INDOOR POSITIONING USING MODULATED ECHO RADIO LOCALIZATION INSTRUMENT (MERLIN)

BY

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THESIS

Submitted in partial fulfillment of the requirements
for the degree of Master of Science in Electrical and Computer Engineering
in the Graduate College of the
University of Illinois at Urbana-Champaign, 2016

Urbana, Illinois

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ABSTRACT

In a world of advanced technology and its close integration within indoor environments, the ability to navigate people and devices indoors has become increasingly important for numerous applications. Global Positioning System (GPS) has solved the issue of positioning and navigation for outdoor environments. However, it fails to achieve a good indoor performance due to the lack of line of sight with the GPS satellites as well as drastic signal attenuation due to buildings. This calls for a new technology to address this field, thus making indoor positioning a focus of research and development in the past decade. This thesis discusses a positioning system called MERLIN, which is based on the phase information of CW RF signals. Different range estimation methods are also discussed. Indoor positioning or localization is bound to become a popular feature in the next generation of wireless systems.

To my Mom and Dad, for their love and support. Thank you for putting me through the best of education.

To Muffin, for being our bundle of joy for the years he was with us. He showed us that 'Love' could be a four legged word.

ACKNOWLEDGMENTS

There are numerous people I would like to thank for their help through the ups and downs of graduate life. I would like to thank them for their guidance, advice, love and support. I am happy to have met some of the best of individuals during my time here at ECE Illinois and I hope to take these memories and experiences with me wherever I go.

Foremost, I would like to express my gratitude to my advisor, Prof. José Schutt-ainé for supporting my decisions through my Master's program. It would have been difficult for me to switch topics and pursue my passion without his unfaltering support.

Secondly, I express my heartfelt thanks to Dr. Serge Minin, who played an instrumental role in the development of my thesis. I sincerely appreciate his endless patience and the time he took out from his busy schedule to brainstorm solutions to my problems.

I would also like to thank Dr. Chandrasekhar Radhakrishnan for strongly encouraging me to pursue graduate school and for believing in me and my decisions through my time here. I truly appreciate his advice on my doubts in making the smallest to the most significant decisions.

I express my gratitude to Prof. Steven Franke for the wonderful lectures in ECE 453. It is easily one of the best courses I have taken and it also inspired me to pursue RF engineering for my graduate studies and professional career.

Furthermore, I would like to thank Prof. Pavan Hanumolu, Prof. Songbin Gong, Prof. Jennifer Bernhard and Prof. Veeravalli for teaching some of the most memorable engineering courses from my graduate life. The knowledge I gained from these courses prepares me well to start my professional career in the industry.

I thank my amazing colleagues, mentors, juniors and friends for the interesting discussions, helpful advice and academic as well as emotional support: Romesh Nandwana, Saurabh Saxena, Rushabh Mehta, Sakshi Srivastava, Maryam Hajimiri, Varun Badrinath Krishna, Aarti Shah, Linjia Chang, Daniel Gardener, Jieping Wang, Ashwarya Rajwardan, Xu Chen, Da Wei, Yubo Liu, Rishi Ratan, Ankit Jain, Xinying Wang, Yi Ren and Thong Nguyen and many others whose names I might have missed.

A special shout out to Sagar Dhawan for listening to me complain through the hard times and for motivating me to stay on track. Last but not least, I would like to thank my family for having encouraged me to study at one of the best engineering colleges, and for supporting my decisions all the way.

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LIST OF ABBREVIATIONS

AWGN	Additive White Gaussian Noise
CW	Continuous Wave
EM	Electromagnetic
FFT	Fast Fourier Transform
FDMA	Frequency Division Multiple Access
RF	Radio Frequency
GLONASS	Russian Global Navigation Satellite System
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
IR	Infrared Radiation
ISM	Industrial, Scientific and Medical
LBS	Location Based Services
LO	Local Oscillator
LoS	Line of Sight
PLL	Phase Locked Loop
POA	Phase of Arrival
RFID	Radio Frequency Identification
RSS	Received Signal Strength
RSSI	Received Signal Strength Indicator
RTOF	Round Trip Time of Flight

Rx	Receiver
SDR	Software Defined Radio
TOA	Time of Arrival
Tx	Transceiver
UWB	Ultra-Wideband
WLAN	Wireless Local Area Network

CHAPTER 1

INTRODUCTION

1.1 Motivation

In the field of wireless communication, location based services and contextual awareness are on the rise. LBSs are applications or programs that rely on the position of the user in order to render services. These services include navigation, healthcare, safety and emergency services, billing and payments, and other personalized services. With many of these services migrating to the modern cellphone as the primary platform, there is a need for a strong, reliable, and accurate positioning technology. So far these services have been satellite based, making its application in an indoor environment a relatively new field. The existing indoor positioning technologies are fairly new and far from scalability. Advancement in indoor localization system design will open up a plethora of opportunities for the wireless industry while significantly improving the value of services already available.

There are multiple technologies in use today to determine the location of a user. GPS, or the Global Positioning System, is the most popular one for outdoor applications [1]. Unfortunately, GPS performance is unsatisfactory inside buildings, near urban canyons and underground. The GPS signal strength is highly attenuated because of the concrete obstacles. This renders GPS ineffective as a source for indoor positioning.

Hence, there is a need to develop a positioning system for indoor environments. However, there are multiple challenges for this task as there are numerous obstacles to EM wave propagation due to walls, furniture and presence of noise or interference. A good positioning system should be able to overcome these obstacles and determine the location with high accuracy. Some of the indoor technologies used today are shown in Fig. 1.1 [2].

The location or position of the user does not have to be absolute. It could

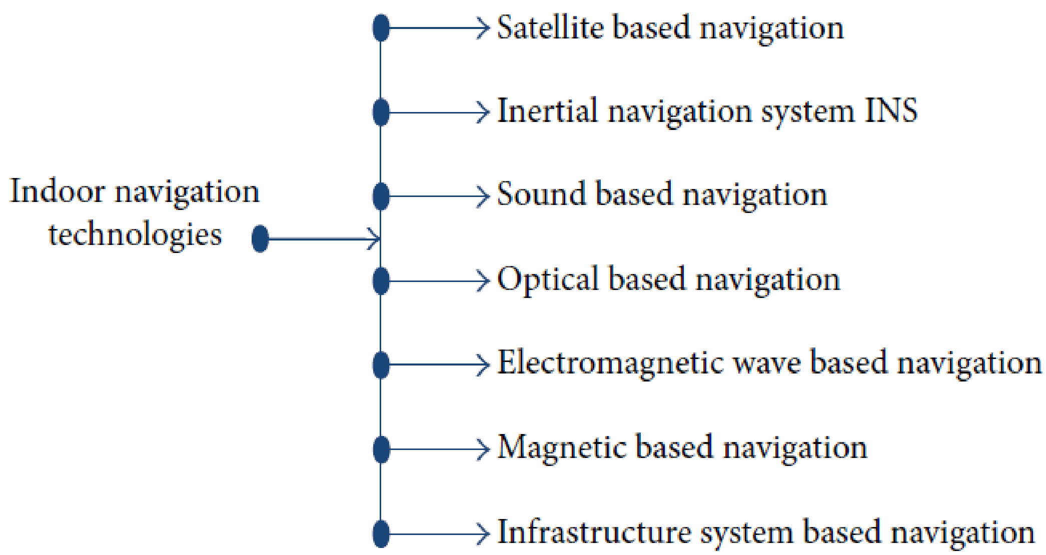

Figure 1.1: Indoor Navigation Technologies

be determined in relation to a pre-determined reference point as well. Thus, a positioning system should be able to estimate the location of a user (absolute or relative).

1.2 Positioning Systems

Positioning systems can be classified as indoor, outdoor or both based on the target environment. For outdoors, Global Navigation Satellite Systems (GNSS) have been in use to provide geo-spatial positioning globally. They rely on small receivers to determine their location based on the time signals transmitted from the satellites using RF. Presently, the United States GPS and Russian GLONASS are operational worldwide. China's *BeiDou-Compass* and European Union's *Galileo* are scheduled to be fully operational by 2020. Applications of these positioning systems range from asset tracking to navigation, geodetic survey and synchronization of telecommunication networks. The most widely used service, GPS, works well outdoors but does not perform well in urban canyons or inside buildings as the signals are highly attenuated by these obstacles. This renders GPS inefficient for indoor positioning.

An indoor positioning or localization system is one that can overcome these hurdles and provide location details for an indoor environment, such as buildings. Indoor environments are much more complex compared to outdoors. This gives rise to challenges like smaller equipment size, no LoS, influence of nearby objects and so on. Multipath is another issue as there are multiple reflective surfaces in an indoor environment. Interference from other wireless systems could also play a role in the overall performance of the indoor positioning system. The degree of accuracy needed for indoor environments is higher as well. An ideal positioning system would overcome all these challenges.

1.3 Applications

The development of an accurate and reliable indoor localization system could lead to exciting developments. The applications mentioned in this chapter give a glimpse of how indoor localization could change the world of wireless technology.

1.3.1 Location Based Services in Indoor Environments

This feature would have the biggest impact on business and marketing related firms. The geographical position of the client could be used to deliver contextually aware information. This feature could be used at venues like museums and fairs for navigation, advertising, information and billing. All these services have a high commercial value.

1.3.2 Smarter Homes

LBSs could be employed at home as well to detect lost items, provide assistance for kids and the elderly and a multitude of other possible applications like housekeeping robots etc.

1.3.3 Medical Care

Indoor positioning could enable accurate tracking of patients and equipment. In emergency situations, tracking of medical personnel becomes important too. If robotic assistance is involved, precise positioning might be helpful.

1.3.4 Social Networking

A large number of people indulge in social networking. Accurate indoor positioning might facilitate easier coordination of joint activities.

1.3.5 Police, Firefighters and Emergency Medical Services

Indoor positioning could provide some major benefits in law enforcement, rescue and fire services. Knowing the exact location of survivors in a building will make the search operations more time and resource efficient.

1.3.6 Self-Driving Automobiles

The advent of self-driving cars calls for a need for accurate positioning in covered environments such as underground tunnels and parking garages.

1.3.7 Industrial Asset Tracking

Most manufacturing processes employ robotics these days. Accurate positions might be useful in course guidance and collision avoidance.

1.4 Outline

This thesis provides a brief overview of indoor positioning history, concepts and technologies. It presents a novel method of range estimation called MERLIN, which when used in conjunction with positioning algorithms should reveal the previously unknown target location. Later, a few possibilities of introducing wireless localization as a feature in future communication devices are discussed.

- Chapter 1 covers the motivation behind this research and describes the primary differences between indoor and outdoor positioning systems.
- Chapter 2 looks into positioning technologies (IR,RF,Cell ID, etc.) being used today.
- Chapter 3 gives a brief overview of indoor positioning systems. It also describes the propagation challenges faced by RF based systems.
- Chapter 4 discusses some location detection techniques and algorithms.
- Chapter 5 introduces MERLIN, our positioning system, and briefly summarizes the process of localization.
- Chapter 6 provides the mathematical foundation for the system. Simulation results for different positioning techniques are also included.
- Chapter 7 presents in-lab measurements for distance estimation using time-domain signals.
- Chapter 8 concludes the thesis with some discussion of future possibilities.
- Lastly, the appendix includes the MATLAB code for the numerical analysis.

CHAPTER 2

POSITIONING TECHNOLOGIES

This chapter presents technologies that have been used in the past for positioning. Figure 2.1 shows the accuracy and range for different technologies [3]. We can also see that many of the technologies rely on EM waves. This chapter will primarily focus on RF based positioning systems.

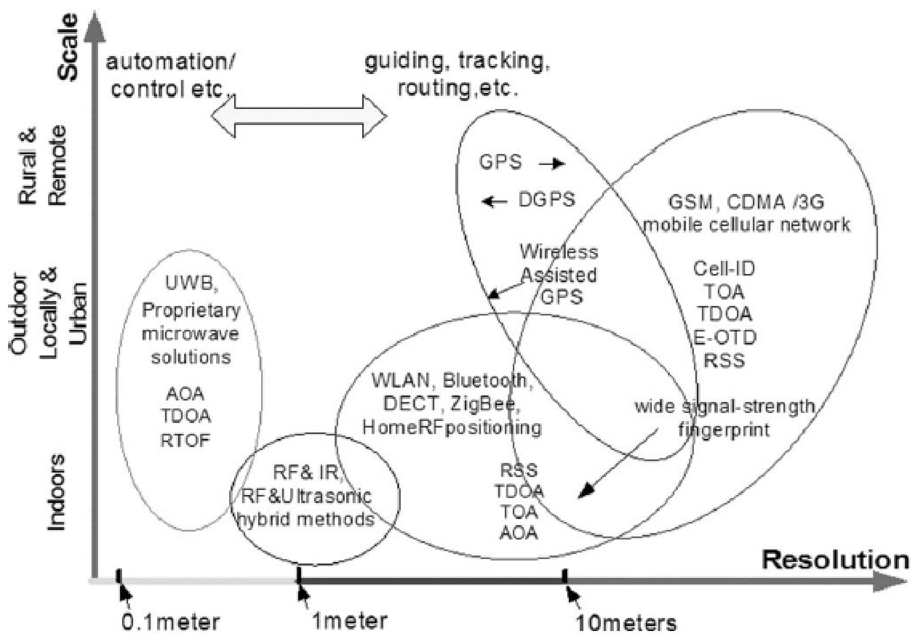

Figure 2.1: Overview of Wireless Positioning Systems

2.1 Global Positioning System (GPS)

GPS is the most popular radio positioning system used worldwide for navigation. However, it works well in outdoor environments only. In indoor environments it performs poorly due to obstruction of LoS between the satellite and the receiver and the attenuation of the signal by buildings and other obstacles [2].

