Draft of April 5, 2016 at 17:00

INDOOR POSITIONING USING RF CW SIGNALS

Draft of April 5, 2016 at 17 : 00

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 close integration of technology within indoor environments, the need for 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 performance inside building 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 for indoor positioning.Thus, indoor positioning has become a focus of research and development in the past decade.This thesis discusses a positioning technique based on RF signals.Different range estimation methods are also discussed. Indoor positioning or localization is bound to become a popular feature in the next generation wireless systems.

To my parents, for their love and support.

ACKNOWLEDGMENTS

TO BE FILLED OUT

TABLE OF CONTENTS

LIST OF FIGURES . . . vii

LIST OF ABBREVIATIONS . . . viii

CHAPTER 1 INTRODUCTION . . . 1
  1.1 Motivation . . . 1
  1.2 Positioning systems . . . 2
  1.3 Outline . . . 3

CHAPTER 2 POSITIONING TECHNOLOGIES . . . 5
  2.1 Global Positioning System (GPS) . . . 5
  2.2 Cell ID . . . 6
  2.3 Infrared Radiation (IR) . . . 6
  2.4 Radio Frequency (RF) . . . 6
  2.5 Hybrid Positioning systems . . . 7

CHAPTER 3 INDOOR POSITIONING OVERVIEW . . . 8
  3.1 Indoor Radio Propagation Issues . . . 8
  3.2 Topologies . . . 10

CHAPTER 4 LOCATION DETECTION TECHNIQUES . . . 11
  4.1 Proximity . . . 11
  4.2 Triangulation . . . 12
  4.3 Scene Analysis . . . 16

CHAPTER 5 SYSTEM OVERVIEW . . . 17
  5.1 RF Based Distance Estimation Model . . . 17
  5.2 Distance Estimation using Phase Shift of Received Signal in Time Domain . . . 18
  5.3 Distance Estimation using Phase of Received Signal in Frequency Domain . . . 18
  5.4 Positioning using Trilateration . . . 19

CHAPTER 6 TIME DOMAIN . . . 21

CHAPTER 7 MATH EQUATIONS . . . 25

CHAPTER 8 PHASE ESTIMATION USING FFT 28

CHAPTER 9 PHASE ESTIMATION USING PLL 34

CHAPTER 10 CONCLUSION 38

CHAPTER 11 FUTURE WORK 39

APPENDIX A APPENDICES 40
  A.1
    Forwardmodel.m 41
  A.2
    bigdelta.m 45

APPENDIX B REFERENCES 46

LIST OF FIGURES

1.1 Indoor Navigation Technologies 2

2.1 Overview of wireless poistioning systems [1] 5

3.1 Causes of Multipath:Reflection,Refraction,Diffraction and Scattering [2] 9

4.1 Classification of location detection techniques [3] 11
4.2 RSSI based positioning [1] 13
4.3 TDOA based positioning [1] 14
4.4 Phase of arrival based positioning [1] 15

5.1 Conceptual diagram 17
5.2 Location Estimation using Trilateration [3] 20

6.1 Signals received at Master unit (Time domain) 21
6.2 Distance Estimation with correction 22
6.3 Received Signal Waveform for $r = 0m$ 23
6.4 Received Signal Waveform for $r = 0.5m$ 24

8.1 FFT plot for S_{t1} 29
8.2 FFT plot for S_{r2} 30
8.3 Distance Estimation with single carrier frequency 31
8.4 Distance Estimation with two carrier frequencies 32
8.5 Distance Estimation with two carrier frequencies 33

9.1 The Dual Phase Locked Loop Structure 35
9.2 Convergence function of a dual PLL 35
9.3 Distance Estimation 36
9.4 Distance Estimation with correction 37

LIST OF ABBREVIATIONS

RF	Radio Frequency
GNSS	Global Navigation Satellite System
GLONASS	Russian Global Navigation Satellite System
LBS	Location Based Services
GPS	Global Positioning System
EM	Electromagnetic
LoS	Line of Sight
IR	Infrared Radiation
RSS	Received Signal Strength
WLAN	Wireless Local Area Network
RFID	Radio Frequency Identification
UWB	Ultra Wideband
FDMA	Frequency Division Multiple Access
CW	Continuous Wave
SDR	Software Defined Radio
IR	Infrared Radiation
TOA	Time of Arrival
RTOF	Round trip time of flight
RSSI	Received Signal Strength Indicator
POA	Phase of Arrival

Tx	Transceiver
Rx	Receiver
CW	Continous Wave
LO	Local Oscillator
PLL	Phase Locked Loop
AWGN	Additive White Gaussian Noise
ISM	Industrial,Scientific and Medical

CHAPTER 1

INTRODUCTION

1.1 Motivation

In the field of wireless communication , locations based services and contextual awareness are on the rise. LBSs or Location based services refer to the applications or programs that rely on the position of the user in order to render services. These services include navigation, healthcare, billing and payments, safety and emergency services. The same concept of LBSs can be applied to the enormous cell phone market. The location of the mobile user could be used to provide them with personalized services. A strong,reliable and accurate positioning technology would be required to facilitate such services.

The main building blocks of an LBSs system would be a software application, communication network, content provider, positioning device, and the mobile unit[3] . 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[4]. 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.

Thus, there is a need to develop of positioning system for indoor environments. However, there are multiple challenges for this task too 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 [3].

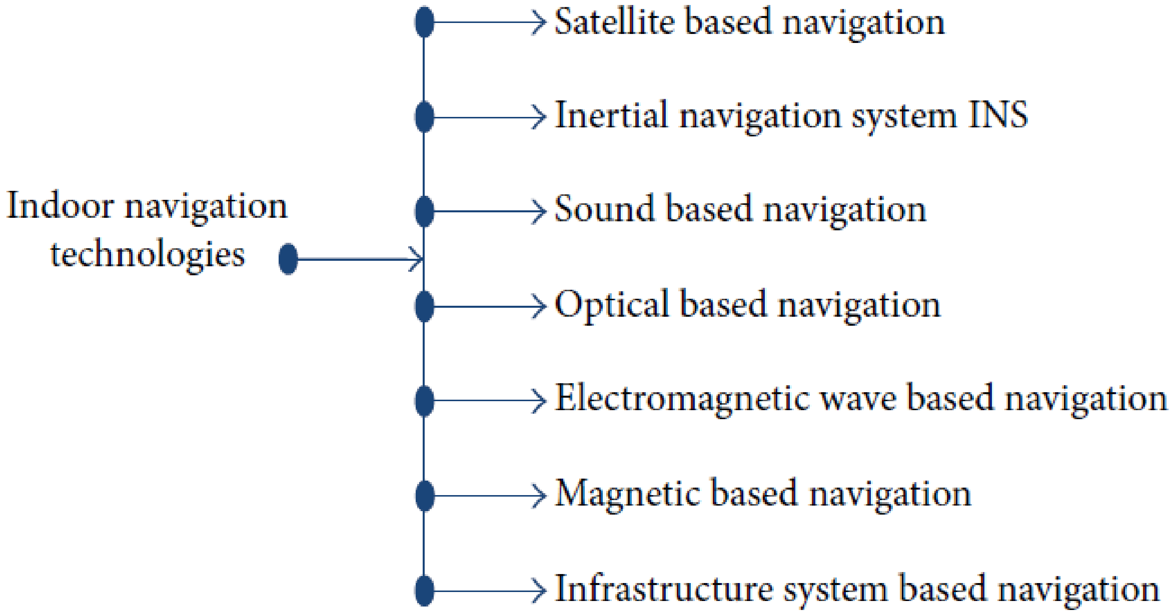

Figure 1.1: Indoor Navigation Technologies

The location of the user could be determined with reference to a predetermined fixed 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, navigation, geodetic survey and synchronization of telecommunications network.The most widely used, GPS service works well outdoors but doesn't 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 system is one that can 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 size,No LoS,influence of obstacles and so on. Multipath is another issue as there are multiple reflective surface in an indoor environment. Interference from other wireless systems could also play a role in the overall performance of the indoor positioning system. A high degree of accuracy is also desirable for an indoor environment. A reliable positioning system needs to overcome these challenges.

