Nodes near the top of the glacier transmitted their data directly to the base station in a single hop approach which was proven to be power inefficient whilst nodes deep inside the glacier broadcasted their data one to another in a multi-hop approach which proven to be beneficial in terms of energy consumption.

The nodes were coordinated by software running on a battery powered microcontroller. To save power, the microcontroller was placed in standby (sleep) mode for the most of the time and was activated only once a day to transmit the collected data to the base station. The purpose of the base station was to collect all the data from the sensor nodes for further processing and to transmit data via a combination of GSM radio links and Internet, to the research team at Southampton.

1.3.2 Military applications

Many military applications of WSNs have been proposed ranging from enemy and asset surveillance to target tracking and elimination [11-13]. An interesting application is the “clever” antitank landmines project, undertaken in the United States. After deployment, the landmines developed in this work could communicate with each other forming ad-hoc WSN, and can even change position [11]. This system of landmines is known as the Self-Healing Minefield (SHM) and is so adaptable to the movements of the enemy that if part of the minefield is breached it can be physically reorganised by moving part of the mines to cover the breached area.

Each tank mine is equipped with a short range radio transceiver with a wide-beam antenna and once it is placed on a mine field it communicates with other mines to form an ad-hoc network. In addition, four rocket thrusters that are attached on each mine allow them to jump into their new position if and when this is required.

Once deployed, mines transmit signals regularly to other mines in the network; an absence of a signal at any time from one or more mines inside the network is interpreted as being caused by a hostile activity thus initiating the process of relocation that can take place within 10 seconds. The SHM network established a robust method to deal with enemy attempts to jam its radio signals. In any interference attempt, to disrupt mine’s communication amongst the mines, these could hop channels between acoustic and spread-spectrum signals [11].
1.3.3 Wireless sensor networks for industrial processes

In industrial settings, WSNs can be used to monitor facilities, to predict possible equipment failures and restrict access to unauthorized personnel thus contributing in improving quality and productivity and reducing operating costs.

A project known as Actuated Acoustic Sensor Networks for Industrial Processes (AASN4IP) was concerned with developing technology to support the monitoring of liquid-based industrial processes by immersed WSNs [14-17]. The project developed a demonstrator system to monitor conditions within nuclear storage ponds. Nodes were mobile small-scale autonomous vehicles, with a spherical hull, propulsion and control systems.

Nodes could communicate with each other and with the base stations outside the pond using acoustic techniques. In the upper areas of the pond, communication between a node and a base station was performed using single hop links. However, deep in the pond, it is believed that multi-hop techniques would be required to propagate data up to the base station.

The communication system supported a localisation system that enabled nodes to establish their position within the pond. This was an important aspect of the project, since readings within the pond are of limited value unless the location of the sensors is known.

In a related work to AASN4IP, reported in [123], a localisation system was developed to locate sensors inside a cylindrical vessel filled with 250 litres of water. Analysis of the localisation methods, using data from acoustic transducers attached on sensor nodes, shown that these could achieve accuracies up to ±5cm [123]. Of interest were the observations that the number of the transmitting transducers, attached on each sensor, as well as their orientation with respect to the receivers have significant impact on localisation [123]. To be more specific it was observed that an increased number of transducers (8) with a specific separation between them could alleviate issues arose from random orientations of the sensors as these rotate inside the water thus improving localisation accuracies.

Research in [18, 19] concerned the deployment of WSNs inside storage biomass products such as silage\(^4\), in order to support early identification of potentially hazardous situations.

\(^4\) Silage here refers to animal food made from a mixture of seeds (i.e. grain or corn) and chopped grass all ensiled in airtight conditions within plastic wrapping for better preservation.
Specifically, the variation of temperature and humidity were monitored to identify the early stages of decomposition.

A preliminary study in [18] examined the impact of biomass on antenna resonance frequency and on transmission range. As in the GlacsWeb project, discussed in Section 1.3.1, the fact that the nodes were to be buried in a medium that was not air was expected to affect the resonance frequency of the antennas and their transmission range.

Tests were carried out using two 433MHz antennas, a homemade loop antenna and a commercially available helix antenna both enclosed in a plastic box to prevent direct contact with the silage. A vector network analyser (VNA) and a spectrum analyser (SA) were used to measure the resonance frequency of the antennas and the transmission range. The experimental setup is shown in figure 3.

![Figure 3. Antenna characterisation inside biomass [18]](image)

Results showed a shift in the resonance frequency for both the antennas, whilst inside silage. However, “detuning” was more intense for the helix antenna (424MHz in air, 345MHz in grain) rather than for the loop (434MHz in air, 429MHz in grain) antenna. The reason for this difference lies on the fact that the near field of the loop antenna is mostly magnetic thus influenced by the permeability of the silage rather than electric as in the case of the helix antenna that depends on the permittivity (dielectric constant) [18, 43]. As therefore, given the permeability of silage is similar to that of air [18, 44] and that the dielectric constant

---

6 Permeability is the degree of magnetisation of a material
(permittivity) was about 35 [18], discrepancies in the resonance shifts between the two antennas were expected.

Transmission range measurements were performed using the SA to measure RSS over distance in the experimental setup seen in figure 3. The results are shown in figure 4.

![Figure 4. RSS over distance inside silage [18]](image)

Results in figure 4 demonstrate that the two helix antenna at 345 and 424 MHz can reach longer transmission range up to 8m whilst the RSS for the loop antenna dropped below noise floor of 105dBm at just 2m [18]. These results are a direct consequence of the characterisation of the near field of the antennas discussed above. The loop antenna had most of its signal reflected back to it rather than radiated thus its transmission range was significantly reduced [18]. On the other hand, helix antenna had most of their signal radiated and as such could reach longer transmission ranges.

Figure 4 revealed another interest observation. From the two helix antenna used, the 345MHz antenna had much higher RSS than the 424MHz antenna over all distance measurements. This was justified on the difference between wavelengths of the two antennas. The 345MHz antenna have larger wavelength compared to the 424MHz one, as indicated in equation (1) thus signals out of 345MHz antenna are susceptible to increased diffraction due to scattering (size of material in silage much smaller than wavelength ~87cm thus signals can bend around obstacles and travel further). As a consequence signals out of the 345MHz antenna have better penetration inside the silage [18].

\[
\lambda = \frac{c}{f}
\]  

(1)

where \(c\) is speed of propagation, \(f\) is the frequency of the signal, and \(\lambda\) is the wavelength of the propagated signal.
As a future work, the authors of [18] proposed using broadband antennas instead of narrowband ones in order to avoid antenna detuning and optimise signal propagation through silage stacks.

Research in [19] examined the impact on the ability of WSNs to broadcast their signals whilst inside a biomass as seen in figure 5. Sensor units (transceiver and batteries) were enclosed (airtight sealed) within a spherical housing to protect them from pressures developing inside stored silages and to prevent any moisture or methane gases from coming in contact with any electrical part of the sensor. Nodes were buried within the silage stack at two depths, 25cm and 50cm. The network had a star topology with nodes transmitting to gateway node located outside the stack and the network

Tests in [19] shown that the sensors could operate for a period of fifty three days, following a specific sleep-wake up approach, whilst transmitting at maximum power of 10mW. This was particularly important given that one of the objectives was to use WSNs to remotely monitor silage stacks, over a long periods, without the need to periodically extract samples from the silage to observe their condition, a practise commonly followed up to date [18, 19]. The maximum distance over which reliable communications, between any one sensor and the gateway, could be achieved was 5m.

As future work, the authors of [19] proposed networking of the sensor nodes, i.e. transferring data from one node to another and then to the gateway, to extend battery life given that individual nodes will not need to transmit at high power levels to reach the gateway directly.
1.4 Localisation

A key aim in many WSN deployments is to enable nodes to be distributed in a casual manner without the need for careful placement [8, 11-13]. This is motivated by a desire to overcome difficulties imposed by the deployment area (war conflicts, toxic substances) as well as to reduce deployment times and costs. However, in many applications, collecting data without information on the position at which sensors operate, it is not beneficial. In these cases some form of localisation procedure is needed. Since the work reported in this thesis is concerned with localisation in WSNs, the topic is introduced here, and will be discussed in detail in later chapters.

A widely used localisation method is the Global Positioning System (GPS) [1, 4, 20, 21]. GPS is a worldwide radio-navigation system formed from a constellation of twenty four satellites and their ground stations. It uses the satellites as reference points to effectively calculate the positions of ground nodes. However GPS is not always suitable for WSNs since GPS receivers are expensive with high power consumption [1, 4, 20,21] and therefore not suitable for use on numerous small and disposable nodes especially in cases were sensors are static thus their position needs to be recorded only once. Further, GPS technology is not suitable for all applications since it does not work well indoors or in the presence of obstacles in the line of sight between the satellite and the receiver [1, 4, 20, 21].

The localisation problem, in WSNs, is typically formulated in terms of few nodes whose positions are known, referred to in literature as anchors and a majority of unknown nodes whose positions are to be determined by the localisation process. Anchors may obtain their coordinates via manual configuration when placed in an area of concern in predefined positions or by other means such as GPS.

Localisation in WSNs typically relies on network communication, and so is sometimes called network-based localisation. It can be performed with or without the use of dedicated hardware. Techniques that use dedicated hardware are range based [1, 22], those that do not are usually, but not exclusively, range-free. Range-based techniques acquire distance information by analysing the strength or time of arrival of received signals [1, 23]. On the other hand, range-free localisation allows nodes to estimate their position using the coordinates of known nodes transmitted to them [24, 25].

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1.5 Thesis motivation and objectives

This research was closely allied to an EPSRC-funded project known as Wireless Sensor Networks for Industrial Processes (WSN4IP) [26-28] at the University of Manchester and shared its motivations. The goal of the WSN4IP project was to investigate the use of wireless sensor networks, immersed within industrial processes, for the purpose of monitoring internal conditions. The term ‘industrial processes’ was interpreted in a broad sense and included processes occurring in the chemical, pharmaceutical and in food industries. For the purposes of simplicity, the focus of WSN4IP was restricted to processes involving particulate solids. The follow-on AASN4IP project (see section 1.3.3) considered liquid-based processes.

The aim of immersing a WSN in a process is to increase the amount of data that is available to operators about the internal state of the process so that, for example, undesirable conditions can be identified (see section 1.3.3 and below). In other situations the information could be used to reduce energy consumption, the usage of raw materials and the amount of waste produced.

The WSN4IP project investigated issues such as node hardware, network communication and localisation. An important part of the project involved the development of a representative demonstrator system. The chosen application was the monitoring of grain stored in silos.

An ever increasing population dictates a constant and high quality food supply, where grain and its products are ranked at the very top of demand [31]. Therefore there is a growing interest in ensuring, not only the production, but also the storage of grain in a safe environment [26-41]. Monitoring grain storage conditions or indeed the storage of any type of crops is important in a number of aspects. Storage of crops in an enclosed space, over long periods, can lead to a build up of heat and humidity ideal conditions for speeding up decomposition and the formation of carcinogenic toxins. The fraction of such toxins existing within a body of grain is governed by strict legislations. If the fraction is too high, the grain cannot be used for human consumption or even for animal feeding given that carcinogenic toxins can reach humans even with animal by-products such as milk [35].

A number of companies are specialized in providing equipment to observe grain conditions, in particular temperature and humidity [32-34]. Nevertheless, up to date, the employed
equipment is wired and although reliable, it is costly and lacks flexibility. However it is difficult to measure internals of granular flow with cabled sensors. To address issues from cabled sensors, the WSN4IP project proposed using WSNs for insertion into a model grain silo as illustrated in figure 6.

![WSN to monitor grain silo](image)

**Figure 6. WSN to monitor grain silo [27]**

Node hardware and software was developed within the project and ultimately experiments on networking where carried out using an immersed network of ten wireless nodes. Details of the WSN4IP nodes and the in-silo experiments can be found in Chapter 7.

As indicated above, localisation was an important part of the WSNIP project that aimed at improving the usefulness of sensing data by determining the spatial variations of key processes enclosed in confined spaces. Researchers working on the WSN4IP project proposed an UWB localisation system a prototype which is discussed in Chapter 4. However the performance of this system was not thoroughly evaluated and from the limited amount of results that had been made available from the rest of the WSNIP team, it appeared that significant room for improvement existed.

The main objective of this research was to build on the knowledge acquired from the WSN4IP project, to implement improvements and develop new methods that will allow for accurate network-based and UWB-based localisation systems for WSNs inside industrial processes.
1.6 Related work

Research in the area of monitoring grain stored in silos, using wireless systems, has not previously examined the issue of localisation. Instead research is primarily focused on the effect of grain and of the silo building material on the propagated signals, in establishing whether communication through grain is possible and at what distances. Various signal types have been considered for propagation inside grain; those include acoustic, narrow band and UWB signals. The use of narrow-band and acoustics signals will be discussed in the following sections whilst the use of UWB technology will be discussed in more detail in chapter 3.

1.6.1 Grain monitoring using acoustic signals

Sound waves have very low frequency (20Hz-20kHz) and can propagate through solids or liquids for longer distances and with lower attenuation than in air [14-17]. For these reasons sound waves are widely used in underwater communications [14-17] and have also been investigated for possible applications in grain monitoring inside silos [36-38].

The use of acoustic signals was practically examined in [36, 38] with the aim of detecting harmful insects penetrated the silo causing damage to the grain that might not be easily observable by eye [36].

The authors of [36] identified that sounds produced by larvae and adult insects whilst in motion or eating have unique time signature thus allowing identifying them. An experimental investigation was carried out using a cylindrical tube filled with 1kg of grain and two piezoelectric transducers immersed in grain. Part of the used grain was infested with larvae and was placed at the middle of the distance in between the two transducers whilst adult insects were thrown inside grain and left to move around freely.

The method of identifying the presence of insects and also filtering out noise signals caused by random grain settling (and other sounds coming from outside the silo) involved of an off-line phase and a real time phase. In the off-line phase, hundred sound samples were collected, half from larvae and another half from adult insects and another hundred samples were taken to characterise noise. In one of the real time measurements, 15 minutes of sound data were recorded that include a mixture of all possible sound signals that can be detected by the
piezoelectric sensors. Once real time data had been recorded these were compared with the data from the off-line phase in order to detect similarities in the patterns thus identifying the presence of the insects.

Work in [37] presented a more thorough analysis of sound propagation inside grain than in [36] with the aim of establish a reference starting point for future implementation of acoustic detection of insects inside grain. An experimental procedure was carried using a 2.5 x 1.3 x 1.6 m container filled with about 5 m$^3$ of wheat and by placing a single speaker and two microphones arranged in a horizontal line 50cm below the surface of the grain. Initially the authors examined whether sound waves actually propagate from grain kernel to grain kernel or whether sound waves travel through the air gaps between grain kernels.

To determine the propagation path of the sound, experiments were carried out using a piezoelectric microphone that initially was situated inside grain and then moved outside 1mm above the grain surface. In both cases, a strike on the outside surface of the tank at about 50cm from the piezo-electric microphones generated sound vibrations detected by both microphones (inside and outside grain) with very small differences in between them. Based on all observations the authors of [37] concluded that sound propagated through the air gaps in between grain kernels. Thereafter, the authors of [37] investigated the effect of frequency on the attenuation of the sound waves. Numerous tests at different frequencies revealed that grain attenuates high frequencies thus it was concluded that the frequency of weak sound waves, generated by insects at 1m from a receiving microphone, should lie within a range lower than 1 kHz in order to be reliably detected [37].

Overall, experimental work presented in [36-38] revealed that it is possible to use acoustic signals to monitor grain inside silo. Nevertheless, it was concluded that grain is a major attenuator that severely limits the distances at which acoustic sensors could operate. Thus, the use of acoustic sensors is not an efficient method to monitor grain since a large number of acoustic sensors will be required to provide effective monitoring of small area of stored grain.

1.6.2 Grain monitoring using narrow band signals

Work presented in [39-41] pointed out that WSNs can be a valuable asset in grain monitoring. Sensors deployed within grain silos can form ad-hoc networks thus allowing
delivering data over long distances, to a central receiver, hence coping with cases were individual sensors will be out of range of the central receiver. To this extent, extensive research was carried out in order to establish the maximum distance within which two battery-operated nodes could communicate between each other.

Reference [39] introduced the idea of monitoring grain in silos using a buried WSN. It was pointed out that multi-hop network would be necessary since individual sensors buried deep within the silo would most likely to be out of range of a base station. [39] reported an effort to establish the maximum distance over which two battery-operated nodes could communicate with each other when immersed in grain.

Work on propagation of RF signals through grain [39, 42] suggested that attenuation of radio frequencies in grain can be estimated by equation (2), [39], given \( \epsilon'' \ll \epsilon' \)

\[
\alpha = \frac{8.686\pi\epsilon''}{\lambda\sqrt{\epsilon'}}
\]  

(2)

where \( \alpha \) represents attenuation in dB per meter of path length, (dB/m), \( \lambda \) is the free-space wavelength for the transmitted frequency, (m) and \( \epsilon' \) and \( \epsilon'' \) are the dielectric constant and loss factors respectively.

Experiments reported in [39] revealed that the dielectric constants depend on the moisture content of the grain and the frequency of the propagated signals. For a fixed quantity of grain with constant moisture content, and propagated signals in the range 900MHz to 10GHz \( \epsilon' \) values of \( \epsilon' \) between 3 to 2.5 and \( \epsilon'' \) values from 0.3 to 0.25 were obtained[39, 42].

As indicated in section 1.3.1, the unlicensed ISM bands are often used in WSNs, in particular the 868MHz and 2.4GHz bands. Based on equation (2), a significant amount of attenuation should be expected in these bands. For example, at 900MHz equation (2) gives attenuation between 11 to 15dBm/m with attenuation at 2.4GHz reaching 30 to 40dBm/m. In order to take advantage of lower attenuation at lower frequencies, the operating frequency in [39] was set around 900MHz.

To practically investigate the maximum distance over which two nodes can communicate with each other, an experimental procedure was carried out in, a grain filled, steel container with four commercially available WSN nodes (Mica motes) as seen in figure 7.
One of the nodes was used as a gateway mote placed at the top of the container with the other three nodes being situated inside the grain at different depths. The operating frequency for the motes was 915MHz transmitted at 1mW. According to [39], the node’s batteries would enable them to operate for up to four years, depending on usage.

Experimental data depicting the maximum and minimum attenuation values as well as the average attenuation over distance are shown in figure 8.

Figure 8a shows the maximum and minimum attenuation values, recorded at the same distances, where it can be seen that these deviate considerably from the average values. Deviations in attenuation were attributed to the multipath effect. Multipath effects arise when...
signals follow multiple paths in their way from the transmitter to the receiver thus creating multiple versions of the same signal. The main cause of multipath in [39] was considered to be the metallic structure of the container, within which tests took place, which caused increased reflections amongst the propagated signals.

Results in figure 8b show that signal attenuation is relatively constant in distances less than 50cm that lies within the near-field region of the 915MHz antennas ($\lambda$=33cm). In near-field region, energy decays very rapidly with distance. On the other hand in the far field region ($>$50cm between transmitter and receiver), it was observed that signal attenuation increases with distance (figure 8b). In addition it was observed that the maximum communication distance between transmitter and receiver was about 2m [39].

Analysis of the results, using equation (2), reveals discrepancies between experimental and predicted theoretical attenuation values. The attenuation at 915MHz based on equation (2) is -15dBm/m thus considering the results in figure 8 and a baseline of -53dBm, the attenuation at 1m will be $-68$ dBm. Nevertheless, the average experimental attenuation at 1m was $-73$dBm [39]. These results highlighted the need to base any radio models relating distance to RSS on experimental data rather than theoretical.

A more comprehensive investigation of grain monitoring using WSN is discussed in [40, 41]. The experimental setup consisted of three ZigBee based nodes and steel container filled with grain. An overview of the experimental setup is shown in figure 9.

![Figure 9. Grain tests experimental setup](image)

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3 Near-field region is defined as the area where the distance from the antenna is well below $1\lambda$.

4 Far-field region is the area where the distance from the antenna significantly exceeds $1\lambda$. 
In order to establish the maximum distance over which two nodes can communicate, tests were contacted to measure the received signal strength (RSS) at the receiving node at different receiver-transmitter separation distances [40]. This was found to be about 1.15m, with any further increase in the separation resulting in a rapid fall in RSS reaching noise floor levels. The experimental results are graphically shown in figure 10.

As far as the lifetime of the ZigBee based nodes is concerned, experiments shown that these can remain functional for more than a year, given the specific sleep and wake-up program that was followed.

![Figure 10. Experimental RSS over distance](image)

Overall the WSN system in [40] shown to meet the requirements of low power consumption and of reliability in collecting and broadcasting the collected data. As future work, the authors identified the need for a better organisation of the network by keeping distances among nodes as small as possible whilst investigating methods to extend the transmission range and to optimise the routing of data from the sensor nodes to the control centre. These aim at reducing energy consumption for individual nodes thus increasing the useful operating time of the network. Further it was proposed that the container with grain could be housed in a room equipped with an air-conditioning system that could adjust humidity and temperature based on readings from the sensors inside grain.

1.7 Thesis layout

The rest of the thesis is organised as follows. The second chapter reviews basic ranging and localisation methods widely used in the literature and a number of which is also used in the localisation methods examined in the rest of the chapters.
The third Chapter introduces UWB technology giving emphasis on parameters of interest such as signal processing, distance estimation and localisation as these were practically examined in the literature.

Chapter 4 presents a prototype UWB-based localisation method, developed for the WSN4IP project, and reviews the algorithm and the experimental procedures followed. Localisation results were thoroughly examined and observations on the impact of received signals on localisation accuracy were recorded.

Work in Chapter 5 builds on the knowledge acquired from Chapter 4 and proposes a number of signal processing techniques contributing to more accurate position estimates as opposed to the results in Chapter 4.

Chapter 6 introduces novel localisation methods deviating from the prototype localisation method discussed in the last two chapters. These methods were based on analysis of theoretical and experimental distance data that shown a repeating pattern of specific observations. These patterns were materialised into localisation algorithms and evaluated using the experimental data derived as discussed in Chapter 4.

Chapter 7 discusses network based localisation for sensors immersed inside a large scale silo. There is detailed explanation of the experimental procedures and of the impact of grain on the propagated signals. In addition the results from the implementation of two network-based localisation algorithms using preliminary experimental data are presented.

An overall discussion of the work presented in this thesis as well as proposed future work is presented in Chapter 8.
CHAPTER 2
BASIC RANGING AND LOCALISATION METHODS

2.1 Introduction

This chapter presents a survey of basic ranging and positioning methods widely discussed in the literature related to WSNs localisation. A number of these methods have been utilised in the practical work discussed in this thesis presented in chapter 4 onwards.

At the beginning of this chapter, a number of fundamental methods of determining distance (known as ranging) and position are presented. Thereafter a number of localisation algorithms are discussed, some of which utilised the basic principles discussed at the start of this chapter.

2.2 Basic ranging techniques

In this section, the two ranging techniques most commonly used in WSNs are introduced. The first technique is based on time measurements and includes Time of Arrival (ToA) and Time-Difference-of-Arrival (TDoA) approaches, whilst the other is based on RSS.

2.2.1 Time-based ranging

There are two basic time-based ranging techniques, ToA and TDoA [49-51]. The ToA method gives range estimates based on a measure of the time it takes for a signal to arrive from a transmitter at a receiver. In TDoA, a number of receiving antennas are considered to allow for range estimates to be computed. To be more specific range estimates, in TDoA, are derived by measuring the difference in the arrival time of the signals at a reference antenna to the signals arrived at the rest of the antennas in the system under concern. ToA and TDoA can be applied using different kinds of signals, such as RF, acoustic or ultrasound [49-51].

There are two basic techniques through which ToA ranging can be implemented. One technique is based on time synchronisation between transmitter and receiver and is known simply as the ToA technique. The other technique is known as Round-trip-time (RTT) and it can give range estimates without the need for time synchronisation [15].
In the ToA technique, transmitting nodes broadcast their information along with the time at which the signal was sent. Once a node receives the signal it can estimate its distance from the transmitter based on the time taken for the signal to arrive [15]. The receiver calculates ToA by subtracting the time of transmission from the time of receipt and then it calculates its distance from the transmitter as follows:

\[ d_{ij} = \text{ToA} \times c \]  \hspace{1cm} (3)

where, \( d_{ij} \) is the distance from transmitter \( i \) to receiver \( j \) (m), \( c \) is the propagation speed (m/s).

The main disadvantage of ToA ranging is the need for accurate time synchronisation between timers in the transmitter and the receiver. Further, depending on the medium within which signals are propagated, multipath effects and noise can have significant impact on the precision of ToA, and techniques to overcome such issues increase the complexity of ToA ranging [38, 15, 8].

TDoA data are computed using the difference in ToA between a reference receiving node/antenna and a number of non-receiving nodes/antenna [38, 41, 15, 33].

A common method used to derive TDoA is cross-correlation between received signals. Cross-correlation is used to find the time required to shift received signals towards the signals at the reference antenna in order to maximise the integral of the product of those two signals [46-48]:

\[ \text{Cor}_{a_j}(\tau) = \int_{0}^{T} X_a(t) \cdot X_j(t - \tau) \cdot dt \]  \hspace{1cm} (4)

where \( X_a \) is the reference signal arrived at time \( t \) and \( X_j \) is the signal from subsequent receiving antenna delayed by time \( \tau \).

A characteristic example of cross-correlation of received signals with the signal at the reference antenna is shown in figure 11. This shows the correlated signals from four antennas located at 10, 20 and 30cm from the reference antenna, located at \( X=0 \)cm.

\[ . \]
TDoA data are converted into distance using an adaptation of equation (3). TDoA data $\Delta t_{ij} = (t_i - t_j)$ that is the difference of ToA at reference receiver $i$ to the rest of receivers $j$ in equation (3) result in distance differences, $\Delta d (d_i - d_j)$ between a transmitter to receiver $i$ and $j$ as follows:

$$\Delta t_{ij} \cdot c = \Delta d_{ij}$$

Equation (5) demonstrates that ranging based on TDoA does required knowledge of at least one distance from the transmitter to the receivers and this can be seen as a drawback compared to ToA based ranging. However there are techniques that remove this requirement as will be discussed latter in Chapter 4. Overall, TDoA-based ranging is advantageous when compared to ToA since with TDoA there is no need for clock synchronisation between the transmitters and the receivers.

The Round-trip-time (RTT) is a technique that can overcome this synchronisation problem. In RTT, the sender transmits a signal and a receiver echoes it back to the original sender whilst receiver nodes record the time taken by a signal to travel from the transmitter to a receiver and back again (RTT)[95]. The distance $d_{ij}$ between transmitter $i$ and receiver $j$, for a given RTT, $T$, is given as follows [95]:

$$d_{ij} = err \times T \times c$$

where $err$ is an error factor attributed to errors in estimating RTT.
2.2.2 Received signal strength (RSS)-based ranging

The RSS-based ranging is widely used for localisation in WSNs [52-58]. This approach is popular because most radio transceivers used in WSN nodes enable measurements of RSS to be obtained and hence no additional hardware is needed in order to compute range estimates. However, it should be noted that such RSS measurements are typically prone to errors.

The RSS radio model employs a path loss equation that allows derivation of the distance between a transmitter and a receiver based on knowledge of the transmitted power of the signal and a measurement of the received power at the receiving node.

An empirical model generally used to characterise RSS as a function of distance in RF channels is the log-normal shadowing model [33, 43, 44]. This model has been confirmed through extensive experimental measurements by numerous researchers and it can provide adequate representation of the variation of the received power with respect to the distance both in indoor and outdoor situations [33, 44]. Shadowing here refers to the random variations experienced in the received signal power at a given distance, caused by obstacles in the path of the signals from the transmitter to the receiver. The model shows that for a given transmission power, there is an exponential fall in the mean RSS with increasing distance between the transmitter and the receiver. Shadowing effects are accounted for in the model through a zero mean Gaussian term. The log-normal law is given by:

\[ P_{\text{RSS}}(\text{dBm}) = P_t(\text{dBm}) - PL_d(\text{dB}) \]  

(7)

In equation (7) the received power \( P_{\text{RSS}} \) is equal to the transmitted power \( P_t \) minus the pathloss power \( PL_d \), where pathloss is given by equation (8)

\[ PL_d(\text{dB}) = PL_{d_0} + 10n_p \log \left( \frac{d}{d_0} \right) + X_\sigma \]  

(8)

where \( n_p \) is the path loss exponent measuring power attenuation relative to distance and \( X_\sigma \) is a random variable with zero mean and \( \sigma^2 \) variance, in RSS measurements, due to log-normal shadowing, \( PL_{d_0} \) is the pathloss at a reference distance \( d_0 \).
Hence if the transmission power $P_t$ is known and the log-normal parameters $d_0$, $\text{PL}(d_0)$, $n_p$ and $\sigma$ for a particular environment as well as the $P_{\text{RSS}}$ are measured then equation (7) can be used to obtain an estimate if the distance between a transmitter and a receiver.

