Geometry Optimization for Passive WiFi Radar Systems

By

Junaid Abdullah

NUST210362816MSEECS61213F

Supervisor

Dr. Syed Ali Hassan

Department of Electrical Engineering

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Approval

It is certified that the contents and form of the thesis entitled "**Geometry Optimization for Passive WiFi Radar Systems**" submitted by **Junaid Abdullah** have been found satisfactory for the requirement of the degree.

Advisor: **Dr. Syed Ali Hassan**

Signature: ____________________

Date: ____________________

Committee Member 1: **Dr. Sajid Saleem**

Signature: ____________________

Date: ____________________

Committee Member 2: **Dr. Hassaan Khaliq**

Signature: ____________________

Date: ____________________

Committee Member 3: **Dr. Fahad Ahmed Khan**

Signature: ____________________

Date: ____________________

Dedication

I dedicate this thesis to my Adviser. I decided more than once not to pursue but he always encouraged me to complete this.

Certificate of Originality

I hereby declare that this submission is my own work and to the best of my knowledge it contains no materials previously published or written by another person, nor material which to a substantial extent has been accepted for the award of any degree or diploma at NUST SEECS or at any other educational institute, except where due acknowledgement has been made in the thesis. Any contribution made to the research by others, with whom I have worked at NUST SEECS or elsewhere, is explicitly acknowledged in the thesis.

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Author Name: **Junaid Abdullah**

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Acknowledgment

I would like to thank my advisor, my parents, my friends and my GEC.

Contents

1 Introduction **1**

1.1 The Radar 1

1.2 Passive Radars 2

  1.2.1 Illuuminator of Opportunity 4

  1.2.2 Passive Multistatic Radar 4

2 Literature Review **7**

2.1 Passive Radar Systems 7

2.2 Geometry Optimization for PMR 9

3 System Model and Optimization **11**

3.1 System Model 11

3.2 Illumination of the Entire Trajectory 13

3.3 Doppler Adjustment 16

3.4 Crammer Rao Lower Bound for Range Resolution 16

3.5 Direct Signal Attenuation 19

3.6 The Admissible Area 20

3.7 The Combined Optimization 21

4 Conclusions and Future Work 24

4.1 Conclusions 24

4.2 Future Work 25

List of Abbreviations

Abbreviation	**Description**
RADAR	Radio Detection And Ranging
CRLB	Cramer-Rao lower bound
GRCSM	generalized radar cross section model
DAB	digital audio broadcast
DVB	digital video broadcast
GSM	global system for mobile communication
LTE	long term evolution
WIMAX	worldwide interoperability for microwave access
WRAN	wireless regional area network
MIMO	multi input multi output
IoO	Illuminator of opportunity
AoI	area of interest
PMR	Passive multistatic radar
TDOA	Time difference of arrival
OFDM	orthogonal frequency division multiplexing
AF	ambiguity function
DSSS	direct sequence spread spectrum
APs	access points
CCF	clutter cancellation filter

List of Tables

3.1 Data set of Access point position (feet) 13

List of Figures

1.1 Bistatic Radar, Distant Transmitter and Reciver 2

1.2 Monotatic Radar, Onboard Transmitter and Reciver 2

1.3 Multistatic Radar 5

1.4 Bistatic Range 5

1.5 Time Difference of Arrival 6

1.6 Bistatic range to locate position of transmitter 6

3.1 Layout of the building with installed APs. The hashed area is the AoI 12

3.2 Conjuncture of the inscribed angle to track target at A-B . . 14

3.3 Conjuncture of the inscribed angle explained 14

3.4 Illumination of the entire trajectory 15

3.5 Doppler Adjustment 17

3.6 A CRLB plot obtained by keeping AP-1 and AP-8 as a transmitter pair. 19

3.7 The constraint of direct signal attenuation. Receiver can be placed in the white region. 20

3.8 Receiver can be placed in the white region 21

3.9 CRLB at Admissible Area 22
3.10 A plot of combined optimization 23

Abstract

Passive multistatic radars (PMRs) are becoming mature in recent times and different kinds of practical system have been developed and studied. Despite the fact that various issues are still under active research, one thing that stands out is that the performance of a passive multistatic radar is greatly dependent on the geometry of the transceivers. In this dissertation, we design a strategy to optimize the position of a receiver for the indoor environment that uses WiFi as an illuminator of opportunity. Furthermore, the proposed technique also provides a method to select the optimal transmitters, among many, for the optimal detection of a target in an indoor area. The subject optimization is achieved based on a case study subject upon which various constraints are applied. In this study, a realistic indoor environment is considered and then a specific area from this geometry is considered as area of interest, (an area where detection is required) and then optimal receiver for position is chosen in the available region.