1.3 Outline

This thesis is intended to give you a brief overview of indoor positioning history,concepts and technologies. It introduces a novel method of range estimation to be used in positioning algorithms and finally it talks about the endless possibilities of introducing wireless localization as a feature in future communication devices.

- Chapter 1 covers the motivation behind this research and describes the differences between indoor and outdoor positioning systems.
- Chapter 2 looks into positioning technologies (IR,RF,Cell ID etc) being used today.
- Chapter3 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 our positioning concept. It mainly focuses on using CW RF signals for distance estimation
- Chapter 6 introduces a time domain approach to distance estimation. It presents a MATLAB model to observe signals in time.
- Chapter 7 presents the mathematical model behind the concept presented in Chapter 5.

- Chapter 8 provides the FFT approach to phase/range estimation.
- Chapter 9 describes the use of a PLL model in MATLAB for phase/range estimation.
- Concludes the thesis with some discussion of future possibilities.
- Lastly, the appendix includes the MATLAB code and the SDR setup instructions.

CHAPTER 2

POSITIONING TECHNOLOGIES

This chapter presents technologies that have been used in the past for positioning. Main focus will be on RF based positioning systems.

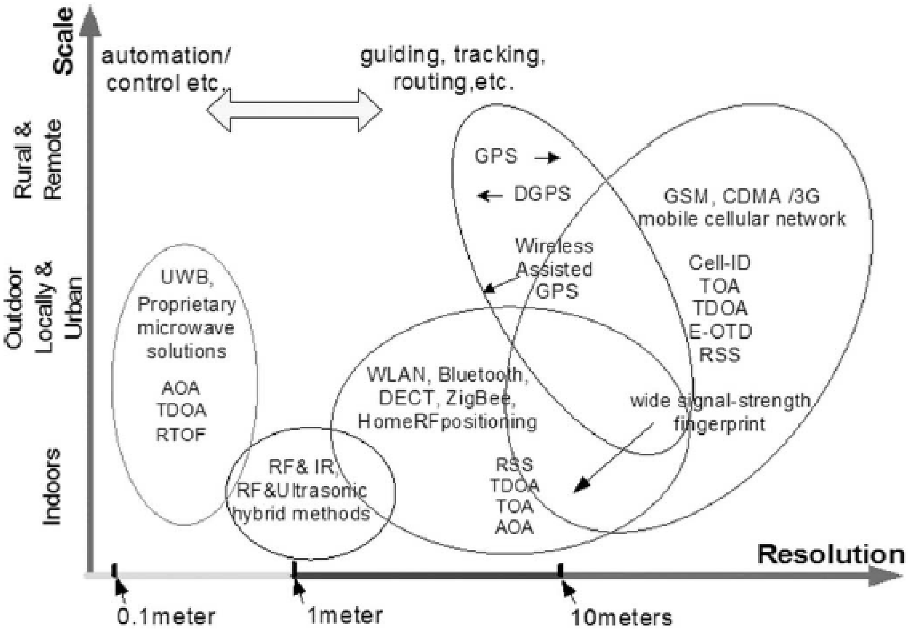

Figure 2.1: Overview of wireless poistioning systems [1]

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[3].

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 near by such that RSS is high.

2.3 Infrared Radiation (IR)

Another commonly used technology is Infrared Radiation (IR).Most IR devices use LoS communication. Main advantage of using this technology is the small and compact device implementation.However, IR signals are limited by interference from fluorescent light and sunlight[5].

2.4 Radio Frequency (RF)

RF is being commonly used as a positioning technology these days. Due to their large wavelength, they can pass through obstacles resulting in a larger range and less complicated hardware.RADAR by Microsoft Research was the first RF based technique for location determination and user tracking [6].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 done through a network of scanning devices at a distance of few meters without the need for LoS communication. Bluetooth community has also been active with positioning applications.It can easily be integrated in to personal devices and operates in the 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[3].

2.4.1 Ultrawideband (UWB)

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

2.4.2 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.

2.4.3 Zigbee

ZigBee is an emerging wireless technology standard, mainly used for short and medium range communications.Distance calculation is based on RSSI values.

2.5 Hybrid Positioning systems

Hybrid Positioning systems are on the rise as well.They are defined as systems for localization of target 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 [3].

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 calculation takes place. There are multiple system topologies that have been used so far.

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 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 cause 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 the density of the medium. The refracted traveling wave changes direction after getting refracted from wall 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.This is often caused by smaller objects such as construction material or small sized indoor equipment.

All of these effects give rise to the Multipath phenomenon. 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 may affect the

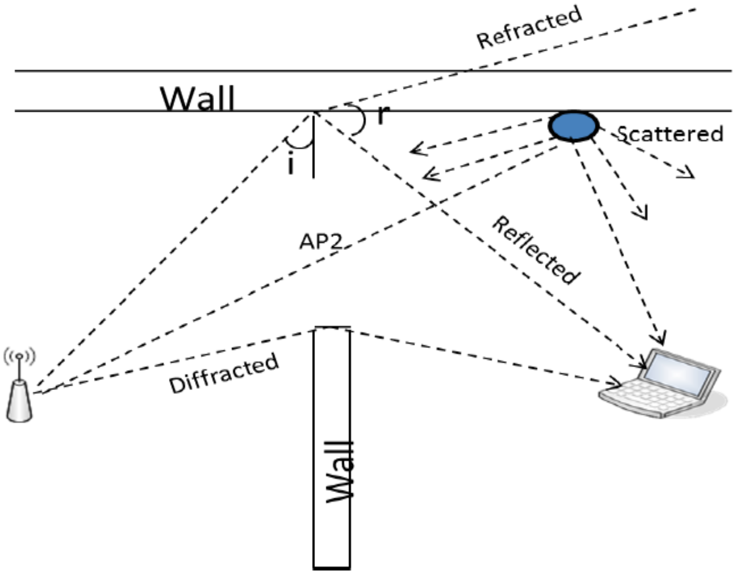

Figure 3.1: Causes of Multipath:Reflection,Refraction,Diffraction and Scattering [2]

range or accuracy of the positioning system.

3.1.1 Signal Attenuation and Noise Sources

This of one of the main problem 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, greater is the attenuation.This is the reason why GPS doesn't work indoors. The signal undergoes sever 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 majorly 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 is calculated. One of the advantages for 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 to be an indirect self-positioning system.

CHAPTER 4

LOCATION DETECTION TECHNIQUES

Numerous different methods can be used for localization. Broadly, they can be classified into Signal strength or proximity, triangulation and fingerprinting or scene analysis.