The pathloss at a reference distance $d_0$ (usually taken at 1m) can, in principle, be computed by employing the free space path loss equation as follows:

$$\text{PL}_{d_0}(\text{dB}) = 10 \log \left( \frac{P_t}{P_{\text{RSS}}} \right) = -10 \log \left[ \frac{G_t G_r \lambda^2}{(4\pi)^2 d_0^2} \right]$$

where $G_t$ and $G_r$ are the gains of the transmitting and receiving antennas respectively and $\lambda$ is the wavelength in meters of the propagated signal.

Figure 12 exemplifies the differences between theoretical and experimental RSS results. Theoretical RSS were derived using the free space model and random Gaussian noise whilst experimental RSS were recorded using ChipconCC1010 transceiver [57].

![Figure 12. Theoretical and experimental RSS [57]](image)

Figure 12 shows that although RSS decreases with an increase in distance (as expected) the theoretical RSS values deviate substantially from the experimental RSS. This observation strengthens the need to use experimental RSS values in order to derive an empirical model that will allow deriving distance estimates out of RSS data.

Equations (7) and (8) can be arranged into equation (10) that is suitable for range estimation:
\[ d = d_0 10^{\xi} \]  

where \[ \xi = \frac{P_1 - P_{\text{RSS}} - PL_{d_0} - X \sigma}{10n_p} \]

As indicated above, the log-normal law is an empirical relationship and as such it is based on experimental measurements of RSS. It has been found that parameters \( PL(d_0), n_d \) and \( \sigma \) depend on the environment in which the experimental measurements were taken. Values of these parameters obtained in one environment are not typically applicable in another [56]. In fact, it has been observed that especially in indoor spaces, it can be difficult to obtain a consistent model relating distance to the signal strength because of increased amount of multipath fading and shadowing effects [33, 42, 44]. Further, in many cases it is difficult to ensure efficient calibration of the transceiver modules used in low cost nodes. Calibration deficiencies can introduce significant errors in RSS measurements [44]. In addition, antenna orientation between a receiving and a transmitting node can have a significant impact on RSS measurements [52].

### 2.3 Basic localisation techniques

Consider a sensor node whose coordinates are unknown. If the distances (ranges) from this node to a set of reference points (anchors), with known coordinates, can be determined, then the position of the unknown node can be found. In the simple case of an unknown node in a two-dimension (2D) scenario, distances from the unknown to three anchors are required. In a three-dimension (3D) case, the distances from the unknown to four anchors are needed.

The basic procedure for performing position determination based on range estimates is known as trilateration. A similar approach based on measures of the angles formed between an unknown node and a set of anchors points is known as triangulation. This is less commonly used in WSNs that trilateration and the more advanced technique of trilateration known as multilateration and as such it is not considered in this research.

The basic principles of trilateration and multilateration localisation techniques are discussed in the following two sections.
2.3.1 Trilateration

Trilateration in 2D employs the known locations of at least three anchors and the distances between an unknown node to the anchors to compute the position of the unknown node [49, 51, 59, 60].

Figure 13, depicts an overview of the trilateration process with three anchors AN₁(X₁, Y₁), AN₂(X₂, Y₂) and AN₃ (X₃, Y₃) and an unknown node UN (X, Y). Here it is assumed that the distances Rᵢ between UN and ANᵢ are known. This means that UN must lie on a circle centred on ANᵢ having a radius Rᵢ. Hence the unknown node lies at the point of interception of the three circled centred around the respective anchors as shown in figure 13.

\[
\begin{bmatrix}
R_1 \\
R_2 \\
R_3
\end{bmatrix} = 
\begin{bmatrix}
\sqrt{(X-X_1)^2 + (Y-Y_1)^2} \\
\sqrt{(X-X_2)^2 + (Y-Y_2)^2} \\
\sqrt{(X-X_3)^2 + (Y-Y_3)^2}
\end{bmatrix}
\]

(11)

The location of UN in figure 13 can be obtained from equation (11) when solving for X and Y as follows [59]:

---

Figure 13. Trilateration diagram
\[
\begin{bmatrix}
X \\
Y
\end{bmatrix} = \begin{bmatrix}
2(X_1 - X_3) & 2(Y_1 - Y_3) \\
2(X_2 - X_3) & 2(Y_2 - Y_3)
\end{bmatrix}^{-1} \begin{bmatrix}
X_1^2 - X_3^2 + Y_1^2 - Y_3^2 + R_3^2 - R_1^2 \\
X_2^2 - X_3^2 + Y_2^2 - Y_3^2 + R_3^2 - R_2^2
\end{bmatrix}
\] (12)

Extending the analysis to 3D is straightforward. In this case, the unknown point is given by the intersection of four spheres centred on the anchor’s positions with radii equal to the distance of each anchor from the unknown. An extended version of this analysis appears in the next section.

### 2.3.2 Multilateration

When attempting to apply range-based localisation to real-world problems, difficulties often arise because of errors in the range estimates and these can significantly impair the accuracy of the position estimates. A technique known as multilateration can be applied to enhance localisation accuracy [49, 59-61]. Multilateration requires that the distance between the unknown and more than three anchors in 2D (3D) are known.

Figure 14, depicts a 3D multilateration process where spheres are centred around four anchors AN1(X1,Y1,Z1), AN2(X2,Y2,Z2), AN3(X3,Y3,Z3), AN4(X4,Y4,Z4) with all the spheres crossing each other at the position of an unknown node UN(X,Y,Z) (yellow star).

Let R1, R2, R3, R4 be the radii of the spheres, seen in figure 14, then the relation between the coordinates of the anchors and the coordinates of the crossing point with respect to the four radii is given as follows [60]:

![Figure 14. Spherical multilateration example](image-url)
The location of the unknown in figure 1 can be deduced from equation (13) when solving for \( X, Y \) and \( Z \) through a set of equations formed when subtracting \( R_{n-1} - R_n \) in order to eliminate \( X \) or \( Z \) parameters accordingly. For example, subtraction of \( R_2 \) from \( R_1 \) will result in the following:

\[
R_{n-1}^2 - R_n^2 = (X - X_{n-1})^2 + (Y - Y_{n-1})^2 + (Z - Z_{n-1})^2 - (X - X_n)^2 + (Y - Y_n)^2 + (Z - Z_n)^2
\]  

(14)

Equation system (14) can be expressed in the form \( A \cdot X = b \) where

\[
A = 2 \times \begin{bmatrix}
(X_n - X_1) & (Y_n - Y_1) & (Z_n - Z_1) \\
\vdots & \vdots & \vdots \\
(X_n - X_{n-1}) & (Y_n - Y_{n-1}) & (Z_n - Z_{n-1})
\end{bmatrix}
\]

\[
b = \begin{bmatrix}
X_n^2 - X_1^2 + Y_n^2 - Y_1^2 + Z_n^2 - Z_1^2 - R_n^2 + R_1^2 \\
\vdots \\
X_n^2 - X_{n-1}^2 + Y_n^2 - Y_{n-1}^2 + Z_n^2 - Z_{n-1}^2 - R_n^2 + R_{n-1}^2
\end{bmatrix}
\]

\[
X = \begin{bmatrix}
X \\
Y \\
Z
\end{bmatrix}
\]  

(15)

The system in equation (15) is over-determined, that is there are more equations than unknowns, and it may be solved by least square estimation (LS) method as discussed in [49, 59-61]. In the above example, the LS method gives the location of the unknown node as follows:

\[
X = A(A^T \cdot A)^{-1} \cdot A^T \cdot b
\]  

(16)

The LS method can reduce the error in the position estimate since it provides the best fit for which the sum of the square of errors between an estimated and a real position attains a minimum value [49, 59-61].

In general, multilateration is considered to be more accurate than trilateration but it involves a higher computational overhead.
2.4 Well-known WSN localisation algorithms

In the previous section, some of the basic concepts of localisation were introduced. This section contains a brief description of a number of well-known range-based and range-free localisation algorithms.

2.4.1 Ad Hoc localisation system

The authors of the Ad Hoc Localisation System method (AHLoS) [59, 61] proposed a distributed localisation technique where unknown nodes can find their position using a limited fraction of anchor nodes. Localisation is based on range information however extensive experiments were carried before deciding whether to use RSS range information from radio frequency signals or ToA ranging data from ultrasound signals. The experiments showed that RSS-based ranging was less accurate than ToA-based ranging as therefore only the latter was used in the localisation process.

In the AHLoS algorithm, nodes that are within communication range of each other, referred as neighbouring nodes, first estimate the distance among them using ToA. Then those unknown nodes, that have established a direct communication link with at least three anchors, can compute their position using the basic multilateration technique discussed in section 2.3. In the AHLoS method this is known as atomic multilateration an example of which is shown in figure 15.

![Figure 15. Atomic multilateration](image.png)

Once the unknown nodes, which were able to find their position, have done so, they become anchors they were used in the localisation process to allow for other unknown nodes to find
their position. This “chain reaction” is continued until all nodes in the network have established their position. The “chain reaction” is described in the literature as iterative multilateration is depicted in figure 16 whereas the unknown node UN₁ is in direct contact with 4 anchor nodes AN₁, AN₂, AN₃ and AN₄ and therefore its position can be estimated using atomic multilateration. On the other hand the unknown node UN₂ is in contact with only two anchors AN₃ and AN₄ and the unknown node UN₁. After UN₁ has been localised, it can act as an anchor enabling UN₂ to estimate its own position using iterative multilateration.

![Diagram of iterative multilateration](image)

Figure 16. Iterative multilateration

Simulation results have shown that when 45 unknown nodes and 5 anchors are placed in a square grid of side 15 meters, the estimated positions based on ultrasound signals can be within 20cm of the actual positions [59, 61].

AHLoS is a localisation scheme that is prone to errors due to the fact that it employs unknown nodes that become anchors through the localisation procedure. However the authors of AHLoS claim that this error accumulation can be controlled and reduced due to the accuracy of the ranging technique used which as indicated above is based on ToA with ultrasound signals [59, 61].

2.4.2 DV-Hop algorithm

The DV-Hop algorithm is a range-free method that allows estimating the position of the unknown nodes based on the number of hops between all nodes and the Euclidean distances between anchors [54,62,120-122]. In DV-Hop localisation, anchor nodes broadcast their locations through the network and compute the minimum number of hops along the routes between each of the anchors. Then the Euclidean distance amongst the anchors is determined.
and the average distances per hop for each of the routes among the anchors are evaluated [54, 62, 120-122].

The average hop-size (CF) between anchor i with coordinates \((X_i, Y_i)\) and anchor j \((X_j, Y_j)\) is estimated by the anchors as follows:

\[
CF_i = \frac{\sum_{j \neq i} \sqrt{(X_i - X_j)^2 + (Y_i - Y_j)^2}}{\sum_{j \neq i} h_{ij}}
\]

(17)

where \(h_{ij}\) is the number of hops between the anchors

The average hop-size, \(CF_i\), is then multiplied by the number of hops between the anchors and unknowns to provide an estimate of the distances between the anchors and the unknowns. These distances along with the coordinates of the anchors are then used within multilateration to find the positions of the unknown nodes.

A simulation result from the implementation of the DV-Hop localisation algorithm is shown figure 17. In this case the average hop size was estimated using Disjkstra algorithm that gives the minimum hop count between anchors [120-122].

![Figure 17. DV-Hop localisation](image)

What can be seen in figure 17 and indeed in numerous other examples in the literature [120-122] is that unknown nodes with the highest number of hops to the anchors result in position estimates with the highest degree of error compare to those with lower number of hops. This is justified by the fact that DV-Hop distances are only an approximation of the straight line distances between anchors and unknowns and the higher the number of hops the higher the
built up error in DV-Hop distances resulting in significant degrading of the localisation results [120-122].

2.4.3 DV-Distance algorithm

The DV-Distance algorithm is closely related to DV-Hope method but it uses the sum of neighbour-to-neighbour distances in place of hop count to derive range information between anchors and the unknowns [61, 62, 121-122].

The average DV-Distance size $D_v$, between anchor $i$ with coordinates $(X_i,Y_i)$ and anchor $j$ $(X_j,Y_j)$ is estimated by the anchors as follows:

$$D_{v_{ij}} = \frac{\sum_{j \neq i} \sqrt{(X_i - X_j)^2 + (Y_i - Y_j)^2}}{\sum_{j \neq i} d_{ij}}$$  \hspace{1cm} (18)

where $\sum_{j \neq i} d_{ij}$ is the sum of the Euclidean distances between all nodes on the route from one anchor to another.

Once anchors compute the DV-Distance size they broadcast this information to the unknown nodes. This allows unknown nodes to use DV-Distance size and the coordinates of the anchors within multilateration to find their positions. A simulated example of a DV-Distance method is shown in figure 18.

![Figure 18. Simulated DV-Distance localisation](image)

Figure 18 shows similar trends as in the DV-Hop algorithm whereas; the further an unknown is from an anchor, the highest the deviation of the position estimates from the true positions. Analogous results were observed through simulations in [61, 62,120-122] with the authors.
pointing out that DV-Distance localisation is highly susceptible to the accuracy of the methods used to derive range estimates.

2.4.4 Iterative localisation algorithms

The authors of [55, 56] propose a method for node positioning based on Maximum Likelihood (ML) estimation. Here the ML technique is used to allow for the computation of position estimates given pair-wise distances amongst the nodes, which are derived from RSS measurements.

The algorithm discussed in [55, 56] is based on distance estimates derived from an empirical radio model derived through an extensive experimentation. Equation (19) next is a modified version of the log-normal shadowing equation presented in section 2.2.2 and shows how the RSS distance $\hat{d}_{i,j}$ is derived:

$$\hat{d}_{i,j} = d_0 \times 10^{\frac{P_i - P_j}{10n}} = d_{i,j} \times 10^{\frac{X_0}{10n}}$$

where $d_0$ is the reference distance in meters (1m), $P_0$ is the received power in free space (watts), $P_{i,j}$ is the RSS power at i received from transmitter j (watts), $n_r$ is the path loss exponent, $X_0$ is a random variable with zero mean and $\sigma^2$ variance representing the standard deviation in RSS measurements due to log-normal shadowing, $X_0=N(0,\sigma^2)$, $d_{i,j}$ is the theoretical Euclidean distance between a transmit point $j(X_t, Y_t, Z_t)$ and a receive point i ($X_i, Y_i, Z_i$) given as follows:

$$d_{i,j} = \sqrt{(X_i - X_j)^2 + (Y_i - Y_j)^2 + (Z_i - Z_j)^2}$$

The ML relative location estimation $\hat{\theta}_R(x, y)$ for the RSS case is given by equation (20):

$$\hat{\theta}_R = \arg \min_x \sum_{i=1}^{m+n} \sum_{j \in H(i,j;0)} \left( \ln \frac{\hat{d}_{i,j}}{d_{i,j}} \right)^2$$

where $m$ is the number of reference nodes, $n$ is the number of the unknown nodes, $H(i,j;0)$ is the number of neighbouring nodes that device i detected.
The minimum value of equation (20) is obtained using an iterative conjugate gradient algorithm. Here, the algorithm takes the true positions of the nodes under concern from which it derives the Euclidean distances and the distances derived through RSS measurements and then through an iterative approach it returns the positions at which equation (18) reaches a predetermined convergence point.

The localisation algorithm in [55, 56] was implemented in practise in a wireless sensor network test-bed of 56 nodes deployed in an indoor office area 16 m by 14 m. Results showed the average location error for all 40 unknown devices to be 2.1 meters. Of the 33 devices located inside the rooms, 22 were estimated to be within the correct room with the other 11 nodes estimated to be either in the immediately neighbouring room or in the hallway just outside the correct room. The maximum localisation error, in all cases, was found to be 4.2 m and the minimum error 0.12 m.

Another iterative minimisation algorithm is discussed in [12] although, in this case, position estimates are derived based on distances out of TDoA data. First of all, TDoA data are converted into distance differences, \( \Delta d \), using equation (5).

The distance difference \( \Delta d_{ij} \) (\( \Delta d_{ij} \approx d_i - d_j \)), can also be computed in theory using the Euclidean distances between a transmitter position at \((X_t, Y_t, Z_t)\) and the \(i^{th}\) and \(j^{th}\) receiving antenna by applying Pythagoras theorem into Cartesian coordinates as follows:

\[
\Delta d_{ij} = \sqrt{(X_i - X_j)^2 + (Y_i - Y_j)^2 + (Z_i - Z_j)^2} - \sqrt{(X_i - X_j)^2 + (Y_i - Y_j)^2 + (Z_i - Z_j)^2}
\]  

(21)

Both the experimental and the theoretical distance differences profile values are then used into an objective function:

\[
F(X, Y, Z) = \arg \min_{x, y, z} \sum_{i=1}^{N} \sum_{j=i+1}^{N} f_{ij}^2(X, Y, Z)
\]  

(22)

where \( f_{ij}^2(X, Y, Z) = (c \cdot \Delta t_{ij} - \Delta d_{ij})^2 \)

The values of \( X_{ij}, Y_{ij} \) and \( Z_{ij} \) minimising the objective function in (22) are taken as the final position of the node to be localised. To solve (22), a quasi-Newton algorithm was used with
initial estimates for \(X_t, Y_t\) and \(Z_t\) being the coordinates of the geometrical centre of the room were the mobile unit is situated.

2.4.5 Centroid algorithm

Centroid algorithms [58, 63] are range-free and compute the coordinates of an unknown node, \(U_n\), by taking the centroid of the positions of two or more anchors with which the unknown node can establish a direct communication link. The coordinates of an unknown node are calculated via equation (23).

\[
\text{UN}_i(x,y) = \frac{1}{n} \sum_{j=1}^{n} \text{AN}_j(x,y)
\]  

(23)

where \(n\) is the number of anchors with which an unknown has direct link and \(\text{AN}_j(x,y)\) denotes the coordinates of the anchors.

A parameter of interest in the centroid algorithm is the connectivity metric \(CM_i\) [4]. Here each anchor periodically transmits a beacon advertising its position. Further, it is assumed that unknown nodes know the periodicity of the beacons from each anchor and so the unknowns can measure the number of beacons received in a fixed time interval [4, 37]. Each unknown node can compute the connectivity metric \(CM_i\) for each anchor node \(i\) over time period \(t\) using the following:

\[
CM_i = \frac{N_{\text{recv}}(i, t)}{N_{\text{sent}}(i, t)} \times 100
\]  

(24)

where \(N_{\text{recv}}(i, t)\) is the number of beacons received from anchor \(i\) in time \(t\) and \(N_{\text{sent}}(i, t)\) is the number of beacons sent by anchor \(i\) in time \(t\).

Figure 19 demonstrates a simulation result, generated by the author using MATLAB using five anchors, depicted with green circles, and three unknown nodes, depicted with yellow circles. What can be seen in figure 19 is that unknown nodes with number 2 and 3 have links to three or four anchors and as such their positions are given (red circles with respective number) as the centroid of those anchors. On the other hand, unknown node 1 has a link only to one anchor, anchor 2, and as such the position of this unknown node is given at the exact position of anchor 2, based on equation (23) resulting in higher localisation errors.
The authors of [63] have conducted an experimental evaluation of the centroid algorithm in a 10mx10m outdoor car park using one unknown node and four anchors. The square parking lot was subdivided into 100 1mx1m smaller grids and measurements were taken by placing the unknown node at each of the 121 intersection points of the gridded area, whilst the four anchor nodes were positioned at the four corners of the car park. In the above experimental set up, anchors transmitted their coordinates every two seconds and all grid points had a link to at least one anchor with a connectivity metric of 90% or more. The average localisation error for all 121 points was 1.83m with the minimum error being 0m and the maximum 4.12m [63].

2.4.6 Weighted centroid localisation (WCL) algorithm

The WCL method [58, 64] is an enhancement to the basic centroid algorithm that provides a more accurate approach to find the position of an unknown node, given the latter can successfully communicate with two or more anchor nodes. The WCL method uses distances derived from RSS or TDoA measurements, as weighting factors applied in the basic centroid calculation.

The algorithm calculates the position of unknown nodes by averaging the weighted sum of the coordinates of the anchors with which an unknown node has links to. The weighting factors are related to the estimated distance $d_{ij}$ between anchor $j$ and unknown node $i$ as follows:

$$\sum_{j=1}^{n} \frac{w_{ij} \times AN_{j}(X, Y)}{\sum_{j=1}^{n} w_{ij}}$$

(25)
where \( w_{ij} = \frac{1}{d_{ij}} \), \( d_{ij} \) is the estimated distance between anchor \( j \) and unknown node \( i \).

WCL was examined, by the author, using the same simulation scenario of anchors and unknowns seen in figure 19. A comparison between the results seen in figure 19 and those in figure 20 revealed that, as long as an unknown node has links to more than one anchor, then the WCL is more accurate than the simple centroid approach.

![Figure 20. WCL localisation](image)

The WCL was evaluated both with simulations and experimental measurements in an outdoor space [58, 64]. In both cases four anchor nodes were placed at the corners of a 43mx43m area that was subdivided into grids and measurements were taken between the anchors and the unknowns inside this area. The average localisation error from all the grid points given by the simulations was 2.6m whilst the experimental error was 5.3m.

The reason why the experimental localisation error was higher than the theoretical value lies in the fact that the distance weights used in WCL were derived from RSS measurements that include real time noise parameters (shadowing). On the other hand, in simulations, noise parameters where introduced randomly and could not account for an accurate representation of a real noise environment [58, 64].

### 2.4.7 Ecolocation algorithm

The Error Controlling Localisation (Ecolocation) method, like many other WSN localisation methods, uses RSS, from a number of anchors, at an unknown node to estimate the position of the unknown node [124]. However, it does not employ the log normal law to associate RSS with distance as discussed in Section 2.2.2. Instead, each node orders the RSS received from
in-range anchors and assumes that the anchor producing the highest RSS is nearest, that producing the next highest RSS is second nearest etc.:

\[ R_i > R_j \Rightarrow d_i < d_j \]  \hspace{1cm} (27)

where \( R_{i(j)} \) is the RSS at the unknown node due to a transmission from anchor \( i(j) \), at distance \( d_{i(j)} \) from the unknown. This ordering is used to compute an \( \alpha \times \alpha \) measurement matrix \( M \), where \( \alpha \) is the number of in-range anchors at the unknown:

\[ M_{ij} = \begin{cases} 
1 & \text{if } R_i < R_j \\
0 & \text{if } R_i = R_j \\
-1 & \text{if } R_i > R_j 
\end{cases} \]  \hspace{1cm} (28)

The echolocation algorithm required that an unknown grid is superimposed upon the environment in which the WSN is deployed. Since the coordinated of each grid point are known, and the coordinates of each anchor are known, then the unknown can compute an \( \alpha \times \alpha \) constraint matrix \( C \) at each grid point:

\[ C_{ij} = \begin{cases} 
1 & \text{if } d_i > d_j \\
0 & \text{if } d_i = d_j \\
-1 & \text{if } d_i < d_j 
\end{cases} \]  \hspace{1cm} (29)

i.e \( C_{ij} \)'s value is set dependent on the relative distance of the grid point with respect to anchors \( i \) and \( j \). This procedure results in a constraint matrix at every grid point. The measurement matrix \( M \) is then compared, on an element-by-element basis, with each constraint matrix \( C \) and the position on the grid with the highest number of matching constraints is taken to be the position of the unknown. If several grid points have the same number of matches, then the centroid of these points is taken to be the location of the unknown [124].

Both the measurement and constraint matrices encode information about the distance of a point (the unknown or grid point) to the set of anchors. The location of the unknown is then chosen on the basis of the grid point whose anchor distance information matches its own most closely [124]. Hence, although multipath/shadowing effects might cause individual contradictions the inequality in equation (27) holds. This ‘majority view’ potentially provides the algorithm with a degree of robustness to multipath effects. The disadvantage of the method is its computational cost. As the grid size is reduced to provide finer resolution, the
effort of computing the constraint matrices, and matching them against the measurement matrix, increases rapidly [124].

A simulation example of the Ecolocation algorithm is shown in figure 21. In this case, nine anchors A1 to A9 are placed on a grid 10×10 whilst the position of the unknown node denoted by the letter P is situated outside the grid (figure 21).

![Ecolocation position estimate](image)

**Figure 21. Ecolocation position estimate [124]**

In the scenario depicted in figure 21, it was assumed that RSS at the unknown node P, from each of the anchors A1 to A9, were directly proportional to the distances of the anchors to the unknown. As a result, unknown node P ranked the anchors, it can communicate with, as follows: A1,A2,A3,A4,A5,A6,A7,A8,A9 and used this ranking to set the constraints in equations (28) and (29). As expected, the location of the unknown node P was given by Ecolocation at point E, indicated by a red star, in figure 21.

The accuracy of Ecolocation was evaluated using experimental data from MICA 2 notes that were placed in indoors and outdoors spaces. Outdoor measurements took place in a car park with eleven nodes randomly distributed over a 144 m² area. At any one time one of the nodes acted as unknown to record RSS, from the rest of the nodes, that were considered as anchors. In this case, absolute localisation error, using Ecolocation, varied from 4m up to few cm. On the other hand, indoor tests took place in an office building 120m² using twelve MICA nodes randomly distributed. Implementation of Ecolocation using data from indoors tests gave errors of more than 1m [124]. Discrepancies in errors were attributed to the amount of obstructions in the line of side between nodes (more obstructions in indoors space- higher errors) and to the orientation of the antenna nodes with respect to each other [124].
Overall it was observed that Ecolocation can provide relative accurate position estimates as long as fluctuations in RSS do not alter significantly most of the set constraints between distances and RSS \[124\].

2.5 Summary

This chapter introduced basic localisation and ranging techniques and has described a number of localisation algorithms that use range and range-free localisation approaches.

A thorough review of both of ranging and range-based localisation revealed that in all cases the quality of the received signals determine the accuracy of the results. To start with, if signals are severely affected by noise this will cause discrepancies in computation of range estimates. Ranging based on RSS can be highly erroneous especially if measurements are taken in indoors areas were multipath is more intense and if the nodes assumed orientations that have negative impact on signal radiation. On the other hand ranging based on ToA and especially TDoA gives more accurate range estimates since times are not affected by major fluctuations as in the case of signals’ amplitude. In the case of TDoA, the use of multiple receive antennas adds diversity to the receive signals thus improving the probability to receive signals least affected by noise.

Of particular interest is the observation that as the number of anchors, an unknown node can communicate with, increases then localisation accuracy increases as well. This is an important observation that can provide a straight forward solution in cases were unknown nodes might be far from anchors i.e increase the number of anchors to extend network coverage thus increase accuracy.

The following chapters present a number of ranging and localisation methods that implement methods discussed in this chapter.
CHAPTER 3
UWB TECHNOLOGY FOR RANGING AND LOCALISATION

3.1 Introduction

To a large extent, research reported in this thesis is concerned with UWB-based techniques for ranging and localisation. This chapter provides relevant background, specifically a review of UWB technology and its application for ranging and localisation purposes.

The chapter begins with an overview of UWB wireless technology and how this compares with other forms of wireless systems. This is followed by a brief consideration of the effect that UWB antennas have on the propagated signals, both at the transmitting and receiving end as this is relevant to some aspects of the research reported in this thesis. A literature review of UWB-based ranging and localisation is then presented.

3.2 UWB technology

UWB systems propagate trains of ultra-short pulses (monocycles) that have widths ranging between 0.5ns to 1.6ns and pulse-to-pulse intervals between 25ns and 1000ns; thus the duty cycles of UWB signals are very low [99]. A typical 0.5ns single monocycle is shown in figure 22 whilst a pulse train with 25ns pulse intervals is shown in figure 23. Note that figures 22 and 23 depict ideal pulses, generated in MATLAB, without considering noise.

![Figure 22. 0.5ns monocycle](image1.png)
![Figure 23. Train of 0.5ns pulses](image2.png)
The mathematical representation of the monocycle seen in figure 23 is the first derivative of the Gaussian pulse that given as follows [94]:

\[
V(t) = \left( \frac{2t}{\tau^2} \right) e^{-\left( \frac{t}{\tau} \right)^2} 
\]

(30)

were \( \tau \) is the pulse width and \( t \) is the period of the pulse

UWB pulses lie within a spectrum between 3.1GHz and 10.6GHz or occupy an absolute bandwidth (BW) that is greater than 500MHz or have a fractional (BW\(_{frac}\)) greater than 20% [80-82, 90]. BW\(_{frac}\), is given as follows:

\[
BW_{frac} = \frac{2\times (BW)}{f_H + f_L} = \frac{2\times (f_H - f_L)}{f_H + f_L} 
\]

(31)

where \( f_H \) is the highest frequency component in the signal and \( f_L \) is the lowest frequency component measured from the -10dB point (figure 24)

The frequency spectrum of a typical 0.5ns UWB pulse is shown in figure 24 where the BW exceeds 500MHz.

