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# Identification & Mitigation of NLOS Information for UWB based Indoor Localization

By

Michal Mati

A Thesis Submitted to the Faculty of Graduate Studies through the Department of **Electrical and Computer Engineering** in Partial Fulfillment of the Requirements for the Degree of **Master of Applied Science** at the University of Windsor

Windsor, Ontario, Canada

2016

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# Identification & Mitigation of NLOS Information for UWB based Indoor Localization

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> > August 15, 2016

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#### ABSTRACT

Technology advancements such as GPS, automation and robotics have completely changed the world and produced new industries, once thought to be unimaginable a century ago. As with all technology, these systems come with limitations and can be further improved. At this time, all of these systems share one common problem; they cannot work together in an indoor environment. The advent of indoor positioning systems aims to create a union between these technologies such as allowing robots to be location aware. Indoor positioning is currently a new technology with no defined standard. Ultrawideband based indoor positioning systems have become popular because of their resistance to multipath and high resolution due to a large bandwidth.

The Ultra-wideband based system in this thesis utilizes the time of arrival technique to calculate distances and thus a user's position. Time of arrival is only reliable when there is a line-of-sight between two transceivers. If there is no line-of-sight, the distances calculated are inaccurate thus impacting the accuracy of a user's position. This thesis proposes a practical, non-hardware intensive solution to identify if there is a no line-of-sight condition and mitigates the measured range between a tag and the anchor nodes. Line-of-sight identification was implemented using the channel impulse response data. Ranging and positioning mitigation was achieved for the identification of no line-of-sight and an improvement factor of 2.81 was achieved for the calculated mitigated position of a tag.

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Abbreviation	Meaning		
GPS	Global Positioning System		
WLAN	Wireless Local Area Network		
UWB	Ultra-Wideband		
IPS	Indoor Positioning System		
ToA	Time of Arrival		
NLOS	No Line-of-Sight		
LS	Least Squares Solution		
LOS	Line-of-Sight		
RSSI	<b>Received Signal Strength Indicator</b>		
TDoA	Time Difference of Arrival		
AoA	Angle of Arrival		
AoD	Angle of Departure		
GHz	Gigahertz		
PSD	Power Spectral Density		
USB	Universal Serial Bus		
UART	Universal Asynchronous Receiver /		
	Transmitter		
SPI	Serial Peripheral Interface		
PRF	Pulse Repetition Frequency		
IEEE	Institute of Electrical and		
	Electronics Engineers		
FPath	First Path Power Level		
MAC	Medium Access Control		
WiCIP	Wireless Communications and		
	Information Processing Lab		
IMU	Inertial Measurement Unit		

# LIST OF ABBREVIATIONS

## **Chapter 1 - Introduction**

#### **1.1 Motivation**

Real time indoor positioning systems are a growing field due to the increase in use of mobile and portable devices. The need of a solution for indoor location based services is increasing [1]. When a person wishes to travel, getting the location and route to a destination has never been easier with the advent of cell phones and Global Positioning Systems (GPS). GPS works well outdoors but has poor performance indoors due signal attenuation from the walls of a building. To get a target's position indoors, a different solution is required; that solution is indoor localization, also known as "indoor GPS". There are a variety of proposed methods to get a user's position indoors, with the most popular using Wireless Local Area Network (WLAN) and Ultra-Wideband (UWB) spectrum. WLAN based systems use finger printing algorithms; however, WLAN based positioning does not provide good accuracy [2]. There is currently no set standard in terms of wireless spectrum for indoor positioning due to all of the various types of complex indoor environments. The best candidate for high accuracy positioning is an UWB based Indoor Positioning System (IPS), especially since UWB does not interfere with other wireless spectrums and has accuracy on the order of centimeters [2]. The downfall of UWB based IPS', particularly systems employing Time of Arrival (ToA), is that they suffer from location inaccuracies due to the multipath effect from physical obstructions found in an indoor environment [3]. These obstructions cause a scenario called No Line-of-Sight (NLOS) to occur between the transmitter and receiver. By identifying and mitigating the inaccuracies caused by NLOS, the biggest downfall of UWB based IPS' could be solved, thus making the system more robust while maintaining accuracy.

#### **1.2 Problem Statement**

As indoor environments can be complex, there is no single model or algorithm that can account for all of the possible scenarios that an IPS might encounter. Some typical indoor environments can include hospitals, residential housing, restaurants, office buildings, malls, and warehouses. All of the mentioned environments can have different probabilities of NLOS occurring through various types of obstructions. Existing Indoor positioning systems that are based solely on Received Signal Strength Indicators (RSSI) are not very accurate due to multipath fading, and require a premade RSSI fingerprint map to be made prior to being deployed. The UWB based IPS systems are very accurate but the biggest challenge faced when using ToA is when there is NLOS between a user and an anchor node. In the case of NLOS, the signal does not take the shortest theoretical path which leads to a positively biased distance reported by ToA calculation. This positively biased ToA calculation is due to the signal taking multiple paths to reach the receiver. The shortest distance between two points is a straight line and when there is an obstruction between these two points, the signal must travel in a nonlinear fashion. NLOS causes the distance reported to always be greater than the LOS distance. Thus, in situations where NLOS conditions occur, the distance reported between an anchor and a tag must always be corrected downwards. Furthermore, in order to mitigate an NLOS reported distance, NLOS must first be identified.

#### **1.3 Thesis Contribution**

The main contributions of this research is a mitigation algorithm that effectively and dynamically mitigates the position of a target if only two anchors remain LOS, along with a method to detect whether the target is NLOS. The mitigation algorithm presented in this research is a geometric based algorithm that utilizes the geometry of the anchor nodes. A similar geometric concept was applied using cellular network towers as in [12], [13].

The proposed algorithm will mitigate the calculated NLOS range between a tag and an anchor, which results in an improvement in of a tag's coordinates after range processing through trilateration. In this writing, the algorithm only handles the case where NLOS occurs in a system setup using three anchor nodes and one anchor experiences NLOS within a single room. The algorithm requires the identification of NLOS for range measurements between the tag and all anchor nodes. Once an anchor is identified as being NLOS, the algorithm will mitigate the NLOS range measurement. The identification of NLOS is developed and implemented into a real time system using the DecaWave TREK1000 system and does not rely on previously sampled measurements. A simulation of the mitigation algorithm is developed and the results are provided. Data for the simulation is acquired using real world experimental data from the TREK1000 system. As NLOS severity increases, the mitigated position becomes more accurate in comparison to the position using the raw range reported. In this research, the experiments use three anchors and one tag to perform simulations and practical implementations to demonstrate the validity and practicality of the solution proposed.

#### **1.4 Thesis Structure**

This thesis is organized as follows: Chapter 1 describes the challenges of UWB based indoor positioning and the contribution of the research on an introductory basis. Chapter 2 provides a technical background for the work presented and a literature review of existing work done in the field of indoor positioning. Chapter 3 provides the proposed methodology and description of the work. Chapter 4 presents the final simulated results for the mitigation algorithm and the NLOS identification results when using the system in a real world implementation with the TREK1000 hardware. Chapter 5 provides a final conclusion and recommendations for future work in the proposed system.

### **CHAPTER 2 – Background & Literature Review**

#### 2.1 Introduction to Ultra-Wideband

UWB is a wireless spectrum with a frequency range spanning from 3.1 to 10.6 gigahertz (GHz). It was first employed by Guglielmo Marconi in 1901 to transmit Morse code; it is by no means a new technology. Since UWB spans over such a large range of frequencies, the Federal Communications Commission (FCC) decided it must regulate UWB such that it does not interfere with other communications standards within the 3.1 to 10.6 GHz band. In order to prevent interference with other IEEE wireless standards, the FCC decided that the maximum transmit power UWB can produce is -41.3 dBm/MHz. Figure 2.1 shows a chart that compares various existing wireless standards in terms of bandwidth and Power Spectral Density (PSD). In Figure 2.1, it is seen that UWB overlaps with the IEEE WLAN 802.11a (Wi-Fi) spectrum. For this reason, it was required that the FCC limit the transmit power of UWB in order to not interfere with existing home Wi-Fi connections.



Figure 2.1: PSD vs. Operating Frequency of IEEE wireless standards [4]

#### 2.2 Advantages of Using UWB for Indoor Positioning

Indoor positioning using the UWB spectrum has been adopted by the market by companies such as Time Domain, DecaWave and UbiSense. UWB offers many advantages to competing IEEE wireless protocols. Some notable advantages of UWB based communications are listed below [8]:

- It can coexist with other IEEE wireless spectrums
- Offers a large channel capacity
- Good performance in noisy environments, works with low SNR
- Low transmit power, hard to detect and intercept
- Resistant to jamming
- High performance in multipath channels

In Table 2.1 [8], UWB is compared to other competing IEEE wireless standards. It is seen that UWB can deliver very high data rates and spans over frequencies, giving it a very high bandwidth. The DecaWave device used in these experiments claims up to 300 meters of range using UWB. All of these factors, in addition to the fact that UWB does not require a separate spectrum license from the FCC, make UWB a good choice for indoor positioning applications. The prime advantages of UWB are the robustness of the signal and the high resolution of the signal due to the large bandwidth [9].

	IEEE Standard									
		WLAN		Bluetooth	WPAN	UWB ZigBee				
	802.11a	802.11b	802.11g	802.15.1	802.15.3	802.15.3a	802.15.4			
Operational Frequency	5 GHz	2.4 GHz	2.4 GHz	2.4 GHz	2.4 GHz	3.1–10.6 GHz	2.4 GHz			
Maximum Data Rate	54 Mbps	11 Mbps	54 Mbps	1 Mbps	55 Mbps	> 100 Mbps	250 Kbps			
Maximum Range	100 meters	100 meters	100 meters	10 meters	10 meters	10 meters	50 meters			

Table 2.1: UWB comparison to competing IEEE wireless standards [8]

#### 2.3 Indoor Positioning Systems: Infrastructure vs. Infrastructure Free Systems

Indoor positioning systems are not yet standardized and there are many proposed solutions which can be broken down into two groups: infrastructure based systems and infrastructure free based systems. Infrastructure based systems are more costly due to the requirement of extra, specialized hardware but also provide much better accuracy while infrastructure free systems are cheaper but are not as accurate. UWB based indoor positioning systems fall under the infrastructure based category.

#### 2.3.1 Infrastructure Based Systems

Infrastructure based systems require specialized hardware that needs to be deployed throughout and indoor setting. Infrastructure based systems can be deployed via:

- Bluetooth
- UWB
- ZigBee
- Light
- Ultrasound
- RFID

Infrastructure based IPS' have more complex hardware that enables ranging techniques such as ToA, Time Difference of Arrival (TDoA) and Angle of Arrival (AoA) to be deployed. The TREK1000 test system is ToA based and in order to wirelessly calculate the time of flight for the signal, all receivers must be synchronized to the same time base.

#### 2.3.2 Infrastructure Free Based Systems

Infrastructure free systems do not require specialized hardware and are marketed as being readily deployable using current technology, namely WLAN (also known as Wi-Fi). Since WLAN is already commonly used within homes, businesses and offices; it is inexpensive and is a good candidate for research as well since industry is more inclined to adapt technologies that do not require high capital investment. The two most popular types of Wi-Fi indoor positioning techniques are:

- Wi-Fi RSSI Fingerprinting
- Wi-Fi RSSI Ranging

RSSI based measurements are popular for indoor positioning using Wi-Fi because RSSI can be easily extracted from off-the-shelf WLAN hardware. TDoA, ToA and AoA are hard to implement in WLAN/Wi-Fi systems because not all off-the-shelf WLAN hardware offers features to calculate these metrics. Calculating time delay and angular measurements using commercial WLAN routers is also more challenging due to the processing of other WLAN traffic and spectrum resolution limitations. Standard WLAN hardware does not provide the time of flight for a packet to a node. RSSI is not very accurate and typically has positioning accuracy of up to 1 meter [5]. To accomplish positioning using WLAN, more than one router would be required for RSSI finger printing. Localization techniques that incorporate RSSI are good candidates for applications such as finding a store in a mall since 1 meter of accuracy is sufficient for this. Any applications requiring very high accuracy, within centimeters, should employ techniques other than RSSI.

#### 2.4 Commercial Applications of Indoor Positioning Systems

IPS' have a broad range of applications. Some applications can include, locating tagged assets in a building such as tools in a factory, locating products stored in warehouses, tracking of employees within an office complex or medical personnel in a hospital, and robot automation within buildings. IPS' can also be used for data mining for marketing companies for scenarios such as observing the most frequent travel path of users within a mall, which can allow prospective business owners to identify the best location to set up a store. IPS' can also be used within malls to gather data about users' shopping habits and identify shopping destinations that users commonly visit. Marketing and advertising companies can then identify where to place advertisements in a mall and what coupons to offer users that frequent certain stores. A geo-fencing system can also be

employed within stores that will identify that a user is inside a certain store and potentially in the future, send coupons and offers directly to a user's mobile phone as soon as they walk into the store. Indoor localization has many applications that would be beneficial to society as long as it does not cross any ethical boundaries.