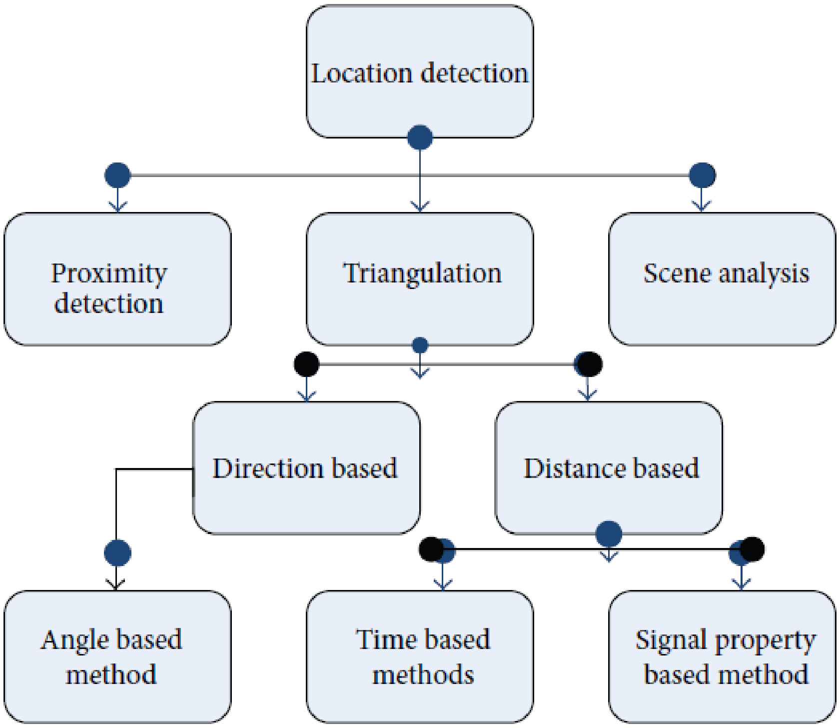

Figure 4.1: Classification of location detection techniques [3]

4.1 Proximity

This method is comparatively easier to implement. The location is determined by 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 like of RFID, Cell ID and other custom devices.

4.2 Triangulation

This uses the geometric properties of triangles to determine estimate the user location. *Lateration* and *angulation* are derivatives of triangulation. Techniques that rely on the measurement of the propagation-time system (e.g., TOA, RTOF and TDOA) are called lateration techniques.AOA estimation is the angulation technique [3].

4.2.1 Lateration

Lateration estimates the the position by measuring the distance of the user from multiple reference points.Thus, it can also be called 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[1].

a.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.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 radiation environment but can be improved by using pre-measured contours at the receiver[8].

b.TOA

The time taken for a signal to travel between two points is directly proportional to the distance between them. For a distance, TOA measurements

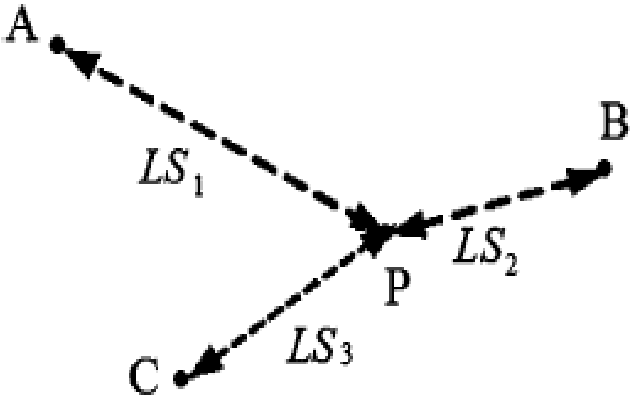

Figure 4.2: RSSI based positioning [1]

must be made with respect to signals from atleast 3 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 be able to determine the actual distance traveled. TOA can be measured using Direct sequence spread spectrum (DSSS) or Ultra wide band (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, assuming 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 $\mathbf{F(x)}$ needs to be minimized.

c.TDOA

This 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.

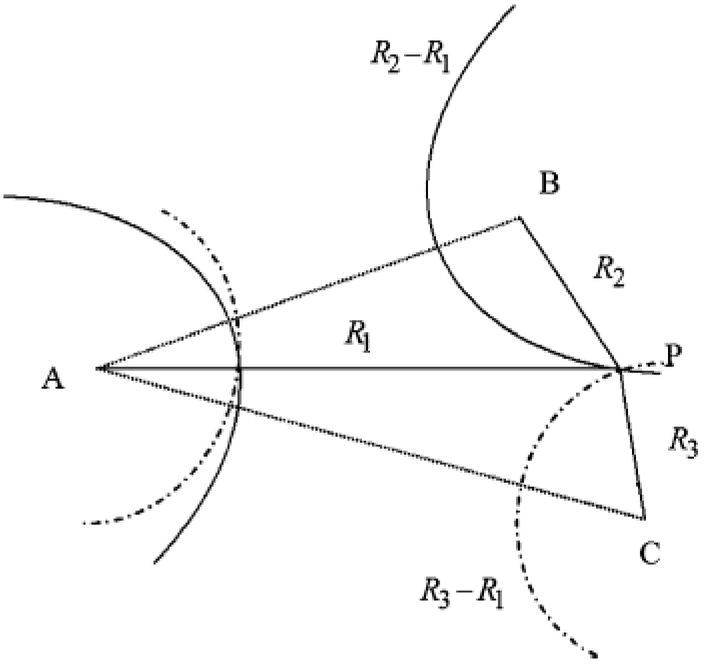

Figure 4.3: TDOA based positioning [1]

d.RTOF

This 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.

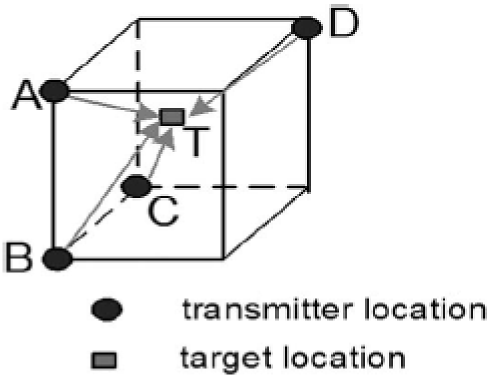

Figure 4.4: Phase of arrival based positioning [1]

e.Phase of Arrival

This method uses the carrier phase (or phase difference) of the received signal to determine the distance. 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 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

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

This method works as long as the distance being estimated is smaller than the carrier wavelength. In phase terms it correspond to the acquired phase ranging from 0 to 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 angle of the signals relative to multiple reference points.The user location can be found from the intersection of the angle direction lines, 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 2 are needed for 2D positioning.Disadvantages include complex hardware implementation and location estimate degradation as the distance increases[1].

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 [1]. An object's location is found by matching new data collected by mobile unit with the *scene fingerprint*. RSS based fingerprinting is very common.

CHAPTER 5

SYSTEM OVERVIEW

This chapter presents a type of RF based remote positioning system.

5.1 RF Based Distance Estimation Model

This thesis presents a POA or Phase of Arrival technique with a different approach to solve the distance estimation problem. We measure the phases of the transmitted and received signals at different frequencies to get the correct distance. Fig 5.1 shows the setup for our model.

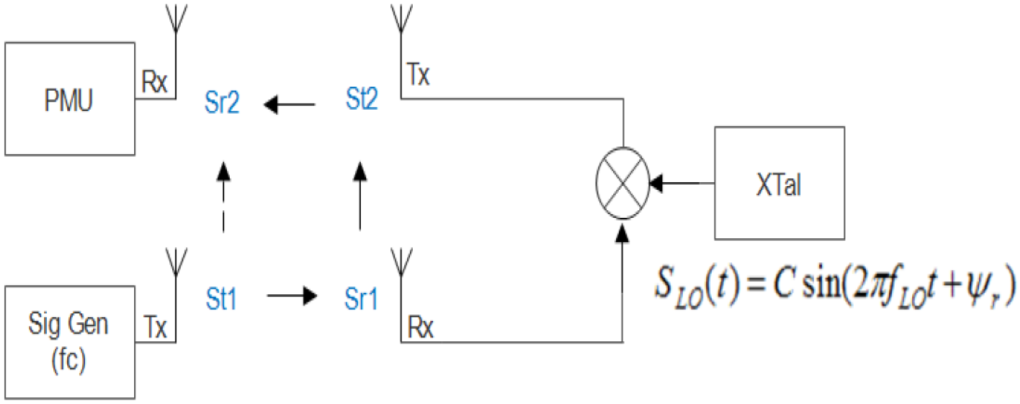

Figure 5.1: Conceptual diagram

It consists of a Master Tx/Rx and a target Tx/Rx. The distance between the master and the target units is r, that needs to be calculated. 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 another CW signal with a frequency offset. 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. 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. 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.