![Figure 24. Wide-band time spectrum](image)

The large BW of UWB signals is advantageous compare with Narrow Band (NB) signals since according to Shannon’s theorem the higher the BW the higher the channel capacity, thus larger amounts of data can be transmitted [98, 100]. Based on Shannon’s theorem UWB systems are suitable for multimedia and video surveillance applications over short distances [70-72, 98].
The complexity and the cost of UWB systems is reduced by the fact that data can be transmitted directly over UWB signals without the need for an extra hardware to perform modulation at higher frequencies as in NB systems. Data modulation in UWB systems is typically carried out using pulse position modulation (PPM) [65]. A further advantage of UWB radio is that no other communication system operates in the same frequency band thus minimising interference. This gives rise to a wide range of UWB applications in areas such as multimedia entertainment and the use of UWB-based sensor networks for maintenance inside aeroplanes as well as the use of wireless UWB-based sensors for patient monitoring inside hospitals [71-72, 96].

The lack of interference between UWB and NB systems is emphasised in figure 26. This shows the power spectral density (PSD) over frequency for UWB and for five common NB systems, GPS, global system of mobile (GSM) phone network, Wi-Fi, wireless local area network (WLAN) and ZigBee. What can be seen in figure 25 is that, other than the fact that UWB systems operate at a different frequency band than the NB systems, the PSD of UWB is very low that is seen as noise floor to NB communication thus further reducing the possibility for interferences from UWB [80, 83].

![Figure 25. Narrow-band and UWB spectrum coverage (adapted from [83])](image-url)

The short duration of the UWB pulses improves their endurance within a dense multipath environment since, in contrast to narrow-band signals, UWB pulses do not overlap with each other [65, 66, 69, 80]. The reception of UWB signals without any overlapping amongst the signals makes it easier to resolve the time of arrival of the leading edges in a method that will be discussed in further detail in chapters 4 and 5.
The properties of UWB transmissions discussed above make it attractive for use in WSNs. To this extent, the Institute of Electronics and Electrical Engineering (IEEE) developed the IEEE 802.15.4a standard for low rate wireless personal area networks (LR-WPANs) [79-81]. The objective of the IEEE 802.15.4a standard was to ensure robust data communication over long distances as well as to provide enhanced positioning capabilities all with minimum interferences to and from existing NB-systems [79-81].

3.3 UWB antenna and their impact on ranging and localisation

Much of the work in this thesis is concerned with a UWB-based positioning system. A key aspect of this, and other similar systems, is the detection of the leading edge (LE) of UWB pulses as they arrive at the receiving antennas. The LEs are considered to be the least affected by multipath and as such are widely used to allow for accurate ranging and localisation. A review of UWB systems revealed that the antennas employed have a significant effect on the propagated UWB pulses, and these effects need to be discussed in order to understand the form of the received signal whose LE is sought in ranging and localisation applications [84-94].

Antennas radiate electromagnetic energy when presented with current at their input (transmitting) or convert electromagnetic energy to current when used for receiving [89, 94]. A magnetic field (B) is induced by the antenna at point P whilst current \( i(t) \) flows through it, as given by the Biot-Savart law [30]:

\[
\vec{d}B = \frac{\mu_0 i(t) dL \sin \theta}{4\pi R^2}
\]

(32)

where \( \mu_0 = 4\pi \times 10^{-7} \) H/m and denotes the permeability of free space (magnetic constant). \( R \) is a distance of point P from current source, \( \theta \) is the angle between the point and the antenna element, \( B \) is the magnetic field and \( dL \) is a differential element of the antenna of length \( L \) as seen in figure 26.
If the current through the antenna varies with time, then the magnetic field varies with time, giving rise to an electric field via Faraday’s law. The electric field due to equation (32) is given as follows [94]:

\[
\mathbf{d} \mathbf{E} = \frac{\mathbf{d} \left( \frac{L}{c} - \frac{R - L \cos \theta}{c} \right) \sin \theta \cdot \mu_0 \cdot d\mathbf{L}}{4\pi R^2}
\]  

(33)

where L is the length of the antenna (seen in figure 26) and c is the speed of propagation of electrons through the space (assumed same speed of propagation through antenna).

The total generated electric field is directly related to the dimensions and the shape of the antenna and as such the total electric field induced in a monopole antenna is [94]:

\[
\mathbf{E} = \frac{\mu_0}{4\pi R^2} \sin \theta \frac{d}{dt} \left( \int_0^L \left[ i \left( t - \frac{L}{c} - \frac{R - L \cos \theta}{c} \right) \right] d\mathbf{L} \right)
\]  

(34)

Equation (34) is representative of an immediate area surrounding the antenna within the near field. In far field, the radiated electric field is taken as [94]:

\[
\mathbf{E} = \frac{\mu_0 c}{4\pi R^2} \frac{\sin \theta}{\cos \theta - 1} \left[ i \left( t - \frac{L}{c} - \frac{R - L \cos \theta}{c} \right) - i \left( t - \frac{R}{c} \right) \right]
\]  

(35)

What can be seen in equation (35) is that the electric field is proportional to the time derivative of the current flowing through the antenna. The impact of differentiation in a narrowband antenna, using continuous signals, such as sine-waves, is limited to phase shifts.
On the other hand, differentiation of UWB pulses results in significant change in pulse shape one or more times depending on the types and number of antenna used [66, 84-94].

An example of the impact of the transmitting antenna on UWB signals is shown in figures 27 and 28 (depicting test cases within an anechoic chamber) [76]. Figure 27 shows a Gaussian pulse transmitted using a cable directly to the oscilloscope without any intermediate antenna being used. On the other hand, figure 28 shows the received pulse but this time transmitted wirelessly using antennas.

The pulse shown in figure 28 is a result of double differentiation of the Gaussian pulse depicted in figure 27 thus verifying that antennas alter the shape of the propagated pulses.

A direct consequence of differentiation of the signals by the antennas is the loss of reciprocity between receiving and transmitting antenna especially in the time domain [76, 84-94]. Another issue of concern, due to the alteration in the shape of the signals, is the detection of the LEs of the received pulses. In cases where a threshold might be used to detect the LEs (discussed in more detail later in this section and in Chapter 5) the process of deriving the threshold should carefully considered alterations in the shape and especially in the time of arrival of the received pulses. An effective threshold and an accurate representation of the LEs are important parameters that can determine localisation accuracy [128, 104, 107].

The fact that propagated UWB pulses undergo significant change (due to the antenna) and lose their original shape is not the only issue of concern. Another factor affecting UWB pulses is the ringing effect that again is attributed to the antennas [90-92]. A major cause of ringing is the fact that pulses propagating through the antenna, from the feeding point to the
end of the antenna, are reflected within the antenna numerous times. As a consequence, signals travel back and forward to the source leading to the formation of standing waves that in turn causes antenna to radiate for a time period exceeding the period of the original pulse fed into the antenna. Examples of ringing, from literature, are shown in figure 29.

![Figure 29. UWB antenna ringing effect [26, 92]](image)

Mismatches between the antenna and the transmission lines, mechanical disparities in the construction of the antenna, its dimensions, especially with respect to the ground plane, can further strengthen ringing effects [90-92].

### 3.3.1 Antenna orientation

Research on range estimation and on range-based localisation showed that multipath is a major cause of errors in both cases. In addition research revealed that the orientation of the receiving antenna with respect to the transmitter’s antenna can have a considerable impact on the accuracy of ranging and localisation [73-75].

Work presented in [73] used one transmitting and one receiving UWB antenna at different angles to examine the effect of antenna orientation on the propagated UWB pulses. A relative orientation of 0° along the azimuth and elevation plane, with the two antennas facing each other, was used as a reference to compare pulses resulting from other angles of orientation. The degree to which received pulses, at a reference orientation of 0° differ from the any other orientation was examined using cross-correlation. Cross-correlation between the pulse at 0° and received pulses at orientation 90°in both the elevation and the azimuth plane is depicted in figure 30.
Cross-correlation plots, in figure 30, indicate that the received pulses were distorted according to the relative orientation between the receiving and the transmitting antenna.

Analysis presented in this section highlights the need for orientation issues to be examined carefully when setting up ranging and localisation systems.

3.4 UWB-based ranging and localisation review

UWB technologies have been used for ranging and localisation in areas such as asset monitoring onboard ships, vehicle sensing, clinical and military applications and the monitoring of industrial processes inside vessels, with reported accuracies reaching 5cm or less [65,67,71,76, 96].

Although there is a plethora of research on UWB technologies analysis of relevant systems is primarily carried out through simulations. This section presents a number of UWB-based ranging and localisation methods that were implemented and evaluated through experiments and present aspects closely related to the research discussed in this thesis.

3.4.1 Basic features of UWB-based ranging and localisation applications

The majority of UWB-based ranging and localisation methods employ a similar set of steps. These include the detection of the LEs, the derivation of ToA or TDoA and the actual ranging and localisation approaches. In most scenarios ToA and TDoA data are derived through post-processing of received signals (i.e cross-correlation) by an algorithm running in MATLAB.
The use of the LEs, to derive ToA and TDoA, has been proven to enhance ranging and localisation accuracies; since these represent a portion of the received signals that arrive first at the receiving antenna and that are least affected by noise. Consider for example the simulated received UWB signal in free space conditions shown in figure 31, the peak of this signal denotes the LE of the signal and is clearly identifiable. On the other hand, figure 32 shows a received signal (captured using a high-speed sampling oscilloscope), in an indoors space, using a receiving antenna situated at 12.8m from a transmitter.

![Figure 31. Received signal in free space][67]  ![Figure 32. Indoors received signal][67]

Figure 32 shows that the experimentally received signal is significantly distorted by multipath, thus making the identification of the LE much more difficult.

The following applications follow similar approaches towards implementing ranging or localisation (use ToA or TDoA) with differences concentrated on the methods used to derive the LEs of the received signals.

### 3.4.2 UWB-based ranging and localisation applications

The authors of [65] developed a prototype UWB system, based on TDoA, for potential use in navigation sensors attached to vehicles. The experimental system is shown in figure 33.

The antennas used in the tests were modifications of the Vivaldi antenna (figure 33) in terms of having two extended circular apertures seen in figure 33, rather than long straight radiation apertures [65] as in conventional Vivaldi antennas. The authors of [65] claimed that the modified antennas were more efficient since they were able to reduce ringing (discussed in section 3.3) given the reduction in the antenna’s area reduced the amount of internal reflections.
The transmitted data was an 8-bit binary pseudo-random code generated by a field programmable gate array (FPGA). The pseudo-random code was generated at specific clock cycles and was directed via wire links to both the DSO and to the pulse generator [65]. As such, the pulse generator was triggered to generate 3ns pulses at the times at which the pseudo-random code was present at its input. The DSO was triggered at specific time intervals to allow for a sampling window that enabled incoming received signals to be captured. Received pulses were saved in the oscilloscope for further processing using MATLAB [65].

Measurements were taken inside an anechoic chamber using one transmitting and one receiving antenna placed at different distances one from the other with one of these (1m) being selected as a reference [65]. Signals received at 1m reference distance were correlated with signals obtained at other separations to obtain TDoA data as discussed in section 2.2.1. Both correlation and range estimation were carried out using dedicated algorithm running in MATLAB. At this stage, it is important to note that since tests were carried out inside an anechoic chamber there was no significant noise affecting the received signals and as such there was no further signal processing, instead the complete raw received signals were passed into the correlation procedure [65].

Measurements were taken at five non-reference distances between the transmitter and the receiver with resulting in an average error of 0.12cm and STD of 0.251cm [65]. Overall, it has to be noted that the employed ranging method served as a proof of concept only as it was
evaluated solely on tests inside an anechoic chamber thus overlooking noise that can exist in real world applications that can affect range accuracies.

Research presented in [66] used UWB technology to develop a positioning system to find the locations of soldiers both inside buildings and outdoors. An experimental setup was established where a number of fixed anchor beacon (anchor) transceivers and one rover (unknown) transceiver as seen in figure 34.

![Figure 34. UWB positioning system [66]](image)

Each transceiver consisted of a low power pulse generator for signal transmission and analogue components (low noise amplifier (LNA)) and a digital circuit to detect the LEs of the received signals [66].

This digital circuit was so configured, using a digital phase lock loop, to allow a pulse to go through it only for a time period equal to the duration (width) of the propagated pulse [66]. Further, the LE detection circuit periodically checked the noise level of the received signals, through a constant false alarm rate (CFAR) loop, and set a threshold above which the detection circuit was triggered ON thus reducing false leading edge detection [66].

The unknown node broadcasted a sequence of UWB pulses that included a short message containing its ID to the anchors. Anchors that have received a signal from the unknown node transmitted a message back to it but at different time intervals (labelled as time offsets $\Delta_i$), pre-assigned to them, in order to avoid signal collisions [66]. In turn, the unknown node performed subtraction between the time offset $\Delta_i$ of the anchor to the time $\Delta_t$ taken for signal
to travel from the unknown to the anchor and back. The outcome of the subtraction in essence represented the TDoA that when multiplied by speed of light gave distance differences that used within a multilateration algorithm to derive the positions of the unknown nodes [66].

Tests with the above system were carried out in both indoor and outdoor environments. In the experimental procedure, the unknown node was placed at eleven different positions around the test area and data were recorded for about 10 seconds and each position. The positioning error in the indoor tests was between 15cm and 90cm whilst for outdoor tests the error remained below 15cm [66].

A prototype UWB-based positioning system, known as the precision asset location system (PAL), was developed in [67] to determine the position of items of cargo on-board ships. Tests were performed over a period of two weeks on a cargo hold (24.4m width, 30.5m length and 8.23m height). Test objectives included evaluating the capability of UWB signals to propagate through dense multipath environment of the ship and to what degree the accuracy of UWB-based localisation was affected in partial LOS blockage in the presence of containers.

The experimental setup consisted of four passive UWB receiving modules, placed at the edges of the testing area, and a number of tags, powered by batteries, that transmitted UWB pulses at 0.25mW. The tags were situated at different locations in the testing area and their positions were measured using a tape measure and a laser surveying system that could achieve 2 to 4mm accuracy. The experimental architecture of the PAL system is shown in figure 35.

The receiving modules were equipped with digital circuit that allowed detecting the ToA of the LEs. The ToA data were then forwarded to a central PC via a wired link (figure 35) were an algorithm running in MATLAB was used to compute TDoA. Once all the TDoA data had been calculated, the positions of the tags were computed using an iterative minimisation algorithm discussed in section 2.4.5.
Measurements revealed that delays spreads, that characterise multipath, were of the order of 3µs in contrast to the typical 300ns delay spread recorded in office and industrial premises. Large delay spreads close to the LE make the detection of LEs more difficult thus jeopardising positioning accuracies [67]. The relative large delay spreads were caused by the presence of metal surfaces and objects in the vicinity of the measurement equipment [67]. The positioning accuracy in the absence of containers was between 0.9m to 1.5m whilst positioning accuracy in NLOS tests, in the presence of containers, was between 3.35m and 3.66m [67].

Work in [76] presented positioning tests inside a typical electronics laboratory. This work attempted to investigate the accuracy of positioning using a low-cost transmitter. The experimental setup consisted of a PC, a triggering unit and a mobile unit representing the unknown node whose position was to be found. The mobile unit transmitted UWB pulses to four receiving antenna attached on a DSO as shown in figure 36.
The PC initiated the tests by sending a signal to the triggering unit via a wired link (figure 36). In response, the triggering unit transmitted an activation code to the mobile unit. This unit was equipped with a pulse generator which broadcasted a UWB signal in response to the activation code. To ensure an effective synchronisation between the transmitter and the receiver, the triggering unit sent a signal to the DSO (see figure 36) that initiated capturing receive signals from the mobile unit over a fixed interval (sampling window).

Measurements were taken at a number of points by placing the mobile unit at different distances (at intervals of 5cm over a 3m) from the receiving antenna, whilst always maintaining line of sight (LOS) between the receiving antennas and the mobile unit.

Digitised received signals were transferred from the DSO to a PC where a MATLAB based algorithm performed cross-correlation amongst all received signals from each antenna to derive TDoA. An iterative minimisation algorithm, discussed in section 2.4.5, used the TDoA data to compute the position of the mobile unit. The positioning error for all measurements was around 58cm with standard deviation reaching 39cm [76].

The authors of [76] characterised their work as a low cost approach, however, they recognised that the use of the DSO can easily label their title as misleading; thus justifying the low cost on the basis that UWB pulse generators could be assembled using cheap components [76]. Regardless whether the experimental setup was cheap or not, tests both inside and outside the anechoic chamber offered a very good understanding of the efficiency of the whole positioning system. More specifically it was observed that antennas acted as differentiators to the propagated signals; a fact that needs to be carefully considered when processing received pulses [76]. Furthermore, experiments carried out in an electronics laboratory showed that the propagated pulses were distorted by both multipath and by inconsistencies in the generation of the pulses due to a clock drift. The clock of the microcontroller controlled the repetition frequency of the transmitted pulses thus any drifting consequently resulted in jitter in generated pulses (~ns) thus causing inaccuracies in TDoA estimates [76].

Work presented in [101] also investigated the impact of LOS and NLOS conditions on UWB-based ranging in real outdoor and indoor scenarios. Experiments were carried out using two prototype UWB radio modules with 500MHz BW and 4GHz centre frequency that were
placed on the floor of the test areas. In all cases, one UWB transceiver was kept at a fixed origin whilst the second transceiver was placed at various distances from the origin. The distances between the two transceivers were measured with a tape.

Each radio module was connected, via a cable, to a PC that allowed processing digitised received signals. An algorithm, running in MATLAB, detected the ToA of the LEs by recording the time at which the sample with the highest amplitude occurred. This was done for both the transmitting and the receiving sides thus providing estimates of the transmitting and receiving times of the pulses. These time estimates were then introduced within an RTT method (see section 2.2.1) to compute the distances amongst the two modules.

LOS tests were conducted inside a library and in an indoors hallway with doors and walls on the both sides of the radio modules as well as with WiFi transmit points. In addition LOS tests took place in an open field far away from buildings [101]. Further, to investigate office like environments, “LOS” tests were conducted with items having low attenuation such as glass, chairs and doors’ obstructing a 3m LOS path in what was called soft-LOS condition [101]. Tests were performed both indoors and outdoors with the two radios placed at 1m up to 45m distances from each other. In all cases distances were measured using a tape. Figure 37 shows the different test scenarios examined in [101].

![Figure 37. Ranging tests at various scenarios [101]](image)

The average ranging error for indoors LOS tests was less than ±20cm whilst the errors for LOS tests in an open outdoors area was less than 10cm. According to the authors of [101], there were fewer obstacles around outdoors tests thus fewer reflections in the propagated signals and as a result accuracies for outdoors tests were better than those for indoors tests.
Note that “Soft” LOS experiments using glass obstacles resulted in an average ranging error of 6 cm with a single door obstructing the LOS giving the highest error of 29 cm [101].

Tests carried out with concrete walls in between the two radio modules were characterised as hard-NLOS. Average ranging error, in hard-NLOS conditions, fluctuated greatly based on the number of interleave walls [101]. The average error with only one wall was obstructing a 4 m LOS path between the two radio modules was 26 cm with the average error increase to 87 cm when four walls obstructed a 14 m LOS path. Of interest was a test case with eleven walls obstructing a 38 m LOS between the radio modules where ranging failed to work since no signals could be received [101].

The authors of [102, 103] developed a prototype 3D UWB localisation system, based on TDoA, in anticipation that this could be used to track lunar/Mars rovers and astronauts when satellite navigation systems won’t be available.

The experimental setup consisted of two commercially available UWB radio modules with 3.2 GHz BW and 4.7 GHz centre frequency. One of the radio modules was used as a receiver to which five antennas were attached to using a power combiner. The so called “One Receiver-Five-Antenna” configuration aimed at eliminating synchronisation issues that might occur when using numerous receivers together in a TDoA scheme. The receiving antennas were fixed at different heights in an outside yard in a 6.1 m radius circle formation centred on a reference antenna. This formation allowed 3D measurements along X, Y and Z axis. The omni-directional antennas were connected to the power combiner using long low-loss cables. Readings from the receiver module were recorded to a laptop using a MATLAB based GUI [38, 39]. The other UWB radio module was used as a transmitted and was placed on a remote controlled vehicle that allowed taking measurements at different locations [102].

Initial tests aimed at deriving TDoA data. To this extent, the LEs of signals at all received antenna were detected using an algorithm that allowed processing all the digitised signals and indentify the absolute peaks that denote the presence of the LE [102]. The LE of the reference received signal (recorded at a reference distance between the transmitter and the receiver) was then cross-correlated to each of the LEs of the signals from each of the five receiving antenna to derive TDoA data as discussed in section 2.2.1.
At the end, TDoA data were used in a least square minimisation algorithm, running on a laptop, to derive the X, Y and Z coordinates of the transmitter [38]. Experimental investigation of the localisation method in [38], shown that it was possible, to track a moving vehicle, with an UWB transmitter on it, in real time with an accuracy of less than 5cm [102].

A similar work to [102] is discussed in [104-106] where once more a pair of PulsON 210 modules was used to investigate a 2D TDoA based localisation system. Experiments were conducted in a sport stadium (10m x 10m) using four static receiving antennas, situated at the edges of the monitoring area. The antennas were connected, via a power combiner, to one of the PulsON 210 modules that in turn was connected to a laptop. The other PulsON 210 module was used as a transmitter whose position was to be found and was placed at different positions around the centre of the four receiving antenna. Both the receiving antenna and the transmitting module were around 1.5 high from the ground.

TDoA data were acquired by subtracting the ToA for all received signals from the ToA of a signal recorded at a reference transmitter-receiver distance [102]. Work in [102] proposed recording the ToA of LE to derive TDoA. As such, two LE detection algorithms have been proposed in [104], the maximum energy selection with search back (MESSB) and the cell (sample) averaging constant false alarm rate (CA-CFAR) algorithms. These algorithms allowed processing all the samples in the received signals, first to derive a threshold and then to use this threshold to detect the LEs. Note that each algorithm employed different approaches in setting an adaptive threshold based on specific empirical observations. A diagram illustrating the basic principle on which these algorithms are based is shown in figure 38.

![Diagram of LE detection algorithms](image)

**Figure 38. LE detection algorithms [104]**
The CA-CFAR algorithm sets the threshold based on the average of the samples, occurring within a specific time frame, representing the portion of the signal within the LEs most probably lies. This time frame was decided empirically through a thorough analysis of numerous received signals. The time at which the first sample, in the received signal, exceeded the threshold was recorded as the ToA of the LE.

On the other hand, the MESSB algorithm employed search-back window to look for the LE. This algorithm implements the search-back window within the same time frame used for the CA-CFAR algorithm. The boundaries of the search-back window are defined by the time at which the sample with the maximum amplitude occurs and by the time at which the sample with the minimum amplitude occurs. The threshold is then set empirically based on the maximum and minimum value of the samples within the search-back window. Once again the ToA of the first sample exceeded this threshold was considered as the LE of the received signals and used to compute TDoA.

Localisation accuracies, using LOS-based experimental data, revealed that both the CA-CFAR and the MESSB algorithms resulted in almost identical positioning errors varying between 5cm and 19cm. On the other hand, processing of NLOS data, using the CA-CFAR algorithm resulted in better accuracies compared to the MESBB algorithm. According to the authors of [104] the CA-CFAR algorithm contributed in more accurate results because it employed a threshold based on the average of a specific part of the received signal. On the other hand, the MESBB algorithm used a threshold that was derived based on the maximum amplitude of a sample considering that this represents a strong noise-free signal. However, in reality the strongest signal doesn’t always represent a noise-free signal. On the contrary, it was observed that a peak in the received signal especially in NLOS conditions can be a noise spike as a result of multipath [104].

Research in [107] carried out an extensive experimental work to examine whether received signal’s noise floor could be used as a threshold above which to detect the presence of a target obstructing LOS. LOS measurements were taken at a distance of 5.5m (measured using a laser range finder) between one transmit and one receive UWB transceivers device from Time Domain Corporation’s PulsON Application Demonstrator (PAD) kit [109]. Further, NLOS readings were taken using an 0.3m cross-section and 0.72m high steel trash that was placed at different distances from the transmit and receive devices.
Figure 39, in [107], showed a typical case of a received UWB pulse with a very low amplitude noise (background noise) appearing prior to the actual ToA of the pulse.

![Figure 39. Noise floor in a received UWB pulse [107]](image)

Initial measurements in [107] where taken in LOS conditions in order to acquire a “noise-free” signal pattern. Thereafter, NLOS received signals were subtracted from the LOS signals to determine a noise floor reference. The noise floor reference was then used as a threshold whereas any received signals whose amplitude exceeded the noise floor indicated the actual ToA of signal from the obstacle (target) in the NLOS condition. That in turn gave the distance of the target between the receiving and transmitting UWB devices [107]. Nevertheless, it was acknowledged that noise fluctuations can occasionally exceed the noise floor threshold thus resulting in erroneous ToA data [107].

The authors of [107] carried out relevant work to study the impact of multipath on UWB signal propagation. Work in [108, 109] consider possible propagation of UWB signals in indoors and urban environment and carried out tests inside a university office 4.04m by 4.2m. Two PulsON UWB transceivers were used to transmit and receive signals centred at 1.9GHz with a BW of 2GHz. Results shown that signal to noise ratio (SNR) decreased as the distance between the transmitter and the receiver increased. To be more specific for every six meter increase in distance, from 0m to 30.56 meters, the SNR reduced by 20dB reaching a minimum of -60dB at 30.56m.
3.5 Summary

Work presented in this chapter introduced general principles governing UWB technology and expanded in detail in examining UWB technology within the context of ranging and localisation.

Starting from the hardware level, literature review on the antennas, used in UWB systems, revealed that these have a significant role in determining the shape of the propagated pulses, a factor that needs to be closely considered during signal processing leading to ranging and localisation. To be more specific, other than ringing effects and the impact of the relative orientation between the transmitting and the receiving antenna the electromagnetic profile of the employed antennas alters the shape of the propagated pulses.

Overview of practical UWB-based ranging and localisation applications, that employ ToA and TDoA techniques, revealed that their accuracy depends greatly to the signal processing techniques used to derive the LEs of the received signals that in turn are used to compute ToA and TDoA. To this extent, a number of techniques have been proposed centred around capturing the LEs. Analysis of the received signals for each application allowed deriving empirical models usually based on a threshold that was used to detect the LEs. A critical factor in detecting the LEs was the environment within nodes were placed with indoors placement presenting a more challenging situation since noise was significantly higher. Nevertheless, both indoors and outdoors experiments shown that both ranging and localisation can achieve accuracies from 5cm in LOS cases to 90cm in heavily obstructed LOS scenarios.

Information acquired in this chapter provided a good understanding of the basic principles governing UWB-based ranging and localisation methods and laid out the path for the introduction of the localisation methods employed in this research presented in the following three chapters.
CHAPTER 4

PROTOTYPE UWB-BASED LOCALISATION METHOD

4.1 Introduction

The localisation approach discussed in this chapter was developed as part of the WSN4IP project (introduced in section 1.5) and forms the basis of the research in this thesis. The initial version of the system was developed by other members of the WSN4IP team, with the aim of providing high positions accuracies for sensors immersed inside industrial processes as discussed in 1.5. The requirement for accurate localisation inside hostile (increased multipath) radio environment, such as grain silos, led to a localisation system being based on UWB technology and TDoA [26-28]. Indeed, the literature review on UWB-based ranging and localisation techniques, presented in the previous chapter, revealed that UWB systems using ToA or TDoA can provide significantly higher accuracy compared with NB-systems.

The aim of this chapter is to provide an overview of the operation of the prototype system and to report the results of an extensive programme of experiments undertaken by the author. Comparatively few measurements were taken with the prototype system by its developers and so an evaluation of its performance was a necessary first step in the development of improvements that can enhance localisation accuracy.

This chapter begins with an overview of the basic localisation system and continues with discussion of the employed localisation algorithm. The localisation hardware, including the electronic and the mechanical parts, is discussed in section 4.4 with experimental localisation results presented in section 4.5.

4.2 Basic localisation system

The basic localisation system developed in the WSN4IP project was intended to be a research vehicle for investigating the localisation of wireless sensor nodes immersed in a process vessel. Measurements to determine the position of an immersed node are taken in by sensors (in this case antennas) located ‘outside’ the process. Although this scenario is applicable to various industrial processes within containers, the actual system was developed and used for
experiments that concerned the grain storage problem discussed in detail in sections 1.5 and 1.6. However, it would also seem to be appropriate for deriving a node’s position in the biomass system and in nuclear ponds, all discussed in section 1.3.3.

An overview of the grain silo localisation system is shown in figure 40 where it is assumed that the wireless sensor nodes have been distributed throughout the silo. The measurements positions (receiving anchor antenna) were located on a single plane above the silo. The reason for this is that it may be expensive, inconvenient or indeed impossible to place receiving anchors in other locations. Consider for example the grain silo problem. It is certainly difficult and inconvenient to locate receiving antennas on the walls of the silo and suspending them within the main body of the silo thus exposing them to the forces imposed by flowing grain. This is undesirable from the perspective of both the grain flow and the antennas.