#### 2.5 Existing Indoor Positioning Techniques

The primary ranging technique used for indoor positioning in this thesis is time of arrival. ToA and other popular indoor positioning techniques are outlined and briefly explained in the following subsections. The DecaWave TREK1000 system uses a two-way ranging ToA technique which does not require precise timing. This method allows for the precise timing of a range signal and greatly minimizes ranging error compared to other positioning techniques.

#### 2.5.1 Time of Arrival Technique

ToA is a technique that involves calculating the distance between two nodes by using the time it takes for the radio signal to travel between the transmitting and receiving node. ToA requires both the anchor and the tag to have a synchronized time base to accurately timestamp packets. If the anchor and tag are not time synchronized, two-way ranging is applied, such as in the DecaWave TREK1000 system, where the ranging message is sent from the anchor to the tag, then back to the anchor to precisely calculate the signal time of flight. More is discussed in Section 3.2.1.

#### 2.5.2 RSSI Fingerprinting

RSSI fingerprinting is commonly used in systems employing WLAN based indoor positioning. RSSI fingerprinting involves taking RSSI measurements from multiple access points at predetermined distance intervals and storing them in a database of measured RSSI values at each point. These premeasured RSSI values are then compared to the measured value from a user which gives an estimation of the position. RSSI fingerprinting is not feasible in practice due to fingerprint maps required to be created. To create a fingerprint map for every possible WLAN access point, for every room, would require extensive setup prior to a system being able to run.

#### 2.5.3 Time Difference of Arrival

TDoA works by calculating the cross correlation between signals arriving at nodes. The nodes must all be time synchronized as well. TDoA and the cross correlation of the signals produce hyperbolas that intersect as a specific point. TDoA allows the anchor nodes to continuously broadcast a range signal and not have to interact with the tag. This allows for many tags to be deployed since they do not communicate with anchor nodes but instead only listen to them. This technique is applied to GPS systems found today. That is why millions of users are able to simultaneously use GPS at the same time. The drawback of this system is that that crystal oscillator on both the tag and the anchor must be perfectly aligned, which is never the case. For this reason, two-way ToA ranging is used.

#### 2.5.4 Angle of Arrival

AoA is a method to obtain the angle of a received signal from a known transmitting node to in order to calculate the position of a user. The angle of signal can be determined if the transmitter and receiver devices use directional antennas and the signal transmitted only under LOS conditions. For the application of indoor positioning, the main disadvantage of AoA is that in NLOS conditions the angle of the incoming signal may be incorrect due to signal reflections (multipath) from obstacles in the room. Signal reflections will cause an incorrect angle to be calculated. A room with many metallic objects can impact the performance of AoA since metallic objects severely attenuate the signal and reflect waves. Angle of arrival requires and array of directional antennas which can only receive signals from a certain direction. Directional antennas are also extra hardware and cost which is a disadvantage to using two-way ToA ranging.

#### 2.6 Physical Hardware Used and Specifications

The hardware used in this thesis is created by DecaWave. The primary reason for choosing the DecaWave hardware is because DecaWave offers low cost products with reasonable line-of-sight accuracy (up to 10cm accuracy), relative to other competing indoor positioning based manufacturers.

#### 2.6.1 DecaWave Hardware

The hardware chosen for the experiments was the EVK1000 and TREK1000 evaluation kit which are manufactured by DecaWave. The hardware in both the EVK1000 and TREK1000 kits consists of the same physical hardware, which is the EVB1000 evaluation board as shown in Figure 2.2. The difference between the EVK1000 and TREK1000 evaluation kits is in the firmware and software provided by DecaWave for each kit.



Figure 2.2: EVB1000 board by DecaWave [6]

The EVK1000 evaluation kit offers firmware to provide a two way ranging distance measurement that displays the distance between two EVK1000 units. It also comes with a premade PC program called "DecaRanging" that displays channel impulse response information along with other diagnostic information. The EVK1000 system was mainly used for acquiring a visual display of channel impulse response information under different NLOS scenarios. The TREK1000 system was used as the IPS. The TREK1000

system is also capable of getting channel impulse response information but this causes the performance of the system to slow down slightly.

The EVB1000 board consists of three main components: the DW1000 chip by DecaWave, the STM32F10x microcontroller by STMicroelectronics, and an UWB omnidirectional planar antenna. The DW1000 chip is responsible for sending out messages through UWB, obtaining channel information and decoding/detecting incoming messages. The DW1000 is the "heart" of the system. The STM32F10x is a 32 bit microprocessor that communicated with the DW1000 chip via Serial Peripheral Interface (SPI) transactions and sends out messages to a PC through Universal Serial Bus (USB) or Universal Asynchronous Receiver/Transmitter (UART). SPI, USB and UART are different types of hardware communication protocols. Figure 2.3 shows a high level system block diagram of the EVB1000 board.



Figure 2.3: EVB1000 System Block Diagram [7]

#### 2.6.2 DW1000 Operating Characteristics

The EVB1000 runs all UWB communication from the DW1000 chip onboard the unit. The operating capabilities of the DW1000 are found in Figure 2.4. There are total of 6 available channels, each with different combinations of center frequency and bandwidth. There are also various preamble codes supporting a 16 or 64 MHz Pulse Repetition Frequency (PRF). The operating capabilities of the DW1000 are based on the Institute of Electrical and Electronics Engineers (IEEE) 802.15.4 standard. For an indepth explanation of the UWB operating parameters, the user is referred to the IEEE 802.15.4 standard.

Channel number (MHz)		Bandwidth <mark>(</mark> MHz)	Preamble Codes (16 MHz PRF)	Preamble Codes (64 MHz PRF)			
1	1 3494.4		1, 2	9, 10, 11, 12			
2	3993.6	499.2	3, 4	9, 10, 11, 12			
3	4492.8	499.2	5, 6	9, 10, 11, 12			
4	3993.6	1331.2 *	7, 8	17, 18, 19, 20			
5	6489.6	499.2	3, 4	9, 10, 11, 12			
7	6489.6	1081.6 *	7, 8	17, 18, 19, 20			
N.B. For correct operation of the DW1000 the software must take care to only allow selection of those preamble codes appropriate for the configured PRF.							

\* The DW1000 has a maximum receive bandwidth of 900 MHz

Figure 2.4: Operating Capabilities of the EVB1000 board.

The selection of channels allows multiple independent IPSs to be set run simultaneously with no interference. This scenario can occur if for instance, a company wishes to track assets and personnel but on two separate systems. It is also important to note that while the IEEE 802.15.4 standard allows a UWB bandwidth of up to 1331.2 MHz, the DW1000 has a maximum receive bandwidth of only 900 MHz. For the experiments shown in this thesis, the TREK1000 system used will be configured to run on channel 2 with a 16 MHz PRF.

#### 2.7 Related Work

A summary of related works is outlined in Table 2.2. The related work entails multiple overlapping areas research, which incorporate research in the UWB spectrum,

NLOS identification and classification, and ranging / positioning methods. This research can be directly applied to the TREK1000 system used in this thesis for a hardware implementation demonstration. As seen from Table 2.2, there is a lack of research in geometric based mitigation, especially using UWB. None of the related works outlined in Table 2.2 provided a hardware implementation.

#### 2.7.1 Geometric Based Mitigation

Geometric based mitigation is based on the geometrical layout of the positioning system. In [12], [13] cell geometry and the base station layout from cellular network towers are utilized. Range scale factors are estimated from a constrained nonlinear optimization problem. The solutions in [12], [13] do not require the identification of LOS/NLOS conditions. For the application in this research, identification and classification of NLOS was incorporated to a geometric based algorithm, along with RSSI measurements in the UWB spectrum. A hardware demonstration was also delivered.

#### 2.7.2 NLOS Identification / Classification

NLOS Identification is a crucial parameter in this research because it enables the ability to only mitigate ranges that are strictly NLOS. This saves processing time and ultimately can lead to increased battery life if the processing is done on a mobile node. Guvenc in [11] proposes NLOS identification using channel statistics such as CIR. Alsindi in [14] goes further and also classifies NLOS by severity. It is classified as being "hard" or "soft". NLOS classification can be an important parameter because it can, in the future, be used as a way to mitigate NLOS range measurements based on the severity of NLOS. The identification and classification of NLOS is accomplished in this research and also applied to a real time hardware implementation.

Author(s)			NL	OS	Underlying Method(s)			ion				
	UWB based	Identification	Classification	ToA / TDoA	AoA	Geometric	RSSI	Position Mitigati	Hardware Implementation	Comments		
Cai, Li, Yuan, Hei (2015)[10]		X					X	X		Wi-Fi based IPS to using only channel state information and RSSI to mitigate NLOS.		
Guvenc, Chong, Watanabe (2007)[11]	x	X		X				x		NLOS identification using channel statistics and CIR.		
Khajehnouri, Sayed (2005) [12]				X	X	X		x		Cellular based; geometric		
Venkatraman, Caffery, You [13]				х	X	X		Х		means of mitigating NLOS.		
Alsindi, Duan, Zhang, Tsuboi (2009)[14]	x	x	x	x	х			х		NLOS channel identification and classification of "hard"/"soft NLOS. Used experimental measurements.		
Wann, Chin (2007)[15]	х	x		х			х	х		Uses a hybrid RSSI / ToA approach to identify and mitigate NLOS.		
Yang, Peipei, Xinwei, Qinyu, Naitong(2006) [16]	X	X	X	X						Used the same DecaWave hardware to study NLOS through different materials. Showed measurement error between "hard" / "soft" NLOS.		
Wann, Yeh, Hsueh [17]	X	X		X	х			х		NLOS identification /mitigation using Kalman filter and hybrid of TDoA / AoA.		
Marano, Gifford, Wymeersch, Win (2010)[18]	x	X		X				X		Study based from experimental measurements using UWB hardware, mitigated position and detected NLOS using channel parameters.		
Research Covered in this Thesis	x	х	х	х		Х	х	X	Х			

Table 2.2: Summary of Related Works

#### 2.7.3 Non- Geometric Based Approaches to Mitigation in NLOS Environments

There are alternative approaches to deal with the problem of NLOS inaccuracies in a ToA based system that are not geometric based, as proposed in this research. The two main approaches are hybrid schemes and techniques involving the Kalman filter. Both of these alternatives are more complex, and require extra information, thus extra hardware and increased cost. These alternative techniques do have their place and are best used in IPS system where NLOS with more than one anchor is extremely high.

#### 2.7.3.1 Hybrid Schemes

Hybrid schemes are common solutions proposed in an attempt to achieve a more accurate position. Chen [19] states that it is reasonable to combine multiple schemes to achieve an accurate position and proposes a geometrical hybrid ToA/AoA scheme. In the hybrid ToA/AoA scheme proposed, the 3D location estimate of a Mobile Station (MS) is found by using the ToA/AoA measurements from the three Base Stations (BS) by finding all possible intersections. Results showed that the scheme accurately estimated the MS despite the NLOS error distribution. Akgul in [20] proposes a hybrid mitigation method where ToA and AoA are used in combination. The paper first explains mechanics of the ToA approach in using either the first peak or the strongest peak, both which are affected by NLOS conditions. The paper then explains how AoA assisted error mitigation can assist by selecting paths that are closest to the previous sampling point. The motivation behind proposed AoA-assisted error mitigation is that the direct path through ToA can be very weak and might not be selected as the first/strongest path. Using AoA, the potential direct path can be selected using a Least Squared (LS) solution. The results showed that the proposed algorithm in [20] performed very close to the actual distance and showed improvement over using the first detected path, which was the NLOS path.

There has been research in using RSSI with ToA to achieve favorable position accuracy [15]. The authors use an unconstrained nonlinear optimization approach to process the ToA/RSSI and show how it performs under different NLOS scenarios. BSs were placed in different configurations and simulated using their proposed algorithm. The ToA/RSSI hybrid algorithm performed better than other algorithms such as the equalweight unconstrained linear test.