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 see 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 distance to estimate the distance between the Master unit and the target unit. More is explained in Chapter 6.The carrier frequency used for this is $150MHz$ with an LO of $20MHz$. The reason why this frequency was chosen was to facilitate the comparison with measurements on a real-time oscilloscope with a $200MHz$ limit.

5.3 Distance Estimation using Phase of Received Signal in Frequency Domain

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 $\approx c$, where c is the speed of light in vacuum and is equal to $3 * 10^8 \frac{m}{s^2}$. 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.

The signals lie in the ISM band around $900MHz$ as it 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 $\approx 0.3m$. The mathematical formulation of the signals is presented in Chapter 7.

5.4 Positioning using Trilateration

This distance r is just 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 the center at the location of the source transmitter. To find the exact location of the target, more number of 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 3 circles as shown in Fig. 5.2, one for each transmitter. The point of intersection of these 3 circles should gives us the exact 2D position of the target. Therefore, this 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. 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

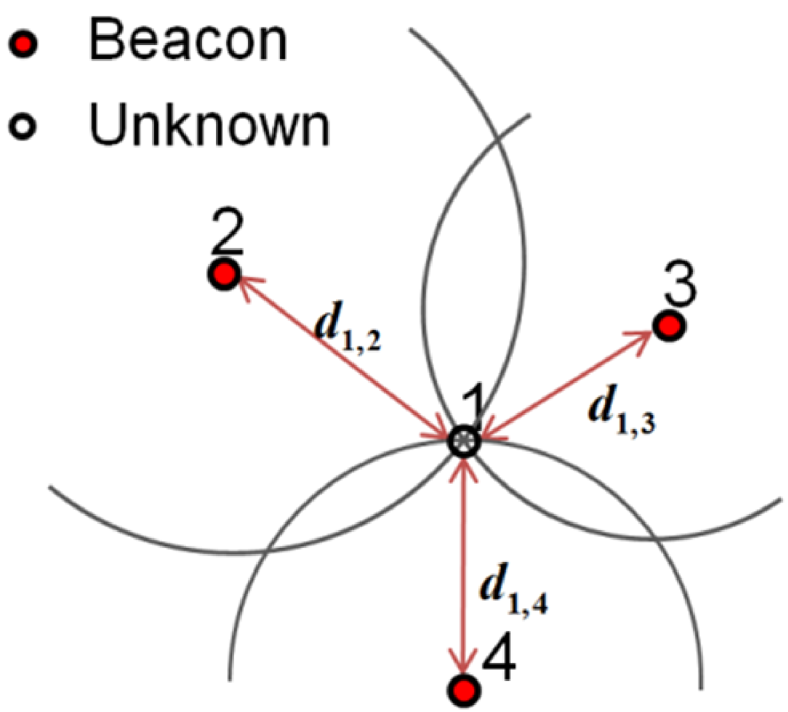

Figure 5.2: Location Estimation using Trilateration [3]

values of (x_1, y_1) that satisfy the set of equations shown in 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 don't 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

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 scopes trigger specification. Variable or infinite persistence enables successive signal captures to be overlaid on the original signal[9].

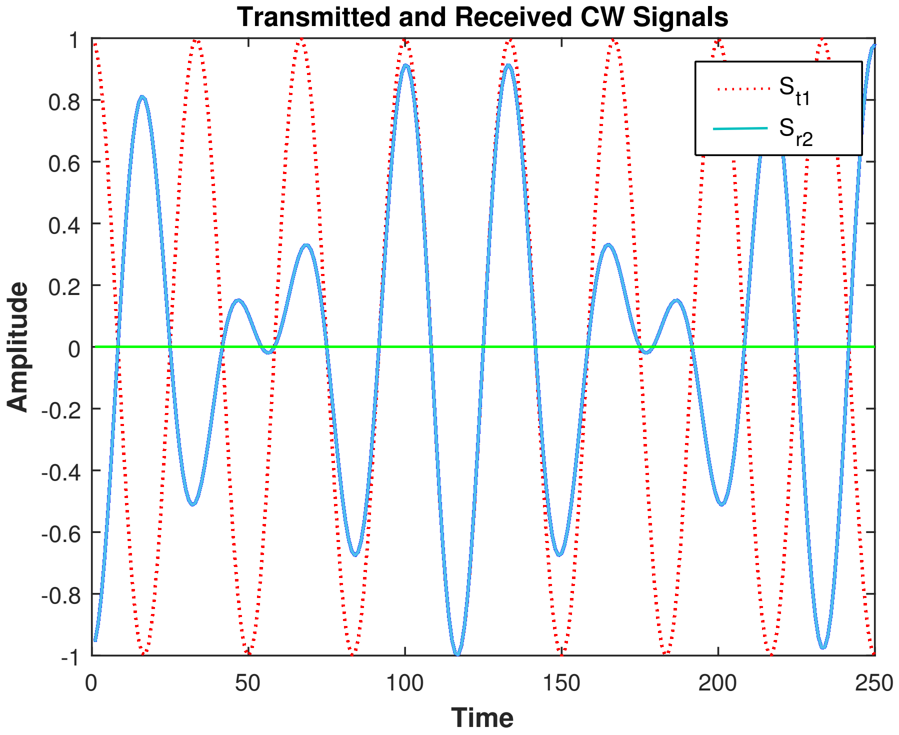

Figure 6.1: Signals received at Master unit (Time domain)

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

- The transmitted signal S_{t1} is received as it is a wireless system. This signal barely travels any distance, and can be assumed to have accumulated no phase.

- The S_{r2} signal, which is a superposition of the S_{r2up} and S_{r2dwn} signal, thus it appears 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. Fig. 6.2 shows the S_{r2} signal with its envelope.