Chapter 1

Introduction

1.1 The Radar

In 1939 Robert Watson Watt, a British scientist experimented that the air borne can be detected by radio waves [1], from that day onward the study of tracking object named as study of radars. There has been a continuous study from that day, on radar system. In the early ages bistatic radars, radars with distant transmitter and receiver shown in Fig. 1.1, got famous and they were the prime part of interest for research in that time [2] . Due to complex calculation of the angle of arrival (AoA), from the echoes of target in the last four decades of twentieth century, major research was conducted about monostatic radar (Transmitter and Receiver is on same platform) shown in Fig. 1.2. In last decade of twentieth century telecommunication technologies are deployed enormously in every part of world in the times of mid nineties at the same time term Passive Radar starting to a appear on surface [18] [19] [20].

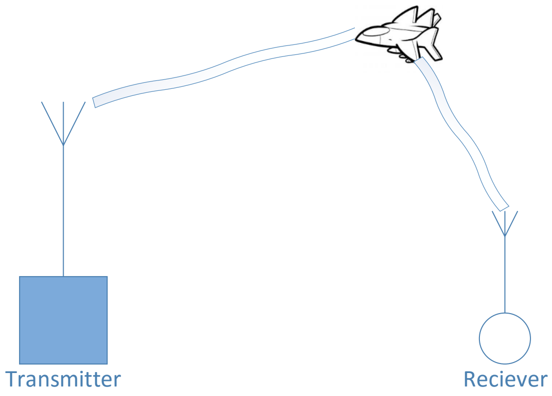

Figure 1.1: Bistatic Radar, Distant Transmitter and Reciver

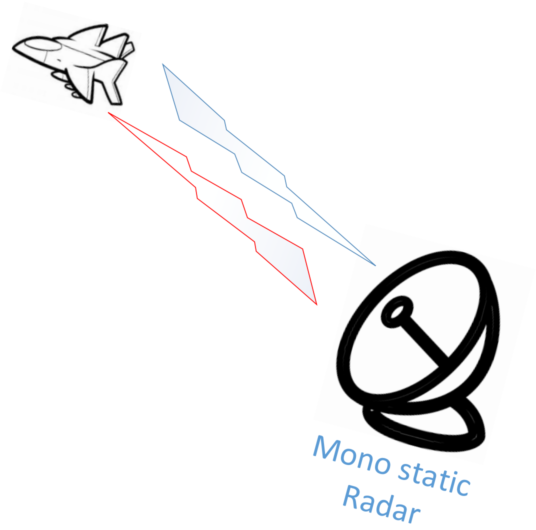

Figure 1.2: Monotatic Radar, Onboard Transmitter and Reciver

1.2 Passive Radars

Till the late nintees every radar system developed need a dedicated transmitter to perform its operation and these type of radars are called active radar. But after the communication revolution new kind of radar system emerged in which there is no need to install a dedicated transmitter but rather utilize the existing illuuminator of opportunity. In passive radars only a receiver is designed and placed among the iluminators which utilized them as transmitters of radar and detection and tracking is performed. Passive radars are one of the progressive technologies [27] in recent times. Passive radar offers many benefits on their counter parts.

1. “Covert operation” is easily achieved using passive radar because they did not need infrastructure or specific location as it is needed in active radars.

2. “Anti jamming” is another benefit as it is more difficult to jam frequencies of different illuminator rather than a single chunk of radar frequencies.

3. “Low cast” as it is described earlier that passive radars only have receivers in comparison to their counterpart so it will offer low cost and cost of deploying a dedicated transmitter is saved in this process.

4. “Frequency reuse” it is embedded in the concept of passive radar as the passive receiver, exploits the already existing illuminator so frequency used by illuminator for communication purpose is reused in radar.

One thing of note is that active radar can be of type mono static or bistatic or even multistatic radar but passive radar can be bistatic or multistatic because transmitter is not there only to serve the purpose for radar but it also has other task to perform.

1.2.1 Illuuminator of Opportunity

Illuminator of opportunity (IoO) are those transmitter of opportunities which can be utilized as the transmitter of radar to track specific area. IoO includes all the transmitter of existing telecoms infrastructure i.e. FM , Digital Audio Broadcast (DAB) , Digital Video Broadcast (DVB) , WiFi , cellular base stations. illuminator of opportunity can be selected on the bases of application , availability of illuminator and on the area where detection is required called area of interest (AoI). So in our case study AoI is indoor and illuminator of opportunity utilized is WiFi.