#### 2.7.3.2 Predictive Schemes – Kalman Filter

The Kalman filter is a commonly used predictive approach to NLOS mitigation. The Kalman filter uses additional measurement inputs that are acquired over time. It is commonly used in GPS navigation for scenarios where the user enters a tunnel and loses sight with the satellites. This type of scenario, where satellite communication is lost, is known as dead reckoning. Commonly used inputs to a Kalman filter are acceleration, velocity, yaw, pitch, and roll. In [21], a modified biased Kalman filter is applied to mitigate NLOS in a system using UWB. The work in [21] uses measured ToA values and uses a modified biased Kalman filter to estimate ToA. The measured ToA, along with the estimated ToA is input to a standard deviation calculation with a sliding window and a LOS/NLOS test is performed. The LOS/NLOS test required the identification of NLOS, which is accomplished using the standard deviation of the range measurement. The results showed that the mitigated range resembled that of the true range. In [22] an Inertial Measurement Unit (IMU) aided TDoA system is used in an indoor environment. The IMU provides accelerometer and gyroscope information. The IMU data, along with the TDoA based system information is used as inputs to the extended Kalman filter. The results demonstrated significant improvements in using an extended Kalman filter over a stand-alone TDoA.

## **CHAPTER 3 – Methodology and Description of the Work**

#### 3.1 System Overview

This chapter explains the proposed work and the methodology of IPSs based on the ToA technique. The out of the box TREK1000 system provides tag tracking features but has no method to detect and mitigate NLOS. The enhancements applied to this system are summarized in Table 3.1 below.

TREK1000 System	Out of Box	Thesis
Capabilities	Solution	Additions
Hardware setup and	v	
connectivity	Λ	
2D/3D Tracking	X	
PC Application /	v	
User Interface	Λ	
NLOS Detection		Х
NLOS Classification		Х
<b>Ranging Mitigation</b>		Х
2D Position		$\mathbf{v}$
Mitigation		Λ

Table 3.1: Thesis Additions to Existing System

The out of box TREK1000 system is able to successfully pair with all anchors/tags, take range measurements and calculate the position of the tag. When an obstruction is placed between a tag and one or more anchors, the position and reported of the tag will be inaccurate. The NLOS inaccuracy varies and depends on the size of the obstruction and the material of the obstruction.

An overall flow chart of this system can be found in Figure 3.1. In the block diagram, the out of box system functions are shown along with the additions presented in this thesis. NLOS is detected by using the channel information and NLOS ranges are mitigated using an algorithm developed. The mitigation of NLOS ranges will result in increased position accuracy.



Figure 3.1: Operational Flow Chart of the IPS with Added Modifications.

#### 3.2 Distance Measurement - Time of Arrival

The method used in this thesis for calculating the distance between the tag and anchors was ToA. In this section ToA is explained, along with problems that may occur using this method. Section 2.5.1 briefly explained the ToA technique.

#### **3.2.1** Time of Arrival – Introduction

ToA is a one dimensional distance estimation technique that involves using two nodes and calculating the total time it takes for a radio signal to travel between the transmitting and receiving antenna. ToA works very well in LOS situations. LOS is defined as both the transmitter and receiver having a clear path between them with no obstructions between them. NLOS is the opposite of LOS, where there is an obstruction between the transmitter and receiver and the signal must use non-direct paths to reach a node, thus not taking the shortest path.

Distance estimation based on the ToA technique is a very time sensitive task. The speed of electromagnetic radiation through free space is the speed of light, c = 299792458 m/s (approximately  $3.00 \times 10^8$  m/s). By knowing the total time it takes for a signal to propagate from one node to another, as well as knowing the speed of the signal, the distance between two nodes can easily be calculated. The formula for calculating distance between two nodes using the ToA technique can be expressed as,

$$d = ct_{prop}, \tag{1}$$

where, c, is the speed of light through free space and  $t_{prop}$  is the propagation time of the radio signal. In practice, there are additional delays that must be accounted for such as hardware and antenna delay. These additional delays can vary, depending on the hardware and antenna used and must be accordingly accounted for in the ToA calculation. Hardware delay is further discussed in Section 3.2.4.

#### 3.2.2 Line-of-Sight Scenario

The ToA technique under LOS conditions is shown in Figure 3.2. From the figure, the  $t_{prop}$  is seen as being 1 nanosecond, thus given the speed of light, the distance is calculated from (1), which results in 0.3 meters.



Figure 3.2: Line-of-Sight in Time of Arrival Technique

#### 3.2.3 No Line-of-Sight Scenario

The weakness of ToA is seen when NLOS occurs. In NLOS conditions, wireless signals that cannot pass through an object must reflect from walls or diffract from an object to reach a target node. Reflection and diffraction of a wireless signal will occur in LOS situations as well but the first signal to reach a receiver will be the direct, unobstructed path. Incoming reflected/diffracted signals entering a receiver are then discarded. An illustration of NLOS reflection and diffraction is shown in Figure 3.3.



Figure 3.3: NLOS and Multipath in Time of Arrival Technique

In NLOS conditions, the incoming received signal is a result of the reflected and/or diffracted signal. This causes  $t_{prop}$  be greater than it should be, which causes calculated distance to be greater. Theoretically in NLOS conditions, the time and distance calculated must always be greater than the time and distance in an LOS path. Since LOS is always the shortest path, there cannot be a situation where the NLOS ToA is shorter

than the LOS ToA. Since a radio wave propagates at the speed of light, a one nanosecond delay equates to a measurement error of 30cm.

The size and position of an NLOS causing obstruction also affects the ToA range calculation. The size of the NLOS causing obstruction and the distance between the anchor and tag is proportional to the measurement error induced by NLOS. A 1m x 1m obstruction will have a larger impact on measurement accuracy in a small room than in a large room.

#### 3.2.4 Real World Applications

In real world applications, the designer must also account for hardware delays to process the signal. As mentioned in Section 3.2.2, a one nanosecond delay causes a 30cm measurement error. When applying ToA in practice, the hardware delay due to processing and sending time of a signal must be known. Processing time of a signal is specific to the hardware itself. Once the hardware delay time is known, the hardware processing time is subtracted from the time of flight to accurately give a correct distance measurement. Figure 3.4 shows the time of flight scenario for the EVB1000 unit [23].

Another factor that affects the ToA is antenna delay. Antenna delay, also known as group delay is calculated by trial and error until the LOS distance measurement is accurate. Since the hardware is all made up of the same components, each EVK1000 unit will have the same antenna delay value. The ToA between an anchor and a tag is calculated by [23] as,

$$ToA = \frac{(2T_{RR} - T_{SP} - 2T_{SR} + T_{RP} + T_{RF} - T_{SF})}{4},$$
(2)

where  $T_{RR}$  is receive response message time,  $T_{SP}$  is send poll message time,  $T_{SR}$  is send response message time,  $T_{RP}$  is receive poll message time,  $T_{RF}$  is receive final message time and  $T_{SF}$  is send final message time.



Figure 3.4: Time of flight in the EVB1000 [23]

#### **3.3 Position Estimation - Trilateration**

Trilateration is a method to determine the relative coordinates of a point using distances to a target node from at least three other reference nodes whose coordinates are known. Trilateration can be done in either 2D or 3D. The choice of using 2D or 3D trilateration is dependent on the application.

#### 3.3.1 Position Estimation - 2D Trilateration

In this thesis, 2D trilateration is the primary focus. A MATLAB simulation of 2D trilateration was used to identify the tag's position once all three ranges were acquired. 2D trilateration requires a minimum of three anchor nodes to determine the location of a tag. Trilateration in 2D solves for the intersection of three circles at a common point.

#### **3.4 Identification of NLOS**

The identification of NLOS is critical component in this thesis. Before the mitigation of an NLOS measurement, it must be determined if the measured distance contains NLOS error. The measured distance between two points using ToA can contain significant positive error bias when NLOS occurs [24]. In this thesis, NLOS is also classified as being "hard" or "soft". The methodology for identifying NLOS is explained in Section 3.4.5, and the classifications used are seen in Section 4.3.1. "Hard" NLOS is defined as being when an obstruction severely attenuates the signal, where as "soft" NLOS is an obstruction that causes mild/low signal attenuation. The primary method for identifying NLOS is based on comparing the Received Signal Strength Indicator (RSSI) and First Path Power Level (FPath) parameters. Through experimental results, the comparison of FPath and RSSI gave an accurate confidence level of NLOS detection.

#### 3.4.1 Received Signal Strength for the DecaWave EVB1000 Hardware

The received signal strength is one of the parameters used in the identification of NLOS. Using the EVB1000 hardware, it was possible to acquire an estimation of the RSSI. From the DW1000 documentation, a model for acquiring an estimation of the RSSI [25]. The model is given as,

$$RSSI(dBm) = 10 \log_{10}\left(\frac{(C)(2^{17})}{N^2}\right) - A,$$
(3)

where *C* is the channel impulse response power, *N* is the preamble accumulation count and *A* is a predefined constant of 115.72 dBm for a Pulse Repetition Frequency (PRF) of 16 MHz or 121.74 dBm for a PRF of 64 MHz.

A chart provided by DecaWave [25], seen in Figure 3.5, illustrates the actual received power vs. the estimate using the model provided in (3). While the RSSI from the EVK1000 hardware is only an estimate, it is seen from the graph that as the RSSI decreases, the accuracy of the model by DecaWave is more accurate thus giving a higher confidence level for NLOS identification when the signal strength is more attenuated.



Figure 3.5: Estimated vs. Actual Received Power levels (dBm)

#### 3.4.2 Preliminary Experiments: NLOS Detection via RSSI

Experiments were performed to find a correlation between NLOS and the RSSI. The hypothesis for this experiment was that by taking the average RSSI between each anchor node and the tag, the anchor experiencing NLOS would have a lower (more negative) RSSI than the average between all three.

#### 3.4.2.1 Experiment 1 – NLOS in the Centre of an Indoor Positioning System

In the first experiment, three anchors were set up in an equilateral triangle formation. The separation between each anchor node was 3 meters, thus the length of the anchor perimeter edge length was 3 meters. The tag node was placed in the direct center of the triangle. An object was then placed between the anchor/tag to mimic NLOS. The object was moved between each anchor/tag. Only one anchor/tag was NLOS in the

system at any given time. An illustration of this setup is shown in Figure 3.6. A sheet of metal was the object placed in between the anchor/tag to create the NLOS condition.



Figure 3.6: Experiment 1 - NLOS Setup

First, the indoor positioning system was run with no object obstructing the view between any anchor/tag to imitate LOS conditions. After collecting the data, the RSSI between each anchor/tag was compared to the reported distance. The average reported LOS distance over a total of 145 measurements was found to be 1.904m. The height of the anchors was 1.61m from the floor. The height of the tag was 1.33m from the floor. Since the reported distance is a vector in the XYZ plane but the 2D map and the distance between each anchor are on the XY plane, the distance must be converted to its XY projection. Table 3.2 compares the reported distance measurements in the XYZ plane and compares the variance and the maximum and minimum reported distance points.

Scenario	Distance	Minimum	Maximum	NLOS %Error
	( <b>m</b> )	( <b>m</b> )	( <b>m</b> )	
LOS	1.904	1.867	1.939	
NLOS Anchor 0 – Tag	2.282	2.229	2.323	+19.85
NLOS Anchor 1 – Tag	2.170	2.133	2.219	+13.97
NLOS Anchor 2 – Tag	2.196	2.159	2.227	+15.33

Table 3.2: Range Comparison between LOS/NLOS - Experiment 1
In the NLOS scenarios, it was seen that an obstruction caused the reported distances to increase between 14-20%. Figure 3.7 compares reported distance with the RSSI. It is seen from the graph that the NLOS RSSI varied from -80.8dBm to -82.12 dBm. The NLOS reported distance deviation varies from 2.133m to 2.323m between all the experiments. At around -80.7dBm, the distinction between LOS and NLOS is seen with the reported distance increasing significantly. It should be observed that there were also a few LOS RSSI measurements that were in the NLOS RSSI range but with the exception that reported distance still stayed accurate. The few LOS outlier points that were greater than -80.8 dBm were the first indication that RSSI by itself is not a very good indicator of LOS/NLOS conditions.



Figure 3.7: Experiment 1 - Results

## 3.4.2.2 Experiment 2 - NLOS in the Corner of an Indoor Positioning System

In the second experiment, three anchors were set up in an equilateral triangle formation. The separation between each anchor node was 3 meters, thus the triangle edge length was 3 meters. The tag node was placed roughly 1.1 meters away from anchor\_0. Again, an object was placed between the anchor/tag to mimic NLOS. The object was moved between each anchor/tag. Only one anchor/tag was NLOS in the system at any given time. An illustration of this setup is shown in Figure 3.8. A sheet of metal was the object placed in between the anchor/tag to create the NLOS condition.



Figure 3.8: Experiment 2 - NLOS Setup

Similar to Experiment 1, the indoor positioning system was run with no object obstructing the view between any anchor/tag to imitate LOS conditions. After collecting the data, the RSSI between each anchor/tag was compared to the reported distance. The average reported LOS distance over a total of 145 measurements was found to be 1.904m. The height of the anchors was 1.61m from the floor. The height of the tag was 1.33m from the floor. Since the reported distance is a vector in the XYZ plane but the 2D map and the distance between each anchor are on the XY plane, the distance must be converted to its XY projection. Table 3.3 compares the reported distance measurements in the XYZ plane and compares the variance and the maximum and minimum reported distance points. For each anchor/tag, the LOS measurement was first taken, then the NLOS measurement was taken.