2.2 Cell ID

Numerous systems use cellular networks for positioning but their accuracy is low. Cellular networks could be used for indoor positioning as long as there is a base station nearby such that the RSS is high.

2.3 Infrared Radiation (IR)

Another commonly used technology is infrared radiation (IR). Most IR devices use LoS communication. The main advantage of this technology is the small and compact device implementation. However, IR signals are limited by interference from fluorescent light and sunlight [4].

2.4 Radio Frequency (RF)

RF is being commonly used as a positioning technology these days. Due to its large wavelength, it can pass through obstacles resulting in larger range and less complicated hardware. RADAR by Microsoft Research was the first RF based technique for location determination and user tracking [5]. It uses RSS fingerprinting and WLAN components. RFID has also proved to be a promising technology for localization applications. RFID enables a one-way wireless communication that uses RF signals and RFID tags for the purpose of tracking. Tracking is carried out through a network of scanning devices at a distance of few meters without the need for LoS communication. The Bluetooth community has also been active with positioning applications. Bluetooth can easily be integrated into personal devices and operates in the license-free 2.4 GHz ISM band. It is also compact, low-cost and low-power. One disadvantage of Bluetooth is its device discovery feature, which gives rise to a localization latency which makes it unsuitable for real-time applications [2].

2.4.1 Ultra-wideband (UWB)

UWB, another radio technology, is meant for short-range, high bandwidth communication, and is very useful in overcoming multipath. A typical UWB system would include a stimulus radio wave generator and a receiver which captures the propagated and scattered wave. UWB hardware implementation is expensive, which becomes a disadvantage for wide-scale usage.

2.4.2 Radar

Radar (RAdio Detection And Ranging) is a technique to measure the distance and angle of incidence to a target. Originally, the radar concept involves determining the time of travel of a signal sent by an antenna and bounced back from a passive reflector. However, a significant amount of energy is lost due to the reflection and steerable antennas are difficult to implement. Thus, the concept can be modified to include more transmitters and active reflectors. Essentially, radars use the linear relation between RTOF and distance for localization. If the signals in each direction are separated in frequency, the signal can travel back immediately. A similar approach is used in our conceptualization of MERLIN.

2.4.3 FM

FM radio signals have also been used for positioning. FM radio uses FDMA, which splits a frequency band into multiple channels that can be used simultaneously. FM radio signals based on signal strength and fingerprinting can be used for indoor navigation. One of the advantages of this technology is the easy availability in most wireless devices.

2.4.4 ZigBee

ZigBee is an emerging wireless technology standard, mainly used for short and medium range communications. Distance calculation is based on RSSI values. ZigBee operates in the unlicensed ISM bands, making it vulnerable to interference from a wide range of signal types using the same frequency.

2.5 Hybrid Positioning Systems

Hybrid positioning systems are on the rise as well. They are defined as localization systems made by combining several positioning technologies. The local positioning systems fail outdoors and the GPS based systems fail indoors. Hence, there is a need for positioning systems that can do both. Several hybrid positioning systems are under development and are used in navigation services like Google Maps for Mobile, Sky Hook, Navizon and Combain Mobile [2].

CHAPTER 3

INDOOR POSITIONING OVERVIEW

A wireless indoor positioning or localization system mainly consists of a transmitter, and a receiver, or the measuring unit where the data processing takes place. Multiple transmitters and receivers maybe used to enable multilateration. This chapter looks at challenges of implementing positioning in an indoor environment. We briefly look at the different topologies of indoor positioning systems as well.

3.1 Indoor Radio Propagation Issues

According to the free-space radio propagation model, radio waves propagate in all directions with a signal power level proportional to $\frac{1}{r^2}$, where r is the distance that the wave travels. The propagation is affected by phenomena such as reflection, refraction , diffraction, and scattering. These result in the attenuation, distortion and additional losses of the transmitted signal.

If uninhibited, radio waves travel in a straight line. However, when they hit obstacles whose dimensions are larger than a wavelength, they get reflected or refracted. Reflection causes loss of signal strength as well. In an indoor environment, there are multiple obstacles to radio propagation such as walls, windows and furniture which cause multiple reflections of signals.

Refraction is caused by change in density of the propagation medium. The refracted traveling wave changes direction after getting refracted from walls and windows. Diffraction occurs when the waves hit sharp objects such as edges of a building. Diffracted waves bend around the object. Scattering is caused by localized non-uniformities in the medium, which are usually smaller objects such as construction material or small sized indoor equipment.

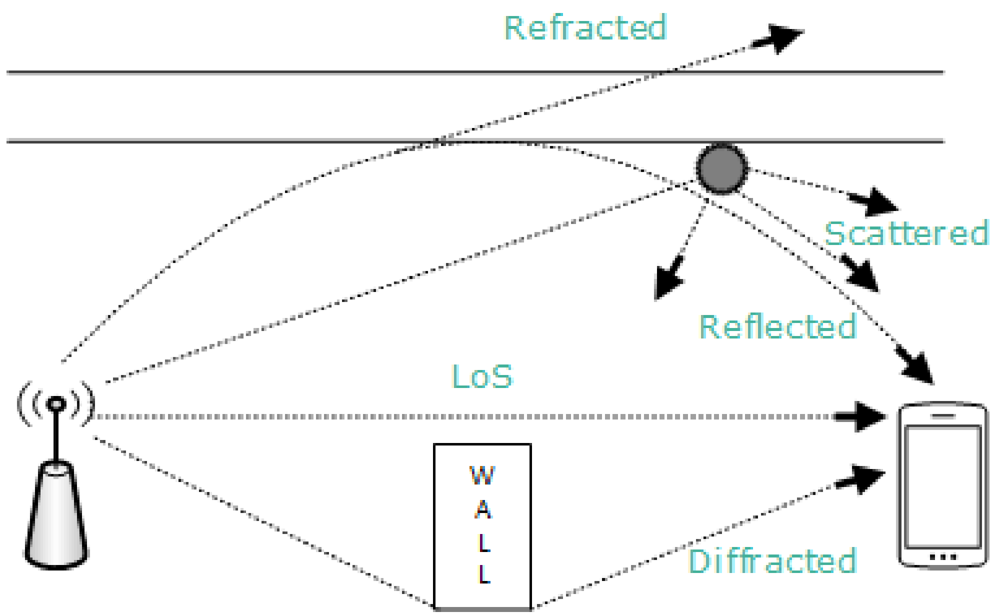

Figure 3.1: Causes of Multipath: Reflection, Refraction, Diffraction and Scattering

All of these effects give rise to the phenomenon of *Multipath*. Multipath refers to propagation of the transmitted signal to the receiver via two or more paths. It causes constructive as well as destructive interference and change of phase of the received signal. In a way, all these issues (shown in Fig. 3.1, adapted from [6]) may affect the range or accuracy of the positioning system.

3.1.1 Signal Attenuation and Noise Sources

Signal attenuation and noise are two of the main problems for a good positioning system. The transmitted signals need to be strong enough to be detected by the receiver. It is difficult to build a good positioning system using weak signals as the desired signal might get buried under noise. Signal attenuation is frequency dependent. The higher the frequency, the greater the attenuation. This is the reason why GPS does not work indoors. The signal undergoes severe attenuation as it passes through the concrete walls and metallic frames of buildings. Besides the attenuation of the signal itself, other factors such as AWGN noise, thermal noise, phase noise in oscillators and frequency synthesizers, and wireless interference from other electronic equipment severely affect the performance of the positioning system.

3.2 Topologies

Based on the role of the different hardware components, the topologies can be defined as in Table 3.1 [7]. To distinguish between remote and self positioning, if the measuring unit is mobile and has the capability to interpret the received signal and find the distance, then it is called a self-positioning system. On the other hand, for remote positioning systems, the signal transmitter is mobile and the measurement units are fixed. At the master station all the data is collected and the positions of the transmitters are calculated. One of the advantages of remote positioning systems is that the mobile device can be small, low-cost and low-power. However, this topology needs a complex backbone network which might be expensive. Different topologies might be better for different applications.

Table 3.1: Wireless Positioning System Topologies

Concept	Definition
Remote positioning	Measurement from remote site to mobile device
Self-positioning	Measurement from mobile unit to usually fixed transponders
Indirect remote positioning	Self-positioning with data communication of measurements to remote site
Indirect self-positioning	Remote positioning with data communication of measurements to mobile unit

If there is a means to communicate with the remote side, then the mobile unit has the option to send its measurements over for calculation. This makes it an indirect remote positioning system. On the other hand, if the measurements are passed from the remote unit to the mobile unit, then it can be considered an indirect self-positioning system.

CHAPTER 4

LOCATION DETECTION TECHNIQUES

Numerous different methods can be used for localization. Broadly, they can be classified into proximity, triangulation and scene analysis. Further classification of location detection techniques is shown in Fig. 4.1(adapted from [2]).

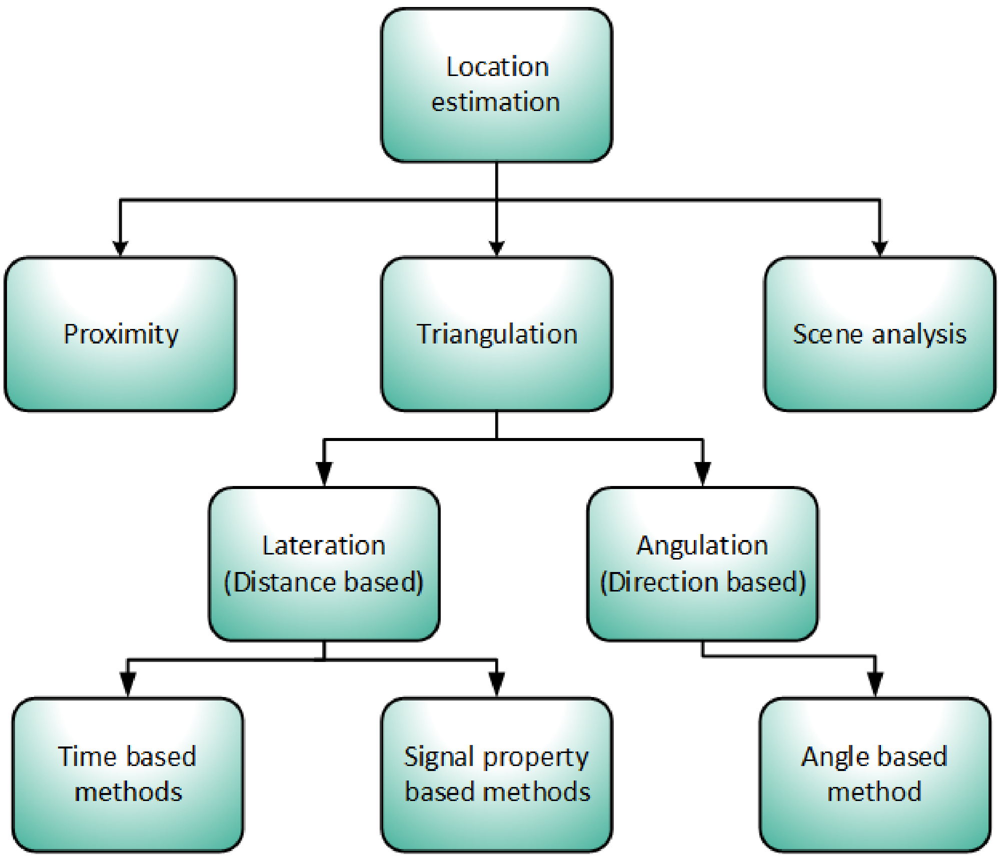

Figure 4.1: Classification of Location Detection Techniques

4.1 Proximity

The proximity method is comparatively easy to implement. The location is determined by the cell of origin (CoO) method where every cell has a known fixed location and a definite range. When more than one cell detects a signal from the target, the location is forwarded to the cell receiving the highest signal strength. This positioning technique is employed by the likes of RFID, cell ID and other custom devices.

