Real-time Wireless Player Positioning System in Basketball

By

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of the degree of Doctor of Philosophy

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Statement of Originality

I certify that the work presented in this thesis is my own work and, to the best of my knowledge, has not been previously submitted for a degree or diploma at any other known educational institution.

To my knowledge and belief this work contains no material that has been previously published or written by any other person except where they are fully acknowledged in accordance with the standard referencing practices and due references are cited.

James A. Kirkup

29th April 2016
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**Abstract**

Positioning systems for the tracking of players in indoor sports provide coaches and educators valuable information for improving player performance and ultimately the team’s offensive and defensive plays. The play area layout in indoor basketball follows international specifications and is replicated at hundreds of venues around the world. A positioning system engineered once can potentially be deployed at multiple locations without redesign.

Player positioning systems that were once mainly dominated by video tracking systems are now possible through current and emerging technologies using wireless RF signal technologies and significant smaller devices. Wearable technology has not only reduced in size considerably but also in cost which are favourable to these wireless positioning systems.

This thesis examines whether a low cost, robust wireless RF signal player positioning system can be implemented in an indoor sporting environment, such as that used by the game of basketball. This system will not only benefit indoor basketball but potentially could be employed for other indoor sports such as indoor soccer, indoor tennis, indoor volleyball, indoor netball, indoor cricket and handball.

The research shows that using trilateration with three or more receivers (anchor nodes) is a low cost technique for position estimation, provided distance estimation uncertainties between the transmitting beacon and receive antennas can be minimised. Under this technique distances are determined by the field strength received at each receiver using the inverse power law relationship. Transmit and receive antenna radiation patterns, both horizontal and vertical, have an impact on distance uncertainty and also in the appropriate system design placement of the receive antennas. The overall pattern from the transmit beacon is subsequently determined by the placement of the beacon on the body. An upper waist mounted and shoulder mounted wearable beacon experiment showed that at 2.4 GHz an upper waist mounted beacon provided the most useable radiation pattern with a 3 dB beam width of approximately 120 degrees (i.e. a bearing range from approximately 300 to 60 degrees). This beamwidth is sufficient to make a wireless RF signal player positioning system viable when 2-4 receiver locations are implemented per half court.
An indoor half-court field strength survey confirmed that there is minimal multipath interference compared to an office or other cluttered environment. This provided a strong valid reason to continue research into a player tracking system using the trilateration technique. To implement a system based on this technique a high level of confidence in position predictability and accuracy under static conditions is first required. A study into the RF signal propagation characteristics of an indoor basketball court, built to international standards, has shown static positional accuracies of less than 0.5 m using two common propagation prediction models (Free-Space and Two-Ray) for distances less than 10m. The study has also shown that there is minimal multipath interference at distances less than 10m in this static environment, which is conducive to these positional accuracies.

For a single player under dynamic conditions the research shows that for distances less than 10m the power distance relationship shows a Ricean type environment where there is one dominant ray and the effect of multipath signals reflected from other surfaces in the vicinity is relatively small. For distances less than 9 meters, nulls of up to 2.5 dB signal variation were observed with the majority of nulls less than 2 dB. For distances up to 2.5 m from the receiver it is possible to achieve accuracies of within 0.3 meters. The main play area for offensive players is either on or outside the basketball key. Importantly, the distance between the key edge and sideline is approximately only 5 m. By employing a combination of quarter-court identification and power/distance estimation methods the research showed that it is feasible to produce a player tracking system under single player conditions using two or more anchor nodes per quarter court.

Using two teams under game pace conditions a study into the effect of multipath interference due to the movement of team players on the received signal has shown to be minimal with signal fluctuations of approximately ±0.5 dB when not obstructed.

It was highlighted during the research there was a need to know which player was dribbling the basketball as this is a key part of information needed for game play analysis. A new method of detecting the bouncing of the basketball, a type of ball possession, was developed using accelerometers. The use of 3-axis accelerometers to indicate a type of ball possession has proven to be feasible when mounting the sensor on the wrist or above the elbow, with the wrist mounting the most predominant results
as expected. The results have shown a clear response signature including a unique spike level and signal response in the bounce process that can be used to flag when the basketball is being bounced. This technique was also found to be true for passing the basketball.

A study using a custom built prototype player tracking software system has confirmed that it is possible to track a player based on received field strength and trilateration in an indoor basketball court environment with positional accuracies achieved within ±0.5 m.
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<td>ACMA</td>
<td>Australian Communications and Media Authority</td>
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<tr>
<td>ADC</td>
<td>Analog-to-Digital Converter</td>
</tr>
<tr>
<td>AFD</td>
<td>Average Fade Duration</td>
</tr>
<tr>
<td>AOA</td>
<td>Angle of Arrival</td>
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<tr>
<td>ATM</td>
<td>Asynchronous Transfer Mode</td>
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<tr>
<td>CFD</td>
<td>Cable Fire Department</td>
</tr>
<tr>
<td>CSV</td>
<td>Comma Separated Values</td>
</tr>
<tr>
<td>CW</td>
<td>Carrier Wave</td>
</tr>
<tr>
<td>DOA</td>
<td>Direction of Arrival</td>
</tr>
<tr>
<td>DTOF</td>
<td>Differential Time of Arrival</td>
</tr>
<tr>
<td>EIRP</td>
<td>Effective Isotropic Radiated Power</td>
</tr>
<tr>
<td>EKF</td>
<td>Extended Kalman Filter</td>
</tr>
<tr>
<td>ERP</td>
<td>Effective Radiated Power</td>
</tr>
<tr>
<td>fps</td>
<td>Frames Per Second</td>
</tr>
<tr>
<td>GNSS</td>
<td>Global Navigation Satellite System</td>
</tr>
<tr>
<td>GPS</td>
<td>Global Positioning System</td>
</tr>
<tr>
<td>HF</td>
<td>High Frequency</td>
</tr>
<tr>
<td>HSGNSS</td>
<td>High-Sensitivity Global Navigation Satellite System</td>
</tr>
<tr>
<td>IEEE</td>
<td>Institute of Electrical and Electronic Engineers</td>
</tr>
<tr>
<td>IMM</td>
<td>Interactive Multiple Model</td>
</tr>
<tr>
<td>IPIN</td>
<td>Indoor Positioning and Indoor Navigation</td>
</tr>
<tr>
<td>IR</td>
<td>Infra-Red</td>
</tr>
<tr>
<td>ISM</td>
<td>Industrial, Scientific and Medical</td>
</tr>
<tr>
<td>ITU</td>
<td>International Telecommunication Union</td>
</tr>
<tr>
<td>KF</td>
<td>Kalman Filter</td>
</tr>
<tr>
<td>LAN</td>
<td>Local Area Network</td>
</tr>
<tr>
<td>LCR</td>
<td>Level Crossing Rate</td>
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</tbody>
</table>
LIPD  Low Interference Potential Devices
LOS   Line-of-Sight
LPM   Location Position Measurement
LSB   Least Significant Bit
MMSE  Method of Least Squares
MUBW  Maximum Usable Beam Width
NBA   National Basketball Association
NBL   National Basketball League
NSF   National Science Foundation
PBX   Private Branch Exchange
PL    Pseudolite (pseudo-satellite)
RF    Radio Frequency
RFID  Radio Frequency Identification
RP-SMA Reverse Polarity SubMiniature version A
RSS   Received Signal Strength
RSSI  Received Signal Strength Indicator
SD    Secure Digital
SMA   SubMiniature version A
SPAWN Sum-product Algorithm over a Wireless Network
TDMA  Time Division Multiple Access
TOA   Time of Arrival
TOF   Time of Flight
TDOF  Time Difference of Flight
UHF   Ultra High Frequency
USB   Universal Serial Bus
UWB   Ultra Wide Band
Wi-Fi Synonym for WLAN
WLAN  Wireless Local Area Network
1. INTRODUCTION

1.1 Overview

This thesis outlines the doctoral research of a ‘Real-time Wireless Player Positioning System in Basketball’ by combining new wireless Radio Frequency (RF) signal technology using real-time sensors with basketball athletes, in an indoor basketball ‘play-area’ environment.

This chapter discusses the background to the research topic, the research question, the significance of the research and finally the outline to the report.

1.2 Background

The use of improvement methods or tools in sport in some form or another has generally existed since athletes began training and performing. In the first Olympics that officially began in Greece in 776 B.C. athletes participated in simple training methods, such as simply practicing their sport under former champions, to improve their skills to introducing some form of tool to enhance their thinking and training.

![Milo of Croton](credit: [1])

**Figure 1: Milo of Croton Credit: [1]**

The legendary Milo of Croton depicted in Figure 1 used to lift a calf overhead every day until it became a full-grown bull. While legends can exaggerate, an athlete would spend most time training the body physically. Time was also spent training the mind in special schools encompassing the concept of “mind, body and spirit”. The need for
coaching and training tools in the sport of basketball continues to be a requirement for coaches and educational trainers as they seek out new ways to improve each player and their overall team’s performance. At the elite professional basketball level the aim is to improve the team’s competitiveness to obtain the match win. One way to achieve this is by improving the player in his or her decisions and actions that leads to the improvement of the team’s overall actions throughout the game. By improving the offensive and defensive plays in a game of basketball a competitive edge can be achieved over the opponents’ team.

At the junior level for children under 12 years of age the aim in coaching includes the benefit to increase the child’s understanding of the sport and improve his or her coordination between mind and body.

“The potential benefits of organised sports for children and adolescents include improvement of health, enhancement of normal physical and social growth and maturation, as well as the improvement of their motor skills and physical fitness, particularly for those who are physically and mentally challenged. In addition, organized sports competitions for children and adolescents can, if properly structured, play an important role in socialization, self-esteem, and self-perception, as well as improving psychological well-being”. [2]

Mohamed and Mohamed [3] undertook a detailed study in this area and their results showed that inclusion in a recreational sports program had a positive effect on improving basic motor skills and health behaviour for children with mental disabilities and normal children. Any tool or method that can assist a child through their respective coaches must be of value for the development of that child.

The use of modern technology in team sports for the improvement of players is well entrenched and continues to grow as more sophisticated and smaller devices and systems become available. One such technology that has an impact on the improvement of players and teams in the sport of basketball is the ability to analysis the movement of players around the court. Positioning systems for the tracking of players in indoor team sports have matured in the last decade prompting a growing interest by researchers in this area. The main motivation for these systems is the valuable information they provide to coaches and educators for improving player
performance and ultimately the team’s offensive and defensive plays. Although outdoor positioning systems for sport have been around for some time, potential systems for implementation in indoor wireless RF signal player positioning and tracking systems were only recently introduced in the mid 2000’s [4] and [5].

As a junior basketball state representative and later as an Australian basketball representative in the 1970’s and 1980’s in Australia, defensive and offensive plays were analyzed using video tape recordings of the game. Electronic components and technology were cumbersome and bulky at this time preventing the employment of intrusive (body-wearing) wireless tracking systems. Video analysis was therefore first proposed for use in team sports for tracking analysis. Erčulj, et al. [6] points out that it was the leap in computer vision analysis after the year 2000 that pushed these tracking systems into team sports. This coincides and is a direct result of the advancement in computer hardware and software systems. Min-Chun, et al. [7] confirmed that in contrast to other popular sports (e.g., soccer, tennis or baseball), only a few works have been completed for basketball video analysis. As a result of the initial work, the majority of tracking systems employed in the sport of basketball are vision based. However, that is about to change as the wireless technology components have now become so small that the employment of an intrusive wireless tracking system is no longer of concern to player discomfort.

Prior to the year 2000, wireless indoor positioning systems for use in tracking individual players in team sports was non-existent. This was mainly due to: 1) the cumbersome nature (form factor) of the electronic components available which would hinder the movement of the player; 2) the safety concerns to other players arising from wearing such devices; and 3) the dislike of wearing such devices by the player’s themselves, which could lead to issues with player performance. As a consequence: (a) the majority of systems developed at that time used video camera technology which is a non-intrusive methodology; and (b) the focus on RF signal systems shortly after the year 2000 was mainly towards indoor environments other than those employed by indoor sporting teams. These include indoor environments such as office and factory buildings. As technology components have now become smaller the introduction of systems using a device worn by the player is now feasible with little discomfort to the player.
1.3 The Research Question

Indoor wireless positioning systems based on radio frequency (RF) signal propagation are reliant on the underlying transmission channel propagation knowledge and the characteristics of the indoor environment. The need for static and non-static signal propagation knowledge in these environments is still important today and highly valued for a variety of indoor environments. There have been surveys and studies conducted on wireless indoor positioning techniques and propagation models [8] and [9] that assist design engineers. Unfortunately, there is no one empirical model or positioning technique suitable for every indoor environment. This is mainly due to the variation in position and shape of the inanimate objects and surfaces between one environment and the next.

The unknown variation in multipath, scattering or shadowing interference to the transmission signal hinders the mathematics required to produce a universal propagation model and indoor tracking system for all indoor environments. This has led to the majority of indoor positioning systems employing elaborate and costly techniques to overcome the inherent multipath problems resulting from these objects.

In contrast, the playing area used by some elite indoor team sports is free from these interfering and varying objects, except for the players, the basketball and the referees themselves. Without a significant multipath problem less complicated positioning techniques can be employed and system development and deployment costs can be reduced.

Consequently, the overall research question becomes:

"Can a low cost, robust wireless RF signal player positioning system be implemented in an indoor sporting environment such as that used by the game of basketball?"

1.4 Purpose of the Research

The purpose of the proposed research was to:

a) Investigate the channel propagation characteristics of a typical indoor basketball court built to international standards and confirm there is a minimal impact of multipath interference;
b) To demonstrate a wireless RF signal player positioning system using the latest technology in component manufacture in the indoor sport of basketball with very little intrusion on the player performance.

### 1.5 Aims and Objectives

The aims and objectives of this study were to satisfy the research question using a scientific method approach and ultimately lead to valid and reliable research results. A breakdown of the aims and objectives are shown in Table 1.

**Table 1: Aims and Objectives**

<table>
<thead>
<tr>
<th>Aims</th>
<th>Objectives</th>
</tr>
</thead>
<tbody>
<tr>
<td>To determine the useable relative beamwidth and main lobe direction from a body mounted RF beacon.</td>
<td>Measure the field strength radiation pattern of a body mounted 2.4GHz beacon and determine its approximate 3db horizontal beamwidth. The influence of the body on the pattern will also be recorded.</td>
</tr>
<tr>
<td>To determine and validate a level of multipath interference (high, medium or low) within a static indoor basketball court environment.</td>
<td>Measure the field strength at strategic locations from a 2.4 GHz beacon located on a basketball court. A quarter of the court is to be used as a representative of the other three quarters. The transmitting beacon is to be located at various positions.</td>
</tr>
<tr>
<td>To produce a RF signal propagation model for an indoor basketball court environment constructed to international specifications.</td>
<td>Develop a mathematical model for predicting received field strength powers using the MATLAB® R2012a program, known modelling theory and recorded data.</td>
</tr>
<tr>
<td>To provide a qualitative level of confidence on the use of a player position location methodology and technique, within a dynamic indoor basketball court environment, through a reliable and validated scientific research study.</td>
<td>Undertake research and field trials, using volunteer basketball players, of a wireless RF signal player positioning and tracking system.</td>
</tr>
<tr>
<td>To implement a prototype low cost and robust beacon and sensor technology for a Player Location and Tracking Information System for use in a wireless indoor basketball player positioning and tracking system.</td>
<td>To: (a) select a suitable beacon and sensor for the trials; and (b) design and develop a computer player tracking information system using appropriate computer hardware and software; to meet the criteria of an indoor positioning methodology and technique, for use in indoor basketball player positioning and tracking.</td>
</tr>
</tbody>
</table>

### 1.6 Significance of the Research

As the play area layout of the basketball court follows international specifications and is replicated at hundreds of venues around the world, scope exists to produce a general
player positioning system suitable for all the venues worldwide for not only basketball but for other indoor sports that use a similar indoor play-area.

An indoor wireless RF signal team player tracking system will provide valuable information comparable to the systems employed in outdoor environments. In particular:

a) To coaches and trainers for the performance improvement of their defensive and offensive plays; and

b) For coaches of youth indoor sporting clubs worldwide to facilitate the developmental growth, both mentally and physically, of the sporting child.

With the use of a wireless RF signal positioning system in basketball a small wireless beacon or sensor is worn by the athlete as part of the positioning and tracking system with very little intrusion on the player. The technology into wireless sensors has also gathered significant momentum in research and design in recent years, where additional information such as heart rate, acceleration and other physical attributes may be derived. This provides scope to expand the proposed basketball position system with this valuable data for analysis and use, some of which is not achievable in video based tracking systems.

By providing a small, low cost, athlete tracking system for indoor courts the system will be available for all schools, clubs and societies world-wide without the high cost boundaries imposed by current commercial systems.

1.7 Thesis Outline

This report is structured with Chapter 2 providing details of the background literature and studies relevant to the research topic. The chapter also provides the current trends in the literature and the gap that exists which allows the placement of the proposed research work within the existing body of literature. Chapter 3 details the design theory used in the research experiments and covers important background theory and equations supporting the methodology. Chapter 4 discusses the research methodology and methods implemented in the research and provides sufficient detail for the work to be repeated and verify the results obtained. The data collection techniques mainly used are those found in the discipline of engineering radio communications and the
discipline of sports science. Chapter 5 presents the findings from the experimental studies undertaken while providing critically informed comments and valid discussions. Chapter 6 presents the conclusions from the experimental research and covers possible work that could be undertaken in the future.
2. LITERATURE REVIEW

2.1 Introduction

An indoor positioning system is an intelligent system that can determine the spatial position of a living or inanimate object within a surrounding structure. The intelligent system that determines the indoor position generally uses one or more positioning techniques in its methodology and it is these techniques that mainly determine the accuracy of the object’s position.

Research and experimentation into suitable indoor positioning techniques has grown in momentum over the past decade and continues to grow as more applications employing this positional knowledge are developed. Indoor positioning and geolocation techniques have already been used in many environments including mining, emergency, health, public safety, military, airports and government and wholesale commercial industries.

This chapter not only includes the technical aspects of the indoor wireless positioning systems, but also focuses on the literature related to the positioning methodologies or techniques suitable for the tracking of players in the sport of basketball. It includes the recent peer-reviewed major works related to the narrow research topic, while focused on the recent major concepts and the relationships between them.

2.1.1 A Wireless RF Signal Indoor Positioning System

Figure 2 depicts the components of what a wireless RF signal indoor geolocation system might look like. These components will vary from system to system and depend on the positioning technique and technology employed. Some positioning technologies have been widely published and continue to be of interest to researchers and engineers [9], [10]. These include Infra-Red (IR), ultra-sound, Radio Frequency Identification (RFID), Wireless Local Area Network (WLAN), Bluetooth, Ultra Wide Band (UWB) and magnetic technology. The positioning system depicted in Figure 2 has six major components. They include:

1) One or more mobile beacons or devices. A beacon can be active (with battery power) or passive (no battery) and can be employed as a receiver, transmitter
or translator with the capability to carry out computations (requiring on-board memory) or not;

2) The wireless sensors that receive the information carrying wave generated or translated from the mobile beacon and passes it onto the positioning technology hardware;

3) The positioning technology that processes the information through physical hardware and forwards the relevant information onto the computer information system through a network interface and various other network architecture components such as routers, switches, etc.;

4) The Positioning Algorithms that may or may not be applied to the relevant technology for use in the computations necessary to determine the spatial location of the mobile beacon(s);

5) The computation that is usually carried out using some form of physical or virtual (cloud) computer system that may or may not draw upon positioning algorithms relevant to the positioning technique. Today many systems use some form of cloud storage where data is saved over the internet to, for example, an online data storage warehouse;

6) The display technology and presentation layer that provides the information to various devices including laptops, tablets, mobile phones etc.

Figure 2: A wireless RF signal positioning system
The positioning methodology, technology and algorithms employed by the positioning system will impact on the accuracy or resolution limits of the position system. Figure 3 shows a comparison of various positioning technologies, which was provided by [9] in their survey of wireless indoor positioning techniques and systems. This modified version, of a popular wireless positioning technology relationship diagram provided by [11], is still of value today and highlights the relationship between technologies and their position estimation accuracies for a typical indoor environment.

Figure 3: Outline of wireless-based positioning systems. Credit: [9] © 2007 IEEE

A typical indoor environment generally includes indoor clutter that impacts on the accuracy of the positioning system. It would be expected that higher resolutions could be obtained for a typical indoor basketball court as the environment is not expected to suffer from severe multipath problems due to the smaller amount of clutter. Multipath interference is a well-known source for limiting the resolution capability for many of the positioning technologies.

Hui, et al. [9] also provided a comprehensive comparison table (Appendix A) of systems and solutions, some of which are no longer current. This is one of the few detailed comparison tables available in recent literature.
2.1.2 The Research Foundation of Wireless RF Signal Positioning in Indoor Environments

A very large amount of literature covers why and how positioning systems came into existence with an equal amount of literature on research that has been conducted in this area. Many textbooks have already been published [12] covering this history and is not provided here. This is a review of the current research and published information in the subject of indoor positioning systems. As the focus is on wireless RF signal positioning, a few paragraphs on the chronological beginning are included to set the origins of this expanding area of interest in wireless technology.

Historically, research into indoor positioning techniques stemmed from earlier foundation research conducted on wireless communications within the telecommunications industry. The use of wireless indoor data or voice communications to replace corded systems was inevitable and was highlighted by [13] in the 1980’s. With the introduction of cordless and mobile telephones corresponding research into propagation in urban areas and the indoor propagation channel began to build, including valuable studies into the mobile radio channel. Research into multipath conducted by [14], [15], [16] and others provided valuable foundation research material for the indoor environment, while those in the cordless telephone business like [17] also provided valuable research for indoor geolocation systems and for Digital Enhanced Cordless Telecommunications, which is now one of the primary standards used for creating cordless phone systems.

Ching-Sheng and Li-Chieh [18] mentioned that research on indoor positioning did not attract attention until after it was proposed by [19] with their SpotON system. Although [19] did have an influence on the research conducted in the early part of that decade, a literature review highlights others who were considering indoor location around this period. Some would propose that [20] with their RADAR system was the main influence.

“In 1997, while engaged in the Defense Advanced Research Projects Agency’s (DARPA’s) Small Unit Operation/Situation Awareness System (SUO/SAS) program, the lead author of this article and his research group noticed the need for fundamental research in accurate indoor geolocation. The follow-up
initiative of the group attracted the attention of Nokia and other Finnish organisations to the commercial importance of indoor geolocation. In recognition of this importance, an NSF grant was awarded to establish a scientific foundation in this field.” [21].

Pahlavan, et al. [21] confirmed that in the telecommunications industry, indoor radio propagation studies were motivated by voice-oriented wireless private branch exchange (PBX) and personal communication services applications as well as data-oriented wireless Local Area Networks (LANs) and wireless Asynchronous Transfer Mode (ATM) services.

Those who began the research into indoor positioning is questionable and would require an extensive detailed historical analysis, which is outside of the scope of this literature review. However, it can be accepted that a greater momentum of research into this area roughly began around the year 2000.

Today, new methods of complimenting and improving existing indoor location technologies have progressed as electronic devices and technologies have become smaller in form factor and more readily available to the general public. However, despite the large amount of research into indoor positioning techniques to date, there is no single indoor positioning technique or propagation model suitable for all indoor environments. The main reason for this is that the very nature of the indoor environment is complicated by the existence of stationary and/or moving objects and that generally no two indoor environments are the same. The shape variation and position from one environment to the next of existing animate and inanimate objects, surrounding materials, fluids and air properties frustrate the mathematics used by researchers to estimate an accurate indoor position of an object. As no two indoor environments are the same it is difficult for an overall ‘silver bullet’ solution that is robust, reliable and at a low cost.

Although recent wireless indoor positioning techniques have been investigated and discussed in literature for over a decade, three recent surveys by [9], [8] & [22] clearly indicate that in the history of wireless communications this emerging indoor positioning market has only begun and that it is a challenging research area to be explored.
At the 2012 Indoor Positioning and Indoor Navigation (IPIN) conference held in Sydney, Australia, there were over a dozen techniques discussed for wireless indoor positioning of static and/or moving objects with improved methods for limiting the position estimation errors. Some of the techniques discussed included Pseudolite, High-Sensitivity Global Navigation Satellite System (HSGNSS), Wireless LAN, UWB Radar, RFID and Received Signal Strength (RSS)/Time of Flight (TOF)/Time Difference of Flight (TDOF). The pursuit of improved position accuracy, lower cost, minimum infrastructure components of the system and environmental considerations have been some of the main causes for this expansion into alternate techniques.

Having now set a chronological starting point of this research topic we can now focus on the narrow topic of the use of wireless RF signal positioning indoors.

2.1.3 The Use of Wireless Indoor Positioning in Indoor Sports

In contrast to the large amount of research literature available on wireless RF signal positioning or tracking for indoor environments in general (where there is existing infrastructure and clutter), there is very little literature available on positioning or tracking of players within indoor team sports. In particular, the indoor sport of basketball.

Also, a literature review shows there is only a moderate amount of literature on wireless RF signal player tracking in outdoor sports. Two reasons for this are: a) the extensive advances of video capture technology using cameras with very little intrusion; and b) the existence of GPS, which is a dominant de facto standard used in positioning for outdoor environments. One recent example in an outdoor environment is the research conducted by [23] who proposed the use of RFID positioning technology in their outdoor player tracker system.

Stelzer, et al. [5] appear to be the first mentioned use of wireless RF signal player and indoor team tracking in their proposed Location Position Measurement (LPM) system. The system became known as ‘InMotio’ and was subsequently employed in an indoor speed skating rink. Although [4] proposed the existence of a number of intrusive team tracking techniques applied to sports, only the research conducted by [5] specifically states for use in indoor sports. Consequently, it could be stated that research into using wireless RF signal positioning and tracking in indoor team sports began in the mid 2000’s.
Since the mid 2000’s there have only been a few positioning systems developed and dedicated to this particular area of interest. Hedley, et al [24] and Sathyan, et al. [25] undertook research into indoor player tracking using the Wireless Ad hoc System for Positioning (WASP), which operates in the 5.8 GHz ISM band with a 125 MHz bandwidth using a Time of Arrival (TOA) technique. Although this system is expensive, accuracies can be achieved to within centimetres.

2.2 Current Research Trends in Wireless RF Signal Indoor Positioning

This section provides a review of the current trends in wireless RF signal indoor positioning/tracking techniques. Scope is limited to those systems that warrant consideration when proposing an indoor wireless positioning system for use in the indoor team sport of basketball.

As previously mentioned, over the past decade a large number of wireless RF signal indoor positioning techniques have been employed and developed using a variety of methodologies and mathematical algorithms. A number of survey papers have been published that include detailed descriptions of these techniques, their advantages, disadvantages and the terminology used in these technologies.

A review of the current literature has provided detailed survey papers published by [26], [9], [27], [28], [8], [22] and [4]. From this literature some research trends can be extracted. Other peer-reviewed published papers have also been examined and provide some insight into research trends that warrant mention in this chapter.

A common thread throughout much of the research in the early part of the last decade was a focus on improving the accuracy of the position estimate. With new techniques and mathematical algorithms being available, it is possible with some systems today to achieve accuracies to within centimetres. Other important considerations have also been steering the mainstream direction of research in positioning. Some of which include: a) reducing the complexity of the system; b) reducing the system cost; and c) reducing the time required to set up and calibrate the system in any given indoor environment.
The following are some of the recent key areas highlighted in literature that is being driven by a large research effort for this specific topic of wireless indoor RF signal positioning.

2.2.1 System Information

The ability to extract intelligent and useful information from any wireless positioning or tracking system beyond the actual location data is extremely useful within the indoor sporting environment where coaches are comparing performance statistics.

It is only recently that additional information apart from position has been considered for use by coaches. Santiago, et al. [4] confirms this and points out that frequently most of systems are not able to extract the higher level metrics such as game situations, team formations or physiological parameters (e.g. fatigue). These metrics were historically difficult to extract. It was also highlighted that current trends seem to point the importance of ball and team tracking together thereby providing a higher level model of the individual player and team behaviour. This is particularly important as ball handling time statistics are valuable to a coach to: a) avoiding the issues with “ball hogging”; b) provide useful information on interpersonal interactions and other aspects in a team environment.

Sathyan, et al. [25] highlighted the need for spatial configurations on the field of play during critical events, such as the transition from attack-defence-attack or penetrating a defensive structure. It could also be argued that the tracking of the basketball referees is important as it impacts on the player’s perception, thinking and position during the game.

Chakraborty and Meher [29] reported some research on ball tracking, but employed video analysis rather than using wireless RF signals. Very little widespread research knowledge is available in this area on wireless systems, which is probably due to commercial-in-confidence requirements of some companies. However, recent commercial products are now available, such as the ‘94Fifty’ from InfoMotion Sports Technologies and ‘EVO ONE’ from Shooters Revolution, that incorporate a wireless sensor inside the basketball using the micro-pump insertion technique pioneered by Spalding and the NBA. This technology will again provide useful information to coaches.
Hedley, et al. [24] stated that further analysis of the data in these player tracking systems is required to provide information such as the total distance travelled, acceleration profile or measures of team coordination. That these are sport specific and that extensive work still needs to be undertaken with sport scientists and coaches to determine what information they need to improve athlete training.

As more positioning systems based on player worn devices become available to sporting teams further ideas on parameters and information will be generated and made available to coaches and training staff. For example, statistics on the number of times a player shot the ball or passed the ball as an assist is a standard statistic recorded today.

Santiago, et al. [4] concluded in their paper that most player tracking systems are still in a very early stage as they only analyse detection and tracking and are not able to extract the higher level metrics such as game situations, team formations or physiological parameters like fatigue. A possible reason for this is that earlier systems were mainly camera based with no wearable devices in play. With the advent of body-worn wireless systems in the future the metrics of heart rate, jump heights, fatigue, etc. will eventually be available to the basketball player.

The recent 2013 MIT SLOAN Sports Analytics Conference is a testament of this growing area. Technologies that can improve this area are in high demand and this is therefore pushing this research trend.

Discussions between researchers, sports scientists and engineers with the coaches and trainers that will be using the system need to take place early in any useful research endeavour. This liaison needs to be open and without the pressures imposed by political or financial gain. The type of system information and how it will be used can then be determined.

2.2.2 Anchor nodes

The number of Anchor nodes or reference receivers in a wireless positioning system is dependent on the positioning technique and algorithms used in the system.

[30] mentioned that they are undertaking further research into cooperative localization to reduce the number of anchor nodes required in large networks for the WASP system. Cooperative localization involves nodes (or beacons) helping each other to
determine their location. Wymeersch, et al. [31] stated that a new era of highly accurate ubiquitous location-awareness is on the horizon, enabled by a paradigm of cooperation between nodes. They described several algorithms and quantified their performance based on UWB ranging models and developed a new one called Sum-product Algorithm over a Wireless Network (SPAWN).

Literature has indicated that reduction of anchor nodes used in wireless RF signal positioning systems continues to be an important technical consideration with need for further research. Zanca, et al. [32] reported that the number of anchor nodes has a direct bearing on the performance of the Received Signal Strength Indicator (RSSI) based localization algorithms used in their experiments, with the preferred number dependent on which of the algorithms is used. Al Alawi [33] in his RSSI location experiments proposed future work to investigate the effect of varying the anchor density on the localization error while [34] reported that by increasing the number of reference nodes from 4 to 6 in a tag-based RSSI ZigBee standard based system the location estimation was improved for their particular environment.

Van de Velde, et al. [35] made the valid point that reference or anchor node placement and maintenance is expensive and usually requires professional maintenance. In their study they investigated the reduction of anchor nodes in UWB systems by obtaining a set of virtual anchor nodes associated with reflections derived from the help of a floor plan. In their paper, a low-complex two-step algorithm was proposed (CUPID) that is able to accurately estimate the user positions using a single anchor node.

The reduction in size, complexity and number of wireless anchor nodes is an ongoing and warranted topic in research as it reduces the costs and implementation/deployment effort of a wireless indoor positioning system.

2.2.3 **Data Filtering**

Data filtering techniques continue to be a focus of research consideration for analysing the tracking data information for improved position accuracy. These range from the most fundamental, long established and widely used approach of the Kalman Filter (KF) and Extended Kalman Filter (EKF) to approaches based on sequential Monte Carlo signal processing or more specifically particle filtering. The KF was first published around 1960 and since then researchers have been improving it with various
editions. Variations include the EKF, the Unscented KF and the Invariant EKF. Even today these available techniques are being used in proposed positioning systems.

Subaashini, et al. [36] proposed future research in filtering techniques for their work on how RF signal strength is affected due to various objects that are generally found in indoor environments. Shuo, et al. [37] compared three indoor Kalman filters, including the EKF, for an indoor passive tracking system. Ozdemir, et al. [38] proposed a new target tracking approach based on the sequential Monte Carlo signal processing or more specifically particle filtering. Sen, et al. [39] proposed an Interactive Multiple Model (IMM) filter to estimate and predict the target’s dynamic state and reports that it outperforms the EKF in simulation. Wherever statistics is involved in positioning, filtering algorithms will be employed to filter out inaccurate data. Ongoing research continues to be driven in this area where there is a noisy environment.

2.2.4 Antennas

Research into the use and construction of antennas for indoor positioning systems is equally important as the tracking technique or any other research component in the positioning/tracking system.

“According to the technology, technique, and nature of the signals being processed, different antennas have been applied for radio frequency (RF) localization systems. The infrastructure of the localization system, formed by reference units, has been mainly integrated with omnidirectional radiation patterns. Nevertheless, diversity of radiation pattern starts to become a desired feature for performance enhancement of these systems, which is possible due to sectorised antenna arrays (SAAs), multiple directive antennas with different discrimination zones, phased arrays, or even adaptive arrays, also called Smart Antennas.” [40].

Bras, et al. [40] reviewed antennas based on three main measurement techniques of RSSI, TOF and Direction of Arrival (DOA). Antenna system technologies for indoor positioning systems continue to be an attractive area for research and researchers continue to build on their predecessors. For example the use of Switched Parasitic Antenna Arrays in base-station tracking, referred by [40] as Phased arrays/ Smart antennas, were previously researched by [41].
The careful selection of the type of antenna used in an indoor location system is somewhat determined by the technology used in the positioning system. For example, directional antennas are used in Angle of Arrival (AOA) techniques. In this case the receiver must measure the direction of the signal from the transmitter with respect to a fixed known direction. Kolodziej and Hjelm [42] pointed out that because this technique requires the use of special antennas, it would not be suitable for a Wireless LAN location-sensing application that mandates the use of standard components.

Directional antennas have the advantage of limiting the number of paths that the transmitted wireless signal may take and therefore reduce multipath interference components. Directional antennas have been researched extensively and continue to be of interest. Cheng, et al. [43] and Preston, et al. [41] investigated using a directional array with only one active element and three parasitic elements and directing the radiation pattern electronically.

Bras, et al. [40] published a review of antennas for indoor positioning systems and provided it as a guide for antenna designers interested in developing suitable antennas for indoor localization systems. Bras, et al. [40] stated that antennas with omnidirectional radiation patterns lead to smaller RSSI variances than directional antennas over the entire radiation pattern making its use preferable for the location fingerprinting method. It is true that the slope on the main lobe of a directional pattern and minor lobes can induce this effect, however, sometimes directional patterns are required to reduce significant multipath interference components from other directions. Bras, et al. [40] confirmed that antennas have a direct impact on system accuracy and on availability, number of reference units (or anchor nodes) required, portability, size, cost and power consumption.

2.2.5 Calibration and Timing

Calibration and in particular timing is crucial in positioning or tracking systems that depend on accurate timing measurements. Those systems based on AOA require additional hardware that needs to be precisely calibrated. Those that are designed around Time of Flight or Time Difference of Flight of electromagnetic waves technique require very accurate timing measurements and high synchronicity. In comparison, timing is not as crucial in RSS/RSSI positioning systems which provides significant benefits in reduced costs and complexity.
Synchronicity is important in systems that employ multiple anchor nodes to receive data for position or tracking analysis.

Woo-Chool and Myung-Hyun [44] used a ZigBee based indoor location system and implemented a timing system that includes stationary active beacons (WiFi Access Points as used by the RADAR system) that periodically transmit signals to the passively listening mobile device. The stationary beacons then estimate the distances between the mobile device and the beacons and forwards the overall instant information onto a network for analysis. Because the system receives simultaneous distance estimates it is likely to perform better tracking. This is because the passive mobile system device obtains only one distance estimate at a time which may have moved between successive estimates.