Scenario	Distance	Minimum	Maximum	% Error
	( <b>m</b> )			LOS / NLOS
LOS Anchor 0 – Tag	1.155	1.095	1.196	
NLOS Anchor 0 – Tag	1.426	1.383	1.467	+23.46
LOS Anchor 1 – Tag	1.051	1.015	1.082	
NLOS Anchor 1 – Tag	1.344	1.329	1.512	+27.87
LOS Anchor 2 – Tag	1.106	1.069	1.148	
NLOS Anchor 2 – Tag	1.382	1.325	1.416	+24.95

Table 3.3: Range Comparison between LOS/NLOS – Experiment 2

In the NLOS scenarios, it was seen that an obstruction caused the reported distances to increase between 25-28%. Figure 3.9 compares reported distance with the RSSI. It is seen from the graph that the NLOS RSSI varied from -80.60 up to -81.63dBm. The NLOS reported distance deviation varies from 1.325m to 1.512m between all the experiments. In this experiment a clear distinction is seen between the LOS range group and the NLOS range group. Compared to Experiment 1, it was seen that the closer an anchor and tag are together, the higher the introduced NLOS error.



Figure 3.9: Experiment 2 Results

### 3.4.3 NLOS Detection via RSSI – Conclusion

Through preliminary experiments, it was shown that using only RSSI was not a good enough indication of whether NLOS conditions occurred or not. If one or more anchors experienced NLOS, it is hard to differentiate which ranges are actually NLOS. For example, if one anchor experiences NLOS and gives an RSSI measurement higher than it should be, it is not known whether this RSSI measurement is high due to the fact that the tag is either far away from the anchor or if there is an obstruction in between. One cannot confidently identify NLOS conditions using RSSI as a sole parameter. It was also seen that as an anchor and tag get closer, the introduction of NLOS will cause the reported range to deviate much more severely than if the tag and anchor were farther apart. It is therefore important to keep the anchor on a much higher elevation than the tag for 2D positioning to avoid this issue.

### 3.4.4 Received Signal Strength in the First Path

Since NLOS detection using RSSI was no sufficient as seen in Section 3.4.2, another solution had to be found to solve the problem of identifying NLOS accurately. The solution found to the NLOS identification problem was incorporating the use of a parameter called the First Path Power Level (FPath). The EVB1000 hardware allows the user to get an estimate of the FPath. FPath is the measure received signal power from the first three arriving pulses of the received signal. This parameter, in conjunction with RSSI would allow for better accuracy in identifying NLOS. The FPath estimate is provided in [25] and is defined as,

$$FPath = 10 \log_{10}\left(\frac{F_1^2 + F_2^2 + F_3^2}{N^2}\right) - A,$$
(4)

where  $F_1$ ,  $F_2$ ,  $F_3$  are first path amplitude points, N is the preamble accumulation count, and A is a predefined constant of 115.72 dBm for a PRF of 16 MHz or 121.74 dBm for a PRF of 64 MHz.

There are instances where the first path signal may have a low amplitude due to NLOS and can be mistaken as noise by the DW1000. To mitigate this, a detection threshold is set as seen in Figure 3.10. Setting the threshold cutoff too high will cause the first path to be ignored and if the cutoff is set too low, it can cause noise spikes to be detected. For this thesis, the default threshold values set by the manufacturer were used.



Figure 3.10: Incoming Receiver Signals

# 3.4.5 Determining NLOS Conditions using RSSI and FPath

By comparing both RSSI and FPath, the identification of NLOS, along with the severity of it was able to be obtained from the EVK1000 hardware. The method used to identify NLOS was to take the difference,  $\Delta$ , between the FPath and RSSI. The formula for the difference was,

$$\Delta = RSSI - F_Path$$
where,
$$\begin{cases}
\Delta < 6 & LOS \\
6 \le \Delta < 7 & LOS More Probable \\
\Delta \ge 7 & NLOS
\end{cases}$$
(5)

It was found experimentally that if  $\Delta$  was over 7dBm, it would identify the presence of NLOS. Through experiments, a difference of 7dBm was had a 92% chance of identifying NLOS and thus 7dBm was chosen as a baseline for certainty of NLOS. The trouble region is when  $\Delta$  is between 6dBm and 7dBm. At longer ranges (>10m),  $\Delta$  was found to fluctuate up to just under 7dBm under LOS conditions. In a real time environment at long ranges (>10m), modifying  $\Delta$  to indicate NLOS at a specific  $\Delta$ through initial calibration before setting up the system would be a viable alternative. NLOS identification experiments were conducted and are covered in Chapter 4. By identifying NLOS conditions, a program could then be developed to mitigate the NLOS reported distances, consequentially also mitigating the position of the target under NLOS.

### 3.5 NLOS Distance Correction – The Proposed Mitigation Algorithm

In a typical non-industrial environment, anchors are located near ceiling level, thus most obstructions are generally avoided. In general for a system with three anchor nodes, the probability of an anchor experiencing NLOS,  $P_N(A_i)$ , is modelled as,

NLOS Probability for one anchor out of three:

$$p = \frac{1}{3}$$
, the probability that anchor is NLOS (6)

$$P_N(A_i) = \binom{3}{1} p(1-p)^2 = \frac{4}{9}, \text{ where } i \text{ is the anchor } ID$$
<sup>(7)</sup>

NLOS Probability for two anchors simultaneously:

$$P_N(A_i \cap A_i) = P_N(A_i) \ P_N(A_i) \tag{8}$$

NLOS Probability for three anchors simultaneously:

$$P_N(A_i \cap A_i \cap A_i) = P_N(A_i) \ P_N(A_i) \ P_N(A_i)$$
(9)

The model assumes that the most likely NLOS scenario encountered will be a single anchor experiencing NLOS. Since a single NLOS anchor is the most common occurrence, it should be handled with the highest priority. While there is a possibility of two or more anchors being NLOS, it was assumed in our model that anchors are placed near ceiling level and that they are placed in strategic locations to minimize NLOS probability. The test environment for our model was an open lab space lab, warehouse and classroom. For the mitigation algorithm, the required criteria are such that:

$$\sum LOS \ anchors = 2 \tag{10}$$

In Figure 3.11, a room with a three anchor setup is shown. Within the boundaries of perimeter formed by the three anchors, a single NLOS reported range can be mitigated

accurately as long as the criteria for the algorithm are met. For systems with more than three anchors, where one or more ranges are NLOS, as long as there is three or more LOS ranges, other NLOS range information may be discarded from the calculation of a tag's position since only three ranges are required for 2D trilateration. The algorithm can also mitigate a tag's position outside the outside of the anchor perimeter, referred to as the outside correction area but the device performing the mitigation algorithm must know if the tag is within the inside or outside of the anchor perimeter. Determining whether the tag is within the anchor perimeter boundaries is explained in a subsequent section of this paper.



Figure 3.11: Typical Three Anchor Setup in a Room

The mitigation algorithm uses all known information in order to calculate a mitigated position. The information required is as follows:

- Two anchors must be reporting a LOS range
- The coordinates of the anchor nodes
- Identification of the anchor experiencing NLOS

### 3.5.1 Mitigation Algorithm within Correction Area

Placing the anchors will form a triangular shape. To get a user's position in a room, the anchors should be placed in the corners of the room in order for the system to work best. Within the boundaries of anchor perimeter formed by the three anchors, an NLOS reported range can be mitigated as long as the criteria for the algorithm are met. The correction area is defined as the area enclosed by the anchors. Mitigation may also take place outside of the correction area but the device performing the mitigation algorithm must know whether the tag is within the correction area boundaries or not. Determining whether the tag is within the correction area boundaries or not, and mitigating the position outside of the correction area will be explained in a Section 3.5.2.

### **3.5.1.1 Calculation of Correction Area Parameters**

From the known information, angles can be calculated within the correction area, which are then used to calculate a mitigated range. By default, anchor coordinates must always be known because trilateration cannot occur without reference points, which is that of the anchor coordinates. For a 2D IPS, the anchors should always be placed at the same height and cannot all lie on the same plane (ex. a straight line). The tag should lie on a Z-plane that is below the height of the anchors. With the coordinates of the anchors known, distances between the three anchors on the XY plane can be calculated as,

$$E_{01} = \sqrt{\left(A_{0_x} - A_{1_x}\right)^2 + \left(A_{0_y} - A_{1_y}\right)^2},\tag{11}$$

$$E_{12} = \sqrt{\left(A_{1_x} - A_{2_x}\right)^2 + \left(A_{1_y} - A_{2_y}\right)^2},$$
(12)

$$E_{20} = \sqrt{\left(A_{2_x} - A_{0_x}\right)^2 + \left(A_{2_y} - A_{0_y}\right)^2}.$$
(13)

Given that all of the anchors cannot all lie on the same axis, a three anchor setup will always form a triangular configuration. The most practical configuration assumes that a room is square or rectangular and that the three anchors are placed in the corners of the room. This anchor configuration will create a right triangle, as shown in Figure 3.11. All three angles within the correction area can be calculated as,

$$\theta_0 = \cos^{-1} \left\{ \frac{E_{12}^2 - (E_{20}^2 + E_{01}^2)}{(-2)E_{20}E_{01}} \right\},\tag{14}$$

$$\theta_1 = \cos^{-1}\left\{\frac{E_{20}^2 - (E_{12}^2 + E_{01}^2)}{(-2)E_{12}^2 E_{01}^2}\right\},\tag{15}$$

$$\theta_2 = \cos^{-1} \left\{ \frac{E_{01}^2 - (E_{12}^2 + E_{20}^2)}{(-2)E_{12}^2 E_{20}^2} \right\}.$$
 (16)

Next, the LOS ranges are used to calculate angles within the correction area. In order to accurately do this, the LOS ranges must be converted from their XYZ plane representation to an XY projection representation. This is further discussed in the next sub section, 3.5.1.2.

# 3.5.1.2 Converting the LOS ranges from 3D to 2D plane representation

Since the tag and anchors lie on two separate Z-planes, the reported ranges between them will be a distance with an XYZ plane representation. Since the requirement is 2D positioning and the distances between the anchors are represented on the XY plane, the reported ranges must also be converted to an XY plane projection. This concept is illustrated in Figure 3.12.



Figure 3.12: Range Vector (R<sub>x</sub>) in 3D and 2D representation

This is done by applying the Pythagorean Theorem in the XZ plane. The height difference between the anchors and the tag,  $\Delta H$ , is taken as,

$$\Delta H = A_{i_z} - T_{i_z} \tag{17}$$

While the anchor height is always known since anchors are static and do not change position, the exact tag height may not be known. For this, two solutions are proposed to estimate the height.

- 1. Assume a measured static tag height based on the application.
- 2. Using trilateration, use the calculated Z-coordinate that is below the plane of the anchor.

In Proposal 1, since 2D positioning is used, it can be presumed that the tag will be ground based. Depending on the application, the height can be entered by the user once as in the case for a robot. The tag height can be assumed to be a general height, such as an average person's height. In proposal 2, trilateration can be used to find the height of the tag being tracked. In trilateration with three anchors, assuming an ideal free-space propagation model, three intersecting spheres are formed. In an ideal scenario with exact range measurements, the spheres will intersect at one common point on the XY plane. The spheres will also intersect at two possible Z-coordinates. Without a fourth anchor, it is not known whether the spheres intersect on the positive Z-axis or the negative Z-axis. Since the tag is always below the anchors, it can be assumed that the target always lies in the negative Z-axis (below the anchor). This Z-coordinate can be provided by the IPS running trilateration. If NLOS occurs, the tag Z-coordinate will become skewed, thus the previous known LOS Z-coordinate should be used. From our measurements using the DecaWave IPS, the Z-coordinate when using three anchors was an approximate estimation of the actual tag height. In real-world applications, the range estimates, even in LOS conditions have error, thus the height will never be a perfect estimate. Next, given the height of the tag, the LOS range measurements can be projected to the respective XY plane measurements by,

$$Range_{XY Projection}(R_{i_{XY}}) = \sqrt{(R_{i\_LOS}^2 - \Delta H^2)},$$
(18)

where,  $R_{i\_LOS}$  is the LOS range measurement between the tag and anchor A, where *i* is the anchor ID. With a tag somewhere within this correction triangle and two LOS XY range projections available, angles  $\theta_{ia}$  and  $\theta_{ib}$  can be calculated, where subscript *i* is the

anchor ID. The calculation of these angles mimics that of the Angle of Departure (AoD) from the anchor [26].