4.2 Triangulation

Triangulation uses the geometric properties of triangles to estimate the user location. *Lateration* and *angulation* are derivatives of triangulation. Techniques that rely on RSS, POA and the measurement of the propagation-time (e.g., TOA, RTOF and TDOA) are called lateration techniques. AOA estimation is the angulation technique [2].

4.2.1 Lateration

Lateration estimates the position by measuring the distance of the user from multiple reference points. Thus, it can also be called the range measurement technique. Besides using RSSI to estimate distance, TOA and TDOA can be used where distance is found by multiplying the propagation velocity with the travel time. RTOF and POA can also be used for range estimation [3].

RSSI

The empirical model based on this method translates the difference between the transmitted signal strength and the received signal strength into distance as shown in Fig 4.2 [3]. At times this involves calculating the path loss due to propagation. Due to multipath in indoor environments, path-loss models are not always applicable. The accuracy of this method is low due to the dynamic nature of the radiation environment but can be improved by using pre-measured contours at the receiver [8].

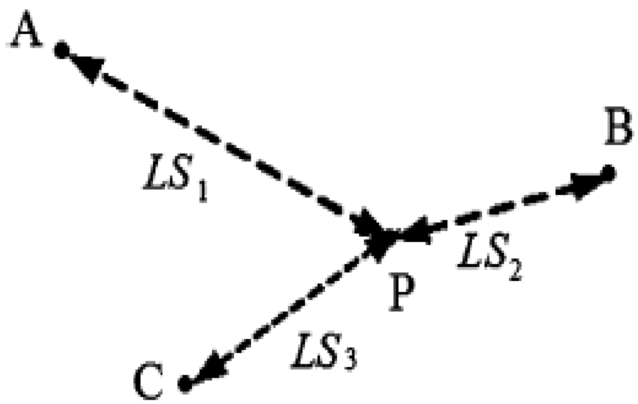

Figure 4.2: RSSI Based Positioning

TOA

The time taken for a signal to travel between two points is directly proportional to the distance between them. For a 2D location, TOA measurements must be made with respect to signals from at least three reference points. The main challenges in using this method are the need for synchronization of the transmitter and the receiver. Also, a time stamp is needed to determine the actual distance traveled. TOA can be measured using direct sequence spread spectrum (DSSS) or ultra-wideband (UWB). A geometric method can be used to compute the intersection points of the circles generated by each reference point for the estimated distance. One could also use the least squares, closest neighbor or the residual weighting algorithm for distance estimation. For example, in the LS algorithm, assume the mobile unit at (x_o, y_o), transmits a signal at time t_o,which is received by N base stations located at $(x_1, y_1), (x_2, y_2), ...(x_N, y_N)$ at time $t_1, t_2, ...t_N$. The cost function is given by

$$\mathbf{F(x)} = \sum_{i=1}^{N} {\alpha_i}^2 f_i^2(x) = 1 \tag{4.1}$$

where α_i is chosen to represent the signal reliability at the receiving location.

$$f_i(\mathbf{x}) = c(t_i - t)) - \sqrt{(x_i - x)^2 + (y_i - y)^2} \tag{4.2}$$

where c is the speed of light and $\mathbf{x} = (x, y, t)^T$. This function is formed for each receiving unit and $f_i(\mathbf{x})$ could be made zero. To determine the location, the function $\mathbf{F}(\mathbf{x})$ needs to be minimized [3].

TDOA

TDOA relies on the time difference between the instances when the transmitter signal arrives at multiple measuring units. Two hyperbolas are formed from TDOA measurements using three measuring units and their intersection point is considered to be the location of the target. Equation (4.3) shows the mathematical expression for the hyperboloid,

$$R_{i,j} = \sqrt{(x_i - x)^2 + (y_i - y)^2 + (z_i - z)^2} - \sqrt{(x_j - x)^2 + (y_j - y)^2 + (z_j - z)^2} \tag{4.3}$$

where (x_i, y_i, z_i) and (x_j, y_j, z_j) are the locations of the measuring units and (x, y, z) is the location of the target. A 2D target location can be found from the intersection of two or more measurements, as shown in Fig. 4.3 [3].

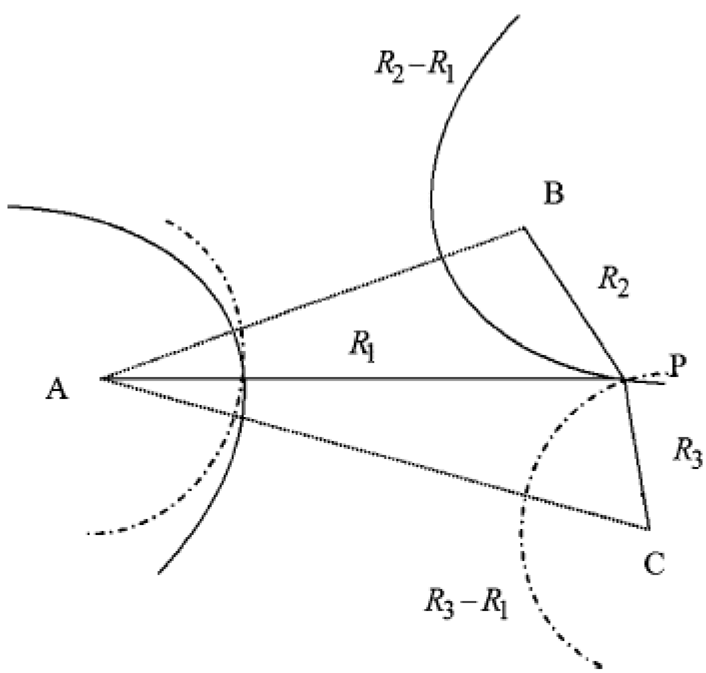

Figure 4.3: TDOA Based Positioning

RTOF

The RTOF technique measures the time of flight of the transmitted signal from the transmitter to the secondary unit and back. This method has a slightly relaxed requirement for time synchronization in comparison to TOA.

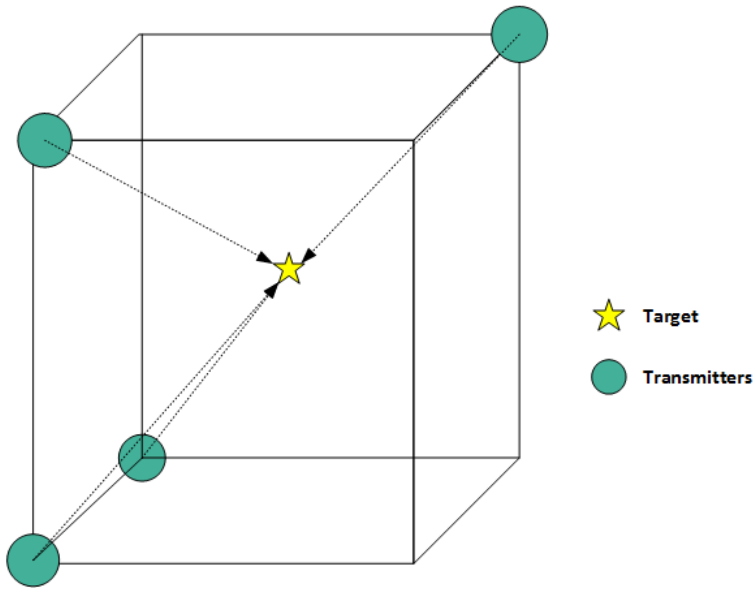

Figure 4.4: Phase of Arrival Based Positioning

POA

POA method uses the carrier phase (or phase difference) of the received signal to determine the distance as shown in Fig. 4.4 (adapted from [3]). All transmitters are considered to transmit sinusoidal signals at the same frequency *f*, with no initial phase offset. These signals are received with an acquired phase due to the transit delay. This delay can be expressed in terms of the carrier wavelength,

$$\phi_n = \frac{2\pi f d_1}{c} \tag{4.4}$$

Here ϕ_n is the acquired phase, d is the distance traveled between the transmitting and receiving end and c is the propagation velocity. The received sinusoidal signal can be represented as

$$S_n(t) = sin(2\pi f t + \phi_n) \tag{4.5}$$

This method works as long as the distance being estimated is smaller than the carrier wavelength. In other words, the acquired phase should not exceed 2π. Once the acquired phase is estimated, one can calculate the distance

$$d = \frac{\phi_n c}{2\pi f} \tag{4.6}$$

Next, we can use the positioning algorithms similar to the ones used in TOA measurements.

It would be best to use the POA method in an indoor environment in conjunction with other methods like TOA or RSSI for better prediction. One drawback of this method is ambiguous phase measurements.

4.2.2 Angulation

Angulation computes the angles of the signals relative to multiple reference points. The user location can be found from the intersection of the angle direction lines shown in Fig. 4.5, which are formed by the circles of radius equal to the distance between the master and the remote unit. One of the advantages is the need for fewer measuring units; only two are needed for 2D positioning. Disadvantages include complex hardware implementation and location estimate degradation as the distance increases [3].

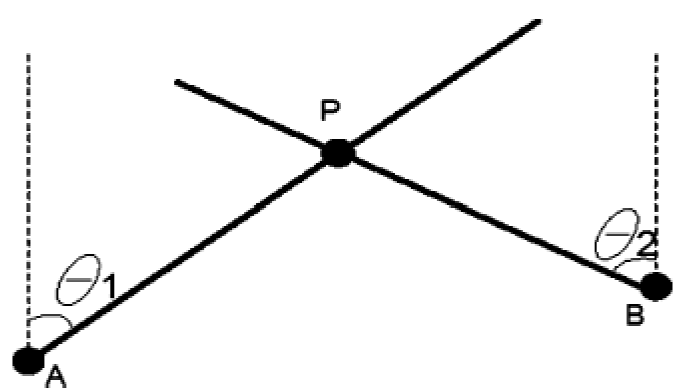

Figure 4.5: Angle of Arrival Based Positioning

4.3 Scene Analysis

Scene analysis depends on data collected previously at a scene to correlate with real-time measurements. Scene analysis using RF signals involves *fingerprinting*, where signal descriptive features or *fingerprints* are collected in advance [3]. An object's location is found by comparing new data collected by the mobile unit with the *scene fingerprint*. RSS based fingerprinting is very common.

CHAPTER 5

SYSTEM OVERVIEW

This chapter presents our RF based remote positioning system, called the Modulated Echo Radio Localization Instrument (MERLIN). This system employs a combination of POA technique for lateration and the reflection concept from radars.

5.1 MERLIN Distance Estimation Model

This model utilizes POA or phase of arrival technique to solve the distance estimation problem. The phases of the transmitted and received signals are measured at different frequencies to get the correct distance. Figure 5.1 shows the setup for our model.

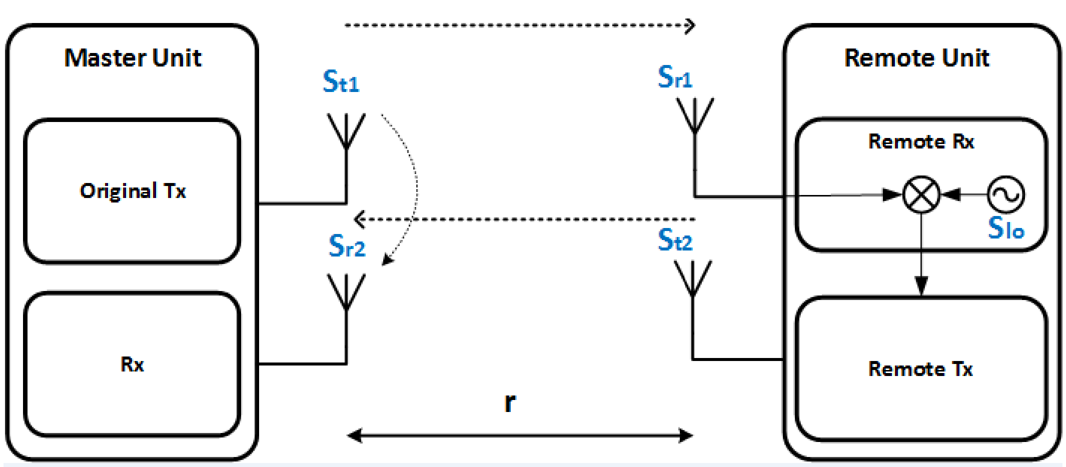

Figure 5.1: Conceptual Diagram

The system consists of a Master Tx/Rx and a target Tx/Rx. The unknown distance between the master and the target units is r. The Master Tx transmits a CW signal, S_{t1}, at frequency f_{c1} with an initial phase offset of Ψ_0. The signal acquires phase as it travels a distance r and is received by the target unit. This signal is mixed with the LO signal, S_{lo}, to generate CW signals with a frequency offset. The mixing of the carrier frequency with the LO signal results in sidebands, hence giving rise to the term *modulated*. The main reason for the use of an offset frequency for the re-transmitted signal is to be able to distinguish between the original transmitted CW signal and the final received CW signal at the master unit in a wireless environment. If this were to be implemented in a wire-line setup, there would be no need to shift the frequency. This newly generated signal, S_{t2}, along with the acquired phase and the phase offset of the LO is transmitted back to the master unit. This reflective action is analogous to an *echo*. The CW signal again accrues phase while traveling the distance r back to the master unit. The sum of all these phases is the overall phase of the signal received at the master unit. Once the phase is estimated, the distance can be calculated as explained in Chapter 6.