Abdat, et al. [22] listed three trends in indoor wireless positioning systems needing further research. They include:

a) Moving away from a single positioning technique to one combining a number of techniques that compensate for the limitations of each individual technique. This was also highlighted by [9] and has been evident in recent conferences on positioning techniques (IPIN 2012). Where appropriate this may be the only course of action, however, an increase in complexity can increase the probability of system failure, greater requirements in maintenance skills and knowledge and can also lead to increased development costs;

b) To address dynamic problems within the environment in a wide scale area such as the number of people and changes to an access point location;

c) Improvement in fingerprinting techniques. Techniques to minimise the task of fingerprinting and improve the accuracy need to be carefully considered before the fingerprinting task is conducted.

Hui, et al. [9] also proposed a number of trends including: a) Internetworking of different wireless positioning systems to extend the positioning range. A typical example of this today is in the use of a Pseudolite (“pseudo-satellite”). These are small transceivers that use the same ground tracking method as GPS satellites but the coverage is small and local. They are combined with GPS satellites to reach areas where the GPS signals are blocked; b) Wireless methods combined with other
technologies such as Infra-Red, inertial, dc electromagnetic and ultrasonic (i.e. sensor fusion); c) The deployment of sensors to improve accuracy and improving the time of deployment; and d) The integration of indoor and outdoor positioning systems.

Other areas impacting on the trends include sensor technology, the network architecture and data storage and retrieval using cloud-based technology. It could be expected that as more systems are developed from researchers and engineers many of these research trends will continue to expand.

This section has only covered a few of the important trends reported in the literature, but do indicate some of the areas under consideration for any wireless RF indoor positioning system.

2.3 **Wireless RF Signal Indoor Positioning Techniques**

The term used to determine the indoor location of an object using wireless technology has sometimes been referred to as position location, local positioning, location sensing, geolocation or radiolocation. The wireless techniques used to determine the location may be based on the physical architecture and layout of the hardware sensors, the mathematical algorithms used on the data gathered from the sensors or a combination of both.

Pahlavan, et al. [21] cited two major challenges for position accuracy to researchers during this time were the complexity of the radio propagation and the ad hoc nature of the deployed infrastructure within the indoor environment. Pahlavan, et al. [21] followed on to state that these two difficulties have generated research into new signalling techniques, new system architectures and in particular, new or improved location finding mathematical algorithms. A review of the literature from 1998 to 2010 confirms this and shows that these two difficulties of the propagation channel are still generating new research and literature in these areas.

Pahlavan, et al. [21] indicated that indoor geolocation was an important emerging technology for commercial, public safety and military applications which still holds true today. Potential needs were described that are available today which include: a) Commercial indoor tracking systems for residential and nursing homes to track people with special needs, the elderly, the blind, portable equipment within hospitals and
finding specific items in warehouses; and b) systems for public safety and the military
that include tracking inmates within prisons or fire fighters and soldiers within
buildings. There are now indoor tracking systems available for use in the mining
industry to track miners in tunnels deep below the earth’s surface. These systems were
mainly developed during and after the mid 2000’s.

The research techniques and systems that were presented at the conference on Indoor
Positioning and Indoor Navigation (IPIN 2012) were concentrated on improving
positioning accuracy and techniques within the indoor working environments where
significant multipath exists. None of these systems were considered for the indoor
sporting environment

This section outlines the main techniques and technologies currently used for indoor
wireless positioning and provides some of the advantages and disadvantages of these
techniques.

2.3.1 Pseudolites and High Sensitivity GNSS

A Pseudolite (PL) is a small pseudo-satellite that is ground based that transmits
Global Navigation Satellite System (GNSS) like signals. Since the beginning of the
GPS system these transmitters have been used in an attempt to bridge the gap between
outdoor and indoor coverage for GNSS positioning. The pseudolite receiver is
constructed with the same technology that is used in a satellite positioning receiver
and therefore can receive signals from both GNSS and PL. This creates what is
proposed in [45] as a seamless coverage.

Kuusniemi, et al. [45] cited a recommendation by the Electronic Communications
Committee (ECC) of the European Conference of Postal and Telecommunications
Administrations (CEPT) which describes a regulatory framework for an authorisation
regime of indoor GNSS PLs and an allocated frequency band of 1559-1610 MHz.
This sets the precedence for the development of new standards and initiatives in this
positioning technique.

This research and the proposed use of PLs have been around for some time. Wang
[46] stated that PLs in positioning and navigation was first discussed by [47] and [48].
Stein and Tsang [49] later proposed the use of PLs and highlighted the improvement
in user location accuracy. The employment of PLs do provide redundancy of
positioning signals to the system user and as noted by [49] logically transforms the PL-supplemented GPS system into a more robust navigation system.

It is well known that the accuracy and availability of a stand-alone Global Navigation Satellite System is limited when subjected to attenuation and degradation from objects obstructing the satellite signal paths. High-sensitivity GNSS (HSGNSS) receivers are capable of detecting useful information from satellite signals that have been attenuated by up to 30 dB [50]. The focus in recent times of HSGNSS has generally been on pseudo range measurements, which limits the positioning accuracy to tens of metres.

Traditional PLs using constant signals rely heavily on accurate timing, identification and signal power using the same receiver technology for both the GNSS and PL signals. If these are not designed correctly this technique can produce severe interference between the terrestrial pseudo-satellite signals and the space-based satellite signals and consequently removes any improvement in positioning accuracy.

Kuusniemi, et al. [45] reported research using pulsed PLs and HSGNSS for navigation and seamless positioning. By using pulsed PL signals to transmit the GNSS-like signal only at particular time instants, interference problems between the terrestrial pseudo-satellite signals and the space-based signals are significantly reduced. Pulsed PLs were strategically placed indoors at known locations at the ends of building corridors to assist the high sensitivity GPS and Russian satellite navigation system (GLONASS).

PL and HSGNSS positioning and tracking receiver technology has been expensive in the cost of components, but prices will eventually come down to make it more attractive for low-end constructors. An advantage of using only PLs compared to a combination of PLs and HSGNSS is that the problem of the relatively long delays to get an initial fix on the location is overcome.

O’Driscoll, et al. [51] undertook a scoping study on PLs and pointed out that broadly speaking, PL applications can be classified as: a) Mixed PL/GNSS – such as aviation applications, open pit mining, etc.; and b) PL only – essentially indoor applications. O’Driscoll, et al. [51] also summarised a number of significant problems/issues with these techniques including: 1) Legal band issues; 2) Interference with existing GNSS
signals; 3) The near/far problem of signal powers; 4) Synchronisation; and 5) Constant monitoring. Although some of the technical issues may not significantly impact an indoor implementation, there is still a need for further investigation and research to overcome the remaining issues to make this technique a practical and cost effective solution for indoor positioning.

2.3.2 Wireless Local Area Network (WLAN)
WLAN technologies have progressed to such an extent that they are widely used in various wireless devices such as PDA’s, laptops, mobile phones, Apple iPad’s, etc. As most indoor office buildings already have some form of LAN architecture for computers, the use of wireless LAN can be easily implemented into the existing architecture at a significantly reduced cost. WLAN was not originally designed for localization, but it can be used in location estimation techniques that use received field strength as the RSSI values are already available and built into the WLAN Access Points (which may already exist) as reference locations and positioning measuring units.

These systems use a radio interface to allow the communication between the anchor nodes and the network. Radio protocols such as those provided by ‘Zigbee’ allows the easy measurement of the radio data packages that can be used to estimate the transmitter to receiver distance using propagation models. Medina, et al. [52] employed the use of RSSI available from the anchor nodes to undertake a feasibility of ultrasound positioning based on the ultrasound signal strength level.

Wireless LAN’s have now been implemented in public areas such as hospitals, train stations, universities, etc.[8]. As with all indoor environments where there is clutter and movement the accuracy of location estimations based on signal strength of WLAN signals is affected dramatically.

A number of techniques exist for the determination of the indoor location using wireless LAN.

a) Using the RSSI value from a number of access points with known co-ordinates and some mathematical algorithms, such as trilateration, the position can be estimated.
b) Employing a previous field strength survey of the area and correlate the real
time field strength with the previously measured data, that is normally stored
in a database for fast retrieval. The process of mapping the known area for
later use is known as location fingerprinting.

c) By dividing up the area into cells with unique id’s and employing an access
point in each cell which then detects the presence of a tag on the object being
tracked. This third method is commonly referred to as RFID and is described
in section 2.3.4.

Research into WLAN positioning began around the year 2000. Bahl and
Padmanabhan [20] undertook extensive research using this technique in their system
known as RADAR.

As pointed out by [53] the market for this technique is growing rapidly as the
flexibility, connectivity, mobility and low cost of this technology meets the needs of
the consumer. An advantage of using this technique is that there is a worldwide
standard on the operating band. A group of specifications has been ratified by the
IEEE 802.11 working group. 802.11b (referred to as “Wi-Fi”) has become the
industry standard operating in the 2.4 GHz band, which is an accepted ISM band
available worldwide.

2.3.3 Ultra Wide Band (UWB)
The use of Ultra Wide Band technologies achieves a higher positioning accuracy due
to its wide bandwidth, which provides a high tolerance to multipath problems in an
indoor environment. UWB operates by sending a series of extremely short pulses
across a very high band of frequencies simultaneously. These are short (~1 nSec)
discrete pulses instead of short RF pulses of high bandwidth. These pulses are thus
only ~30 cm wide in distance and therefore can be distinguished between distances
greater than this. Consequently, the transmitted UWB short-duration radio waves have
reached their destination before they can reflect off walls, ceilings or other objects,
thereby removing the opportunity for interference effects on the received signal.

Up to now UWB has been used in the unlicensed frequency band of the RF spectrum
commonly used for garage door openers, portable telephones and baby monitors.
However, the Australian Communications and Media Authority (ACMA) have
recently announced that spectrum and regulations will be made available to facilitate the introduction of UWB devices into the Australian market. This was highlighted in a conference paper by [54] at the recent IPIN 2012 conference. The frequencies under consideration are 3.6-4.8 GHz and 6.0-8.5 GHz. The ACMA are also considering further spectrum above 10 GHz for the expansion of UWB technologies. Until a dedicated band is allocated deploying UWB systems their existence are seen as unwanted noise to other systems in the licensed bands. In some countries it is illegal to deploy them.

Mucchi, et al. [55] showed how a real-time location system based on UWB impulses can be used to collect the cinematic parameters of a moving athlete in order to define the health status of an athlete objectively. The well-known commercially available UWB system Ubisense was used in the experiments which demonstrated that UWB localisation can be used to show an increase in the muscular capacity and measure it. The Ubisense system uses unidirectional tags with a conventional bidirectional time division multiple access (TDMA) control channel. Tags transmit UWB signals to networked receivers and are located using angle of arrival and differential time of arrival (DTOA or TDOA).

Kolodziej and Hjelm [42] stated some of the advantages of UWB as follows:

- The wide-bandwidth communication protocol means that a device will consume very little transmit energy while transmitting large amount of data.
- UWB is superior to infrared, ultrasonic and other radio-based positioning systems in terms of accuracy.
- Compared with radio frequency identification (RFID) technology, UWB has a better range for positioning and tracking.
- High tolerance to Multipath.
- High-speed data transmit capabilities.
2.3.4 RFID

Historically, the first RFID applications were developed in conjunction with RADAR technology during the Second World War and were referred to as Identification Friend or Foe (IFF) systems to detect friendly airplanes [56].

RFID systems are generally short range and use RFID tags which are database accessible through an RFID scanner. The basic RFID system consists of three components: a) the transmitter; b) a transceiver with decoder; and c) a RFID tag electronically programmed with unique information, such as its code. When polled by a remote interrogator (e.g. reader), the RFID tag (transponder) will reply with some identification data (e.g. a number). As pointed out by [57], in a passive RFID system the reader transmits a modulated RF signal to the tag which is made up of an antenna and integrated circuit chip. The chip receives power from the antenna and responds by varying its input impedance and thus modulating the backscattered signal.

This system is used in many warehouses where RFID scanners are installed throughout the facility which keeps track of the RFID tag attached to items. The item containing the RFID tag passes a particular scanner, retrieves the identification code and sends it to the server and database, which is used to keep track of all the items in the warehouse. RFID tags are now becoming much smaller and in some cases are used instead of bar codes. It is expected that eventually bar codes will be replaced. The accuracy of RFID depends on the number and placement of RFID scanners. RFID systems are generally used for identifying and tracking objects within a few square metres.

Low frequency and High Frequency RFID systems are short range systems based on inductive coupling between the reader and the tag antennas through a magnetic field. UHF RFID systems have also been researched and developed and are long range systems which employ the propagation of electromagnetic waves between the reader and the scanner. The problem with UHF RFID systems is that their performance is an issue in the near field where there is a presence of various dielectric and conducting objects close to the RFID tag. Research into near field issues is still continuing with developments in RFID tags with dual HF/UHF ability. Another technology that will improve the practicality of RFID systems is the use of flexible printed circuits. This
organic technology has already been developed by several companies and is a new era of research for this century.

Some advantages of RFID systems include:

- There is no requirement for contact or line-of-sight.
- Tags can be read through a variety of substances and at high speeds.
- It is well suited to a wide range of automated data collection and identification applications.
- High accuracy due to very short operating range.

Unfortunately, RFID can be a costly technology in some industries where a large number of tags and readers are required.

2.3.5 Time of Flight (TOF) and Time Difference Of Flight (TDOF)

The Time of Flight (sometimes referred to as Time of Arrival TOA) technique is grounded on estimating the time or arrival of a transmitted signal by a mobile device to a minimum of three base or anchor receivers. As the distance travelled is simply the speed of light times the travel time, the three calculated distances to base receivers can be used to calculate the mobile position using triangulation.

The Time Difference of Flight (sometimes referred to as Time Difference of Arrival TDOA) technique is based on the time difference of arrival for a transmitted signal at multiple pairs of base receivers. Firstly, a measurement is taken of the difference in distance to two reference stations (anchor node, access point or base station) with known locations. This results in an infinite number of locations that satisfy the measurement and when plotted forms a hyperbolic curve (Angle of arrival technique uses circles). A second distance difference measurement is then taken to a different pair of reference stations and a second hyperbolic curve is formed. The intersection of the first and second hyperbolic curves estimates the position of the mobile device. The TDOA positioning technique is sometimes referred to as multilateration.

TOF signal measurement was the founding technology used in GPS system where the uni-directional satellite signal is used to estimate the distance. This positioning
technique is difficult to support in Bluetooth technology as the time delay used to calculate the distance is extremely small.

Advantages include:

- Much improved accuracy compared with RSS/RSSI and AOA.
- The technique is independent of the wireless signal technology such as TDMA.

TOA and TDOA require a network structure that is well synchronised, both at the receiver and transmitter. The absolute time synchronisation must have at least a precision comparable to the desired positioning accuracy. Achieving this high synchronicity results in higher developmental and system component costs. For example the clock information has to be distributed and kept in the mobile unit.

2.3.6 Received Signal Strength / Received Signal Strength Indicator

Given the high multipath fading conditions that exist in a normal indoor environment it is understandable that positioning systems based purely on the received signal strength are virtually non-existent. Under such high multipath, small-scale fading conditions, the instantaneous received signal strength will fluctuate rapidly over time which makes accurate distance measurement based on received field strength very difficult.

The majority of the positioning systems that employ the received signal strength technique generally use a combination of existing measured field strengths recorded over the given area, known as “fingerprinting”, and the actual measured values. The prior fingerprint measurements are stored in a database and used in conjunction with the actual measured values in the mathematical calculations of the actual position.

RSS and RSSI techniques use the well-known inverse proportional relationship between received signal strength and distance that can be represented linearly for part of the propagation path. With additional knowledge of the propagation channel characteristics a model can be developed using the channel parameters for employment in the distance calculations.

Two methods are used to determine the position of the mobile device. The first method undertakes a field strength field survey (mapping) of the area in question.
before hand and stores the results for later comparison and distance retrieval. The second uses the RSS at three anchor nodes and then employs the mathematical geometry-of-circles principle of trilateration to estimate the location.

RSS methods usually employ statistical methods due to the fast fading variability which results from multipath interference.

Recently this positioning technique was employed in the new Bluetooth standard which enables RSS to be discovered without time consuming pre-connection. Bluetooth has a wide market and has been widely used in mobile devices such as phone, tablets, etc.

Yapeng, et al. [58] investigated a Bluetooth positioning system using RSSI, triangulation and three distance-based algorithms of Least Square Estimation, Three-border and the Centroid Method. The study was implemented using five Android (open source operating system) mobile phones as one mobile device and four reference nodes around a 6 x 8 square metre classroom. They reported that the study yielded good results. They plan to conduct further research into more complicated scenarios with this system and with more algorithms.

The advantages of using this type of positioning technique are:

- The majority of readily available radio modules and sensors already provide a received signal strength indicator removing the need for dedicated additional hardware for this parameter. [11] states that because of this implementing a local positioning system within a wireless communication system is more or less a software topic and proprietary hardware is not required.

- This is the easiest metric to obtain and does not require any additional signal processing which are required in AOA or TOA/TDOA.

Disadvantages include:

- RSS estimation is not very accurate where there is a high multipath existence.

- For an ordinary moving object wearing a beacon, the random changes of radiation pattern and polarization of the radiated signal will cause an unpredictable signal pattern to the RSS signals received by the reader. This
will also occur for any nearby moving objects in range of the transmitting beacon as well. Various statistical methods are therefore used to minimise this unpredictability.

- Path loss determines the signal power decay with distance from the transmitter and therefore average values are used instead of instantaneous values. This of course is dependent on the variation in ground reflection coefficient, multipath components and obstructions.

2.3.7 **Angle of Arrival (AOA)**

This technique uses the angle of arrival of the received signals from the mobile device to two or more reference receivers of known location. By employing directional antennas and using simple geometric equations, the distances from the mobile device to the receivers can be calculated. Straight lines can thus be obtained using these angles between the reference receivers and the mobile device where the intersection of these straight lines provides an estimate of the mobile position.

This positioning technique overcomes the variability in signal strength inherent under normal conditions in the RSS/RSSI technique due to multipath etc.

Wing Hung, et al. [59] conducted experiments on a complete active RFID indoor positioning system based on an analog phased array antenna. By steering the main beam of each reader’s phased array of 8 monopole elements, the angle of arrival of the active RFID tag was obtained and the tag’s position through triangulation. Accuracies as high as ±1 m were demonstrated in an indoor environment.

Disadvantages of this technique include:

- The technique requires the addition of complex antenna arrays at the anchor nodes (reference points) and is highly dependent on the accuracy of these antennas and their calibration.

- Accuracy is dependent on a line-of-sight signal. However, this is also an issue with the majority of other positioning techniques that use RSS/RSSI and TOA/TDOA in an indoor environment.
2.4 Current and Potential Wireless Indoor Sport Player Tracking Systems

A range of wireless RF signal indoor positioning systems have been developed in the past decade that could potentially be used for the tracking of players in indoor sports. Some of these systems will continue to improve as research into new methods to locate is transferred into commercially available components. The success of these existing systems will depend on: a) The robustness of the system to changes in the indoor environment, while still having the ability to scale as new technology becomes available; b) Continued research improvements in hardware and algorithms to reduce the position or tracking error; c) Reducing the physical impact of the deployed system on the indoor environment; and c) Improvements in the reduction of system cost and setup time.

Table 2 provides a sample of current or potential systems that could be employed in a wireless RF signal indoor player positioning system.

Table 2: Current or Potential Wireless Indoor Sport Player Positioning Systems.

<table>
<thead>
<tr>
<th>System</th>
<th>Range/Location Technique</th>
<th>Accuracy</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inmotio LPM</td>
<td>TDOA</td>
<td>&lt; 10 cm</td>
<td>Inmotio <a href="http://www.inmotio.eu/en-GB/20/lpm-technology.html">http://www.inmotio.eu/en-GB/20/lpm-technology.html</a></td>
</tr>
<tr>
<td>WiTracker</td>
<td>WLAN(RSS)</td>
<td>1.4 – 3 m</td>
<td>Research Paper [60]</td>
</tr>
<tr>
<td>Fraunhofer RedFIR</td>
<td>TDOA</td>
<td>&lt; 3 cm</td>
<td>Fraunhofer IIS <a href="http://www.iis.fraunhofer.de/en/ff/lok/proj/redfir.html#">http://www.iis.fraunhofer.de/en/ff/lok/proj/redfir.html#</a></td>
</tr>
<tr>
<td>Fraunhofer Awiloc</td>
<td>WLAN(RSS)</td>
<td>1-5 m</td>
<td>Fraunhofer University research <a href="http://www.iis.fraunhofer.de/en/ff/lok/tech/feldstaerke/rssi.html">http://www.iis.fraunhofer.de/en/ff/lok/tech/feldstaerke/rssi.html</a></td>
</tr>
<tr>
<td>Fraunhofer BlackFIR</td>
<td>TOF/OA</td>
<td>0.5 – 1 m</td>
<td>Fraunhofer University research <a href="http://www.iis.fraunhofer.de/en/ff/lok/proj/blackfir.html#">http://www.iis.fraunhofer.de/en/ff/lok/proj/blackfir.html#</a></td>
</tr>
<tr>
<td>Microsoft RADAR</td>
<td>WLAN(RSS)</td>
<td>2-3 m</td>
<td>Microsoft research <a href="http://research.microsoft.com/en-us/projects/radar/">http://research.microsoft.com/en-us/projects/radar/</a> [20]</td>
</tr>
<tr>
<td>WASP</td>
<td>TOA</td>
<td>&lt; 0.5 m</td>
<td>CSIRO research <a href="http://www.csiro.au/en/Research/DPF/Areas/Wireless/WASP">http://www.csiro.au/en/Research/DPF/Areas/Wireless/WASP</a> [30]</td>
</tr>
</tbody>
</table>
It was found that only those organisations related to the WASP and possibly the Inmotio LPM positioning systems have indicated they intend to enter into the indoor player tracking commercial space.

### 2.5 Positioning Mathematical Algorithms

The majority of mathematical algorithms used in positioning systems are based on the received signal strength use the RSSI to determine the distance between the beacon or object of interest and the fixed node or receiver. This distance estimation is commonly referred to as ranging. In indoor environments the localization errors due to random multi-path interference components, etc. has meant the introduction of statistical methods and other techniques into the calculations to help improve the position estimation.

Secco, et al. [28] gave a brief survey of the mathematical methods used in indoor tracking localisation. The mathematical techniques they indicated are grouped into four categories. They are: a) geometry-based methods; b) minimization of the cost function; c) fingerprinting; and d) Bayesian techniques.

For player tracking the Bayesian localizer calculates the prior probability as the uniform distribution over all locations. In other words, before each attempt at localization, the target is equally likely to be at any of the locations in a fingerprint map (derived beforehand). In order to achieve higher accuracy, this prior probability is calculated using prior knowledge of the target’s likely motion, historical information from previous user habits, collision detection, and anything else that affects the prior probability.
Zanca, et al. [32] reported a comparison between four localization algorithms used in wireless positioning techniques based on radio signal strength measurements. These were considered to be the best known localization algorithms when deployed in real-world environments. The algorithms considered were: a) Min-Max; b) Multilateration; c) Maximum Likelihood; and d) Ring Overlapping based on Comparison of Received Signal Strength Indication (ROCRSSI).

Chong, et al. [63] proposed the ROCRSSI algorithm to achieve high positional accuracy with reduced communication overhead with a smaller number of required anchor nodes. The ROCRSSI algorithm distinguishes nodes into two distinct categories of beacons and unknown nodes. The beacons have a known position, while the unknown node locations are estimated by using the RSSI values obtained from the beacon nodes. This is a similar technique to the cooperative localization method mentioned in section 2.2.2.

If algorithms are to be employed in any positioning/tracking system their choice will be dependent on the environment and whether the mobile target is static or moving. In the case of a basketball player scenario the target is moving erratically with varying acceleration and speed.

### 2.6 Location Fingerprinting

Location Fingerprinting is termed after the technique of matching the fingerprint of a signal characteristic (usually field strength) that is based on location. Two stages are involved in the process. They are: a) The offline stage where a site survey is conducted in the proposed area of coverage to gather the signal characteristic and store it in a database for later retrieval; and b) the online stage where the positioning technique compares the real-time measured values with the stored values to estimate the location.

Location Fingerprinting can also be used to gain the wireless RF signal channel propagation characteristics for a predictive mathematical model, where more than one site has a common environment, as measurements on a site by site basis can be very costly. Propagation models based on the channel characteristics can be effective in estimating the position of an object and can therefore be developed as a low-cost and simpler alternative.
In comparison to proximity and trilateration techniques alone, location fingerprinting provides a high level of accuracy. Abdat, et al. [22] stated that location fingerprinting was still the most suitable technique for indoor wireless positioning compared to other indoor positioning techniques due to its low cost and that its location accuracy is adequate for indoor environments such as malls and in buildings.

There are four common location fingerprinting-based positioning algorithms which use the pattern recognition technique between the real-time values and those stored. They are: a) k-nearest-neighbour (kNN); b) neural networks [64]; c) probabilistic methods; and d) support vector machine (SVM);

2.7 Location Estimate Accuracy in Basketball

Positional accuracy has been one of the main driving forces in research in the last decade for wireless indoor positioning systems.

Frencken, et al. [65] showed that the Inmotio LPM system produces highly accurate position and speed data in static and dynamic conditions and argue that technologies with high sampling frequencies open up new applications and types of analyses in sports science.

Positional accuracy of a wireless RF signal positioning system may be the goal of many researchers, however, in choosing a technique for implementation the question that should initially be asked is: What is the position information going to be used for? If it is to simply determine whether the mobile device is in a particular room of a building then accuracies in cm’s is not required. In a cell-ID WI-FI based system the accuracy will be dependent on the cell size. In the Location Fingerprinting method, granularity is an important factor to consider. For example, what should the spacing be of the pre-measured field strength map or grid to achieve the desired accuracy?

The positioning system accuracy can have a direct relationship to the cost of the overall system. Generally, for higher accuracies, additional complex technology and hardware components are needed resulting in higher commercial system costs. An example of this is the synchronisation of clocks needed to meet the accurate timing requirements for TOF/TDOF positioning systems.
Abdat, et al. [22] confirmed the general opinion that for most location finding scenarios such as malls or in buildings, there is no need to achieve very high accuracies to within centimetre precision.

For player positioning and tracking in the game of basketball the positioning accuracy is related to the horizontal space that a player occupies on the court. Obviously, it would not be required to have accuracies in the order of a few centimetres as this distance would almost never be realised between players. The amount of space allocated to each player could be used to determine the accuracy requirements of the player positioning system. The basketball players occupy a certain amount of area in the playing area. They may be standing up, bent over in a defensive stance or bent over with the basketball. For a positioning system that is tracking the players of only one team a positioning accuracy of ±1 metre would probably suffice.

For a system that estimates the position of players from both teams at the same time consideration would need to be given to the interaction between offensive and defensive players. In a man-to-man defence structure the distance between body torso centres varies greatly. However, most of the time the minimum distance is approximately 1.0 m. Again, a minimum system accuracy of ±1 metre would suffice for the majority of the game time. In the worst case scenario, players would be located at the same position. However, this could be accounted for in the positional data processing. We would know which one is the defensive or offensive player and a simple adjustment on the display could be made, as the defensive player is nearly always between the offensive player and the basketball scoring ring.
3. DESIGN THEORY

3.1 Introduction

The tracking of people within indoors can be achieved through many different methodologies as discussed in chapter 2 and highlighted in Appendix A. This thesis specifically concentrates on the tracking of basketball players in an indoor basketball court environment using the signal strength of wireless RF signals. Traditionally this has been difficult in a cluttered indoor environment where objects such as tables, chairs, industrial plant equipment hinder and interfere with the received signal. However, the environment associated with a basketball game is quite free from these obstructions and therefore there is potential to utilise simple wireless signal positioning or tracking techniques. In addition, there is a need to pass player information such as dribbling the ball to the tracking information system. As players will already be wearing wireless sensors, the use of these existing electronic devices and the communications channel is preferred.

This chapter sets out the background theory needed to build on to accomplish the experimental research and findings into the tracking of a wearable transmitting beacon. As such, this chapter does not contain all of the basic theory that would otherwise be commonly known by the reader with expertise in this field. Many of these basic theoretical aspects can be read in undergraduate textbooks that are readily available [14, 66-71]. Section 3.2 and 3.3 highlight the use and placement of wearable sensors. Section 3.4 considers the frequency allocation while Section 3.5 details antenna beam width and polarisation considerations. Section 3.6 considers the radiated transmitted power requirements and the horizontal radiation pattern of a wearable beacon is discussed in Section 3.7. Section 3.8 finalises the initial design theory considerations by detailing the receive antenna type and possible locations for the receive antenna. Section 3.9 details the channel model approach for considering indoor propagation while indoor fading statistical models and static indoor propagation models are considered in Sections 3.10 and 3.11 respectively. Section 3.12 considers the impact of dynamic movement. Section 3.13 details the theory behind a technique to detect ball possession by a player. Section 3.14 presents the
impact of multipath on the accuracy of the player positioning with the theory behind four Rician fading statistical parameters. Section 15 highlights the quantisation errors present in analog to digital convertors. Section 16 discusses the general movement of players depending on their role in the game and the impact on the expected results. Section 17 outlines the theory behind the trilateration technique used to determine the player position. Finally, Section 18 discusses the player positioning accuracy using a graphical method employing uncertainty ellipses.

3.2 The Use of Wearable Sensor Beacons in Indoor Player Positioning

Recently the wearing of electronic instruments by players to assist basketball coaches in some countries has been prohibited in the professional high level competitions (e.g. NBA) due to the safety of the players in essentially a contact sport and the distraction to the game by players, coaches and referees. This was mainly due to the physical size of electronic devices. Players also feel uncomfortable with wearing these devices. For this reason research into using electronic wearable devices in basketball for tracking of players has been virtually non-existent. Now that inertial sensors have become an integral part in everyday life, some of these devices that are smaller than 5 cm in length and weigh less than 25 g are readily available [72] and physically acceptable to been worn by players. The advantage of these devices is that as well as sending a tracking signal they can also send other useful information for coaches such as heart rate, accelerometer data, etc. They are currently being used in basketball training in the united states NBL and as the devices become physically smaller they will enter the arena of the live game. We are on the cusp of this happening now.

3.3 Placement of a Wearable Transmitting Beacon and/or sensors

Generally in most sports the most common locations for the placement of a wearable sensor is on the chest, the upper back, the arm or the wrist. However, depending on the application it could be anywhere on the body provided there is a suitable solution for mounting the sensor. For a wearable transmitting beacon where line-of-sight to a receiver is important, the placement of the beacon and the receiver location must be
considered together. The location on the body should be chosen for maximum received signal strength with minimum signal variation or disruption. For example, if the chest is facing the receiving antenna more than any other body location then this would be the preferred location and a simple chest strap would facilitate the mounting.

The game of basketball can be a fast moving impact sport and this needs to be taken into account for the design of the beacon/sensor. The sensor firstly needs to be mechanically protected and capable of withstanding impacts. For example, many chest mounted sensors are enclosed in flexible rubber attached to a chest strap. The earlier versions used hard plastic to protect the sensor. Wrist mounted sensors are now produced with a wrist band made from flexible elastomer material.

For the case of a wearable transmitting beacon the overall radiation pattern produced by the body/beacon combination is important (see section 3.5). For an offensive player who is mostly facing the basketball ring, the sensor is easily placed on the upper back. However, there may be occasions where the player is facing away from the ring. Therefore, a beacon located in the vertical forward plane of the body may also be required.

The accuracy of a positioning system based on the received field strength is highly dependent on the unwanted variation of the signal strength at a given location. To minimize variations in signal strength for a transmitting beacon due to movements of the body affecting the transmitting radiation pattern, it is an advantage to select a body mounting position that has the least movement in the pattern. It is considered that the arms, legs and the head have more overall movement than the torso. Consequently, directly under the sternum and at the top of the thoracic region on the back of the torso are the preferable locations (see Figure 4).
Figure 4: Locations for placement of beacon (copied with permission [73] under CC by SA 4.0)

The side of the shoulder is also potentially useable and should not be discounted as a possibility when conducting radiation pattern tests. Figure 5 shows the placement of the beacon under the chest and an accelerometer sensor on the wrist.

Figure 5: Beacon and accelerometer placements on the wrist, above the elbow and the front of the chest.
3.4 Frequency Considerations

In most countries the frequency spectrum is maintained and licensed through their government. For example, in Australia the main controlling body is the Australian Communications and Media Authority.

According to the 2013 Australian Radiofrequency Spectrum Plan 2013 [74] the 918 – 926 MHz, 2.4 – 2.5 GHz, 5.725 – 5.875 GHz and 24 – 24.25 GHz bands are some of the bands designated for industrial, scientific and medical (ISM) applications. Radio communication services within these bands must accommodate interference from other sources in the vicinity.

For the purposes of this research the ISM 2.4 – 2.5 GHz UHF band was chosen for a number of significant reasons. These are:

a) To obtain a licence on any other non-ISM band is expensive and is against the objective of a low cost solution;

b) Electronic components are readily available in this band;

c) At these higher frequency bands, the transmitting and receiving antenna sizes and other components are physically smaller compared similar components in the VHF ISM band. Up until recently the size of the components has been a limiting factor in the use of wearable sensor or beacon devices;

d) The power requirement to transmit a wireless RF signal over the basketball court at this frequency is relatively low (microwatts to milliwatts). For coverage from the sideline to the basketball key the distance is approximately 5 m. The equation for free space path loss $PL$ in dB is given by

$$PL = 20\times\log_{10}(d) + 20\times\log_{10}(f) - 27.55$$  \hspace{1cm} (1)

where $d$ is the path distance in meters and $f$ is the frequency in MHz.

Figure 6 highlights that as the frequency is increased from 2.4 GHz to over 10 GHz, the free space path loss using (1) increases.
e) At lower UHF frequencies, such as 900 MHz, deep fades occur in the received signal as the distance from the transmitter increases (due to the direct and ground reflected signal). Where the distance accuracy is based on field strength this variation is too great for such a positioning system methodology. At 2.4 GHz and higher this issue is not such a problem at distances less than approximately 10 m.

Although the 2.4 GHz band is suitable for this research project, in the longer term a higher frequency ISM band, such as 5.8GHz, would be an advantage. The two main reasons are smaller electronic components and overall physical form factor and the presence of interference from other services on the band would be reduced. The current 2.4 GHz band is quite congested with services including cordless telephones, baby monitors, wireless LAN’s (WiFi) including routers and modems, video game consoles, digital cameras, digital audio players and smart mobile phones. Some of these services have already migrated to the higher frequency band.
3.5 Beam Width and Polarization Considerations

3.5.1 Omnidirectional versus Directional

The radiation pattern defined by the transmitting and/or receiving antenna can impact on the overall design of the positioning system including the power requirements needed to provide a reliable signal over the propagation channel. For a theoretical isotropic antenna the field intensity radiates equally in free space in all directions and is no stronger in one direction compared to another. It is therefore considered to have no directivity. Practical antennas that approximate this characteristic in one plane are said to have an omnidirectional pattern in that plane. In reality, practical antennas still have some form of directivity as the antenna never has the same intensity in all directions. For directional antennas the radiated field intensity in one direction is usually a lot greater than others and therefore has directivity. The graph of the actual, or relative, field intensity at a fixed distance as a function of the bearing from the antenna is referred to as the radiation pattern. This radiation pattern is generally provided by antenna manufacturers as a polar graph for both the vertical and horizontal planes, or visually as a 3D image showing all angles in an x, y and z coordinate system. Typically the horizontal radiation pattern is described from 0 to 360 degrees and the vertical radiation pattern from 0 to 180 degrees.

By using an omnidirectional pattern for both the transmitting and receiving antennas much of the power is wasted in directions that are not required. For example, a receive antenna located on the side of the court would not require radiation away from the playing court. In fact, an omnidirectional radiation pattern would potentially increase the reflections and interference from audience wireless devices. The radiation patterns for the receive and transmit antennas should be reduced to directional patterns that meet the desired coverage area and therefore minimise the amount of multipath interference. The front to back ratio of these antennas should also be as high as possible to reduce unwanted signals being received.

The advantage of a directional pattern is that power that would otherwise be wasted is redirected into the main transmitting lobe and any side lobes that are created. Therefore, less power is required to achieve the same effective radiated power (ERP) in the desired coverage angles. A disadvantage of the directional pattern is that care must be taken to ensure that the beamwidth of the main lobe covers the desired area.
with minimal variation in signal over the given target area. UHF panel antennas are available in a wide range of horizontal beam widths and are typically called sector antennas. Figure 7 shows a typical 180 degree sector antenna suitable for 2.4 GHz.