# **3.5.1.3** Mitigation Algorithm (Within Correction Area)

With the distances between the anchors calculated and anchor ranges converted into 2D representations, the mitigation algorithm can developed so long as the tag remains within the area enclosed by the anchors; the "correction area". The mitigation algorithm can be calculated for NLOS occurring at a single anchor through:

# **Algorithm:**

# **R**<sub>0</sub> Estimation (A<sub>0</sub> is NLOS):

$$\theta_{1a} = \cos^{-1} \left\{ \frac{R_{2XY}^2 - (E_{12}^2 + R_{1XY}^2)}{(-2)E_{12}R_{1XY}} \right\}$$
(19)

$$\theta_{1b} = \theta_1 - \theta_{1a} \tag{20}$$

$$R_{0_{corrected}} = \sqrt{E_{01}^2 + R_{1_{XY}}^2 - (2E_{01}R_{1_{XY}}\cos(\theta_{1b}))}$$
(21)

### **R1 Estimation (A1 is NLOS):**

$$\theta_{0a} = \cos^{-1} \left\{ \frac{R_{2XY}^2 - (E_{20}^2 + R_{0XY}^2)}{(-2)E_{20}R_{0XY}} \right\}$$
(22)

$$\theta_{0b} = \theta_0 - \theta_{0a} \qquad \text{where, } [\theta_{0a} > 0] \tag{23}$$

$$R1_{corrected} = \sqrt{E_{01} + R_{0XY}^2 - (2E_{01}R_{0XY}\cos(\theta_{0b}))}$$
(24)

### **R2** Estimation (A2 is NLOS):

$$\theta_{1a} = \cos^{-1} \left\{ \frac{R_{0_{XY}}^2 - \left(E_{12}^2 + R_{1_{XY}}^2\right)}{(-2)E_{12}R_{1_{XY}}} \right\}$$
(25)

$$\theta_{1b} = \theta_1 - \theta_{1a} \tag{26}$$

$$R2_{corrected} = \sqrt{E_{12}^2 + R_{1XY}^2 - (2E_{12}R_{1XY}\cos(\theta_{1b}))}$$
(27)

From the experimental data collected from the DecaWave IPS, the LOS range measurements had some error on the order of a few centimeters. This results in an imperfect intersection from the three range measurements, which creates a potential region that the target can be in. To further estimate the position of the tag within the potential region, a least square estimation [27] can be applied.

Increased range accuracy was attained by using one of the possible corrected ranges calculated in (21), (24) or (27) and then positively biasing it by adding the calculated range with the NLOS range and averaging it. Positive biasing was achieved by,

$$R_{i_{corrected\_bias}} = \frac{\left[R_{i_{corrected}} - \sqrt{(R_{i_{NLOS}})^2 - (\Delta H)^2}\right]}{2}.$$
 (28)

Once the NLOS range has been mitigated, the measured NLOS range is replaced with the mitigated range and used as the range parameter in the trilateration function to determine the tag's coordinates.

### **3.5.2** Mitigation Algorithm Outside of Correction Area

A complete indoor positioning system should be able to correct a tag's position anywhere within a room. The limitations of Section 3.5.1 allow the tag's position to only be calculated if it is inside the perimeter formed by the anchors. This means that for a rectangular or square room using three anchors, correction can only take place for up to 50% of the total room area. This is certainly not desirable unless only half of a rooms area is utilized, which is unlikely. In order to have correction capability for 100% of a room, the mitigation algorithm must know if the tag lies outside of the correction area. Once the tag location is identified as being inside or outside the correction area, the algorithm from Section 3.5.1.3 is modified to enable correction for 100% of the room.

## 3.5.2.1 What changes when the Tag is outside the correction area?

For a right triangle anchor configuration (refer to Figure 3.11), when the target is outside of the correction area, the range mitigation for the anchor 1, which is opposite of the hypotenuse will vary since,

$$\theta_{0b} = \theta_0 - (\pm \theta_{0a}) \tag{29}$$

When the tag is outside of the correction area, the calculated angle,  $\theta_{0a}$  should be negative and should therefore be added to  $\theta_0$ , producing:

$$\theta_{0b} = \theta_0 - (-\theta_{0a}). \tag{30}$$

To determine if the point lies outside of the correction area, a line test is used. The anchors adjacent to the hypotenuse of the correction area triangle are not affected if the target is outside of the correction area due to the trigonometric identity,

$$\cos(\theta) = \cos(-\theta) \tag{31}$$

To illustrate this concept, from Figure 3.11, knowledge of whether the tag is in the correction area is only needed for anchor 1, while for anchor 0 and 2, it is not required due to the identity in (31). If the target is outside of the correction area, then (29) is used in substitution of (23).

### 3.5.2.2 Determining Whether Tag lies in Inside or Outside of Anchor Area

As mentioned in the previous section, a line test can be used to check if a point lies inside of a triangular perimeter. The line test method requires slightly more computation and can be used for any anchor configuration. Some anchor configurations may be in the shape of a triangle whose edges do not lie against a wall. For example, an isosceles triangle will have at least two different anchor boundary edges that a tag can cross.

If the anchor configuration is a right triangle, the simplest solution is to set the single anchor boundary line as the reference line and set an arbitrary reference point that also lies within the anchor boundaries. For a system where the anchor orientation is to the left of the origin, the following formula is used to determine whether the tag lies inside of the anchor area:

$$\left(\overrightarrow{AB} \times \overrightarrow{AP_{ref}}\right) \cdot \left(\overrightarrow{AB} \times \overrightarrow{AP_{tag}}\right) \ge 0.$$
(32)

In (32), ABC is the triangle perimeter formed by the anchor configuration. The length of the triangle sides are obtained from (11), (12), and (13). Vector,  $\overrightarrow{AB}$  is formed by taking the distance between the anchors on the primary boundary line.  $\overrightarrow{AP_{ref}}$ , is a vector that originates from an arbitrary point that always lies within the perimeter of the anchors.  $\overrightarrow{AP_{tag}}$  is the vector formed form the coordinates of the anchor that forms the primary boundary line, to the coordinates of the tag. If the final result is greater or equal than 0, the point must lie within the anchor area.

### 3.5.2.3 Mitigation Algorithm: Outside Anchor Area

If the computed location of the tag is found to lie outside the anchor area, the formulas in Section 3.5.1.3 are used with the exception that  $\theta_{0a}$ , in (30) will be added to  $\theta_A$  for the anchor experiencing NLOS that is located directly across an anchor boundary line. For a right triangle, the mitigation algorithm for the anchors that lie on the anchor boundary line does not need to be modified due to (31). The algorithm has two potential scenarios that must be accounted for. The first scenario is that the tag's true position can lie directly on the boundary line, and if the anchor across the boundary line experiences NLOS, the actual position will lie in between two possible calculated solutions. The second scenario is if the true position of the tag lies inside the anchor boundary area but near the boundary line, NLOS can cause the anchor to appear outside the boundary line and possibly beyond the second solution. These two scenarios must be addressed and minimized. The next few sections will explain this in more detail.

#### 3.5.2.4 Scenario #1: True position of tag near but inside anchor boundary line

If the true position of the tag is on the hypotenuse edge of the correction area and NLOS causes it to be appear just outside of the correction boundary, the R1 estimation formula will encounter accuracy loss. The R1 estimation formula can have two potential results, which lie opposite of each other, across the hypotenuse. The mitigated range calculated for A1 is always chosen as the range that is less than the NLOS range. If the actual tag position,  $P_{true}$ , is in between these two possible results, then the error is the distance away from the true position from the two possible solutions,  $P_{S1}$  and  $P_{S2}$ . Distance between the results can be expressed as,

$$d_{error} = \sqrt{(P_{S1_x} - P_{S2_x})^2 - (P_{S1_y} - P_{S2_y})^2}$$
(33)

The maximum distance error would occur if the true position of the tag,  $P_{true(x,y)}$ , very close to solution #1 but NLOS causes the tag's position to appear just beyond the solution #2, which would cause the algorithm to choose the second solution. This maximum error scenario is shown in Figure 3.13.



Figure 3.13: Maximum Error Possible – Derror

If the NLOS tag position is anywhere between solution 1 and 2, the default solution chosen will be solution 1 since NLOS always causes an increase in reported distance, thus, the mitigated distance must be less than the NLOS reported distance. The distance error,  $d_{error}$ , reaches a maximum as the true position of the tag approaches solution 2 and NLOS severity decreases to a point that the NLOS distance is very slightly higher than the true position distance from anchor 1 but not less than the distance to solution two from anchor 1.

# Solution:

To provide the best result and minimize  $d_{error}$ , the calculated mitigated range for solution 1 and the NLOS range are both are added together and averaged. Positive biasing is performed to avoid undershooting the tag's position. To positively bias the range result, the following is applied,

$$R_{1hypotenuse\_bias=} \frac{R_{1hypotenuse} + \sqrt{(R_{i_{NLOS}})^2 - (\Delta H)^2}}{2}$$
(34)

The positive biasing of the range result in (34) is also used for the anchors that form the anchor boundary line. Even though scenario 1 does not affect anchors 0 and 2, positive biasing provided better experimental results that did not undershoot the actual range.

# 3.5.2.5 Scenario #2a: Tag True Position is on the Anchor Boundary

If the NLOS tag position is slightly outside the anchor boundary, it is possible that the true position of the tag can also on or slightly outside the boundary line. Depending on the severity of NLOS, there can also be a problem at anchor 1that can cause the tag's position to appear anywhere before or after solution 2. If the tag's true position is beyond the boundary line but before solution 2, the algorithm would cause solution 1 to be chosen, causing range error. If NLOS is very severe, the NLOS tag position can appear to be beyond solution 2, which would make solution 2 be chosen as it is the closest range value that is lower than the NLOS range. From an algorithm standpoint, the algorithm does not know what the true position of the tag is. The algorithm must use all available information to make the best prediction.

# Solution:

A secondary boundary line is used to avoid the issues stated in scenario 2. The NLOS coordinates of the tag are used in the boundary line check. If anchor 1 experiences NLOS, first a check is made to see whether the tag lies between the anchor boundary line and the secondary boundary line.



Figure 3.14: Hypotenuse and Boundary Line

To determine if the tag lies in between the two boundary lines, the following formula is used,

Side = 
$$(B_x - A_x)(P_y - A_y) - (B_y - A_y)(P_x - A_x)$$
  
where,  

$$\begin{cases}
Side < 0, & point lies left of the line \\
Side > 0, & point lies right of the line \\
Side = 0, & point lies on the line
\end{cases}$$
(35)

In (35), *B* is the endpoint coordinate of the line, A is the start point coordinates of the line, and *P* is the raw coordinates of the NLOS tag. As seen in Figure 3.14, a boundary line is drawn. The tag's true position is outlined by a black dot. The NLOS position is outlined by an asterisk, "\*". For the test cases presented in this thesis, the boundary line is offset from the hypotenuse line by 20%. This offset can be adjusted depending on the types of possible predictable NLOS that can occur. A logical check is performed to determine if the NLOS tag coordinates lie in between the hypotenuse and boundary line. Given the condition that,

$$\left[Side_{Boundary\,Line} < 0\right] \land \left[Side_{Hypotenuse} > 0\right] = True, \tag{36}$$

then the point must lie between the two lines. The parameters in (36) can also indicate if the tag is inside or outside of the correction area. If the logical condition in (36) is found to be 'true', the following modified mitigation formula is applied for anchor 1,

$$R_{1_{hypotenuse}} = \frac{\left[R_{1_{solution\_1}} + R_{1_{solution\_2}}\right]}{2}.$$
(37)

Since, there are two possible solutions for the range between anchor 1 and the tag, with each being on opposite sides of the anchor boundary line, both are added together and averaged. Positive biasing, as in (34), is again performed to avoid undershooting the tag's position. To positively bias the range result, the following is applied,

$$R_{1hypotenuse\_bias=} \frac{R_{1hypotenuse} + \sqrt{(R_{i_{NLOS}})^2 - (\Delta H)^2}}{2}$$
(38)

### 3.5.2.6 Scenario #2b: Tag NLOS Position Beyond the Secondary Boundary Line

If the tag NLOS position is detected to be beyond the secondary boundary line, then the true position of the tag is also most likely to be beyond or around the secondary boundary line. The angle is calculated using (30) followed by (24) and then the result is biased as in (34). This results in solution 2 being the most correct solution.

### 3.5.3 Complete Mitigation Algorithm

By determining identifying NLOS as in Section 3.4, and whether the tag lies inside or outside of the anchor boundary area, the methodology in Sections 3.5.1 and 3.5.2 can be combined into one full program. In a test environment with the conditions that three anchors are configured in a right triangle set up in a single room, and that are at least two anchors are LOS, a single final algorithm can be developed that encompasses Sections 3.5.1 and 3.5.2. The pseudo code for this algorithm is shown below.