5.2 Distance Estimation using Phase Shift of Received Signal in Time Domain

The transmitted signal takes time to travel to the target object and back. If we look at the signals received at the master unit in time-domain, we observe that the signal S_{r2} is delayed as a function of the distance traveled. We compare the position of the nulls in the envelope signal for different distances to estimate the distance between the master unit and the target unit. More is explained in Chapter 6. The carrier frequency used for this observation is 150 MHz with an LO of 20 MHz. This frequency was chosen to facilitate the comparison with measurements on a real-time oscilloscope with a 200 MHz limit.

5.3 Distance Estimation using Phase of Received Signal in Frequency Domain

The phase estimation for the frequency domain relies on Fast Fourier transforms. For these simulations, the signals lie in the ISM band around 900 MHz as this frequency does not require a license for usage and does not interfere with the widely used Wi-Fi signals in an indoor environment. The wavelength at such frequencies is ≈ 0.3 m. The mathematical formulation of the signals is presented in Chapter 6. The frequencies of operation can be changed; however the main concept of this model should still be applicable.

5.4 Positioning using Trilateration

The distance r determined from the phase information of the received signals is an indication of how far the target is from the known location. If we draw a locus of the points that are a distance r away from the source, then we get a circle with radius r and center at the location of the source transmitter. To find the exact location of the target, more transmitters are required. On using two more transmitters at known locations, we can draw the locus of the possible location of the target with respect to each transmitter. This gives us three circles as shown in Fig. 5.2 [2], one for each transmitter. The point of intersection of these three circles should give us the exact 2D position of the target. Therefore, this positioning technique makes use of the following:

- Distance of the target from three different transmitters whose locations are known.
- Geometrical coordinates of the three points.

For example, if we determine the distance r_{21} between node 2 and the target (represented by 1 in Fig. 5.2), we can conclude that the target lies on the circumference of the circle with radius r_{21} centered at node 2. We can use the Euclidian distance equation to represent the circle, as shown in Eq. (5.1).

$$(x_1 - x_2)^2 + (y_1 - y_2)^2 = r_{21}^2 \tag{5.1}$$

where (x_1, y_1) and (x_2, y_2) are the coordinates of the target and the node 2 master unit respectively. The location of nodes 2, 3 and 4 are known. The location of the target is unknown. To determine the location of the target we need to find values of (x_1, y_1) that satisfy the set of equations shown in

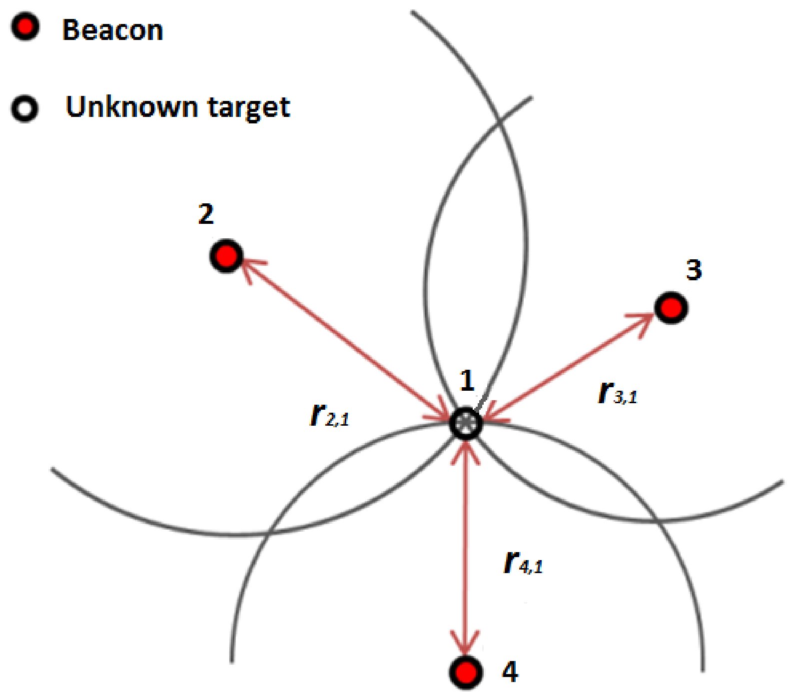

Figure 5.2: Location Estimation using Trilateration

Eq. (5.2).

$$\begin{bmatrix} (x_1 - x_2)^2 + (y_1 - y_2)^2 \\ (x_1 - x_3)^2 + (y_1 - y_3)^2 \\ (x_1 - x_3)^2 + (y_1 - y_3)^2 \end{bmatrix} - \begin{bmatrix} r_{21}^2 \\ r_{31}^2 \\ r_{41}^2 \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix} \tag{5.2}$$

This is the trilateration method of location determination. It maybe possible that due to noise, the curves do not intersect at a particular point. Thus, it is better to have more than the minimum number of transmitters to increase the possibility of an accurate prediction. One could also implement the Kalman filter algorithm to disregard the unlikely positions from the predictions. Kalman filter, or the linear quadratic estimation (LQE), uses a series of measurements observed over time, containing statistical noise and other inaccuracies, and produces estimates of unknown variables that tend to be more precise than those based on a single measurement alone.

CHAPTER 6

NUMERICAL SYSTEM MODEL AND SIMULATIONS

In this thesis, we mainly look at positioning using phase information of the received CW signal. The task of finding the target position can be broken down further into:

- Formulating the transmitted and received signals
- Determining the phases of the signals on the receive end
- Estimating distance from phase information

It is assumed that propagation velocity of the waves is c, where c is the speed of light in vacuum and is equal to $\approx 3 * 10^8 \frac{m}{s^2}$. In reality, the velocity of wave propagation depends on the material medium and is defined by $v = \sqrt{\frac{1}{\mu\epsilon}}$, where μ is the magnetic permeability of the material and ϵ is its dielectric constant. In an indoor environment, signals might travel slower due to the presence of media other than air.

Say the original transmitted signal from the master unit is a CW signal at frequency f_c with amplitude proportional to a constant A, and a phase offset of ψ_o:

$$S_{t1}(t) = Asin(2\pi f_c t + \psi_o) \tag{6.1}$$

This signal travels to the remote unit distance r away and accrues phase such that

$$S_{r1}(t) = Bsin(2\pi f_c(t + \frac{r}{c}) + \psi_o) \tag{6.2}$$

where S_{r1} is the signal received at the target unit. On this end, the signal is mixed with an LO signal at frequency f_{lo} and amplitude C. ψ_r is the phase offset introduced by the LO.

$$S_{lo}(t) = Csin(2\pi f_{lo} t + \psi_r) \tag{6.3}$$

After mixing, the signal is translated to frequencies $f_c + f_{lo}$ and $f_c - f_{lo}$ to give S_{t2},

$$\begin{aligned}
S_{t2}(t) &= S_{r1}(t) * S_{lo} \\
&= Bsin(2\pi f_c(t + \frac{r}{c}) + \psi_o) * Csin(2\pi f_{lo}t + \psi_r) \\
&= \frac{BC}{2} * cos[(2\pi f_c(t + \frac{r}{c}) + \psi_o) - (2\pi f_{lo}t + \psi_r)]... \\
&\quad - cos[(2\pi f_c(t + \frac{r}{c}) + \psi_o) + (2\pi f_{lo}t + \psi_r)] \\
&= \frac{BC}{2} * cos[2\pi(f_c - f_{lo})t + 2\pi f_c\frac{r}{c} + \psi_o - \psi_r]... \\
&\quad - cos[2\pi(f_c + f_{lo})t + 2\pi f_c\frac{r}{c} + \psi_o + \psi_r]
\end{aligned} \tag{6.4}$$

The signal described in Eq. (6.4) is then transmitted back to the master unit (original transmitter), where it is called S'_{r2}. The signal received at that end is described in Eq. 6.5). This includes the original signal S_{t1}.

$$\begin{aligned}
S_{r2} &= S_{t1} + S'_{r2} \\
&= Asin(2\pi f_ct + \psi_o) + \frac{BC}{2} * [cos(2\pi(f_c - f_{lo})(t + \frac{r}{c}) + 2\pi f_c\frac{r}{c} + \psi_o - \psi_r)... \\
&\quad - cos(2\pi(f_c + f_{lo})(t + \frac{r}{c}) + 2\pi f_c\frac{r}{c} + \psi_o + \psi_r)] \\
&= Asin(2\pi f_ct + \psi_o) + \frac{BC}{2} * [cos(2\pi(f_c - f_{lo})t + (4\pi f_c - 2\pi f_{lo})\frac{r}{c} + \psi_o - \psi_r)... \\
&\quad - cos(2\pi(f_c + f_{lo})t + (4\pi f_c - 2\pi f_{lo})\frac{r}{c} + \psi_o + \psi_r)]
\end{aligned} \tag{6.5}$$

The received signal is composed mainly of three frequencies, $f_c, f_c + f_{lo}$ and $f_C - f_{lo}$. Defining the phase of arrival of the received signal at each of these frequencies,

$$\begin{aligned}
\angle S_{f_c} &= \psi_o \\
\angle S_{r2_{up}} &= (4\pi f_c - 2\pi f_{lo})\frac{r}{c} + \psi_o + \psi_r) \\
\angle S_{r2_{dwn}} &= (4\pi f_c - 2\pi f_{lo})\frac{r}{c} + \psi_o - \psi_r)
\end{aligned} \tag{6.6}$$

where $S_{r2_{up}}$ is at $f_c + f_{lo}$ and $S_{r2_{dwn}}$ is at $f_c - f_{lo}$. To eliminate the unknown offsets we use Eq. (6.7).

$$\begin{aligned}\Delta &= \angle S_{r2_{up}} + \angle S_{r2_{dwn}} - 2\angle S_{f_c} \\ &= 8\pi f_c \frac{r}{c}\end{aligned} \tag{6.7}$$

Hence, if we can acquire phase information of the transmitted and received CW signals, then we can determine the distance r using Eq. (6.8).

$$r = \frac{c \cdot \Delta}{8\pi \cdot f_c} \tag{6.8}$$

where c is the propagation velocity.

6.0.1 Use of Multiple Frequencies

There is one drawback with such a model. The distance estimated will always have an ambiguity of being of the form $r+n\lambda_c$, where n is an integer multiple and λ_c is the wavelength of the carrier. To avoid this ambiguity we can make use of two carrier frequencies f_{c1} and f_{c2}. The first step would be to use f_{c1} to calculate Δ. The second step would be to repeat the same calculation for f_{c2}. This gives us two values, $\Delta_{f_{c1}}$ and $\Delta_{f_{c2}}$. Using this information, we can calculate the quantities mentioned in Eq. (6.9).

$$\begin{aligned}\Delta_{big} &= \Delta_{f_{c1}} - \Delta_{f_{c2}} \\ f_{diff} &= f_{c1} - f_{c2}\end{aligned} \tag{6.9}$$

These values can be substituted into Eq. (6.8) to give Eq. (6.10).

$$r = \frac{c \cdot \Delta_{big}}{8\pi \cdot f_{diff}} \tag{6.10}$$

Equation (6.10) gives us the distance between the master and remote unit. This is the required distance.

6.1 Analysis in Time Domain

We can look at what the signals would look like in the time-domain. For this purpose, one could use a real-time oscilloscope. In run mode, the scope continues to acquire and display each condition that matches the scope's trigger specification. Variable or infinite persistence enables successive signal captures to be overlaid on the original signal [9].