The localisation problem in this research was formulated as follows. A node requiring localisation transmits UWB pulses to an antenna array located at the top of the silo as seen in figure 41. The receiving antenna array comprises two orthogonal sets of N evenly horizontally spaced antennas, which define the X and Z measuring coordinate system. Here, for the purposes of TDoA measurements, one of the antennas in the array was treated as a reference (see below). The Y coordinates were measured vertically downwards from the
receiving array. Hence the receiving antenna array was located in the plane \( Y=0 \) which was assumed to coincide with the top of the silo.

The multiple receiving antennas have two roles. The first was to allow signals, from a transmit node, to arrive at different times at each antenna thus setting the basis for TDoA measurements. In addition, multiple receiving antennas offered spatial diversity, which increases the probability that at least some of signals will arrive at the antennas with reduced noise elements thus improving localisation accuracy [26, 27]. TDoA data were used to determine estimates of the difference in the distances between node and receiving antenna i, and the node and the reference receiving antenna.

Distance estimation, using TDoA data, and the prototype localisation algorithm are discussed in more detail in the following sections.

### 4.3 Distance difference estimation

The first stage of the prototype localisation method involved deriving TDoA data via a cross-correlation of the LE waveforms of the received signals since LE represent the portion of the signals that were considered to be less affected by noise, thus enhancing ranging and localisation accuracies, as seen in a number of similar applications discussed in section 3.4.2.

As mentioned above, the WSN4IP UWB transmitter produces a train of Gaussian pulses that are based on the function given in equation (30) in Chapter 3. Figure 41 shows a plot of the second derivatives of such pulse train, generated by a MATLAB program. Based upon the discussion of section 3.3, it is clear that figure 41 represents an idealisation of the received UWB signal.

An example of a real received signal, obtained from the WSN4IP system is shown in figure 42. Comparing the LE in figure 42 to the signal in figure 41, it can be seen that the LE of this signal is a good approximation to the theoretical signal. However, subsequent parts of the signal are contaminated by multipath components. Note that in figure 42, and in all following figures depicting experimental readings, a negative time frame is shown since the reference at the DSO was set on the negative scale instead of starting from zero; without this having any impact on the quality of the measurements.
The prototype localisation method employed a range gate to isolate the LE of the received signals. This LE detection method is called range gate LE detection (RGLED). The range gate is said in [26-28] to be a ‘temporal band-pass filter’ that in essence is a square window used to restrict the part of the signal under consideration to that which could plausibly have arrived over the shortest path from the transmitter, whilst rejecting the rest of the received signal. Range gate parameters, specifically the start time of the window and its duration, determined the portion of the signal to be searched for the LE, which was identified by eye i.e. the LE detection procedure was not automated.

An example of the RGLED implementation for the signal seen in figure 42 is shown below in figure 43.
Once the LEs were isolated, the next step was to obtain TDoA information. TDoA data were derived using cross-correlation of all signals at receiving antennas to signals at the reference receiving antenna as discussed in section 2.2.1.

TDoA data were then multiplied by the speed of signal propagation inside grain to compute distance difference information. For non-reference antenna the distance difference $D$ is given by:

$$D = \Delta t \cdot c_0$$  \hspace{1cm} (36)

Distance difference $D$ represents the distance from the transmitter to antenna $n$ ($R_n$) minus the distance from the transmitter to the reference antenna ($R_0$) as illustrated in figure 4.4. Note that, in accordance to the experimental arrangement, receiving antennas lie on a plane where $Y=0$ whilst a reference antenna $(X_0, Y_0)$ lie at origin of axes at $(0,0)$.

![Figure 4.4. Distance difference diagram](image)

Hence equation (36) can be rewritten as follows:

$$R_n - R_0 = \Delta t \cdot c_0$$  \hspace{1cm} (37)

If the distance of the transmitting node from the reference antenna $R_0$ is known, then it is possible to compute the distances of each of the other receiving antenna to the transmitting node, i.e.
\[ R_n = \Delta t \cdot c_0 + R_0 \]  

(38)

However, none of the distances in equation (38) are known, thus an iterative procedure was adapted that allows estimating distances between the transmitter and the receiving antennas. Distances are then used to derive the position of the transmitter. This procedure is discussed in more detail in the following section.

**4.4 Localisation algorithm**

The prototype localisation algorithm exploits the mathematical relation connecting the distance differences to the coordinates of both of the transmitter and of the receiving antenna to compute the position of the transmitter.

Each distance \( R_n \), in equation (38), effectively defines a circle\(^5\) centred on a corresponding receiving antenna, upon which the transmitting node must lie. In principle, the circles centred on each antenna, on one axis (X or Z) of the receiver array, all intersect at unique point, which defines the X or Z coordinate of the transmitter accordingly. This is illustrated in figure 45. The radii of the circles along X axis (same for Z axis), plotted in figure 45, are given as follows:

\[ R_n = \sqrt{(X_t - X_n)^2 + (Y_t - Y_n)^2} \]  

(39)

where \( X_t, Y_t \) are the coordinates of the transmitter and \( X_n, Y_n \) are the coordinates of the receiving antenna as seen in the following figure.

---

\(^5\) Actually, it defines a sphere. However, the prototype localisation method simply uses circles.
The coordinates of the transmitter can then be derived when solving equation (39) for X, Y and Z using multilateration.

Multilateration involves subtracting the $n^{th}$ from $m^{th}$ equation in equation (39), thus eliminating Y parameters, and solving for $X_t$:

$$X_t = \frac{R^2_{x_n} - R^2_{x_m} + \left(X^2_n - X^2_m - 2 \cdot X_n - 2 \cdot X_m\right)}{2 \cdot (X_n - X_m)} \quad (40)$$

Likewise the unknown $Z_t$ position is derived by subtracting the $n^{th}$ equation from $m^{th}$, thus resulting in:

$$Z_t = \frac{R^2_{z_n} - R^2_{z_m} + \left(Z^2_n - Z^2_m - 2 \cdot Z_n - 2 \cdot Z_m\right)}{2 \cdot (Z_n - Z_m)} \quad (41)$$

Finally, the Y coordinates for X and Z axis are derived by substituting $X_t$ and $Z_t$ independently into (38) and solving for Y:

$$Y_{t_{\zeta}} = \sqrt{\left[R_{\zeta_n} - c_0 \cdot \Delta t_n\right]^2 - \left(\zeta_t - \zeta_n\right)^2} \quad (42)$$

where $\zeta$ is either $X_t$ or $Z_t$ accordingly

A key assumption in the above equations is that the distance $R_0$ from the transmitter to the reference antenna in equation (38) is known. This is not the case, and so a set of assumed values for $R_0$ were introduced in equation (38) to allow estimating distances used in equations (40) to (42). The assumed $R_0$ values span the physically plausible range of $R_0$ based on the size of the vessel used in the experiments. In other words, the localisation calculation is repeated a large number of times for different assumed values of $R_0$. In cases where the assumed value of $R_0$ deviate from the true value, the points of intersection between arbitrary pairs of circles centred on antennas will not coincide. This is illustrated by the inset plot in figure 46.
From the above, it can be seen that for each assumed value of $R_0$, a set of intersection points are generated and the average X,Y and Z coordinates of these points are calculated, along with the variance of the distribution of points of intersection. The prototype localisation algorithm chooses as the true $R_0$ the assumed value of $R_0$ that minimises the variance of the points of intersection. In other words, the value of $R_0$ resulting in a set of intersection points with minimum standard deviation is taken to be the true value.

On completion of all iterations, at each assumed distance $R_0$, a single (X,Y,Z) position was derived by taking the average of all of the individual generated positions and the standard deviation (STD) was computed:

$$f(R_0) = \frac{1}{N} \sum_{n=0}^{N-1} \sqrt{(X_n - \bar{X})^2 + (Y_n - \bar{Y})^2}$$

(43)

The assumed range estimate $R_n$ minimising equation (43) was then substituted in equations (40) to (42) to derive the final X, Y and Z positions of the transmitting node.

4.5 Algorithm implementation

The prototype localisation algorithm discussed in the previous sections was implemented in a MATLAB program that runs on a PC. Input data required by the program include digitised versions of the signals received by each of the antennas in the receiving array and range gate parameters. The digitised signals are stored in Excel files, and the range gate parameters are derived from a visual inspection of the signal from the reference antenna.
The program is executed in a number of stages. In the first stage, the sampled signals are read from file and their LEs are isolated using the range gate parameters derived from an inspection of the signal at the reference antenna. The LEs are then cross-correlated to derive TDoA data, Δt = (t_1 - t_n) that in turn were used to estimate distances between the transmitter and the receiving antenna array.

Distance differences are obtained from the TDoA values by multiplication by the speed of propagation in grain. It is important to note this is different from the signal propagation speed in air, due to differences in the dielectric constants. As indicated in section 1.6.2, the literature suggests that dielectric constant of grain is between 2.5 and 2 an observation that was confirmed by WSN4IP researchers in their measurements over frequencies between 1GHz to 8GHz [28]. The speed of propagation is equal to the inverse of the square root of the medium’s dielectric constant [111], and as such the propagation speed c used in the algorithm was $1.875 \times 10^8$ m/s.

In the second major stage of the program’s execution, the iterative procedure discussed in the previous section is applied to the data for a number (n) of assumed values for $R_0$. In the code, these, assumed values range from 0.1m to 1.5m, in steps of 0.01m. Distance difference data are combined with the assumed value of $R_0$, defining the radii of the circle on which the transmitter is thought to lie. This enables all points of intersection between circles to be computed and the mean and STD of the distribution of the intersection points to be found. This process is repeated for all n assumed values of $R_0$ and the value that minimised the STD is selected as the true value. This minimisation is illustrated in figure 47, which shows a plot of the STD cost function in equation (43).

![Figure 47. Variance minimisation Vs assumed distances [27]](image-url)
Note that there are two values for the Y positions— one for the X coordinate and one for Z coordinate given equation (42) gives Y estimates using the equations of circles (2D).

4.6 The localisation system

A basic experimental UWB-based positioning system was developed by WSN4IP researchers as shown in figure 48. This consisted of a cylindrical plastic container, 1.5m high and 1m in diameter, was filled with grain.

![Figure 48. UWB positioning in a grain silo [27]](image)

The following sections discuss in detail both the electronic and mechanical systems employed in the localisation procedure.

4.6.1 Electronic systems

The electronic system consisted of two parts: the circuitry inside the node and the external system. In terms of the former, it should be noted that in the work reported in this chapter, and in chapters 4 and 5, only the hardware associated with localisation were included within the nodes (see section 1.5). The external system included the receiving antenna array, a Digital Sampling Oscilloscope (DSO), a PC and a number of other elements.

Transmitting nodes were equipped with a pulse generator that generated UWB pulses with a width of 0.5ns. The pulse generator circuit (figure 49) comprised an avalanche transistor driven by a 1MHz crystal oscillator, through a frequency divider, thus setting the output pulse repetition frequency (PRF) at 500kHz. The avalanche transistor requires 70V to operate.
which is provided by a DC to HV DC converter that takes 2.4V from a battery embedded within the transmitting node.

![Figure 49. Pulse generator circuit [27]](image)

Initially the pulse generator was powered by two AA rechargeable batteries but that was not efficient as the batteries needed long time to recharge thus causing delays in the experiments. In all measurements presented in this thesis, the pulse generator was powered via cables connected to an external power supply.

Both the transmitting and the receiving antenna were ring monopole broadband antenna that can handle UWB pulses. Receiving antenna were fabricated exclusively from FR4 substrate whilst a number of receiving antenna used a combination of FR4 substrate and flexible ground plane with another set of receiving antenna being made exclusively from the flexible material. The ring shape of the antenna and the flexible ground plane allowed mounting the antennas inside the protective spheres. The transmitting antennas are seen in figures 50a and 50b whilst the receiving antenna is shown in figure 50c.

![Figure 50. Ring monopole transmit and receiving antennas](image)
As stated in section 1.5, experiments were performed in small scale and large scale vessels. Tests in the small vessel employed single antennas as the one seen in figure 50b, on the other hand in the large vessel tests were carried out using pairs of transmit antennas placed inside mortar shells as seen in figure 51.

![Figure 51. Transmitting antenna for tests in the large vessel](image)

Figure 51 shows two ring monopole antennas fabricated from FR4 substrate with a flexible ground plane fixed on each of the hemispheres of the protective cover. The antennas were placed with orthogonal polarisation so they could propagate simultaneously but minimise signals from one antenna interfering with signals from the other antenna. The two antennas were connected together via a broadband signal combiner that in turn was connected to the pulse generator (figure 49) to enable the antennas to transmit simultaneously. The two antenna formation aimed to alleviate problems which would arise from random orientation (see section 3.3.1) of nodes inside grain silos and hence approach the condition where the antenna array could be regarded as omni-directional.

Received signals were amplified using a LNA (to boost the weak received signal (~µV) and then digitized using an Agilent 54854A DSO. It is important to note that received signals enter the DSO through two different antennas at the same time. Signals from the array of the receiving antenna are used within correlation procedure to provide TDoA information. Signals from a second receiving antenna (not part of the receiving antenna array), situated at a fixed position inside the grain, are used by the triggering circuit to start the sampling procedure. The objective of the triggering circuit was to detect received pulses and in turn trigger the DSO to start sampling [26-28]. The DSO was configured to sample signals from
the antenna array at five giga samples per second (GSa/s). A received UWB pulse trail captured using the DSO can be seen in figure 52.

![DSO UWB pulse trail](image)

**Figure 52. DSO UWB pulse trail**

The averaging function of the DSO was enabled in order to remove random noise thus guaranteeing the reliability of the detected signals and consequently the reliability of the whole localisation procedure.

### 4.6.2 Mechanical system

The mechanical parts of the system included two plastic vessels to hold the grain, a system based on an industrial vacuum cleaner, for filling and emptying the testing vessel, a set of plastic mortar shells to hold the node electronics and supports for the antenna array.

The small vessels used in tests were located in a university electronics laboratory whilst the large vessels were located at a wide space of a University Chemical engineering laboratory. Strict health and safety requirements imposed specific working regulations to protect users from damaging effects of grain dust as well as to prevent users from falling inside the vessels during experiments (handmade safety net acquired by the author, seen in figure 53c, required). Nevertheless, these health and safety regulations caused significant delays in large scale tests resulting in a limited number of experimental data compared to the data from small scale tests.

In all cases a second plastic vessel was used for grain storage to enable the primary vessel, in which the experiments were contacted, to be partially or fully emptied for the purposed of the nodes. Figure 53a shows a schematic diagram of the system used to convey grain from one
vessel to another. The conveyor system was based on a powerful industrial vacuum cleaner and a hopper, seen in figures 53b (small scale tests) and 53c (large scale tests). The hopper was filled with grain from one vessel (filled with grain) and then transferred to the top of the empty vessel to release the grain.

![Diagram of conveyor system with hopper](image)

(a) Grain conveyor  (b) Small vessel test rig  (c) Large vessel test rig

**Figure 53. Experimental rig**

One of the main issues with grain transfer was the time (~1hour) required to fill or empty the vessels to place or remove nodes accordingly. As therefore, a faster method of node insertion and removal, in small scale tests, was developed by the author. This used a hollow metal tube that can be seen in figure 54. The tube was pushed inside grain at the desired position and the vacuum cleaner (figure 54) used to remove the grain from the tube. Here it is important to note that the tube was always placed 15cm deeper than the required position to compensate for measuring node’s positions from the upward side of the sphere. The penetration of the tube into the grain was eased by helical extensions on its outside periphery which allowed the tube to be ‘screwed’ into and out of the grain.

Once grain had been removed from the tube the node and the required depth was reached, the sphere was placed inside and measurements taken of its position with a 1.5m rule and a tape. The rule was placed on the middle, upward side (facing top of the silo), of the spheres to measure the depth, Y coordinates, whilst the tape was used to measure X and Z coordinates from the ruler. It is estimated that the accuracy of these measurements was ±5cm in all cases.
Once nodes were placed at the required position, the tube was removed from grain by pulling it upwards, in clockwise and anticlockwise rotations, whilst grain at the immediate external side of the tube was pulled away by hand. Throughout the tube extraction process, the rule was hold firmly on the top of the sphere minimise possible displacements from the required position. The exact point of the tube extraction was marked to allow using the tube once measurements were completed to extract the spheres. It is estimated that during the extraction of the tube there was slide movement of the node but that wasn’t significant and certainly less than 5cm.

Overall, since measurements of the sphere positions was taken from their centre and given their diameter was 15cm deviations in position estimates, by the localisation method, within ±10cm is an acceptable degree of error. Even though the tube-based procedure for inserting and removing nodes was quicker that partially emptying/refilling the vessel, still required a lot of effort and could have taken from one hour up to four hours to be completed, depending on the depth to which a node had to be delivered.

The whole procedure of placing a node inside grain, taking of measurements and the extraction of the nodes from grain required a lot of effort and could have taken from one hour up to four hours depending on the depth to which a node had to be delivered.

Preliminary small scale tests were performed using a single receiving ring monopole antenna that was placed on a rotating plastic rig situated on the top of a vessel as seen in figure 55. This antenna was continuously connected to the DSO, via a cable, and was moved in steps of
10cm a time, across the plastic rig, to allow for sixteen measurements to take place eight along the X axis and another eight along Z axis. Note that another antenna on the side of the tank (seen in figure 55) was constantly connected on the DSO and, acted as a clock, to trigger the DSO to start sampling in the presence of received signals [26-28].

![Figure 55. Single receiving antenna on a rotating rig](image)

In a later stage of the research, a different arrangement was employed were nine receiving antenna were fixed on cross formation (figure 56) with respective cables connecting one antenna at a time to the DSO. This cross antenna arrangement was developed by the author along with another researcher working on WSN4IP project. Notice that all antenna faced in the same direction, in another measure, to combat orientation issues. To this extent, transmitting nodes were placed inside the small vessel in a way so that their antenna faced the receiving antenna in the same orientation.

The plan view of the silo with the orthogonal antenna array made of ring monopole antennas is shown in figure 56.

![Figure 56. Small vessel receiving antenna on a cross formation](image)
The large scale vessel is shown in figure 57a with the same receiving antenna formation used in small scale vessel also used on the top of the large vessel as seen in figure 57b.

![Large testing vessel](image1)

![Received antenna on top of large vessel](image2)

(a) Large testing vessel  (b) Received antenna on top of large vessel

**Figure 57. Large silo and receiving antenna**

In all cases receiving antenna were held at their position on the plastic rig using plastic screws to prevent interferences to the received signals. Further, during tests, only one receiving antenna was connected to the DSO thus only one measurement was taken a time.

The procedure of connecting the antenna cables to the LNA and to then to the DSO needed special attention since cables had to be firmly connected to the LNA to prevent erroneous measurements. As therefore, every time a new cable had to be connected to the LNA a wrench was used to ensure the cable was firmly connected to it.

### 4.7 Experimental investigation

Extensive evaluation of the prototype localisation method was carried out by the author through a study of thirty test cases; fifteen along X axis and of another fifteen along Z axis resulting in 202 measurements for tests in the small vessel and in 30 measurements in the large vessel. The MATLAB algorithm gave TDoA estimates and the positions of the transmit nodes and as such those two were used to evaluate the accuracy of the localisation procedure.

Figure 58 shows the measured positions (measured manually using a ruler) of the transmitting nodes inside the grain silo as opposed the estimated positions for each test case via the prototype method for both small scale tests and for large scale tests. Note that the numbers inside every marker depict a different transmitter position representing a different
experiment. In all cases the measured positions are depicted by yellow squares whilst the estimated positions are depicted by red circles. The dimensions of the testing vessels are denoted by the red square enclosing the results.

![Diagram of experiment setup]

(a) Small scale tests  
(b) Large scale tests

**Figure 58. X axis position estimates from prototype method**

The absolute error (AE) ($AE = |\text{Experimental position} - \text{Measured position}|$) for the X coordinates, from each test, is presented in histograms in figure 58 and 59. Note that in all histograms the results for tests in the small vessel are presented with the first 16 experiment numbers whilst results from the large vessel are presented in experiment numbers 17 to 19. In all cases the experiment numbers in the histograms in figure 59 and in all histograms presented thereafter represent different experiments conducted at different positions inside the test vessels.

![Histograms of AE for X and Y coordinates]

(a) AE for X coordinates  
(b) AE for Y coordinates

**Figure 59. AE for experiments across X axis**

The estimated and the measured Z positions, for each experiment, are shown in figure 60.
The AEs for the estimated Z coordinates are shown in figure 61.

Table 1 gives the mean AE (MAE) for all X and Z positions. Note that a single, common, Y estimate for X and Z results is derived by taking the average of the two Y estimates recorded for X and Z readings.

<table>
<thead>
<tr>
<th></th>
<th>Small scale tests</th>
<th>Large scale tests</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>X</td>
<td>Yx</td>
</tr>
<tr>
<td>MAE(cm)</td>
<td>10.84</td>
<td>21.5</td>
</tr>
<tr>
<td>STD(cm)</td>
<td>12.12</td>
<td>22.53</td>
</tr>
</tbody>
</table>

Table 1: Prototype localisation MAE and STD

Figure 60. Z axis position estimates from prototype method

Figure 61. AE for experiments across Z axis
4.7.1 Analysis of experimental results

A close examination of the localisation results, out of the prototype method, showed that errors are directly related to the TDoA data. As such, understanding errors in TDoA will help improve understanding of the localisation results.

This section presents an analysis of the experimental TDoA used to derive the position estimates. For practicality reasons, TDoA data were multiplied by the speed of signal propagation inside grain thus resulting in an experimental distance difference $D_{exp}$. Given the coordinates of the transmitting and receiving antennas, distance differences could be estimated in theory thus providing a basis to which experimental distance difference can be compared to. The mean absolute error (MAE) between the experimental and theoretical distance difference profiles was used to evaluate the accuracy of the experimental data:

$$\text{MAE} = \frac{1}{n} \sum_{i=1}^{n} |D_{\text{theor}}^i - D_{\text{exp}}^i|$$

(44)

Table 2 shows an example of distance difference profile values, obtained using the RGLED method, at transmitter position of $X=42\text{cm}$, $Z=42\text{cm}$ and $Y=72\text{cm}$.

<table>
<thead>
<tr>
<th>Receiving antenna positions</th>
<th>0cm</th>
<th>10cm</th>
<th>20cm</th>
<th>30cm</th>
<th>40cm</th>
<th>50cm</th>
<th>60cm</th>
<th>70cm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Theoretical profile(cm)</td>
<td>0</td>
<td>-4.6</td>
<td>-8.1</td>
<td>-10.4</td>
<td>-11.3</td>
<td>-10.9</td>
<td>-9.14</td>
<td>-6.10</td>
</tr>
<tr>
<td>Experimental profile(cm)</td>
<td>0</td>
<td>14.5</td>
<td>10.2</td>
<td>6.4</td>
<td>4.3</td>
<td>3.4</td>
<td>3.11</td>
<td>6.7</td>
</tr>
<tr>
<td>Absolute Error(cm)</td>
<td>0</td>
<td>19.1</td>
<td>18.3</td>
<td>16.8</td>
<td>15.6</td>
<td>14.3</td>
<td>12.25</td>
<td>12.8</td>
</tr>
<tr>
<td>MAE(cm)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>13.64</td>
</tr>
</tbody>
</table>

Table 2: RGLED distance difference profiles along X axis

What can be seen in table 2 is that experimental distance difference values deviate substantially from the theoretical distance difference; an observation seen throughout results acquired using the RGLED method.

Figures 62 and 63 show the MAE for distance differences computed via the RGLED method, for each experiment, averaged over the number of the receiving antenna in the X and Z axis respectively. The MAE recorded in table 2 is given at experiment number 2 in figure 63.
Table 3 gives the overall MAE and STD values for distance difference profiles for both small scale and large scale tests.

<table>
<thead>
<tr>
<th></th>
<th>Small vessel tests</th>
<th>Large vessel tests</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>X</td>
<td>Z</td>
</tr>
<tr>
<td>MAE (cm)</td>
<td>9.21</td>
<td>8.76</td>
</tr>
<tr>
<td>STD (cm)</td>
<td>11.65</td>
<td>9.57</td>
</tr>
</tbody>
</table>

Table 3: RGLED distance difference profile errors

The following results, for transmitting node at X=42 cm, Y=72 cm, representing experiment number 2 in figures for X axis results in section 4.7, reveal the drawbacks in the RGLED localisation method. Figures 64 and 65 show both the raw received signals and the gated signals at the reference antenna.

What can be seen in figure 65 is that the gated signal at the reference is a good representation of 2\textsuperscript{nd} derivative of Gaussian pulse as discussed in chapter 3.
Figure 67 shows a gated received LE, for transmitting node at X=42, Y=72, at an antenna 10cm from the reference of which the raw received signal is shown in figure 66. Here it can be seen that the gated LE starts at the exact time as the signal in figure 65 something that shouldn’t happen given its distance from the reference antenna. Further, the waveform in figure 67 deviates from the expected second derivative of a Gaussian pulse that was expected as discussed in chapter 3.

![Figure 66. Raw signal at reference at 10cm](image1.png)  
![Figure 67. LE at 10cm from the reference](image2.png)

The signal in figure 67 gave rise to an error of 19.1cm in the computed distance difference. An increased error in distance differences is a characteristic of the effect of the RGLED method and its failure to detect the appropriate LEs.

### 4.8 Summary

This chapter presented a prototype UWB-based localisation method where LEs have significant role in determining the accuracy of localisation. Nevertheless, the process followed in selecting the LEs was not automated and lacked robustness.

The dependency of position estimates on the LEs is reflected on the errors recorded for individual experimental distance difference profiles and their respective localisation errors; whereas the latter increases or decreases depending on whether distance difference profile error increases or decreases respectively.

The MAE and the STD for positions estimates in the small vessel exceeded 10cm whilst exceeded 70cm for positions in the large vessel. Reflecting the errors in position estimates the MAE and STD for the distance differences exceeded 8cm in most cases. A total of 68.75% of
all position estimates resulted in errors exceeding 10cm with a 46.87% of all distance differences MAE being above 10cm for all measurements.

To deal with problems rising in the prototype localisation method and specifically in the LEs detection method, a new approach was examined were LEs are adaptively selected for each received signal in automated method discussed in the following chapter.
CHAPTER 5
ADAPTIVE LEADING EDGE DETECTION

5.1 Introduction

Chapter 4 introduced a UWB-based localisation method for wireless sensor nodes immersed in a process vessel, which in this work was a grain silo. The results of an extensive programme of testing showed that results obtained with this method were highly prone to errors. Further analysis of the results indicated that an important source of error was the accuracy with which the LEs of the signals, received by the antenna array were detected. In many cases the LEs do not appear to be correctly detected leading to errors in computed cross-correlations between signals. Information out of cross-correlations was used to derive TDoA values which were consequently in error, a fact that is confirmed by comparison with theoretical values. TDoA data forms the input to the localisation algorithm and so the transmitter locations computed by the method were incorrect.

The LE detection method used by the localisation system described in Chapter 4 was based on parameters derived by observation of a single signal by a human user of the system. These parameters were then applied to all other signals emerging from the receiver array. There are numerous potential problems with this procedure including the fact that LE identification was based on human observation and the results are likely to vary over time in an unpredictable manner, especially when determined by different users. Moreover, a technique requiring human intervention is not viable for practical systems. Another important problem is that the LE detection criteria for a signal received on channel i (i.e from the i^{th} antenna in the array) are independent of this channel. Given that a key aspect of LE detection is to distinguish a LE from the noise floor of a particular channel, it seems reasonable that an algorithm seeking to detect a signal LE on channel i should consider the noise floor on that channel.

This chapter presents two new LE detection methods that are automated, in the sense that neither required input from a human user. Moreover, both determine detection for a signal on channel i, by measuring parameters associated with channel i. The first method developed is called the Basic Advanced LE Detection (BALED) method, which employs a measured
threshold in LE detection. This is discussed in section 5.2. The second method, presented in section 5.3, is an improved version of BALED so called IALED. Results obtained from applying the two approaches are presented in section 5.4 and these are compared with the results acquired from applying the ‘manual’ technique used in Chapter 4.

5.2 Basic advanced LE detection method

The BALED uses a single threshold to identify the LE of an incoming UWB pulse. The BALED is similar to the methods in [104, 107] discussed in section 3.4.2 although those methods considered using a threshold to only derive the ToA of the LEs. The novelty of the BALED method lies on the fact that it uses a threshold to detect the start of the LE (can be considered as ToA) but it goes one step further and detects a complete waveform that is used within correlation to derive TDoA.

The threshold applied to the signal received from antenna i in the receiver array (i.e. the signal received on channel i) is computed from measurements of the noise floor on that same channel. The noise floor is defined as that part of the received signal that precedes the arrival of the actual received pulse as in [107]. Figure 68 shows a typical received signal, for a transmitting node at X=72cm, Y=42cm, Z=42cm, were the noise floor is easily identifiable.