If a directional receiving antenna on the side of the court receives a signal on a bearing that lies on the edge of its radiation pattern lobe then large signal variations can occur with only small changes in bearing angle. This introduces another error which reduces the accuracy of the position estimation. This sharp drop off of the main lobe constrains the use of the directional pattern to a maximum usable beam width.

![Horizontal radiation pattern of a Superpass WiFi 2.4 GHz 180° vertically polarised sector antenna](image)

**Figure 7**: Horizontal radiation pattern of a Superpass WiFi 2.4 GHz 180° vertically polarised sector antenna [75]. The radial units are dB relative to the main beam direction.

### 3.5.2 Beam Width and Side Lobe Reduction

If a rectangular aperture of height $l_x$ and width $l_y$ (across the x-y plane) is excited by a uniform field distribution then the normalised radiation intensity $F(\theta)$, at a fixed distance $R$ from the aperture is given by [71] as:

$$F(\theta) = \text{sinc}^2\left(\frac{\pi l_y \sin \theta}{\lambda}\right) \quad \text{(x-z plane)}$$

(2)

where $\theta$ is the angle between the z-axis and x-axis and $\lambda$ is the wavelength. $F(\theta)$ is symmetrical in the x-z plane with the maximum in the direction of the point at distance $R$. The half power beamwidth about the z-axis is given as:
\[ BW_{xz} = 0.88 \frac{\lambda}{l_x} \]  \hspace{1cm} (3)

Equation (3) also applies in the y-z plane. [71] states that this uniform aperture distribution gives a far-field radiation pattern with the narrowest possible beamwidth. However, the pattern also includes side lobes. Minimal or no side lobes is preferred to avoid receiving interfering signals arriving from directions outside of the main beam of the antenna pattern. The same consideration is to be given to the transmitting antenna to avoid unwanted multipath signals being created and received as interference. To overcome this issue, a tapered aperture distribution is used where the maximum radiation intensity \( F(\theta) \) of the pattern is at the center of the aperture which then decreases rapidly toward the edges of the main lobe. A steeper taper has the benefits of lower side lobes and a wider main lobe. Figure 8 shows a depiction of this where the \( k_x \) constant corresponds to the steepness of the taper.

![Figure 8: A cylindrical reflector with increased aperture taper and corresponding beamwidth.](image)

### 3.5.3 Maximum Usable Beam Width

The beamwidth of a directional antenna is the angular range of the main directional lobe that lies within the -3 dB or -10 dB less than the maximum power for that lobe. This beamwidth is closely related to the directivity of the antenna. Free-space directivity can be determined by comparing the spherical three-dimensional pattern of the directional antenna with a perfect spherical three-dimensional pattern of an isotropic antenna. The directivity of the antenna is calculated by the ratio of the
maximum power density which will occur at one or more points on the sphere to the average power density over the entire sphere. The -3 dB points (half power points) are generally used in communication system link design to minimise unnecessary interference at the receiver input from adjacent channels and other interfering signals.

In a positional system it is necessary to constrain the signal variation produced by a directional antenna pattern to be less than these half power beamwidth values to achieve a tighter value of the radiation pattern signal variation. For the purposes of this design the term Maximum Useable Beam Width (MUBW) of the horizontal radiation pattern will be used. Figure 9 shows an example of a signal variation allowance of only 1 dB giving a MUBW of 120 degrees.

For a triangulation or trilateration distance positioning system based on the received signal strength the maximum useable beam width will be based on a predetermined allowable signal strength variation rather than the usual -3 dB or -10 dB points. Similar consideration could be given to the vertical radiation pattern. This allowable signal strength variation will impact on the error in the distance estimation for a received signal.

Figure 9: Maximum useable beam width of 120°.
3.5.4 Player and Court Interaction

By considering how the basketball players are situated on the court and their movements, transmitting and receiving antenna radiation patterns can be tailored favourably to meet the requirements of the play area and the positioning system. We know that basketball players while in offensive movements are mainly facing the basketball ring and are generally facing away from the sideline. We also know that in most cases there is direct line of sight (LOS) between those offensive players at the side of the basketball key and the court sideline if the transmitting beacon is mounted on the back of the players. It is generally only when offensive players enter the basketball key that congestion arises between offensive and defensive players and the duration of LOS signal obstruction or loss rises.

Firstly, if we are not interested in the location of players within the basketball key (note that offensive players without the ball only have 3 seconds of regulation time within the key) but only in their position outside of the basketball key during offensive plays, then the coverage area required for consideration is reduced.

Secondly, the design only needs to consider one quarter of the basketball court as the other three quarters can be considered identical. Therefore, if the radiation patterns of the transmitting and receiving antennas meet the requirements for one quarter of the court they can be mirrored for the other three quarter areas on the basketball court.

3.5.5 Polarization

Linearly and vertical polarised antennas are generally preferred for wearable mobile devices as an omni-directional radiation pattern is desirable before the body influence is introduced. A simple horizontally polarized antenna would introduce the need to re-orientate the transmitting antenna constantly under mobile conditions because of its directional characteristics. Horizontally polarized omni-directional antennas have been constructed using stacked broadband elements that radiate as slots. However, these designs are a lot more complicated compared to the grounded quarter wave monopole on-board printed meander antenna utilised in this research and would not be practicable.
3.6 Radiated Transmitted Power Requirements

The international basketball court specifications state that the basketball play area is 28 m long by 15 m wide. The system design covers only a quarter of the court as the other three quarters are mirror images. This equates to an area of 14 m long by 7.5 m wide. As the majority of the time the offensive drills are outside the basketball key the area in question is reduced to 7 m long by 5.5 m wide. As there is a minimum requirement for two receivers in the trilateration method, the coverage area will be half again with a maximum path distance of less than 7 m.

The transmitting beacons used in this research have a transmitter input power of 0 dBm (dB above 1 mW) or 1 mW. To determine the approximate path loss over 7m the following assumptions were made:

a) The transmit and receive antenna heights were chosen to be 1.38 m, representing the beacon at chest height on a 203 cm high player. (In choosing a receiving height, consideration was given to the Fresnel zone clearance to minimize multipath reflection interference from the surface of the court);

b) The frequency was chosen to be 2.4 GHz located at the bottom of the 2.4 – 2.5 GHz ISM band. Reasons for this choice are detailed in section 3.4;

This results in a path loss of -56.96 dB and a received power at the receiver antenna terminals of 2 microwatts. Most RF signal receivers have a sensitivity of -85 dBm or less, which is more than capable of receiving this RF signal strength without interference from the noise floor.

The ACMA have restricted power levels in the 2.4GHz ISM band to 4W EIRP for digital modulation transmitters and 10 mW for other transmitters that are not frequency hopping or telecommand and telemetry[76]. These are classed as low interference potential devices (LIPD). There is no requirement to apply for this type of licence and these power limits are well above the requirements needed for this research project.

In 2008 data communication transmitters used indoors in the 57-66 GHz band were added to the LIPD class licence which supports wireless personal area networks (WPANs) in indoor environments. An ‘all transmitter’ class was also added to the 5.725 to 5.875 GHz band which enables the use of short range low power transmitters
using analogue modulation techniques in the 5.8 GHz ISM band. This opens up scope for moving the operating frequency to a higher frequency as discussed in section 3.4.

3.7 Horizontal Radiation Pattern of a Wearable RF Beacon

For a transmitting beacon mounted on the body torso the radiation pattern and ERP are significantly modified due to the presence of the human body. To consider any placement of receive antennas for coverage of the basketball court consideration must be given to the overall ERP and the resulting radiation pattern due to the body presence. The radiating signal will not penetrate through the body, however, there is diffraction involved which could increase the radiated pattern beamwidth around the body to what otherwise would be expected. The beamwidth can become much less as the body becomes part of the antenna and splits up the beam into many lobes.

The placement of a wearable beacon on the player and the receiver location from the body will determine the MUBW and direction. Minimising any signal strength variations in the signal path will improve the received power and so the estimated distance accuracy.

In a basketball court environment, where a player is wearing a beacon and moving horizontally or vertically, it would be ideal to have the radiating pattern with minimal or no transmitting signal strength variation towards the receiver, no wastage of radiated power in non-useable directions and no unforced interference due to multipath. In this ideal case the required transmitting beam width in the horizontal plane would be determined by the variation in position of the player (see Figure 10).

By measuring the radiation pattern from the transmitting beacon on a human body the signal variation from 0 to 360 degrees horizontally and from 0 to 180 degrees vertically can assist in determining the useable beam width.

Consequently, the MUBW within the measured horizontal radiation pattern will be dependent on: a) the maximum signal level variations acceptable; and b) the position of the player on the court wearing the beacon with respect to the receivers. Ideally the bearings to both receivers from the body worn beacon should fall within the MUBW.
Figure 10: Player position consideration in transmitting beamwidth requirements. (Clipart (copied with permission [77]))

The body-affected radiation pattern can be obtained by mounting the beacon on the body, rotating the body and measuring the field strength in the far-field at a stationary receiver location. This sort of experiment can be conducted within a large anechoic chamber or on an open field away from buildings and trees. The large open field was chosen as it was slightly easier to carry out the measurement.

In an experiment to measure the radiation pattern in the horizontal plane, a subject was asked to stand on a large rotating disk (‘Lazy Susan’) shown in Figure 11 which was located in an open field.

Figure 11: A ‘Lazy Susan’ test rig constructed for a body worn beacon radiation pattern measurements.

The field strength meter was located some distance away from the subject in the far field region to avoid any near-field affects. The subject with the transmitter was
rotated in discrete bearing intervals from 0 to 360 degrees in the horizontal plane and the received field strength was measured. Typically measurements are made with and without the effects of the body.

Welch et al. [78] conducted a similar experiment previously for the United States Naval Academy while looking at the effects of human body interaction with a close proximity UWB antenna. It was pointed out that a tripod mounted antenna measurement technique is quite common in similar tests and is routinely utilized during the characterization of the UWB channel. As with this research, Welch et al. [78] was concerned that the human body may affect the RF propagation, AOA (a technique for position estimation) and the systems user’s orientation relative to the surrounding environment. Welch et al. [78] obtained radiation patterns for frequencies between 2 – 5 GHz in the far field region of the transmitting antenna.

Varnoosfaderani et al. [79] conducted experiments at 2.45 GHz to improve the radiation characteristic performance of wearable antennas and during the research employed a wooden rotator and tripod to undertake signal strength power measurements at 15 degree intervals through 360 degrees at a distance of 3m. A wearable sensor beacon was mounted on the upper arm of a female subject. The subject was positioned off-centre on the wooden rotator to ensure the distance between the sensor beacon and the receiving antenna did not significantly change. Varnoosfaderani et al. [79] confirmed the significant impact that the body has on the wearable beacon’s radiation characteristics and provided a technique to improve this.

3.7.1 Far-field distance calculation for radiation pattern measurements
To undertake radiation pattern measurements on a test antenna the receiving antenna should be located in the far field to avoid the influence of the charges and currents presented at the electromagnetic source. The wave radiating from a point source is spherical in shape but at a sufficiently large distance the wavefront across the receiving aperture can be considered as planar which simplifies the mathematical calculations of the radiated field. [71] Beyond the reactive near field, which is the region very close to the antenna, the antenna’s radiated field is divided into two regions. The radiating near field (the Fresnel field) and the radiating far field (the Fraunhöfer field). The distance (m) to the far field region is related to the largest
linear dimension of the transmitting antenna aperture and the carrier wavelength \cite{69} and is given by:

\[ D = \frac{2L^2}{\lambda} \]  

(4)

Where \( L \) is the largest linear dimension of the physical antenna (m), \( \lambda \) is the wavelength and \( D \gg L \). At a distance \( D = 0 \) equation (4) does not hold so large scale propagation prediction models use a close-in reference distance as a power reference point.

In the case of small antennas where \( D < \lambda/2 \) this far field boundary equation yields a distance less than \( \lambda/2 \). Silicon Laboratories [80] recommends that the far field distance in this case should be at least two wavelengths, even if the antenna is small. At 2.4 GHz this alternate recommendation gives a distance of 0.25 m.

3.8 Receive antenna type and location

In the case of offensive players, where a wearable beacon is located on the back of the torso, then one side of the court is obstructed by the body and possibly by other players and the other side has mostly direct line-of-sight conditions.

If the receive antenna is located on the side of the court then a directional pattern is needed with a high front-to-back ratio to avoid wastage of energy and to reduce interference from unwanted multipath signals from the court side seating and walls. There are other potential locations for positioning the receive antenna, including:

3.8.1 Above the basketball backboard

This location current is used to display the score using and electronic scoreboard. It would require specialised hardware and would be subject to vibration as the ball comes into contact with the basketball. Severe movement is also likely when a player undertakes a ‘dunking’ of the ball.

3.8.2 Directly below the basketball backboard

This location would be ideal if it were not for the fact that many shots that are missed pass this area and are likely to damage the receive antenna. The other concern is the
multipath interference from reflections of the transmitted signal off the metal basketball ring and its struts.

3.8.3 At the end of the court
The main disadvantage of directly in the centre of the end court end line is the reflections from the basketball backboard and the high obscurity from other players to the line-of-sight signals. This location is also subject to frequent clashes of players as they approach the ring at speed and overshoot the end line. Near the junction of the key line and the court end line/baseline (see Figure 12) would be better. This location is preferable to behind the backboard to minimise signal obstruction from player congestion within the basketball key and damage due to players.

![Figure 12: Optional position for a receiver.](image)

3.8.4 On the roof
The logistics of this location would make it difficult to achieve a simple installation. Also, many venues have very high ceilings above 20 m. This distance is too great for a reliable distance estimation based on received signal strength due to the depth of nulls.

3.8.5 Under the court
At most indoor basketball court venues there is no access to below the basketball court. This prevents the practical implementation in this location, without dismantling the court. However, the concept is worthy of consideration if the exact propagation characteristics through this floor medium is known.
3.9 **Channel Modelling**

There are two main approaches to modelling a radio channel for propagation. (Domazetovic, Greenstein et al. [81]). The first approach is deterministic (i.e. where there is no randomness involved), which is based on ray tracing that takes into account the interfering reflections and diffractions that reach the receiver. These interfering signals arrive at the receiver with variations in magnitude, phase and delay and combine vectorially. Generally, details of the environment such as position of walls and ceilings and other above surface fixed objects are required. Additional consideration is required if objects in the environment are moving. This approach has mainly been used for indoor applications. However, for this research the second approach known as stochastic (i.e. based on using probability) was adopted, where a large number of measurements were taken and statistical modelling applied to the measured data.

3.10 **Indoor Statistical Model Distributions**

There are many types of statistical data distributions with a shape approximately described by a normal curve (a normal distribution or Gaussian distribution [82]). The Gaussian distribution is a continuous probability distribution that has a bell-shaped probability density function. A Gaussian distribution is commonly used in signal propagation prediction models to determine the received field strength where there is channel variation due to random spatial or temporal movements.

There are two main statistical distribution types used in an indoor environment such as that considered for an indoor basketball venue.

3.10.1 **Rayleigh Distribution**

The Rayleigh distribution is typically used to describe the nature of the received signal in a propagation channel that experiences fading. Fading causes a variation in the received signal magnitude and is caused by multipath interference, diffraction and changes in the propagation path. It is most notable in a mobile radio channel environment and where there are objects that can reflect or refract the original signal back to the receiver. A Rayleigh distribution is used to mathematically describe the statistical varying nature of the received multipath signal levels.
3.10.2 Rician Distribution

When there is a dominant non-fading signal between the transmitter and receiver such as the direct LOS signal, the small-scale fading envelope follows a Rician distribution. In this case the random multipath signal components arriving at the receiver from different directions are added to the stationary dominant component. This causes a dc component to be added to the mean of the random multipath signals, which would otherwise be zero. This dc offset is the main difference between whether the distribution is considered as Rician or Rayleigh. Therefore, as the dominant signal becomes weaker the distribution moves towards a Rayleigh distribution.

3.10.3 Small and Large Scale Fading

[69] Propagation models that show the rapid fluctuations of the received signal over very short travel distances or short time durations, such as those experienced inside buildings, are called small scale fading models. Normally in indoor environments the received signal undergoes rapid fluctuations in amplitude due to multipath and other factors about a mean value. This is typical of small scale fading that appears as signal fluctuations about a mean a long way from the transmitter but over a short distance. As the distance from the transmitter is increased significantly compared to the wavelength closer to the transmitter the local average received signal will gradually decrease (i.e. the inverse square law dominates). This slower varying local average value is the value determined in large-scale propagation models and is referred to as large-scale fading.

3.11 Static Indoor Propagation and Empirical Path Loss Models

Indoor wireless positioning systems that are based on radio frequency (RF) signal propagation are reliant on the underlying transmission channel propagation knowledge and the characteristics of the indoor environment. The need for static and non-static signal propagation knowledge in these environments is important. There have been surveys and studies conducted on wireless indoor positioning techniques and propagation models such as Yanying, Lo & Niemegeers [8] and Hui et al. [9] that assist the design engineers. Unfortunately, there is no one empirical model or positioning technique suitable for every indoor environment. This is mainly due to the variation in position and shape of the inanimate objects and surfaces between one environment to the next. This unknown variation in multipath, scattering or
shadowing interference to the transmission signal hinders the mathematics used by researchers to produce a universal model. However, the playing area used by some elite indoor team sports is mainly free from these interfering and varying objects, except for the players and referees themselves. As the play area layout follows international specifications and is replicated at hundreds of venues around the world, scope exists to produce a general propagation model.

These radio signal propagation models can be determined using empirical methods and statistics and are founded on fitting mathematical models to on-site measurements. The potential benefits from this to the design engineer of an indoor player positioning system is that expensive site measurement techniques can be avoided in favour of a low cost propagation model, which is also a simpler alternative.

A Gaussian (or normal) distribution is commonly used in signal propagation prediction models to determine received signal strength where there is signal variation due to random shadowing, clutter, spatial or temporal movements. For this environment where there is a dominant stationary non-fading signal component (ie line-of-sight), the small-scale (fast) fading Gaussian spread generally follows a Rician distribution [69] & [71].

There are two empirical path loss models typical in these environments.

### 3.11.1 Free Space Path Loss Model
Both theoretical and measurement-based propagation models show that the average received signal power decreases logarithmically with distance. The Log-distance path loss model is given by

\[
PL(dB, d \geq d_0) = PL(d_0) + 10n \log_{10}(d/d_0)
\]

where \( n \) is the path loss exponent (slope index) that indicates the rate that path loss increases with distance, \( d_0 \) is a close in reference distance, \( PL(d_0) \) is the average path loss measured or a free space calculation from the transmitter to \( d_0 \) and \( d \) is the separation distance in metres from the transmit antenna to the receive antenna. The reference distance \( d_0 \), was chosen to be 1m as it must be in the far field of the transmitter but with a significant signal strength. Figure 13 shows this reference measurement being conducted within an anechoic chamber.
Where there is surrounding clutter variation at different locations, measurements would be different to the average value predicted in equation (5). The path loss $PL(dB)$ at a given distance would be random and distributed log-normally about the mean distance value. In this case an additional random variable $X_{\sigma}(dB)$ would need to be added to the equation, referred to as log-normal shadowing by [69]. $X_{\sigma}$ is usually a zero-mean Gaussian (normal) distributed random variable with a standard deviation $\sigma$ (also in dB).

By using a straight line linear regression and fit using the method of least square errors (MMSE) on the recorded measurements and those predicted by the free space path loss model, a path loss exponent $n$ was obtained.

### 3.11.2 Two-Ray Path Loss Model

The simplest ray-tracing model applicable to indoor propagation is the “Two-Ray model”, which is applicable when the direct ray and the ground reflection signal dominates the received signal. Figure 14 shows this model graphically which takes into account the direct signal path and one reflected path off the ground surface.
Comparison of ray-tracing methods with empirical data in literature has shown that it can accurately model the received signal within indoor environments with appropriately adjusted diffraction and reflection coefficients [67].

The average power received at the receiver is made up of the combined line-of-sight $E_{LOS}$ signal (the direct ray), travelling a distance $d_d$ and a reflected signal $E_R$ traveling a total distance of $d_1$ plus $d_r$ (see Figure 14). At any given frequency the total received field strength (mV/m) is given by $|E_{TOTAL}| = |E_{LOS} + E_R|$ and was calculated using the following equation.

$$|E_{TOTAL}| = \left| \left( \frac{E_0}{d_d} \right) e^{-jkd_d} + \Gamma \left( \frac{E_0}{d_r} \right) e^{-jkd_r} \right|$$  \hspace{1cm} (6)

Where $E_0$ is the measured field strength (mV/m) at a close in reference distance $d_0$ in metres;

- $d_d$ is the line-of-sight distance from transmitting to receiving antennas in metres;
- $d'$ is the total distance travelled by the reflected signal in metres (ie $d_1 + d_r$);
- $k$ is the wave number (phase constant) and is determined by $2\pi f/c$, where $f$ is the frequency (2.4GHz) and $c$ is the speed of light;
- $\Gamma$ is the reflection coefficient [69], which depends on the angle of incidence $\theta_i$, the wave polarisation and frequency. It is also dependent on the relative permittivity and conductivity of the reflecting surface, which were taken to be 1.99 and 0.012 S/m respectively [83].
3.11.3 Reflection Coefficient

In the Two-Ray model the plane of incidence is the surface of a basketball court which is made up of highly polished hard wood, which is a lossy material. If the reflecting material is lossy then some of the original signal will be lost due to absorption (refracted into the lossy material) and this will reduce the electric field intensity of the reflected signal. The complex permittivity of a lossy material is given by:

\[ \varepsilon = \varepsilon_0 \varepsilon_r - j\varepsilon' \]  

(7)

where

\[ \varepsilon' = \frac{\sigma}{2\pi f} \]  

(8)

In this equation \( \sigma \) is the conductivity of the reflecting material in Siemens/meter, \( \varepsilon_0 \) is the electric permittivity in a vacuum and \( \varepsilon_r \) is the relative permittivity of the dielectric reflecting material.

In Recommendation ITU-R P.1238-7 (02/2012) [83] Table 3 is given for propagation of indoor radio communication systems and radio local area networks in the frequency range 900 MHz to 100 GHz.

Table 3: Parameters for the relative permittivity and conductivity of building materials

<table>
<thead>
<tr>
<th>Material class</th>
<th>Relative permittivity</th>
<th>Conductivity (S/m)</th>
<th>Frequency range (GHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>c</td>
<td>d</td>
</tr>
<tr>
<td>Concrete</td>
<td>5.31</td>
<td>0.0326</td>
<td>0.8095</td>
</tr>
<tr>
<td>Brick</td>
<td>3.75</td>
<td>0.038</td>
<td>0.0</td>
</tr>
<tr>
<td>Plasterboard</td>
<td>2.94</td>
<td>0.0116</td>
<td>0.7076</td>
</tr>
<tr>
<td>Wood</td>
<td>1.99</td>
<td>0.0047</td>
<td>1.0718</td>
</tr>
<tr>
<td>Glass</td>
<td>6.27</td>
<td>0.0043</td>
<td>1.1925</td>
</tr>
<tr>
<td>Ceiling board</td>
<td>1.50</td>
<td>0.0005</td>
<td>1.1634</td>
</tr>
<tr>
<td>Chipboard</td>
<td>2.58</td>
<td>0.0217</td>
<td>0.7800</td>
</tr>
<tr>
<td>Floorboard</td>
<td>3.66</td>
<td>0.0044</td>
<td>1.3515</td>
</tr>
<tr>
<td>Metal</td>
<td>1</td>
<td>(10^7)</td>
<td>0.0</td>
</tr>
</tbody>
</table>
With the complex permittivity of the reflecting material known the reflection coefficient $\Gamma$ for a RF signal where the E-Field is vertically polarized may be determined using the following equation.

$$\Gamma = \frac{\sin \theta_i - \sqrt{\varepsilon_r - \cos^2 \theta_i}}{\sin \theta_i + \sqrt{\varepsilon_r - \cos^2 \theta_i}}$$

(9)

Plots of the estimated received field power (dBm) versus $\log_{10}(d)$ for the Two-Ray Path Loss model could be determined and a linear regression using MMSE on the recorded measurements can determine a path loss exponent $n$.

### 3.11.4 Two-Ray Path Loss Nulls

As the distance from the transmitter increases, the resultant received signal wave changes in amplitude due to the constructive and destructive effects of the two rays (direct and ground reflected). The effect on the resultant received signal is a series of maxima and minima usually referred to as multipath fading.

At VHF frequencies, fading nulls due to two-ray multipath interference can be very deep. Although these nulls only occur over a short distance they still have significant impact. In a distance estimation methodology based on received field strength this problem presents significant inaccuracies in the positioning estimation. However, as the frequency increases to 2.4 GHz and above, these nulls become significantly smaller and become even less of an issue for close-in distances less than 7 m. Consequently, this issue is minimised in an indoor basketball court environment as the distances required for coverage are less than approximately 7.5 m.

### 3.12 Dynamic Indoor Propagation

The study of dynamic basketball player tracking within indoor environments require consideration of additional influencing factors compared to those where the players are standing still or in a static scenario. These include: (a) the speed of the player (therefore the beacon) and the resulting Doppler shift effect on the receiving signal and the frequency; and (b) the effect of movement and/or direction of travel of a player to the beacon’s transmitting antenna orientation. Although the frequency variations due to Doppler shift is likely to be negligible due to the low speeds of
players, a change in transmit antenna orientation can influence the strength of the received RF signal depending on the radiation patterns of both the transmit antenna on the body and the sideline receive antennas.

By recording received field strengths versus absolute distance over a number of dynamic paths as a player moves towards the receiver, a power law model can also be developed and the value of $n$ determined.

As well as conducting constant mobile propagation tests over predetermined straight-line paths on the basketball court, a predetermined offensive drill could be conducted at a variable game pace with a change in direction. The advantage of this second scenario is that it would include both arbitrary and fast movements typical in a basketball game.

In any mobile environment consideration is usually given to the Doppler shift effect on the received signal frequency, due to the movement of the transmitter or receiver. However, the maximum velocity likely to be obtained by a player in indoor team sports such as basketball is much less than 10 m/s. These low velocities will have a negligible effect on the received frequency.

### 3.13 Ball Possession

Possession of the basketball by a player is also valuable information for coaches and trainers as identifying the player with the ball is important in recording and assessing team strategies. Previous research into the tracking of a ball in sport has been based on using video analysis or through the use of wireless sensors/beacons placed within the ball. As an alternative, the use of accelerometer sensors could be considered so that international rules of the game are not violated. Accelerometer sensors have been used to monitor the movements of the body as previously reported by Neville et al. but have not been considered for ball possession [84]. These sensors can potentially be used to recognize when a player is bouncing the basketball (dribbling), thereby indicating one form of ball possession.

Using the dominant accelerometer plane of a 3-axis accelerometer sensor it is possible to detect the downward point where the ball leaves the hand in a typical basketball dribble. At this point there will be no acceleration until the ball comes into contact...
with hand again in its upward rising motion. By detecting the pattern signature recorded for the acceleration over time during this ball bounce process it is feasible to detect this pattern if it occurs many times by the average acceleration levels. Typically these levels may be within the 0 to 4g m/s² range, however, they may be higher depending on the strength of the bounce. The combination of acceleration level and repetition can provide a unique pattern associated with the ball bouncing and hence, ball possession. Figure 15 shows a typical accelerometer pattern of this type. The direction of acceleration will be dependent on the orientation of the sensor.

![wrist falling and rising](image)

Figure 15: Typical wrist mounted accelerometer sensor patterns for bouncing a basketball.

### 3.14 Multipath impact on the accuracy of team player positioning

In a basketball game there are up to 10 moving bodies on the court (not including two referees). These additional moving objects may give rise to multipath interference to the desired received signal and therefore to the reliability of the received data. A large variation in received signal level due to multipath interference and obstruction has a direct impact on the accuracy of the algorithm used to estimate the player’s position. Typical Rician fading statistical parameters include level crossing rate, average fade duration, Rician k-factor, the Rice probability density function and the cumulative Rice distribution. These parameters provide some means of gauging the reliability of the received signal strength.

#### 3.14.1 Level Crossing Rate and Average Fade Duration

The performance and reliability of the received signal at the receiver is crucial where even a slight loss in signal can impact dramatically on a positioning system based on
signal strength. It is impossible with such a system for a player to be at one location and in the next instant, for example, be 3m away.

The two most often used fading statistics are the Level Crossing Rate and the Average Fade Duration.

The Level Crossing Rate (LCR) \( N_L \) is defined as the expected rate at which the received signal crosses a specified signal level in the positive direction \([70]\). It is determined by counting all crossings \( N_c \) with a negative slope at a specified crossing signal level \( L \) for the duration of the fading record of \( T \) seconds and is given by

\[
N_L = \frac{N_c}{T} \quad (10)
\]

The average fade duration (AFD) \( t_L \) is defined as the average time that the signal remains below a specified signal level after crossing that level in a downward direction as is given by

\[
\overline{t_L} = \frac{1}{N} \sum_{i=1}^{N} t_i \quad (11)
\]

where \( N \) is the total number of fades and \( t_i \) is the time duration of each individual fade below a specified signal level.

The product of equations (10) and (11) leads to the cumulative distribution function (CDF) that the received signal is above the threshold level \( L \), and is given by

\[
N_L t_L = \frac{1}{T} \sum_{i=1}^{N} t_i = \text{Prob}(R \leq L) \quad (12)
\]

where \( R \) is the received signal level.

3.14.2 Rician k-factor and Cumulative Distribution function

A typical parameter used to measure the severity of fading is known as the Rician k-factor \( k \), which is the power ratio of the fixed dominant signal to the fading components. It is given by
\[ k = \frac{\text{Power in dominant signal}}{\text{Power in all other components}} = \frac{A^2}{2\sigma^2} \]  

(13)

where \( A \) is the peak amplitude of the direct wave and \( \sigma \) is the standard deviation of the overall received signal envelope \( R \). As the value of \( k \) approaches 0, the distribution approaches a Rayleigh distribution. As \( k \) becomes very large the distribution approaches a standard Gaussian distribution which is centred around a mean.

### 3.15 Quantization Errors within Analog to Digital Convertors

Variation in received RF signal powers can also occur when using digital electronics in the receiving system. Quantization errors in digital field strength meters occur from converting the received analog RF signal to digital. The internal analog to digital converter (ADC) resolution is the smallest incremental change that can be recognized. The corresponding change in the digital output is usually expressed in terms of the least significant bit (LSB). Typical low cost hand-held analyzers convert the analog input signal to a 10-bit digital value. This change due to quantization error can generally be considered as white noise and would normally be reduced in measurements by averaging the samples. The RF explorer spectrum analyser does use quantization, however, where most chip vendors for RSSI have an accuracy of 1 dB steps, the RF Explorer implements a linear response with a higher accuracy of 0.5 dB resolution steps.

### 3.16 Player movements within a typical offensive play in respect to tracking

The movement of players and their interaction within a basketball game should be considered when focusing on tracking one or more players. If the game involved a constant close interaction similar to a busy train station platform then the ability to receive line-of-sight RF signals would be hindered considerably to a point where the simple method of using the combination of distance/power estimation and triangulation would fail. This breakdown would also occur within the basketball key where players are in close contact vying for a rebound (where the basketball is falling after hitting the ring and/or backboard without goal success). However, when the basketball is outside of the basketball key, offensive strategies and offensive plays
occur with offensive players separated most of the time. When offensive players are separated it is usual for the defensive players to be separated as well if they are playing a man-to-man defence. Further, there is some distance between offensive and defensive players. Even in a zone defence where the defensive players are located within the basketball key there is some distance between the defensive players.

With the knowledge that static separation is favourable for location estimation using triangulation we also need to consider the movements of the offensive players in a typical offensive play.

3.16.1 Guard Player
These players are usually smaller in size compared to centre players with play areas at the top of the basketball key or between the key and the sideline. In an offensive drill they may cut across the key in movement but usually end up in these play areas to either shoot, pass or feed the ball to the centre player.

During a basketball game the defensive player will be located somewhere between the player wearing the beacon and the basketball ring. Under this scenario signal obstruction between the beacon and side court receivers is less likely to occur.

3.16.2 Forward Player
These players normally conduct play between the key and the sideline to feed the centre players with the ball. They may occasionally swap positions with a centre player or cut across the key like guards in an offensive drill. In their normal play area, like the guards, are less likely to have significant fading from defensive players between them and sideline receivers.

3.16.3 Centre Player
These players are generally the largest in size and height and their vicinity of play is normally just outside the basketball key line. This occurs most of the time as basketball rules state that they have only 3 seconds of allowed time within the key during an offensive move. They will generally be on the side of the key, but can at times play anywhere around the key line. They may also cut across the key during play. These players will experience LOS obstructions the most due to other players between them and the sideline. These players will also mostly be facing away from
the basketball ring towards the sideline when they are in play with the feeder (forward or guard).

3.16.4 Referees
These participants are generally outside of the play area. Typically one referee covers play from behind the baseline which is located behind the backboard. The baseline forms the length of potential movement for this referee which will not impact on the direct line-of-sight signal between the player and a sideline receiver.

A second or even third referee maintains a distance from the play trying not to interrupt the game. One or two referees undertake this task. These referees may on occasion cross the direct line-of-sight signal path between the player and the sideline receiver.

3.17 Trilateration by using the Geometry of the Circle
The majority of wireless RF indoor positioning systems in literature that derive an unknown position by the use of mathematical laws use some form of historical mathematical formula found in Euclidean geometry. In particular, the Law of Cosines, the Geometry of the Circle, Trigonometry and the Pythagorean theorem.

Trilateration is one mathematical technique used in these wireless positioning systems to approximate the player’s position and is based on the calculated or known distances from the player to two or more known locations (receivers). Approximate distances to each receiver can be determined from the signal strength or time delay recorded at each of the receivers, as there is a direct relationship between signal strength (or time delay) and the distance travelled by the signal.

Figure 16 depicts the use of this trilateration technique. By using the geometry of circles, absolute or relative locations can be determined by the recorded measurement of distances. In two-dimensional geometry if a point lies on two curves such as the boundaries of two circles then the two circle centre locations and the two radii distances provide sufficient information to narrow the possible locations down to two. When a third intersecting circle is known it is possible to determine one unique location.
Figure 16: Trilateration using two or more known centre locations and radii.
If two centre circle locations lie on the basketball sideline in a straight line it is possible to reduce the number of intersecting circles to only two to achieve one unique location as the other possible alternative position lies outside of the basketball court. Two dimensional mathematical algorithms have been widely published and in use to determine the x and y co-ordinates for the unknown location $P_x$.

### 3.18 Player Positional Accuracy using Uncertainty Ellipses
If an estimation of a single distance dimension uncertainty (m) based on received power vs distance for a moving player from two or more receiving antennas is possible, then ellipse plots can be drawn at various locations on the basketball court showing the level of distance uncertainty in the direction of each receive antenna. If the major axis of the uncertainty ellipse is aligned with one reference antenna, producing a major axis point of uncertainty on the ellipse, then the minor axis point of uncertainty on the ellipse can be calculated if an uncertainty point anywhere else on the ellipse is known. This other uncertainty point on the ellipse can be determined by the uncertainty from a second reference antenna. Therefore, using ellipse mathematics, it is simply a matter of adding or subtracting the signal distance variability from the player location estimation to produce an ellipse. When the distance uncertainty in the received signal strength on both the major and minor axis are the same then a circle will be formed around the location instead of an ellipse.
The equation for an ellipse [85] centred at the origin can be written as follows:

\[
\frac{x^2}{a^2} + \frac{y^2}{b^2} = 1
\]  \hspace{1cm} (14)

where \(x\) is the major axis and \(y\) is the minor axis and \(a\) and \(b\) are point values of these axes respectively that lie on the ellipse.

Aligning the major axis with the receive antenna that has the larger distance uncertainty will give us the major axis point \(a\) of the uncertainty ellipse at a position on the court \(P(x,y)\). At any point on the ellipse the location \(E(x,y)\) must satisfy equation (14). The minor distance uncertainty from a second receive antenna will provide a point on the ellipse. This second point can be used to calculate the minor axis point \(b\) on the ellipse by rearranging equation (14) to become:

\[
b = \frac{a \cdot |y_1|}{\sqrt{a^2 - x_1^2}}
\]  \hspace{1cm} (15)

A representation of this uncertainty ellipse determination is given in Figure 17.

**Figure 17:** Uncertainty ellipse. The base receiver furthest away (Rx1) will determine the uncertainty (m) for the major axis while the minor axis uncertainty is determined from equation (15) using the uncertainty (m) from the other base receiver (Rx2). When both major and minor uncertainties are the same a circle will be formed.
3.19 Chapter Summary

This chapter has outlined the design considerations for implementing a wireless player tracking system, the factors that need to be taken into account for focusing the research in this field and the associated theory related to the research.