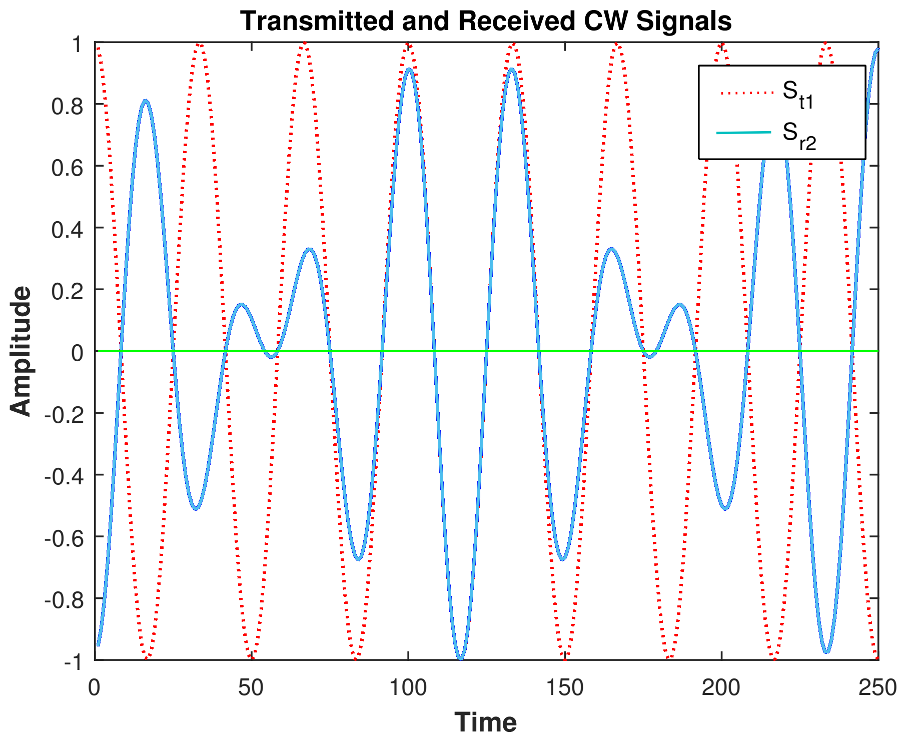

Figure 6.1: Signals Received at Master Unit (Time Domain)

Figure 6.1 shows what the received signals would look like at the master unit. The received signal is composed of:

- The transmitted signal S_{t1}, which is received due to the wireless nature of the system. This signal barely travels any distance and can be assumed to have accumulated no phase.
- The round-trip S_{r2} signal, which is a superposition of the S_{r2up} and S_{r2dwn} signals, giving it the appearance of being amplitude modulated.

The S_{r2} signal is delayed in time as it travels a long distance. The time delay is proportional to the distance traveled. In order to find the distance traveled by the wave, we use the nulls of the envelope of the signal. Figure 6.2 shows the S_{r2} signal with its envelope.

The nulls are a clear indication of how the waveform moves as distances increase. We can use the time difference between nulls for zero distance and

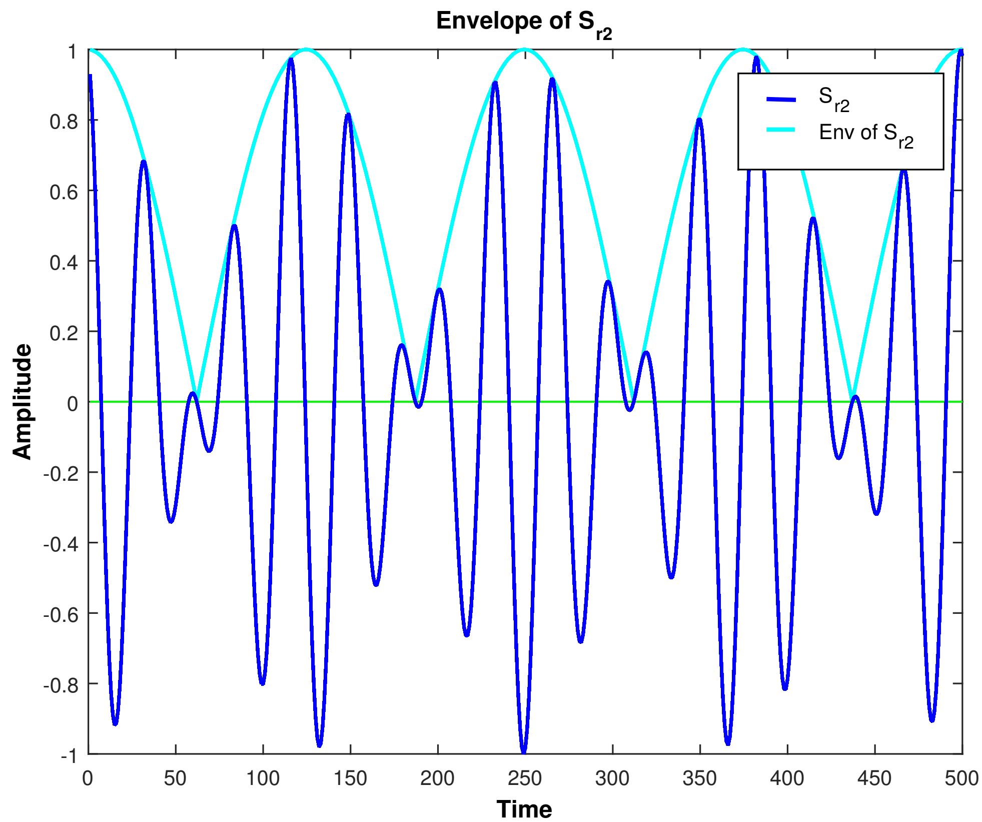

Figure 6.2: Signal S_{r2} and Its Envelope in Time Domain

some distance r to calculate the distance traveled by the wave. Figure 6.3 shows the received signals in time domain for $r = 0$.

Figure 6.4 shows the signals for $r = 0.5$ m. We can see from the markers in Fig. 6.3 and Fig. 6.4 that the nulls of the envelope lie at time stamps 62 and 54 respectively. The time step, t_{step} for these calculations is 0.2 ns. This translates to

$$\begin{aligned} t_{null}(r = 0\,\mathrm{m}) &= 62 \times t_{step} = 62 \times 0.2 \times e^{-9}\,\mathrm{s} = 12.4\,\mathrm{ns} \\ t_{null}(r = 0.5\,\mathrm{m}) &= 54 \times t_{step} = 54 \times 0.2 \times e^{-9}\,\mathrm{s} = 10.8\,\mathrm{ns} \end{aligned} \tag{6.11}$$

To calculate the distance we use the following relation between the change

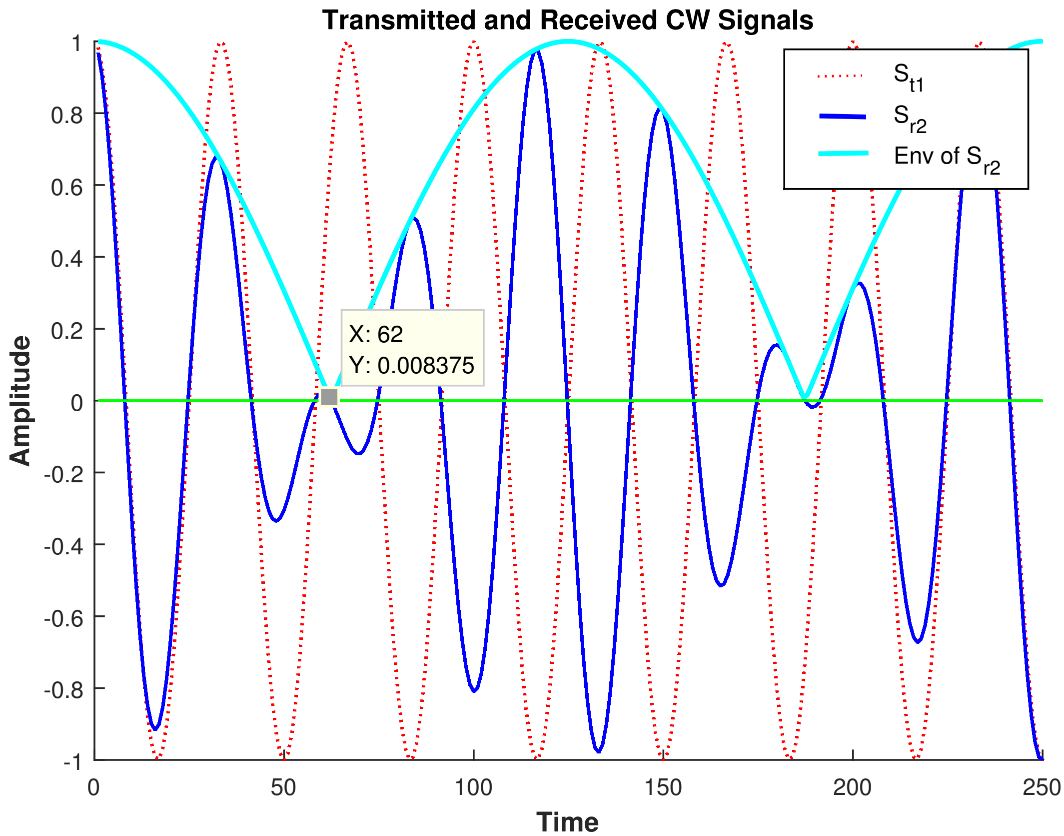

Figure 6.3: Received Signal Waveform for $r = 0$ m

in phase and the distance traveled:

$$\begin{aligned} \Delta\phi &= \frac{2\pi f_{env} r}{c} \\ r &= \frac{\Delta\phi}{2\pi f_{env}} \cdot c \\ &= \frac{\omega_{env}\Delta t}{2\pi f_{env}} \cdot c \\ &= c \cdot \Delta t \end{aligned} \tag{6.12}$$

where $\Delta\phi$ is the phase change due to the distance traveled by the wave and is also equal to $\omega_{env} \cdot \Delta t$, f_{env} is the frequency of the envelope of S_{r2}, ω_{env} is the angular frequency of the envelope and is equal to $2\pi f_{env}$ and c is the speed of light$\approx 3 \times 10^8$ m/s. If we know the shift in time of the waveform, we should be able to determine the distance using Eq. (6.11) and Eq. (6.12):

$$\begin{aligned} r &= c \cdot (12.4 - 10.8) \cdot 10^{-9} \\ &= 0.48\,\mathrm{m} \approx 0.5\,\mathrm{m} \end{aligned} \tag{6.13}$$

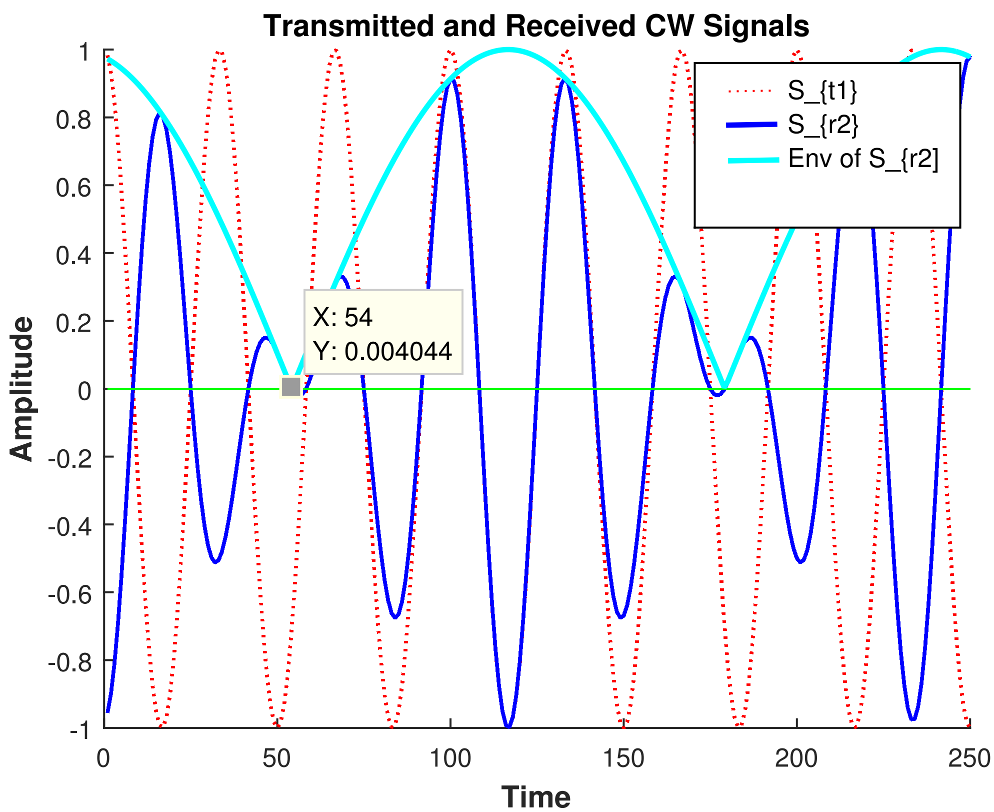

Figure 6.4: Transmitted and Received Signal Waveform for $r = 0.5$ m

Thus, we were able to recover the distance from the time-domain waveforms.