1.2.2 Passive Multistatic Radar

Multistatic radar is a bistaic radar having multiple transmitter or receivers to track specific target shown in Fig. 1.3. Passive multistatic radar (PMR) is the type of radar in which either more than one illuimnator of opportunity is utilized or more than one passive receiver is placed to track objects. Mutistatic radar is extension of bistatic radar. Bistatic range parameter associated with bistatic radar is also associated with PMR described in here. In this figure two illuminator has been utilized and one passive receiver receive echoes from target. This mode of PMR have been used for our case study.

Bistatic Range

Time difference of arrival (TDOA) [16] is one of the techniques used while tracking objects and in bistatic and multistatic radars employing TDOA, the measured range is known as bistatic range. It is a relative measurement of

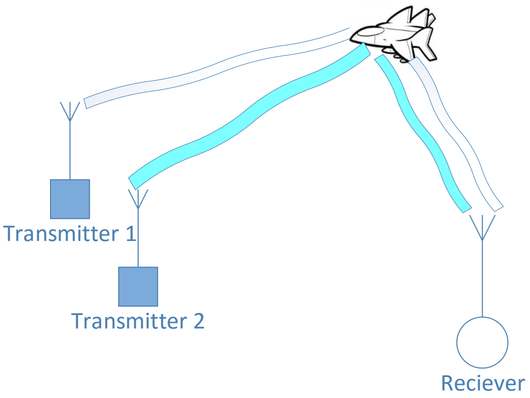

Figure 1.3: Multistatic Radar

distance from the target to the receiver and the transmitter shown in Fig. 1.4. Unfortunately TDOA does not results in one location rather than this range could be realized by an ellipse on this ellipse all the points have same TDOA as shown in Fig. 1.5.

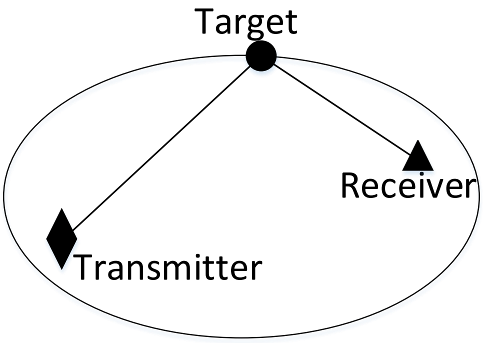

Figure 1.4: Bistatic Range

For locating the exact position of target further processing is performed and different techniques are available for them in literature, one of them is to calculate the angle of arrival [24] which is error prone. Apart from calculating the actual angle of arrival, at least two independent measurements

$$R_b = \sqrt{(x - x_{tx})^2 + (y - y_{tx})^2} + \sqrt{(x - x_{rx})^2 + (y - y_{rx})^2},$$

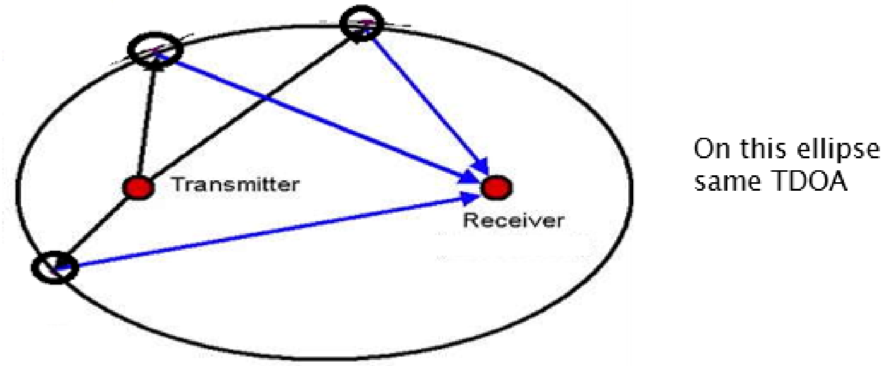

Figure 1.5: Time Difference of Arrival

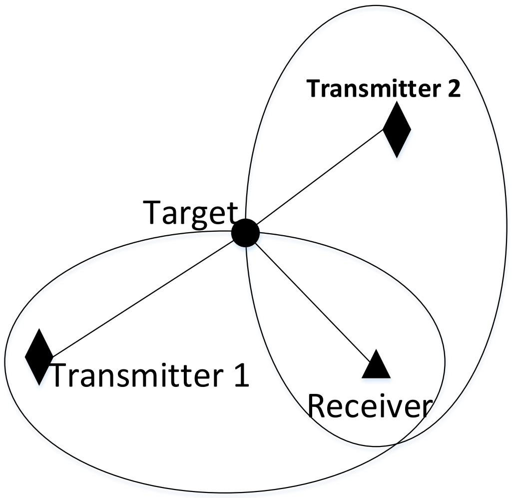

Figure 1.6: Bistatic range to locate position of transmitter

are required to locate the position of a target explained in Fig 1.6.