Antenna and propagation characteristics unique to indoor propagation on a basketball court have been highlighted. The practical implementation of sensors and RF beacons into the basketball game have been discussed with consideration for beacon/sensor placement, player type, receive antenna type and location.

Two path loss models and statistical fading parameters were covered which will be used in determining whether wireless RF signal strengths can be used as a means of distance estimation in an indoor basketball court environment.

The extraction of accelerometer pattern recognition data was discussed and highlighted the potential to indicate the bouncing of the ball by a player and hence, ball possession. This is necessary in any player tracking system for coaches and instructors. The method of trilateration was covered and an introduction to position uncertainty using ellipses was discussed.

In the next chapter the methodology of this research is presented.
Some of the content within this chapter was partly discussed and published in the following author’s publications:


4. METHODOLOGY

4.1 Introduction

This chapter details the methods and techniques used for data collection for each experiment. The chapter provides sufficient quantitative detail for the work to be repeated while verifying the results that were obtained. Sections 4.1.2 through to 4.1.10 provides an introduction to the environment and equipment used. The data collection techniques focus on the discipline of engineering radio communications and propagation. However, there are aspects of some data collection techniques that are associated with the discipline of sports science. This is to be expected as these two disciplines continue to merge with new advances in technology. Details of the data collection techniques used in this research are covered in sections 4.2 through to 4.12. Section 4.13 concludes this chapter with a summary of the methodology and research methods employed.

4.1.1 Methodology

The methodology in any research project is crucial to the foundation of the research methods and their justification for use in that research. Crotty and James Bennett Pty. Ltd. [86] pointed out that methodology fits into four basic elements of the research process. These are: a) Methods: the techniques or procedures used to gather and analyse data related to some research question or hypothesis; b) Methodology: the strategy, plan of action, process or design lying behind the choice and use of particular methods and linking the choice and use of methods to the desired outcomes; c) Theoretical Perspectives: the philosophical stance informing the methodology and thus providing a context for the process and grounding its logic and criteria; and d) Epistemology: the theory of knowledge embedded in the theoretical perspective and thereby in the methodology.

Kothari and ebrary Inc. [87] stated that research methods are all the methods/techniques that are used for the conduct of research or the methods the researchers use in performing research operations. He stated that research methodology is a way to systematically solve the research question or problem and explained that research methodology not only considers the research methods but also
the logic behind the methods in the context of the research study. He stated that an explanation needs to be given as to why a particular research method or technique is used and why others are not so that research results are capable of being evaluated by others as well as the researcher.

“There is not a right methodology or even a right set of methodologies. The choice of methodology (with its underlying theoretical perspective and its related set of methods) is determined by the kinds of research questions one can ask, and conversely certain research questions can best be addressed with certain methodologies” [88].

4.1.2 Methodology and Methods
There are a number of research philosophies (Theoretical Perspectives) that impact on the methodology adopted by any research project. Some of these include Positivistic, Interpretative, Critical and Pragmatic. Both Positivistic and Interpretive are the main driving philosophies behind this study with available methodologies of Experimental Research, Survey Research, Ethnography, Phenomenological Research, Grounded Theory, Heuristic Theory, Action Research, Discourse Analysis and Feminist Standpoint Research.

The experimental research methodology is generally adopted in these types of engineering and scientific research studies in carefully controlled and structured environments that enable the causal relationships to be identified and analysed.

“The experiment method gives the best approach for the study of cause and effect relationship under controlled conditions. This is a popular method for research in the field of natural sciences where the operating conditions can be controlled, to explain changes in dependent variables, on account of change in independent variables”. [89].

This research work focused around an indoor play area of a basketball court which meets international specifications. In terms of validity this means that these tests can be confidently reproduced on a ‘test-bed’ that is readily available and repeatable.

4.1.3 Environment and Equipment
The environment and equipment used for this research did not require ethical approval. However, ethical approval was sought and approved for the use of human
subjects in some of the indoor basketball data collection techniques. All volunteers in these studies were amateur basketball players and were informed of the reasons for the study and signed consent forms to participate in the study. The ethics protocol number assigned by Griffith University Ethics Committee was ENG/16/12/HREC.

Three main environments were utilised including an outdoor sports oval, an indoor basketball court (built to international specifications) and an anechoic chamber. The main test equipment consisted of a hand-held spectrum analyser, various UHF receive antenna types, a 2.4 GHz RF signal transmitting beacon, a laptop and the necessary coaxial and USB connecting cables. Some of the studies required customised purpose-built equipment and/or software programs.

4.1.4 zCore RF Beacon
The transmitted signal used for all the received field strength experiments was derived from a wireless accelerometer sensor (known as “zCore”) [90], developed in-house by the Centre for Wireless Monitoring and Applications, Nathan Campus, Griffith University. The sensor transmits a continuous carrier wave signal on 2.4 GHz at a power output of 1 mW (0 dbm). The transmitting beacon uses a grounded quarter wave meander antenna printed on FR4 type circuit board. This antenna and the whole sensor/beacon is housed in a small plastic box (see Figure 18). This inertial sensor uses the NORDIC nRF24L01+ transceiver chip operating at an on-air data rate of 2 Mbps with a potential frequency deviation of ±320 KHz and a RF power accuracy of ±4 dB.

Figure 18: zCore RF beacon
4.1.5 **Protek RF Field Strength Analyser**

The field strength meter employed for the far field radiation pattern tests was a Protek 3290N RF Field Strength Analyser capable of measuring RF signals within the frequency range 100 kHz to 2.9 GHz with a reference level accuracy of ±2 dB.

The receive antenna on the Protek analyser is a wideband standard dipole ‘rubber duck’, suitable for the above frequency band and was connected to the field strength meter via an N type connector. The receive antenna has a gain of approximately 0 dBd (2.15 dBi) and is linearly polarized. No details were available on the radiation pattern specifications for the Protek receive antenna, however, the pattern was expected to have a typical donut shaped omnidirectional pattern.

4.1.6 **RF Explorer Spectrum Analyser**

The hand-held spectrum analyzer used mostly in this study was a low cost hand held spectrum analyser suitable for the 2.4 GHz band, referred to as the “RF Explorer”. The unit was developed by Arocholl and was used to measure received field strength in dBm. The RF Explorer has an amplitude resolution of 0.5dBm, with an amplitude stability and accuracy of ±3 dBm. The RF Explorer purchase includes helical whip antenna. This is a quarter wave vertically polarised monopole antenna with a gain of approximately 2.1 dB above an isotropic radiator (2.1 dBi) for the 2.4 GHz band (specifications state that it is tuned to a frequency of 2450 MHz). The RF explorer has a recorded field strength sampling rate of approximately 10 samples/s and has the capability to record and log the received power with associated time stamps to a computer using a USB cable.

4.1.7 **Custom Built Test Rigs**

To carry out the human mounted beacon radiation pattern tests two test rigs and one waist belt were constructed.

Figure 19(a) shows Test Rig 1 (commonly known as a “Lazy Susan”) which was constructed out of 17mm thick circular plywood pieces and a 12 inch diameter circular bearing. A similar apparatus has been used in previous studies of this nature [78]. This platform was capable of supporting an adult. The rig has angle markings in 15 degree graduations to allow the subject wearing the transmit beacon to be accurately rotated through 360 degrees. A latch was provided to prevent slippage when stepping on and off the rig.
Figure 19: (a) Test Rig 1 for Human Mounted Beacon Radiation Pattern Measurements; (b) Test Rig 2 for Beacon Radiation Pattern Measurements without Body Influence.

Figure 19(b) shows Test Rig 2 which was constructed from 25 mm dowel pieces and a wooden plywood stand. A vertical dowel piece is adjustable in height for torso waist height and two horizontal dowel pieces are adjustable for shoulder and waist width. This rig allows for the elevated mounting of the beacon without the influence of the human body.

Figure 20 shows a chest strap constructed from 4 inch wide elastic with two Lycra (a synthetic elastic and fibre material) pouches attached for containing the transmitting beacon. A Velcro strap was attached to allow for variation in waist length. This belt allowed the beacon to be fixed in front of the chest and aligned either vertically or horizontally. Medical tape was employed in the tests for positioning the beacon on a person at shoulder height.

Figure 20: Elastic belt to hold the beacon at chest level.
4.1.8 **TP-Link 2.4 GHz Directional Antenna**

The TP-Link (model TP-ANT2409A) 2.4 GHz antenna is a vertically polarised directional antenna with a gain of 9 dBi, a horizontal beamwidth of 60° and a vertical beamwidth of 76° (see Appendix B). The antenna comes with 100 cm CFD-200 low loss connecting cable with a RP-SMA Female connector. An SMA adapter was required to connect this antenna to the RF Explorer.

4.1.9 **SuperPass 2.4 GHz 180 Degree Sector Directional Antenna**

The SuperPass (model SPDG11H) 2.4 GHz antenna is a 180° sector patch antenna with a gain of approximately 3.5 dBi, a horizontal beamwidth of 180° and a vertical beamwidth of 70° (see Appendix C). The antenna is small with dimensions 52 mm x 113 mm x 30 mm and uses a female N type connector.

4.1.10 **Sony Video Recorder**

The video recorder used in some of the experiments is a Sony 80GB Hard Disk Drive Full High Definition Camcorder, model number HDR-XR100E. This video camera is capable of a recording from 60 frames per second (fps) up to 240 fps with up to 1920 x 1080 high definition resolution.

4.2 **RF Radiation Pattern Measurements from a Body Mounted 2.4GHz Beacon**

To determine the horizontal beamwidth of a transmitting antenna, radiation pattern tests are usually carried out in an environment free from signal interference, which may include interference due to signals reflected from nearby objects (multipath). The three options for testing environments considered in this radiation pattern experiment were:

a) Within an anechoic testing chamber;

b) Using near field techniques; or

c) On an open outdoor playing field free from obstructions or nearby objects.

Due to ease of access, setup time and cost, an open outdoor playing field was chosen for radiation pattern measurements. This option requires the measurements to be taken in the far-field (i.e. a separation distance large enough to be away from the influence...
of the charges and currents presented at the electromagnetic source). The far field separation distance in this case is larger than would be expected from the small beacon antenna alone due to the influence of the body, which contains over 50% water. This body influence (effective coupling) increases the effective aperture length of the beacon antenna and consequently, the separation distance needed for far-field measurements.

For both the transmit and receive antenna locations the ground surface should be as flat as possible and preferably with little variation in moisture content over the transmitting path to minimise variations in the surface reflection coefficient. For example, this would exclude testing over large water puddles that may exist on the playing field, etc.

The outdoor playing field chosen was the Griffith University Sports Oval due to its close proximity. Figure 21 shows the layout of oval No. 2 which is approximately 180 m x 136 m in size.

![Figure 21: Map of Outdoor Playing Field Oval No. 2.](image)

**4.2.1 Custom Built Test Rigs**

**4.2.2 RF Beacon and Field Strength Meter**

To conduct the radiation pattern tests the zCore was used as the transmitting beacon and the Protek analyser was used to record the field strength.
No details were available on the horizontal and vertical radiation pattern specifications for the zCore transmit antenna prior to these tests, however, it was noticed that the antenna trace has several bends and is similar to a meander antenna design. This provides for a compact layout and may exhibit a more uniform radiation pattern in the horizontal plane when vertical orientation of the beacon is not possible [91].

The transmit antenna is linearly polarised with the main E field or dominant polarisation component in parallel to the vertical orientation of the antenna (see Figure 22).

Orientation of “z-core” meander antenna correctly for vertical polarisation.

Figure 22: zCore orientation for radiation pattern measurements

The cross-polar radiation component is made up of the orthogonal polarisation components in the far field. That is, the components of the radiation pattern that are horizontally polarised. (Thiel & Smith [92], p. 31).

4.2.3 Transmit and Receive Locations in Open Field

The receive antenna location (i.e. the location of the field strength analyser) was located at a horizontal distance of 15m from the transmit antenna for the radiation pattern (see Figure 23). This distance was chosen as it equates to roughly half the basketball court length and the maximum distance a beacon would need to transmit, given that each half of the court will have RSSI receivers. The exact distance will
vary slightly due to the offset of the mounted beacon on the waist and shoulder with respect to the centre of the body torso and Test Rig 1.

The receive antenna was fixed and the transmit antenna was rotated from 0 to 360 degrees using Test Rig 1.

![Diagram of test arrangement](image)

**Figure 23: Test arrangement for radiation pattern measurements.**

### 4.2.4 Measurements

The horizontal radiation pattern derived from a body mounted beacon was conducted under two scenarios. The first scenario was with the isolated transmitter, and the second was with the transmitter on the human body. Figure 24 shows the Protek placed on the ground to avoid the influence of holding the analyser’s antenna close to the body.

![Image of Protek placement](image)

**Figure 24: Placement of the Protek for radiation pattern measurements**
All data for this experiment was hand recorded and then copied to a computer spreadsheet file. The MATLAB® R2012a program was employed to produce the effective radiation patterns. In all measurements undertaken the Protek was away from objects (except the observer). All tests were conducted over a moderately dry, grass covered earth plane (a soccer field) and in the far-field zone. Using equation (4) the far-field boundary distance (see section 3.7.1) for a frequency of 2.4 GHz and a physical zCore antenna length of 12mm is approximately 2.3 mm. Using the alternate equation recommended by [80] the far field distance is approximately 62.5 mm. The chosen test distance of 15 m is well beyond these two far field boundary distances and therefore will avoid any problems with near field source effects.

Two transmit beacon mounting positions were used on the outside of a clothed subject (see Figure 25). They were:

- Position 1 - in front of the torso at waist height (under the chest) with the direction of the main radiating lobe facing horizontal;
- Position 2 - at the shoulder height with the direction of the main radiating lobe facing vertically upwards.

![Figure 25: zCore mounting positions. The beacon was mounted on the outside of a clothed subject. Body outline photo permission: © Can Stock Photo Inc. / eveleen](image)

### 4.2.5 Test Rig 2 Radiation Pattern Test

This test was initially conducted with the Test Rig 2 located on the top of Test Rig 1 and the transmitting beacon located at a position 1 where the front of the torso would normally be (see Figure 26).
Field strength measurements at 15 degree intervals were recorded over 360 degrees at 15 m from the beacon using the Protek spectrum analyser on the ground and with a vertically polarised 9 inch detachable whip receive antenna.

The beacon was then located at position 2 (see Figure 26) where the shoulder would be and field strength measurements were again taken at 15 degree intervals over 360 degrees at a horizontal distance of 15 m with the Protek measuring instrument vertically orientated on the ground.

![Image](image.jpg)

**Figure 26**: Two black pouches mounted on 6cm square plywood pieces representing the two test positions on the body.

### 4.2.6 Human Beacon Mounted Radiation Pattern Test

Test Rig 2 was replaced with an adult representing a basketball player. The field strength measurements and procedures were the same as outlined in section 4.3.5.

To conduct the waist-mounted beacon tests the custom elastic belt was strapped around the torso just underneath the chest. This provided a secure location which did not move during the tests.

To conduct the shoulder mounted beacon tests the beacon was mounted on the left shoulder on top of the body shirt using medical tape. This again did not present any problems of movement. It was observed while carrying out this test that any
adjustment to the centre of gravity of the body by movement could adjust the bearing setting of Test Rig 1. This would also occur if the test rig was not level due to the low friction level of the test rig bearing. Some friction mechanism installed on the rig would overcome this problem.

When tests were conducted without the influence of the body, Test Rig 2 was adjusted to accommodate the width of the body torso or the length along the shoulder to match where the beacon was placed on the body. The design of Test Rig 2 proved useful in this adjustment process, however, it was noted that a heavier base is needed to prevent the rig from falling over.

4.3 Half Court Propagation Survey with Receive Antenna Under Backboard

One possible location of a receive antenna investigated was directly under the backboard. No previous studies have been reported or how a 2.4 GHz signal would propagate over one half of an indoor basketball court.

4.3.1 Test Rigs

Test Rig 2 and a third wooden test rig was used for this experiment where the receive antenna was located directly beneath the centre of the backboard and basketball hoop (see Figure 27).

![Image of receive antenna mounted under backboard](image)

**Figure 27:** Receive antenna mounted under backboard. Note the forward tilt of the white panel antenna.
4.3.2 Receive Antenna

The TP-LINK directional antenna was used for receiving the beacon signals which was connected to the RF Explorer using a USB cable to measure the received power in dBm.

4.3.3 Measurements

To undertake the field strength survey, half the basketball court was broken up into a grid (see Figure 29) of 1.0m resolution between the centre line and the end line of 14 m (X plane) and the 15 m width of the court (Y plane) giving a total of 230 measurement locations.

The receive antenna was placed directly under the bottom centre of the backboard. The mounting angle ($\theta_4$) for the receive antenna was determined from a series of calculations based on Figure 28. The objective was to utilise the main directional radiation pattern beamwidth to cover the required area while minimizing any reflections from the metallic basketball ring and/or backboard.

The test rig with the beacon attached was then placed at each of the measurement grid points with the main lobe of the transmitting beacon’s radiation pattern directed towards the receive antenna. Figure 30 shows the experimental setup.

Figure 28: Antenna mounting angle ($\theta_4$) for receive antenna placed immediately below the backboard of the basketball hoop.
Figure 29: Half basketball court divided into 1m measurement grid.

Figure 30: Receive antenna and transmitting beacon mounting.
4.4  **Indoor Path Propagation Measurements Over Selected Half Court Paths from a 2.4 GHz Waist Mounted Beacon**

To further investigate the field strength propagation and determine a generic indoor propagation model, a number of paths were chosen with varying realistic and practicable receiver locations for varying distances up to 15 m (see Section 4.3.3 for this chosen distance).

4.4.1  **Measuring equipment**

The indoor basketball court (play area) chosen for this study was constructed to international standards [93] with thin planks of hardwood laid side-by-side across the court (see Figure 30).

![Figure 31: Indoor basketball court floor construction](image)

One quarter area of the court was used to undertake the measurements being representative of the other three quarters. The received power (dBm) was recorded using the RF explorer with an accuracy of 0.5 dBm. The receive antenna used in the previous experiment (see section 4.4) was used in this experiment. The transmit beacon antenna (see section 4.3.2) was orientated to provide a vertically polarized omni-directional radiation pattern. Both transmit and receive antennas were mounted on custom built wooden test rigs (see Figure 33).
4.4.2 Measurements

A series of straight paths traversing a quarter of the court floor (see Figure 32) were chosen with 0.5 m step distance measurements along each path giving a total of over 200 measurement sites. Each measurement location was free from objects within the immediate area.

The transmit and receive antenna heights were set to 1.45 m above the court surface (see Figure 34), representing the height of a beacon mounted under the chest (waist level) of an elite basketball player. The portable spectrum analyzer (RF Explorer) was taped to the receiving test rig and connected to a laptop via a 3m USB data cable. Using the specified zCore antenna length of ~12 mm (largest linear dimension) a far-field boundary distance $D$ was calculated (see section 3.7.1, equation (4)).

$$D = \frac{2 \times (0.012)^2}{0.125} = 0.0023 m$$

All measurements were conducted in the far-field region of the transmitting antenna. The paths used were typical for players outside of the basketball key.

![Figure 32: Measurement paths over quarter court. The transmit and receive antennas were both mounted 1.45 m above the wooden floor.](image)
Figure 33: Custom built test rigs with beacon mounting pouch on left and receiving antenna panel on right.

- 2.40082GHz Beacon (off resonance)
- -46.5dBm @ 1m
- Vertical Polarisation
- Azimuth: 0 degrees, Tilt: 0 degrees
- CW signal

Figure 34: Receive antenna and transmitting beacon mounting.
4.5 **Receive Antenna Gain Tests in an Anechoic Chamber**

The total link budget for the system prior to the SMA input port of the RF Explorer consists of the gains and losses due to the UHF directional antenna, the connecting coaxial cable and the SMA adapter (SMA Female to RP SMA Male). These parameters were measured as they form part of the experiment factors affecting the received signal strength at the antenna input terminals.

The antenna gain was determined using the gain-comparison method with a known reference antenna [94]. A simple and straightforward method of measuring the gain of an antenna is by use of the gain-comparison method by a known calibrated reference antenna. By measuring the field strength from a common transmit antenna using firstly the reference antenna and then the antenna under test (AUT) we can obtain the difference in field strength in decibels, which is then added to the reference antenna gain to give the gain of the AUT. For this measurement to be accurate the distance between the transmit antenna and both receive antennas must be the same, both receive antennas are to be mounted at the same height and there are to be no interfering signal sources.

The result was compared with the specifications provided by the manufacturer.

4.5.1 **Equipment**

An anechoic chamber located at Griffith University, Nathan Campus, was used to obtain the gain of the receiving feed system using the standard whip antenna that was shipped with the RF Explorer as a reference antenna (see section 4.1.6).

The TP-Link directional antenna was used to receive the signal and was connected to the RF Explorer using a SMA female to RP-SMA Male adapter with an insertion loss of less than 0.2 dB. The RF Explorer was then connected to a laptop computer via a 3 m USB cable outside of the anechoic chamber with the field strength measurements displayed on the laptop using the RF Explorer client software.

4.5.2 **Measurements**

Figure 35 shows the measurement setup with the 2.4 GHz zCore beacon placed in a black cloth pouch adhered to a piece of flat wood and mounted on a piece of dowel at a distance of 2.34 m from the receive antenna at a height of 1.27 m.
Figure 35: Measurement setup in anechoic chamber. The receive antenna is the white panel mount antenna positioned on the small wooden table.

Figure 36: (a) Measurement with standard helical whip antenna; (b) with directional receive antenna.

Figure 36 (a) shows the standard whip antenna and Figure 36 (b) shows the directional patch antenna in the anechoic chamber. The height of the transmitting antenna was adjusted for horizontal alignment. This was acceptable because of the high operating frequency of 2.4 GHz.
4.6 Dynamic tracking of a 2.4 GHz Waist Mounted Beacon for Indoor Player Positioning

The wireless RF signal propagation (RSS technique) from a body-mounted zCore beacon and the information from body mounted accelerometer sensors were investigated to confirm the feasibility of dynamically tracking a single basketball player and ball possession on a basketball court. Apparent frequency variations (Doppler Shift) due to a player’s movement was considered, but was not expected to have an impact on the results.

4.6.1 Single player tracking

As only the play around the basketball key (the area surrounding the basket) is of interest in this study the centre of the court around the centre circle was removed from consideration. The zCore beacon [90] was located on the body directly under the front of the chest using a custom built elastic fabric strap. The beacon signal was received by the TP-Link directional antenna and passed to the RF Explorer mounted at the lower portion of the test rig (see Figure 37) and connected to a laptop. The transmit and receive antenna heights were set to 1.45 m. A series of straight paths traversing a quarter of the court floor (see Figure 38) was chosen for moderately paced dynamic tests. The test paths were divided up into 1m distance makings from the starting point using tape on the floor which were clearly visible by a single high definition video camera (see section 4.1.10). Wearing the beacon under the chest, the test subject was asked to move towards the receiving antenna at a moderate pace along the length of each path, sounding out as each distance marker was reached. Slower movements were chosen in this experiment to obtain a more accurate confirmation of the subject’s position. Due to the short distance from the video camera to the markers parallax errors were minimized. From the video playback these markers were used to determine the time taken to pass each marker by the subject’s feet. The RF Explorer has the capability to record and log the received power with associated time stamps. Approximate velocities and plots of signal strength vs distance were obtained by correlating the RF Explorer time stamps with the video timing and distance markers. Beacon position accuracies recorded through the video camera to within 0.1m were achievable. The accuracy and precision of the player position and therefore the beacon was determined by these markings as viewed through the Sony high definition video camera.
Figure 37: Experiment layout for dynamic tests.

- Single video camera located approximately 5m from sideline and 4m above court to view subject and the 1m equidistant floor markings along each path.

Figure 38: Seven measured paths over quarter court (blue, green and red). Each arrow head indicates the position of the receive antenna and direction of travel.
4.6.2 Ball possession

Three zCore accelerometer sensors were configured to record/log the 3 axis data wirelessly on a nearby laptop. Figure 39 shows the three sensors mounted behind the right wrist, behind the right elbow and directly under the players’ chest centred using fabric straps. Before starting the test all sensors were synchronized. The experiment consisted of three tests: a) bouncing the ball while stationary; b) bouncing the ball while moving slowly along a 5 m path; and c) bouncing the ball vigorously along the 5m path. This procedure was repeated with a subject that does not dribble the basketball as well.

![Sensor Locations](image)

**Figure 39: Accelerometer sensor positions for ball bouncing**

4.6.3 Single player tracking and ball possession at fast pace

A third experiment was conducted with a different subject wearing three zCore sensors (see Figure 40) who was asked to undertake a predetermined offensive drill as shown in Figure 41. The equipment used previously was employed. The subject was asked to run to a marker on the court floor then, while moving, catch a basketball thrown to him near that marker and dribble at a fast pace in a straight line path. The path was approximately 9m long with 1m equidistant tape markers on the court floor. This experiment included both arbitrary and fast movements typical in a basketball game. Both signal field strength and acceleration measurements were recorded as in the previous two experiments.
Figure 40: Accelerometer sensor positions on the player.

Figure 41: The path of an offensive drill at fast pace.
4.7 The Number of Base Receivers, their Locations and Antenna Beamwidth

One quarter area of the court was used as the sample play area for consideration on the number and placement of the base receivers. This area is representative of the other three quarters of the court. Full court coverage would therefore be achieved by multiplying the number of base receivers required by four. To use the trilateration method for position estimation a minimum of three receivers is usually required. The placement of these receivers was determined after considering the following:

a) The horizontal radiation pattern produced from a player-worn RF beacon (see section 4.3). To ensure this angle covers the base receive antennas;
b) The direction the player is facing;
c) Minimising base receiver damage from contact by players beyond the court boundary;
d) The distance before multipath fading and received signal variation became too large (see section 3.11.4) and therefore not suitable. Player position estimation accuracy is related to the variation in received field strength;
e) The angle formed at the player-worn beacon between each base receiver bearing. To ensure the beamwidth of the beacon transmitting antenna is sufficient to cover the base receive antennas; and
f) The reduction of multipath interference due to walls, metallic structures (e.g. backboard mounting brackets, basketball hoop and audience seating).

Considering the above factors a scaled drawing of a quarter of the basketball court, a protractor, a ruler, the beamwidth of the receive antenna and player-worn beacon were used to determine the most practical positions for three base receivers. These positions would then be used in both static and dynamic experiments. A location directly under the backboard was ruled out after the half court propagation survey experiment (see section 4.4) as it is highly likely the base receiver would be damaged in a live game and the potential signal scattering/multipath effects due to the nearby steel structures associated with the backboard and hoop.

The beamwidth for the receive antennas and the antenna used by the zCore antenna were fixed as these were commercially purchased. The beamwidth for the player-worn zCore beacon was determined to be 120° (see section 5.2). The horizontal
beamwidth for the chosen commercially available receive antennas was 60° for the TP-Link and 180° for the SuperPass.

The receive and transmit antennas could have been designed and custom built using tailored beamwidth considerations (see section 3.5.2). Investigations were conducted into the design of a single micro strip inset patch antenna for the receive antenna. However, design results confirmed that beamwidths beyond 90 degrees for a single patch is very difficult. Further, the design of more complicated stacked micro strip patches was considered to be a very time consuming process and beyond the scope of this research.

4.8 Player Positional Accuracy
This analytical investigation used the data obtained from section 4.7 for a moving player over a given distance to investigate the accuracy and single dimension uncertainty based on received power vs distance for a moving player.

4.8.1 Software Development
A graph of distance vs received power (dBm) at the receiver for each path was produced using MATLAB® R2012a to highlight the variability of signal strength based on distance. This variability in signal strength at selected distances was used to plot a number of uncertainty ellipses at various locations within the play area. The software program was developed in-house using MATLAB® R2012a.

4.8.2 Uncertainty Ellipse
Uncertainty ellipse plots were produced based on the use of two receiving antennas selected out of a total of three receiving locations around the basketball court (two located on the sideline and one on the baseline) providing a total of three uncertainty ellipse plots at each location. By using the recorded signal variability from the relevant distance vs signal strength path plot, at a given distance from the receive antenna, the ellipse was drawn by determining the major and minor semiaxis. As only the play area around the basketball key (the area surrounding the basket) is of interest in this study, the centre of the court around the centre circle was not included.
4.9 *RF Explorer 2.4 GHz Hand Held Spectrum Analyser Test in an Anechoic Chamber*

In this experiment the RF Explorer was set to record the data to a cumulative CSV file, which records the raw data with no post-processing, to observe the accuracy of the received signal strength over a period of time and to some extent the reliability of the RF Explorer. The tests were conducted in the Anechoic Chamber located at Griffith University, Nathan campus.

The RF Explorer, as with most digital hand-held field strength analysers using RSSI have an inherent signal amplitude variation due to the internal quantization error occurring from converting the received analog RF signal to digital. The internal ADC resolution of 0.5dB is the smallest incremental change that can be recognized. The corresponding change in the digital output is usually expressed in terms of the least significant bit. The hand-held analyzer converts the analog input signal to a 10-bit digital value. This change due to quantization error can generally be considered as white noise and would normally be reduced in measurements by averaging the samples.

The RF Explorer uses an improved form of RSSI in its conversion from a received analog signal into a valid dBm measurement. The problem with RSSI is that it is very manufacturer dependent. The RSSI is not normalized across devices where every vendor or product defines and implements it in their own way. Although all must follow the IEEE 802.11 specification, the way the RSSI value is obtained can vary from each manufacturer. Here, the RSSI_Max value was chosen and then the range divided into the various levels. For this dependency on the manufacturer, a specific manufacturer table is needed to obtain a RSSI to dBm value as an integer for each level. The RSSI reading is generally intended to be used in a relative manner where the absolute accuracy of the RSSI reading is not specified or required in the specifications. Consequently, the use of a traditional RF signal strength measurement is not the same as RSSI as many would report due to the way it is derived. The RF Explorer was chosen due to its low cost and as it offers a more precise linear response in dBm resulting in a 0.5 dB resolution.
4.9.1 Measurements
Three RF Explorers were tested for received strength over time using the zCore beacon at distances of 1m and 2.5m with the RF Explorer program set to save the raw data to a cumulative CSV file. Figure 42 shows the setup of the test. The received field strength over a short period of time was recorded in a log file on a laptop computer outside of the closed anechoic chamber.

Figure 42: RF Explorer setup for testing real and average receiving modes.

4.10 Multipath Impact Study on Indoor Wireless Team Player Positioning

In a typical basketball game there are up to 10 moving bodies on the court (not including two referees). These additional moving objects may give rise to multipath interference to the desired received signal and therefore to the reliability of the sensor/beacon data. A large variation in received signal level due to multipath interference and obstruction has a direct impact on the accuracy of the position calculation and can result in a high data bit error rate.

A single transmitting beacon was mounted on a purpose built test rig at a height in this case of 1.38 m above the court floor. This rig was located at the top of the key, approximately 5.1 m away from the sideline receiver. This particular player height is reached in most professional teams. The height and weight of all subjects in this study are shown in Table 4.
Table 4: Basketball Player Statistics

<table>
<thead>
<tr>
<th>Subject</th>
<th>Height (cm)</th>
<th>Weight (kg)</th>
</tr>
</thead>
<tbody>
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<td>1</td>
<td>188</td>
<td>78</td>
</tr>
<tr>
<td>2</td>
<td>202</td>
<td>103</td>
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<td>96</td>
</tr>
<tr>
<td>12</td>
<td>205</td>
<td>99</td>
</tr>
<tr>
<td>Mean</td>
<td>198.3 ±6.5</td>
<td>94.7 ±15.4</td>
</tr>
</tbody>
</table>

The transmitting signal was received by the RF Explorer mounted on a second wooden test rig. The output of the RF Explorer was connected to a computer laptop to record the signal level (dBm) and time stamp over the testing period. A picture of the equipment layout and positioning is shown in Figure 43. The RF Explorer was mounted on the wooden tripod at the left hand sideline.
To minimize reflections from behind the receive antenna the SuperPass 180° sector antenna was used.

4.10.1 Measurements

Two teams of 5 volunteer players, each with high basketball playing skills, were asked to conduct a normal scrimmage under game pace conditions while avoiding the wooden test rig, located at the top of the basketball key. A video of the game play session was also recorded to determine when players were near or had obstructed the main LOS signal path.

Typical Rician fading statistical parameters include level crossing rate, average fade duration, Rician k-factor, the Rice probability density function and the cumulative Rice distribution were determined. These parameters provide some means of gauging the reliability of the received signal.

The experiment began with all players initially in their offensive and defensive starting positions. The recording of both video and received field strength samples commenced following the coach’s instruction to commence play. A total of approximately 33 seconds of play was obtained for a typical guard/forward player analysis. The field strength meter has a sampling rate of approximately 10 samples/s.
This equates to 33 seconds x 10 samples of field strength measurements per second = 340 data points.

By analysing the video at slow speed in combination with the recorded received field strength it was possible to see the effect on the received signal due to nearby players moving near the stationary beacon or through the beacon to receiving antenna transmission path.

4.11 Basketball Passing Detection using Accelerometers

A technique for detecting particular wrist and arm movements using accelerometers was previously discussed in section 4.7.2 for ball bouncing. By identifying a unique accelerometer signal signature in a given axis or plane it can be determined if a player is passing the basketball using this same technique. This is also valuable information needed for the coach in the tracking system.

4.11.1 Measurements

Two zCore accelerometer sensors were used to record the 3 axis data wirelessly on a laptop. Figure 44 shows the two sensors mounted behind the right wrist and behind the right elbow. The sensors were synchronized before the test began. The passing motion was also recorded on video. The test subject had significant experience in passing a basketball and was asked to undertake a series of standard two-handed basketball passes to an assistant with a distance separation of approximately 5m.

Figure 44: Basketball pass with full extension of arms
4.12 Prototype Tracking System Team Player Positioning

To confirm the ability to track players a software program was developed in Visual C# employing the RF signal strength versus distance power law relationship, using the trilateration positioning technique, a chest mounted sensor and two base receivers with each consisting of a RF Explorer and SuperPass antenna. The software program implemented the algorithms used for determining the distances between the body-worn beacon and the two base receive antennas and display the calculated position of the beacon on a laptop screen. Figure 45 shows a flowchart outline of the prototype positioning system.

Figure 45: Flowchart outline of the prototype positioning system.

4.12.1 Equipment

Figure 46 shows two custom built receive antenna mounts used to mount the SuperPass 180 degree sector receive antennas at a height of 1.27 m above the court floor. They were located on the sideline approximately at 1.200 m and 5.325 m from the baseline. These locations were selected for their optimum coverage after a careful graphical analysis including consideration for: a) the problem of increasing minima, null or trough size with distance typical with ground reflection and observed (see Section 5.4.4); b) the quarter court layout; c) the possible player position and direction; and d) the radiation patterns for the transmitting beacon and receiving antennas. A RF Explorer was embedded inside each high density foam stand with a USB cable connection from each receiver to a single laptop. The basic elements of the prototype system are shown in Figure 47. A custom software program was developed.
in Visual C# to process the received signal level from the two base receivers. The laptop is a Lenovo model T500 running a Intel® Core™ 2 Duo P8400 @ 2.26GHz processor with a Windows 32-bit operating system. Because the speed of the software processing is a lot greater than the sampling rate from the RF Explorers the received data could be processed in real time and it was not necessary to buffer or average the input power levels. The program also stored on hard disk a log of time and field strength from each base receiver that can be used by the program for later playback and analysis.

Figure 46: Sideline positioning of custom built receive antenna mounts. Each mount contains a networked RF signal receiver.

Figure 47: Basic elements of the prototype wireless RF tracking system.
4.12.2 Measurements

Seven test locations outside the basketball key where the subject remained still and one predetermined path for player movement were chosen to record the real-time positional accuracy. The software program displays a background image of the basketball court and the court lines. A 1m green circle was drawn at the estimated position which was updated as new real-time positional data arrived for software processing. Visually it was easy to observe whether the estimated position was within ±0.5 m of the actual position, or path, by observing if the actual position or path was within the 1m diameter green circle. Two defence players were asked to stand near the measured positions but within the basketball key to replicate a game scenario. The two algorithms used to estimate the location of the body-worn beacon were: a) the Free Space Path Loss Model derived from section 4.5; and b) the mathematical relationship of trilateration (see section 3.1.7) between the body-worn beacon and the two receiving antennas.