# Mitigation Algorithm for a Right Triangle - Pseudo Code:

1	If (NLOS Anchor == $A0 \parallel A2$ )
2	Run Algorithm from Section 3.5.1 positively bias result
2. 3	Fnd
з. 4	
т. 5	If (NLOS Anchor $== A1$ )
5. 6	Check if tag within anchor boundary Run algorithm from Section 3.5.2.2
0. 7	encer y lag winn ancher boundary. Nun algorinningrom Section 5.5.2.2
7. 8.	If (Inside Anchor Boundary)
9.	Subtract $\theta_{A_{\alpha}}$ to algorithm in Section 3.5.1, positively bias result.
10.	//Solution 1
11.	End
12.	
13.	If (Outside Anchor Boundary)
14.	<i>Check if tag is beyond anchor boundary but before secondary boundary.</i>
15.	
16.	If (anchor_boundary < tag_position < secondary_boundary)
17.	Create two solutions by using $\pm \theta_{Aa}$ for the algorithm in Section 3.5.1
18.	Take average of Solution 1&2, (Section 3.5.2.5) and positively bias
19.	result.
20.	End
21.	
22.	Else If(tag_position > secondary boundary)
23.	Add $\theta_{Aa}$ to algorithm in Section 3.5.1, positively bias result.
24.	//Solution 2
25.	End
26.	End
27.	
28.	Trilateration() again using the mitigated range.

# **CHAPTER 4 – Simulation & Hardware Implementation**

## 4.1 Simulation

The mitigation algorithm simulations were developed and tested in MATLAB. The simulations involved developing 2D trilateration to determine a tag's coordinates given three ranges and anchor coordinates, and the creation of the mitigation algorithm to apply to compare the mitigated result to the NLOS result and the true position of the tag. The method to compare the true position of the tag with the mitigated result was done by taking the distance between the true and mitigated position. The results would be summarized and presented via a histogram.

## 4.1.1 2D Trilateration Simulation

A 2D trilateration simulation was developed in MATLAB in order to be able to determine the tag's respective coordinates (x,y) and test the mitigation algorithm in an offline manner. For the purposes of this paper, 'offline' is defined as collecting raw data using the TREK1000 hardware and storing it on a file. The raw data would then be imported into MATLAB and algorithms would be run on a simulated, non-real time environment in MATLAB. The 2D MATLAB trilateration simulation would also allow a user to visually see the target on a map with respect to the anchors.

The benefit of having a MATLAB trilateration simulation is because during the development of the algorithm, it can be rapidly developed and tested repeatedly under different variations of correction algorithms and compared to the uncorrected result. The simulation avoids the tedious task of having to constantly re-flash the hardware every time a software change is made. Once a desired correction algorithm performance is achieved, it can be implemented into the real time TREK1000 system. The resultant coordinates of trilateration from the MATLAB implementation developed matched that of the coordinates from the DecaWave sample program output, given that that information inputs are equivalent.

The 2D trilateration program is a function whose inputs are the anchor coordinates  $(x_n, y_n)$ , where *n* is the anchor id, and the three distances reported between each anchor to the tag. The function is represented below with a total of nine inputs.

$$Trilateration_{2D}(x_1, x_2, x_3, y_1, y_2, y_3, r_1, r_2, r_3)$$
(39)

The function 'Trilateration\_2D()' will return the (x,y) coordinates of the tag. The coordinates are then mapped to a graph which provides a 2D representation of a room with the anchors places in specified locations. A final result of this is seen in Figure 4.1.



Figure 4.1: 2D Trilateration Simulation in (a) along with magnified view in (b)

## 4.1.2 Mitigation Algorithm in MATLAB

The mitigation algorithm was simulated in MATLAB using previously collected live information. The mitigation algorithm consists of three separate scripts which handle the case of NLOS for A0, A1, and A2. A separate script was also created to analyze the results for A0, A1, and A2 and combine them into one overall result. An overall result per room as well as a final result for all the rooms combined is delivered by the fourth script. The subsections below explain the testing procedure and the MATLAB simulation in more detail.

# 4.1.2.1 Test Setup & Procedure

Real world data was first collected and stored using the TREK1000 equipment. Three different rooms were used in the experiments. The anchors were arranged at different distances for reach room. The tag was moved around to three positions per room as well. NLOS was created for each anchor at a time with the tag in the same position by using a 0.48m x 0.44m Styrofoam board coated with aluminum foil. The aluminum foil would act as a metallic layer to attenuate the UWB signal and prevent it from passing through the Styrofoam board. The aluminum foil board was placed about halfway in between the specific anchor and tag that were to simulate artificial NLOS. An example snapshot of how NLOS was created artificially by using an aluminum foil covered board is shown below in Figure 4.2.



Figure 4.2: Creation of Artificial NLOS in the Warehouse Area

The experiments performed were uniform for all test environments. A testing rubric of the experiments is shown below in Table 4.1.

N =	401		Test Scenari	o (N measuremen	nts)
Room	<b>Dimensions</b> (m)	LOS	A0 NLOS	A1 NLOS	A2 NLOS
Warehouse	3.6 x 8.34	Х	Х	Х	Х
WiCIP Lab	4.88 x 9.06	Х	Х	Х	Х
<b>Capstone Room</b>	8.24 x 8.56	х	Х	Х	X

Table 4.1: Testing Rubric for the experiments

As indicated in the test rubric, three rooms of different dimensions and environments were tested in. For each test scenario, 401 ranging measurements were taken. A full test would equate to a total of 1604 range measurements per room. In each room, the tag was placed in three different stationary positions. For each stationary tag position, each test scenario was conducted as per the rubric in Table 4.1. An example layout of the testing conducted in the WiCIP Lab is shown below in Figure 4.3. P1, P2, and P3 are the testing points where the tag was placed. A0 is placed at the origin and the other anchors are placed to the left and/or below the origin, thus negative coordinates are used for A1 and A2.



Figure 4.3: WiCIP Lab Test Layout

### 4.1.2.2 Loading and Processing the Data in MATLAB

After the TREK1000 system collected the data, it was saved to a .CSV file. Each of the four test scenarios per room has an individual .CSV file so that data could be isolated and analyzed independently. The desktop application was modified so that the data is presented into an easily readable format that is stored in a .CSV file. Three scripts were created in MATLAB for each NLOS scenario that could occur at an anchor. In each of the LOS test scenarios per each tag point, 401 ranging measurements and the associated calculated coordinates were taken and averaged to give a reference for LOS conditions.

The five reference data variables for the LOS data files were the three ranges from the anchors to the tag; R0, R1, R2, and the coordinates of the tag; x, y. For the NLOS data files, all individual raw, uncorrected ranges and coordinates were loaded into MATLAB. The coordinates of the anchors were also added to the script. After the NLOS ranges were loaded into MATLAB, the mitigation algorithm was run for each range and the mitigated range would then replace the NLOS range and send to the trilateration function.

### 4.1.2.3 Benchmarking the Mitigation Algorithm

The resulting coordinates from the mitigated range and the raw NLOS coordinates are compared to the average of the LOS coordinates by taking the distance between the two coordinates. The average LOS tag coordinates is also referred to as the "true position". The parameter,  $d_{NLOS}$ , is the distance delta from the true coordinates using the raw, NLOS measurements with no mitigation algorithm applied, which is given as,

$$d_{NLOS} = \sqrt{(x_{LOS} - x_{NLOS})^2 + (y_{LOS} - y_{NLOS})^2}$$
(40)

Consequentially, the parameter,  $d_{Mitigated}$ , is the distance delta from the true coordinates using the calculated coordinates from the mitigation algorithm, and is given as,

$$d_{Mitigated} = \sqrt{\left(x_{LOS} - x_{Mitigated}\right)^2 + \left(y_{LOS} - y_{Mitigated}\right)^2} \tag{41}$$

As the error in (41) approaches zero, the closer the calculated mitigated position is to the true position. In practice there will always be a small amount of error because the ranging information from all of the anchors varies slightly with each measurement. The error is then shown on a histogram graph comparing the NLOS error with the mitigated error, in respect to the true coordinates.

## **4.2 Simulation Results**

The relation of the two distance parameters,  $\frac{d_{NLOS}}{d_{Mitigated}}$ , gives a performance metric called the improvement factor. The improvement factor is a metric used to benchmark the performance of the mitigated solution by using the ratio of the distance of the NLOS tag to the true position against the distance of the mitigated tag distance to the true position. The larger the improvement factor, the more accurate the tag's mitigated position is

compared to the raw NLOS position. The standard deviation of the NLOS and mitigated distance ratios are also shown as  $\sigma_{NLOS}$  and  $\sigma_{Mitigated}$ , respectively. The relation of  $\frac{\sigma_{NLOS}}{\sigma_{Mitigated}}$  is also shown in Tables 1 and 2. The calculation of standard deviation is found by,

$$\sigma = \sqrt{\frac{\sum_{i=1}^{N} d^2}{N}}$$
(42)

### 4.2.1 Range Mitigation Results per Room

The mitigation algorithm was simulated in MATLAB using the collected experimental range measurements to observe the effect of range mitigation. Table 4.2 shows a comparison of the true, mitigated and NLOS range measurements as  $R_{true}$ ,  $R_{Mit}$ , and  $R_{NLOS}$ , respectively for the lab room as shown in Figure 4.3. A graphic comparison of the  $R_0$  range measurements for Position 1 (P1) in the lab room is also shown in Figure 4.4. From Table 4.2, it is observed that the mitigation algorithm provides a closer range estimate in reference to the true range.

		I	ab Roo	m
N= 1	203	R <sub>true</sub> (m)	R <sub>Mit</sub> (m)	R <sub>NLOS</sub> (m)
Po	$R_0$	6.999	7.004	7.156
sitio	<b>R</b> <sub>1</sub>	6.936	7.060	7.105
n 1	<b>R</b> <sub>2</sub>	2.589	2.629	2.892
Po	$R_0$	4.955	4.883	5.126
sitio	<b>R</b> <sub>1</sub>	4.878	4.978	5.194
n 2	<b>R</b> <sub>2</sub>	4.455	4.373	4.650
Pos	$R_0$	2.887	2.832	3.120
sition	$R_1$	2.909	2.779	3.182
ω	$R_2$	6.634	6.690	7.027

Table 4.2: True vs. Mitigated vs. NLOS Range Results

From Figure 4.4, it is observed that the mitigated range has a lower deviation compared to the NLOS range measurements. Deviation of range measurements also occur in perfect LOS conditions using the TREK1000 system. The range measurement deviation for the NLOS and mitigated range,  $\sigma_{R_{NLOS}}$  and  $\sigma_{R_{Mit}}$  respectively, is shown in Table 4.3.



Figure 4.4: Mitigated vs. NLOS  $R_0$  for Lab, Position 1.

N- 1	203	La	ab	Class	room	Ware	house
19-1	203	$\sigma_{R_{NLOS}}$	$\sigma_{R_{Mit}}$	$\sigma_{R_{NLOS}}$	$\sigma_{R_{Mit}}$	$\sigma_{R_{NLOS}}$	$\sigma_{R_{Mit}}$
Рс	R <sub>0</sub>	0.0234	0.0129	0.0175	0.0111	0.0185	0.0124
ositic 1	$R_1$	0.0171	0.0901	0.0377	0.0218	0.0179	0.0180
on	<i>R</i> <sub>2</sub>	0.0155	0.0195	0.0158	0.0173	0.2742	0.1370
Po	R <sub>0</sub>	0.0231	0.0142	0.0181	0.0111	0.0149	0.0108
ositic 2	$R_1$	0.0177	0.0099	0.0169	0.0135	0.0212	0.0200
on	<i>R</i> <sub>2</sub>	0.0201	0.0124	0.0357	0.0230	0.0183	0.0122
Рс	R <sub>0</sub>	0.0185	0.0124	0.0149	0.0108	0.0163	0.0108
ositio 3	R <sub>1</sub>	0.0179	0.0180	0.0212	0.0200	0.0152	0.0076
nc	$R_2$	0.2742	0.1370	0.0183	0.0122	0.0208	0.0122

Table 4.3: Deviation Mitigated vs. NLOS Ranges

An overall summary of the improvement of the mitigated ranges in comparison to the NLOS ranges is shown Table 4.4. From Table 4.4, the parameter  $\varepsilon_{Mit}$ , is the percent

error of  $R_{Mit}$  relative to  $R_{true}$ . The parameter,  $\delta_{imp}$ , is the percent error improvement in range error resulting from the mitigation algorithm compared to the NLOS measurement, in relation to the true range. The average  $\delta_{imp}$  for the lab, classroom and warehouse was 4.23%, 5.65%, and 5.68% respectively. An overall average of these values yields a  $\delta_{imp}$ of 5.18%. From Table 4.4, it is seen that  $\varepsilon_{Mit}$  was low for most of the measurements. Generally,  $R_1$ , had a larger  $\varepsilon_{Mit}$  because the mitigation algorithm relies on the secondary boundary line to predict the tag's NLOS position. Range accuracy for an anchor across a boundary line can be affected by the offset of the secondary boundary line.