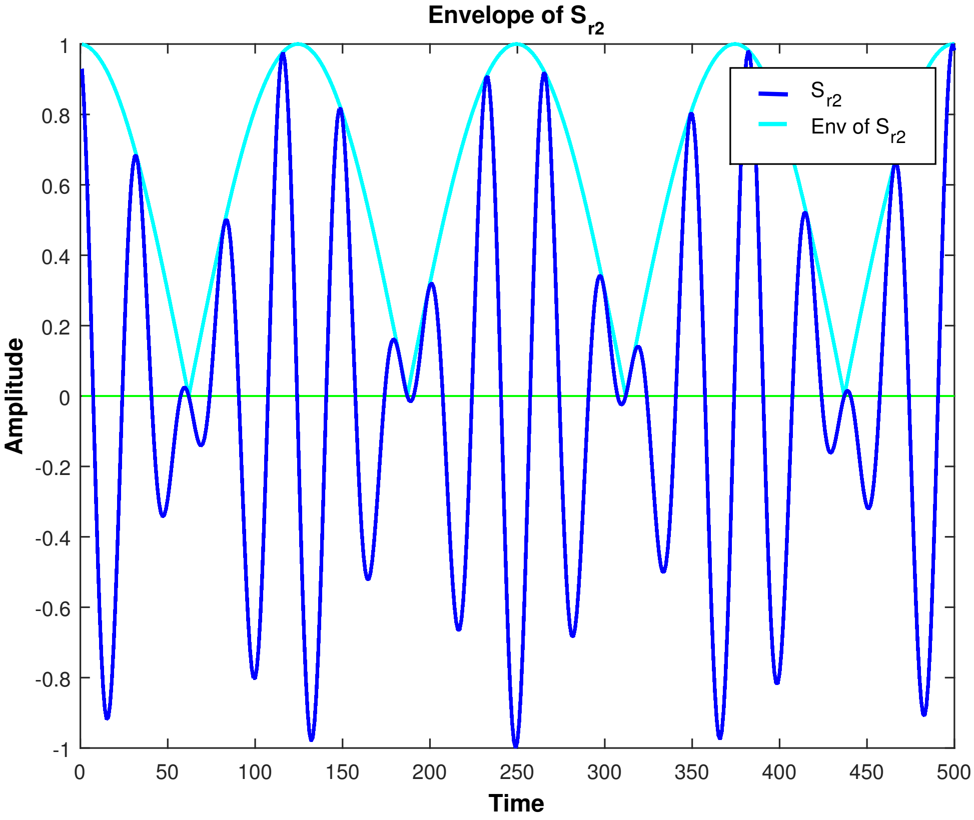

Figure 6.2: Distance Estimation with correction

The nulls are a clear indication of how the waveform moves as distances increase. We can use the time difference between nulls for a zero distance and some distance r to calculate the distance traveled by the wave. Fig. 6.3 shows the received signals in time domain for $r = 0$.

Fig. 6.4 shows the signals for $r = 0.5m$. We can see from the markers in Fig. 6.3 and Fig. 6.4, that the nulls of the envelope lie at time points 62

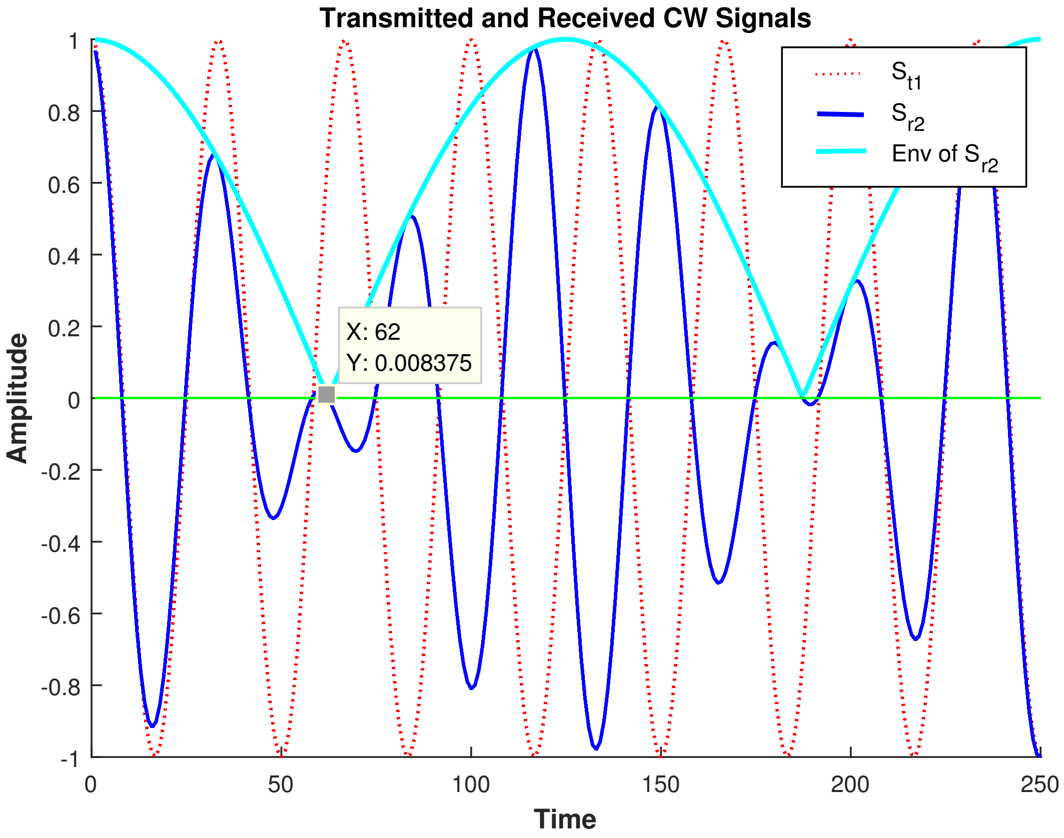

Figure 6.3: Received Signal Waveform for $r = 0m$

and 54 respectively. The time step, t_{step} for these calculations is $0.2ns$. This translates to

$$\begin{aligned} t_{null}(r = 0m) &= 62 \times t_{step} = 62 \times 0.2 \times e^{-9}s = 12.4ns \\ t_{null}(r = 0.5m) &= 54 \times t_{step} = 54 \times 0.2 \times e^{-9}s = 10.8ns \end{aligned} \tag{6.1}$$

To calculate the distance we use the following:

$$\begin{aligned} \Delta\phi &= \frac{2\pi f_{env} r}{c} \\ r &= \frac{\Delta\phi}{2\pi f_{env}} \cdot c \\ &= \frac{\omega_{env}\Delta t}{2\pi f_{env}} \cdot c \\ &= c \cdot \Delta t \end{aligned} \tag{6.2}$$

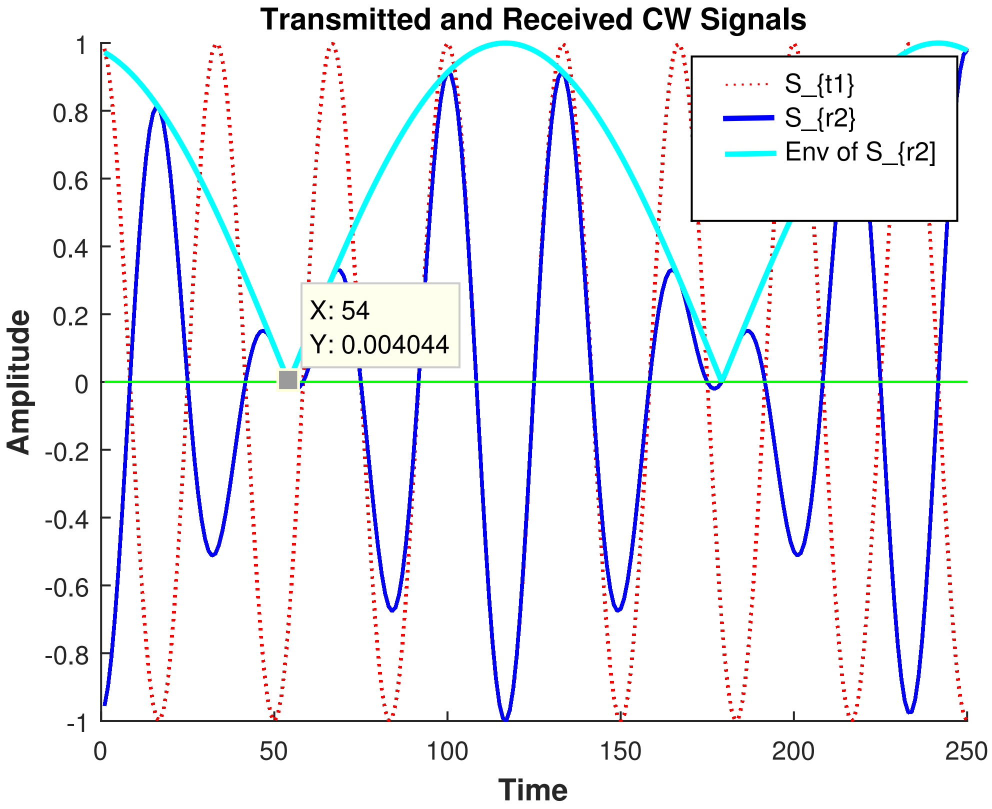

Figure 6.4: Received Signal Waveform for $r = 0.5m$

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 $2\pi f_{env}$,
c is the speed of light$\approx 3\times 10^8 \frac{m}{s}$. If we know the shift in time of the waveform, we should be able to determine the distance using Eqn. (6.1) and Eqn. (6.2)
,