4.13 Chapter Summary

This chapter outlines the research methods adopted in this study. The experiments conducted away from the indoor basketball court were used to obtain reference information on the equipment being used or additional information needed for an on-court analysis. These include the radiation pattern from body worn beacon in section 4.3, receive antenna and feed line losses in section 4.6 and a RF Explorer reliability test in section 4.10.

Several experiments were used to characterise the propagation on a typical indoor basketball court built to international standards in section 4.4 to confirm the suitability of the environment for distance estimation based on received field strength. Further analysis was then conducted in section 4.5 on selected paths to assist in the suitable placement of two or more receiving antennas and the development of suitable prediction models.

Section 4.7 introduced players wearing a beacon and in particular dynamic movement into the analysis. This section also introduced an initial analysis of using an accelerometer sensor to detect the bouncing of the basketball through a unique recorded signal signature. Section 4.8 considered the placement of the base receiver
antennas. Section 4.9 builds on the data collection method by detailing how uncertainty ellipses at various locations on the basketball court were obtained using an in-house developed software program. Section 4.11 presented the method and data collection procedure for considering multipath interference due to multiple players in the vicinity of the body worn transmitting beacon. Section 4.12 presented a method for detecting ball passing. Section 4.13 completes the study by detailing the data collection techniques used to undertake a test of a prototype basketball player tracking and positioning system.

The next chapter details the results obtained from the data collection discussed in this chapter and provides a discussion on these results.

Some of the content within this chapter was partly discussed and published in the following author’s publications:


**Journal Papers**


5. RESULTS AND DISCUSSION

5.1 Introduction
This chapter presents the results for each of the experimental studies undertaken in this research and provides comments and discussions that are relevant to the findings. Each experiment builds on its previous to achieve an answer to the overall research question and confirm the corresponding hypothesis or disprove it. The main graphs and tables relevant to the discussions are included in this chapter. Further material on software programs are referenced and included in the appendices. Sections 5.2 through to 5.10 cover each of the research experiments with the background methodology for these covered previously in Chapter 4. Each experimental results section includes some concluding comments.

5.2 RF Radiation Pattern Measurements from a Body Mounted 2.4GHz Beacon

5.2.1 Introduction
To choose the most effective court side receive antenna locations for a triangulation positioning system based on received field strength, it is necessary to know the useable radiation pattern from the transmitting body-worn beacon. Generally, when offensive players are at one end of the basketball court they are facing the ring. This means that the existence of a main radiating lobe would be in one particular direction, regardless of whether the beacon is mounted on the front or back of the body.

Knowing the transmitting and receiving antenna radiation patterns assists in the system design of receiving antenna placement to avoid deep nulls or large variations in received signal strength. Large variations in the received signal strength reduces the accuracy significantly in a positioning methodology based on received field strength.

5.2.2 Results
Horizontal radiation patterns were produced from received field strength measurements (see table 5), using the MATLAB® R2012a program, for both waist-mounted beacon and left shoulder-mounted beacon tests.
Table 5: Radiation pattern measurements of a body worn RF beacon.

<table>
<thead>
<tr>
<th>Bearing</th>
<th>Waist Mounted (dBm)</th>
<th>Shoulder Mounted (dBm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Without Body</td>
<td>With Body</td>
</tr>
<tr>
<td>0°</td>
<td>-81</td>
<td>-80</td>
</tr>
<tr>
<td>15°</td>
<td>-80</td>
<td>-80.4</td>
</tr>
<tr>
<td>30°</td>
<td>-80.6</td>
<td>-81.5</td>
</tr>
<tr>
<td>45°</td>
<td>-81.6</td>
<td>-82</td>
</tr>
<tr>
<td>60°</td>
<td>-82</td>
<td>-84.2</td>
</tr>
<tr>
<td>75°</td>
<td>-80.3</td>
<td>-87.7</td>
</tr>
<tr>
<td>90°</td>
<td>-81.5</td>
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<td>-100</td>
</tr>
<tr>
<td>180°</td>
<td>-81.4</td>
<td>-100</td>
</tr>
<tr>
<td>195°</td>
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<td>-100</td>
</tr>
<tr>
<td>210°</td>
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<td>300°</td>
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<td>-85.8</td>
</tr>
<tr>
<td>315°</td>
<td>-84</td>
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<tr>
<td>345°</td>
<td>-80.7</td>
<td>-80.1</td>
</tr>
</tbody>
</table>

These are shown in Figure 48 and Figure 49 respectively. A comparison with and without the influence of the body can easily be observed in these figures.

The Protek signal analyser has a minimum reading of approximately -107 dBm. For the tests it was decided to impose a cut-off limit of -100 dBm to allow for inaccuracies in the analyser and to be above the 2.4 GHz noise floor. Therefore, those measurements shown at -100 dBm on the radiation patterns are either at this value or lower. Although the separation distance and radiated transmitted power was adequate to obtain an approximate radiation pattern and beam width for the waist mounted beacon, the results for the shoulder mounted beacon were not as forthcoming. An increase in radiated transmitted power, keeping the preferred separation distance, would have improved the accuracy and reliability for the shoulder mounted position.
Figure 48: Vertically polarised radiation pattern for waist mounted beacon (with and without body influence). The zero angle is the horizontal axis.

Figure 49: Horizontally polarised radiation pattern for left shoulder mounted beacon (with and without body influence) with the vertically polarised receive antenna at 45°. The zero angle is the horizontal axis.
The results for the shoulder mounted beacon showed a distinct two lobe radiation pattern and some measurements were recorded around -95 dBm, which is close to our set limit for the Protek analyser and well below those recorded for the waist mounted beacon.

The radiation pattern for the waist mounted beacon without the influence of the body shows a relatively omnidirectional pattern with variations of 0 dB to 4 dB. The radiation pattern for the waist mounted beacon with the influence of the body shows a main lobe with a -3 dB beam width of approximately 120 degrees. The pattern shows a significant drop (< -100 dBm) in level as the bearing rotates behind the torso. This is expected as the majority of the signal is absorbed or reflected by the body.

The overall front to back ratio for the beacon antenna was 20 dB or greater. It is expected that a similar main lobe and beam width in the opposite direction would be obtained if the beacon was mounted behind the torso at the same height.

The radiation pattern for the shoulder mounted beacon without the influence of the body shows two main lobes at approximately 330 degrees and 180 degrees. These tended to correlate with the radiation pattern with body influence, except for around the 60 to 110 degree bearing range. In this range the shoulder mounted beacon with body influence outperformed the shoulder mounted beacon without body influence, which is a result contrary to the trend in rest of the pattern bearings.

The mounting orientation of the RF beacon at the shoulder and waist locations were different. This has a significant effect on the radiated pattern.

It should be noted that the meander antenna on the ‘zCore’ transmitting beacon has a small electrical component (micro SD memory) adjacent to it, which would have some effect on the overall antenna radiation pattern. Further theoretical and practical analysis of the meander antenna / SD memory combination would need to be conducted to verify this.

For a triangulation or trilateration distance positioning system based on the received signal strength it is important to minimise receive signal strength variations from interfering signals to improve the position estimation.
In a basketball court environment where the players wearing beacons are moving horizontally and vertically it would be preferable to have a completely omnidirectional pattern with minimal transmitting signal strength variation. In this ideal scenario the useable beam width in the horizontal plane would be 0 to 360 degrees. However, in practice the radiation pattern is directional due to the presence of the body with a useable beam width significantly smaller.

For these outdoor tests the ground surface both absorbs and reflects the transmitted signal producing an interfering reflected signal at the receive antenna. The strength of this interfering reflected signal is mainly dependent on the reflection co-efficient of the earth’s surface and the angle of arrival. The value of this reflection co-efficient is expected to be different in a basketball court environment as the surface is made up of highly polished wood, not soil.

5.2.3 Conclusion

The results for the waist mounted beacon (mounted just below the chest), as expected, indicates one main lobe towards the front and a deep null at the back of the torso with a measured front to back ratio of greater than 20 dB. The measured radiation pattern for the waist mounted beacon with body influence shows a -3 dB beam width of approximately 120 degrees (i.e. a bearing range from approximately 300 to 60 degrees). Consequently, this would be the maximum useable beam width. A second beacon on the rear of the body could also be considered if an extension to the useable beam width and a more omnidirectional pattern was required.

A shoulder mounted beacon with body influence provided two lobes. One with a -3 dB beam width of approximately 55 degrees (from 315 to 10 degrees) and the other of approximately 110 degrees (from 80 to 190 degrees). This second lobe to the rear of the torso provides a comparable beam width to the waist mounted beacon’s main lobe. It was confirmed in these tests that the body influence affect does significantly change the far-field radiation pattern as expected and well documented previously in literature [78].

As the surface reflective co-efficient in an indoor basketball court is quite different to the ground surface used in these tests it is expected that the received field strengths would be slightly different, however, the radiation patterns would be approximately the same.
5.3 Propagation Survey with Receive Antenna Under Backboard

5.3.1 Introduction
It was necessary to obtain an initial understanding of how RF signals would propagate across an indoor basketball court and whether this indoor environment was conducive to the research proposal, given the potential of multipath interference from court side stands, metal roof beams, building walls, etc.

This experiment was designed to confirm that this environment is vastly different to an indoor office or commercial factory environment described by most of the literature. In these type of environments, the field strength predictions vary greatly due to high levels of multipath interference from equipment, tables, chairs, humans, etc.

5.3.2 Results
Figure 50 shows a predicted field strength coverage map using a two-ray path loss model over half a basketball court using a custom built MATLAB® R2012a software program. The plot shows the expected troughs and peaks that get worse as the distance between the transmitter and receiver is increased greater than approximately 7.5 m. However, below this distance these troughs are less than 3 dB which is a favourable prediction. It is expected that the measured plot would not be as smooth due to reflections off nearby metal objects such as the backboard structure and the basketball ring.
Figure 50: 3D representation of the predicted field strengths (dBm) over half court with a 1m grid. The red coloured areas indicate closest to the receiving antenna

Table 6 shows the recorded field strength from a directional receive antenna mounted directly under the backboard at a height of 2.68 m and a 2.4 GHz transmitting beacon located at various grid locations over half a court at a height of 1.45 m. The 14 m x 15 m half court was broken up into a 1.0m square grid between sidelines and the court baseline. Row X14 is located along the baseline behind the backboard. The backboard is located at 1.2 m from the baseline. The negative sign has been removed from all dBm values for ease of presentation. The receive antenna positioned at the bottom of the backboard was located at Y7.5, X12.8. ie 1.2 m away from the court baseline.

Table 6: Half Court Field Strength Measurements (dBm with negative sign removed) with Receive Antenna directly under backboard.

<table>
<thead>
<tr>
<th></th>
<th>Y0</th>
<th>Y1</th>
<th>Y2</th>
<th>Y3</th>
<th>Y4</th>
<th>Y5</th>
<th>Y6</th>
<th>Y7</th>
<th>Y8</th>
<th>Y9</th>
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<th>Y13</th>
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<th>Y15</th>
</tr>
</thead>
<tbody>
<tr>
<td>X0</td>
<td>77.5</td>
<td>71.0</td>
<td>73.4</td>
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<td>69.7</td>
<td>70.1</td>
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<td>66.5</td>
<td>69.1</td>
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<td>69.1</td>
<td>77.7</td>
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</tr>
<tr>
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<td>69.1</td>
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<td>74.8</td>
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<td>71.2</td>
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</tr>
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<td>72.0</td>
<td>72.9</td>
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<td>75.6</td>
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<td>X 4</td>
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<td>81.0</td>
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</tr>
<tr>
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<td>X 12</td>
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<td>70.0</td>
<td>68.4</td>
<td>71.7</td>
</tr>
</tbody>
</table>

Figure 51 shows a 3D dimensional colour representation of this data using a custom built MATLAB® R2012a software program (see Appendix D). Except for the extremities, this 3D graph shows that in front of the receiving antenna and less than 9m the variation in signal strength for the majority of cases is 3 dB or less as the transmit and receive distance separation increases. Under free space conditions, the reduction in field strength over distance is expected to follow the inverse square law relationship between field strength and distance. It is noted that some of the measurements taken in Table 6 are unexpected and were explored as anomalies generated by the equipment being used. For statistical purposes they can be considered as outliers.

The 3D graph in Figure 51 also shows a series of troughs and peaks as the distance from the receiver is increased. This is also to be expected due to reflections from the court floor and interfering with the received line-of-sight signal at the receiving antenna. This interference results in a series of peaks and troughs as the reflected signal falls in and out of phase with the direct signal.
Figure 51: 3D representation of the measured field strengths (dBm) over half court with a 1m grid (height = 1.45 m). The transmitter was moved in 1m steps in the horizontal plane. The red coloured areas indicate the highest field power and are located closest to the receiving antenna.

It can be seen that results close to the receiving antenna differ from the predicted values. It was expected that there might also be reflections from the metal material making up the backboard, the ring and their mounting structures which would affect the results close to the receive antenna.

5.3.3 Conclusion

The propagation over in an indoor basketball court built to international specifications from a 2.4GHz transmitting beacon was investigated. Results show that for the majority of locations the RF signal will vary approximately 3 dB or less for a receive antenna mounted directly under the basketball backboard.

It can be concluded that it is feasible that the indoor basketball court environment is suitable for the tracking of basketball players based on received signal strength techniques. Further in-depth experiments were conducted to confirm this favourable result and investigate other aspects in player position estimation and tracking.
5.4 *Indoor Path Propagation Measurements Over Half Court Paths*

5.4.1 *Introduction*
In this study, propagation models based on the classical Free Space Loss and Two-Ray models were tested using a basketball court as the sample play area (15 m x 28 m), with an additional 2 m of clearance to any obstructions such as team bench seating. These radio signal propagation models were determined using empirical methods and statistics and are founded on fitting mathematical models to on-site measurements.

5.4.2 *Results*
The recorded measurements were entered into a computer program, developed in-house using the MATLAB® R2012a program (Appendix D), to produce scatter plots of received field strength and received power for distances up to 10 m as shown in Figures 52 and 53. The receiver was located at 1 m intervals along selected paths (see section 4.5.2) with a vertically polarised receive antenna.

![Scatter Plot of Received Signal Strength vs Distance](image)

*Figure 52: Received signal strength vs. Log-distance recorded for all paths.*
The plotted data in Figures 52 and 53 show a received power level variation of 3dB or less and highlights the trend of peaks and nulls typical from to a multipath signal being reflected off the court surface. This low signal variation provides sufficient evidence for the use of both free space and two-ray models in this investigation.

5.4.3 Free Space Path Loss Model

A straight line linear regression and fit using the method of least square errors (MMSE) on the recorded measurements and those predicted by the free space path loss model resulted in a path loss exponent $n$ of 2.05. A Gaussian random variable with zero mean and a calculated standard deviation $\sigma$ of 1.03 dB could be added to account for random shadowing interference. Plots of the estimated power (dBm) versus log10($d$) at the various measurement sites for the Free Space Path Loss model are shown in Figure 54 along with the straight line fit.

5.4.4 Two-Ray Path Loss Model

A linear regression using MMSE on the recorded measurements resulted in a path loss slope of 2.04. Plots of the estimated received field power (dBm) versus log10($d$) for the Two-Ray Path Loss model are also shown in Figure 54. The programming code used for generating these plots using MATLAB® R2012a is shown at Appendix D.
Figure 54: Measured and Estimated Received Powers for Free Space and Two-Ray Models over half court paths with vertical polarisation. The receiver was located at 1m intervals up to 10m.

The results shown in Figure 54 indicates that for distances less than 10m there is very little interference from the ground reflection or other multipath signals. This confirms an environment of a Rician distribution type under static conditions with a dominant line-of-sight signal component. The measured and calculated results also show that the measurements match closely with the maxima and minima trend observed in the Two-Ray model predictions. It is observed that the value for the path loss exponent $n$ of 2.04 (Two-Ray) and 2.05 (Free Space) is very close to the value of 2.0, which is typical for a free space indoor environment. The value of $n$ will have a larger value when obstructions are present.

Indoor wireless positioning systems that are based on radio frequency (RF) signal propagation are reliant on the underlying transmission channel propagation knowledge and the characteristics of the indoor environment. The need for static and non-static signal propagation knowledge in these environments is still important in this application.

5.4.5 Conclusion

A sufficient number of field strength measurements were recorded over a typical indoor play area used by the sport of basketball to be a representative sample for this study. Free Space and Two-Ray path loss propagation models were successfully produced from these measurements for distances less than 10m. The prediction
models showed that margin errors of less than 1 dB are feasible where the accuracy of this value is constrained by the resolution limits of the hand held spectrum analyzer.

By understanding the static signal propagation characteristics of the play area, further study was undertaken to include the effects of a moveable transmitting beacon mounted on a player and its impact on the accuracy of the position estimation. The measurements showed that the direct LOS signal was dominant and therefore the measurement sample follows a typical Rician distribution. It is possible that this will change to a Raleigh type distribution when movement is introduced to the beacon and when other players and referees are considered within the play area. Values used for the reflection coefficient in the Two-Ray prediction model were derived from a ITU-R study [83]. Further investigation into the material reflection properties of the court surface could be undertaken to improve on the accuracy of these values.

A high level of confidence in position predictability and accuracy under static conditions is required. This study met this requirement and provided motivation for further research work in dynamic indoor wireless player positioning systems.

5.5 2.4 GHz Directional Receive Antenna Gain Tests in an Anechoic Chamber

5.5.1 Introduction
Confidence on the specified antenna gain and radiation pattern for any commercially available receive antenna can be obtained through experimental measurement by using well known procedures such those proposed by [94].

A simplified procedure called the gain-comparison method (see section 4.6) was conducted. By using the RF Explorer in the test there was no added variation in results due to differences in measuring equipment. This experiment showed the differences in gain between the whip antenna supplied with the hand held spectrum analyser (RF Explorer) and the TP-LINK 2.4 GHz patch antenna used in the basketball court field strength surveys. It also confirmed the vendors stated antenna gain.
5.5.2 Results
Table 6 shows the measurements undertaken in an anechoic chamber using the whip antenna supplied with the hand held spectrum analyser (RF Explorer) as the reference. The directional patch antenna was employed in the field survey experiments undertaken. An RF beacon operating with a CW signal at approximately 2.4 GHz was used as the source. The testing parameters were as follows.

Receive Operating Frequency: 2.400182 MHz
Antenna Height: 1.27 m
Distance between antennas: 2.34 m
SMA Adapter: <0.15 dB
100cm Patch Antenna feedline (CFD 200) loss: ~0.54 dB/m

<table>
<thead>
<tr>
<th>Table 7: Receive antenna calibration test using RF Explorer</th>
</tr>
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<tbody>
<tr>
<td>Receive Antenna</td>
</tr>
<tr>
<td>Helical Whip Antenna (reference) quarter wave vertically polarised monopole. Received field strength at antenna input(2.1 dBi gain)</td>
</tr>
<tr>
<td>TP-LINK 2.4GHz Patch Antenna (9 dBi gain)</td>
</tr>
<tr>
<td>Received field strength at antenna input for test antenna</td>
</tr>
</tbody>
</table>

These results were derived from the RF Explorer hand held spectrum analyser with ±0.5 dB resolution.

5.5.3 Conclusion
The results showed that the gain of the test patch antenna falls within a reasonable tolerance of the vendor’s specified gain of 9dBi even with the addition of the cable and connection losses.

5.6 Dynamic tracking of a 2.4 GHz Waist Mounted Beacon
5.6.1 Introduction
Object tracking within typical indoor environments containing static infrastructure objects has been widely reported in the last decade resulting in a variety of positioning techniques. In this study the wireless RF signal propagation (RSS technique) from a body-mounted 2.4 GHz beacon and the information from body mounted accelerometer sensors were investigated to confirm the feasibility of dynamically
tracking a single basketball player and ball possession on an indoor basketball court. It was reported previously (section 5.4) that for an indoor basketball court under static conditions, for distances less than 10 m, there is very little interference from the ground reflection or other multipath signals. Actually, variations of less than 3 dB were observed and reported.

5.6.2 Results

5.6.3 Single Player Tracking

The signal strength measurements were analyzed using MATLAB® R2013a. Figure 55 shows comparisons between the various paths of received field strength versus absolute distance over each dynamic path as the player moved towards the receiver. The data was fitted to the power law relation:

\[ P(d) = \frac{P_0}{d^n} \]  

(16)

where \( d \) is the separation distance (m), \( P_0 \) the power at 1 m from the transmitter and \( n \) the power factor (for free space \( n \approx 2 \)) to be determined.
Figure 55: Field strength vs. absolute distance for a chest mounted transmitter on a player running at a moderate pace. The positions were determined using a predefined track and a synchronised video record.

5.6.4 Ball Possession

A straight line linear regression fit using the method of least square errors was applied to all paths separately for the measured values. In this study $n \approx 2.3$ (Pearson squared correlation coefficient $r^2 = 0.42$) which is comparable with a previous study conducted under static conditions (section 5.4). Table 8 shows the variation in $n$ and the speed of movement for all paths.

Figures 56 - 58 show distinctive pattern signatures recorded from the dominant accelerometer sensor Y plane of a right handed subject bouncing a basketball. The accelerometer sensor was positioned on the wrist. Stationary, slow moving and moderately fast ball dribbling were recorded. The x axis shows a sample of time taken from the path recording at a 100 Hz sampling rate. Each major spike shown represents a portion of the ball bounce process. The y axis shows acceleration, selected for the $\pm 4g$ m/s$^2$ range. Pattern signatures from the dominant accelerometer Y plane were also recorded on a second right-handed subject for three sensors positioned on the wrist, the arm (above the elbow) and immediately below the chest centre respectively. These are shown in Figures 59 - 61 respectively. The chest mounted sensor recording shown in Figure 61 highlights that a noticeable pattern signature is not always distinguishable for the chest sensor position.

Table 8: Path loss slope exponents and velocities under dynamic movement.

<table>
<thead>
<tr>
<th>Path No.</th>
<th>Distance travelled (m)</th>
<th>$n$</th>
<th>Average Velocity (m/S)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>9-1</td>
<td>-2.09</td>
<td>0.66</td>
</tr>
<tr>
<td>2</td>
<td>7.5-1.5</td>
<td>-2.40</td>
<td>0.61</td>
</tr>
<tr>
<td>3</td>
<td>5.8-0.8</td>
<td>-2.02</td>
<td>0.49</td>
</tr>
<tr>
<td>4</td>
<td>7.9-0.9</td>
<td>-2.44</td>
<td>0.62</td>
</tr>
<tr>
<td>5</td>
<td>5.8-0.8</td>
<td>-2.21</td>
<td>0.57</td>
</tr>
<tr>
<td>6</td>
<td>7.8-0.8</td>
<td>-2.43</td>
<td>0.59</td>
</tr>
<tr>
<td>7</td>
<td>7.5-0.5</td>
<td>-2.41</td>
<td>0.62</td>
</tr>
<tr>
<td>All Paths</td>
<td>9-0.5</td>
<td>-2.3</td>
<td>0.60</td>
</tr>
</tbody>
</table>
Figure 56: Right wrist accelerometer patterns of first right-handed subject for stationary ball bouncing.

Figure 57: Right wrist accelerometer patterns of first right-handed subject for a slow moving dribble.
Figure 58: Right wrist accelerometer patterns of first right-handed subject for a moderately fast dribble.

Figure 59: Moderately fast accelerometer patterns of a second right-handed subject for the right wrist.
Figure 60: Moderately fast accelerometer patterns of a second right-handed subject for above the right elbow.

Figure 61: Moderately fast accelerometer patterns of a second right-handed subject for directly under the chest centre.

The ball bounce events are evident as large positive spikes from the right wrist and right elbow, but are not so clear in the chest located accelerometer profiles.

Measurements were taken using two different player participants for moderately fast pace who had different bouncing techniques. It is expected that a player who has been playing basketball for many years will develop a ‘soft touch’ approach to bouncing
the ball. In this case the ball will leave from the tip of the fingers in most cases as the final extension to the arm, hand and fingers are reached. A player with less experience or a player performing an odd bounce may have more of a ‘jerking’ or abrupt type bounce, where the full extension may not have been realized. Figure 58 and Figure 59 show that there is some difference between bounce acceleration profiles for the two players. The first subject had approximately 2 years of experience at local club level during high school, whereas the second subject had approximately 20 years of experience with Olympic level representation. Further work is needed using a large number of players with various levels of experience and skill so that more definitive ball-carrier identification can be made using the accelerometer records.

5.6.5 Single Player Tracking and Ball Possession at a Fast Pace

Figure 62 shows a plot of field strength versus absolute distance under fast pace conditions for a third test subject. This subject was currently playing at the first grade level in Brisbane, QLD. It is clear from this plot that there is sufficient field strength variation to use a RSS based estimation technique for position under dynamic conditions. The plot is similar to the slower movement data obtained shown in Figure 55.

Figure 62: Analysis of fast paced ball dribble showing Field strength vs. absolute distance.
Figure 63: Accelerometer pattern of third subject right wrist sensor.

Figure 63 shows measurements of the accelerometer sensor connected to the wrist from the dominant Y plane under fast paced conditions. This recording shows that acceleration was over-range for almost all ball impacts with the hand, but the identification of the bounce is still clearly evident. The results show three dribble durations each consisting of a major spike immediately followed by a much lesser spike. In each signature case the first spike is greater than the second spike and the dip between spikes rarely drops below 0g acceleration. The graph also shows the movement of arms upon commencement of the drill leading up to the catch. An analysis of the pattern is as follows: (a) 21600 (start); (b) 21755 – 21825 (catch point); (c) 21825 – 21875 (1st bounce); (d) 21875 – 21930 (2nd bounce); (e) 21930 – 21980 (3rd bounce); and (f) 22000 (ball hand slap).

5.6.6 Conclusion

For a single player under dynamic conditions the results for received power versus court distances less than 10m (see Figure 55) highlighted a power distance relationship of a Rician type environment with $n \approx 2.3$. There is one dominant direct ray and the effect of multipath signals reflected from the court floor, walls and other persons in the vicinity is relatively small. For distances less than 9 meters, nulls of up to 2.5 dB signal variation were observed with the majority of nulls less than 2 dB. Although only a small number of distance markers could be used to locate intervals along each path, the large number of power level measurements (> 800) recorded
provided results favourable for a received power versus distance position estimation technique. As expected, the distance estimation accuracy significantly improved as the beacon was closer to the receiver where the slope in Figure 55 is greater. For example, at distances up to 2.5 m from the receiver it is possible to achieve accuracies of within 0.3 meters. Under fast movement conditions, expected in a game, similar results support the received power versus distance position estimation technique. Compared to a previous study under static conditions (section 5.4) movement and direction of travel will result in some change in transmit antenna orientation. This can lead to an increase in random variation in received field strength and consequently reduce position precision.

The main setup area for offensive players is either on or outside the basketball key. The distance between the key edge and the sideline is approximately 5 m. By employing a combination of quarter-court identification and power/distance estimation methods, it is feasible to produce a player tracking system under single player conditions using three or more anchor nodes.

The validity of an indoor wireless player positioning system in a dynamic team environment using only one anchor node with a player in line-of-sight has been addressed in this study using one player under moderate and fast paced conditions. Indoor sports that could employ a single player position estimation system include indoor tennis, badminton and volleyball. Future work will assess the effect of multiple players and multiple beacons with multiple anchor nodes. To achieve quarter court coverage using triangulation a minimum of three anchor nodes/receivers will be required in each quarter court.

The use of 3-axis accelerometers to indicate ball possession has proven to be feasible when mounting the sensor on the wrist or above the elbow, with the wrist mount giving the most predominant results. The results have shown a clear response signature for all subjects including a unique spike level and signal response in the bounce process that can be used to flag when the basketball is being bounced. These acceleration spikes were clearly observed above those created by foot fall (the contact of heel and the ball of the foot on the floor) and other player movements. They were also clearly absent under conditions where the player was not bouncing the ball (see Figure 63). Unique acceleration spikes could not always be easily distinguished in the
accelerometer record when the sensor was located under the front of the chest and therefore this would not be a reliable signature for detection use. This is mainly due to body attenuation of the hand-ball contact signal. Recordings of all chest responses were therefore not reported.

The comparison of ball dribbling by three different players (Figures 56 - 58, 59 and 63) could not confirm significant difference in signatures from the accelerometer sensors located on the wrist. However, they did show a variation in acceleration or dribble force exerted by each player. Typically players with more confidence in dribbling can exert a higher down force as shown in Figure 63 where the acceleration is greater than 4g. Through post data processing this study has shown that it is possible to identify a unique signature from a triaxial (3 axis) accelerometer sensor mounted on the wrist for use as a ball dribbling possession indicator.

There may be scope to investigate body network communications as a solution to include a wrist sensor in the overall player positioning system and further work in accelerometer sensor post data analysis and signature detection are required to implement this solution for ball possession.

5.7 **The Number of Base Receivers, their Locations and Antenna Beamwidth Consideration**

Figure 64 shows the base receiver locations after careful consideration of key design factors (see sections 3.8.3 and 4.8) for offensive player positional coverage over quarter court (excluding inside the basketball key). For offensive players the RF beacon would be worn on the back of the torso as they would mainly be facing the ring.
Figure 64: Base Receiver Locations

Base receiver numbers 1 to 3 in Figure 64 were determined to have the following x and y co-ordinates.

Rx 1: (-0.5 m, 3.5 m)

Rx 2: (1.2 m, 8.0 m)

Rx 3: (6.2 m, 8.0 m)

There will be positons in Figure 64 using the beamwidth determined for the player-worn beacon in section 5.2 of 120° where this beamwidth will not enclose all three base receivers. For example, for a player at a position between Rx 2 and Rx 3 near the sideline and facing the ring a back mounted beacon will not have an unobstructed line of sight to Rx1. In this scenario, where there are three base receivers, two body-worn beacons mounted on the front and back of the torso would be required for positional coverage to these areas. The majority of the quarter court area is not affected by this problem.

Although receiver antenna positions were chosen to minimise the likelihood of a player running into the antenna, this occurrence cannot be completely ruled out. The
size of the antenna mount is to be designed to remove any injury to a player if this does occur and it should not distract the player’s concentration from the game.

An investigation into the appropriate beam width for each receive antenna was also conducted based on Figure 6.4. From Figure 6.4 a beamwidth of approximately 120° is also considered to be suitable for each base receiver antenna.

The beamwidth of the base receive antennas is highly dependent on their placement in Figure 6.4 for the player positioning system. The majority of high level indoor basketball court venues have seating to the side of the rectangular basketball court and at each end. For safety reasons, international specifications indicate that the distance from the court boundary to these seats is to be a minimum of a 2 m and is to be clear to allow for run-off by the players or referees. Unfortunately, journalists have been known to encroach into this area to obtain a better photograph. Reflections off these seating stands can give rise to unwanted multipath interference. To minimise this multipath interference the corresponding directional horizontal radiation pattern should have a high front-to-back ratio to significantly reduce the power level of interference signals from behind due to the seating.

5.7.1 Conclusion
Locations for up to three base receivers and their antennas were determined to be suitable and practical for use in the player positioning system. Locations were chosen to minimise an event of the player running into the base receiver antenna mount, however, the antenna mounts should be designed to remove any chance of injury. For example, enclosing the mounts in a soft absorbent material. It was determined that a minimum beamwidth of 120° from the player transmitter and for the base receive antennas would be sufficient. However, section 5.12 showed that 180° could be used for the base receive antennas.

5.8 Player Positional Accuracy

5.8.1 Introduction
From the research studies on dynamic movement reported it is possible to estimate a level of positional accuracy depending on the location on the basketball court in relation to the receiving antennas. This can be represented as a series of uncertainty
ellipses with the major and minor axis of the ellipse determined from the signal power level at the two receiving antennas (see section 3.1.7). To achieve this representation, a plot of the basketball court and a sample of uncertainty ellipses at various locations were produced.

5.8.2 Results

Figure 65 shows the estimation of a single dimension uncertainty based on received power vs distance for a moving player. It can be seen that as the distance to the player decreases the accuracy increases significantly. There is a condition when the received power levels at each of the receiving antennas create similar uncertainties on the major and minor axis of the uncertainty ellipse. In this case a circle of uncertainty is formed. The previous study on dynamic movement [1] provided a level of player positional accuracy to within 0.5 m for distances less than 9 m, which varied depending on the location on the basketball court in relation to the receiving antennas.

![Figure 65: Path distance uncertainty using received power at 2.4 GHz and an RSSI uncertainty of 0.5 dB.](image_url)

Figure 65 shows that the positional error is dependent on the slope of the signal curve. For variations of up to 3 dB for distances less than 7.5 m, position estimation accuracies of 0.5 m are achievable. For a conveyor belt tagged parcel processing system this would be unacceptable. However, for a basketball game where the space
taken up by an offensive player is generally 1-2 m this falls well within an acceptable level of inaccuracy. Figure 66 shows a plot of uncertainty ellipses at various sample locations. The uncertainty ellipses and the corresponding graphics were produced by a purpose built software program written in MATLAB using MATLAB® R2012a and known ellipse equations (see section 3.18). The program code is shown in Appendix D, Section 8.4.2.

![Figure 66: Sample path uncertainty plots on one quarter of the basketball court based on a 0.5 dBm signal variation in signal strength.](image)

### 5.8.3 Conclusion

The predicted uncertainty ellipses did not take into account the variation that would occur due to multipath interference on the received signal from multiple players. Typically a game of basketball would consist of 5 basketball players per team and 2 or 3 referees on court at the same time. The results give a conservative view of the likely uncertainty with the use of two receive antennas when one moving basketball player was considered.
5.9  **RF Explorer 2.4 GHz Hand Held Spectrum Analyser Test in an Anechoic Chamber**

5.9.1  **Introduction**

Generally, the cost of field strength measuring equipment will vary based on the frequency range and the accuracy. This cost can vary in the order of a few thousand dollars up to 10’s of thousands of dollars. The RF explorer is a low cost device (~$160.00 AUD @ 2015). Because of the low cost of this unit it was necessary to obtain some form of reliability of measurement results under ideal conditions, such as those that would be experienced in an anechoic chamber.

5.9.2  **Results**

Three RF explorer units were tested on received field strength at separation distances of 1m and 2.5 m within an anechoic chamber with the results recorded to a cumulative CSV data file. Table 9 shows a comparison between three units at 1 m and 2.5 m.

<table>
<thead>
<tr>
<th>Unit</th>
<th>RF1</th>
<th>RF2</th>
<th>RF3</th>
<th>RF1</th>
<th>RF2</th>
<th>RF3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dist.</td>
<td>1m</td>
<td>2.5m</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>No of Readings</td>
<td>312</td>
<td>276</td>
<td>281</td>
<td>267</td>
<td>264</td>
<td>267</td>
</tr>
<tr>
<td>Frequency offset (MHz)</td>
<td>182</td>
<td>75</td>
<td>75</td>
<td>182</td>
<td>75</td>
<td>182</td>
</tr>
<tr>
<td>Min</td>
<td>-61</td>
<td>-62</td>
<td>-57</td>
<td>-68.5</td>
<td>-68</td>
<td>-68</td>
</tr>
<tr>
<td>Av.</td>
<td>-60.68</td>
<td>-61.45</td>
<td>-56.78</td>
<td>-67.095</td>
<td>-67.076</td>
<td>-67.03</td>
</tr>
<tr>
<td>Median</td>
<td>-60.5</td>
<td>-61.5</td>
<td>-57</td>
<td>-67</td>
<td>-67</td>
<td>-66.5</td>
</tr>
<tr>
<td>Max</td>
<td>-60.5</td>
<td>-61</td>
<td>-56.5</td>
<td>-66.5</td>
<td>-66.5</td>
<td>-66.5</td>
</tr>
</tbody>
</table>

The results in Table 9 show that variations from 0.5 - 1.0 dBm occurred for units 1 and 2 for both 1m and 2.5 m distances. The results also showed a significant variation between RF Explorer unit 3 and the units 1 and 2 at the 1m distance. To further investigate these variations, time plots were produced for each of the above scenarios in the following plots. The RF Explorer mode indicated as either Average or Real in
the titles of the plots have no bearing on the recorded raw data. The average or real modes can be used for post processing of the data by the unit when not saving the data to a cumulative CSV file. Figure 67 shows a sample plot of received field strength versus time for RF Explorer unit 3.

![Figure 67: Plot of received signal (dBm) versus time recorded within an anechoic chamber. The quantization of 0.5 dBm is clearly evident.](image)

These results show that there are significant amplitude variations in the measurements at random times. These glitches are either generated within the RF transmitting beacon or within the RF explorer unit. Figures 68 - 73 show the recorded measurements for each of the RF explorer units with obvious anomalies removed from most of them. These amplitude anomalies may have caused the small number of unexpected results observed in the indoor basketball court field strength survey (section 5.3).