Chapter 2

Literature Review

2.1 Passive Radar Systems

Passive radars rely on existing illuminators of opportunity to perform various sensing operations such as target detection and localization [4]. Early research work was focused on the covert operation ability of passive radars [15], and the ability of anti jamming [25], these characteristic are embedded in the concept of passive radar. The receiver of passive radar was designed using conventional active radar techniques and special purpose hardware was used [26]. This research was focused using passive radar as extension and backup for active radars.

After that early research the area of passive radar become much more active and then various illuminators of opportunities have been studied and analyzed such as digital audio broadcast (DAB) [6], digital video broadcast (DVB) [7], and cellular signals [8] among others. However, to perform radar detection operation in indoor environments, a natural strategy is to use the

WiFi technology, which is widely used for internet connectivity almost everywhere [12].

WiFi is an IEEE 802.11 access complaint technique with various release versions, which generally operates in 2.4 GHz or 5.8 GHz bands and can deliver data rates up to 600 Mbps using the most recent technologies of orthogonal frequency division multiplexing (OFDM) and multiple-input multiple output (MIMO) systems. Active research has been conducted to perform various operations for passive radars using the WiFi signals. Whereas the early research on WiFi-based passive radars focused on the ambiguity function (AF) analysis of its waveforms [11], many recent advances such as through the wall (TTW) sensing have been demonstrated practically on various test-beds [9]. Many researchers have demonstrated to detect motion of either a human or a vehicle through WiFi signals [10] using 2D target profiling. Many signal processing algorithms have also been designed for Wifi OFDM signal [30]. Various modes of direct sequence spread spectrum (DSSS) operation of WiFi for use in passive radars have been studied in [17]. Wifi beacons have many desirable characteristics to be used as illuminator [17]. Considering all this we have used WiFi illuiminators in this study for detection in indoor environment. Passive radars are generally deployed in bistatic and multistatic configuration. In a bistatic configuration, a transmitter and a receiver is used to perform target detection whereas in multistatic passive radars, a number of transmitters and receivers is utilized to perform the operations

2.2 Geometry Optimization for PMR

Geometry optimization in radar system is achieved by placing the receiver and transmitter of radar at most suitable position to maximize the performance of radar while observing some constraints. Geometry optimization of passive radar is different than active radar In passive radar geometry optimization means to estimate the best suitable position for receiver and the selection of best transmitter among the available ones. In passive radar system usually the placement of transmitter is out of the hand of radar designer.

Geometry of a radar system have been an important topic as from the start of radar theory [21] In conventional active radar or in PMR studied have carried out to optimize the geometry [22] [23] [29] but To the best of the authors' knowledge, no significant work has been performed to optimize the geometry of a passive radar receiver in indoor environments when WiFi signals are used as illuminators. Valeria *et al.* in [13] optimize the geometry of a passive receiver for outdoor environments where the target can appear only at a discrete number of points in a vertical line using FM as illuminator.

In this study, we extend the approach in [13] and study an optimization approach using a set of constraints, which can be used to locate a WiFi-based passive radar receiver in an indoor environment when multiple transmitters (access points) are installed in a building. We intend to place the receiver in such a manner that the movement of a target can be detected in a specified area of interest (AoI). The AoI is an entire region, as opposed to some discrete locations, which in our case is a room in a building. We define four constraints that include the evaluation of a Cramer Rao bound (CRB), and provide a map as to which transmitters can be used in connection to an optimized geometry of the receiver such that a successful detection of the target can be achieved. We have evaluated the best available position for receiver considering all the available APs taking two at time by doing this we also finds the best transmitter pair for our multistatic radar.

After defining our system model in the next Chapter, then we further discussed the various constraints that are applied on the indoor geometry. Finally, the effects of all individual constraints are combined to provide a consensus about the optimal receiver position.

Chapter 3

System Model and Optimization

3.1 System Model

We study a special square geometry having an area of 200 × 200 square feet to model a real life scenario. Consider a geometry as shown in Fig. 3.1, which depicts a block of building. The access points (APs) represent the 2D coordinates of the transmitters installed in this building block. The center of the AoI is assume to be at origin, i.e, (0,0) coordinates on the 2D plane, and the position of the APs are evaluated accordingly. For a given area of interest (AoI), where the target detection is required, the proposed technique selects a transmitter pair and finds the position of the passive receiver to optimize the target detection and tracking in PMR. The area of interest is marked in Fig. 3.1. The x and y coordinate positions of APs are given in table, 3.1. In this study, all the transmitters are assumed to have omni-directional antennas and the passive receiver has a directional antenna with the main beam angle $\alpha = 90°$, which is comprised of its 3-dB beam width and it has back lobe angle $\beta = 45°$.