![Received signal 10cm](image1.png)  ![Closer view of signal at 1ns/div](image2.png)

(a) Received signal 10cm  (b) Closer view of signal at 1ns/div

**Figure 68. Noise floor identification**

The noise floor on channel i is used in the setting of a threshold for the LE detection on the same channel. Specifically, it was observed that, in all cases, the noise on channel i approximates a Gaussian distribution as shown in the histogram in figure 69; that depicts the
distribution of the noise floor for eight signals at eight different antenna (different colour depicts different signal).

![Histogram of received signal noise floor]

**Figure 69. Histogram of received signal noise floor**

The threshold for LE detection is then set as an integer multiple (α) of the STD to avoid noise spikes being erroneously identified as the LEs of the received pulses. For example, if α = 2, then 95% of the noise distribution lies below the detection threshold, and if α = 3 then almost 98% of the noise distribution lies below the detection threshold [113].

Relative to the RGLED method discussed in the previous chapter, the BALED method has the advantage that is automated and hence produces a greater degree of consistency than the method associated with the RGLED approach. It also takes into account the channel noise, which forms the background against which the LE must be detected.

The BALED method follows an adaptive approach to detect the LE. At the beginning the algorithm records the STD of the noise floor, for each individual received signal, and sets a threshold above which the LE is to be detected. It is important to note that the BALED method can adjust the threshold accordingly to accommodate for increased or decreased STD. Nevertheless, in all cases the threshold remains above a specific level (three times the STD) in order to avoid picking up noise spikes instead of the LE. The time at which the amplitude of a sample, within the received signal, exceeds the computed threshold, determines the start of the LE.

The following pseudo-code describes the procedure with which the BALED method detects the beginning of the LE:
1. FOR $i=1$ to all received signals, $N$
2. Compute noise floor standard deviation, $\text{STD}(i)$
3. Compute threshold, $\text{THRESHOLD}(i)=\text{STD}(i)\times\alpha$
4. IF $\text{THRESHOLD}(i)$ less than minimum value $\beta$ then set $\text{THRESHOLD}(i)=\beta+\gamma$
5. END IF
6. FOR $j=N$ to $P$ samples
7. IF sample($j,i$) $>$ Threshold($i$)
8. Start($i$) $=$ $j$
9. END IF
10. END FOR
11. END FOR

Threshold values $\alpha$ ($\alpha > 1$), $\beta$ and $\gamma$, in the pseudo-code, were empirically selected based on thorough analysis of data available.

The time at which the LE begins, is used as a reference from which three successive crossings with the zero axis are recorded in order to capture a complete LE that is used within correlation to derive TDoA.

An example of a LE taken out of the experimental procedure is shown in figure 70 (for transmitter at $X=42\text{cm}$, $Y=72\text{cm}$ and received signal at $10\text{cm}$ from reference antenna) where the start of the LE as well as three successive crossings with the zero axis are clearly marked. The pulse in figure 70 approximates the 2$^{\text{nd}}$ derivative of the Gaussian pulse that was expected to be seen at the receiving antenna.

![Figure 70. LE at X=10cm](image)

At this stage, it is important to mention that both the BALED and the IALED methods record LEs that approximate the second derivative of the Gaussian pulses as discussed in section 4.2.
The following flow chart exemplifies all the steps involved in the Baled method and how these are linked to the RGLED localisation algorithm.

![Flow chart](image)

**Figure 71. BALED-based localisation method**

Detailed experimental evaluation of the BALED method will be discussed in detail in section 5.4. Further analysis of the results, out of the BALED method, revealed that these are prone to errors due to the possibility that noise spikes could mistakenly detected as the LEs.

An example of the deficiencies in the method presented here is exemplified in figures 72 and 73 that show a raw received signal at 60cm from the reference receiving antenna for transmitter at X=75cm, Y=30cm and its detected LE respectively.

The LE pulse, seen in figure 73, resulted in a distance difference value of -94.4cm instead of -44.5 that was expected at the specific transmitter position. On the other hand, if the correct LE pulse (sown inside red circle in figure 72) was selected then the distance difference value resulted in -45.74cm that is very close to the theoretical value.
Additional study of distance difference and localisation results revealed that in some cases the error was high when pulse duration extends beyond 1ns. One such case can be seen in figures 74 and 75 that shows a raw received signal and the gated signal respectively at 40cm from the reference antenna at transmitter of X=70cm, Y=30cm.

The waveform in figure 75 is significantly distorted by multipath, thus giving a distance difference of -6.98cm instead of -33.7cm that was the expected value.

To deal with problems in the BALED method an improved advanced LE detection method (IALED) was developed.

5.3 Improved advanced LE detection method

IALED attempts to combat the deficiencies observed in the basic method by taking advantage of the restricted area of the vessel in which measurements took place. In order to deal with problems observed in BALED method two approaches have been developed.
In order to deal with issues arose from prolonged signals (see figure 75) it was examined whether it is possible to process the earliest part, in time, of the LEs since the further in time the signal the further multipath increases. This reduced portion of the LE is considered only for the cases when the time difference between the start of the LE, and the time at which the maximum or the minimum of the LEs occurs, exceeds 0.5ns.

Figure 76 shows a typical LE when used in the localisation process results in accurate results. What is seen here, is that both the maximum and minimum points after the start of the LE are within 0.5ns.

![Figure 76. LE minima and maxima points](image)

Figure 78 shows a gated signal for transmitter at $X_t=70cm$, $Y_t=30cm$ where only two crossings with the zero axis are considered thus giving a reduced waveform than in figure 78.

The raw received signal for the gated pulse is shown in figure 77.

![Figure 77. Raw received signal at 40cm](image)  ![Figure 78. Detected LE at 40cm](image)

The LE, seen in figure 78, resulted in a distance difference of -24.92cm deviating by only 7.61 cm from the expected theoretical distance difference value.
In order to deal with cases where the LE is missed, when is taken to be far away from the expected time it should have occurred, a boundary was set within which to look for the LE. Given the dimensions of the container in which the tests were carried out, and the positions of the receiving antennas, it is possible to restrict the search for the LE. Specifically, since adjacent antennas are separated by 10cm up to 80cm, then it is anticipated that the LEs will occur within short time period from each other. In fact, analysis of all available data revealed that LEs occur within about 3ns from the start of the LE recorded at the reference antenna.

Here the 2ns limit between pulses can be confirmed mathematically based on the example seen in figure 79.

![Figure 79. 3ns Pulse limit example](image_url)

In the example depicted in figure 79, given a transmitter position T (X=18cm, Y=10cm) and two receiving antenna A(X=0m, Y=0m) and B(X=80cm, Y=0cm) then Pythagoras theorem will give the distance of the transmitter to receiving antenna B at 80.62cm. The optimum propagation time, (time=distance/speed), of a signal from the transmitter to receiving antenna A will be 0.33ns whilst the propagation time to receiving antenna B will be 2.7ns, given speed of propagation is 1.9E11m/s.

The flow chart in figure 80 shows all the steps involved in the IALED method where the first three steps are the same as in the RGLED method. The time period from the start of the LE at the reference antenna within to look for the ToA of signals at the rest of the antennas is denoted by the letter ε, also the optimum duration of the LE is denoted by letter τ.
5.4 Evaluation of the BALED method

The need for the BALED method was thoroughly discussed in the previous sections, yet a comparison between experimental distance difference profiles, obtained both by the RGLED LE detection method and the BALED method, reinforces the need to implement an adaptive LE detection approach.

Figure 81 shows the measured positions (obtained manually using a ruler) of the transmitting nodes as opposed the estimated positions via the BALED localisation method presented in this chapter.
Figure 81. Measured and estimated X axis positions

Figure 82 gives the AE for the estimated positions for all data recorded along X axis.

Figure 82. AE for X axis positions

Figure 83 shows the measured as opposed to the estimated positions for data recorded along Z axis.

Figure 83. Measured and estimated Z axis positions
Figure 84 gives the overall AE for measurements along Z axis and the respective overall AE positioning error along Y axis.

![Graphs showing AE for Z coordinates and Y coordinates](image)

**Figure 84. AE for Z position estimates**

The MAE and STD for X, Y and Z position estimates when using the BALED localisation method are shown in table 4.

<table>
<thead>
<tr>
<th></th>
<th>Small vessel tests</th>
<th>Large vessel tests</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>X</td>
<td>Ys</td>
</tr>
<tr>
<td>MAE(cm)</td>
<td>5.93</td>
<td>10.7</td>
</tr>
<tr>
<td>STD(cm)</td>
<td>5.934</td>
<td>7.54</td>
</tr>
</tbody>
</table>

**Table 4: BALED MAE and STD**

5.4.1 Analysis of BALED results

A more detail analysis of the BALED localisation method is carried out based on an examination of the acquired distance difference profiles. The MAE for all distance differences are shown in figures 85 and 86.

![Graphs showing distance difference X axis and Z](image)

**Figure 85. Distance difference X axis**  **Figure 86. Distance difference Z**
Table 5 gives the MAE and STD for the distance difference profiles acquired using the BALED method.

<table>
<thead>
<tr>
<th></th>
<th>Small vessel tests</th>
<th>Large vessel tests</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>X</td>
<td>Z</td>
</tr>
<tr>
<td>MAE (cm)</td>
<td>3.3</td>
<td>4.23</td>
</tr>
<tr>
<td>STD (cm)</td>
<td>4.5</td>
<td>4.1</td>
</tr>
</tbody>
</table>

**Table 5: BALED distance difference profile errors**

The following four figures show characteristic examples of the improvements achieved in distance difference computation when using the BALED method as opposed to the RGLED method. All figures give plots of both theoretical and experimental distance differences against the receiving antenna positions for a transmitter position inside the small vessel. Note that theoretical distance difference profiles were acquired for the transmitter position used in the experiments and for a reference receiving antenna position at X=0cm, Y=0cm, Z=0cm.

Figure 87a shows the experimental distance difference profile, for a transmitter at X=53cm, Y=89cm, derived using the LE detection method used in the RGLED method presented in the previous Chapter. In addition figure 87b shows the experimental distance difference profile, at the same transmitter position, computed based on the BALED method. Both figures show the theoretical distance difference profiles at X=53cm, Y=89cm for comparison.

![Figure 87a: RGLED method](image)

![Figure 87b: BALED method](image)

Figure 87. Distance difference profiles at X=53cm, Y=89cm (experiment number 3)
Similarly, figure 88 shows the theoretical against the experimental distance difference profiles computed based on the RGLED method on BALED for a transmitter position of X=42cm, Y=72cm.

![Figure 88. Profiles at X=42cm, Y=72cm (experiment number 3)](image)

What can be seen in the above figures is that the BALED method outperforms the RGLED method resulting in more accurate distance differences and consequently giving more accurate position estimates. Nevertheless, it was observed that there are cases where BALED fails to produce good representations of distance differences thus introducing errors in localisation. Two characteristic examples of distance differences pointing out the weaknesses of BALED method are shown in figure 89.

![Figure 89. Profiles at Z=44cm, Y=45cm (experiment number 16)](image)

The MAE for the profile seen in figure 89b, derived when using BALED, was 25.3cm resulting in 9.1cm AE in the position estimate.
5.5 Evaluation of the IALED method

Figure 90 shows the measured as opposed the estimated positions along X axis.

![Figure 90. Measured and estimated X axis positions](image)

(a) Small vessel tests  
(b) Large vessel tests

The AE for X position estimates are graphically shown using histograms in figure 91.

![Figure 91. AE for X axis position estimates](image)

(a) AE for X coordinates  
(b) AE for Y coordinates

Figure 92 shows the measured as opposed the estimated positions across Z axis.

![Figure 92. Measured and estimated Z axis positions](image)

(a) Small vessel tests  
(b) Large vessel tests
The AE for estimated $Z$ coordinates are depicted in a histogram in figure 93.

![Histogram of AE for Z coordinates](image1)

![Histogram of AE for Y coordinates](image2)

**Figure 93. AE for measurements across Z axis**

The MAE and STD for all position estimates using the IALED localisation method are given in table 6.

<table>
<thead>
<tr>
<th></th>
<th>Small vessel tests</th>
<th></th>
<th>Large vessel tests</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>X</td>
<td>Yx</td>
<td>Y</td>
</tr>
<tr>
<td><strong>MAE(cm)</strong></td>
<td>5.1</td>
<td>7.51</td>
<td>7.81</td>
</tr>
<tr>
<td><strong>STD(cm)</strong></td>
<td>4.4</td>
<td>6.4</td>
<td>5.94</td>
</tr>
</tbody>
</table>

**Table 6: IALED localisation method MAE and STD**

5.5.1 Analysis of IALED results

Figures 94 and 95 next depict the distance difference MAE for the data points along X and Z axis at which readings were observed.

![Distance difference X axis](image3)

![Distance difference Z axis](image4)

**Figure 94. Distance difference X axis**

**Figure 95. Distance difference Z axis**
The MAE and STD for distance differences along X axis as well as the MAE and STD for distance differences along Z axis are given in table 7.

<table>
<thead>
<tr>
<th></th>
<th>Small vessel tests</th>
<th>Large vessel tests</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>X</td>
<td>Z</td>
</tr>
<tr>
<td>MAE(cm)</td>
<td>2.9</td>
<td>3</td>
</tr>
<tr>
<td>STD(cm)</td>
<td>2.55</td>
<td>2.5</td>
</tr>
</tbody>
</table>

Table 7: MAE for IAELED distance difference profile errors

Figures 96 and 97 exemplify the enhance accuracies achieved with the IALED method compared to profiles computed using the RGLED LE detection method, the BALED and IALED methods. Figure 96 depicts profiles for transmitter position at Z=44cm and Y=45cm.

Likewise figure 97 shows profiles for transmitter position at Z=44cm and Y=45cm for all employed LE detection methods where IALED is shown to be the most accurate.
Figures 98 and 99 show the raw received signal and LE respectively for a signal at the reference receiving antenna, for a transmitter at $X_t=70\text{cm}$, $Y_t=30\text{cm}$.

Figure 98. Reference received signal  
Figure 99. LE at reference antenna

Figure 101 presents the gated signal for the same received signals as in figure 73, in page 108, but this time using IALED. Here, it can be seen that the gated signal is different from the one shown in figure 73 that was detected solely based on the noise floor threshold.

Figure 100. Raw received signal at 60cm  
Figure 101. Detected LE at 60cm

The LE, in figure 101, ($X_t=70\text{cm}$, $Y_t=30\text{cm}$) gave a distance difference of -45.7cm compared to the theoretical distance difference of -44.5 The example seen in figure 101 and indeed many other cases revealed that IALED can deal effectively with noise spikes and can give more accurate results compared to the original noise floor based threshold detection.

Overall, results from experimental distance differences and localisation estimates using all the LE detection methods showed that although there are improvements for the results out of the small vessel tests, results using data out of the large vessel tests do not provide firm conclusions. Nevertheless, analysis of raw received signals revealed that signals in the small test vessel were least affected by noise as opposed to signals out of the large vessel as seen in figures 102 and 103 respectively (received signals at an antenna 20cm from the reference).
Figure 102. Raw signal at X=28, Y=89cm  
Figure 103. Raw signal at X=17, Y=150cm

Figure 103 shows a representative case of a received signal in the large vessel where increased noise caused problems in the detection of the LEs and subsequently contributed in increase errors in distance and position estimates.

5.6 Summary

This chapter presented two adaptive LE detection methods that significantly improve positioning accuracy as opposed to the RGLED method discussed in the previous chapter.

Table 8 gives the MAE for positions estimates using all LE detection methods in all tests inside the small and in the large vessel.

<table>
<thead>
<tr>
<th>Algorithm</th>
<th>Small vessel MAE (cm)</th>
<th>Large vessel MAE (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>X</td>
<td>Y</td>
</tr>
<tr>
<td>Prototype (RGLED)</td>
<td>10.84</td>
<td>20.7</td>
</tr>
<tr>
<td>Prototype (BALED)</td>
<td>5.93</td>
<td>11.95</td>
</tr>
<tr>
<td>Prototype (IALED)</td>
<td>5.1</td>
<td>7.81</td>
</tr>
</tbody>
</table>

Table 8: MAE for all position estimates

Table 8 shows that the BALED and IAELED methods outperform the RGLED-based localisation method in terms of localisation accuracy. To be more specific, in a total of 64 position estimates for X, Z and their respective Y coordinates, 48.44% of positions had errors above 10cm for the RGLED method, 39.54% of position estimates had errors above 10cm for the BALED method whilst only 18.75% of position estimates had errors above 10cm when employ the IALED-based localisation method. In addition the advanced LE detection methods resulted in position estimates with reduced STD thus confirming the advanced LE detection methods are more accurate that the RGLED method.
The MAE for distance differences derived using all mentioned LE detection methods are summarised in Table 9.

<table>
<thead>
<tr>
<th>Algorithm</th>
<th>Small vessel MAE(cm)</th>
<th>Large vessel MAE(cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>X</td>
<td>Z</td>
</tr>
<tr>
<td>RGLED</td>
<td>9.21</td>
<td>8.76</td>
</tr>
<tr>
<td>BALED</td>
<td>3.3</td>
<td>4.23</td>
</tr>
<tr>
<td>IALED</td>
<td>2.9</td>
<td>3</td>
</tr>
</tbody>
</table>

Table 9: Distance difference MAE

Table 9 supports the trends observed in the position estimate results, whereas once more, the IALED method gives more accurate results. In fact, 46.88% of distance profiles derived from the RGLED method had errors above 5cm. 31.25% of profiles from the BALED method had errors above 5cm and only 18.75% of profiles from the IALED method had errors above 5cm.

On the whole, this chapter shown that the accuracy with which LEs are detected and the resulting distance difference values determine to great extent the localisation accuracy. A close examination of all distance difference values out of the IALED method showed that these don’t follow any specific trends with respect to the size of the observed errors. Distance difference values for transmitters deep inside the small vessel, up to 90cm, shown to be as accurate as distance difference values observed at small depths of 30cm. As far as tests in the large vessel, the limited amount of data (only three test cases) can only serve as reference for future work and cannot be used to provide solid conclusions; although it was observed that an increased noise made LE detection and computation of distance difference values less accurate.

Position estimates and distance differences achieved higher accuracies when using the IALED method. As such IALED-based data are used to evaluate the novel localisation methods presented in the following chapter.
CHAPTER 6

NOVEL LOCALISATION METHODS

6.1 Introduction

The work discussed in chapters 4 and 5 considered a positioning method that was based solely on the geometry of circles. This chapter presents alternative localisation methods that are based on analysis of experimental distance difference profiles and on mathematical expressions used to derive the distance differences.

Methodical analysis of numerous theoretical and experimental distance difference profiles revealed that these follow specific trends that are repeated throughout all test results and can be used to derive the positions of the transmitting nodes.

This chapter presents a thorough analysis of 2D and 3D theoretical distance difference profiles encapsulating the trends leading into the identification of the transmitting node’s position. All the observations are mathematically proven and incorporated into novel localisation algorithms. Experimental distance difference profiles were introduced within the new localisation algorithms to validate their accuracy.

6.2 Theoretical distance difference profile analysis

The prototype localisation method discussed in Chapter 4 essentially decomposed the 3D localisation problem into 2D localisation problems in orthogonal planes. Hence, the discussion of distance difference profiles starts with a consideration of the 2D case, which provides a context for the analysis which applied to the 3D case.

6.2.1 Analysis of 2D theoretical distance difference profiles

Trends observed in the experimental distance difference profiles obtained using the localisation approach discussed in Chapter 4, led to a simple theoretical investigation. Based on observed profiles, a simple MATLAB model was developed to predict the distance difference profiles that would be observed by a number of receivers situated at the top of a 2D vessel with a transmitting node placed at different locations beneath the receivers. This is
a subtraction of the measurements taken in the X (or Z) planes in the experiments reported in Chapter 4.

In the results presented in the next section in all cases the reference receiving point was situated at (X, Y, Z) = (0, 0, 0) as illustrated in figure 104.

![Diagram](image)

**Figure 104. 2D distance difference diagram**

The following figures depict theoretical distance difference profiles taken at a number of points along X axis. It is important to note that the same plots would have been resulted if receiving points were situated along Z axis.

Figures 105 and 106 depict five distance difference profiles, taken at five different Y positions at two fixed X transmitting positions of 28cm and 72cm respectively.

![Profile Images](image)

**Figure 105. Profiles at X_t=28cm**

**Figure 106. Profiles at X_t=72cm**

Figure 107 shows five distance difference profiles based on eleven receiving points with the transmitter at X = 50 cm.
An examination of the distance difference profiles appearing in figures 105 to 107 reveals that, in all cases, the minimum of all profiles approximates closely the position of the transmitter along X (or Z) axis. In addition, it appears that, in the situations where the distance difference profile becomes negative, the negative part of the curve is symmetrical about the transmitter position. Finally, distance difference profiles seem to become flatter as the depth of transmitter increases, for a fixed X transmitter coordinate.

6.2.2 Analysis of 3D theoretical distance difference profiles

The analysis presented here makes the transition from 2D distance difference profiles to 3D profiles using a scenario where a process is enclosed in a cuboid shaped vessel. A sensor whose position is to be computed is immersed within the process and is able to transmit data to an array of receivers located in a measurement plane above the vessel. The 3D localisation process within a cuboid volume is illustrated in figure 108.

Theoretical 3D distance difference values, $D$, are obtained from the familiar equation (44). The position of the transmitter is $(X_t,Y_t,Z_t)$ and the positions of the receiving points scattered in a plane are $(X,Y,Z)$ as seen in figure 108.

$$D = R - R_{\text{ref}}$$  \hspace{1cm} (44)$$

where

$$R_{\text{ref}}^2 = (X_0 - X_t)^2 + (Y_0 - Y_t)^2 + (Z_0 - Z_t)^2$$  \hspace{1cm} (45)$$

$$R^2 = (X - X_t)^2 + (Y - Y_t)^2 + (Z - Z_t)^2$$  \hspace{1cm} (46)$$
Without loss of generality, Y coordinates across the measurement plane are considered to be at zero and the reference point of TDoA calculations was X=0cm, Y=0cm, Z=0cm.

**Figure 108. 3D distance difference profile on a plane**

A 3D MATLAB model, based on the scenario discussed above was developed and a number of 3D plots of distance difference profiles over received antenna positions across X and Z axis were produced (figure 109). In all cases it was observed that the 3D plots form surfaces whose minimum coincides with the X and Z position of the transmitters. One such example is illustrated in figure 109 that shows a 3D profile for a transmitter at \((X_t, Y_t, Z_t) = (50, 50, 50)\).

**Figure 109. Distance difference profile on a plane \((X_t, Y_t, Z_t) = (50, 50, 50)\)**

Likewise different transmitting positions result in 3D profile surfaces with the minimum giving the X and Z positions as seen in figures 110 and 111.
The observations made with respect to the 2D model, about the symmetry of the negative part of the distance difference curve and about the flattening of the profile curves, are repeated in the 3D profiles as seen in figures 112 and 113.

Further analysis of several theoretical distance difference profiles, revealed that the position of the transmitting node defines an axis of symmetry whereas any two negative values resulting from equidistance, \( \Delta \chi \), receiving points, from a transmitter position, \( X_t \), result in distance difference values that are equal between them.

A clear view of the distance difference symmetry about the axis, defined by the position of the transmitting node, is seen in figure 114 where it is obvious that any two profile points that are equidistant from the transmitter are equal between them.
Theoretical proofs for the properties observed in the analysis of both 2D and 3D distance difference plots are presented in the next section whilst a number of simple approaches to localisation, based on these properties, are discussed in section 6.3 onwards. Note that the properties discussed above were also observed in experimental distance difference profiles seen in Chapter 5 and as such the localisation methods presented in this chapter were evaluated using experimental data.

6.2.3 Properties of distance difference profiles

In this section, a number of properties of distance difference profiles are proved. Before the analysis is presented, a recap of the physical situation that is modelled is now given. As discussed in section 6.2.1, it is assumed that all the receiving antennas are located in a plane that lies immediately above the vessel. This plane is called the measurement plane and it contains the origin of coordinates and the X and Z coordinates as seen in figure 108. The Y axis is measured perpendicular to this plane, positive into the vessel. See figure 108.

What follows are proves of a number of theorems derived based on trends in TDoA profiles discussed in the previous two sections.

**Theorem 1:** The minimum of the distance difference surface recorded in the measurement plane is located at the X, Z coordinates of the transmitter.

**Proof:** The above theorem may be proved by taking the first and second derivatives of equation (44) as follows:
\[ \nabla D = \frac{\partial D}{\partial X} + \frac{\partial D}{\partial Y} + \frac{\partial D}{\partial Z} \]  
(47)

\[ \nabla^2 D = \frac{\partial^2 D}{\partial X^2} + \frac{\partial^2 D}{\partial Y^2} + \frac{\partial^2 D}{\partial Z^2} \]  
(48)

In order to determine the stationary points in the 3D surface the first order gradient in equation (47) is set to zero and solved for X and Z as follows:

\[ 2(X - X_t) = 0 \]  
(49)

\[ 2(Z - Z_t) = 0 \]  
(50)

Equations (49) and (50) indicate that stationary points exist when \( X = X_t \) and \( Z = Z_t \). In order to determine if the stationary points represent a minimum or a maximum or a saddle point, the second derivatives of equation (44) must be considered as in equations (51) and (52):

\[ \frac{\partial}{\partial X} \left( \frac{\partial D}{\partial X} \right) = \frac{\partial}{\partial X} (X_n - X_t) \]  
(51)

\[ D \frac{\partial^2 D}{\partial X^2} + \left( \frac{\partial D}{\partial X} \right)^2 = 1 \]  
(52)

At \( X_t = X_n \)

\[ \frac{\partial D}{\partial X} = 0 \]  
(53)

And so equation (52) becomes

\[ \frac{\partial^2 D}{\partial X^2} = \frac{1}{D} \]  
(54)

A similar equation to (54) exists for the second derivative with respect to Z.

A stationary point is a maximum if the inequality in equation (55) is true [112]:

\[ \Delta < 0 \quad \text{and} \quad \frac{\partial^2 D}{\partial X^2} < 0 \quad \text{or} \quad \frac{\partial^2 D}{\partial Z^2} < 0 \]  
(55)

Similarly, equation (56) states that a stationary point is minimum if and only if the following is true [112]:

\[ \Delta < 0 \quad \text{and} \quad \frac{\partial^2 D}{\partial X^2} > 0 \quad \text{or} \quad \frac{\partial^2 D}{\partial Z^2} > 0 \]  
(56)
where

\[ \Delta = \frac{\partial^2 D(X,Z)}{\partial (XZ)^2} - \frac{\partial^2 D(X,Z)}{\partial X^2} - \frac{\partial^2 D(X,Z)}{\partial Z^2} \]  \tag{57} 

In equation (57) \( D \) is always positive thus stationary points across both \( X \) and \( Z \) axes are always positive. Further, \( \Delta \) in equation (57) is always negative given that \( \frac{\partial^2 D(X,Z)}{\partial (XZ)^2} = 0 \).

Therefore, given the two necessary conditions for a stationary point to be minimum are satisfied in equation (56), it can be concluded that distance difference distribution over the measurement plane has a minimum at the position of the transmitter i.e. at \((X_t, 0, Z_t)\).

**Theorem 2:** The distance difference surface observed in the measurement plane for which distance differences are negative, is symmetrical about the line \( X_t = 0, Z_t = 0 \).

**Proof:** Consider the distance difference \( D_{t+\Delta} \) at a point \((X_t+\Delta_x, 0, Z_t+\Delta_z)\):

\[ D_{t+\Delta} = \sqrt{(X_t + \Delta_x - X_t)^2 + (Y_t)^2 + (Z_t + \Delta_z - Z_t)^2} - \sqrt{(X_0 - X_t)^2 + (Y_t)^2 + (Z_0 - Z_t)^2} \]  \tag{58} 

Similarly, the distance difference \( D_{t-\Delta} \) at a point \((X_t-\Delta_x, 0, Z_t - \Delta_z)\) is:

\[ D_{t-\Delta} = \sqrt{(X_t - \Delta_x - X_t)^2 + (Y_t)^2 + (Z_t - \Delta_z - Z_t)^2} - \sqrt{(X_0 - X_t)^2 + (Y_t)^2 + (Z_0 - Z_t)^2} \]  \tag{59} 

Hence:

\[ D_{t+\Delta} = D_{t-\Delta} \]  \tag{60} 

for any values of \( \Delta_x \) and \( \Delta_z \).

Note, however, that distance differences will vary along circles centred on the transmitter position as discussed in the following theorem.

**Theorem 3:** Curves of constant distances difference are circles in the measurement plane, centred on \((X_t, 0, Z_t)\).

**Proof:** Consider the distance difference, \( D \), at a position \((X_t+R\cos\theta, 0, Z_t+R\sin\theta)\) where angle \( \theta \) and distance \( R \) are seen in figure 115. Figure 115 shows the contour plot of distance.
difference profiles where all distance differences are circles centred on the position of the transmitter in this case \((X_t, Z_t) = (50, 50)\).