![Figure 68: Plot of received signal (dBm) versus time for unit 3 in real mode at 2.5m.](image)
Figure 69: Plot of received signal (dBm) versus time for unit 2 in real mode at 2.5m.

Figure 70: Plot of received signal (dBm) versus time for unit 1 in real mode at 2.5m.

Figure 71: Plot of received signal (dBm) versus time for unit 3 in average mode at 1m.
Figure 72: Plot of received signal (dBm) versus time for unit 2 in average mode at 1m.

Figure 73: Plot of received signal (dBm) versus time for unit 1 in average mode at 1m.

Figures 68-73 also indicate another type of signal amplitude variation. This variation is partly due to the internal quantization error occurring from converting the received analog RF signal to digital.

Because of this quantized nature, most reasonably priced WiFi modems that can also provide RSSI values have a resolution of only 1 dB. In this application the experiments require at least 0.5 dB, especially when analysing difficult parts of the distance-field strength curve where the slope gradient is low. The RF Explorer unit used in these research experiments offer a linear response in dBm with a relative resolution of 0.5 dB. This is better than WiFi modems and most other equipment of this type. It is anticipated that a non-RSSI method of reading the signal strength will be used in the final system with accuracies of within 0.5 dBm.
5.9.3 Conclusion

Received field strength tests on three separate RF Explorer units were conducted within an anechoic chamber at distances of 1 m and 2.5 m using recorded raw data to a cumulative CSV file. The results show that accuracies of within ±0.5 dBm are achievable using either of the units.

An anomaly was discovered causing a glitch to occur in the recorded measurements at random times. However, this anomaly was not serious enough to prevent the use of the equipment in the tests. Overall the 2.4G RF Explorer units performed well and are suitable for the experiments conducted in this research.

5.10 Multipath Impact Study on Wireless Player Positioning

5.10.1 Introduction

Two teams of 5 volunteer players per team, each with high basketball playing skills, were asked to undertake a training scrimmage using techniques and offensive drills used in a real game at real game pace. This experimental study introduced into the research the movement of local players within the vicinity of the transmitting beacon and considered the multipath interference due to these extra moveable objects. This is an important research aspect of the positioning system as previous experiments have only been conducted with a single subject wearing the transmitting beacon in an object free environment.

5.10.2 Results

Three offense player scenarios were used in this set of experiments.

5.10.3 Guard Player

During a basketball game the defensive player will be located somewhere between the player wearing the beacon and the basketball ring. Under this scenario signal obstruction between the beacon and side court receivers is less likely to occur.

Figure 74 shows a plot of the dominant RF signal without players. The plot shows a variation which is partly due to quantization error occurring from converting the received analog RF signal to digital. The internal analog to digital converter resolution
of 0.5 dB is evident. The corresponding change in the digital output is usually expressed in terms of the least significant bit. The hand-held analyzer converts the analog input signal to a 10-bit digital value. This change due to quantization error can generally be considered as white noise and would normally be reduced in measurements by averaging the samples. Some of the variation in Figure 74 may also be due to the frequency and/or power stability of the transmitted signal.

![Graph](image)

**Figure 74:** Received power vs time of dominant signal without players. The received signal strength resolution is 0.5 dB.

A statistical analysis of this dominant signal data results in a mean of -62.5 dBm with a standard deviation of 0.63 dBm.

**5.10.4 Forward Player**

To achieve a representative sample of data for forward positional players the data obtained from the RF signal and video recording was analyzed to remove most of the occurrences of deep fading due to signal obstruction. Only signal variations due to minor obstruction, multipath and the inherent variation of the transmitting and receiving equipment were considered by manual removal of these data points. A reduced plot of the received signal vs time for dynamic game play movement, without significant fading from player obstruction, is shown in Figure 75. This reduction still has fading due to background reflection.
A statistical analysis on this reduced data results in a mean power level of \(-62\, \text{dBm}\) with a standard deviation of 1.24 dB.

A further analysis of this reduced data was conducted in conjunction with the recorded video data to remove any minor fading effects due to obstruction and/or near-obstruction. This finally resulted in a reduced signal fading range of approximately \(-60.5\, \text{dBm}\) to \(-63.5\, \text{dBm}\) about the mean (i.e. approximately 3 dB).

5.10.5 Center Player

These players are generally the largest in size and height and their vicinity of play is normally just outside the basketball key defining lines. This occurs most of the time as basketball rules state that they have only 3 seconds of allowed time within the key. They will generally be on the side of the key, but can at times play anywhere around the key line. They may also cut across the key during play. These players will experience LOS obstructions the most due to other players between them and the sideline. These players will mostly face away from the basketball ring towards the sideline.

The raw measured data (shown in Figure 76) shows the major obstructions to the LOS dominant signal caused by players moving between the beacon and the receiver as would be expected.
Under game play conditions this is expected to be similar to a worst case scenario where fading nulls from 20 to 30 dB may occur. However, as the players are moving quite rapidly these nulls will usually only occur for very short periods of time.

The players wear two beacons (the front chest and one placed on the back). Investigations into the appropriate wearing of the strap and position of the two beacons might be further analyzed for best performance.

![Graph of received power vs. time for dynamic game play with LOS obstruction by other players.](image)

**Figure 76: Received power vs time for dynamic game play with LOS obstruction by other players.**

A statistical analysis of the data recorded in Figure 76 results in a mean of -63 dBm with a standard deviation of 3.8 dB. The time between readings was approximately 100 mS.

### 5.10.6 Fresnel Zone Clearance

Test results showed that as a player approached the LOS path there was an occasional increase and/or decrease to the received signal before the deep dominant signal fade occurred. This is highlighted in Figure 77. This occurrence is expected as the dielectric properties of the human body above 1 GHz introduces a scattering effect on the RF signal. This multipath signal occurs as the offending obstruction moves within the 1st Fresnel zone of the LOS path and to a lesser extent the 3rd and 5th Fresnel zones.
Figure 77: Received Power vs Time showing addition and/or subtraction of fading before and after significant obstruction.

5.10.7 Rician Fading Statistics

Level Crossing rates, Average Fade Durations and Cumulative Distribution Function plots were obtained for all three types of player scenarios using (1), (2) and (3), Chapter 3, section 3.14.1.

Figures 78 and 79 compare the Rician average fade duration parameters for the three player types: a) a forward or centre playing in a forward position with duration 33.5 seconds; b) a centre with duration 89.4 seconds; and c) a guard or a forward playing in a guard position with duration 52.4 seconds (shown in Figure 79).

Figure 78: Average fade duration for unobstructed game play for a forward player (indicated by a solid line with a circle marker) and a centre player (indicated by a solid line with a star marker).
Figure 79: Average fade duration for unobstructed game play for a guard player (indicated by a solid line with a diamond marker).

Figures 78 and 79 confirm that the average fade duration reduces when the detection threshold is reduced, which is to be expected. The lower recorded duration time from 89 seconds for a centre player to 33 seconds for a forward player corresponds to the greater average fade shown for forward players above -60.5 dBm in Figure 78. At these levels for shorter periods of time there are less occurrences of positive threshold crossings resulting in the indicated higher average fade duration.

Figure 80 compares the Rician level crossing rates for the three player types and shows an unusually higher level crossing rate for a guard compared to a forward or centre. This higher result is due to the large variability in the dominant signal from quantization and signal variations mentioned previously. Figure 80 also highlights the deeper fades due to more obstructions by the wider threshold range. The results generally show a higher level crossing rate for a centre player compared to a forward player. The Centre/Forward legend describes a forward player or a centre player playing in a forward positon. In the forward positon there are less LOS signal obstructions compared to the typical centre player offense position. For the guard player there is no recorded data greater than -61.5 dBm due to multipath interference. This is shown in Figure 80 as an abrupt stop in the data plot.
These results highlight the impact that obstructions or near obstructions have on the received signal even under worst case conditions. The LOS signal obstructions are not expected to be frequent resulting in plot values that look more like those shown between 55 and 60 seconds in Figure 75. Using equation (12) (section 3.14) the cumulative distribution function is shown in Figure 81. This result shows that the probability on the received power dropping below the median threshold of -62.5 dBm is approximately 30%. Typically a threshold would be set at a value a lot lower than this median. The position estimation threshold would normally be somewhere in the vicinity of the mean signal level which would need to be considered in the final design of the system. The performance of the communications of the positioning system, which is directly linked to the position estimation, is sensitive to both the number of times that a low threshold is crossed and the duration of time the received signal remains below the given threshold. For example, a player cannot suddenly disappear at one location and reappear at another incorrect position just because the signal level has faded below the threshold. This factor would need to be included in the design of the system. Signal variability and therefore positional variation (see section 5.7) has shown that for a signal variation of 3 dB the positional accuracy varied by only 0.5 m. From a median threshold of -62.5 dBm this equates to a lower
threshold of -65.5 dB. At this value the level crossing rate is less than 0.5/sec. Figure 81 shows that even if the received signal did drop by 3 dB from the median threshold the probability that it would drop further is very small thereby maintaining a positional accuracy of ±0.5 m.

![Figure 81: CDF of fading for dynamic game play for a forward and centre player (indicated by a dotted line with a star marker superimposed on a circle marker), a guard player (indicated by a dashed line with a diamond marker).](image)

The severity of fading in a Rician fading environment (the Rician k-factor) was calculated for all three player types by the method described in Section 3.14.2. Table 10 compares these with their corresponding LCR and AFD values.

<table>
<thead>
<tr>
<th>Player Position</th>
<th>( N_L ) (sec(^{-1} ))</th>
<th>( \bar{\tau}_L ) (sec)</th>
<th>k-factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Guard</td>
<td>1.9</td>
<td>0.3</td>
<td>13.9</td>
</tr>
<tr>
<td>Guard/Forward</td>
<td>2.3</td>
<td>0.2</td>
<td>7.2</td>
</tr>
<tr>
<td>Centre</td>
<td>1.8</td>
<td>0.3</td>
<td>3.5</td>
</tr>
</tbody>
</table>

Table 10 confirms that as the player type moves to play in a vicinity similar to that of a centre player the k-factor is reduced. This corresponds to moving the fading distribution closer to that of a Rayleigh type and away from a Gaussian type that is centred about the mean.
The Rician distribution approximates a Rayleigh distribution when the Rician k-factor $k \ll 1$, and reduces to it when $k=0$. The k-factor shown of $3.5$ confirms that a Rice distribution is still applicable for analyzing centre player fading statistics.

The transmitting beacon in this study was mounted on a rigid stationary test rig. Under normal game conditions the player would be moving and rotating to some degree both in the horizontal and vertical direction. Therefore, there is likely to be some variation in received signal strength due to the orientation of the transmitting antenna horizontal and vertical radiation patterns. This has shown to have some impact on the sensor data signal variation. This needs to be considered further in the design and construction of the moving wearable sensor transmitting antenna and the fixed sideline receiving antennas. The final position estimate must be determined using the maximum received signal as almost all types of channel interference result in a decrease in signal strength. Increases in signal strength above a LOS value is rare. For dynamic game play without LOS obstruction (see Figure 75), peak values of -60.5 dBm or less were mainly observed. The signals recorded at -60 dBm showed a level crossing rate of 0.5/sec or less. For a forward or centre player over the recorded time of 33.5 seconds this corresponds to 1.5% of the time.

5.10.8 Conclusion

A statistical analysis of the results from this experiment has provided level crossing rate and average fade duration for various received threshold levels and confirmed a Rician fading environment for both guard, forward and centre players under normal game conditions.

The effect of multipath interference due to the movement of team players on the received signal has shown to be minimal with signal fluctuations of approximately ±0.5 dB with a corresponding positional uncertainty from Figure 65 (see section 5.8.2) of less than 0.5 m. Additional slight variations to this are potentially due to frequency and/or radiated transmitted power stability. Although the results in this study are limited by the accuracy of the hand-held spectrum analyzer, there is sufficient evidence to support the conclusion that multipath interference due to multiple player movement is not significant. For a game play of 33.5 seconds the average fade duration from Figure 78 (see section 5.10.7) for both forward and centre players was less than 0.3 seconds which is 1% or less of the time.
Receiver sensitivity is a key factor in the design and overall cost of the receiver and impacts on the reliability of the received signal. The tests showed that in the event of fading due to an obstruction a reliable measureable signal could still be achieved based on the receiving equipment used. It is anticipated, however, that a higher performance receiver and sensor would be employed in the final design of a player positioning system.

5.11 Basketball Passing Detection using Accelerometers

5.11.1 Introduction
Previous studies on detecting particular wrist and arm movements were conducted and reported using body worn accelerometers in section 5.6.4. If ball bouncing can be detected using the detection of a unique accelerometer signal signature then it is feasible that the act of ball passing could also be detected.

The standard two-hand basketball pass consists of a number of natural motions by the arms and hands. Initially the ball is brought towards the chest to gain maximum momentum on the pass. The arms and hands are then extended to the maximum as the ball leaves the finger tips (see Figure 44, section 4.12.1). There are other types of ball passing, however, this study only concentrated on the common two-hand pass.

5.11.2 Results
Distinctive pattern signatures from the dominant accelerometer Y plane of passing a basketball were recorded for a sensor positioned on the wrist and above the elbow for a right-handed subject.
Figure 82: Distinctive pattern signatures from the Y plane of a right wrist mounted accelerometer sensor for a right-handed subject passing the ball with two hands.

Figure 82 shows a distinctive pattern for the 6 recorded basketball passes. The timing of these passes were correlated with the timing on the recorded video file. The other large variation signatures shown represent catching the basketball with two hands.

A close up sample pattern of the y-axis for the 3-axis wrist mounted accelerometer sensor is shown in Figure 83, selected for the ±4g m/s² range.

Figure 83: Distinctive pattern signature from the Y plane of a right wrist mounted accelerometer sensor for a right-handed subject passing the ball with two hands.
By using a small amount of processing logic in the player tracking system it would be possible to detect whether a player who has the ball has passed it onto another player. Further investigation is needed in this area of processing and also to investigate the effect of varying the speed of the passing action on the pattern signature.

5.11.3 Conclusion

The use of 3-axis accelerometer sensors to indicate a ball passing action has proven to be feasible when mounting the sensor on the wrist. The results have shown a clear unique signal response signature in the ball passing process that can be used to flag when the basketball is being passed.

5.12 Prototype Tracking System

5.12.1 Introduction

In this final experiment the hardware of a prototype tracking system was constructed and a software computer program produced to confirm the hypothesis of the research that an indoor basketball player tracking system could be produced wirelessly using RF signals based on received signal strength (to determine distance) and trilateration.

5.12.2 Number of Receive Antennas per Quarter Court

While investigating the number of receive antennas required to produce a prototype system it was found that the original requirement for three antennas could be reduced to two. This is because of the way the location prediction is calculated. With three concentric circles it is possible to estimate the position within a small area with size less than the cross-sectional area of a typical basketball player. When there are only two receive antennas the estimation results in two possible locations. However, because the receiving antennas lie along the court sideline one of these positions is located inside the court and the other outside. By using simple logic in the processing the incorrect position can be ignored.

5.12.3 Results

Positional accuracies of within 0.5 m were obtained for 7 stationary positions. For the player movement test, positional accuracies of ±0.5 m were obtained as the subject moved along the predetermined test path. Figure 84 shows the prototype display with
the stationary test positions and the dynamic movement line. Also shown are sample of test position numbers used for further analysis.

Figure 84: Prototype graphic display showing static test positions (black coloured crosses) and dynamic movement (purple arrow line) with the estimated position shown as a green coloured cross-hair circle.

Figure 85 shows a screen capture of a live video recording of the laptop screen while the test was being conducted and data recorded at test position 1. The image shows the demonstration software screen and the location of the player.

Figure 85: Prototype as viewed on laptop computer for test position 1.
Figures 86 to 95 show plots of the recorded received power (dBm) and distance (m) versus time (s) for stationary positions 1, 2, 3, 4, and 7 (Figure 84).

Figure 86: Plot of received power (dBm) and estimated distance (m) to receiver base 1 for fixed test position 1.

Figure 87: Plot of received power (dBm) and estimated distance (m) to receiver base 2 for fixed test position 1.

Figure 88: Plot of received power (dBm) and estimated distance (m) to receiver base 1 for fixed test position 2.
Figure 89: Plot of received power (dBm) and estimated distance (m) to receiver base 2 for fixed test position 2.

Figure 90: Plot of received power (dBm) and estimated distance (m) to receiver base 1 for fixed test position 3.

Figure 91: Plot of received power (dBm) and estimated distance (m) to receiver base 2 for fixed test position 3.
Figure 92: Plot of received power (dBm) and estimated distance (m) to receiver base 1 for fixed test position 4.

Figure 93: Plot of received power (dBm) and estimated distance (m) to receiver base 2 for fixed test position 4.

Figure 94: Plot of received power (dBm) and estimated distance (m) to receiver base 1 for fixed test position 7.
Figure 95: Plot of received power (dBm) and estimated distance (m) to receiver base 1 for fixed test position 7.

Figures 96 and 97 show plots of the recorded received power (dBm) and distance (m) versus time (s) for the dynamic movement test.

Figure 96: Plot of received power (dBm) and estimated distance (m) to receiver base 1 for dynamic movement test.

Figure 97: Plot of received power (dBm) and estimated distance (m) to receiver base 2 for dynamic movement test.

The results shown in Figures 86 through to 97 indicate signal variations less than 3 dB at a given distance. This corresponds to an estimated distance accuracy of less than
±0.5 m from each of the base receivers. This tolerance is observed in each of the above plots on the right side y-axis. The results also clearly show the quantisation shift within the receiving equipment (see section 3.1.5).

5.12.4 Time Synchronisation
The sample rate from each RF Explorer is approximately 100mS. The prototype software program receives a power level value from each unit, processes the relationship with distance for each value then calculates the position in an extremely small time (much less than 10mS and typically in the order of microseconds) which is well within this sampling period. Once the system has processed the data it then waits for the next sample pair to arrive. Because of the fast computer processing speed, for general position estimation it does not matter if the start time for each unit is not exactly synchronised as long as the power levels have not changed significantly. It would be preferable that the sampling rate for each unit be approximately the same but this also is not critical. If the sampling rates are different then eventually a power level value will be read from a different sampling period for the unit with the smallest sampling rate. This, however, is not a problem for positional error as the player movement is very slow compared to the 100mS sampling rate resulting in virtually no distance travelled. Therefore, a similar power level value to the original would be received and used in the calculations. For other information metrics where the time received from each base receiver correlation critical further investigation into the timing system will need to be conducted.

5.12.5 Cumulative Errors and Uncertainties due to Significant Fading and other Signal Level Variations with respect to time.
When a significant drop or increase in signal power is received the positioning system cannot simply display the player at some other location some distance away. For example, the player cannot be shown to appear at the baseline, disappear from the system display and in the next instant reappear at the top of the key. To overcome this problem the program has been designed to determine if the incoming power levels are considered reasonable. The research has shown that the variation due to obstruction from another player in a game occurs over a very small time in the order of 200 mS (see Figure 77, section 5.10.6). Also, these significant signal variation periods do not occur consecutively. During this time the player would only be expected to move a very short distance (less than ~1 m) based on the low speeds of a player. By setting a
distance limit then the player can be shown to remain at the position before this critical period, appear as a different colour during this period and then shown at the new position after this critical period. Additional mathematical predictive theorems could also be incorporated if the player is moving during these large signal variation periods based on player direction.

5.12.6 Conclusion
Tests using a prototype player tracking system has confirmed that it is possible to track a player based on received field strength and trilateration in an indoor basketball court environment with positional accuracies achieved within ±0.5 m (less than the size of a player). Further investigation into broadening the vertical and horizontal radiation pattern of the body-worn transmitting beacon is needed to further minimize receiving signal variation due to body movement.

5.13 Cost Consideration

5.13.1 Introduction
A costing analysis is dependent on the costs of the day and the existence of vendors for equipment. For example, during the dynamic research experiments using the sector antenna the original vendor source for this antenna was no longer available. The antenna was alternatively sourced directly from the manufacturer at an increased cost. By the time a fully developed player tracking system is ready for commercial use it is expected that costs of technical equipment and even the equipment itself may have changed.

5.13.2 Cost Analysis
A current cost analysis was performed on the overall system with the results kept in confidence. The proposed system, ignoring research/developmental costs, is significantly less expensive than current systems used in many of the high performance competitions such as the NBA in America. Sport VU camera based basketball system is one such system based on video at a cost greater than USD $100k/year. Other authors have also confirmed this expectation.

It was known before this research began that the costs of sensors (including small RF beacons, accelerometers and field strength measuring equipment) had dropped
considerably in the past 20 years. After an initial analysis, the estimated cost of the prototype tracking system for full court coverage is less than AUD $10k outright.

5.13.3 Conclusion
A cost analysis has shown that a prototype tracking system for full court coverage is within reach for most high level basketball organisations. It is expected that a similar system that is still adequate for player positioning but with reduced performance and cost would be available for schools and community organisations.

5.14 Chapter Summary
It was confirmed that an indoor basketball court is suitable for signal propagation and that it adheres to a Rician environment with little multipath. Experiments were conducted to show that a position and tracking system based on received field strength and the use of trilateration theory could be used in such an environment. The chapter covered the uncertainty of dynamic player movement on positional accuracy and the introduction of additional players within the play environment in respect to multipath interference. Both of these concerns were found not to have a significant effect on the player location prediction. Experimental results were highlighted for detecting ball possession and ball passing using accelerometers as a significant new approach to providing useful necessary information to the overall tracking system. This chapter also detailed the results of the reliability tests conducted on the ‘RF Explorer’ handheld spectrum analyser which was used in many of the research experiments and highlighted the valid use of this instrument.

The next chapter presents the final conclusions and recommendations for further research.
Some of the content within this chapter was partly discussed and published in the following author’s publications:


6. CONCLUSIONS AND FURTHER RESEARCH

6.1 Conclusions

This thesis has presented a detailed study into a low cost method of using RF wireless signals and signal strength for tracking basketball players within an indoor environment. This technique has not previously been proposed in the game of indoor basketball as wearable tracking devices up until recently were bulky and practicably unrealistic. The research analysis has shown that the system can be implemented in an indoor sporting environment, such as that used by the game of basketball. This technique has significant potential for use in other indoor sports that share the same indoor play area. Also, as the play area is built to international specifications the technique could be replicated at numerous venues around the world.

The detailed research undertaken has proved the hypothesis presented at the beginning of this study and introduced advancements into basketball player tracking for the purpose of providing information to coaches and trainers. These advancements include the confirmation that the use of wearable RF wireless beacon devices into the sport of basketball can be used to track players. Also, the use of accelerometers can be used to complement this technology to determine whether a player is bouncing the ball (a form of ball possession) or whether the ball has been passed.

It has been shown that the radiation pattern from a body-worn beacon will produce a main radiation lobe with a -3 dB beam width of approximately 120 degrees, which can be used successfully in the planning of side court receive antennas for the tracking system.

The indoor basketball court environment was tested for its transmission channel propagation characteristics by conducting a field strength survey over half of the court. With no players it was found to have little to no multipath interference impact and therefore would be favourable for a tracking system based on received field strength. With the introduction of a single player wearing a 2.4 GHz beacon under the chest two field strength prediction models based on the classical Free Space Path Loss and Two-Ray Path Loss models were developed using field strength data recorded
from a number of paths over the play area. The prediction models highlighted that margin errors of less than 1 dB are feasible.

The introduction of a moving single player into the environment showed that for distances less than 10 m the power distance relationship was of a Rician type environment with essentially one dominant direct ray and one much smaller ray reflected from the court floor. Nulls of up to 2.5 dB signal variation were observed with the majority of nulls less than 2 dB. A subsequent power law relationship model was developed under dynamic conditions with a power factor and Pearson squared correlation coefficient comparable to the study conducted under static conditions.

The study highlighted the need for additional information on ball possession in order for the tracking system to be useful for the basketball coach. Consequently, research into the use of accelerometers, in particular, the detection of a distinct acceleration signal pattern from bouncing the ball, was investigated and introduced into the research as a means of accomplishing this.

It was confirmed that a unique signature pattern from a wrist-worn accelerometer could be used to detect when a player is bouncing the basketball. Comparisons of mounting the accelerometer on the wrist, above elbow or directly below the chest showed that the wrist mounting position provided the strongest and most reliable signal for recording the accelerometer pattern signature.

A theoretical player positional accuracy study was undertaken based on the research and measurements undertaken on dynamic movement. This study looked at the level of positional accuracy depending on the location on the basketball court and in relation to the receive antennas. A plot of uncertainty ellipses highlighted the affect that the slope of the power distance curve has on the predicted distance uncertainty as the distance from a particular receive antenna is increased. The plot showed that for variations of up to 3 dB for distances less than 7.5 m, positional accuracies of 0.5 m are achievable from the transmitting beacon.

An anechoic test on the 2.4 GHz hand held spectrum analyser that was used throughout the main research showed that the device suffered from quantization errors of ±0.5 dB and occasional glitch variations at random times. However, despite these
issues it was concluded that this instrument was satisfactory for the experiments conducted in this research.

With the confidence achieved from the static and dynamic studies with one player, the introduction of multiple players into the test environment was undertaken to determine if multipath interference was significant under this new scenario. The multipath interference study was conducted on the received signal from a stationary transmitting beacon located at the top of the key while two basketball teams scrimmaged at game pace within the vicinity and around the beacon. It was shown that for most of the time (90%) the interference was minimal with signal fluctuations of approximately ±0.5 dB. Plots of level crossing rate and average fade duration for various received threshold levels confirmed a Rician fading environment for both guard, forward and centre players under normal game conditions.

An expanded investigation into the use of 3-axis accelerometer sensors and pattern signature analysis was applied to the act of passing the basketball ball. A study confirmed that a unique signal response of the ball passing process could be detected and therefore used to flag when the basketball is passed by the player with a wrist mounted accelerometer.

A simple prototype software application was developed to process the received field strength at each receiver and using the position estimation technique of trilateration it was proven to be capable of tracking a basketball player wearing a transmitting beacon.

Finally, a costing analysis on the prototype system using today’s costs was undertaken that confirmed that a low cost (less than AUD $10k outright) wireless RF signal player positioning system could be produced.

6.2 Further Research and Future Work

The study carried out in this thesis highlighted a number of areas that could be further explored to enhance and build upon the knowledge gained so far.

6.2.1 Development of a Complete System
The most important future work is the development of a complete system to apply to games in real time. The research covered so far provides a beginning foundation for this to begin. A full player tracking system will need to consider:

a) A dual RF beacon chest strap to be mounted on the front and back of the torso with no impairment to the player’s performance and a method to distinguish between the two beacons by the receiving system. Alternatively, one RF beacon feeding a body mounted antenna that covers both the front and rear directions.

b) A wireless network between the base side-line receivers and the tracking software system installed on one or more portable laptops and/or tablets;

c) Sensor communication information from a wrist mounted accelerometer sensor, contained in a wrist strap, for ball bouncing and passing detection information to the player tracking software system. Additional sensors in the wrist strap for heart rate, etc. may also be included in this information;

d) A method to distinguish between the beacons assigned to each player for player ID detection and the type of player information provided to the tracking system (e.g. basketball singlet number).

6.2.2 Transmitting Radiation Pattern Horizontal and Vertical Beam Width

The research showed that a transmitting horizontal 3 dB beam width of 120° was achievable from a body mounted beacon worn just under the chest. This arc value is suitable to enclose the required bearings towards the two sideline receive antennas for the majority of cases. Further investigation into increasing the beam width is required for those other cases.

The positional accuracy has a dependency on the variation of the received signal strength at the receiving antennas. This variation will occur at the edge of the main transmitting pattern lobe, either in the horizontal or vertical planes. This cannot be avoided for a directional pattern. However, the variation can be minimised by increasing the beam width so that the desired bearings are enclosed in the beam width before they reach these side lobe areas. Although the 3dB beam width for the transmitting body-worn beacon was shown to be 120° the usable beam width with minimal signal variation is in the order of 60° - 90°. The worst case scenario is when the subject is facing in a direction where only one of the two sideline receive antenna
bearings is enclosed in the usable beam width. Further investigation would be useful into the body worn transmitting beacon to increase the beam width and overcome this signal variation issue and achieve a minimum of 120° usable beamwidth while addressing those minority cases. This may involve the requirement of two transmitting beacons; one on the front and the other on back of the subject’s torso.

The research also highlighted a minimum horizontal beam width of 120° was required for the base receive antennas. The commercially available SuperPass 180° sector antennas also showed to work very well for the base receivers in the prototype system tests.

6.2.3 Reflection Properties of a Typical Indoor Basketball Court
No investigative study has been conducted on the reflection properties of a typical basketball court floor built to international specifications. Typically, these floors are made of highly polished hard wood panels with various construction methods for support underneath.

For the Two-Ray Prediction model determined in this research the reflection coefficient was taken from typical values used for hard wood. Experiments have been conducted on obtaining this value from various type of office floors previously in literature. A similar suitable experiment should be developed to analyse a number of basketball court floors to obtain a mean value for the reflection co-efficient.

6.2.4 Accelerometer Signal processing of Distinct Signatures for Ball Dribbling and Passing
This method for detecting the bounce of the ball, or for passing it, meant that a more informed system would be available to the coach or trainer. This and the tracking of players completes the foundation information needed in analysing offensive plays/drills by a team in basketball.

To implement this technique in practice further research is needed to undertake the processing of the signals including analysing the amplitude and time period of the signature parts and the signature shape itself. In detecting the bounce of a basketball it was found in the research that a more experienced player had significantly higher acceleration amplitudes, which are more than likely due to the confidence of the player and therefore a faster bouncing technique.
At present, the best location for the accelerometer sensor is on the wrist while the player transmitting beacon is located on either the front or back of the body's torso. This presents the issue on whether these signals should be passed to the sideline receiver together or as separate transmitted signals. Further study is needed in this area to facilitate the transfer of information from both sources to the player tracking system.

6.2.5 Improved technology and Suitable Operating Frequency

By the time this thesis is published, sensor technology and signal processing would have changed dramatically. The accelerometer sensor electronics and technology used in this research is already over 4 years old with the size of these units continuing to reduce. It is expected that a basketball player tracking system built using today's technology would have already undergone a number of significant upgrades through research in less than ten years.

One particular aspect of the basketball player tracking system that requires further research is the appropriate frequency allocation for the player tracking system. Already, the 2.4 GHz band is becoming congested with a myriad of devices such as smart phones, wireless modems (WiFi), baby monitors, computers, etc. Some of these devices have now migrated to the popular higher 5 GHz range to minimise this interference.

The research conducted in this thesis was based in an indoor environment at a frequency of 2.4 GHz (ISM band), with only minimal device presence and multichannel interference. A study needs to be undertaken to compile a list of devices likely to cause interference to the player tracking system in an indoor basketball court environment. From this a detailed interference field study needs to be undertaken. A suitable operating frequency or band can then be recommended.

The multiplexing of signals from all the players with ID codes also has to be carefully considered to provide a sufficient flow of system information in the network and prevent bottle necks. As video is not being transmitted the bandwidth requirements are reduced significantly, which is an advantage. However, there are up to possibly ten information data streams (5 players per team) that may need considered in the player tracking system.
6.2.6 Small Receive Antenna Size

The sideline receive antennas and their mounting structures need to have a very small form factor and almost be invisible to the basketball players. The reason for this is:

a) To significantly reduce the potential for injury to a player who runs into it. Obviously, all basic safety measures such as soft padding, etc. will be designed into the receive antenna structure; and

b) To remove any distraction to players, referees and even spectators.

The first reason can easily be accommodated with suitable padding. Padding can be seen on many of the televised basketball courts for the floor to backboard support structure. So, this is not uncommon. However, the second reason is a lot harder to solve as it involves the electromagnetic design of the receive antenna which is based on many aspects including the operating wavelength of the received RF signals. The trade-off of maximum efficiency and performance, matching impedance, etc. will need to be considered. Scope therefore exists to conduct further research into a suitable receive antenna and mounting structure that is significantly smaller in size. Given the general antenna rules that a large beamwidth requires a small aperture and a small beamwidth requires a large aperture, a specific design in this application will be primarily vertical. This is similar to the cellular telephone antennas in base stations where the horizontal beamwidth is 120 degrees and the vertical beamwidth is less than 10 degrees.

6.2.7 Final Design Information Metrics and Future Research

The need for a variety of information was highlighted to some extent in section 2.2.1. Further consideration will now be given here for the sorts of information that will be available to basketball coaches in the final design as well as potential areas that could be considered in future research.

Some useful metrics that could be employed for basketball coaches and will be considered for inclusion in the final design are as follows:

6.2.8 Ad hoc disruptions in play

Ad hoc disruptions in the structured offensive and defensive team “plays” by individual players so-called “creative license” on play-moves, either intentionally or unintentionally. These play variations can impact on the momentum of a teams’
confidence and lead to unnecessary turn-overs. This is especially true when co-
operation between players is based on the premises that there are rules, procedures
and strategies agreed to by each player and directed by the coach prior to play.

By monitoring the areas where players are expected to be in an agreed offensive or
defensive play it is possible to raise a flag to the coach if this does not occur.

6.2.9 Court time player loading.
On-court time is particularly important for player fatigue. This time does not only
include the time the player is physically on the court, but also considers the total
amount of energy expelled by the player due to actions such as: a) ball shooting; b)
rebounding effort; c) type of defence. i.e. high-intensity defence within the key, man-
to-man, full court press, half court press or zone defence; and d) falls and recovery
from either player-induced or non-player induced impact. All these actions affect the
player’s fatigue indicator.

The ability to measure some form of physical fatigue metric can be difficult.
However, it can be suggested that there is a relationship between fatigue and a
decrease in mean acceleration of a player over a given time. These loads could
potentially be monitored. Inertial sensors such as accelerometers built into the
transmitting beacon and/or located elsewhere on the body can be used in this instance.
As a basketball player I experienced this relationship on many occasions. A study
conducted by [95] also showed that over time physical performance averages can
differ based on the running demands of the player. Another metric of total distance
travelled throughout the course of a game by a player can also be linked to player
fatigue and is ultimately dependent on the player’s physical fitness level.

6.2.10 Player concentration.
Mental fatigue has been shown to decrease a player’s physical performance, is related
to the player’s cognitive ability and results from prolonged periods of cognitive
activity. The level of mental fatigue is also dependent on how intense the level of
concentration is required over a given period. An increase in the failure of a player to
be in the right position in a game play can be an indicator of mental fatigue.
6.2.11 Jump Heights.
The ability to jump is critical in rebounding (i.e. recovery of the basketball after it hits the backboard). The use of accelerometers can determine this metric and used by the coach in player position assignments. For example, a forward/centre player currently playing in a centre position may be swapped with another forward/centre player to improve rebounding for recovery of the basketball.

Some metrics require the use of sensors such as accelerometers. Initially, the proposed design will be based purely on position and tracking with the available metrics derived from these measurements. As the total distance travelled metric is required in the final design, a positioning accuracy of 1m or less is adequate at this time. This concurs with the accuracy requirements indicated previously (section 2.7).

6.2.12 Future Research.
Future system design research will look at the inclusion of inertial sensors (e.g. accelerometers), heart-rate monitoring, the use of body networks, coach-to-player voice communications and public viewing interactivity.

Also, a wide scope of potential research exists in using player tracking tools to assist mentally challenged (able to learn) children as mentioned briefly in the introduction. This area of research could include positive feedback systems to assist in the cooperation of the child in indoor sport.

6.3 Summary
This thesis has presented the research findings for a new technique into the tracking of an offensive basketball team player in an indoor sporting environment using well known wireless engineering concepts. The thesis has also presented a novel technique for determining if a player has bounced or passed the basketball using accelerometer sensors. These two aspects encompass the major contributions from the research conducted.

Three significant aspects have made this technique useable in an indoor basketball court environment. These are: (a) the absence of reflective objects except for players and referees; (b) the small propagation distances of less than 7.5 m; and c) the reduction in size of wearable sensors/beacons.
The thesis has highlighted that the proposed player tracking system has the potential to be used for other indoor sports that use the same indoor environment such as soccer, volleyball, tennis, etc. The system could also be installed at many indoor venues around the world where the construction of the court is built to international specifications.

Using accelerometer sensors for action detection such as dribbling, or passing a basketball will enrich the tracking information provided to the coach or referee.

The overall aim of this thesis was to prove the hypothesis that RF wireless signals and signal strength could be used to track basketball players in an indoor environment resulting in an engineering solution where the overall cost of such a system is low. This thesis has presented the findings necessary to prove that this can be achieved.