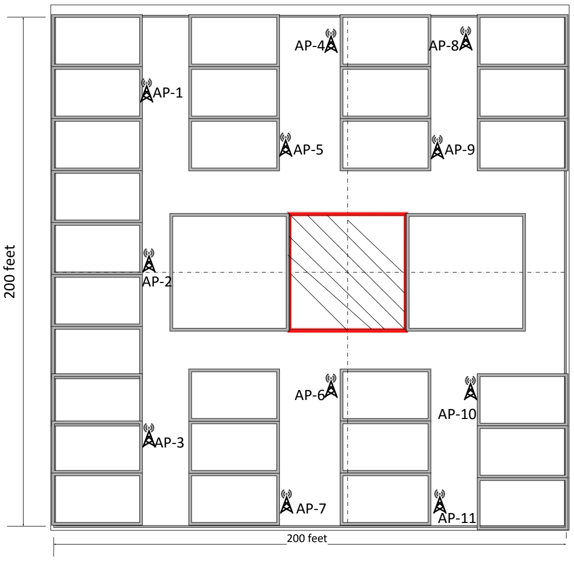

Figure 3.1: Layout of the building with installed APs. The hashed area is the AoI

For a given AoI, the proposed technique will evaluate every combination of available transmitters and check the entire region available for the position of the receiver. In this case, there are eleven available transmitters hence for the given AoI, fifty five combinations can be tried and ranked. All the available positions for the receiver on the given geometry are checked by satisfying four different constraints, which are described in the next section. We examine the individual effects of these four constraints on the geometry in this given case of study.

Table 3.1: Data set of Access point position (feet)

AP Number	X coordinate	Y coordinate
1	-81.5	66.67
2	-81.5	00.00
3	-81.5	-66.67
4	-3.7	85.20
5	-26.67	-46.30
6	-3.7	-48.15
7	-26.66	-92.50
8	50.40	87.00
9	31.9	44.44
10	50.4	-49.6
11	33.33	-94.44

3.2 Illumination of the Entire Trajectory

In the first constraint, it is ensured that the position of the receiver illuminates the complete AoI, and is based on the conjuncture of inscribed angle shown in Fig. 3.3. It states that the value of intercepted arc formed by the angle (shown as 2α) is double with respect to the inscribed angle (α). The area of illumination in this case is the chord formed by joining the two ends of intercepted arc. The arc will be illuminated by the passive receiver having main lobe angle α placed outside the two replicated circles such as the one drawn in Fig. 3.2 at opposite sides of chord A-B.

This constraint is generally independent of the location of transmitters and involves only AoI, and the 3-dB beam width of the receiver. Hence for

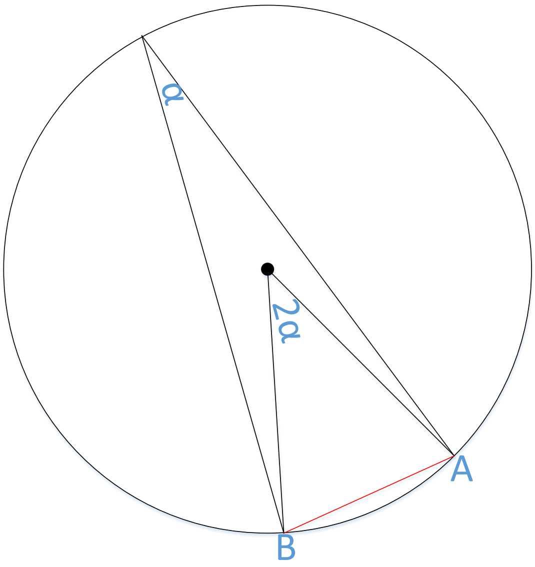

Figure 3.2: Conjuncture of the inscribed angle to track target at A-B

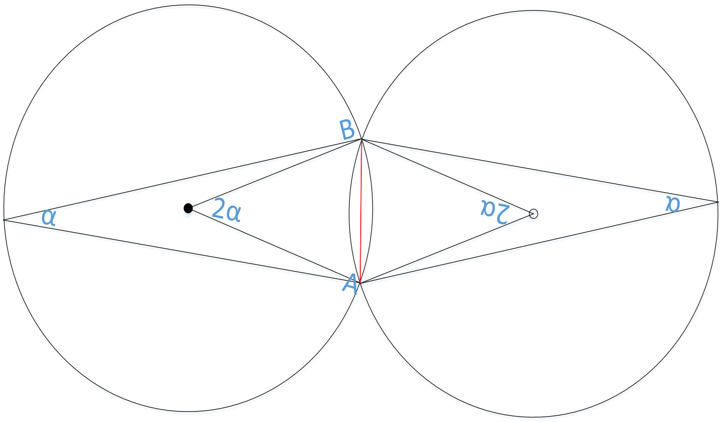

Figure 3.3: Conjuncture of the inscribed angle explained

the given AoI, this needs to be calculated once. With the help of conjuncture of inscribed angle, we have extended this notion to the whole area trajectory instead of a single chord by satisfying the constraints in both horizontal and vertical dimensions. For the marked AoI of Fig. 1, it is measured and shown in Fig. 3.4, where the receiver can be placed anywhere but in the shaded region.