$$\begin{aligned} r &= c \cdot (12.4 - 10.8) \cdot 10^{-9} \\ &= 0.48m \approx 0.5m \end{aligned} \tag{6.3}$$

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

CHAPTER 7

MATH EQUATIONS

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:

$$S_{t1}(t) = Asin(2\pi f_c t + \psi_o) \tag{7.1}$$

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

$$S_{r1}(t) = Bsin(2\pi f_c(t + \frac{r}{c}) + \psi_o) \tag{7.2}$$

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 .

$$S_{lo}(t) = Csin(2\pi f_{lo} t + \psi_r) \tag{7.3}$$

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

$$\begin{aligned} S_{t2}(t) &= S_{r1}(t) * S_{lo} \\ &= Bsin(2\pi f_c(t + \frac{r}{c}) + \psi_o) * Csin(2\pi f_{lo} t + \psi_r) \\ &= \frac{BC}{2} * cos[(2\pi f_c(t + \frac{r}{c}) + \psi_o) - (2\pi f_{lo} t + \psi_r)]... \\ &\quad - cos[(2\pi f_c(t + \frac{r}{c}) + \psi_o) + (2\pi f_{lo} t + \psi_r)] \\ &= \frac{BC}{2} * cos[2\pi(f_c - f_{lo})t + 2\pi f_c \frac{r}{c} + \psi_o - \psi_r]... \\ &\quad - cos[2\pi(f_c + f_{lo})t + 2\pi f_c \frac{r}{c} + \psi_o + \psi_r] \end{aligned} \tag{7.4}$$

The signal described in Eq.(7.4) is then transmitted back to the Master unit (original transmitter). The signal received at that end is described in

Eq.(7.5). This includes the original signal S_{t1}.

$$\begin{aligned}S_{r2} &= S_{t1} + S_{t2}\\ &= Asin(2\pi f_c t + \psi_o) + \frac{BC}{2} * [cos(2\pi(f_c - f_{lo})(t + \frac{r}{c}) + 2\pi f_c \frac{r}{c} + \psi_o - \psi_r) ...\\ &\quad - cos(2\pi(f_c + f_{lo})(t + \frac{r}{c}) + 2\pi f_c \frac{r}{c} + \psi_o + \psi_r)]\\ &= Asin(2\pi f_c t + \psi_o) + \frac{BC}{2} * [cos(2\pi(f_c - f_{lo})t + (4\pi f_c - 2\pi f_{lo})\frac{r}{c} + \psi_o - \psi_r) ...\\ &\quad - cos(2\pi(f_c + f_{lo})t + (4\pi f_c - 2\pi f_{lo})\frac{r}{c} + \psi_o + \psi_r)]\end{aligned} \tag{7.5}$$

The received signal is composed of mainly 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,

$$\begin{aligned}\angle S_{f_c} &= \psi_o\\ \angle S_{r2_{up}} &= (4\pi f_c - 2\pi f_{lo})\frac{r}{c} + \psi_o + \psi_r)\\ \angle S_{r2_{dwn}} &= (4\pi f_c - 2\pi f_{lo})\frac{r}{c} + \psi_o - \psi_r)\end{aligned} \tag{7.6}$$

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.(7.7)

$$\begin{aligned}\Delta &= \angle S_{r2_up} + \angle S_{r2_dwn} - 2\angle S_{f_c}\\ &= 8\pi f_c \frac{r}{c}\end{aligned} \tag{7.7}$$

Thus if we can acquire phase information of the transmitted and received CW signals then we can determine the distance r using Eq. (7.8).

$$r = \frac{c\Delta}{8\pi f_c} \tag{7.8}$$

where c is the propagation velocity.

7.0.1 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. Step 1 would be to use to f_{c1} to calculate Δ. Step 2 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. (7.9).

$$\begin{aligned} \Delta_{big} &= \Delta_{f_{c1}} - \Delta_{f_{c2}} \\ f_{diff} &= f_{c1} - f_{c2} \end{aligned} \tag{7.9}$$

These values can be substituted into Eq. (7.8) to give Eq. (7.10).

$$r = \frac{c\Delta_{big}}{8\pi f_{diff}} \tag{7.10}$$

Equation 7.10 gives us the distance between the master and remote unit. This is the required distance.

CHAPTER 8

PHASE ESTIMATION USING FFT

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. The 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 are assumed to be zero for simpler calculations. These quantities can be modified to observe their effect on location tracking.

For $f_{c1} = 910MHz$, $f_{c2} = 920MHz$ and $f_{lo} = 20MHz$, we implement the mathematical model described in Chapter 7. Note that $\lambda_{c1} = 0.3294m$ and $\lambda_{c2} = 0.3259m$. 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 atleast 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. 8.1, where we can see that the peak lies at f_{c1}.

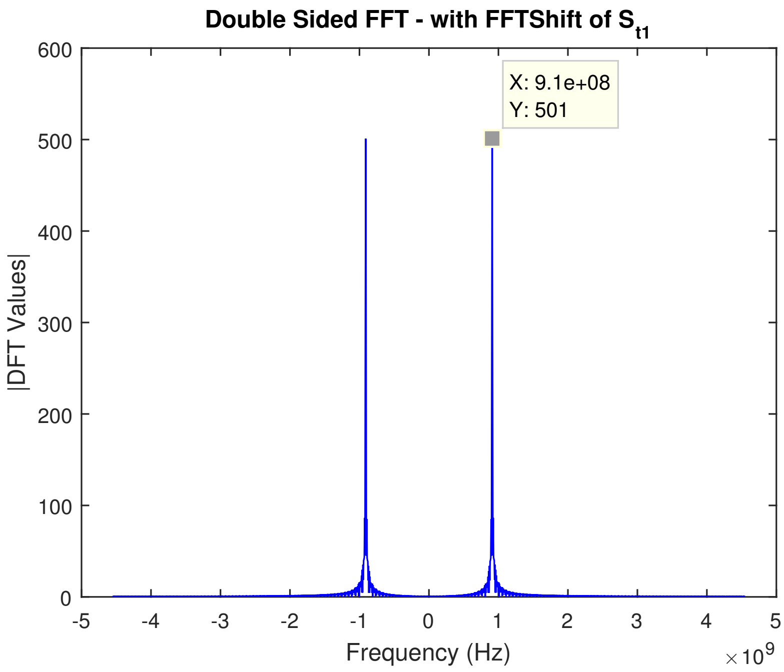

Figure 8.1: FFT plot for S_{t1}

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. 8.2, where we can see that the peak lies at $930MHz$ and $890MHz$.