By introducing an information channel from the player to the coach through tracking using wearable sensor devices, the game of basketball will be enriched for the better of both players and team coaches or trainers. The research conducted in this thesis will lay a foundation for future technological advancements in the game of basketball and other indoor team sports in this area of player tracking information.
7. REFERENCES


8. APPENDICES

8.1 Appendix A: Wireless-based positioning system comparison

Very few detailed comparison tables on wireless positioning systems exist in published literature. Shown in Table A-1 is a detailed comparison from a study conducted by [9]. The reader should be aware that some of these systems no longer exist and that the original journal paper should be read for the source of the references indicated in this table.
<table>
<thead>
<tr>
<th>System/Solution</th>
<th>Wireless technologies</th>
<th>Positioning algorithm</th>
<th>Accuracy</th>
<th>Precision</th>
<th>Complexity</th>
<th>Scalability/Space dimension</th>
<th>Robustness</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Microsoft RADAR [35, 36]</td>
<td>WLAN, Received Signal Strength (RSS)</td>
<td>K-NN, Viterbi-like algorithm</td>
<td>3–5m</td>
<td>50% within around 2.5 m and 90% within around 5.9 m</td>
<td>Moderate</td>
<td>Good/2D,3D</td>
<td>Good</td>
<td>Low</td>
</tr>
<tr>
<td>Horus [37,38]</td>
<td>WLAN RSS</td>
<td>Probabilistic method</td>
<td>2m</td>
<td>90% within 2.1m</td>
<td>Moderate</td>
<td>Good/2D</td>
<td>Good</td>
<td>Low</td>
</tr>
<tr>
<td>DIT [41, 19]</td>
<td>WLAN RSS</td>
<td>MLP, SVM, etc</td>
<td>3m</td>
<td>90% within 5.12m for SVM, 90% within 5.40m for MLP</td>
<td>Moderate</td>
<td>Good/2D,3D</td>
<td>Good</td>
<td>Low</td>
</tr>
<tr>
<td>Ekahau [11]</td>
<td>WLAN RSS</td>
<td>Probabilistic method (Tracking assistant)</td>
<td>1m</td>
<td>50% within 2m</td>
<td>Moderate</td>
<td>Good/2D</td>
<td>Good</td>
<td>Low</td>
</tr>
<tr>
<td>SnapTrack [7]</td>
<td>Assisted GPS, TDOA+</td>
<td>Least Square/RWGH</td>
<td>5m-50m</td>
<td>50% within 25m</td>
<td>High</td>
<td>Good/2D,3D</td>
<td>Poor</td>
<td>Medium</td>
</tr>
<tr>
<td>WhereNet [14]</td>
<td>UHF TDOA</td>
<td>Least Square</td>
<td>2-3m</td>
<td>50% within 3m</td>
<td>Moderate</td>
<td>Very good / 2D,3D</td>
<td>Good</td>
<td>Low</td>
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<tr>
<td>Ubisense [13]</td>
<td>unidirectional UWB TDOA+ AOA</td>
<td>Least Square</td>
<td>15m</td>
<td>99% within 0.3m</td>
<td>Real time response (1Hz – 10 Hz)</td>
<td>2-4 sensors per cell (100-1000m); 1 UbiTag per object/2D,3D</td>
<td>Poor</td>
<td>Medium to High</td>
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<tr>
<td>Sapphire Dart [10]</td>
<td>unidirectional UWB TDOA</td>
<td>Least Square</td>
<td>&lt;0.3m</td>
<td>50% within 0.3m</td>
<td>response frequency (0.1Hz – 1Hz)</td>
<td>Good/2D, 3D</td>
<td>Poor</td>
<td>Medium to High</td>
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<tr>
<td>SmartLOCUS [8]</td>
<td>WLAN(RSS) + Ultrasonic(ROF)</td>
<td>N/A</td>
<td>2-15cm</td>
<td>50% within 15cm</td>
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<td>Good/2D</td>
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<td>Medium to High</td>
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<td>EIRIS [12]</td>
<td>IR + UHF (RSS) + LF</td>
<td>Based on PD</td>
<td>&lt;1m</td>
<td>50% within 1m</td>
<td>Medium to High</td>
<td>Good/2D</td>
<td>Poor</td>
<td>Medium to High</td>
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<td>SpotON [28]</td>
<td>Active RFID RSS</td>
<td>Ad-Hoc location</td>
<td>Depends on cluster size</td>
<td>N/A</td>
<td>Medium</td>
<td>Cluster at least 2 Tags/2D</td>
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<tr>
<td>LANDMARC [29]</td>
<td>Active RFID RSS</td>
<td>K-NN</td>
<td>&lt;2m</td>
<td>50% within 1m</td>
<td>Medium</td>
<td>Nodes placed densely</td>
<td>Poor</td>
<td>Low</td>
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<tr>
<td>TOPAZ [11]</td>
<td>Bluetooth (RSS) + IR</td>
<td>Based on PD</td>
<td>2m</td>
<td>95% within 10m</td>
<td>Positioning delay 15-30s</td>
<td>Nodes placed every 2-4 m</td>
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<td>Medium</td>
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<td>MFS [1]</td>
<td>QDMA</td>
<td>Ad-Hoc location</td>
<td>10m</td>
<td>50% within 10m</td>
<td>1s</td>
<td>Excellent/2D,3D</td>
<td>Good</td>
<td>Medium</td>
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<td>GPS [61]</td>
<td>DECT cellular system</td>
<td>Gaussian process (GP), ANN</td>
<td>7.5 m for GP; 7 m for ANN</td>
<td>50% within 7.2m</td>
<td>Medium</td>
<td>Good/2D</td>
<td>Good</td>
<td>Medium</td>
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<td>Robot-based [44, 46, 49]</td>
<td>WLAN (RSS)</td>
<td>Bayesian approach</td>
<td>1.5 m</td>
<td>Over 50% within 1.5m</td>
<td>Medium</td>
<td>Good/2D</td>
<td>Good</td>
<td>Medium</td>
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<td>MultiLoc [74]</td>
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<td>SMP</td>
<td>2.7 m</td>
<td>50% within 2.7m</td>
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<td>Good/2D</td>
<td>Good</td>
<td>Medium</td>
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<td>TIX [75]</td>
<td>WLAN (RSS)</td>
<td>TIX</td>
<td>5.4 m</td>
<td>50% within 5.4m</td>
<td>Low</td>
<td>Good/2D</td>
<td>Good</td>
<td>Medium</td>
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<td>UnitPoint 3D-ID [57]</td>
<td>UHF (40MHz) (RTOF)</td>
<td>Bayesian approach</td>
<td>1 m</td>
<td>50% within 1m</td>
<td>5s</td>
<td>Good/2D,3D</td>
<td>Good</td>
<td>Low</td>
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<td>GNM fingerprinting [31]</td>
<td>GSM cellular network (RSS)</td>
<td>Weighted ANN</td>
<td>5 m</td>
<td>80% within 10m</td>
<td>Medium</td>
<td>Excellent / 2D,3D</td>
<td>Good</td>
<td>Medium</td>
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8.2 Appendix B: Receive Antenna 1 - TP-LINK 2.4GHz Directional Antenna

2.4GHz 9dBi Indoor/Outdoor Directional Antenna
TL-ANT2409A / TL-ANT2409B

Features:
- Compliant with 802.11b/g/n, 2.4GHz wireless application
- 9dBi signal gain
- Directional operation
- 100cm low loss CFD-200 cable
- RP-SMA Female connector (TL-ANT2409A)
- N Type Female connector (TL-ANT2409B)

Description:
TP-LINK 9dBi 2.4GHz Indoor/Outdoor Directional Antenna, TL-ANT2409A & TL-ANT2409B are designed to strengthen the signal power, increase the wireless range, reduce dead spot, and give you reliability at high data rates for indoor/outdoor usage.

Radiation Patterns:
- V-Plane Co-Polarization Pattern
- H-Plane Co-Polarization Pattern
2.4GHz 9dBi Indoor/Outdoor Directional Antenna

**Specifications:**

- **Frequency Range:** 2.4GHz–2.5GHz
- **Impedance:** 50 Ohms
- **Gain:** 9 dBi
- **VSWR:** 1.92 : 1 Max
- **Polarization:** Linear, Vertical
- **Beamwidth (HPBW):** Horizontal 60°
  - Vertical 76°
- **Connector:** TL-ANT2409A: RP-SMA Female
  - TL-ANT2409B: N-Type Female (Jack)
- **Cable:** 100cm CFD-200
- **Radiation:** Directional
- **Application:** Indoor/Outdoor
- **Mount Style:** Pole Mount / Wall Mount
- **Dimensions (L x W x H mm):** 120 x 120 x 40 mm
- **Operating Temperature:** -10°C–60°C (14°F–140°F)
- **Storage Temperature:** -40°C–80°C (-40°F–176°F)
- **Operating Humidity:** 10%–90% non-condensing
- **Storage Humidity:** 5%–90% non-condensing
- **Standards:** RoHS, WEEE

**Diagram:**

- **TL-ANT2409A:** 2.4GHz 9dBi Indoor Directional Antenna
- **TL-ANT2409B:** 2.4GHz 9dBi Outdoor Directional Antenna

**Package:**
- 9dBi Panel Directional Antenna
- Installation mounting kits
- User Guide

**Optional Accessories:**
- 5meters Antenna Extension Cable
  - TL-ANT24EC55
- 3 Meters Antenna Extension Cable
  - TL-ANT24EC35
- Pigtail Cable
  - TL-ANT24PT
8.2.1 Radiation Patterns for TP-Link Antenna.
H-Plane Co-Polarization Pattern
### 8.3 Appendix C: Receive Antenna 2 - SuperPass 2.4GHz 180 Degree Sector Directional Antenna

**2.4GHz 3.5dBi 180 degree Sector Panel Antenna**

*Model Number: SPDG11H*

---

#### Technical Specifications

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<th>No</th>
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<tr>
<td>1</td>
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<td>Impedance</td>
<td>50 Ω</td>
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<td>3</td>
<td>VSWR (or Return Loss)</td>
<td>≤ 1.5:1 ( or ≥ 14dB)</td>
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<td>4</td>
<td>Gain</td>
<td>≥ 3.5dBi</td>
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<td>5</td>
<td>Polarization</td>
<td>Vertical, Linear</td>
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<td>3dB Horizontal Beamwidth</td>
<td>180°</td>
<td>See attached plot</td>
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<td>7</td>
<td>3dB Vertical Beamwidth</td>
<td>90°</td>
<td>See attached plot</td>
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<td>8</td>
<td>Front to Back Ratio</td>
<td>≥ 5.8dB</td>
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<td>Max. Power Input</td>
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<td>Connector</td>
<td>N/SMA Female, Bottom-Feed</td>
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<td>Appearance</td>
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<td>12</td>
<td>Size</td>
<td>52× 113× 30 [mm]</td>
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<td>13</td>
<td>Radome Material</td>
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<td>Radome Color</td>
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<td>Wind Loading (Frontal)</td>
<td>≥ 10Kg 200km/h</td>
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<td>18</td>
<td>Temperature Range</td>
<td>-45 to +75 °C</td>
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<td>19</td>
<td>Storage Temperature</td>
<td>-30 to +75 °C</td>
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<td>DC-Ground</td>
<td>Yes</td>
<td>Or Custom Design</td>
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<td>Mounting Hardware</td>
<td>Gear Clamp</td>
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<td>22</td>
<td>Life Expectancy</td>
<td>20 years</td>
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</table>
8.4 Appendix D: MatLab Code

8.4.1 Program code for half court paths.

clf();
clear;
clearvars;
hold off;

%==================================================================
% Calculation of received power versus distance over selected half court paths.
% by James A Kirkup 28/11/12
% support by David V Thiel
% School of Engineering - Griffith University
%==================================================================

ht = 1.45; % Transmit antenna height (m)
hr = 1.45; % Receive antenna height (m)
c = 3e8; % Speed of light m/s
freq = 2.400182e9; % Frequency in MHz
lambda = c/freq; % Wavelength in meters
k = 2*pi*freq/c; % wave number
kdeg = k*180/pi;
e0 = 8.85e-12; % Electrical permittivity of free space
sigma = 0.012; % wood conductivity S/m
er = 1.99; % relative permittivity of wood;
Eta0 = 120 * pi; % (Wave Impedance of Free Space (Eta) ~ 376.99111)

%==================================================================
% create an array for all the paths distance (m), Power (dBm)
%==================================================================
z_measV=[1.0-45.5;
1.0-46.0;
1.0-45.8;
1.0-45.5;
1.0-46.2;
1.0-46.1;
1.0-46.0;
1.0-45.5;
1.0-45.5;
1.0-45.2;
1.0-45.0;
1.5-49.1;
1.5-49.5;
1.5-49.5;
1.5-49.2;
1.5-49.9;
1.5-49.6;
1.5-49.6;
1.5-49.6;]
1.5 -49.5;
1.5 -49.5;
2.0 -53.2;
2.0 -54.2;
2.0 -53.2;
2.0 -53.8;
2.0 -53.8;
2.0 -53.75;
2.0 -53.5;
2.0 -53.0;
2.0 -53.0;
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2.5 -55.5;
2.5 -55.5;
2.5 -56.0;
2.5 -56.0;
2.5 -56.0;
2.5 -55.6;
2.5 -56.3;
%2.5 -53.0;
%2.5 -53.5;
%2.5 -53.0;
%2.5 -52.8;
3.0 -57.8;
3.0 -58.5;
3.0 -57.5;
3.0 -58.0;
3.0 -58.8;
3.0 -58.0;
3.0 -57.5;
3.0 -57.5;
3.0 -56.8;
3.0 -57.5;
3.0 -57.5;
3.5 -59.0;
3.5 -59.5;
3.5 -58.5;
%3.5 -60.5; %outlyer
3.5 -59.2;
3.5 -58.4;
3.5 -58.5;
3.5 -58.5;
3.5 -59.0;
3.5 -59.2;
3.5 -58.8;
4.0 -60.0;
%4.0 -62.0;
4.0 -60.0;
4.0 -60.5;
4.0 -60.5;
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</table>
\[
P_0 \text{dBm} = \frac{P_0}{10}; \quad \text{Power in } \text{dBm} \text{ received.}
\]
\[
P_0 = \frac{10^{P_0 \text{dBm}}}{10^{10}} \times 1 \text{e}^{-3}; \quad \text{Power in } \text{watts} \text{ received.}
\]
\[
E_0 = \sqrt{\frac{P_0 \cdot 120 \pi \cdot 4 \pi}{7.943 \lambda^2}} \quad \text{V/m field strength at antenna terminals}
\]
\[
P_0 \text{dBm} = 20 \log_{10}(E_0 \cdot 1000); \quad \% \text{Field strength at antenna terminal in } \text{dBm.}
\]
\[
d_0 = 1; \quad \% \text{Close in reference distance (m)}
\]

%=================================
% loop through data
%=================================

\[
\text{for } a = 1: \text{length}(z_{\text{measV}})
\]
\[
\text{tr_dist}(a) = z_{\text{measV}}(a,1);
\]
\[
z_{\text{meas}}(a) = z_{\text{measV}}(a,2);
\]
\[
z_{\text{measAdj}}(a) = z_{\text{measV}}(a,2)-9;
\]
\[
Pr = (10^{(z_{\text{measV}}(a,2)/10)})^{1 \text{e}^{-3}}; \quad \% \text{Watts}
\]
%From above equation
\[ Efs(a) = \text{abs} \left( \sqrt{\left( Pr \times 120 \pi \times 4 \pi \right) / \left( 7.943 \times (\lambda^2) \right)} \right); \quad \% \text{V/m} \]

\[ EdBm(a) = 20 \times \log_{10}(Efs(a) \times 1000); \quad \% \text{Received Field Strength dBm} \]

\( dd = \text{tr\_dist}(a); \quad \% \text{Direct ray distance (m)} \)

\( dr = \sqrt{(ht + hr)^2 + \text{tr\_dist}(a)^2}; \quad \% \text{Reflected ray (m)} \)

\( \log\_ratio(a) = \log_{10}(dd/d0); \)

\( z\_measV\_Adj(a) = z\_measV(a,2) - 9; \)

\( ec = \text{er} + \text{j} \left( \frac{\sigma}{2 \pi \times \text{freq} \times e0} \right); \)

\[ \text{ground\_incidence\_angle} = \text{atan}((ht + hr)/\text{tr\_dist}(a)); \quad \% \text{incidence angle on the ground for reflected ray} \]

\[ \text{horizontal\_angle} = \text{atand}((hr - ht)/\text{tr\_dist}(a)); \quad \% \text{angle between tx and rx for direct ray} \]

\%radiation pattern adjust
\%ground reflection signal loss due receive antenna vert pattern
\n\[ \text{ground\_incidence\_angle\_Deg} = \text{atanl}((ht + hr)/\text{tr\_dist}(a)); \]

\[ \text{if} \left( \text{ground\_incidence\_angle\_Deg} \leq 10 \right) \]
\[ \quad \text{Er\_loss} = 0; \]
\[ \text{elseif} \left( \text{ground\_incidence\_angle\_Deg} > 10 \land \text{ground\_incidence\_angle\_Deg} \leq 20 \right) \]
\[ \quad \text{Er\_loss} = -1; \]
\[ \text{elseif} \left( \text{ground\_incidence\_angle\_Deg} > 20 \land \text{ground\_incidence\_angle\_Deg} \leq 30 \right) \]
\[ \quad \text{Er\_loss} = -2; \]
\[ \text{elseif} \left( \text{ground\_incidence\_angle\_Deg} > 30 \land \text{ground\_incidence\_angle\_Deg} \leq 40 \right) \]
\[ \quad \text{Er\_loss} = -3; \]
\[ \text{elseif} \left( \text{ground\_incidence\_angle\_Deg} > 40 \land \text{ground\_incidence\_angle\_Deg} \leq 45 \right) \]
\[ \quad \text{Er\_loss} = -4; \]
\[ \text{elseif} \left( \text{ground\_incidence\_angle\_Deg} > 45 \land \text{ground\_incidence\_angle\_Deg} \leq 50 \right) \]
\[ \quad \text{Er\_loss} = -5; \]
\[ \text{elseif} \left( \text{ground\_incidence\_angle\_Deg} > 50 \land \text{ground\_incidence\_angle\_Deg} \leq 55 \right) \]
\[ \quad \text{Er\_loss} = -6; \]
\[ \text{elseif} \left( \text{ground\_incidence\_angle\_Deg} > 55 \land \text{ground\_incidence\_angle\_Deg} \leq 60 \right) \]
\[ \quad \text{Er\_loss} = -8; \]
\[ \text{elseif} \left( \text{ground\_incidence\_angle\_Deg} > 60 \land \text{ground\_incidence\_angle\_Deg} \leq 65 \right) \]
\[ \quad \text{Er\_loss} = -9; \]
\[ \text{elseif} \left( \text{ground\_incidence\_angle\_Deg} > 65 \land \text{ground\_incidence\_angle\_Deg} \leq 70 \right) \]
\[ \quad \text{Er\_loss} = -10; \]
\[ \text{elseif} \left( \text{ground\_incidence\_angle\_Deg} > 70 \land \text{ground\_incidence\_angle\_Deg} \leq 75 \right) \]
\[ \quad \text{Er\_loss} = -12; \]
\[ \text{elseif} \left( \text{ground\_incidence\_angle\_Deg} > 75 \land \text{ground\_incidence\_angle\_Deg} \leq 80 \right) \]
\[ \quad \text{Er\_loss} = -12; \]
\[ \text{elseif} \left( \text{vertical\_transmit\_angle\_to\_ground} > 80 \land \text{ground\_incidence\_angle\_Deg} \leq 85 \right) \]
\[ \quad \text{Er\_loss} = -13; \]
\[ \text{else} \]
\[ \quad \text{Er\_loss} = -14; \]
\[ \text{end} \]

\[ \text{Er\_loss} = 10^{\text{Er\_loss}/20}; \quad \% \text{Pattern loss} \]
%Ground reflection signal loss due transmit antenna vert pattern.
%As ht and hr heights are the same the angle of concern will be the same.

vertical_transmit_angle_to_ground = ground_incidence_angle_Deg;

if (vertical_transmit_angle_to_ground <= 10)
    Er_lossi = 0;
elseif (vertical_transmit_angle_to_ground > 10 && vertical_transmit_angle_to_ground <= 20)
    Er_lossi = -0.5;
elseif (vertical_transmit_angle_to_ground > 20 && vertical_transmit_angle_to_ground <= 30)
    Er_lossi = -1.1;
elseif (vertical_transmit_angle_to_ground > 30 && vertical_transmit_angle_to_ground <= 40)
    Er_lossi = -1.93;
elseif (vertical_transmit_angle_to_ground > 40 && vertical_transmit_angle_to_ground <= 45)
    Er_lossi = -2.79;
elseif (vertical_transmit_angle_to_ground > 45 && vertical_transmit_angle_to_ground <= 50)
    Er_lossi = -3.5;
elseif (vertical_transmit_angle_to_ground > 50 && vertical_transmit_angle_to_ground <= 55)
    Er_lossi = -4.43;
elseif (vertical_transmit_angle_to_ground > 55 && vertical_transmit_angle_to_ground <= 60)
    Er_lossi = -5.57;
elseif (vertical_transmit_angle_to_ground > 60 && vertical_transmit_angle_to_ground <= 65)
    Er_lossi = -7.0;
elseif (vertical_transmit_angle_to_ground > 65 && vertical_transmit_angle_to_ground <= 70)
    Er_lossi = -8.93;
elseif (vertical_transmit_angle_to_ground > 70 && vertical_transmit_angle_to_ground <= 75)
    Er_lossi = -10.8;
elseif (vertical_transmit_angle_to_ground > 75 && vertical_transmit_angle_to_ground <= 80)
    Er_lossi = -11.35;
elseif (vertical_transmit_angle_to_ground > 80 && vertical_transmit_angle_to_ground <= 85)
    Er_lossi = -11.85;
else
    Er_lossi = -12.0;
end

Er_lossi = 10^(Er_lossi/20); %Pattern loss

Z3 = sqrt((ec - (cos(ground_incidence_angle)*cos(ground_incidence_angle))))/ec;
\[ Z_4 = \sqrt{ec - (\cos(\text{ground\_incidence\_angle}) \times \cos(\text{ground\_incidence\_angle}))}; \]

% reflection coefficient variations
% Siwiak et al., Goldsmith
Ref1_Coeff3 = (\sin(\text{ground\_incidence\_angle}) - Z_3) / (\sin(\text{ground\_incidence\_angle}) + Z_3);
% J.D. Parson's, Rappaport, Anderson, et al.
Ref1_Coeff4 = (ec \times \sin(\text{ground\_incidence\_angle}) - Z_4) / (ec \times \sin(\text{ground\_incidence\_angle}) + Z_4);
% use this one

Ed = (E0/dd) \times \exp\left(\frac{-j \times dd \times k}{2}\right); % direct Signal
Er = (E0/dr) \times \text{Ref1\_Coeff4} \times \exp\left(\frac{-j \times dr \times k}{2}\right); % reflected Signal

% E_{total} = Ed + Er \times \sin(\text{ground\_incidence\_angle}) \times \text{Er\_loss};
% V/m - there is no adjustment for Ed as heights are the same ie \cos(0) = 1
E_{total} = Ed + Er \times \text{Er\_lossi} \times \text{Er\_loss};

Etota = \text{abs}(E_{total}); % V/m
Power(a) = 20 \times \log_{10}(Etota \times 1000);

Pr = \left(\frac{E_{total}^2}{(120 \times \text{pi})}\right) \times \left(\frac{(7.943 \times (\lambda^2))}{(4 \times \text{pi})}\right); % Power Watts at receiver terminal
PrdB(a) = 10 \times \log_{10}\left(\frac{Pr}{1 \times 10^{-3}}\right); % dBm
error(a) = Power(a) - EdBm(a);
sqrerror(a) = error(a) \times error(a);

end

%=======================================
% Find variance and standard deviation of half court paths for 2 Ray Model
%=======================================

sumsqr = \text{sum(sqrerror)};
sigma_squared = sumsqr / \text{length(z\_measV)}; % MSE
s = \text{sym}(sigma_squared);
ss = \text{double}(s); % variance
sig = \text{sqrt}(ss); % standard deviation

%=======================================
% figure(1);
% Scatter Plot of Received Signal Strength vs Distance
%=======================================

figure(1);
set(gca, 'LooseInset', get(gca, 'TightInset'));
semilogx(tr_dist, EdBm, 'k*');
xlabel('T-R Separation Distance (m) log(d)', 'fontsize', 16);
ylabel('E_{total} Received (dBm)', 'fontsize', 16);
h = legend('Measured');
set(h, 'fontsize', 14);
title('Scatter Plot of Received Signal Strength vs Distance', 'fontsize', 14);
hold on

%=======================================
% Determine the slope (or exponent) of the Two-Ray model by using polyfit
%===============================================
polyfit(tr_dist, PrdB, 1)

n=sym('n');

%=======================================================================
% Minimum mean square error for Two-Ray Model path loss of half court
% do=1m close in reference distance
%=======================================================================
for i=1:length(z_measV)
p2(i)=P0dBm - n*abs(P0dBm - PrdB(i));
j1(i)=z_measV(i,2)^2-(2*z_measV(i,2)*p2(i))+p2(i)^2;  %%(a-b)^2 = a^2 - 2ab + b^2
end
j1=sum(j1)
j_derivative=diff(j1,1); %Differentiate
n_MMSE=solve(j_derivative)
a=sym(n_MMSE)
b=double(a)

%=======================================================================
% Scatter Plot of Measured Received Power vs Distance
%=======================================================================
figure(2);
%Received Power Scatter Plot log distance
set(gca, 'LooseInset', get(gca, 'TightInset'));
semilogx(tr_dist, z_meas, 'k*');
xlabel('T-R Separation Distance (m) log(d)');
ylabel('Recieved Power (dBm) @ receiver');
hold on;

for i=1:length(z_measV)
p2(i)=P0dBm - abs(P0dBm - PrdB(i));
j1(i)=z_measV(i,2)^2-(2*z_measV(i,2)*p2(i))+p2(i)^2;  %%(a-b)^2 = a^2 - 2ab + b^2
end

%=======================================================================
% Plot of Two-Ray Predicted Received Power vs Distance
%=======================================================================
figure(3);
set(gca, 'LooseInset', get(gca, 'TightInset'));
semilogx(tr_dist, p2, 'k*');
xlabel('T-R Separation Distance (m) log(d)');
ylabel('Recieved Power (dBm) @ receiver');
h2=legend('Two-Ray Predicted');
title('Plot of Two-Ray Predicted Received Power vs Distance', 'fontsize',14);
hold on;

%====================================
%Free Space log distance path loss model
%====================================

% find slope exponent for free space model for half court paths
% do=1m close in reference distance
%====================================

n = sym('n');
for i=1:length(z_measV)
    pf(i)= P0dBm -(10*n*log10(tr_dist(i)/d0));
    j1(i)=z_measV(i,2)^2-(2*z_measV(i,2)*pf(i))+pf(i)^2; %%(a-b)^2 = a^2 - 2ab + b^2
end
j1=sum(j1);
j_derivative= diff(j1,1);
n_MMSE=solve(j_derivative);
a=sym(n_MMSE);
bfs=double(a) %the value of n

%====================================
% find variance and standard deviation of half court paths
%====================================

for i=1:length(z_measV)
    pfreeSpace(i)= P0dBm -(20*log10(tr_dist(i)/d0)); %dBm
    pf(i)=P0dBm -(10*bfs*log10(tr_dist(i)/d0)); %dBm
    Pr = (10^(pf(i)/10))*1e-3; %Watts
    E(i) = abs(sqrt((Pr*120*pi*4*pi)/(7.943*(lambda^2)))); %V/m
    j1(i)=z_measV(i,2)^2-(2*z_measV(i,2)*pf(i))+pf(i)^2; %%(a-b)^2 = a^2 - 2ab + b^2
end
j1=sum(j1);
sigma_squared = j1/length(z_measV);
s = sym(sigma_squared); %variance
ss = double(s);
sig = sqrt(ss); %standard deviation
c=sym(sig);
dfs=double(c)

%figure(4);
%Field strength
%set(gca, 'LooseInset', get(gca, 'TightInset'));
%loglog(tr_dist,abs(Etotal),'r^',tr_dist,Efs,'k*',tr_dist,E,'o');
%xlabel('T-R Separation Distance (m) log(x)');
%ylabel('Received Field Strength (mV/m)','fontsize',16);
%legend('Two-Ray', 'measured', 'Free Space');
%title('Comparison of Free Space and Two-Ray Path Loss Models');
%hold on;

%=====================================  
% Plot of Comparison of Free Space and Two-Ray Path Loss  
% Models against measured with line of best fit.  
%=====================================  
figure(5);  
%Power  
set(gca, 'LooseInset', get(gca, 'TightInset'));  
semilogx(tr_dist, PrdB, 'r^', tr_dist, z_meas, 'k*', tr_dist, pf, 'o', tr_dist, pfreeSpace, 'x');  
xlabel('T-R Separation Distance (m) log(d)', 'fontsize', 16);  
ylabel('Received Power (dBm) @ receiver', 'fontsize', 16);  
h=legend('Two-Ray', 'Measured', 'Free Space Model', 'Free Space');  
set(h, 'fontsize', 14);  
title('Comparison of Free Space and Two-Ray Path Loss Models', 'fontsize', 14);  
hold on;  

%Free Space line of best fit  
x=[1.0:1.0:10.0];  
y=-46.5-10*bfs*log10(x);  
semilogx(x,y);  
hold on;  

% figure(6);  
% %Power  
% %set(gca, 'LooseInset', get(gca, 'TightInset'));  
% %semilogx(tr_dist, p2, 'r^', tr_dist, z_meas, 'k*', tr_dist, pf, 'o');  
% %xlabel('T-R Separation Distance (m) log(d)', 'fontsize', 16);  
% %ylabel('Received Power (dBm) @ receiver', 'fontsize', 16);  
% %h=legend('Two-Ray', 'Measured', 'Free Space');  
% %set(h, 'fontsize', 14);  
% %title('Comparison of Free Space and Two-Ray Path Loss Models', 'fontsize', 14);  
% %hold on;  
%
%
%
% %Free Space line of best fit  
%x=[1.0:1.0:10.0];  
%y=-46.5-10*bfs*log10(x);  
%semilogx(x,y);  
%hold on;  

%Two Ray line of best fit  
x=[1.0:1.0:10.0];  
p=-46.6031,-49.9203,-52.4545,-54.6064,-56.1647,-57.4507,...  
%-58.5664,-59.6316,-60.4695,-61.2944,-61.7933,-63.5191,-62.7190,...  
%-63.4374,-65.9489,-65.9945,-64.4576,-64.3120,-65.7011];  
%y=P0dBm - b*abs(P0dBm - p);  
%semilogx(x,y,'-r^');  
%hold on;
8.4.2 Program code for Uncertainly Ellipse Plots.

% Position error analysis of trialateration system.
% Determine and plot uncertainty ellipses between base receivers
% Author: James Kirkup.
% Date: February 2014

clf();
clear;
clearvars;
hold off;

% Base receiver antenna positions
Rx1 = [-0.5,3.5];
Rx2 = [1.2,8.0];
Rx3 = [6.2,8.0];

% Format Figure
% Create a border rectangle
rectangle('Position',[0.0,0.0,14.0,7.5], 'LineStyle','-','LineWidth',2,'EdgeColor','k')
axis([-3.0 17.0 -3.0 10.5])
set(gca, 'LooseInset', get(gca, 'TightInset'));
% grid
xlabel('East(m)','fontsize',16);
ylabel('North(m)','fontsize',16);
set(gca,'XTick',[0:1:14]);
set(gca,'YTick',[0:1:9]);
hold on;

% Horizontal grid
x=0:1.0:14;
y=0:0.5:7.5;
for k = 1:length(y)
    line([x(1) x(end)], [y(k) y(k)],'Color','k','LineWidth',0.5,'LineStyle',':')
end

% Vertical grid
for k = 1:length(x)
    line([x(k) x(k)], [y(1) y(end)],'Color','k','LineWidth',0.5,'LineStyle',':')
end

hold on;
% Plot receiving locations
x1=[-0.5,3.5];
% x=0.5;
% y=2.45;
plot(Rx1(1), Rx1(2), '-.r^')
text(x1(1)-1.0, x1(2)+1.0, 'Rx Ant 1', 'Color', 'k', 'FontSize', 14);
text(x1(1)-1.0, x1(2)+0.5, '(-0.5,3.5)', 'Color', 'k', 'FontSize', 14);
x2=[1.2,8.0];
% x=1.2;
% y=8.5;
plot(Rx2(1), Rx2(2), '-.r^')
text(Rx2(1)+0.2, Rx2(2), ' Rx Ant 2 (1.2,8.0)', 'Color', 'k', 'FontSize', 14);
x3=[6.2,8.0];
% x=6.2;
% y=8.5;
plot(Rx3(1), Rx3(2), '-.r^')
text(Rx3(1)+0.2, Rx3(2), ' Rx Ant 3 (6.2,8.0)', 'Color', 'k', 'FontSize', 14);

xlim([-1.0,15.0])
ylim([-1.0,11.5])
hold on;

% Basketball Key
x=0:0.1:5.8;
y=2.45;
plot([x(1) x(end)], [y y], 'Color', 'k', 'LineWidth',2);
hold on;
x=5.8;
y=0:0:0.01:2.45;
plot([x x], [y(1) y(end)], 'Color', 'k', 'LineWidth',2);

th = linspace( pi/2, 0, 100);
R = 1.8; % or whatever radius you want
x = R*cos(th) + 5.8;
y = R*sin(th) + 0;
plot(x,y,'Color', 'k', 'LineWidth',2); axis equal;

x=1.5;
y=1.5;
text(x, y, 'Basketball Key', 'Color', 'k', 'FontSize', 14); % 'FontSize',14);

th = linspace( pi/2, pi, 100);
R = 1.8; % or whatever radius you want
x = R*cos(th) + 14;
y = R*sin(th) + 0;
plot(x,y,'Color', 'k', 'LineWidth',2); axis equal;

text(11, 2.5, 'Centre Circle', 'Color', 'k', 'FontSize', 14); % 'FontSize',14);

% array of sample court positions (x, y)
courtPos=[2.0, 6.5]
%========================================
%Positional errors determined from received power vs distance
%measurements.
%========================================
Rx_error = [0.2, 0.3, 0.5, 0.75]; %+/- errors for distances 0 to 2m, 2 to 4m, 4 to 7.5m and 7.5 to 9m respectively.

for i=1:length(courtPos)

% Determine distance to courtPos from Rx
if (courtPos(i,1) < Rx3(1)) && (courtPos(i,2) > Rx1(2))
    DistRx1_X = courtPos(i,1) - Rx1(1);
    DistRx1_Y = courtPos(i,2) - Rx1(2);
    DistRx1 = sqrt(DistRx1_X^2 + DistRx1_Y^2);
    DistRx2_X = courtPos(i,1) - Rx2(1);
    DistRx2_Y = Rx2(2) - courtPos(i,2);
    DistRx2 = sqrt(DistRx2_X^2 + DistRx2_Y^2);
    DistRx3_X = Rx3(1) - courtPos(i,1);
    DistRx3_Y = Rx3(2) - courtPos(i,2);
    DistRx3 = sqrt(DistRx3_X^2 + DistRx3_Y^2);
    CP=1.0
end

if (courtPos(i,1) > Rx3(1)) && (courtPos(i,2) > Rx1(2))
    DistRx1_X = courtPos(i,1) - Rx1(1);
    DistRx1_Y = courtPos(i,2) - Rx1(2);
    DistRx1 = sqrt(DistRx1_X^2 + DistRx1_Y^2);
    DistRx2_X = courtPos(i,1) - Rx2(1);
    DistRx2_Y = Rx2(2) - courtPos(i,2);
    DistRx2 = sqrt(DistRx2_X^2 + DistRx2_Y^2);
    DistRx3_X = courtPos(i,1) - Rx3(1);
    DistRx3_Y = Rx3(2) - courtPos(i,2);
    DistRx3 = sqrt(DistRx3_X^2 + DistRx3_Y^2);
    CP=2.0
end

if (courtPos(i,1) < Rx3(1)) && (courtPos(i,2) < Rx1(2))
    DistRx1_X = courtPos(i,1) - Rx1(1);
DistRx1_Y = Rx1(2) - courtPos(i,2); 
DistRx1 = sqrt(DistRx1_X^2 + DistRx1_Y^2);

DistRx2_X = courtPos(i,1) - Rx2(1); 
DistRx2_Y = Rx2(2) - courtPos(i,2); 
DistRx2 = sqrt(DistRx2_X^2 + DistRx2_Y^2);