For the next three constraints, the positions of the transmitters play a vital role. However, we present herein the constraints by selecting AP-1 and AP-8. Similar technique can be applied to all transmitter pairs to check the optimal solution for best detection.

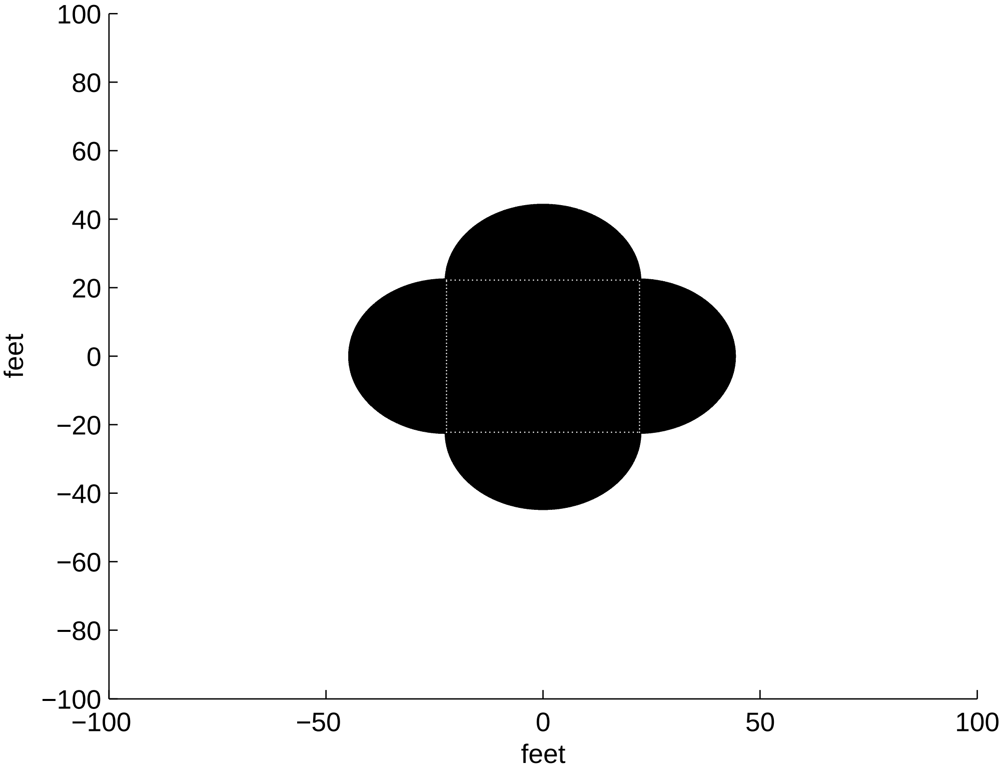

Figure 3.4: Illumination of the entire trajectory

3.3 Doppler Adjustment

The clutter cancellation filter (CCF) does not allow any echoes with a zero Doppler frequency [14]. The second constraint is to adjust the Doppler error caused by mainly two reasons, which are as given.

1. In a bistatic radar system, the geometry of a transmitter-receiver pair forms an ellipse and if the target is present at a tangent to that ellipse, the receiver will receive a zero Doppler, which is independent of the target movement.
2. A same base line for the transmitter and the receiver position will also results in a zero Doppler independent of the target movement.

In this second constraint, the geometry is adjusted to avoid zero Doppler problem and the shaded region in Fig. 3.5, for given AoI, shows the area where the receiver cannot be placed for a specific transmitter pair AP-1 and AP-8.

3.4 Crammer Rao Lower Bound for Range Resolution

Time difference of arrival (TDOA) [16] is one of the techniques used while tracking objects and in bistatic and multistatic radars employing TDOA, the measured range is known as bistatic range. It is a relative measurement of distance from the target to the receiver and the transmitter. Apart from calculating the actual angle of arrival, at least two independent measurements