Figure 115. Contour plot for \((X_t, Z_t) = (50\,\text{cm}, 50\,\text{cm})\)

The distance difference equation becomes as follows:

\[
D = \sqrt{(X_t + R\cos\theta - X_i)^2 + Y_t^2 + (Z_t + R\sin\theta - Z_i)^2} - \sqrt{(X_0 - X_i)^2 + Y_i^2 + (Z_0 - Z_i)^2}
\]  \hspace{1cm} (61)

Simplifying equation (61) gives:

\[
D = \sqrt{R^2 + Y_t^2} - \sqrt{(X_0 - X_i)^2 + Y_i^2 + (Z_0 - Z_i)^2}
\]  \hspace{1cm} (62)

In equation (62) distance difference is independent of \(\theta\), and constant for constant \(R\), and hence curves of constant distance difference in the measurement plane are circles centred on \((X_t, 0, Z_t)\) for a fixed transmitter and reference antenna position.

**Corollary 2.1:** In the measurement plane, distance difference increases with distance \(R\) from \((X_t, 0, Z_t)\).

**Proof:** Consider two points at distance \(R_1\) and distance \(R_2\) from point \((X_t, 0, Z_t)\) in the measurement plane. Assume \(R_2 > R_1\). Then by equation (63):

\[
D_{R_2} - D_{R_1} = \sqrt{R_2^2 + Y_t^2} - \sqrt{R_1^2 + Y_t^2}
\]  \hspace{1cm} (63)

This is positive and so distance difference increase with distance \(R\) from \((X_t, 0, Z_t)\).

**Theorem 4:** The points of zero distance difference in the measurement plane lie on a circle of radius \(K\), where
For fixed transmitter and reference antenna positions:

$$(X-X_t)^2 + (Z-Z_t)^2 = K^2$$

where $K^2 = (X_0 - X_t)^2 + (Z_0 - Z_t)^2$  

\textbf{Corollary 4.1}: The points of zero distance difference on the $X$ and $Z$ axes are:

$X_{\text{def}} = X_t \pm K$ and $Z = Z_t \pm K$

\textbf{Corollary 4.2}: $K$ is the projection on the measurement plane from the reference node to the transmitter.

\textbf{Theorem 5}: Distance difference profiles flatten (i.e. variations amongst distance difference values reduces) as the depth of the transmitter inside a vessel increases.

\textbf{Proof}: As has already been demonstrated, distance difference is given by:

$$D = \sqrt{(X-X_t)^2 + (Y_t)^2 + (Z-Z_t)^2} - \sqrt{(X_0-X_t)^2 + (Y_t)^2 + (Z_0-Z_t)^2}$$

Consider a fixed, finite values $X_t$, $Z_t$, $X_0$, $Z_0$ and $X$, $Z$ positions within the measurement plane directly above the vessel.

As $Y_t$ increases, the difference between the two square root terms will be reduce and therefore the distance difference curves become flatter (reduce in height) as transmitter depth $Y_t$ increases. As $Y_t \to \infty, D \to 0$.

\textbf{Corollary 5.1}: The value of the maximum distance difference at $X=X_t$, $Z=Z_t$ in equation (66) given by:

$$D = Y_t - \sqrt{K^2 + Y_t^2}$$

where $K$ is defined in equation (64)

The effect of flattening of the distance difference when $Y_t$ increases is illustrated in figure 116 for $X_0=50\text{cm}$ $Z_0=0\text{cm}$.
Figure 116. Maximum distance difference Vs depth

Figure 116 implies a problem with establishing the Y coordinate of sensor nodes buried deep inside a vessel. From the above graph it can be seen that the peak distance difference varies between 50cm and 15cm over a depth of the first 50cm, but subsequently distance difference varies between 15cm and about 10cm. This suggests that performing depth estimation using a single TDoA value is likely to result in increased errors since it will be difficult to distinguish a unique Y, especially in the presence of errors.

**Theorem 6:** Each transmitter position within the vessel gives rise to a unique distance difference profile in the measurement plane.

**Proof:** Consider the distance difference equation

\[
D = \sqrt{(X - X_t)^2 + (Y - Y_t)^2 + (Z - Z_t)^2} - \sqrt{(X_0 - X_t)^2 + (Y_0 - Y_t)^2 + (Z_0 - Z_t)^2}
\]

(68)

Consider the 2D case localisation with a transmitter and received positions as illustrated in figure 117.
When the transmitter occupies the position shown, in figure 117, a distance difference function is produced along the X axis, i.e. a distance difference value exists for each point X, which is known to have a minimum at $X = X_t$ (Theorem 1). The position of the zero crossings of the curve is also defined by the transmitter position (Theorem 4). Then again consider that the transmitter position is changed by a small amount $\delta X$ to $(X_t + \delta X, Z_t)$. The distance difference profile produced is very similar to the previous profile, but displaced by $\delta X$ i.e the minimum of the distance difference curve us now located at $X_t + \delta X$, the lower zero crossing is still 0, but the upper zero crossing is now $2(X_t + \delta X)$. Hence the second distance difference profile is different from the first.

From the above arguments it can be concluded that the distance difference profiles arising from a transmitter at a fixed depth $Y_t$, but at every possible X position are unique.

Now consider that the transmitter position is changed by a small amount $\Delta y$ to $(X_t, Y_t + \Delta Y)$. This results in a distance difference profile with a minimum in the same transmitter position as the original case. However, from Theorem 3, it is clear that the height of the distance difference curve of the profile resulting from a transmitter at $(X_t, Y_t + \Delta Y)$ is smaller than that corresponding to the original case. Again the two curves are distinct.

From the argument of the previous paragraph, profiles originating from transmitters, at a fixed $X_t$ coordinate but different $Y_t$ coordinates, are distinct.

The above arguments generalise to the 3D case in the obvious manner. Hence, it can be concluded that each unique transmitter position within the vessel gives rise to a unique distance difference profile.

It should be noted that Theorem 6 applies only to transmitter positions within the vessel. From the distance difference equation and from figure 117, it is clear that a transmitter located at $(X_t, -Y_t)$ i.e. above the vessel, would produce the same distance difference profile as the transmitter located at $(X_t, Y_t)$. 

6.3 Novel localisation algorithms

The following sections present localisation methods based on the information acquired from analysis of distance difference profiles presented in the previous three sections. All methods were incorporated into 2D algorithms since TDoA results were derived based on an algorithm that treated X and Z readings independently as discussed in Chapter 4. Note that some algorithms implement a straightforward implementation of the mathematics and the theory defining each method whilst other algorithms introduce certain variations to enhance localisation accuracy.

All localisation methods were executed in MATLAB and evaluated using experimental distance difference profiles derived from the IALED method discussed in chapter 5. In addition, a number of localisation methods employ theoretical distance difference profiles derived based on the configuration discussed in section 6.2.1 and specifically figure 104.

6.4 Basic profile positioning method

The analysis of distance difference profiles, presented in the previous section, shows these have a minimum at the position of the transmitter. Hence it is possible to estimate the X and Z coordinated of the transmitter position from a set of measurements taken at a variety of locations over the measurement plane Y=0. However, this approach does not provide information about the Y coordinate of the transmitter. Nevertheless, since the \( X_t \) and \( Z_t \) coordinated can be estimated and distance differences are measured, then an approximate value for \( Y_t \) can be obtained.

Consider equation (theorem 3). If this is evaluated at \( (X_t, 0, Z_t) \) (recall that the reference position is at \( (0,0,0) \)), then it becomes:

\[
D = Y_t - \sqrt{X_t^2 + Y_t^2 + Z_t^2}
\]  

(69)

where \( D_t \) corresponds to the minimum value of the distance difference profile along X axis

Rearranging and squaring both parts of equation (69) gives the following:

\[
D^2 + Y_t^2 - 2DY_t = X_t^2 + Y_t^2 + Z_t^2
\]  

(70)

Finally, solving equation (70) for \( Y_t \) results in the following:

.
\[ Y_t = \frac{D_t^2 - (X_t^2 + Z_t^2)}{2 \cdot D_t}, \quad Y_t = -\frac{D_t^2 - (X_t^2 + Z_t^2)}{2 \cdot D_t} \] (71)

Note that although equation (71) indicates there are two estimates for \( Y_t \), one positive and one negative, for any \( X_t \) or \( Z_t \) position, only the positive solution is physically realistic due to the arrangement of the measurement system. To be more specific, given that the vessel is isolated in the positive \( Y_t \) part of the coordinate space and the transmitter is located within the vessel, then the positive solution for \( Y_t \) is the correct one.

Note that \( Y_t \) estimates using the approach discussed above are clearly sensitive to errors in the measurement of distance differences and in the \( X_t \) and \( Z_t \) estimates.

6.4.1 MATLAB algorithm

The principles of the simple profile-based localisation method were incorporated in a MATLAB program. The program treats the \( X_t \) and \( Z_t \) axes independently and uses the minima in the distance difference profiles to deduce the \( X_t \), \( Y_t \) and \( Z_t \) coordinates of the transmitter.

The basic method STRAIGHT-FORWARD (BMSF) was examined using a number of theoretical distance difference profiles. Here it is important to note that, in all cases, the algorithm choose the \( X_t \) or \( Z_t \) position of the transmitter to be at the receiving antenna position corresponding to the minimum distance difference profile value.

In the example seen in figure 118a, the BMSF algorithm chooses the position of the transmitter to be at 50cm and used equation (71) to compute the \( Y_t \) at 30cm, as expected.

![Figure 118. Theoretical profiles](image)
Additional plots at different transmitter positions revealed certain weaknesses in the BMSF algorithm. Figure 118b shows a profile taken at transmitter position of X=44cm and Y=30cm. In this case, BMSF choose the transmitter position to be at X=40cm, Y=23.31cm resulting in an error of 6.69cm.

Another situation where the BMSF algorithm results in errors is when more than one distance difference profiles have the same minimum value. This is exemplified in the example seen in figure 119 where the highlighted profile values at receiving antenna at 40cm and 50cm are the same. In such cases the BMSF algorithm simply processes the first minimum value and the corresponding receiving antenna. The estimated positions for the profile seen in figure 119 were $X_t=40cm$ and $Y_t=21.96$ as opposed to the expected position of $X_t=45cm$, $Y_t=30cm$.

![Figure 119. Profile for $X_t=44cm$, $Y_t=30cm$](image)

It is clear that the accuracy of the BMSF is limited by the number of the receiving antenna. In any case, in real applications, it is anticipated that the number of receiving antennas will be limited and as such other methods need to be considered to improve the accuracy of the BMSF method. To deal with problems in the BMSF algorithm, as discussed above, two modified versions of the BMSF method were developed.

The first approach considered interpolating a least squares best fit of the profiles to increase the resolution of the distance different profiles with respect to the receiving antenna. This method is called basic method least squares (BMLS). When the BMLS method was implemented for the data seen in figures 120 and 121 the accuracy improved significantly as opposed to the BMSF method. The BMLS resulted in $X=44cm$, $Y=31.71cm$ for data in figure 120 and $X=45cm$, $Y=31.81cm$ for data in figure 121. Absolute errors in these cases were about 1cm as opposed to the basic method were errors reached up to 6cm.
A second approach considered using the first derivative of the equation giving the least square curve best fitted into the experimental data to find the minimum of the profiles. This method was named basic method least squares derivative (BMLSD).

Experimental evaluation of three basic localisation methods BMSF, BMLS, and BMLSD is discussed in the following sections. A reminder that the terms Absolute Error (AE) refer to the absolute results of the subtraction of the experimental from the measured values and Mean Absolute Error (MAE) denotes the mean of the AE for all distance differences or position estimates for X or Z axis accordingly. As in the previous two chapters the AE are shown in histograms whilst the position estimates are plotted on scale against the measured positions.

6.4.2 BMSF experimental evaluation

First of the basic localisation algorithms to be examined is the BMSF. Figure 122 shows the measured positions of the transmitting nodes as opposed the estimated positions along X axis.
The AEs from the implementation of the BMSF approach for data along X axis are shown in figure 123.

Figure 123. X axis coordinates error

(a) X axis coordinates error  
(b) Yx axis coordinates error

Figure 124 shows the measured positions and the estimated positions along Z axis.

Figure 124. BMSF positions along Z axis

(a) Small vessel tests  
(b) Large vessel tests

Figure 125 show the AEs for Z position estimates.

Figure 125. Z axis coordinates error
The MAE for BMSF for all positions along both X axis and Z axis as well as the respective STDs are summarised in Table 10.

<table>
<thead>
<tr>
<th></th>
<th>Small vessel tests</th>
<th>Large vessel tests</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>X</td>
<td>Yx</td>
</tr>
<tr>
<td>MAE (cm)</td>
<td>9.63</td>
<td>27.96</td>
</tr>
<tr>
<td>STD (cm)</td>
<td>12.5</td>
<td>40.86</td>
</tr>
</tbody>
</table>

Table 10: MAE and STD for the BMSF

In general, the AEs for position estimates in the BMSF method showed a small increase compared to the AEs in the IALED-based localisation method. The MAE for X and Z positions when using the BMSF (Table 10) was about 4cm higher than the one recorded for the IALED-based method, in Table 6 (pg118), for both small and large vessel tests. In addition, the MAEs for Y estimates out of the BMSF were about five times larger than the ones observed from the implementation of the prototype localisation algorithm using IALED.

6.4.3 BMLS experimental evaluation

The second basic algorithm to be examined is the BMLS. The position estimates and the localisation accuracies are graphically displayed in the following figures.

Figure 126 shows the measured positions of the transmitting nodes and the estimated positions along X axis.

![Figure 126. BMLS measured and estimated X axis positions](image)

The histograms showing the AEs for X position estimates are shown in figure 127.
Figure 127. X axis coordinates error

Figure 128 shows the measured positions and the estimated positions along Z axis.

Figure 128. BMLS measured and estimated Z axis positions

The AEs for position estimates along Z axis are shown in figure 129.

Figure 129. Z axis coordinates error
The MAE for the BMLS, for all positions along both X axis and Z axis as well as the respective STDs are shown in table 11.

<table>
<thead>
<tr>
<th></th>
<th>Small vessel tests</th>
<th>Large vessel tests</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>X</td>
<td>Yx</td>
</tr>
<tr>
<td>MAE(cm)</td>
<td>4.31</td>
<td>7.14</td>
</tr>
<tr>
<td>STD(cm)</td>
<td>3.42</td>
<td>7.42</td>
</tr>
<tr>
<td></td>
<td>X</td>
<td>Yx</td>
</tr>
<tr>
<td></td>
<td>37.57</td>
<td>64.31</td>
</tr>
<tr>
<td></td>
<td>29.9</td>
<td>44.03</td>
</tr>
</tbody>
</table>

Table 11: MAE and STD for the BMLS method

Results from the implementation of the BMLS, using experimental data from the small vessel, showed a reduction in the MAEs for X and Z positions of about 5cm compared to the BMSF. A more noticeable reduction in the MAE, reaching 20cm, was observed in the computation of the Y estimates for small vessel tests (table 11). Similar trends were observed for data out of large vessel tests for Z positions and especially for Y positions where the MAE was reduced by a staggering 85cm compared to the ones in table 10.

6.4.4 BMLSD experimental evaluation

The final basic localisation approach to be examined is the BMLSD. The following figures depict the localisation results for the BMLSD method.

Figure 130 shows the measured positions of the transmitting nodes as opposed the estimated positions, using BMLSD, along X axis.

![Figure 130. BMLD measured and estimated X axis positions](image)

The AEs for X position estimates are shown in the histograms depicted in figure 131.
Figure 131. X axis coordinates error

Figure 132 shows the measured positions as opposed the estimated positions along Z axis.

Figure 132. BMLD measured and estimated Z axis positions

The AEs for Z position estimates using BMLSD are shown in figure 133.

Figure 133. Z axis coordinates error
The MAE for the BMLSD, for all positions along both X axis and Z axis as well as the respective STDs are shown in table 12.

<table>
<thead>
<tr>
<th></th>
<th>Small vessel tests</th>
<th>Large vessel tests</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>X</td>
<td>Yx</td>
</tr>
<tr>
<td>MAE(cm)</td>
<td>5.56</td>
<td>13.13</td>
</tr>
<tr>
<td>STD(cm)</td>
<td>6.2</td>
<td>11.65</td>
</tr>
</tbody>
</table>

Table 12: MAE and STD for the BMLSD

The MAEs in table 12 are similar to the ones observed in table 11 for the BMLS method. This was expected since both the BMLS and the BMLSD methods are based on the derivation of the minimum out of the least square best fit curve.

A characteristic example of the improvements in localisation accuracy, in the basic method, when using the least square best fit, can be seen in figure 134.

Figure 134. Basic localisation Z=65cm, Y=30cm

Figure 134 shows the distance difference profile for the experiment number 11. The BMSF method gives a position estimate Z at 80cm (minimum of the experimental profile) giving an error of 15cm (AE shown in figure 125) and Y=50cm with an error of 20cm (AE shown in figure 125). On the other hand a BMLSD implementation for the same data resulted in a Z position of 73cm giving an error of just 8cm and Yz of 35.1cm with an error of only 5.1cm the BMLSD (AEs shown in figure 133).
6.5 Centroid based localisation

The centroid based localisation method is essentially an advanced variation of the basic method described in section 6.4 and deals effectively with the problem arose from the use of a single receiving antenna position as the position of the transmitter.

In section 6.2.2 it was observed that distance difference values resulting from equidistantly separated receiving antenna, from a transmitter, give the same distance difference data. This statement can be used in reverse to allow for the position of the transmitting node to be estimated. In fact any two distance difference values that are equal to each other reveal that their respective receiving points are equidistant from the transmitter. As such, it is possible to take the centroid of those particular receiving points to find the position of the transmitting node along X and Z axis.

In an example shown in figure 135 a transmitter is located at X=50cm, Y=50cm. Distance difference points D₁, D₂ and D₃ are equally distant from the transmitter as points D₆,D₅ and D₄ respectively.

![Figure 135. Equidistance receiving antenna positions](image)

The mean of the distance difference points, in figure 135, along receiving antenna position axis, D₁D₆(0+100/2), D₂D₅(20+80/2) and D₃D₄ (40+60/2) all point to the exact position of the transmitter. The centroid of all mean positions gives a unique value that is the position of the transmitting node.

Two versions of the centroid method were incorporated into two algorithms and tested using all available experimental data.
The first version implemented the exact mathematical expressions presented in the previous section; this was called basic centroid localisation (BCL). Nevertheless, it was observed that the presence of distance profile points out of the axis of symmetry, centred on the transmitter, can cause increased errors with positioning errors increase as the number of distance profile points out of the axis of symmetry increases.

The following figures shows how the presence of distance profile points out of the axis of symmetry can affect localisation accuracy. In these figures the term original data refers to the raw experiment distance difference data, out of the IALED method, whilst least squares refers to the fit of least squares into those raw data. Note that the flat green line in figure 136 indicates a function in the BCL algorithm that forces the best fit to terminate at zero axis. This allows processing data that are below the zero axis and are part of the symmetrical curve thus enhancing localisation accuracy.

![Figure 136. BCL plots](image)

(a) $X_t=40\text{cm}, Y_t=89\text{cm}$  
(b) $X_t=30\text{cm}, Y_t=89\text{cm}$

To improve accuracy, the BCL approach considered taking the centroid of those receive antenna positions corresponding to pairs of distance difference values that resulted in a subtraction result (between them) that was less than 2cm. In figure 136a, only pairs CG, DF, DE, DF and EF had a difference less than 2cm in between them, thus only those were considered to be equidistant from the transmitter. As such, points A, B and H were excluded from the localisation process.

To further deal with problems arose from the use of the BCL method; two approaches were incorporated into another algorithm named advanced centroid localisation (ACL) method. In the first approach, only distance profile points with negative sign are considered in the localisation process. This effectively deals with problems such as those illustrated in figure.
136b whereas an increased number of positive profiles points exceed the desired transmitter’s axis of symmetry profile values. The second approach implements a least squares best fit approximation along with interpolation of numerous points into the existing distance profile points thus forming a new curve that always ensures crossings with the zero axis. This deals with localisation problems rose from cases where distance profile points do not cross the zero axis such as the case seen in figure 136a.

6.5.1 MATLAB algorithm

The above statements were incorporated into a mathematical expression seen in equations (72) and (73). Any two distance difference values, \( D \), out of an \( n \) receiving antenna positions minimising equation (72) indicate that these are equidistant from the transmitter.

\[
F(X^n_i, X^n_j, Z^n_i, Z^n_j) = \left[ \arg \min_{X^n_i, X^n_j} (D^n_i - D^n_j)^2 \right, \left[ \arg \min_{Z^n_i, Z^n_j} (D^n_i - D^n_j)^2 \right] \tag{72}
\]

The mean centroid of all positions minimising equation (72) over an \( n \) number of distance difference values, were used in equation (73) to find the final X and Z positions of the transmitting node:

\[
(X, Z) = \frac{1}{n} \sum \left( \frac{X^n_i + X^n_j}{2}, \frac{Z^n_i + Z^n_j}{2} \right) \tag{73}
\]

Finally the centroid X and Z position estimates are substituted in equation (71) to compute the Y coordinates of the transmitter. However, equation (71) requires a value for distance difference as well. As therefore, the mean of the distance difference values corresponding to respective equidistance receiving X or Z points from the transmitter, was used as follows:

\[
(D_X, D_Z) = \left( \frac{D^n_i + D^n_j}{2}, \frac{D^n_i + D^n_j}{2} \right) \tag{74}
\]

6.5.2 BCL experimental evaluation

The accuracy of the BCL method is examined using the experimental distance difference values derived from tests in the small and in the large testing vessels.

Figure 137 shows the measured positions as opposed the estimated positions along X axis.
The AE for data along X axis are shows in the histograms in figure 138.

Figure 139 shows the measured positions of the transmitting nodes along Z axis.

Figure 137. Measured and estimated X axis positions

Figure 138. X axis coordinates error

Figure 139. Measured and estimated Z axis positions
The MAE for the implementation of the BCL approach for data along Z axis are graphically shown in figure 140.

![BCL](image)

**Figure 140. Z axis coordinates error**

The MAE for the BCL method, for all positions along both X axis and Z axis as well as the respective STDs are shown in table 13.

<table>
<thead>
<tr>
<th></th>
<th>Small vessel tests</th>
<th>Large vessel tests</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$X_t$</td>
<td>$Y_{x_t}$</td>
</tr>
<tr>
<td><strong>MAE(cm)</strong></td>
<td>6.9</td>
<td>27.45</td>
</tr>
<tr>
<td><strong>STD(cm)</strong></td>
<td>5.8</td>
<td>21.15</td>
</tr>
</tbody>
</table>

**Table 13: MAE and STD for the BCL method**

The BCL method appeared to be equally ineffective as the BMSF approach, especially when concerns Y estimates, with MAE reaching 20cm and 90cm for tests in the small and in the large vessels receptively. This degradation in the computation of Y was caused by the fact that certain values within the distance difference profiles were excluded from the localisation process. The exclusion of a number of distance difference values from an already limited amount of eight or five values inevitably reduces the probabilities for an accurate localisation result. A similar condition with increased errors in Y estimates was observed in the BMSF method.

**6.5.3 ACL experimental evaluation**

Figure 141 shows the measured positions of the transmitting nodes as opposed the estimated positions along X axis for the ACL method.
Figure 141. Measured and estimated X axis positions

The AE for data along X axis are graphically shown in figure 142.

Figure 142. ACL X axis coordinates error

Figure 143 shows the measured positions as opposed the estimated positions along Z axis.

Figure 143. Measured and estimated Z axis positions

The AE for Z position estimates are shown in figure 144.
The overall MAE for the ACL method, for all positions along both X axis and Z axis as well as the respective STDs are shown in table 14.

<table>
<thead>
<tr>
<th></th>
<th>Small vessel tests</th>
<th>Large vessel tests</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>X</td>
<td>Yx</td>
</tr>
<tr>
<td>MAE (cm)</td>
<td>7.1</td>
<td>8.13</td>
</tr>
<tr>
<td>STD (cm)</td>
<td>6.7</td>
<td>7.7</td>
</tr>
</tbody>
</table>

Table 14: MAE and STD for the ACL method

The ACL algorithm resulted in X and Z positions with a slight increase in MAE, up to 3cm, from the results in BCL method. This was not unexpected since the two algorithms followed different approaches in estimating the position of the transmitter. Nevertheless, the ACL method performed much better than the BMSF approach and provided as accurate results as the BMLS and the BMSD methods.

Of interest is the significant improvement in the MAE for the Y estimates, up to 13cm for the small vessel and up to 20cm for the large vessel tests, which is achieved when using the ACL method. This improvement is attributed to the ability of the ACL method to include a significant higher number of distance difference values (using interpolation into least squares) when estimating the centroid thus dealing with possible outliers that cause errors in the BCL method.

The following two figures show plots of experimental distance differences over the receiving antenna positions when using BCL (original data) and the ACL method (least square).
Figure 145. Basic centroid localisation Z=43cm, Y_t=92cm

Figure 145a shows a basic localisation result where the minimum of the distance difference profile resulted in a Z position of 43cm giving an error of 2cm and Yx of 100.8cm with an error of 8.8cm. On the other hand the least squares best fit, shown in figure 145b, resulted in a minimum of 43cm giving an error of just 0cm and Yx of 91.8cm with an error of 0.2cm.

6.6 Comparative positioning method

The comparative localisation method is different from the methods discussed so far, in this chapter. First it adopts an iterative approach and second it provides Y estimates independently of X and Z estimates unlike all the methods discussed so far.

The comparative method followed an iterative approach whereas numerous theoretical distance difference profiles, $D_T$, were computed over the testing area and then compared to the experimental distance difference profile, $D_E$, in a much up process to identify the position of transmitting node. The X, Z and Y positions resulting in a theoretical distance difference profile minimising the least square approximation in equation (75) were taken as the final positions of the transmitter.

$$\left( X^n_t, Z^n_t \right) = \arg \min_{X_t, Z_t} \left( D^n_{E_t} - D^n_{T_t} \right)^2$$  \hspace{1cm} (75)

The operating principle of the comparative method was based on the fact that the measurement arrangement implied that for different transmitter positions there will always be a different distance different profile. This uniqueness of the profiles was used as a fingerprint to allow for the positions of the transmitter to be derived.
6.6.1 MATLAB implementation

An initial study considered a localisation approach whereas the whole vessel is divided into a grid of 1cm² squares covering all of its area. Here it is assumed that unknown nodes are placed on the grid (figure 146a) and theoretical distance difference readings are recorded along each and all unknown nodes with each and all of the receiving antennas. The above procedure gives a number of distance difference profiles, covering every possible combination between a transmitter and a receiver.

![Figure 146. Comparative positioning diagrams](image)

In order to reduce the number of iterations required in the initial brute force approach a new method was developed. This method builds on the basic profile method whereas the X and Z coordinates of the transmitting nodes are given based on the minimum of the profiles. Based on the approximations of X and Z coordinates the comparative methods looks in an area covering ±10cm from initial X and Z estimates. Simultaneously the algorithm looks for the Y positions of the transmitter.

The algorithm compares the experimental distance profile with numerous theoretical distance profiles within an area covering 10cm from either side of X or Z estimates as well as covering a vertical area of the container just below the estimated X or Z positions as seen in figure 146b. The choice for a look-up area of 10cm on either side from X or Z estimates was based on the analysis of experimental results in the previous chapter. To be more specific the overall localisation error for positions along X and Z axis in chapter 5 was less than 10cm.
The ±10cm covering area was chosen in order to increase the probability for the comparative method to give a good approximation of the transmitter position.

6.6.2 Experimental evaluation

Figure 147 shows the measured positions of the transmitting nodes as opposed the estimated positions along X axis for the comparative method.

![Figure 147. Measured and estimated X axis positions](image)

The AEs from the implementation of the comparative approach are shown in figure 148.

![Figure 148. X axis coordinates error](image)

Figure 149 shows the measured positions as opposed the estimated positions along Z axis.
Figure 149. Measured and estimated Z axis positions

The AE for data along Z axis are graphically shown in figure 150.

Figure 150. Z axis coordinates error

The MAEs for the comparative method, for all positions along both X axis and Z axis as well as the respective STDs are shown in table 15.

<table>
<thead>
<tr>
<th></th>
<th>Small vessel tests</th>
<th></th>
<th>Large vessel tests</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>X</td>
<td>Yx</td>
<td>Y</td>
</tr>
<tr>
<td>MAE(cm)</td>
<td>4.13</td>
<td>8.2</td>
<td>9.81</td>
</tr>
<tr>
<td>STD(cm)</td>
<td>3.3</td>
<td>6.7</td>
<td>6.15</td>
</tr>
<tr>
<td></td>
<td>X</td>
<td>Yx</td>
<td>Y</td>
</tr>
<tr>
<td></td>
<td>51</td>
<td>5.66</td>
<td>18</td>
</tr>
<tr>
<td></td>
<td>24.64</td>
<td>3.8</td>
<td>21.86</td>
</tr>
</tbody>
</table>

Table 15: MAE and STD for the comparative method

The comparative method is the only one, from the seven new approaches discussed in this chapter, that follows an iterative approach towards estimating the position of the transmitting node. Nevertheless, although the average execution time for a single run of this algorithm (~3s) is 20 times the average execution time for the rest of the algorithms (~0.15s); the
accuracies observed when using the comparative method are favourably comparable with the rest of the methods especially when regards to the MAE for the large vessel tests.