6.2 Analysis in Fourier Domain

As mentioned in the previous sections, the determination of the phase of the received signals is the key to finding the location of the target. This mathematical model was implemented in MATLAB. Mainly two methods were used to determine the phase of the signals: FFT and PLL . This chapter goes over the implementation of the FFT method.

The band of operation for this setup is chosen to be in the license-free ISM range. We also assume the amplitude coefficients of the transmitted signals to be 1. Initially, the phase offset at the transmitter, as well as the phase offset introduced by the local oscillator, is assumed to be zero for simpler calculations. These quantities can be modified to observe their effect on location tracking.

For $f_{c1} = 910$ MHz, $f_{c2} = 920$ MHz and $f_{lo} = 20$ MHz, we implement the mathematical model described earlier in this chapter. Note that $\lambda_{c1} = 0.3294$ m and $\lambda_{c2} = 0.3259$ m. These values need to be kept in mind, as for distances beyond half a wavelength (one full wavelength in round trip), the issue of unambiguity is introduced. This is resolved using at least two different frequencies, and is the main reason for the use of f_{c2}.

Listing 1: Sampling Frequency and Time Vector

```
fs_fc2=10*f_c2;
t_fc2=0:1/fs_fc2:1000*1/fs_fc2;
```

For FFT, the sampling rate is defined in Listing 1. The number of the points were chosen for convenience, so that the expected FFT peaks are at a frequency that is an integer multiple of the sampling frequency. The double sided FFT plot for the transmitted signal is shown in Fig. 6.5, where we can see that the peak lies at f_{c1}.

If the FFT peak is not at f_{c1}, then we can find the index for the closest frequency using Listing 2.

Listing 2: To find closest f value

```
s_t1err=abs(f-f_c);      %Minimizing difference
[idx idx]=min(s_t1err); %Index of closest
                         %frequency
closestf=f(idx);         %Closest frequency
```

The double sided FFT plot for the received signal is shown in Fig. 6.6, where we can see that the peak lies at 930 MHz and 890 MHz.

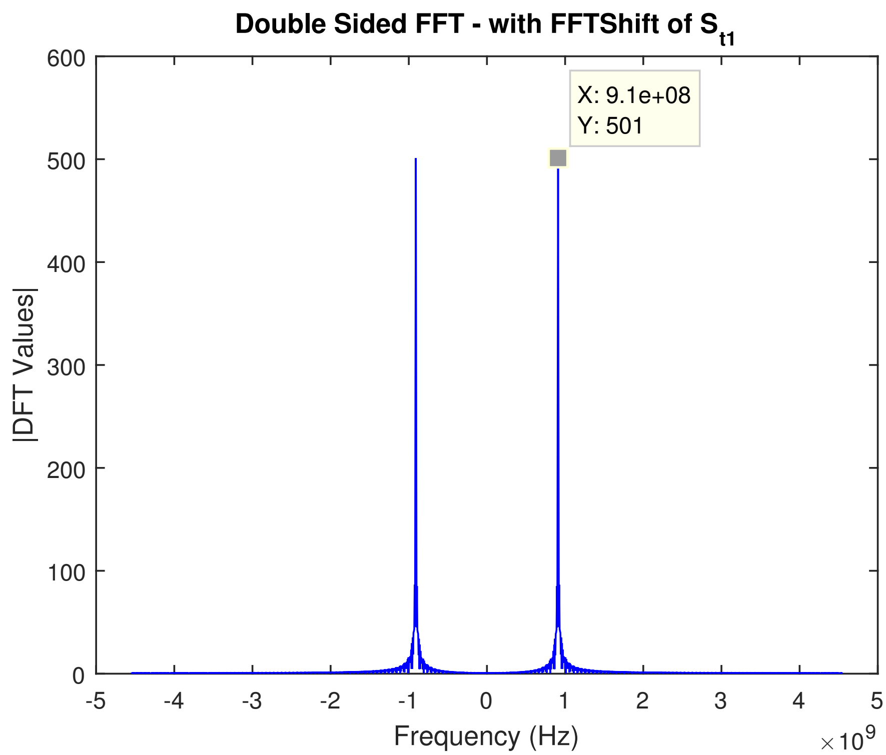

Figure 6.5: FFT Plot for S_{t1}

To obtain the phase information for different frequencies, there are multiple approaches like using the *phase* or *angle* commands in MATLAB. In this script the tan inverse relation shown in Listing 3 is used to obtain the phase of S_{t1} , S_{r2up} and S_{r2dwn}. Here, X is the transmitted signal S_{t1}.

Listing 3: Calculating phase information

```
phase=atan2(imag(X),real(X))*180/pi;
```

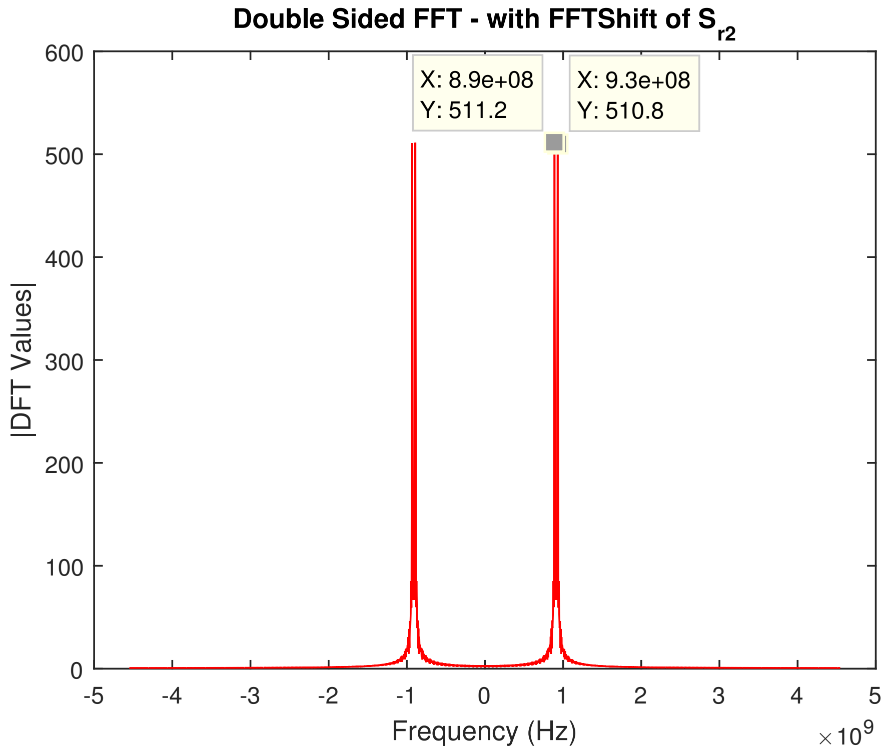

Figure 6.6: FFT Plot for S_{r2}

The phase information is substituted in Eq. (6.7) and Eq. (6.8). On comparing the actual distance with the estimated distances, we notice that some of the distances are negative. Slight modification shown in Listing 4 is used to correct it. Figure 6.7 shows the comparison results after the modification.

Listing 4: For negative distances

```
if r_cal<0
    r_cal=r_cal+((lambda_fc)/2);
end
```

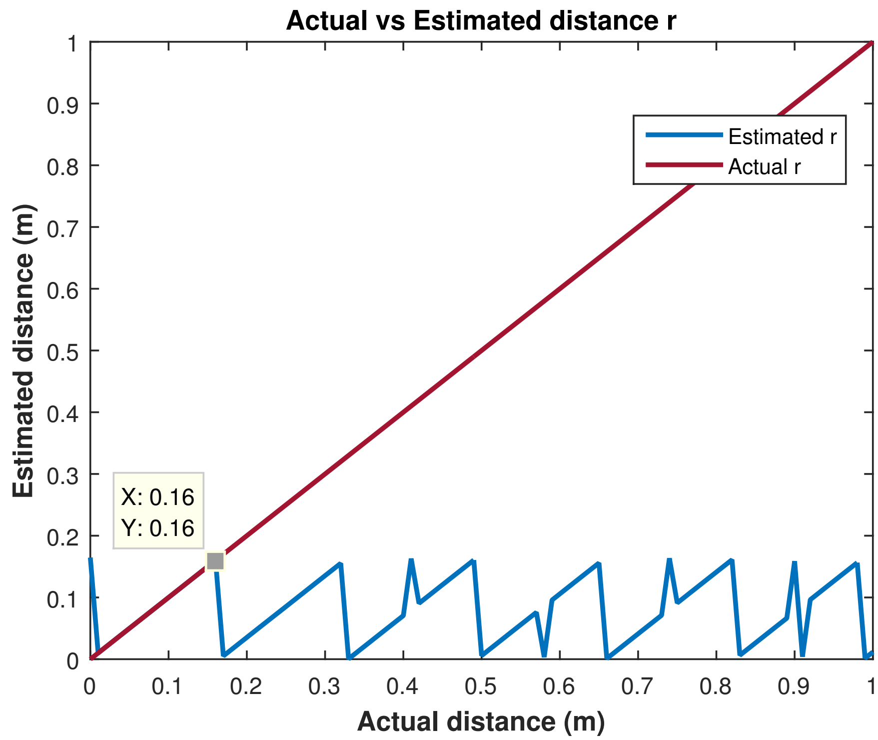

Figure 6.7: Distance Estimation with Single Carrier Frequency

We can see that the method with single carrier frequency fails beyond a distance of 0.16 m which is equal to $\frac{\lambda_{fc1}}{2}$. Beyond this distance the problem of wavelength ambiguity kicks in. To overcome this we use two carrier frequencies.

We introduce the concept of *Bigdelta* which is basically from Eq. (6.9). Listing 5 shows the code for it.

Listing 5: Bigdelta

```
Bigdelta=(delta_fc2-delta_fc1);
r_cal_del=(Bigdelta*c)/(8*pi*fdiff);
```

The estimated distance is shown in Fig. 6.8. We observe that the method fails for some values of r. It can be seen be seen that when it fails the estimated value of r is negative. On investigating further, it was noticed that this was due to the 2π periodicity of the wrapped phase. Changes were made to the code as shown in Listing 6.

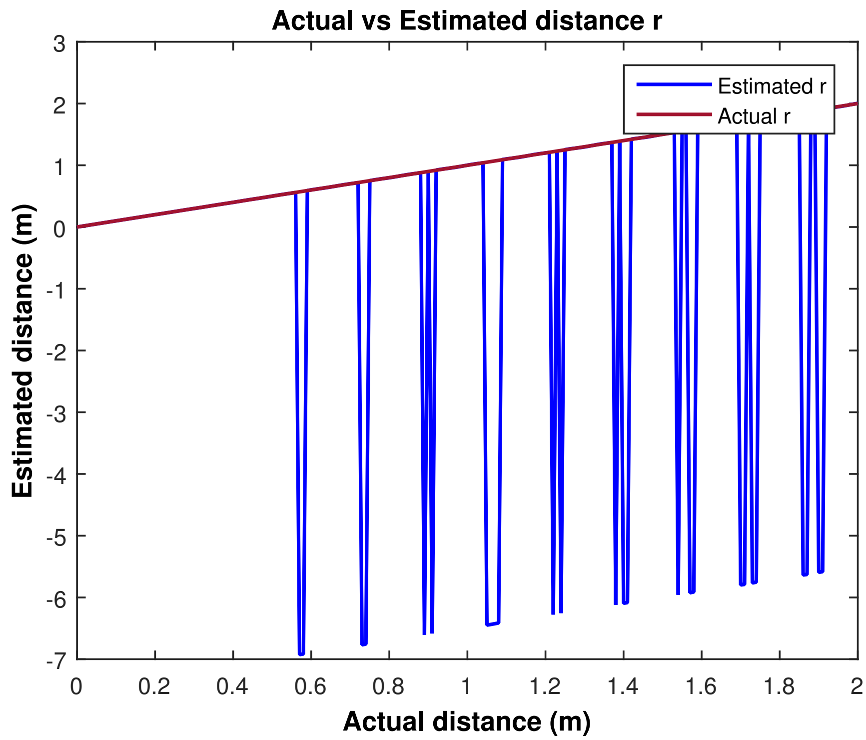

Figure 6.8: Distance Estimation with Two Carrier Frequencies

Listing 6: To unwrap phase

```
if delta_fc1>delta_fc2
    delta_fc2=delta_fc2+(2*pi);
    Bigdelta=(delta_fc2-delta_fc1);
    r_cal_del=(Bigdelta*c)/(8*pi*fdiff);
else
    r_cal_del=(Bigdelta*c)/(8*pi*fdiff);
end
```

The outcome after the changes are made is shown in Fig. 6.9. The distance is correctly tracked without any wavelength or phase ambiguity.