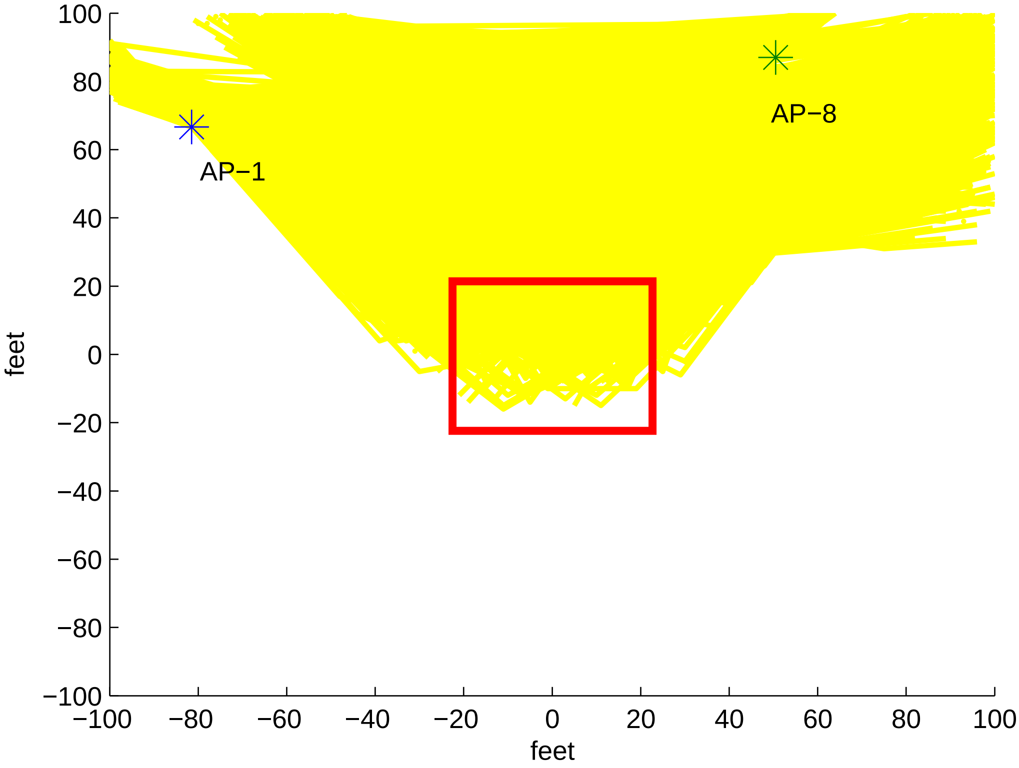

Figure 3.5: Doppler Adjustment

are required to locate the position of a target. Hence for obtaining the Cramer-Rao lower bound (CRLB), which is used to access the accuracy of target's position, the two independent measurements required are given as

$$\tilde{R}_{b_n} = R_{b_n} + \epsilon_{r_b}, \qquad n = \{1, 2\}, \tag{3.1}$$

where $\tilde{R}_{b_n}$ is the measured bistatic range and R_{b_n} is the actual bistatic range. The ϵ_{rb} in (3.1) represents the measurement error and is modeled as a Gaussian random variable (RV) with zero mean and variance σ^2, where the variance is dependent upon the type of illuminator used. For a WiFi-based passive radar, the σ^2 is generally taken to be 25 meters [5]. For a 2D space, both $\tilde{R}_{b_n}$ and R_{b_n} are functions of target's position, which is represented by a 2D coordinate system, i.e., (x,y). The expression for bistatic range, R_b, as a function of target's position, is given as

$$R_b = \sqrt{(x - x_{tx})^2 + (y - y_{tx})^2} + \sqrt{(x - x_{rx})^2 + (y - y_{rx})^2}, \tag{3.2}$$

where (x_{tx}, y_{tx}) and (x_{rx}, y_{rx}) represent the positions of the transmitter and the receiver, respectively. In calculating the uncertainty in the position of target through CRLB, the parameter of interest taken is θ=[x y]. The Fisher information matrix for this parameter is given as

$$\mathbf{I}(\theta) = \frac{1}{\sigma^2} \begin{bmatrix} \frac{\partial^2 \tilde{R}_b}{\partial x \partial x} & \frac{\partial^2 \tilde{R}_b}{\partial x \partial y} \\ \frac{\partial^2 \tilde{R}_b}{\partial y \partial x} & \frac{\partial^2 \tilde{R}_b}{\partial y \partial y} \end{bmatrix}, \tag{3.3}$$

where $(\mathbf{I}(\theta))^{-1}_{(1,1)}$ results in the CRLB of σ_x^2 and $(\mathbf{I}(\theta))^{-1}_{(2,2)}$ results in the CRLB of σ_y^2. Accumulated effect on a 2D plane can be well observed by the horizontal range resolution given as

$$\sigma_h = \sqrt{\sigma_x^2 + \sigma_y^2}. \tag{3.4}$$

The CRLB plot for the horizontal range resolution using AP-1 and AP-8 as a transmitter pair is shown in Fig. 3.6. It can be noticed that the receiver should be placed on those points where the values of CRLB are small. Doing so, accurate position about the target's position can be obtained. This CRLB