### 6.7 Analytical localisation method

The analytical localisation method unlike the previous methods is based solely on the solution of the equations giving the distance difference profiles. This new localisation method essentially computes the position of the transmitter through a derivation of closed form solution of sets of non-linear equations. Equations consist of known (from experiments) distance difference values, \( D_i, D_j \), the coordinates of a reference receiving antenna \((X_0, Y_0, Z_0)\) and the coordinates \((X_n, Y_n, Z_n)\) of subsequent \(n\) receiving antennas as seen in figure 151.

![Figure 151. Receive and transmit position coordinates](image)

For an arbitrary pair of receiving antenna, the non-linear equation relating distance difference data to the coordinates of both of the transmitting node and the receivers is given by the familiar equation (75). Here it is important to note that the measuring arrangement discussed in chapter 4 imposed that TDoA and consequently distance difference data are derived in 2D, i.e. there are always two sets of TDoA measurements one for X axis and another for Z axis. For the analytical method the familiar distance difference equation in 2D is given as follows:

\[
D_{x_i} = \sqrt{(X_{\zeta} - X_i)^2 + (Y_{\zeta} - Y_i)^2} - \sqrt{(X_0 - X_i)^2 + (Y_0 - Y_i)^2}
\]  

(76)

where \( \zeta \) is either i or j
In equation (76) there are two unknowns, the coordinates of the transmitting node \((X_0, Y_0)\), given that parameter \(Dx_i\) is derived from the experiments whilst the coordinates of the receiving antennas are measured by the user. Solving equation (76) for \(X_t\) and \(Y_t\) respectively will result in the location of the unknown node. Note that analysis proceeds with presentation of \(X\) axis equations since these will be the same for \(Z\) axis as well.

As in all localisation methods presented in chapter 4 onwards the measurement plane on which receiving antenna lie, seen in figure 151, is taken as \(Y=0\) thus in all cases \(Y_i=0\). Further the reference antenna (seen in figure 151) is located at the edge of the testing vessel thus defining the origin of the coordinates i.e. \((X_0, Y_0, Z_0)=(0,0,0)\). As therefore, with \(X_0\), \(Y_0\) and \(Y_i\), in equation (76), all set to zero, equation (76) can be solved for \(X_t\), for \(\zeta=i\) as follows:

\[
X_t = \frac{D^2_{x_i} + X_i^2 - 2 \cdot D_{x_i} \left( \frac{X_{i_t}}{2} \sqrt{\frac{X_{i_t} - D^2_{x_i} + 4 \cdot Y_{i_t}^2}{D^2_{x_i} - X_i^2}} \right)}{D^2_{x_i} + X_i^2 - 2 \cdot D_{x_i} \left( \frac{X_{i_t}}{2} \sqrt{\frac{X_{i_t} - D^2_{x_i} + 4 \cdot Y_{i_t}^2}{D^2_{x_i} - X_i^2}} \right)}
\]  

(77)

Similarly, solving equation (76) for \(Y_t\), for \(\zeta=j\), with both \(X_0\) and \(Y_0\) set to zero gives:

\[
D_{x_i} + \sqrt{X_{i_t}^2 + Y_{i_t}^2} = \sqrt{(X_j - X_i)^2 + Y_{i_t}^2}
\]  

(78)

Squaring both sides of equation (78) gives:

\[
D_{x_i}^2 + 2 \cdot D_{x_i} \cdot \sqrt{X_{i_t}^2 + Y_{i_t}^2} + X_{i_t}^2 + Y_{i_t}^2 = (X_j - X_i)^2 + X_{i_t}^2 + Y_{i_t}^2
\]  

(79)

Simplifying (79), rearranging and squaring results in:

\[
4 \cdot D_{x_i}^2 \cdot (X_{i_t}^2 + Y_{i_t}^2) = X_{i_t}^2 \cdot (X_j - 2 \cdot X_i)^2 - 2 \cdot D_{x_i}^2 \cdot X_j \cdot (X_j - 2 \cdot X_i) + D_{x_j}^4
\]  

(80)

Rearranging equation (80) gives:

\[
4 \cdot D_{x_i}^4 \cdot Y_{i_t}^2 = X_{i_t}^4 - 4 \cdot X_{i_t}^2 \cdot X_i + 4 \cdot X_{i_t}^2 \cdot X_i^2 - 2 \cdot D_{x_i}^2 \cdot X_j \cdot X_i + 4 \cdot D_{x_i}^2 \cdot X_j \cdot X_i + D_{x_j}^4 - 4 \cdot D_{x_j}^4 \cdot X_{i_t}^2
\]  

(81)
Solving equation (81) for $Y$ results in:

$$
Y_t = \frac{1}{2 \cdot D_{x_j}} \begin{bmatrix}
\left(D_{x_j} + X_j\right) - \left(D_{x_j} - X_j\right) & \left(D_{x_j} + X_j - 2 \cdot X_t\right) & \left(D_{x_j} - X_j + 2 \cdot X_t\right)
\end{bmatrix}
\left(\left(D_{x_j} + X_j\right) - \left(D_{x_j} - X_j\right) & \left(D_{x_j} + X_j - 2 \cdot X_t\right) & \left(D_{x_j} - X_j + 2 \cdot X_t\right)
\right)^{-1}
$$

(82)

Substituting $Y_t$ from equation (82) to equation (77) eliminates $Y_t$:

$$
X_t = \frac{1}{2 \cdot D_{x_j}} \begin{bmatrix}
D_{x_i} \cdot X_i^2 - D_{x_i} \cdot D_{x_j}^2 \cdot D_{x_j} + D_{x_j} \cdot X_i^2 & 
2 \cdot D_{x_i} \cdot X_j + 2 \cdot D_{x_j} \cdot X_i &
\end{bmatrix}
\begin{bmatrix}
D_{x_i} \cdot D_{x_j} - D_{x_i} \cdot D_{x_j}^2 + D_{x_j} \cdot X_j^2 - D_{x_j} \cdot X_i^2 &
2 \cdot D_{x_j} \cdot X_i - 2 \cdot D_{x_i} \cdot X_j
\end{bmatrix}^{-1}
$$

(83)

Equation (83) contains only known quantities thus allowing $X_t$ to be calculated. A similar approach to the derivation of equation (83) results in equation (84) that gives the $Z$ coordinates of the transmitter.

$$
Z_t = \frac{1}{2 \cdot D_{z_j}} \begin{bmatrix}
D_{z_i} \cdot Z_i^2 - D_{z_i} \cdot D_{z_j}^2 \cdot D_{z_j} + D_{z_j} \cdot Z_i^2 &
2 \cdot D_{z_i} \cdot Z_j + 2 \cdot D_{z_j} \cdot Z_i &
\end{bmatrix}
\begin{bmatrix}
D_{z_i} \cdot D_{z_j} - D_{z_i} \cdot D_{z_j}^2 + D_{z_j} \cdot Z_j^2 - D_{z_j} \cdot Z_i^2 &
2 \cdot D_{z_j} \cdot Z_i - 2 \cdot D_{z_i} \cdot Z_j
\end{bmatrix}^{-1}
$$

(84)

Once $X_t$ and $Z_t$, for each experiment, were derived, these were substituted in equation (82) to derive $Y_t$ estimates.

Solving sets of non-linear equations as described above results in multiple $X_t$, $Z_t$ and $Y_t$ estimates. In fact there are as many solutions as the number of the receiving antennas. To derive single positions out of a $k$ number of $X_t$, $Y_t$ and $Z_t$ values these were substituted back to equation (76) to derive analytical-based distance differences $D_{\text{anl}}$ that are directly comparable to the original distance differences, $D_{\text{orig}}$, giving the analytical localisation results in the first place. As therefore a least square approximation, in equation (85), was used whereas the $X_t$, $Y_t$ and $Z_t$ coordinates, from the analytical algorithm, that produce $D_{\text{anl}}$ values minimise equation (85) are chosen as the final $X_t$, $Y_t$ and $Z_t$ coordinates of the transmitting nodes.
\[
(X_t, Z_t, Y_t) = \min \sum_{i=1}^{k} [D_{i,\text{anl}}^{f} - D_{i,\text{org}}^{f}]^2
\]  

(85)

6.7.1 Experimental evaluation

The analytical localisation algorithm was examined at a practical level through all available experimental distance difference values.

Figure 152 shows the measured positions as opposed the estimated positions along X axis.

![Figure 152. Measured and estimated X axis positions](image)

The AEs for data along X axis are shown in figure 153.

![Figure 153. X axis coordinates error](image)

Figure 154 shows the measured positions and the estimated positions, computed using the analytical method, along Z axis.
The AEs for data along Z axis are shown in figures 155.

The MAE for the comparative method, for all positions along both X axis and Z axis as well as the respective STDs are shown in table 16.

<table>
<thead>
<tr>
<th></th>
<th>Small vessel tests</th>
<th></th>
<th>Large vessel tests</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>X</td>
<td>Yx</td>
<td>Y</td>
</tr>
<tr>
<td>MAE(cm)</td>
<td>5.32</td>
<td>9.3</td>
<td>9.4</td>
</tr>
<tr>
<td>STD(cm)</td>
<td>4.2</td>
<td>6.4</td>
<td>6.15</td>
</tr>
</tbody>
</table>

Table 16: MAE and STD for the Analytical method

The analytical method proved, once again, that using all distance difference values, in each experiment, to compute the position of the transmitter is best way to move forward. Accuracies in the analytical method were as good as the accuracies observed in the advanced IALED, BMLS and in ACL.
6.8 Summary

This chapter presented the theory behind seven novel TDoA-based localisation methods. These methods were evaluated using experimental distance difference values; obtained using the IALED method that provided the most accurate results (discussed in chapter 5).

The MAE from all localisation methods, using data from tests in the small vessel, discussed in chapter 4, 5 and 6 are summarised in table 17.

<table>
<thead>
<tr>
<th>Algorithm</th>
<th>X</th>
<th>Y</th>
<th>Y'</th>
<th>Y''</th>
<th>Z</th>
</tr>
</thead>
<tbody>
<tr>
<td>Prototype (RGLED)</td>
<td>5.81</td>
<td>18.9</td>
<td>19.02</td>
<td>19.14</td>
<td>7.4</td>
</tr>
<tr>
<td>Prototype (BALED)</td>
<td>4.3</td>
<td>7.14</td>
<td>10.3</td>
<td>13.41</td>
<td>9.6</td>
</tr>
<tr>
<td>Prototype (IALED)</td>
<td>5.6</td>
<td>13.35</td>
<td>12.83</td>
<td>12.3</td>
<td>4.71</td>
</tr>
<tr>
<td>BMFS</td>
<td>9.63</td>
<td>27.96</td>
<td>37.2</td>
<td>44.42</td>
<td>9.42</td>
</tr>
<tr>
<td>BMLSD</td>
<td>4.31</td>
<td>7.14</td>
<td>10.3</td>
<td>13.41</td>
<td>4.62</td>
</tr>
<tr>
<td>BMLSD</td>
<td>5.56</td>
<td>13.13</td>
<td>12.72</td>
<td>12.3</td>
<td>4.71</td>
</tr>
<tr>
<td>BCL</td>
<td>6.9</td>
<td>27.45</td>
<td>22.83</td>
<td>18.2</td>
<td>5.94</td>
</tr>
<tr>
<td>ACL</td>
<td>6.98</td>
<td>8.6</td>
<td>9.5</td>
<td>10.35</td>
<td>7.91</td>
</tr>
<tr>
<td>Comparative</td>
<td>4.13</td>
<td>8.2</td>
<td>9.92</td>
<td>11.44</td>
<td>5.4</td>
</tr>
<tr>
<td>Analytical</td>
<td>5.32</td>
<td>9.3</td>
<td>9.4</td>
<td>9.5</td>
<td>6.43</td>
</tr>
</tbody>
</table>

Table 17: MAEs for all localisation methods in the small vessel

A detailed analysis of the performance of the prototype localisation algorithm in chapters 4 and 5 revealed that the accuracy of LE detection methods and consequently the accuracy of distance difference values determine the precision of the localisation results. Furthermore, a close examination of the distance difference profiles showed that errors are distributed amongst all values randomly, that is no individual distance difference value at any receiving antenna-transmitter combination shown to be consistently more accurate than any other case.

The above observations can be used to interpret the MAEs in table 17. The prototype RGLED-based algorithm provided highly erroneous results since the method used to detect the LE resulted in erroneous distance difference values. The implementation of two advanced LE detections methods (BALED, IALED) especially of the IALED method improved localisation accuracies (see chapter 5).

The BMSF and the BCL methods employed only a limited quantity of the available distance difference values, in each experiment. Here, the exclusion of some values couldn’t guarantee that the remained values were not affected by noise to the extent that their usage could provide accurate results. In fact, the design of the BMSF and of the BCL algorithms was
based on observations from analysis of theoretical distance difference profiles and didn’t take into account the presence of noise. As such, the MAEs for those two methods especially the once concerning Y estimates, in table 17, are representative of the deficiencies of the algorithms. Note that the rest of the new algorithms employed all the distance difference values obtained at each experiment and implemented advanced methods to deal with errors in distance difference values.

A review of all MAEs in table 17 points out that Y estimates in all algorithms are significant higher that X and Z position estimates. This is a direct result of the use of equation 71 to estimate $Y_t$ that is deeply dependent on the accuracy of the minimum value in the distance difference profile. Note that the minimum value in the distance difference profile appears both in the numerator and in the denominator of equation (71) thus any errors in these values can have significant impact on $Y_t$. This can be explained through an example as follows.

Consider a transmitter, in a 2D plane, at $X_t=42\text{cm}$, $Y_t=72\text{cm}$ in the setup seen in figure 104, giving a minimum distance difference value of $-11.3\text{cm}$. If $X$ in equation 71 remains constant at 42cm but the minimum of the distance difference value is altered in $\theta$ steps (0.5cm up to 6cm) then this introduces errors in the computation of $Y_t$. A plot of the absolute distance difference errors (i.e. $|{-11.3}-\theta|$) against the absolute errors in $Y_t$ ($|72- Y_t$ from equation 71]) is shown in figure 156.

![Figure 156. Errors in profiles Vs errors in $Y_t$](image)

Figure 156 demonstrates that even a small increase in the distance difference error of 0.5cm results in an increase in $Y_t$ errors of 10cm, reaching an increased $Y_t$ error of 90cm even with 6cm error in the minimum distance difference value. These observations verify the
dependency of $Y_t$ on the value of the distance difference and justify the increased errors in $Y_t$ estimates even when errors for $Z_t$ and $X_t$ are low.

Similar trends in the MAEs, to the once characterised localisation in the small vessel, were observed in the MAEs for localisation inside the large vessel as seen in table 18.

<table>
<thead>
<tr>
<th>Algorithm</th>
<th>Large vessel MAE (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>X</td>
</tr>
<tr>
<td>RGLED</td>
<td>33.75</td>
</tr>
<tr>
<td>BALED</td>
<td>25.4</td>
</tr>
<tr>
<td>IALED</td>
<td>26.45</td>
</tr>
<tr>
<td>BMSF</td>
<td>30</td>
</tr>
<tr>
<td>BMLS</td>
<td>37.57</td>
</tr>
<tr>
<td>BMLSD</td>
<td>37.7</td>
</tr>
<tr>
<td>BCL</td>
<td>24.67</td>
</tr>
<tr>
<td>ACL</td>
<td>28.6</td>
</tr>
<tr>
<td>Comparative</td>
<td>51</td>
</tr>
<tr>
<td>Analytical</td>
<td>37.22</td>
</tr>
</tbody>
</table>

**Table 18: MAEs for all localisation methods in the large vessel**

The MAEs depicted in table 18, in particular those for $Y$ estimates were significantly higher than the MAEs in table 17. Here, the increase in the errors is directly related to the increased errors attained in the estimation of distance differences as discussed in chapters 4 and 5.At this stage it should be noted that large scale tests were only preliminary and substantially more measurements are required to allow expressing solid conclusions on the impact of placing the transmitters in large distances (>2m) from the receiving antennas.
CHAPTER 7

NETWORK-BASED LOCALISATION

7.1 Introduction

The UWB-based localisation methods, discussed in the previous three chapters, are all range based, by the classification introduced in chapter 2. Special-purpose hardware is used to estimate range (actually range/distance difference), which is then used in the determination of the position of nodes. Although the investigations of the previous chapters showed that a positional accuracy of less than 5cm can be achieved under laboratory conditions, there are at least two reasons to believe that this accuracy might be problematic in very deep silos.

The first reason for believing that it might not be possible to obtain as good accuracy on large silos, as in the laboratory, concerns the results of measurements, taken in the larger vessel and reported throughout the last two chapters. From the limited data available it appears that for the transmission powers used in the tests, the maximum transmission range of the UWB pulses from the nodes is approximately 2m. The second reason is a corollary of Theorem 5 from chapter 6. For fixed $X_t$ and $Z_t$, distance difference reduces with increasing $Y_t$. This means that a fixed-size error in distance difference estimate will lead to increasing errors in the estimate of $Y_t$ as the depth of the transmitter inside a vessel increases. The quality of the estimates for $X_t$ and $Z_t$ will also be affected, since according to Theorem 5 (in chapter 6), distance difference profiles become flatter as transmitter depth increases, making the estimation of the position of minimum distance difference increasingly error prone.

On the basis of the above reasoning, it was decided to investigate the applicability of network-based techniques for localisation, of the type discussed in chapter 2 and which used the sensor node’s NB RF transceivers. The RSS data were collected during a set of in-silo networking experiments and used to evaluate the feasibility of network-based positioning.
The WSN4IP node hardware and software are briefly reviewed in section 7.2 and issues concerning antenna and node radiation are considered in section 7.3. A set of networking experiments, conducted in a large vessel are briefly summarised in section 7.4 and section 7.5 contains preliminary results obtained using some of this data with a MATLAB implementation of two network-based localisation methods. The data used were produced by another member of the WSN4IP team and only became available at a later stage of the current work. Hence only preliminary results are included.

7.2 WSN4IP nodes

In this section the basic hardware and software of the WSN4IP nodes is introduced briefly. The radiation patterns of the node’s antenna and of the complete node are also discussed and the impact of grain on propagated signals is thoroughly examined.

7.2.1 WSN4IP hardware and software

Sensor node hardware and software were developed in the WSN4IP project. The node hardware was based around a backplane organisation that included a number of printed circuit boards (PCB), a microcontroller PCB, an RF transceiver PCB, a sensor PCB, an UWB transmitter PCB and a battery board as illustrated in figure 157.

![Figure 157. WSN4IP sensor node integrated parts [28]](image_url)

The microcontroller PCB was based on a PIC32 microcontroller with an on-board RAM and 2GB flash memory. This board executes system software, principally the communication protocol stack (see below) and application-level software. The RF transceiver board is based...
around a Chipcon CC1101 transceiver which operates in the 868 MHz range of unlicensed ISM bands. This particular device was chosen because it is highly configurable in terms of many important radio parameters such as transmission power, frequency bands etc. This degree of configurability was necessary due to the lack of knowledge of the radio channel in grain. The board also contained a quarter wavelength helical antenna.

**Figure 158. WSN4IP sensor node**

The UWB circuit has already been discussed in chapter 4 and the sensor PCB was not used in this work and is not discussed further. It should be noted that although all the elements discussed above were built and tested, the complete node shown in figure 157 was never integrated within the lifetime of the WSN4IP project. In particular, the UWB positioning system has not been integrated with the rest of the node hardware.

The generation of UWB pulses was controlled by hardware that was independent of the software running on the PIC microcontroller. However, in the future it is anticipated that the PIC microcontroller will control both data communication and UWB propagation. The employed UWB localisation system was discussed in greater detail in chapter 4.

Tests were carried out in large scale silos (2.5m deep, 1m across) filled with grain. Further details of the testing arrangements can be found in chapter 4.

### 7.3 Node radiation characteristics

In network-based localisation using RSS, the antennas employed in the system have a key role in determining localisation accuracy [52]. It has been observed that the use of antennas in non-air medium as well as the orientation between receiving and the transmitting antennas
can have significant impact on RSS [52, 18,38, 39]. To investigate the behaviour of the antennas used in the WSN4IP node a programme of measurements was undertaken by the author and other members of the WSN4IP team.

Measurements were taken inside an anechoic chamber, in air and with the antennas immersed inside grain using a Vector Network Analyser (VNA). Note that prior to any measurements with the VNA a full calibration procedure was followed to remove systematic errors resulting from external parameters such as the cables connecting the antenna to the VNA.

7.3.1 Antenna response in air

Prior to any tests, the radiation pattern of the antenna was derived through measurements inside an anechoic chamber using the arrangement seen in figure 159.

The radiation pattern of the antenna alone for the ZY plane with the antennas facing each other is shown in figure 161.
On the other hand the radiation pattern of the antenna alone for the XY plane with the antennas facing each other is shown in figure 162.

Figures 161 and 162 indicate that the antenna’s radiation pattern is almost isotropic in planes perpendicular to the axis of the antenna, but significant directionality exists, with strong side lobes, in planes containing the antenna’s axis.

The next issue to be considered was the effect of the antenna sheath. The antennas were off-the-shelf components that were supplied in a protective plastic sheath. However the sheath had to be removed to allow the antennas to fit into the enclosing mortar shells. Information on the characteristics of the antennas and in particular its frequency were specified by the
manufactured through tests in air. Tests were carried out using a VNA to examine the effect of removing the sheath on the helical antenna coil. In the above measurements, a single antenna was connected, via a cable to the VNA, in order to measure the input reflection coefficient, S11, at 868MHz. The reflection coefficient S11⁵ provides an indication of how well an antenna is tuned to work in a specific environment; the smaller the value of S11 the better the antenna works since it shows that the overall reflected voltage from the antenna into the VNA is less than the voltage going into the antenna.

S11 measurements with (covered) and without (bare) the sheath, are shown in figure 163. These results revealed that the removal of the plastic sheath shifts the resonance frequency from the nominal value of 868MHz (measured resonance in figure 163 was 872.5 MHz) to about 925MHz [114].

![Figure 163. Antenna response in air [114]](image)

The shift in the resonance frequency is caused by the different dielectrics surrounding the metal antenna coil. Detuning of antenna in grain is discussed in the following section.

7.3.2 Antenna response inside grain

Research in the GlacsWeb project [8-9] and in the networking experiments in silage [18-19] revealed that antennas detune when operating in a non-air medium. In this connection, tests were carried out by the author and other members of the WSN4IP team to establish the impact of grain on the antennas.

⁵ S11 is a measure of the ratio of voltage reflected from the antenna back to the VNA over the voltage delivered to the antenna. The smaller the S11 the better the antenna works.
Initial measurements were taken with the single antennas covered with the protective sheath being buried in grain. These results are shown in figure 164.

![Antenna in air](image1.png) ![Antenna inside grain](image2.png)

**Figure 164. Antenna response in air and in grain**

Figure 164a shows that S11 is at -16dB at 868MHz when the antenna is in air whilst figure 164b shows that S11 goes to -25dB when the same antenna is immersed inside grain. The frequencies at which the antenna is most responsive shifted from 868MHz in air to about 633MHz in grain.

The shifts in resonance frequencies are attributed to the high dielectric constant $\varepsilon'$ of grain ($\varepsilon'$=3) compared to only $\varepsilon'$= 1 for air that causes a reduction in the speed of the propagating radio signal. The speed of propagation equals to the inverse of the square root of the medium’s dielectric constant [43, 45]. An increase in the dielectric constant will reduce the speed of the propagating signals inside silage thus reducing the frequency of the signals.

The decrease in the speed of the propagating wave reduces the wavelength $\lambda$ of the radio signal as depicted in equation (1). In this equation the frequency of the radio signal is fixed, thus a change in the speed of the radio signal results in a change of the wavelength. The length of the antennas used in the experiments was quarter wavelength long, tuned to work at free space.

To alleviate the problems caused by the detuning of the antennas inside grain, the length of the antennas was systematically reduced, to match up the wavelength inside grain, until resonance returned to the nominal value. Figure 165 illustrates a tuned 868MHz antenna operating inside grain.
Figure 165. Tuned antenna inside grain

Figure 165 shows the frequency response of 868MHz antenna after tuning. It can be seen that the S11 went up to -37.5dB which is an indicative of the reduction of the reflected signals from the antenna which is a significant improvement. Further the resonance frequency returned at 868MHz.

7.3.3 Antenna response whilst inside mortar shells

Results presented in the previous section were obtained with the antenna in physical contact with the grain, which is not representative of the WSN4IP nodes, where the antenna will be in contact with the air inside the node’s mortar shell. As therefore it was anticipated that the antenna will behave differently from what was discussed in section 7.2.2. To investigate how the antenna responds whilst inside the mortar shell further tests were carried out.

For these tests, the antenna SMA coaxial connector was disconnected from the CC1101 transceiver on the WSN4IP node and connected to the VNA via a cable as seen in figure 166.

Figure 166. Antenna inside the protective sphere [114]

Figure 167 compares the response of the antenna (S11) when inside the sphere enclosing the WSN4IP nodes (figure 166) and when outside.
Figure 167. Antenna response inside the protective sphere [114]

Figure 167 shows the antenna response in three situations a) using the single antenna in air (as in section 7.2.1), b) when antenna was inside the mortar shell in air (see figure 166) and c) when the antenna was inside the protective mortar shell that was buried inside grain. What is shown in figure 167 is that there are no major variations in the antenna response in any of the test cases and that the antennas behave in the same way as in an air environment. This can be explained based on the fact that the VNA measures $S_{11}$ by sending a very small amount of voltage and measuring how much of this is reflected back to it, that is $S_{11}$ represents a measure of the immediate surrounding area (smaller than near field region) of the antenna that is limited within the area bounded by the volume of the protective sphere.

7.4 The effect of antenna orientation

The effect of antenna orientation is of interest, since it is expected that nodes inserted in a silo will assume a random orientation with respect to their antennas. The radiation pattern in figure 162 gave a first indication that the orientation of the antennas is a major factor that needs to be considered carefully in the effort for RSS-based localisation [52].

A preliminary study, conducted by the author, showed that antenna orientation can have significant impact on RSS. To this extent, measurements were carried out using a VNA and two 868MHz helical antennas.

Prior to any measurements, using the VNA, a full calibration procedure was followed. Calibration is a procedure that improves the accuracy of VNA results by removing systematic errors resulting from external parameters such as cables and any other equipment connected.
to the VNA. The magnitude and the phase of these errors cannot be predicted and therefore it is considered that they add a certain degree of uncertainty to the measurements, thus making calibration even more essential [129]. Further the averaging function of the VNA was enabled so that the average of 128 measurements was recorded for each of the S parameter readings, thus increasing in the accuracy of the results [129].

Two antennas, one transmitting and one receiving were connected to the VNA to measure received signal strength (S21) for antenna orientations seen in figure 168.

![Antenna orientation positions](image)

**Figure 168. Antenna orientation positions**

The transmitting power was set at 10dBm throughout the experiments and measurements were taken at 868MHz. Measurements in air were taken using antennas that were tuned to operate in air. On the other hand measurements inside grain were taken using antennas tuned to operate in air as well as antennas tuned to work inside grain. Tuning of the antennas was achieved by shortening the length of their metal coil to bring the wavelength of the antenna to a level that allowed antennas propagate at 868MHz inside grain. Results from these measurements are shown figure 169.

![Antenna tests inside grain and in air](image)

**Figure 169. Antenna tests inside grain and in air**
What can be seen in figure 169 is that RSS reduces as the distance between the receiving and transmitting antennas increases. Further, antenna orientation and specifically elevation orientation caused significant attenuation with a reduction of 10dBm in RSS when compared with the azimuth antenna orientation.

### 7.5 The effect of WSN4IP antenna orientation

The radiation patterns of the antenna in orthogonal planes are discussed briefly in section 7.2.2. However, since the antenna is partly located within the backplane structure of the node (see photograph in figure 170a), its radiation pattern is likely to be affected by this. In addition, it is expected that during grain flow node’s antenna will assume a random orientation.

The radiation pattern of the helical antenna, discussed in section 7.2.1, showed that this changes according to the angle between transmitting and receiving antennas. This effect is anticipated to be more intense in the case of the antenna inside the WSN4IP node; given a significant portion of the antenna is surrounded by the metallic backplanes that include live components; adding to the causes of possible distortions to the antenna radiation pattern.

To examine the impact of the WSN4IP backplanes on the radiation pattern of the antenna, a programme of measurements was undertaken in the anechoic chamber utilising a fixed dipole antenna, acting as a transmitter. The node itself was not operational during these experiments and although the battery was inside the node this was not connected to the node. The output of the WSN4IP antenna was fed via a cable to a VNA to acquire the radiation pattern. The node was placed on a turntable as shown in figure 170 allowing it to be rotated in small increments about the axis between measurements.