N= 1	.203	Lab		Classro	om	Wareho	Warehouse			
		ε <sub>Mit</sub> (%)	$\delta_{imp}$ (%)	ε <sub>Mit</sub> (%)	$\delta_{imp}$ (%)	ε <sub>Mit</sub> (%)	$\delta_{imp}$ (%)			
Ро	R <sub>0</sub>	0.08	2.18	0.91	2.37	1.90	6.18			
sitio	<i>R</i> <sub>1</sub>	1.78	0.65	2.32	2.24	4.47	4.91			
n 1	<b>R</b> <sub>2</sub>	1.55	10.13	3.73	15.31	0.84	5.08			
Ро	R <sub>0</sub>	1.46	1.99	1.34	3.94	0.63	5.70			
sitio	<i>R</i> <sub>1</sub>	2.05	4.42	2.76	2.35	0.56	8.30			
n 2	<b>R</b> <sub>2</sub>	1.83	2.57	0.42	5.66	0.24	4.98			
Ро	R <sub>0</sub>	1.90	6.18	0.63	5.70	0.29	4.59			
sitio	<i>R</i> <sub>1</sub>	4.47	4.91	0.56	8.30	3.04	1.99			
n 3	<i>R</i> <sub>2</sub>	0.84	5.08	0.24	4.98	3.09	9.35			

Table 4.4: Ranging Mitigation Error and Improvement

## 4.2.2 Position Mitigation Results per Room

A summary of the results in a room, per position is presented in Table 4.5. From the table, the total number of measurements was for reach position was N=1203; a total stemming from the 401 measurements per each anchor per position. The improvement factor varied from 1.5902 to 12.5054. This was due to the severity of the NLOS encountered. If the NLOS range measurements were only slightly greater than the actual LOS range measurements, due to NLOS being "soft", the improvement factor will be lower as the margin of error is lower.

The mitigation algorithm successfully improved the accuracy of the target's coordinates for all positions within the three rooms listed in the Table 4.5. The standard deviation of the distance deltas was also smaller for the calculated coordinates resulting from the mitigation algorithm.

		<b>Results Per</b>	Tag Posit	ion in a Rooi	n
N = 1203	Anchor Position	$rac{d_{NLOS}}{d_{Mitigated}}$	$\sigma_{NLOS}$	$\sigma_{Mitigated}$	$\sigma_{NLOS} \over \sigma_{Mitigated}$
	1	1.5902	0.5304	0.4206	1.2611
Lab	2	2.7754	0.5438	0.3264	1.6661
	3	4.4264	0.5132	0.2439	2.1041
	1	2.1172	0.6915	0.4753	1.4549
Classroom	2	2.2224	0.7294	0.4893	1.4907
	3	8.0237	0.5872	0.2073	2.8326
	1	2.099	0.7264	0.5014	1.4487
Warehouse	2	12.5054	0.6567	0.1857	3.5363
	3	3.3077	0.6224	0.3422	1.8188

Table 4.5: Experimental results for each position.

In Figure 4.5 the position accuracy is shown for the classroom setting, for anchor 0 NLOS. The histogram indicates the distance delta from the true coordinates for both the NLOS and mitigated results. The CDF for this histogram is also provided. A significant improvement can be observed. The mitigated result provides a position that is on average within 7cm of the true position, compared to 40cm on average for the NLOS position.



Figure 4.5: Position Accuracy for Classroom, Anchor 0 – NLOS

In Figure 4.6, a comparison of the performance is shown for each position overall, per room. It is clearly seen that the mitigation algorithm, on average, provides a much more accurate position. The standard deviation is also lower for the mitigation position solution. For most of the scenarios shown in the figure, the position accuracy more than doubles.



Figure 4.6: Mitigation Results for Each Room - Per Position

## 4.2.3 Overall Mitigation Results

A total overall summary of the experiments is also given in Table 4.6. On average, the mitigation algorithm provided an improvement factor of 2.8174 between the three rooms Overall, from the three rooms, the standard deviation of the results provided by the mitigated algorithm was lower than that of the raw NLOS results. This can also been seen in the histogram in Figure 4, where  $d_{NLOS}$  spans over a greater area than  $d_{Mitigated}$ . This was apparent on all histograms for all anchors per position, for every room.

N=3609	Room Dimensions	$rac{d_{NLOS}}{d_{Mitigated}}$	$\sigma_{NLOS}$	$\sigma_{Mitigated}$	$\frac{\sigma_{NLOS}}{\sigma_{Mitigated}}$
Lab	3.6m x 8.34m	2.4504	0.5293	0.3381	1.5655
Classroom	4.88m x 9.06m	2.661	0.6721	0.4116	1.6329
Warehouse	8.24m x 8.56m	3.3408	0.6699	0.3665	1.8278
	Average:	2.8174	0.6237	0.3720	1.6754

Table 4.6: Overall experimental results for each room.

The mitigation algorithm provided an overall combined improvement factor of 2.8174 for all of the rooms, with a deviation improvement of 1.6754. The difference in deviation between the NLOS solution and mitigated solution was 0.2517 meters. For the individual rooms, the improvement factor varied from 2.4504 to 3.3408. The improvement factor for the tag positions throughout the experiment varied from 1.5902 up to 12.5054. It was seen that that the more severe the NLOS obstruction, the greater the ranging error; thus the greater the improvement factor. If the wide aluminum foil board was placed directly in front of the tag, it would cause a greater deviation in NLOS reported distance than if it were to be placed somewhere in between the anchor and tag, thereby producing a higher improvement factor.

# 4.3 Hardware & Software Implementation

This section of the thesis focuses on the practical implementation aspect of the research. The main focus points of this paper were to identify NLOS conditions and to mitigate NLOS measurements. In order to be mitigate a range, it must first be determined that a range needs to be mitigated in the first place. In this work, there was both a hardware and software aspect.

### 4.3.1 NLOS Identification Using the EVB1000 Board

As discussed in Chapter 3, in order to detect NLOS, the difference between the FPath and the RSSI was used. Both of these parameters were not direct values taken from the EVB1000 but were instead calculated estimates that required multiple variable inputs that were taken from the registers of the EVB1000. NLOS can be identified visually using the Channel Impulse Response (CIR). Figure 4.7 shows the CIR graph for LOS and NLOS. It is seen visually that the NLOS CIR graph has a large amount of noise, and the first incoming pulse has amplitude similar to the rest of the incoming pulses.



(a) Channel Impulse Response for LOS



(b) Channel Impulse Response for NLOS

Figure 4.7: Live Channel Impulse Response Graphs

# 4.3.2 Obtaining the First Path Power Level and RSSI Values from the Registers

In order to obtain the first path power level of the signal, the variables F1, F2, F3, C and N needed to be recovered from the registers of the DW1000 chip. Figure 4.8 below shows an example of two registers, RX\_FINFO and RX\_FQUAL from which N (RXPACC), C (CIR\_PWR) and F3 (PP\_AMPL3) are extracted from [25]. All of the required variables are extracted from registers like these.

REC	EG:10:00 – RX_FINFO – RX Frame Information																														
31	30	29	28	27	26	25	24	23	22	21	20	19	18	17	16	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
RXPACC RXPSR									PSR	RXI	PRF	RNG	RX	BR	RXN	ISPL	-	R	XFL	.E			R)	KFLI	EN						
					(	)						(	)	(	)	0	(	)	(	)	0		0					0			
REC	G:12	2:04	1 – I	RX_	FQ	UAL	. – F	Rx F	ran	ne C	)ua	lity	Info	orm	atio	on (	Oct	ets	4 t	o 7,	2x1	.6-b	oit v	alu	es)						
31	30	29	28	27	26	25	24	23	22	21	20	19	18	17	16	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
	CIR_PWR																	PF	Ρ_Α	MP	L3										
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

Figure 4.8: Reading Registers to Get Parameters for FPath.

The registers for these values were indexed as shown in the above figure, where each indexed register consisted of 32 bits (4 bytes). The function used to recover these values was

dwt\_read16bitoffsetreg(int regFileID,int regOffset),

which was part of the Decawave API. In total there was three sets of these variables; one set for each anchor/tag combination. These values are calculated from each anchor/tag that is being used. It should be noted that to recover N, a bitwise mask of 0xFFF was applied to the register 0x10 and then shifted to the right by 32 bits. Table 4.7.

Register Description	Register Mnemonic	Value from Register	Register File (hex)	Byte Offset for Value (hex)
Receive Time Stamp	RX_TIME	F1	0x15	0x7
Rx Frame Quality information	RX_FQUAL	F2	0x12	0x2
Rx Frame Quality information	RX_FQUAL	F3	0x12	0x4
Rx Frame Quality information	RX_FQUAL	С	0x12	0x6
RX Frame Information	RX_FINFO	Ν	0x10	(0x10&0xFFF) >> 0x20

Table 4.7: Values Mapped to Registers

## **4.3.3** Delivering the Register Values to the Gateway Anchor (Anchor 0)

After recovering the required values from each anchor/tag as described in the previous section, the values had to be transmitted to the computer which was connected to anchor 0 to be processed. Only anchor 0 is connected to a computer, thus only F1, F2, F3, C and N between anchor 0/tag is directly accessible. The values from Anchor 1/tag and 2/tag need to somehow be provided to the computer in order to detect NLOS between those nodes. The problem is that anchor 1 and 2 are physically placed on opposite ends of the room. To acquire the values between the other anchors/tag, the Medium Access Control (MAC) layer was modified so that the frames exchanged between each of the anchors/tag included the required information and passed it back to anchor 0.

## 4.3.3.1 Message Scheme during Ranging

The message scheme sent between an anchor/tag during ranging is as follows: poll, response, final, report. This is the default messaging scheme provided by DecaWave on the TREK1000 system. An illustration of this scheme [23] is shown below in Figure 4.9. In order to get the required values from all of the anchor/tag combinations, the messages were modified to include the required values. This is further explained in the next sections.



Figure 4.9: Messages Exchanged between Anchor/Tag during ranging [23]

# 4.3.3.2 Frame Format of the Messages

Each message (poll, response, final, report) has a slightly different type of frame. A frame is the arrangement of a sequence of packets in a digital message. A packet is the unit of data digitally transmitted between a sender and a receiver. The standard IEEE 802.15.4 frame format is shown in Figure 4.10 below.



Figure 4.10: General IEEE 802.15.4 Frame Format [23]

The required values are inserted into the Ranging Message portion of the frame which is located at octet 9 and so forth, as seen in the above figure. Out of the four messages sent between the anchor/tag (ie. poll, response, final, report), only the final and report message needed to be modified to include the required data.

The Ranging Message portion of the final message was modified to include F1, F2, F3, C and N which would only be calculated on the tag. The tag would calculate these values every time it exchanged a message with an anchor. The final message was

changed	to be as	seen in	Figure 4.1	I. Additions	s to the fi	inal message f	format are indic	ated
by shade	ed cells.							

						New fields	inserted in	nto frame:	
Field:	Function	Poll TX	Resp RX	Final TX	C	N	<b>F</b> 1	F?	F3
	Code	Time	Time	Time	C	1	I I	Γ <i>Δ</i>	гJ
Field	1 Byte	5 Bytes	5 Bytes	5 Bytes	4 Bytes	4 Bytes	2 Bytes	2 Bytes	2 Bytes
Size:									
Buffer	9	10 - 14	15-19	20-24	25-28	29-32	33-34	35-36	37-38
Indices:									

(a) Frame format between Tag / Anchor ranging together

				New fields inserted into frame:				
Field:	Function Code	Calculated TOF*4	Range Number	С	Ν	<b>F1</b>	F2	F3
Field Size:	1 Byte	5 Bytes	1 Byte	4 Bytes	4 Bytes	2 Bytes	2 Bytes	2 Bytes
Buffer Indices:	9	10-14	15	16-19	20-23	24-25	26-27	28-29

(b) Frame format for anchor final report message to gateway anchor

Figure 4.11: Frame Additions

## 4.3.4 Mitigation Algorithm PC Software Implementation

The mitigation algorithm was also implemented on the software portion of the TREK1000 system. Once NLOS was identified, the mitigation algorithm would be run. For the software portion of the work, both the NLOS and mitigated position would appear on the screen to visually demonstrate how effective the algorithm is. If two or more anchors out of the three are NLOS, the algorithm will not be run and a message will appear. The program will also show which anchor(s) are experiencing NLOS and display color coded severity classification. The classifications was chosen based on testing with NLOS causing objects (including humans) and how they impacted the ranging result. Studies as in [28] show that NLOS ranging results vary depending on the obstructions present. In [28], it was shown for example that a glass wall had a lower impact on NLOS positive range biasing than a door. NLOS classification can be used as a further parameter in future mitigation algorithms which may rely on NLOS severity. More on NLOS classification can be found in Section 4.4.2. NLOS was classified and color coded in the following manner:

Δ Value	Color	Interpretation
$\Delta < 7$	No Color	LOS
$7 \ge \Delta \ge 10$	Yellow	Light NLOS
$10 \ge \Delta \ge 13$	Orange	Moderate NLOS
$\Delta > 13$	Red	Severe NLOS

Table 4.8: PC Software NLOS Color Coding

The hardware implementation section involved acquiring the RSSI and FPath parameters from the hardware and delivering them to the PC software based portion of the work. The parameters needed to be extracted from the DW1000 registers were F1, F2, F3, N and C. Once acquired, these parameters were then transmitted over UWB by adding them to the super frame. After all of the transmitted parameters are received at the gateway anchor (anchor 0), they are parsed by the PC software and are used as inputs to (3), (4), (5) to identify NLOS. Once NLOS is detected, the software implemented mitigation algorithm would be run accordingly, in real time.