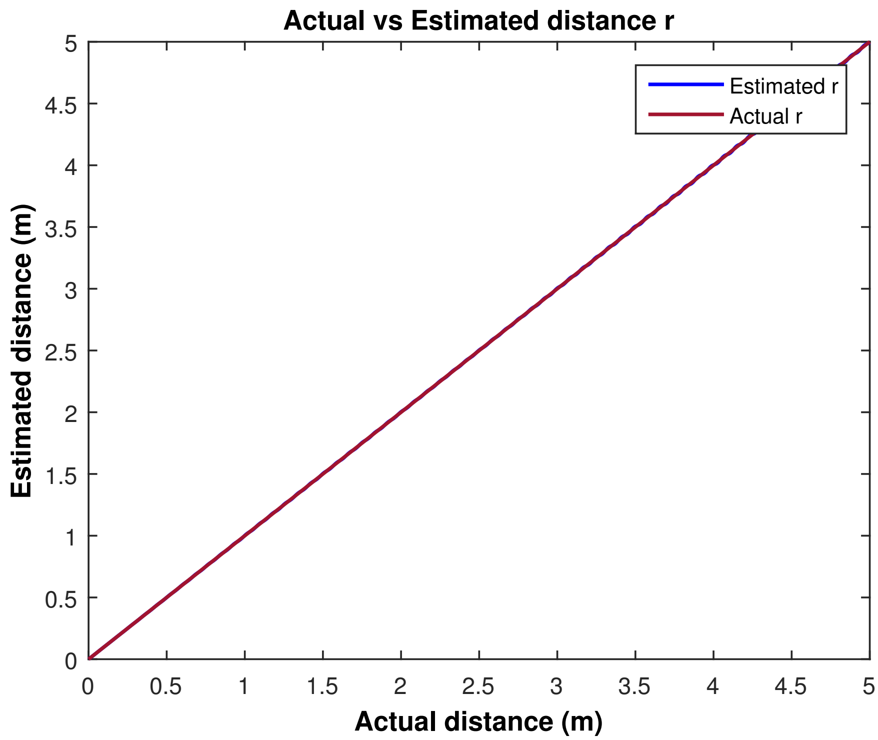

Figure 6.9: Distance Estimation using Two Carrier Frequencies (No Ambiguity)

Hence, Fourier analysis of the transmitted and received signals yields the correct distance between the master unit and the target unit.

6.3 Analysis using Phase Lock Loop

The computational cost of using the FFT method for phase tracking is high. This section shows an alternate method using the well-known phase locked loop (PLL). A PLL is a feedback system that generates a signal locked to the phase of a reference signal.

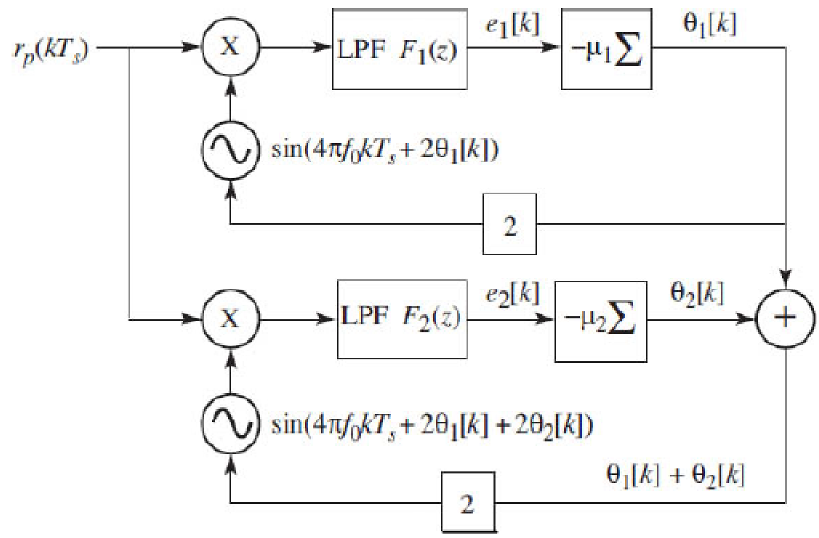

Figure 6.10: The Dual Phase Locked Loop Structure

The objective of the PLL is to minimize the phase error between the incoming CW signal and the newly generated signal. Any phase misalignment in the new carrier with respect to the incoming CW signal results in a non-zero phase angle of the I and Q vectors, so that the magnitude and direction of the phase difference can be detected and used as feedback to correct the new signal.

When there is a difference in the transmitted frequency and the frequency assumed at the receiver, problems arise. As it is extremely difficult to have two oscillators exactly aligned, it is important to find ways to estimate the frequency from the received signal. Thus, it is advised to use a PLL that can track phase as well as frequency. This section uses a method of indirect frequency estimation. In this method two PLLs are cascaded: one for frequency specification and the other for phase. Figure 6.10 shows the scheme.

Say the received signal is of the form $r_p(t) = cos(4\pi f_c t + 2\phi)$. This signal serves as the reference for the two loops. For the first loop, if the oscillator frequency is $2f_o$, then the phase estimate $2\theta_1$ converges to a ramp with slope equal to $2\pi(f_0 - f_c)$. Equation (6.14) shows the convergence relation.

$$\theta_1(t) \rightarrow 2\pi(f_0 - f_c)(t) \tag{6.14}$$

Here, b is the y-intercept of the ramp. The phase estimate of the first loop θ_1 is added to the theta estimate of the second loop, θ_2. The output of the second oscillator is shown in Eq. (6.15).

$$sin(4\pi f_0 t + 2\theta_1(t) + 2\theta_2(t) = sin(4\pi f_0 + 4\pi(f_c - f_0)t) + 2b + 2\theta_2(t)) \\ \rightarrow sin(4\pi f_c t + 2b + 2\theta(t)). \tag{6.15}$$

Essentially, the top loop determines the carrier frequency which is used by the second loop. $\theta_2(t)$ converges to $\phi - b$. A sinusoid of frequency $2\pi f_0 t$ and phase $\theta_1 + \theta_2$ is indistinguishable from a sinusoid of frequency $2\pi f_c t$ and phase θ_2. These values can then be used to generate a signal that is aligned with $r_p(t)$ in both phase and frequency. This scheme was also implemented in MATLAB.

Listing 7 shows the code form of the received signal.

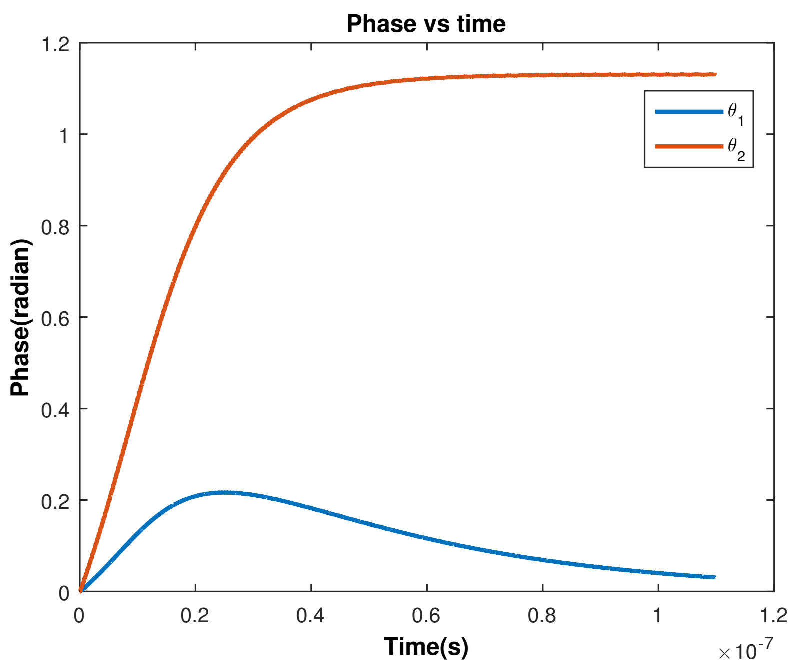

Figure 6.11: Convergence Function of a Dual PLL

Listing 7: Received up and down signals

```
rp_up=cos((4*pi*(f_c+f_lo)*t)+(2*(4*pi*f_c+2*pi*
    f_lo)*(r/c)));
rp_dwn=cos((4*pi*(f_c-f_lo)*t)+(2*(4*pi*f_c-2*pi*
    f_lo)*(r/c)));
```

Figure 6.11 shows that the PLL converges to a particular phase depending on the phase of the input signal. The phase estimate of the first pll, θ_1, converges to a ramp. The phase estimate of the second pll, θ_2, converges to a constant.

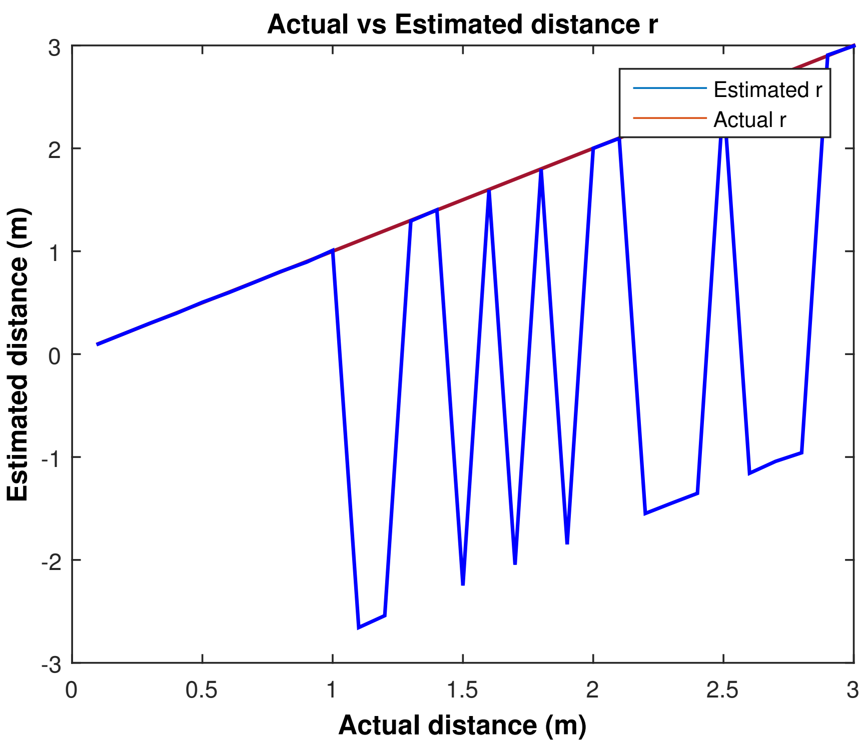

Figure 6.12: Distance Estimation using PLL

Figure 6.12 shows the distance estimation using the dual PLL method at two carrier frequencies with a modified *Bigdelta* function. It is observed that there is an error in estimation due to the 2π phase periodicity experienced in the FFT estimation as well. The calculated phase is modified by a factor of π to yield the correct distance. The modification is shown in Listing 8.

Listing 8: Avoiding Phase Ambiguity

```
if  r_cal_del2<0
          delta_pll2=delta_pll2+(pi);
          Bigdelta=(delta_pll2-delta_pll);
          r_cal_del=(Bigdelta*c)/(8*pi*fdiff);
```

Figure 6.13 shows the distance estimation with the phase correction. The calculated distance closely follows the actual distance.

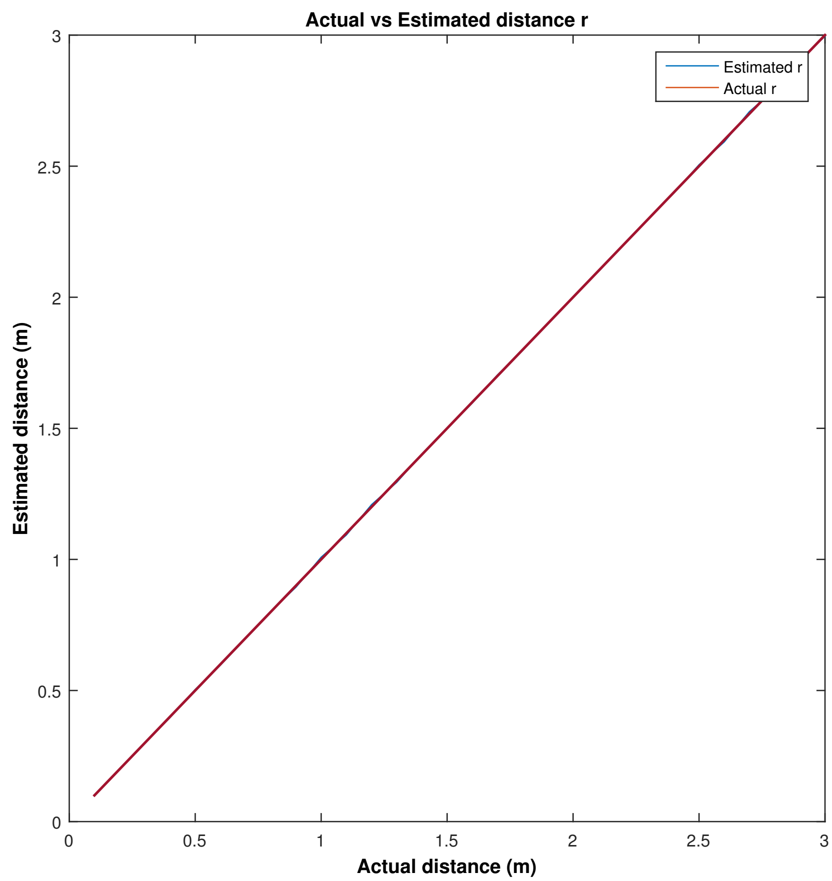

Figure 6.13: Distance Estimation with Correction using PLL

Thus, we were able to use three different techniques to extract distance information from the received signal characteristics: null positions in time domain, Fourier analysis, and phase determination using PLL.