![Image](image.png)

(a) WSN4IP node rotating anticlockwise  
(b) Dipole 868MHz antenna

**Figure 170. WSN4IP node Vs dipole in anechoic chamber starting at 0°**
The radiation pattern of the WSN4IP node antenna at an angle to the dipole of 0° is shown in figure 171.

![Figure 171. Radiation pattern for the WSN4IP node at 0°](image171.png)

The radiation pattern in figure 171 indicates there are two side lobes with the stronger lobe resulting when the WSN4IP antenna and the dipole face each other from the side of the WSN4IP node that there is no backplane.

To further understand the effect of random orientation of WSN4IP nodes, while these move with grain flow, a more detailed 3D radiation pattern of the WSN4IP antenna was derived by the author of [114] over numerous angles (shown on each axis) as seen in 172.

![Figure 172. WSN4IP antenna 3D radiation pattern [114](image172.png)

The WSN4IP antenna radiation pattern, shown in figure 172, is severely asymmetric with a number of significant null points. These are related mainly to the backplane structure and partly to the manual method used to place the node at different angles that introduced a level.
of errors [114]. Figure 172 serves to indicate that antenna gain can change very rapidly for a small angle variation (1° to 2°) [114]. As such in cases were simple log-normal law is used to interpret RSS to distance, strong RSS could be perceived as nodes being close to each other were in fact nodes are far apart and vice versa.

The author of [144] investigated the possibility of using information from the 3D pattern to implement corrections to RSS, assuming that the orientations of received and transmitter are known. This appears to be possible, however, as noted in [114], it is difficult to ensure an error free radiation pattern that will cover every possible angle thus any compensation on RSS based on the antenna patterns could not ensure 100% effectiveness.

Overall, these results demonstrate that for an efficient localisation approach using RSS information it will be necessary to take into account the relative orientation of the receiving and the transmitting antenna. Similar observations were recorded in extensive RSS measurements in [52] where it is also stated that antenna orientation is a major factor that needs to be examined carefully when considering RSS-based localisation.

7.6 Networking experiments in grain

A programme of networking experiments was designed by another member of the WSN4IP team in which the ability of nodes immersed in grain to form network links was investigated. This study used ten nodes and produced data about the variation of RSS with transmission power and position, and the influence of transceiver variables such as transmitter power, carrier frequency, data rate etc on parameters such as bit and packet error rates [114].

Since the RSS data were needed for the preliminary assessment of network-based localisation, the author assisted in the design and implementation of the experiments.

7.6.1 Experimental configuration

A total of ten nodes were placed at predetermined positions inside the large silo that was introduced in chapter 4. Nine nodes were placed in a rectangular grid in a plane in the centre of the vessel. A 10th node was located at the top of the silo and was used for the purpose of providing timed transmissions to control the other nine nodes and the progress of the experiments. The experimental arrangement is shown in figure 173.
The experiments were performed according to a pre-programmed schedule. For a particular combination of transceiver parameters each of the nine nodes in the grid in turn took the role of transmitter, whilst all other nodes were placed in receiver mode. Nodes stored received data in their own flash memory for later retrieval and processing.

The results discussed in section 7.2.3 showed RSS can vary rapidly with angle at fixed transmission power and distance. It was anticipated that the 3D radiation pattern shown in figure 172 could be used to associate RSS to a particular direction thus dealing with random fluctuations in RSS due to orientation. However, this required the relative orientation of the transmitter and receiver to be known. Based on the intended arrangement of nodes specified above, it was necessary to ensure that the nodes were all in a fixed orientation. This was a difficult practical problem to solve given that any accurate placement of nodes in the silo had to be followed by the insertion of grain, which could easily disturb the position and orientation of the nodes.

After many different options had been considered, a system which fixed the nodes in position in an empty silo and which kept their position during filling of the silo was chosen. A node suspension ‘structure’ was created from high tensile-strength fishing line and plastic tubing both of which were unlikely to affect the RF transmissions occurring during the experiments. The structure was supported from a metal bar across the top of the silo. Each mortar shell had eye-hooks glued to the top and bottom to allow the assembly of the node array, as can be seen in figure 174. Plastic tubes were inserted through the bottom of the spheres to prevent the

Figure 173. Node's positions inside silo
shells from rotating and helping them to maintain a fixed node orientation. The whole assembly was attached to another mortar shell (anchor) that was placed in the bottom of the silo to guarantee nodes did not move with the flow of grain whilst the silo was filled. The anchor was fixed at the bottom of the silo thanks to the heaviness of grain and it balances the whole apparatus through the filling process.

The whole assembly was lowered into the silo and measurements taken prior and after the silo was filled with grain. Lowering of the assembly into the silo required significant effort that was made even more difficult by the presence of a safety net covering the silo opening and from the heaviness of the whole assembly. The author worked along a co-researcher from the WSN4IP project and devised a method that allowed the lowering the assembly in steps and the attachment of the plastic bar to sets of three nodes at a time until all nodes were placed inside the silo and attached to the plastic bars.

The complete experimental assembly with the nodes attached to the plastic bars and the fishing wire is shown in figure 174.

![Experimental apparatus](image)

**Figure 174. Experimental apparatus**

Measurements, using the apparatus in figure 174, were conducted both in air and whilst the silo was filled with grain at six different data rates: 1.2, 2.4, 4.8, 10, 28.4 and 76.8 in kb/s and at a frequency range at 50kHz intervals between 867MHz to 869MHz. Further for each data rate, nine transmitting powers were examined: 0.62, -3.52, 5.76, 7.67, -8.02, 10.15, -13.24, -18.27, -25.25 in dBm [114].
The RSS register, on each transceiver (Chipcon CC1101), is eight bits wide and is accurate to ±0.5dBm. As such another WSN4IP researcher attempted to calibrate RSS to improve its accuracy [114]. Calibration involved using a signal generator to generate signals of known power and frequency to allow measuring RSS. In the first stage, the signal generator was connected, via a cable, to the antenna input of the node’s transceiver. In the other stage, the signal generator was connected, via a cable, to a power meter thus providing a more accurate RSS measurement. These tests revealed that, in both cases, variations in frequency didn’t have significant impact on RSS. On the other hand, tests with different transmit powers shown that the CC1101 transceiver could accurately detect signals up to certain transmit powers [114]. The information from RSS calibration was used to process the experimental results accordingly. More details on this work can be found in [114].

The following sections present networking and localisation results based on a data rate of 4.8kb/s at a transmit power of -3.52dBm at 868MHz. These values were chosen as being representative of typical network behaviour of the obtained results.

7.6.2 Networking results

The networking experiments produced an extremely large amount of data about networking in grain. However, the general trends relevant to this work can be summarised as follows. RSS does appear to reduce with increase distance and over the frequency range investigated; carrier frequency has no impact on RSS [114]. Hence in most experiments, the network had full connectivity, as shown in the sample plot of figure 175. However, at highest datarates and lowest transmission powers, only partial connectivity was observed [114].

![Figure 175. Network connectivity](image)
The experimental data only became available late in this project and so there was not time to perform an extensive study of network-based localisation using all data. It was decided to consider a single set of experimental results and to apply two simple network-based positioning algorithms to the data. The selected results were obtained under the same conditions as figure 175 i.e. a transmit power of -3.52dBm, a carried frequency of 868MHz and a data rate of 4.8kb/s. This particulate condition was chosen because it was representative of many others.

Figure 176 shows characteristic RSS plots against distance for nodes 3 and 8. These figures, and indeed all of the figures showing RSS over distances, indicate that although RSS varies randomly with distance the overall trend is for RSS to reduce as distance between a transmit and a receive node increases.

The variability in RSS is mainly attributed to the WSN4IP backplanes, surrounding the antenna, that alter the radiation pattern of the antennas as discussed in section 7.5. A characteristic example of the impact of the backplanes is the overall observation that nodes on the same horizontal level had higher RSS amongst them than any other orientation. This observation is supported by the antenna radiation pattern shown in figure 171 where WSN4IP antenna radiation was stronger on the sides were backplanes didn’t obstruct LOS of the antenna.

An additional cause of random RSS fluctuations is the fact that signals propagate from an air environment inside the protective shells, through grain and back to air inside another mortar.
shell. This inevitable gives rise to multipath due to multiple reflections and refractions thus causing random fluctuations in RSS.

The variability of these results, which are typical of the RSS data reported in [114], means that it is not possible to derive reliable log law parameters (e.g. path loss). In turn, this means that it is not feasible to use any network-based positioning approach which relied on the log law described in section 2.2.2.

Based on the above, it was decided to use two localisation algorithms that are relatively robust to random RSS fluctuations

7.6.3 Localisation results

Network based localisation was implemented using information from RSS signals derived in the experiments described above. Note that in any one time a node on the grid placement is considered to be the unknown node whose position is to be estimated. At the same time the rest of the nodes are considered to be anchors and are used as such in the localisation process.

The first attempt for localisation employed the centroid approach discussed in section 2.4.6. In this case, given all nodes can communicate with each other (figure 175), in principle, if anchors can broadcast their coordinates to the unknown then the latter can compute its position as the centroid of all anchors. However, this is a very simplistic and inaccurate approach. A more accurate localisation method considered employing information from experimental RSS data.

Given information from RSS signals and specifically given the fact that RSS values are significantly stronger for nodes on the same horizontal level (figures 176a-176b) then it is possible to associate RSS with specific node positions and use this information to compute the positions of the unknown nodes. To be more specific if an unknown node can receive the locations of a number of anchors along with respective RSS from those anchors then it can sort anchors with respect to RSS. In this way an unknown can take the centroid of those anchors giving the strongest RSS to compute its position. This approach incorporated in an algorithm running in MATLAB and executed using experiments RSS data.
Figure 177a shows the estimated positions for all nodes in the system. In this case, since RSS was strongest amongst nodes on horizontal level and given there were only two anchors for one unknown, position estimates were derived using the centroid of only two anchors. On the other hand, figure 177b shows an implementation of the same method but this time using four anchors, in the localisation process, with the highest RSS to the unknown.

![Figure 177](image)

(a) Two anchors centroid  
(b) Four anchor centroid

**Figure 177. RSS based centroid localisation**

The MAE for position estimates using the centroid of only two anchors was 0.31m for X positions whilst MAE for Y estimates was 0.18m. These results are justified by the fact that the unknown nodes are on the same Y level as the anchors and as such Y estimates errors are low. Note that the highest Y error occurs for node 1 since this doesn’t have any nodes on the same horizontal level. In Figure 177b it is obvious that an increase in the anchors in the centroid causes position estimates to be drawn closer to the centroid of the experimental setup with subsequent increase in localisation error. In fact the MAE for four anchors in the centroid was 0.33m for X positions and 0.305m for Y positions.

The proposed centroid-based localisation approach depends on the principle that RSS values will follow specific trends based on the orientation amongst sensor’s antennas. To this extent, it serves to indicate that associating RSS to antenna orientation can be useful tool in localisation especially in cases were nodes might be inside dynamic processes causing random changes in nodes orientation.

Network-based localisation was also implemented using the Ecolocation algorithm discussed in section 2.4.8. Figure 178a and 178b shows the estimated positions using Ecolocation against the measured positions when using two anchors and with four anchors respectively.
Ecolocation results using experimental RSS readings, in grain tests, shown to reach accuracies between 0.1m and 1m [125].

These results compare favourably to the experimental investigation of Ecolocation presented in section 2.4.8 where for indoors tests using 12 nodes over an area of 120 m$^2$ the localisation errors were at about 100cm.

7.7 Summary

Work presented in this chapter examined network based localisation within the context of localisation of sensors inside vessels filled with grain.

Based on the knowledge acquired from literature review on networking inside non air medium, presented in sections 1.3 and 1.6 preliminary tests were conducted to determine the impact of grain on the sensor nodes. These results revealed that as long as the antennas are inside the protective mortar shell then grain doesn’t cause detuning. However, the fact that signals need to propagate from air (inside mortar shells) through grain and back to air raises certain concerns since it inevitably gives rise to reflections and refractions all contributing to multipath that makes localisation based on RSS challenging.

Analysis of the antenna radiation pattern, whilst inside the WSN4IP node, shown that this is affected by the PCB boards. The correlation between antenna orientation and the node’s PCBs is a critical factor that needs to be considered carefully especially in RSS based localisation. To this extent, the two algorithms examined in this chapter showed that RSS-based localisation depends greatly to all of the parameters affecting RSS.
CHAPTER 8
DISCUSSION AND FUTURE WORK

8.1 Discussion

This chapter begins with a summary of the work that has been carried out during this research project and the results that have been obtained. A number of issues that have been raised by the UWB-based localisation work are considered in section 8.2 with issues related to network-based localisation being discussed in section 8.3. Proposals for further work on all localisation methods are discussed in the last two sections of this chapter.

8.2 Thesis summary

The work presented in this thesis concerns the localisation of wireless sensor nodes that are immersed in an industrial process contained inside vessels. Chapter 1 discussed the motivation for the work and explained that the techniques developed were to be applied to the localisation of sensor nodes within grain silos. The basic theory behind localisation, and network-based localisation algorithms developed for WSNs, are discussed in chapter 2. Since this work, for reasons discussed in section 1.5, has been concerned with further development of a UWB-based localisation system, a review of UWB-based localisation systems is presented in chapter 3.

Chapter 4 contains a discussion of the prototype UWB-based localisation system that formed the basis of this work. The system consists of an antenna array mounted above the process vessel which receives UWB pulses, transmitted by WSN nodes that need to find their positions. Received signals from the antenna array are digitised by a DSO and processed by a MATLAB program running on a PC. The software identifies the LEs of the signals arriving at each antenna and used this information to derive TDoA data. TDoA data are then used in an iterative, positioning algorithm, to calculate an estimate of the transmitter’s position.

The hardware and software of the prototype localisation system are outlined in chapter 4. The developers of this system did not perform a detailed experimental investigation of the performance of this system, and so this was undertaken as an early part of this research. The
results are presented and discussed in sections 4.7 to 4.9. An analysis of the results obtained from this experimental study using the RGLED method revealed that large localisation error were often (69% of all position estimates) caused by an incorrect estimate of the LE positions. To be more specific, in a total of 64 position estimates for X, Z and their respective Y coordinates, 48% of positions had errors above 10cm. In addition 47% of the distance difference profiles derived from the RGLED method had errors above 5cm. The errors arose because the LE identification procedure was based on user observation of signals and was difficult to apply consistently.

In response to the problems described in chapter 4, two automated LE detection algorithms the BALED and the IALED were developed and thoroughly examined in chapter 5. Results showed that 40% of position estimates had errors above 10cm for the BALED method whilst only 19% of position estimates had errors above 10cm when using the IALED-based localisation method. The respective data for distance differences for the BALED method resulted in 31.25% of errors above 5cm with the errors in IALED almost halved with only 18.75% of errors above 5cm. Data from the IALED method proven to be the most accurate from all LE detection methods with errors halved when compared to the prototype RGLED method presented in chapter 4.

Chapter 6 concerned with using the properties of distance difference profiles (equivalent to TDoA profiles) measured by an antenna array mounted above the process vessel of interest, to determine the position of the transmitter. The chapter begins with a number of simple, mathematical proofs of the properties of distance difference profiles and is followed by proposals for seven localisation algorithms, all of which are related to the distance difference approach. The results of the IALED method giving the most accurate distance difference profiles, in chapter 5, were reprocessed with each of these new localisation algorithms. Review of MAEs for all the new methods showed that these range from 4cm up to 10cm for X and Z position estimates. However MAEs for Y positions, in cases reached up 30cm. The reason for this, is the direct dependency of the mathematical equation, giving Y estimates, on distance differences as described in section 6.7.

The average execution time for all algorithms was measured using a stop watch function in MATLAB (tic-toc). The execution time for the new localisation algorithms presented in Chapter 6 was about 0.15s except for the comparative method for which the execution time.
reached 3s. These times compare favourably with the average execution time of the prototype localisation algorithm (discussed in chapter 4) that was 0.25s. Note that the time it takes to compute TDoA using cross-correlation is about 23s, and so reducing the execution time of the localisation algorithm only has a small impact on the overall time needed to compute the position of the transmitter.

Network-based localisation is re-introduced in chapter 7. Data for its implementation became available at a late stage of this research, and so there was only time for a limited study. The data was obtained from experiments that were designed for the purpose of obtaining a sound understanding of the RF channel in grain and investigating networking issues such as link formation [114]. However, RSS data produced from these experiments provided data that could, in principle, be used with a variety of network-based localisation schemes that use RSS for some kind of range estimation (typically via the log-normal law- see section 2.2.2). Unfortunately, the hardware design of the wireless sensor nodes, along with the location of the antenna in the middle of the node electronics, gave rise to a severely non-uniform node radiation pattern (seen in section 7.2.4). Experimental RSS results from [114] show some of the expected trends (e.g. falling RSS with increasing received-transmitter separation), but are not consistent enough to enable trends (e.g. the log normal law in section 2.2.2) to be clearly identified. The results show noticeable variation with direction relative to the transmitter’s antenna.

Given the difficulties with the experimental data, the Centroid [58,63] and Ecolocation [124] algorithms were selected for application to the experimental results, since the Centroid approach merely required the existence of links to anchors, and the Ecolocation algorithm works by ranking the RSS values at the receiver due to transmissions from all in-range anchor nodes. This makes the method robust to issues such as multipath [124].

Due to time constraints, the algorithms were applied to a single test case, selected on the basis that it is representative of other results obtained under a variety of experimental conditions. Applying the Centroid method gives localisation errors of less than 20cm for Y positions and up to 40cm for X and Z position estimates. Results obtained with the Ecolocation algorithm had localisation errors ranging from 5cm up to 100cm. These compare favourably with the results obtained in an indoors measurement procedure, in [124], in artificial circumstances (e.g. the anchors are, in most cases, very close to the unknown). Considering that localisation
errors can be as low as 5cm then further investigation of these techniques could be worthwhile.

8.3 Future work on UWB-based localisation

UWB-based localisation was shown to work under laboratory conditions with accuracies reaching few centimetres. However, implementation of this method in large-scale industrial settings will require certain adaptations concerning mainly the power consumption of the sensor nodes, the use of DSO with respect to its cost and practicality and the implementation of the distribution of receive antennas.

8.3.1 UWB-receivers

Experimental work on localisation, presented in chapters 5 and 6, was based on the use of a DSO to capture receiving signals from a single transmitting node. Here the use of the DSO arose from the need to capture very short pulses (~ns) with adequate resolution that will then allow the processing of these signals in order to derive TDoA. The use of an expensive DSO in industrial premises is undesirable not least since these can be damaged thus costing lots of money to be replaced. To this end, further work is required to make the receive part of the localisation system more practical with one method being replacing the DSO with cheap and less energy demanding alternatives that, will nevertheless, allow capturing received signals with adequate resolution.

Literature in [116-117] pointed out that sampling received UWB pulses using fast ADCs with sampling rate of the order of giga samples per second (GS/s), can be very expensive both in money and in energy consumption and severely limits application areas. Research in [117] pointed out that there are techniques that employ numerous low speed ADCs in order to achieve satisfactory sampling rates. However, these techniques consume a lot of energy and cause an increase of noise in the sampled signal.

To deal with issues arising from the need to use high sampling rates, research in [116-117] proposed using sub-sampling; thus allowing recording UWB pulses at a lower rates, that nevertheless, allow for a satisfactory reproduction of the received signals.
Work in [116] proposed a sub-sampling technique whereby sets of circuits was used to widen the duration of the received UWB pulses, whilst the basic pulse shape amplitude remained relatively unchanged. Extending the duration of the pulses allowed using slow ADCs to capture the received pulses. The functionality of the sub-sampling circuit was tested using a low sampling oscilloscope with 500 MS/s sampling rate. Results using a 0.3ns signal showed that the sub-sampling circuit can produce as good representation of the received signal as in the case when the signal is fed directly to an oscilloscope with a sampling frequency of 70GS/s. The subsampling circuit in [116] was used in a localisation method developed by the authors in [119] with reported localisation accuracies reaching the millimetre range.

A preliminary study of experimental TDoA used in this thesis revealed that it is possible to use a lower number of samples to capture a received signal whilst maintaining the same degree of accuracy as in the case of using the maximum sampling rate. A received signal captured by the DSO (sampling at 5GS/s) consisted of 131036 samples with the gated signal containing 520 samples. The following table summarises the MAE for distance differences for a total number of 48 individual distance difference values.

<table>
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<th>Transmitting coordinates</th>
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<th>5</th>
<th>10</th>
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<td></td>
<td></td>
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<td>2.2</td>
<td>14.4*</td>
<td>3.97</td>
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</table>

Table 19: Sub-sampling MAEs in cm

Table 19 demonstrates that sub-sampling can give as accurate results as in the case of using maximum amount of samples. This observation indicates that it is possible to use an analogue to digital converter (ADC) with low sampling rate in the order of mega samples per second (MS/s) to capture UWB pulses.

*MAE exceeding 4cm indicate the presence of one or more large outliers caused by failure of the LE detection methods to detect the correct LE.
Building on knowledge from the literature and on the indications that sampling at a lower rate can give accurate results as seen in table 19, future work should consider employing a circuit build of a number of ADCs to sample incoming UWB pulses instead of using a DSO.

8.3.2 Placement of receiving antennas

In the experiments undertaken in this work a cross receiving antenna formation was situated on the top of a round and square vessels (see section 4.6.2). Although this appeared to provide satisfactory results this particular antenna formation might not be practical in real world scenarios. Indeed, the very presence of the receiving antennas in the middle of the large silo opening caused problems in filling of the silo with grain. The antennas had to be removed during the filling in process to minimise spilage of grain kernels whilst these hit the the antenna formation and to protect the antennas themsevles from falling appart.

Other than practicality issues, it is of interest to explore alternative placements of receiving antennas with respect to localisation accuracy. To this extent, simulations presented in [123] based a TDoA-based localisation scenario, similar to the research presented in this thesis, considered placing the receiving antenna at different positions inside a cylindrical vessel. Results in [123] showed that placing the receivers at the extremities (top, bottom and middle i.e. as shown in figure 179) of the vessel can improve localisation accuracies. This is justified by the fact that the largest the separation between the receiving antennas and the transmitter the higher the spatial diversity that is achieved thus improving the probabilities of receiving signals with reduced noise parameters.

Figure 179. Alternative receiving antenna placements

Results obtained from the experiments conducted in the larger silo (see chapters 5 and 6) seemed to indicate difficulties in the reception of signals from transmitters buried at depths
below about 150cm. However, there is another potential issue in localising nodes buried at large depths within a silo or other vessel, and that concerns the effect, described in Theorem 5, section 6.2.3, that deviation between distance differences reduces significantly as transmitter depth increases.

For example, consider the following table, obtained by using equation 67 to compute the minimum value in a distance difference profile. The calculations were performed on the basis of a cylindrical silo of height 80m and diameter 30m, dimensions that are typical of the largest silo in the world [127]. Assume that the coordinate system is the same as that discussed in chapter 4 and used throughout chapters 4 to 6, and that a transmitter is located on the silo’s axis of symmetry, with the reference antenna located at (0m,0m,15m). Under these assumptions, the value of K in equation 67 is 15, and the variation of the minimum value of distance difference, $D_{\text{min}}$, occurring in profiles at different depth is shown in table 20.

<table>
<thead>
<tr>
<th>$Y_t$(m)</th>
<th>$D_{\text{min}}$(m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>-5</td>
</tr>
<tr>
<td>40</td>
<td>-2.72</td>
</tr>
<tr>
<td>60</td>
<td>-1.85</td>
</tr>
<tr>
<td>80</td>
<td>-1.39</td>
</tr>
</tbody>
</table>

Table 20: Depth accuracy

This shows that the issue of the flattening of distance difference profiles with increasing depth is not likely to cause significant difficulties even in the largest silos since $D_{\text{min}}$ is still distinguishable at large depths.

To summarise the above discussion, it appears that they key limitation to localisation in large vessel is the distance over which UWB pulses can be transmitted to enable them to be received and processed to find the LE. Clearly this could be addressed by building arrays of receiving antennas into the walls of a large silo. Wall location is necessary to avoid the damage that would inevitably occur if antennas were mounted on struts that project into the body of the material within the silo. Building antennas into the walls of new silos is potentially expensive, and in silos of large diameters still may not enable signals from the transmitters near to the centre of the silo to be received by the antenna array. The distance
over which UWB signals can be transmitted in grain and other types of material stored in silos needs to be studied to establish the applicability of the type of UWB-based positioning discussed in this thesis to the largest silos.

Nevertheless, there many silos and storage facilities that are significantly smaller than the maximum size discussed above. In particular, flat storage facilities are fairly common in the grain industry where floor areas are large and depths are much smaller than in large silos. This is the kind of silage storage that is discussed in reference [18, 19] and was reviewed in section 1.3.3. The type of UWB-based positioning techniques discussed in this thesis could be adapted for such environments.

8.4 Future work on network-based localisation

Time did not allow an in depth study of network-based localisation. However, some preliminary results were obtained using RSS data from within the larger vessel described in section 7.6.2. The main issues of concern regarding this data were the position of the antenna inside the WSN4IP node and the severely non-uniform radiation pattern produced by the node. This means that the node orientation, which is difficult to predict, if a node moves freely with the flow of grain, as seen in figure 180, is likely to have an impact on the ability of the node to acquire meaningful RSS data from its neighbours.

Figure 180. Random antenna orientation

Many WSN applications are essentially 2D, or closely approximate this, and so it is relatively straightforward to ensure an approximately uniform radiation pattern in the plane. See for
example, the whip antenna polar plot in figures 161 and 162. However, industrial processes are essentially 3D and if network-based localisation is to be explored further in this context, then it is important for a node to have an approximately uniform radiation pattern in 3D.

One way to achieve a uniform radiation pattern is through the use of patch antennas as discussed in [115] where four directional (~90° coverage) patch antennas were placed around a sensor node as shown in figure 180. The antennas were controlled by a switch network that allowed the switching of antennas for transmitting or receiving according to a control signal issued by the node microcontroller. Note that at any one time only one antenna was active however the switching time was set at 150ns that according to the authors gave enough time for the antennas to transmit or receiving signals [115].

![Angular antennas around a sensor node](image)

**Figure 181. Angular antennas around a sensor node [115]**

The objective of the work in [115] was to use multiple antennas to read RSSI whilst the node was taking different orientations with respect to a static transmit node that was equipped with a quarter wavelength whip antenna. This allowed determining the orientation of the node in the testing space given that, according to the authors, strongest RSSI values occurred only when the radiation lobes of the directional antenna meet the radiation lobes of quarter wave whip antenna [115].

Similarly work in [123] attempted to deal with the rotation of the nodes under water and the assumption of random orientations, between the acoustic transducers and the receivers, using multiple transducers attached on the outer surface of round nodes. Extensive analysis showed that using eight transducers could deal effectively with orientation problems [123].

Using patch antennas on the WSN4IP node would require the removal of the whip antenna and an investigation of the number and placement of patch antennas around the periphery of
the node, in order to provide as uniform radiation pattern as possible, whilst keeping cost, complexity and power consumption within reasonable limits.

Returning to the issue of large silos discussed in the previous section, the possibility of combining UWB-based positioning with network-based positioning could be explored. In such cases, nodes that are within range of a receiving antenna array can have their position established relatively accurately using the UWB-based system. The position of such a node could be transmitted from the external PC via the network back to the node itself, which could then act as an anchor for nodes that are out of range of a receiver array.

8.5 Future work on the node’s power supply

In principle, nodes could remain immersed in a process for a considerable time and so conserving energy to prolong battery life becomes important.

The electronics inside the nodes, for both UWB and network-based localisation, were powered by rechargeable batteries. The batteries, powering the WSN4IP nodes, used for network-based localisation, lasted for one day because the nodes undergone numerous tests using different transmit powers and datarates [114]. Similarly the batteries for UWB-tests lasted for about a day of tests. In all cases the batteries had to be recharged for many hours thus causing delays in the experimental procedures.

The requirements for monitoring industrial processes such as grain inside silos necessitate that sensors nodes should be able to operate for long periods of time (months). Indeed the software designed for the WSN4IP nodes utilises a sleep-wake up schedule that allows nodes to be active only for specific small time intervals whilst remaining in a low power mode for most of the time [114].

The proposed sleep-wake up schedule in [114] entails that nodes are synchronised to transmit and receive at predetermined time intervals based on a clock provided by the microcontroller. However the use of microcontroller’s clocks and possible jitter that might occur have been reported to cause discrepancies the data acquired by the nodes [114, 76]. To deal with those issues, future work could consider using RF signals transmitted by nodes to trigger receive nodes to wake up thus avoiding the need for clock synchronisation [68-69].
Future work could also examine how long a network of WSN4IP nodes could operate using energy saving techniques and also investigate techniques that will allow nodes to harvest energy from their surrounding environment. Energy harvesting will allow charging the batteries without the need for the nodes to be extracted from the monitoring process thus providing extra monitoring time [70, 118,126].
REFERENCES


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