### **4.4 Implementation Results**

Using the TREK1000 system, the EVK1000 boards were reprogrammed to provide to provide RSSI and FPath signal information. The signal information was used to accurately identify NLOS. While the mitigation algorithm was able to be successfully simulated and demonstrated using MATLAB, the functionality of NLOS detection was not able to be simulated using MATLAB. A practical implementation was used to demonstrate the ability to identify NLOS.

#### 4.4.1 NLOS Identification Results per Room

Using the same data set as for the experiments in Section 3.4.2, including the logged RSSI and FPath value, an observation was able to me made upon analysis of this data. Since the experiments in Section 3.4.2 were run as controlled experiments, where NLOS was artificially created and the identification of NLOS was known empirically, the data was compared to the empirical observations.
For each tag position in a room, NLOS was artificially created by placing an object between each anchor and the tag, with only one NLOS anchor at a time. The mean of the RSSI and FPath values for each anchor (402 measurements for each anchor) was taken and compared by taking the difference between the two parameters,  $\Delta$ . The results are shown in Table 4.9, a, b, c.

Warehouse N=1206		A0 is NLOS			A1 is NLOS			A2 is NLOS		
		RSSI	FPath	Δ	RSSI	FPath	Δ	RSSI	FPath	Δ
Position 1	A0	-83.96	-102.15	18.19	-81.40	-86.50	5.10	-80.94	-86.55	5.62
	A1	-83.55	-88.47	4.92	-85.75	-101.62	15.87	-84.26	-88.77	4.50
	A2	-82.43	-87.67	5.25	-83.51	-87.62	4.11	-87.53	-103.63	16.10
Position 2	A0	-86.24	-98.76	12.51	-80.79	-86.10	5.31	-82.69	-86.54	3.85
	A1	-82.10	-86.61	4.51	-85.40	-99.23	13.83	-81.81	-87.01	5.20
	A2	-83.23	-88.88	5.66	-83.43	-88.68	5.25	-88.29	-103.47	15.17
Position 3	A0	-85.89	-100.94	15.04	-82.99	-88.17	5.19	-82.67	-88.01	5.35
	A1	-82.35	-86.54	4.19	-86.45	-103.46	17.01	-82.41	-86.59	4.18
	A2	-81.98	-88.37	6.39	-83.24	-87.91	4.68	-86.41	-100.00	13.60
	A2	-81.98	-88.37	6.39	-83.24	-87.91	4.68	-86.41	-100.00	13.60

(a) Warehouse NLOS Identification Results

Classroom N=1206		A0 NLOS			A1 NLOS			A2 NLOS		
		RSSI	FPath	Δ	RSSI	FPath	Δ	RSSI	FPath	Δ
	A0	-83.87	-107.43	23.56	-83.12	-89.44	6.31	-81.90	-88.89	6.98
Position 1	A1	-82.78	-87.80	5.01	-85.62	-111.24	25.62	-83.33	-88.83	5.51
	A2	-80.25	-86.02	5.77	-80.39	-85.99	5.60	-82.28	-100.64	18.36
Position 2	A0	-85.54	-97.90	12.37	-82.12	-87.80	5.68	-81.55	-87.86	6.31
	A1	-81.57	-87.74	6.17	-86.72	-97.68	10.96	-81.81	-88.22	6.40
	A2	-81.66	-88.12	6.46	-81.70	-87.73	6.03	-83.41	-105.27	21.87
Position 3	A0	-83.64	-100.83	17.19	-81.55	-88.05	6.50	-81.18	-87.79	6.60
	A1	-81.43	-87.81	6.38	-84.08	-97.57	13.49	-80.64	-87.39	6.75
	A2	-80.76	-86.33	5.57	-80.73	-86.25	5.52	-84.12	-100.80	16.68

(b) Capstone Lab NLOS Identification Results

Lab N=1206		A0 NLOS			A1 NLOS			A2 NLOS		
		RSSI	FPath	Δ	RSSI	FPath	Δ	RSSI	FPath	Δ
Position 1	A0	-82.86	-103.23	20.38	-82.31	-88.42	6.10	-81.93	-88.09	6.16
	A1	-81.56	-87.71	6.15	-83.29	-101.79	18.49	-82.54	-89.02	6.48
	A2	-80.79	-86.48	5.69	-80.74	-86.14	5.40	-81.88	-103.23	21.34
Position 2	A0	-83.27	-103.16	19.89	-82.09	-88.06	5.97	-81.25	-87.70	6.45
	A1	-81.37	-86.76	5.39	-82.80	-104.08	21.28	-81.40	-86.74	5.34
	A2	-80.95	-87.26	6.31	-81.49	-86.87	5.38	-82.91	-96.97	14.06
Position 3	A0	-82.08	-100.93	18.84	-81.63	-87.79	6.16	-81.11	-87.54	6.43
	A1	-81.00	-87.02	6.02	-82.51	-96.70	14.19	-80.74	-87.22	6.48
	A2	-82.51	-88.62	6.10	-82.31	-88.84	6.53	-83.02	-108.44	25.42

(c) WiCIP Lab NLOS Identification Results

Table 4.9: NLOS Identification Results Per Room

In Table 4.9, the mean of RSSI, FPath, and  $\Delta$  are displayed for every anchor node in each position, for each room. From the tables, it was again observed that RSSI does not vary much under NLOS conditions. This further strengthens the preliminary RSSI experiments performed, such as those in Section 3.4.2. On the other hand, the FPath parameter varied greatly for an anchor experiencing NLOS. In all of the experimental results, the mean FPath for the anchor experiencing NLOS was significantly higher (>6dBm) than the FPath values for the LOS anchors.

The reason the difference,  $\Delta$ , between RSSI and FPath is used as an NLOS indicator instead of solely using FPath is because as mentioned previously, RSSI will not deviate much during NLOS conditions unlike FPath. In a scenario where all three anchor nodes are NLOS, the FPath parameter will be high for all of the anchors. Under this scenario it cannot be distinguished whether all of the anchors are experiencing NLOS or if the signal is a weak LOS signal. By using  $\Delta$ , a much more accurate prediction can be made. In Table 4.9, the  $\Delta$  for the anchor experiencing NLOS is highlighted. For all of the NLOS scenarios,  $\Delta$  was >10. By selecting  $\Delta$ >7 for the NLOS identification cutoff, a 90% NLOS identification accuracy was achieved.

Possible error in NLOS identification originated from a signal loss due to a long distance between the anchor and tag or from interference from other wireless signals.  $\Delta$  in

the WiCIP lab and capstone room was higher for LOS signals than in the warehouse area. The warehouse area does not have much Wi-Fi connectivity compared to the other two test rooms which are full of overlapping Wi-Fi access points. It is also difficult to identify NLOS when  $6 \le \Delta < 7$  because during this interval, NLOS causing obstructions may be insignificant, such as a person walking in between an anchor and a tag when the area of the room is large. When  $6 \le \Delta < 7$ , it had minimal error impact on the range measurements.

#### 4.4.2 NLOS Classification

In the experiments performed, it was empirically found that NLOS can be classified as "hard" or "soft". NLOS is said to be "hard" when signal attenuation due to the obstruction is very high, which causes  $\Delta$  to be >10. NLOS is said to be "soft" when signal attenuation due to an obstruction is on the lower end, which was found to be when  $7 > \Delta > 10$ . An example of "hard" NLOS would be when the aluminum board that was used in the experiments causing a  $\Delta >10$ . An example of "soft" NLOS would be a person in between an anchor/tag or an obstruction that is relatively small in comparison to the distance between the anchor/tag, such as a computer monitor.

<b>Δ Range</b>	Observation
$7 \ge \Delta \ge 10$	Highly likely to be "soft" NLOS
$\Delta > 10$	Highly likely to be "hard" NLOS

Table 4.10: Hard and Soft NLOS Classification Range

The detection of NLOS using the EVB1000 hardware was successful. By taking the difference between RSSI and FPath, the parameter,  $\Delta$ , was obtained. In the experiments, if  $\Delta$  was >7, then NLOS is present. As seen from the results Table 4.9, the NLOS anchors all had a  $\Delta$  that was >7.  $\Delta$  was much higher than 7 in the experiments because an aluminum foil covered board that was used in the experiments was a relatively large obstruction. For scenarios where a human walks in between the anchor/tag,  $\Delta$  jumps to around the 7 range. A low  $\Delta$  (7>  $\Delta$ >10) can be classified as "soft" NLOS. A high delta ( $\Delta$ >10) can be classified as "hard" NLOS.

# **CHAPTER 5 – Conclusion and Future Work**

#### **5.1 Conclusion**

In this thesis, NLOS conditions are identified classified and a target's NLOS position is successfully mitigated when only two LOS anchors are available by utilizing the physical geometry of the anchor distributions in a room. The model in this research assumed that the probability of one anchor experiencing NLOS out of three anchors is highest, thus a mitigation algorithm handling this most common case is proposed. The mitigation algorithm was able to mitigate a target's position, with increasing accuracy as the NLOS severity increased. In the experiments presented in this paper, an average improvement factor of 2.8174 was achieved using the proposed mitigation algorithm compared to the unmitigated NLOS out of the box solution. The standard deviation of the mitigation results was also lower than that of a system running no correction algorithm, with the standard deviation of the mitigated solution being 0.2517 meters less than the NLOS solution on average, across all the test rooms. No extra hardware or physical complexity is required when compared to other mitigation techniques such as the Kalman filter and hybrid schemes involving angle of arrival/ time of arrival. With the success in identifying NLOS, the proposed algorithm was able to be successfully implemented in the TREk1000 hardware. A 90% NLOS identification rate was achieved, with the identification error being primarily due to very light NLOS obstructions, such as a human being. For this reason, the severity of NLOS conditions was classified into "hard" or "soft" NLOS, which gave an estimate of how severely the signal was being attenuated. When NLOS was identified and classified as "soft", especially when  $6 \le \Delta < 7$ , it was challenging to accurately identify NLOS. The mitigation algorithm can be chosen to run at a user's preference, such as only running when NLOS is moderate to severe.

## **5.2 Future Work**

There is much future work in UWB based indoor positioning using time of arrival as this topic is relatively new. To begin, future work may directly involve an expansion of the work covered in this thesis. NLOS mitigation can be done for scenarios where two or all of the anchors in a system using three anchors are NLOS. A possible solution to scenarios where more than a single anchor is NLOS would be to apply weighted factors to NLOS classification by correlating NLOS severity with the associated positive range bias due to NLOS and then mitigate by using a model that can match NLOS weighted factors to an approximate distance error. Other areas of future work may include expansion of the research in this thesis to be able to cover multiple rooms and a study on various room compositions and how materials and temperatures in a room may affect indoor positioning on the UWB spectrum.

In the work covered in this thesis, only a single room was used at once. The ability to cover all the rooms in a building, with many sets of anchors per room will be critical. As a user moves from room to room, the ability for an anchor to handoff the tag to another room's anchor is important, particularly since the geometry of anchor locations is used. Geometric based algorithms will need to be able to dynamically change the positioning orientation of the anchors used, as new anchors will range with the tag as a user moves around a building and some tags will need to be discarded due to leaving a room or an area. If a room contains many metallic objects, there may be more multipath and the performance of an IPS will differ compared to a room with no metallic objects. The effect of temperature on UWB indoor positioning may also be a good area of future work as indoor environments may not be climate controlled and may be very hot in the summer or very cool in the winter. This may cause objects inside of a room to exhibit different attenuation and reflection behavior, which may have an effect on indoor positioning systems.

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