CHAPTER 7

MEASUREMENTS

In-lab measurements were carried out as a proof of concept. The benchtop model was implemented using cables to eliminate any errors due to wireless factors. The lab setup included a signal generator for transmission of S_{t1} at frequency f_{c1}. At the transmitting end the signal was split using a power splitter and sent to the reflector unit on the other end of the room, as well as to a real-time oscilloscope which sits on the original transmitting end. The signal is received by a mixer on the other end. This mixer is also fed an LO signal, S_{LO}, giving rise to two new frequencies, $f_{c1} \pm f_{lo}$. These signals are transmitted back to the oscilloscope at the master unit through cables.

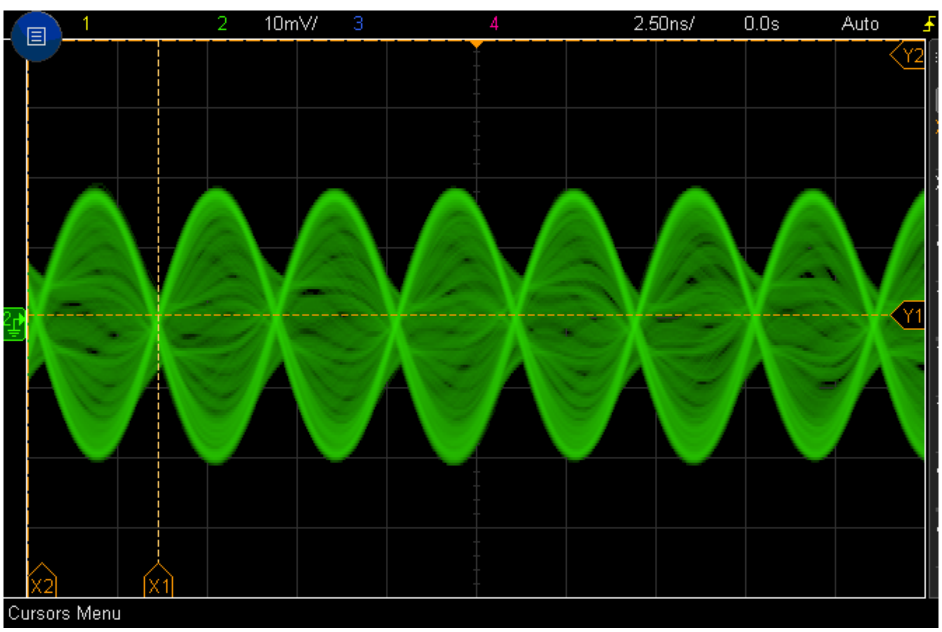

Figure 7.1: S_{r2} with a Null at Cursor *X1*=-8.880 ns

The original signal S_{t1}, is observed on channel 1. This signal undergoes a negligible phase shift due to the small distance between the signal generator and the oscilloscope. The combination of the $f_{c1} \pm f_{lo}$ signals, S_{r2}, is observed on channel 2 as shown in Fig. 7.1. The oscilloscope data is triggered to the S_{t1} signal.

A cable of unknown length is added to the wired path in between the master unit and the reflector unit. This introduces a further delay in the path of the received signal, S_{r2}.

7.1 Shift of Envelope Nulls

The delay is noticeable as a shift of the nulls of the envelope towards the right as shown in Fig. 7.2.

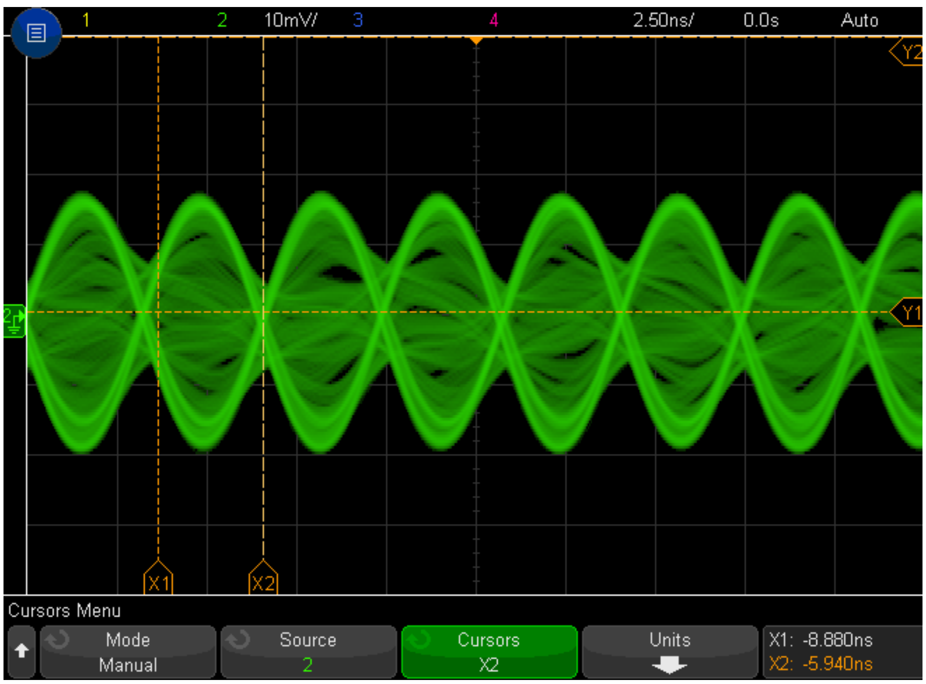

Figure 7.2: Delayed S_{r2} with a Null at Cursor *X2*=-5.94 ns

The difference between the x-cursors gives us the shift in the nulls. From prior knowledge and the oscilloscope data

$$\begin{aligned}
\Delta x &= -5.94 - (-8.88)\,\mathrm{ns} = 2.94\,\mathrm{ns} \\
v &= \frac{1}{\sqrt{\epsilon_{teflon}}} = \frac{1}{\sqrt{2.1}} = 0.7 * c \\
r &= v * \Delta x = 0.7 * c * 2.94 * 10^{-9} = 0.60\,\mathrm{m}
\end{aligned} \tag{7.1}$$

The length of the cable was measured and found to be ≈ 0.58 m, which is very close to calculated length shown in Eq (7.1). Thus, the shift of the nulls indicates the delay added in the path.

CHAPTER 8

CONCLUSION AND FUTURE WORK

Different technological solutions for wireless indoor positioning and navigation were discussed and implemented in code. Although multiple approaches exist to handle the indoor positioning problem, current solutions cannot achieve the performance that significant applications require. In short, requirements for different application environments are accuracy, range, availability, and costs for implementation. To achieve these specifications, a good variety of research approaches is required.

Some of the future trends of wireless indoor positioning systems are the following [2]:

- New hybrid solution for positioning and tracking estimation in 4G with the currently available position system,
- Need for cooperative mobile localization which will help mobile nodes, working with each other, to determine their locations,
- New innovative mobile applications in which location information can be used to improve the quality of the user experience and to add value to existing services offered by wireless providers.

With the integration of more and more wireless technology and the advent of IoT, localization is bound to have a significant impact in the field of wireless systems. The applications can range from smarter asset localization at industrial plants to the experience of augmented reality. Several big companies in the wireless domain have picked up on this hunch, and have employed several intensive research activities in this field.

This thesis is a first step to indoor positioning using MERLIN. Future work in this direction could involve observing the effects of non-idealities in the system such as noise and phase drifts which would occur in realistic implementations. This approach could also be developed using software defined radio. SDR is an emerging, state-of-the-art technology which features modulation/de-modulation and other techniques in digital signal processing (DSP) in software as opposed to hardware. The extreme flexibility of the SDR technology is also very useful in areas where evaluation and analysis of RF signals is needed, making it suitable for location determination.

APPENDIX A

MATLAB CODE

A.1 Forwardmodel.m

Listing 9: Code 1

```
close all;
clc;
%For a different r

%Amplitude Coefficients
A=1;
B=1;
C=1;
%Distance r, speed of light,frequencies, time step
prompt='Enter value of r in meters:';
r=input(prompt)
c=2.99792458e8;
f_c=910e6;
lambda_fc=c/f_c;
tdiff=2*r/c;
f_lo=20e6;
fs=10*f_c;
t=1/fs:1/fs:10000*1/fs;
x=0*t;
```

Listing 10:

```
% signal transmitted
s_t1=A*cos(2*pi*f_c*t);


% Signal received
s_r1=B*cos((2*pi*f_c*t)+(2*pi*f_c*(r/c)));

% Mixer LO signal
s_lo=C*cos(2*pi*f_lo*t);
% Signal transmitted from the repeater
s_t2_mul=s_r1.*s_lo;

s_t2_up=cos((2*pi*(f_c+f_lo)*t)+(2*pi*f_c*(r/c)))
    ;

s_t2_dwn=cos((2*pi*(f_c-f_lo)*t)+(2*pi*f_c*(r/c))
    );

s_t2=0.5*B*C*(s_t2_dwn+s_t2_up);

% Signal received at PMU
s_r2_dwn=cos((2*pi*(f_c-f_lo)*t)+((4*pi*f_c-2*pi*
    f_lo)*(r/c)));

s_r2_up=cos((2*pi*(f_c+f_lo)*t)+((4*pi*f_c+2*pi*
    f_lo)*(r/c)));

s_r2=0.5*B*C*(s_r2_dwn+s_r2_up);

s_r1=B*sin((2*pi*f_c*t)+(pi/2));
```

Listing 11:

```
% FFT Calculation
nfft=1820;
X=fftshift(fft(s_t1,nfft));

title('Double Sided FFT - with FFTShift');
xlabel('Frequency (Hz)')
ylabel('|DFT Values|');

%Extract amplitude and phase of frequency components (amplitude and phase spectrum)
df=fs/nfft; %frequency resolution

sampleIndex = -nfft/2:nfft/2-1; %ordered index for FFT plot
f=sampleIndex*df; %x-axis index converted to ordered frequencies
figure;
plot(f,abs(X),'b');

%%To find closest f value
s_t1err=abs(f-f_c);%Minimizing difference
[idx idx]=min(s_t1err);% Index of closest frequency
closestf=f(idx);%Closest frequency

s_r2_uperr=abs(f-(f_c+f_lo));%Minimizing difference
[idy idy]=min(s_r2_uperr);% Index of closest frequency
closestf1=f(idy);%Closest frequency


s_r2_dwnerr=abs(f-(f_c-f_lo));%Minimizing difference
```

Listing 12:

```
[idz idz]=min(s_r2_dwnerr);% Index of closest frequency
closestf2=f(idz);%Closest frequency


% Phase calculations
phase=atan2(imag(X),real(X))*180/pi; %phase information
phase(idx);

Z=fftshift(fft(s_r2_dwn+s_r2_up,nfft));
plot(f,abs(Z),'r');

% figure;
phase2=atan2(imag(Z),real(Z))*180/pi; %phase information

% plot(f,phase2); %phase vs frequencies
phase2(idz);

%%%Calculating delta and r_cal
delta_fc1=degtorad(phase2(idz)+phase2(idy)-2*phase(idx));

r_cal=(delta_fc1*c)/(8*pi*f_c);

r_cal;

Forwardmodel_trial;
bigdelta;
```

A.2 bigdelta.m

Listing 13: Code 2

```
Bigdelta=(delta_fc2-delta_fc1);
if delta_fc1>delta_fc2
    delta_fc2=delta_fc2+(2*pi);
    Bigdelta=(delta_fc2-delta_fc1);
    r_cal_del=(Bigdelta*c)/(8*pi*fdiff);

else
    r_cal_del=(Bigdelta*c)/(8*pi*fdiff);

end
r_cal_del;
```

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