DistRx3_X = Rx3(1) - courtPos(i,1); 
DistRx3_Y = Rx3(2) - courtPos(i,2); 
DistRx3 = sqrt(DistRx3_X^2 + DistRx3_Y^2); 
CP=3.0
end

%Ellipse errors are dependent on distance to location.
%Determine major or minor ellipse error and ellipse angle rotation
%between Rx1 and Rx3
%=================================================
% Ellipse formed from Rx1 and Rx3
%=================================================

if (courtPos(i,1) > Rx3(1)) && (courtPos(i,2) < Rx1(2))
    DistRx1_X = courtPos(i,1) - Rx1(1); 
    DistRx1_Y = Rx1(2) - courtPos(i,2); 
    DistRx1 = sqrt(DistRx1_X^2 + DistRx1_Y^2);

    DistRx2_X = courtPos(i,1) - Rx2(1); 
    DistRx2_Y = Rx2(2) - courtPos(i,2); 
    DistRx2 = sqrt(DistRx2_X^2 + DistRx2_Y^2);

    DistRx3_X = courtPos(i,1) - Rx3(1); 
    DistRx3_Y = Rx3(2) - courtPos(i,2); 
    DistRx3 = sqrt(DistRx3_X^2 + DistRx3_Y^2); 
    CP=4.0
end

Major1_3=0.0; 
Minor1_3=0.0; 
Major2_3=0.0; 
Minor2_3=0.0; 
Major1_2=0.0; 
Minor1_2=0.0;

if DistRx1 > DistRx3  % therefore assign DistRx1 to align with the major axis
    if (DistRx1 > 7.5) && (DistRx1 <= 9)
        Major1_3 = Rx_error(4);
    elseif (DistRx1 > 4.0) && (DistRx1 <= 7.5)
        Major1_3 = Rx_error(3);
    elseif (DistRx1 > 2.0) && (DistRx1 <= 4.0)
        Major1_3 = Rx_error(2);
elseif (DistRx1 <= 2.0)
    Major1_3 = Rx_error(1);
end
if (DistRx3 > 7.5) && (DistRx3 <= 9)
    Minor1_3 = Rx_error(4);
elseif (DistRx3 > 4.0) && (DistRx3 <= 7.5)
    Minor1_3 = Rx_error(3);
elseif (DistRx3 > 2.0) && (DistRx3 <= 4.0)
    Minor1_3 = Rx_error(2);
elseif (DistRx3 <= 2.0)
    Minor1_3 = Rx_error(1);
end

%Major axis magnitude 'a' becomes the same as the major error
a = Major1_3;
if courtPos(i,1) < Rx3(1)  % for position either above or below Rx1
    %Determine ellipse angle between major axis and horizontal for courtPos(i,1) < Rx3(1)
    theta1_3_Maj = atand(DistRx1_Y/DistRx1_X);
    %Determine X1 and Y1 for point on ellipse from Minor Rx1
    %determine angle between horizontal and point on ellipse bearing
    %towards Rx1
    theta1_3_Point_Bearing = atand(DistRx3_Y/DistRx3_X);
    %determine angle between major axis and point on ellipse
    if courtPos(i,2) > Rx1(2)
        theta = theta1_3_Point_Bearing - theta1_3_Maj;
    elseif courtPos(i,2) < Rx1(2)
        theta = theta1_3_Point_Bearing + theta1_3_Maj;
    end
elseif courtPos(i,1) > Rx3(1)  % for position below Rx1
    %Determine ellipse angle between major axis and horizontal for courtPos(i,1) < Rx3(1)
    theta1_3_Maj = atand(DistRx1_Y/DistRx1_X);
    %Determine X1 and Y1 for point on ellipse from Minor Rx1
    %determine angle between horizontal and point on ellipse bearing
    %towards Rx1
    theta1_3_Point_Bearing = atand(DistRx3_Y/DistRx3_X);
    %determine angle between major axis and point on ellipse
    if courtPos(i,2) > Rx1(2)
        theta = theta1_3_Point_Bearing + theta1_3_Maj;
    elseif courtPos(i,2) < Rx1(2)
        theta = theta1_3_Point_Bearing - theta1_3_Maj;
    end
end
X1 = Minor1_3 * cosd(theta);
Y1 = Minor1_3 * sind(theta);

%Determine minor axis magnitude b from point X1,Y1 on ellipse
% b = a * | y1 | / sqrt(a^2 - x1^2)

b1 = Major1_3 * abs(Y1);
b2 = sqrt(abs(Major1_3^2 - X1^2));
b = b1/b2; %minor axis magnitude

%Determine ellipse angle for major axis to rotate ellipse
if courtPos(i,2) > Rx1(2)
    theta1_3 = -atand(DistRx1_Y/DistRx1_X);
elseif courtPos(i,2) < Rx1(2)
    theta1_3 = atand(DistRx1_Y/DistRx1_X);
else
    theta1_3 = 0;
end
end

if DistRx3 > DistRx1 % therefore assign DistRx3 to align with major axis
    if (DistRx3 > 7.5) && (DistRx3 <= 9)
        Major1_3 = Rx_error(4);
    elseif (DistRx3 > 4.0) && (DistRx3 <= 7.5)
        Major1_3 = Rx_error(3);
    elseif (DistRx3 > 2.0) && (DistRx3 <= 4.0)
        Major1_3 = Rx_error(2);
    elseif (DistRx3 <= 2.0)
        Major1_3 = Rx_error(1);
    end
end

if DistRx1 > 7.5 && (DistRx1 <= 9)
    Minor1_3 = Rx_error(4);
elseif (DistRx1 > 4.0) && (DistRx1 <= 7.5)
    Minor1_3 = Rx_error(3);
elseif (DistRx1 > 2.0) && (DistRx1 <= 4.0)
    Minor1_3 = Rx_error(2);
elseif (DistRx1 <= 2.0)
    Minor1_3 = Rx_error(1);
end

%Major axis magnitude 'a' becomes the same as the major error
a = Major1_3;

if courtPos(i,1) < Rx3(1) % for position either above or below Rx1
    %Determine ellipse angle between major axis and horizontal for courtPos(i,1) < Rx3(1)
    theta1_3_Maj = atand(DistRx3_Y/DistRx3_X);

    %Determine X1 and Y1 for point on ellipse from Minor Rx1
    %determine angle between horizontal and point on ellipse bearing
    %(towards Rx1)
theta1_3_Point_Bearing = atand(DistRx1_Y/DistRx1_X);

%determine angle between major axis and point on ellipse
theta = theta1_3_Maj - theta1_3_Point_Bearing;
elseif courtPos(i,1) > Rx3(1) % for position below Rx1
%Determine ellipse angle between major axis and horizontal for courtPos(i,1) < Rx3(1)
theta1_3_Maj = atand(DistRx3_X/DistRx3_Y);

%Determine X1 and Y1 for point on ellipse from Minor Rx1
%determine angle between horizontal and point on ellipse bearing
%(towards Rx1)
theta1_3_Point_Bearing = atand(DistRx1_X/DistRx1_Y);

%determine angle between major axis and point on ellipse
theta = theta1_3_Point_Bearing - theta1_3_Maj;
end

X1 = Minor1_3 * cosd(theta);
Y1 = Minor1_3 * sind(theta);

%determine minor axis magnitude b from point X1,Y1 on ellipse
% b = a * | y1 | / sqrt(a^2 - x1^2)

b1 = Major1_3 * abs(Y1);
b2 = sqrt(abs(Major1_3^2 - X1^2));
b = b1/b2; %minor axis magnitude

%determine ellipse angle for major axis
if courtPos(i,1) < Rx3(1)
    theta1_3 = -atand(DistRx3_Y/DistRx3_X);
elseif courtPos(i,1) > Rx3(1)
    theta1_3 = -90 - atand(DistRx3_X/DistRx3_Y);
else
    theta1_3=0;
end

%Create an ellipse

%# ellipse centered at (courtPos(1),courtPos(2)) with axes length
%# major, minor, rotated theta degrees
%# (drawn using the default N=36 points)

p = calculateEllipse(courtPos(i,1), courtPos(i,2), a, b, theta1_3);
%p = calculateEllipse(courtPos(i,1), courtPos(i,2), Major1_3, Minor1_3, theta1_3);
plot(p(:,1), p(:,2), 'b:', 'LineWidth',3.5);
hold on;

%Determine major or minor ellipse error and ellipse angle rotation
%between Rx2 and Rx3
if DistRx2 > DistRx3  % therefore assign DistRx2 to align with major axis
    if (DistRx2 > 7.5) && (DistRx2 <= 9)
        Major2_3 = Rx_error(4);
    elseif (DistRx2 > 4.0) && (DistRx2 <= 7.5)
        Major2_3 = Rx_error(3);
    elseif (DistRx2 > 2.0) && (DistRx2 <= 4.0)
        Major2_3 = Rx_error(2);
    elseif (DistRx2 <= 2.0)
        Major2_3 = Rx_error(1);
    end
    if (DistRx3 > 7.5) && (DistRx3 <= 9)
        Minor2_3 = Rx_error(4);
    elseif (DistRx3 > 4.0) && (DistRx3 <= 7.5)
        Minor2_3 = Rx_error(3);
    elseif (DistRx3 > 2.0) && (DistRx3 <= 4.0)
        Minor2_3 = Rx_error(2);
    elseif (DistRx3 <= 2.0)
        Minor2_3 = Rx_error(1);
    end
    %Major axis magnitude 'a' becomes the same as the major error
    a = Major2_3;

    %Determine ellipse angle between major axis and horizontal for courtPos(i,1)
    theta2_3_Maj = atand(DistRx2_Y/DistRx2_X);

    %Determine X1 and Y1 for point on ellipse from Minor Rx1
    %determine angle between horizontal and point on ellipse bearing
    %(towards Rx1)
    theta2_3_Point_Bearing = atand(DistRx3_Y/DistRx3_X);

    %determine angle between major axis and point on ellipse
    if courtPos(i,1) > Rx3(1)
        theta = theta2_3_Point_Bearing - theta2_3_Maj;
    elseif courtPos(i,1) < Rx3(1)
        theta = 180 - theta2_3_Point_Bearing - theta2_3_Maj;
    end
    X1 = Minor2_3 * cosd(theta);
    Y1 = Minor2_3 * sind(theta);

    %Determine minor axis magnitude b from point X1,Y1 on ellipse
    % b = a * | y1 | / sqrt(a^2 - x1^2)
    b1 = Major2_3 * abs(Y1);
    b2 = sqrt(abs(Major2_3^2 - X1^2));
    b = b1/b2;  %minor axis magnitude
% Determine ellipse angle for major axis to rotate ellipse
theta2_3 = atand(DistRx2_Y/DistRx2_X);
end

if DistRx3 > DistRx2  % therefore assign DistRx3 to align with major axis
  if (DistRx3 > 7.5) && (DistRx3 <= 9)
    Major2_3 = Rx_error(4);
  elseif (DistRx3 > 4.0) && (DistRx3 <= 7.5)
    Major2_3 = Rx_error(3);
  elseif (DistRx3 > 2.0) && (DistRx3 <= 4.0)
    Major2_3 = Rx_error(2);
  elseif (DistRx3 <= 2.0)
    Major2_3 = Rx_error(1);
  end
  if (DistRx2 > 7.5) && (DistRx2 <= 9)
    Minor2_3 = Rx_error(4);
  elseif (DistRx2 > 4.0) && (DistRx2 <= 7.5)
    Minor2_3 = Rx_error(3);
  elseif (DistRx2 > 2.0) && (DistRx2 <= 4.0)
    Minor2_3 = Rx_error(2);
  elseif (DistRx2 <= 2.0)
    Minor2_3 = Rx_error(1);
  end
% Major axis magnitude 'a' becomes the same as the major error
a = Major2_3;

% Determine ellipse angle between major axis and horizontal for courtPos(i,1) < Rx3(1)
theta2_3_Maj = atand(DistRx3_Y/DistRx3_X);

% Determine X1 and Y1 for point on ellipse from Minor Rx1
% determine angle between horizontal and point on ellipse bearing
% (towards Rx1)
theta2_3_Point_Bearing = atand(DistRx2_Y/DistRx2_X);

% determine angle between major axis and point on ellipse
if courtPos(i,1) > Rx2(1)
  theta = 180 - theta2_3_Point_Bearing - theta2_3_Maj;
elseif courtPos(i,1) < Rx2(1)
  theta = theta2_3_Point_Bearing - theta2_3_Maj;
end
X1 = Minor2_3 * cosd(theta);
Y1 = Minor2_3 * sind(theta);

% Determine minor axis magnitude b from point X1,Y1 on ellipse
% b = a * | y1 | / sqrt(a^2 - x1^2)
b1 = Major2_3 * abs(Y1);
b2 = sqrt(abs(Major2_3^2 - X1^2));
b = b1/b2;  % minor axis magnitude
% Determine ellipse angle for major axis to rotate ellipse
theta2_3 = -atan(DistRx3_Y/DistRx3_X);
end

% Create an ellipse
p2 = calculateEllipse(courtPos(i,1), courtPos(i,2), a, b, theta2_3);
plot(p2(:,1), p2(:,2), 'r:', 'LineWidth', 2.5);

% Determine major or minor ellipse error and ellipse angle rotation
% between Rx1 and Rx2

%=================================================================================
% Ellipse formed from Rx1 and Rx2
%=================================================================================

if DistRx1 > DistRx2 % therefore assign DistRx1 to align with major axis
    if (DistRx1 > 7.5) && (DistRx1 <= 9)
        Major1_2 = Rx_error(4);
    elseif (DistRx1 > 4.0) && (DistRx1 <= 7.5)
        Major1_2 = Rx_error(3);
    elseif (DistRx1 > 2.0) && (DistRx1 <= 4.0)
        Major1_2 = Rx_error(2);
    elseif (DistRx1 <= 2.0)
        Major1_2 = Rx_error(1);
    end
if (DistRx2 > 7.5) && (DistRx2 <= 9)
    Minor1_2 = Rx_error(4);
elseif (DistRx2 > 4.0) && (DistRx2 <= 7.5)
    Minor1_2 = Rx_error(3);
elseif (DistRx2 > 2.0) && (DistRx2 <= 4.0)
    Minor1_2 = Rx_error(2);
elseif (DistRx2 <= 2.0)
    Minor1_2 = Rx_error(1);
end

% Major axis magnitude 'a' becomes the same as the major error
a = Major1_2;

if courtPos(i,1) < Rx2(1) % for position either above or below Rx1
    theta1_2_Maj = atand(DistRx1_Y/DistRx1_X);

    % Determine angle between major axis and horizontal for courtPos(i,1) < Rx3(1)
    % %theta1_2_Maj = atand(DistRx3_Y/DistRx3_X);

    % Determine X1 and Y1 for point on ellipse from Minor Rx1
    % Determine angle between horizontal and point on ellipse bearing
    % (towards Rx1)
    theta1_2_Point_Bearing = atand(DistRx2_Y/DistRx2_X);

    % Determine angle between major axis and point on ellipse
    if courtPos(i, 2) > Rx1(2)
        theta = theta1_2_Point_Bearing - theta1_2_Maj;
    end
end
elseif courtPos(i, 2) < Rx1(2)
    theta = theta1_2_Point_Bearing + theta1_2_Maj;
end

elseif courtPos(i, 1) > Rx2(1) % for position below Rx1
    % Determine ellipse angle between major axis and horizontal for courtPos(i, 1) < Rx2(1)
    theta1_2_Maj = atand(DistRx1_Y/DistRx1_X);

    % Determine X1 and Y1 for point on ellipse from Minor Rx1
    % determine angle between horizontal and point on ellipse bearing
    % (towards Rx1)
    theta1_2_Point_Bearing = atand(DistRx2_Y/DistRx2_X);

    % determine angle between major axis and point on ellipse
    if courtPos(i, 2) > Rx1(2)
        theta = theta1_2_Point_Bearing + theta1_2_Maj;
    elseif courtPos(i, 2) < Rx1(2)
        theta = theta1_2_Point_Bearing - theta1_2_Maj;
    end
end

X1 = Minor1_2 * cosd(theta);
Y1 = Minor1_2 * sind(theta);

% Determine minor axis magnitude b from point X1, Y1 on ellipse
% b = a * | y1 | / sqrt(a^2 - x1^2)

b1 = Major1_2 * abs(Y1);
b2 = sqrt(abs(Major1_2^2 - X1^2));
b = b1/b2; % minor axis magnitude

% Determine ellipse angle for major axis to rotate ellipse
if courtPos(i, 2) > Rx1(2)
    theta1_2 = -atand(DistRx1_Y/DistRx1_X);
elseif courtPos(i, 2) < Rx1(2)
    theta1_2 = atand(DistRx1_Y/DistRx1_X);
else
    theta1_2 = 0;
end

if DistRx2 > DistRx1 % therefore assign DistRx2 to align with major axis
    if (DistRx2 > 7.5) && (DistRx2 <= 9)
        Major1_2 = Rx_error(4);
    elseif (DistRx2 > 4.0) && (DistRx2 <= 7.5)
        Major1_2 = Rx_error(3);
    elseif (DistRx2 > 2.0) && (DistRx2 <= 4.0)
        Major1_2 = Rx_error(2);
    elseif (DistRx2 <= 2.0)
        Major1_2 = Rx_error(1);
end
if (DistRx1 > 7.5) && (DistRx1 <= 9)
    Minor1_2 = Rx_error(4);
elseif (DistRx1 > 4.0) && (DistRx1 <= 7.5)
    Minor1_2 = Rx_error(3);
elseif (DistRx1 > 2.0) && (DistRx1 <= 4.0)
    Minor1_2 = Rx_error(2);
elseif (DistRx1 <= 2.0)
    Minor1_2 = Rx_error(1);
end

% Major axis magnitude 'a' becomes the same as the major error
a = Major1_2;

if courtPos(i,1) < Rx2(1) % for position either above or below Rx1
    % Determine ellipse angle between major axis and horizontal for courtPos(i,1) < Rx2(1)
    theta1_2_Maj = atand(DistRx2_Y/DistRx2_X);

    % Determine X1 and Y1 for point on ellipse from Minor Rx1
    % determine angle between horizontal and point on ellipse bearing
    % (towards Rx1)
    theta1_2_Point_Bearing = atand(DistRx1_Y/DistRx1_X);

    % determine angle between major axis and point on ellipse
    theta = theta1_2_Maj - theta1_2_Point_Bearing;
elseif courtPos(i,1) > Rx2(1) % for position below Rx1
    % Determine ellipse angle between major axis and horizontal for courtPos(i,1) < Rx2(1)
    theta1_2_Maj = atand(DistRx2_X/DistRx2_Y);

    % Determine X1 and Y1 for point on ellipse from Minor Rx1
    % determine angle between horizontal and point on ellipse bearing
    % (towards Rx1)
    theta1_2_Point_Bearing = atand(DistRx1_X/DistRx1_Y);

    % determine angle between major axis and point on ellipse
    theta = theta1_2_Point_Bearing - theta1_2_Maj;
end

X1 = Minor1_2 * cosd(theta);
Y1 = Minor1_2 * sind(theta);

% Determine minor axis magnitude b from point X1,Y1 on ellipse
% b = a * | y1 | / sqrt(a^2 - x1^2)

b1 = Major1_2 * abs(Y1);
b2 = sqrt(abs(Major1_2^2 - X1^2));
b = b1/b2; % minor axis magnitude

% Determine ellipse angle for major axis
if courtPos(i,1) < Rx2(1)
    theta1_2 = -atand(DistRx2_Y/DistRx2_X);
end
 elseif courtPos(i,1) > Rx2(1)
    theta1_2 = -90 - atand(DistRx2_X/DistRx2_Y);
 else
    theta1_2 = 0;
 end

data2 = courtPos;

% Create the ellipse
p3 = calculateEllipse(courtPos(i,1), courtPos(i,2), a, b, theta1_2);
plot(p3(:,1), p3(:,2), 'k:', 'LineWidth', 1.5);
hold on;
end

% Print a legend
% Distance Errors:
% 0 to 2m: +/- 0.2m
% 2 to 4m: +/- 0.3m
% 4 to 7.5m: +/- 0.5m
% 4 to 9m: +/- 0.75m
8.4.3 Program code for half court field strength survey 3D plot.

```matlab
% ------ Program code for half court field strength survey 3D plot ------
% Half Court Field Strength Survey 3D plot (Measured vs Two-Ray Model) of
% a 2.4GHz RF beacon
% by James A Kirkup (2014)
% This Program produces a 3D plot using the Matlab surf() function
% for displaying a 3D surface of the form Z = F(X,Y). Plots are produced
% for both measured and predicted results. The predicted results are determined
% using the Two-Ray Path Loss model.
% ------
clf();
clear;
clearvars;
hold off;

% Calculation of received power versus distance

ht = 1.45; % Transmit antenna height (m)
hr = 2.68; % Receive antenna height (m)
d = 0 : 0.1 : 30; % Vector of distance values (m)
di = 0; % Indirect ray distance to ground (m)
dr =0; % Reflected ray distance to receive antenna (m)
Gt = 1; % Gain of transmit antenna (dB)
c = 2.99792458e8 % Speed of light m/s
freq = 2.400182e9; % Frequency in MHz
lambda = c/freq; % Wavelength in meters
e = 3; % dielectric constant 30 for good ground (Hollister) 3 for wood
re = -1; % reflection coefficient for earth
delta_phi = 0; % phase difference between direct and reflected rays
Pr = 0; % Receive Power
k = 2*pi*freq/c; % wave number
e0 = 8.85e-12; % Electrical permittivity of free space
sigma = 0.012; % conductivity S/m
er = 1.99; % relative permittivity of wood;
Eta0 = 120 * pi; % Wave Impedance of Free Space (Eta) ~ 376.99111

P0dBm = -46.5; % at receiver input terminal at reference distance 1m.
P0 = (10^((P0dBm/10))*1e-3); % watts at receiver input terminal.
Prec = (|E0|^2 / 120*pi) x (lambda^2 * Dir / 4*pi)
% also, Directivity D (dB) = 10logD, therefore for 9dBi is 7.943
% But, meter is calibrated to actual using quarter wave monopole (2.1dB)
% therefore actual additional gain is 9-2.1 = 6.9dB ie 4.89 not 7.943
E0 = abs(sqrt((P0*120*pi*4*pi)/(7.943*(lambda^2)))) % V/m field strength at antenna terminals 9.33

PO_dBm = 20*log10(E0*1000); % Power at antenna terminal in dBm.
d0 = 1; % Close in reference distance (m)

% Half court is broken up into a grid (14m x 15m)
x_txa = [0:12];
```
x_txa = 12.8 - x_txa; % Backboard is at a distance of 1.2m from baseline
y_txa = [0:15];
y_txa = 7.5 - y_txa;
z_txa = [ [0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0]', [0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0]' ... ];

z_meas = [ [-77.5 -71.0 -73.4 -70.1 -71.0 -69.7 -70.1 -71.0 -69.4 -67.3 -66.5 -69.1 -73.0 -69.1 -77.7 -74.5 -71.2]', [-70.4 -70.1 -69.1 -71.1 -74.8 -70.1 -71.2 -69.0 -73.2 -69.3 -71.2 -70.0 -69.0 -72.2 -68.8 -73.5]' ... ];

z_meas = [ [-71.6 -72.0 -72.9 -70.0 -71.8 -68.9 -72.1 -66.6 -69.1 -69.4 -69.5 -70.8 -70.8 -74.5 -71.2 -68.1]', [-70.1 -70.5 -70.0 -68.7 -68.2 -67.2 -69.1 -69.0 -70.4 -69.3 -67.4 -68.1 -69.0 -75.6 -76.0 -72.0]' ... ];

z_meas = [ [-68.5 -69.9 -69.5 -71.2 -69.2 -67.2 -66.4 -66.5 -66.8 -68.0 -71.9 -72.0 -68.5 -72.5 -81.0]', [-69.0 -70.5 -68.2 -69.0 -66.7 -68.5 -67.0 -66.4 -66.5 -67.8 -70.0 -66.6 -67.0 -75.3 -69.0 -69.0]' ... ];

z_meas = [ [-70.0 -68.7 -67.7 -66.7 -67.3 -66.1 -68.3 -67.5 -67.1 -69.9 -67.7 -67.4 -73.1 -69.8 -76.0 -74.5]', [-69.2 -69.2 -68.6 -67.1 -68.2 -66.5 -67.5 -63.2 -64.6 -66.9 -66.5 -69.0 -68.9 -74.0 -69.9 -73.0]' ... ];

z_meas = [ [-73.0 -68.5 -67.2 -68.2 -71.0 -66.6 -63.2 -66.5 -66.7 -62.5 -68.9 -67.2 -67.3 -66.25 -74.6 -67.8]', [-71.5 -69.3 -70.0 -70.1 -69.0 -67.4 -63.8 -61.7 -63.2 -60.3 -63.2 -66.5 -67.2 -68.5 -69.3 -71.0]' ... ];

z_meas = [ [-72.6 -69.0 -69.0 -66.2 -66.5 -66.2 -61.5 -60.5 -60.3 -60.6 -67.0 -66.1 -66.5 -76.0 -73.2 -71.2]', [-74.2 -71.5 -69.9 -67.4 -66.3 -65.3 -61.3 -59.7 -58.9 -65.9 -66.1 -66.3 -75.0 -66.8 -68.5 -68.6]' ... ];

j = j + 1;
i = 1;
end
z_txf = flipud(z_tx); %flip direct distance matrix up

%========================================================================================================%
%Main while loop for all grid locations
%using equations for two ray model
%========================================================================================================%
i=1;
j=1;
while (j<=max(size(x_txa)))
    while (i<=max(size(y_txa)))
        d = z_txf(i,j);
        dd = sqrt((ht - hr).^2 + d.^2); % Direct ray distance (m)
        drt = sqrt((ht + hr).^2 + d.^2); % Total reflected ray distance (di + dr) (m)
        ground_incidence_angle = atan((ht + hr)/d); %incidence angle on the ground for reflected ray
        horizontal_angle = atand((hr - ht)/d); %angle between tx and rx for direct ray
        %===================================================================================================%
        %radiation pattern adjust
        %ground reflection signal loss due receive antenna vert pattern +
        %adjustment due to antenna tilt (-12 degress)
        ground_incidence_angle_Deg = atand((ht + hr)/d) - 12;
        if ground_incidence_angle_Deg <= 10
            Er_loss = 0;
        elseif (ground_incidence_angle_Deg > 10 && ground_incidence_angle_Deg <= 20)
            Er_loss = -1;
        elseif (ground_incidence_angle_Deg > 20 && ground_incidence_angle_Deg <= 30)
            Er_loss = -2;
        elseif (ground_incidence_angle_Deg > 30 && ground_incidence_angle_Deg <= 40)
            Er_loss = -3;
        elseif (ground_incidence_angle_Deg > 40 && ground_incidence_angle_Deg <= 45)
            Er_loss = -4;
        elseif (ground_incidence_angle_Deg > 45 && ground_incidence_angle_Deg <= 50)
            Er_loss = -5;
        elseif (ground_incidence_angle_Deg > 50 && ground_incidence_angle_Deg <= 55)
            Er_loss = -6;
        elseif (ground_incidence_angle_Deg > 55 && ground_incidence_angle_Deg <= 60)
            Er_loss = -8;
        elseif (ground_incidence_angle_Deg > 60 && ground_incidence_angle_Deg <= 65)
            Er_loss = -9;
        elseif (ground_incidence_angle_Deg > 65 && ground_incidence_angle_Deg <= 70)
            Er_loss = -10;
        elseif (ground_incidence_angle_Deg > 70 && ground_incidence_angle_Deg <= 75)
            Er_loss = -12;
        elseif (ground_incidence_angle_Deg > 75 && ground_incidence_angle_Deg <= 80)
            Er_loss = -12;
        elseif (ground_incidence_angle_Deg > 80 && ground_incidence_angle_Deg <= 85)
            Er_loss = -13;
        end
    end
    j = j + 1;
end
i = i + 1;
else
    Er_loss = -14;
end

Er_loss = 10^(Er_loss/20); %Pattern loss

ground reflection signal loss due transmit antenna vert pattern
% distance to refelection point. Values interpreted between bearings.
d1 = ht/tand(ground_incidence_angle_Deg);
%vertical transmit angle to ground
vertical_transmit_angle_to_ground = 90 - atand(d1/ht);

if vertical_transmit_angle_to_ground <= 10
    Er_lossi = 0;
elseif (vertical_transmit_angle_to_ground > 10 && vertical_transmit_angle_to_ground <= 20)
    Er_lossi = -0.5;
elseif (vertical_transmit_angle_to_ground > 20 && vertical_transmit_angle_to_ground <= 30)
    Er_lossi = -1.1;
elseif (vertical_transmit_angle_to_ground > 30 && vertical_transmit_angle_to_ground <= 40)
    Er_lossi = -1.93;
elseif (vertical_transmit_angle_to_ground > 40 && vertical_transmit_angle_to_ground <= 45)
    Er_lossi = -2.79;
elseif (vertical_transmit_angle_to_ground > 45 && vertical_transmit_angle_to_ground <= 50)
    Er_lossi = -3.5;
elseif (vertical_transmit_angle_to_ground > 50 && vertical_transmit_angle_to_ground <= 55)
    Er_lossi = -4.43;
elseif (vertical_transmit_angle_to_ground > 55 && vertical_transmit_angle_to_ground <= 60)
    Er_lossi = -5.57;
elseif (vertical_transmit_angle_to_ground > 60 && vertical_transmit_angle_to_ground <= 65)
    Er_lossi = -7.0;
elseif (vertical_transmit_angle_to_ground > 65 && vertical_transmit_angle_to_ground <= 70)
    Er_lossi = -8.93;
elseif (vertical_transmit_angle_to_ground > 70 && vertical_transmit_angle_to_ground <= 75)
    Er_lossi = -10.8;
elseif (vertical_transmit_angle_to_ground > 75 && vertical_transmit_angle_to_ground <= 80)
    Er_lossi = -11.35;
elseif (vertical_transmit_angle_to_ground > 80 && vertical_transmit_angle_to_ground <= 85)
    Er_lossi = -11.85;
else
Er_lossi = -12.0;
end

Er_lossi = 10^(Er_lossi/20) \% Pattern loss

\% Radiation pattern adjust
\% Direct signal loss due receive antenna vert pattern
receive_incidence_angle_Deg = abs(atand((hr - ht)/d) - 12);
if receive_incidence_angle_Deg <= 10
    Er_lossRx = 0;
elseif (receive_incidence_angle_Deg > 10 && receive_incidence_angle_Deg <= 20)
    Er_lossRx = -1;
elseif (receive_incidence_angle_Deg > 20 && receive_incidence_angle_Deg <= 30)
    Er_lossRx = -2;
elseif (receive_incidence_angle_Deg > 30 && receive_incidence_angle_Deg <= 40)
    Er_lossRx = -3;
elseif (receive_incidence_angle_Deg > 40 && receive_incidence_angle_Deg <= 45)
    Er_lossRx = -4;
elseif (receive_incidence_angle_Deg > 45 && receive_incidence_angle_Deg <= 50)
    Er_lossRx = -5;
elseif (receive_incidence_angle_Deg > 50 && receive_incidence_angle_Deg <= 55)
    Er_lossRx = -6;
elseif (ground_incidence_angle_Deg > 55 && ground_incidence_angle_Deg <= 60)
    Er_lossRx = -8;
elseif (ground_incidence_angle_Deg > 60 && ground_incidence_angle_Deg <= 65)
    Er_lossRx = -9;
elseif (ground_incidence_angle_Deg > 65 && ground_incidence_angle_Deg <= 70)
    Er_lossRx = -10;
elseif (ground_incidence_angle_Deg > 70 && ground_incidence_angle_Deg <= 75)
    Er_lossRx = -12;
elseif (ground_incidence_angle_Deg > 75 && ground_incidence_angle_Deg <= 80)
    Er_lossRx = -12;
elseif (ground_incidence_angle_Deg > 80 && ground_incidence_angle_Deg <= 85)
    Er_lossRx = -13;
else
    Er_lossRx = -14;
end

Er_lossRx = 10^(Er_lossRx/20) \% Pattern loss

\% Direct signal loss due transmit antenna vert pattern
\% Transmit incidence angle Deg
transmit_incidence_angle_Deg = atand((hr - ht)/d);
if transmit_incidence_angle_Deg <= 10
    Er_lossTx = 0;
elseif (transmit_incidence_angle_Deg > 10 && transmit_incidence_angle_Deg <= 20)
    Er_lossTx = -0.5;
elseif (transmit_incidence_angle_Deg > 20 && transmit_incidence_angle_Deg <= 30)
    Er_lossTx = -1.1;
elseif (transmit_incidence_angle_Deg > 30 && transmit_incidence_angle_Deg <= 40)
    Er_lossTx = -1.93;
elseif (transmit_incidence_angle_Deg > 40 && transmit_incidence_angle_Deg <= 45)
    Er_lossTx = -2.79;
elseif (transmit_incidence_angle_Deg > 45 && transmit_incidence_angle_Deg <= 50)
    Er_lossTx = -3.5;
elseif (transmit_incidence_angle_Deg > 50 && transmit_incidence_angle_Deg <= 55)
    Er_lossTx = -4.43;
elseif (vertical_transmit_angle_to_ground > 55 && vertical_transmit_angle_to_ground <= 60)
    Er_lossTx = -5.57;
elseif (vertical_transmit_angle_to_ground > 60 && vertical_transmit_angle_to_ground <= 65)
    Er_lossTx = -7.0;
elseif (vertical_transmit_angle_to_ground > 65 && vertical_transmit_angle_to_ground <= 70)
    Er_lossTx = -8.93;
elseif (vertical_transmit_angle_to_ground > 70 && vertical_transmit_angle_to_ground <= 75)
    Er_lossTx = -10.8;
elseif (vertical_transmit_angle_to_ground > 75 && vertical_transmit_angle_to_ground <= 80)
    Er_lossTx = -11.35;
elseif (vertical_transmit_angle_to_ground > 80 && vertical_transmit_angle_to_ground <= 85)
    Er_lossTx = -11.85;
else
    Er_lossTx = -12.0;
end

Er_lossTx = 10^(Er_lossTx/20); %Pattern loss
%===============================================================================
ec=er + 1i*(sigma/(2*pi*freq*e0));
Z3 = sqrt((ec - (cos(ground_incidence_angle)*cos(ground_incidence_angle))))/ec;
Z4 = sqrt(ec - (cos(ground_incidence_angle)*cos(ground_incidence_angle)));
%reflection coefficient
Refl_Coeff4 = ((ec*sin(ground_incidence_angle)-Z4)/(ec*sin(ground_incidence_angle)+Z4)); %J.D. Parson's(!!!), Rappaport, Anderson, et al
Ed=(E0/dd)*exp(-1i*dd*k); %direct Signal
Er=(E0/drt)*Refl_Coeff4*exp(-1i*drt*k); %reflected Signal
%Etotal(a)=Ed + Er*sin(ground_incidence_angle)*Er_loss; % V/m there is no adjustment for Ed as heights are the same ie cos(0) = 1
Etotal(i,j)=Ed*Er_lossRx*Er_lossTx + Er*Er_lossi*Er_loss; % V/m there is no adjustment for Ed as heights are the same ie cos(0) = 1
Etota = abs(Etotal(i,j)); %V/m
Power(i,j)=20*log10(Etota*1000);
\[ Pr = \left( \frac{E_{\text{total}}^2}{120 \times \pi} \right) \times \left( \frac{(7.943 \times (\lambda^2))}{4 \times \pi} \right) \] %Power Watts at receiver terminal

\[ Pr_{\text{dB}}(i,j) = 10 \times \log_{10}(Pr/1 \times 10^{-3}) \] %dBm

\[ z_{\text{pred}}(i,j) = Pr_{\text{dB}}(i,j); \] 

\[ i = i + 1; \]

\[ j = j + 1; \]

\[ i = 1; \]

\[ z_{\text{predf}} = \text{flipud}(z_{\text{pred}}); \] %flip matrix up

figure(1);
\texttt{h1Surface = surf(z_{\text{predf}}); \%3D color plot}
\texttt{zlabel('Field Strength (dBm)')}
\texttt{xlabel('Distance (m)')}
\texttt{ylabel('Distance (m)')}
\texttt{axis([0 15 0 15 -80 -55])}
\texttt{colorbar('eastoutside');}
\texttt{\%hold on}

figure(2);
\texttt{hSurface = surf(z_{\text{meas}});}
\texttt{zlabel('Field Strength (dBm)')}
\texttt{xlabel('Distance (m)')}
\texttt{ylabel('Distance (m)')}
\texttt{axis([0 15 0 15 -80 -55])}
\texttt{colorbar('eastoutside');}