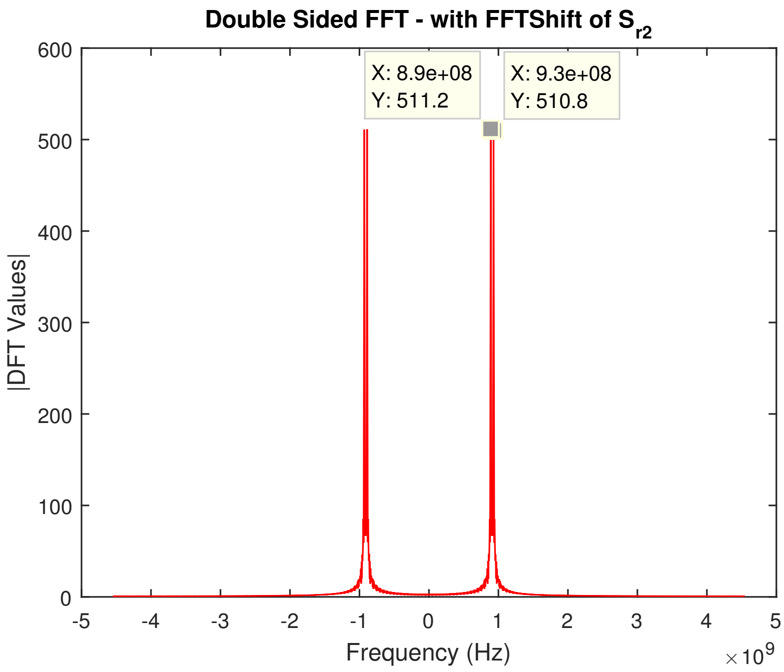

Figure 8.2: FFT plot for S_{r2}

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}.

Listing 3: Calculating phase information

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

The phase information is substituted in Eq.(7.7) and (7.8). On comparing the actual distance with the estimated distance we get a relation shown in Fig.8.3.The calculated distance is negative for some values of r. Slight modification shown in Listing 4 is used to correct it.

Listing 4: For negative distances

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

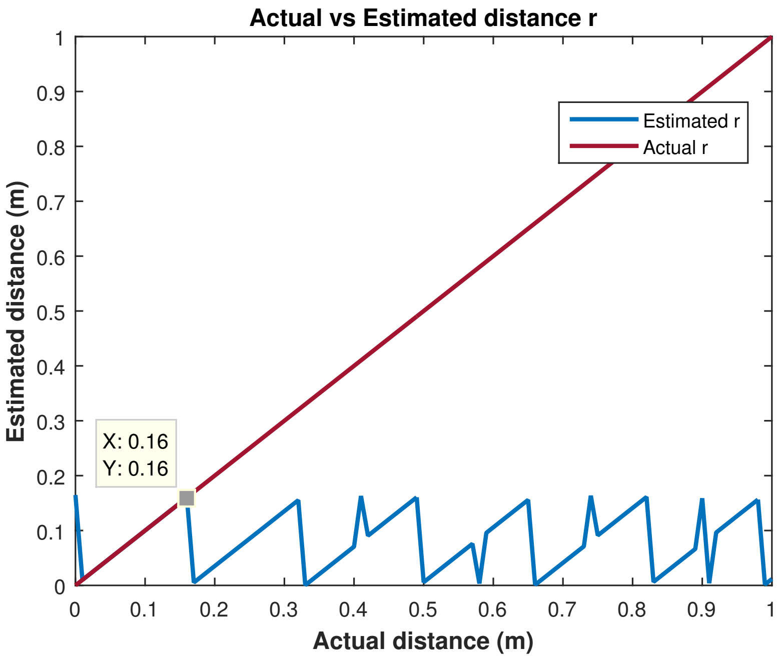

Figure 8.3: Distance Estimation with single carrier frequency

We can see that the method with single carrier frequency fails beyond a distance of $0.16m$ 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. (7.9).Listing 4 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. 8.4.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 5.

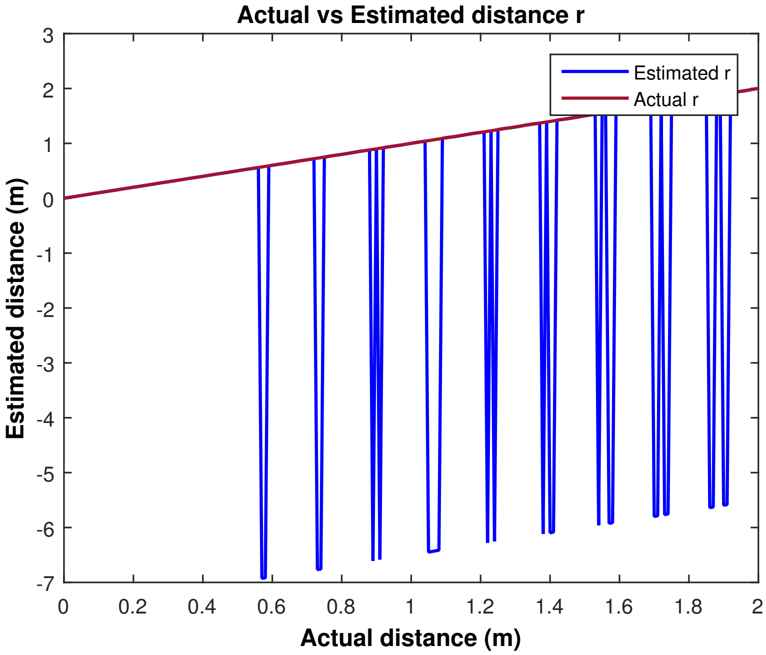

Figure 8.4: Distance Estimation with two carrier frequencies

Listing 6: i

```
f 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 changesare made is shown in Fig. 8.5. The distance is correctly tracked without any wavelength or phase ambiguity.

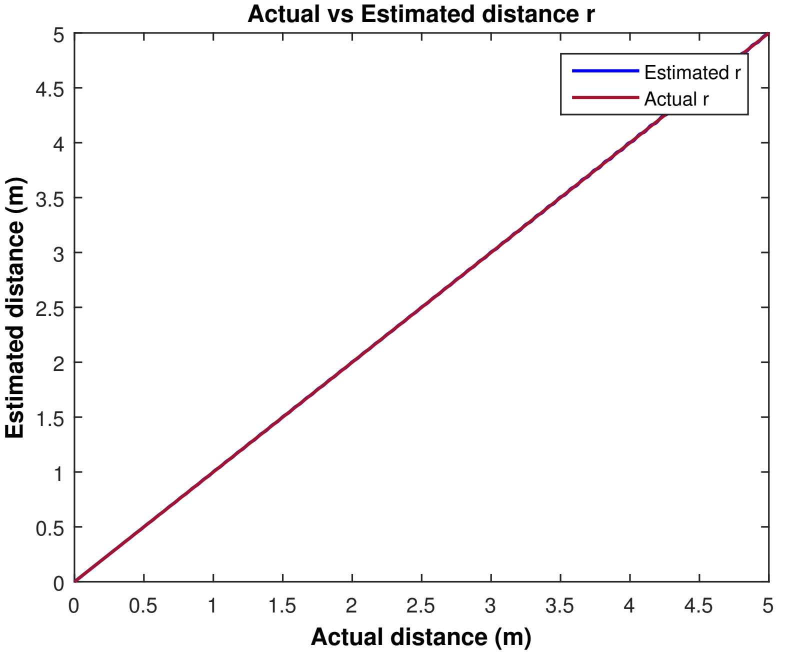

Figure 8.5: Distance Estimation with two carrier frequencies

CHAPTER 9

PHASE ESTIMATION USING PLL

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

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, its 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. Fig 9.1 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 9.1 shows the convergence relation.

$$\theta_1(t) \rightarrow 2\pi(f_0 - f_c)(t) \tag{9.1}$$

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

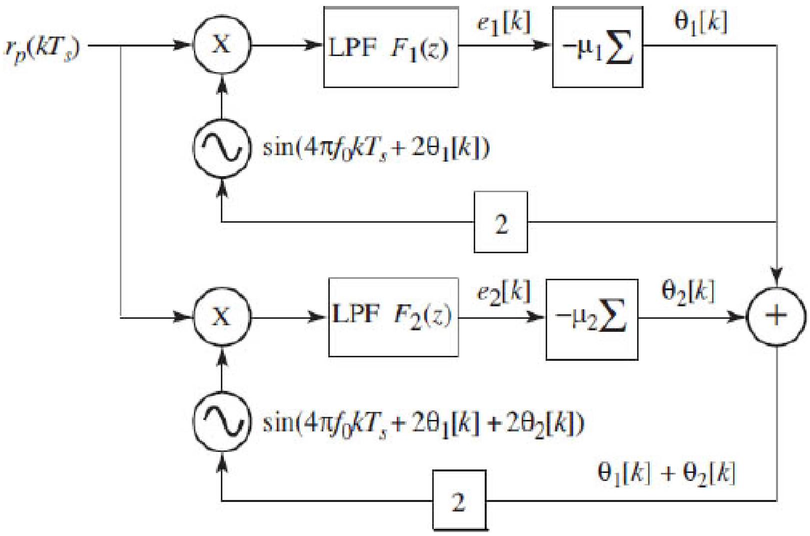

Figure 9.1: The Dual Phase Locked Loop Structure

second oscillator is shown in Eq. (9.2).

$$\begin{aligned} sin(4\pi f_0 t + 2\theta_1(t) + 2\theta_2(t) &= sin(4\pi f_0 + 4\pi(f_c - f_0)t) + 2b + 2\theta_2(t)) \\ &\rightarrow sin(4\pi f_c t + 2b + 2\theta(t)). \end{aligned} \tag{9.2}$$

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 implemented in MATLAB.

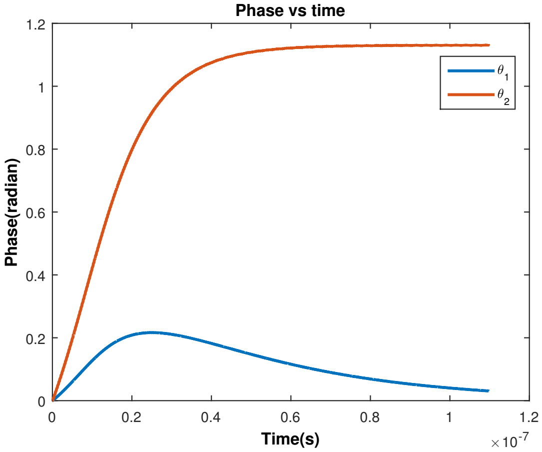

Figure 9.2: Convergence function of a dual PLL

Listing 6 shows the code form of the received signal.

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)));
```

Fig. 9.2 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.

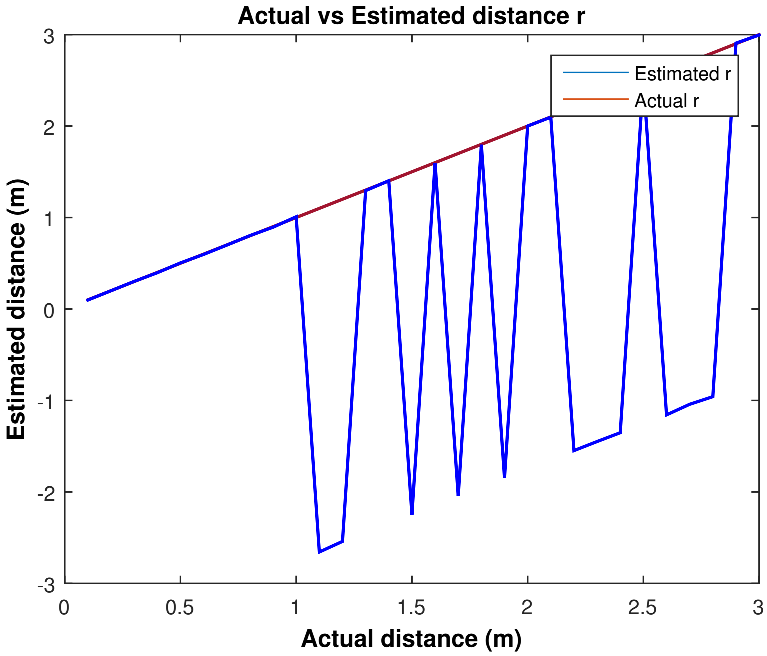

Figure 9.3: Distance Estimation

Fig. 9.3 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 previous chapter as well. The calculate phase is modified by a factor of π to yield the correct distance.

Listing 8: Received up and down signals

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

Fig. 9.4 shows the distance estimation with the phase correction. The calculated distance closely follows the actual distance.

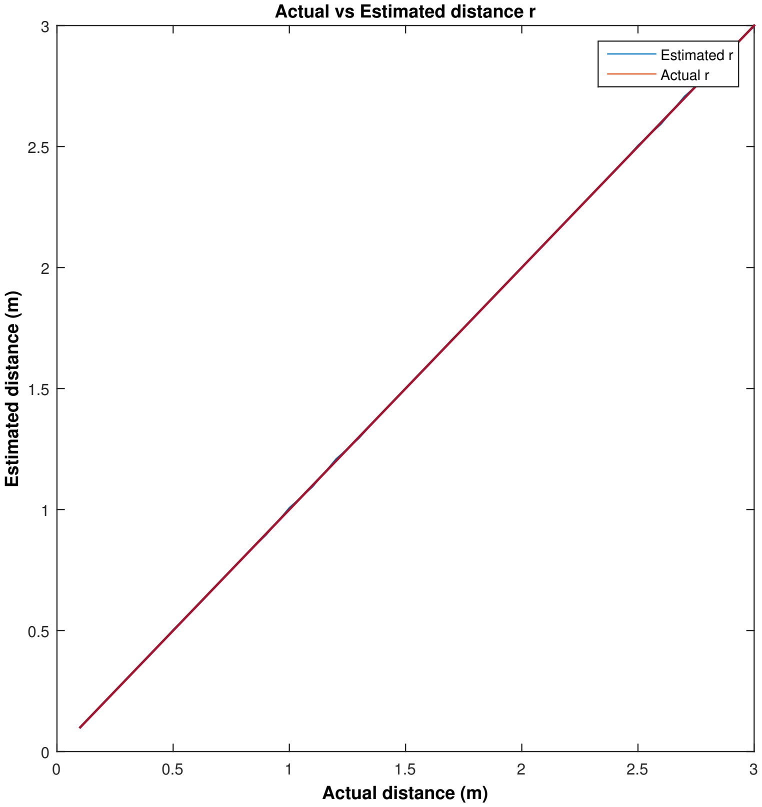

Figure 9.4: Distance Estimation with correction

CHAPTER 10

CONCLUSION

CHAPTER 11

FUTURE WORK

APPENDIX A

APPENDICES

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;

% 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)));
```

Listing 10: contd.

```
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));


% 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');
```

Listing 11: contd.

```

%%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
[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);
```

Listing 12: contd.

```
%%%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;
```

APPENDIX B

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