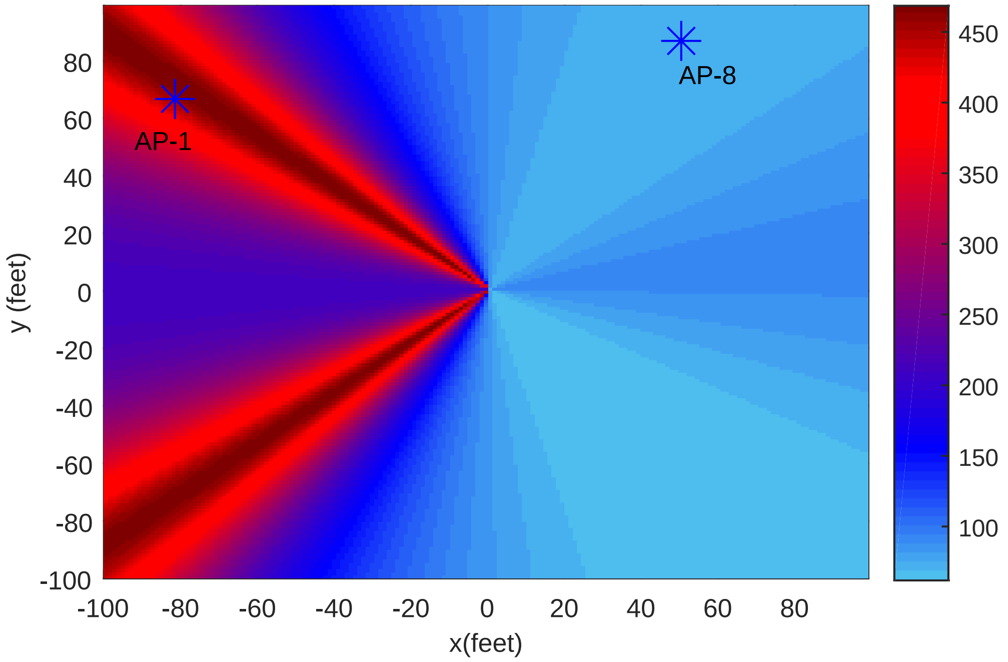

Figure 3.6: A CRLB plot obtained by keeping AP-1 and AP-8 as a transmitter pair.

plot is obtained by taking average on complete AoI.

3.5 Direct Signal Attenuation

In this constraint, the direct signal from the transmitter is attenuated and only the echoes from the target are allowed to reach the receiver. To achieve this, the conjuncture of the inscribed angle explained in Fig. 3.3 is used by having the back lobe angle $\beta = 45°$. However, this is done in the opposite manner as the area inside the outer circle will be allowed to place the receiver. By observing this constraint, the direct signal from transmitter is received in the back lobe of receiver and only echoes from target are allowed for the

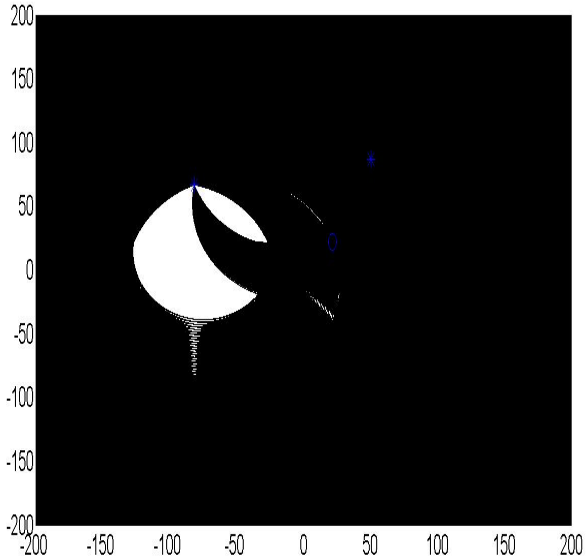

Figure 3.7: The constraint of direct signal attenuation. Receiver can be placed in the white region.

main lobe. The shaded region in Fig. 3.7 cannot be selected for receiver placement for the given AoI in Fig. 3.1.

3.6 The Admissible Area

These constraints described in previous sections calculates the area where the passive receiver, can be placed by combining areas in figures, 3.4 3.5 3.7 the final admissible position of a receiver according to all constraint is obtained in Fig. **??**, and this area is dependent on specific transmitter pair (AP1,AP8) and on specific AoI , AoI is marked white and position of the pair of APs, are also marked for different set of (APi,APi) it will be different and in this case study i ranges from 1 to 11. It is evident from CRLB and this combine plot of admissible area that best receiver position with least CRLB can not

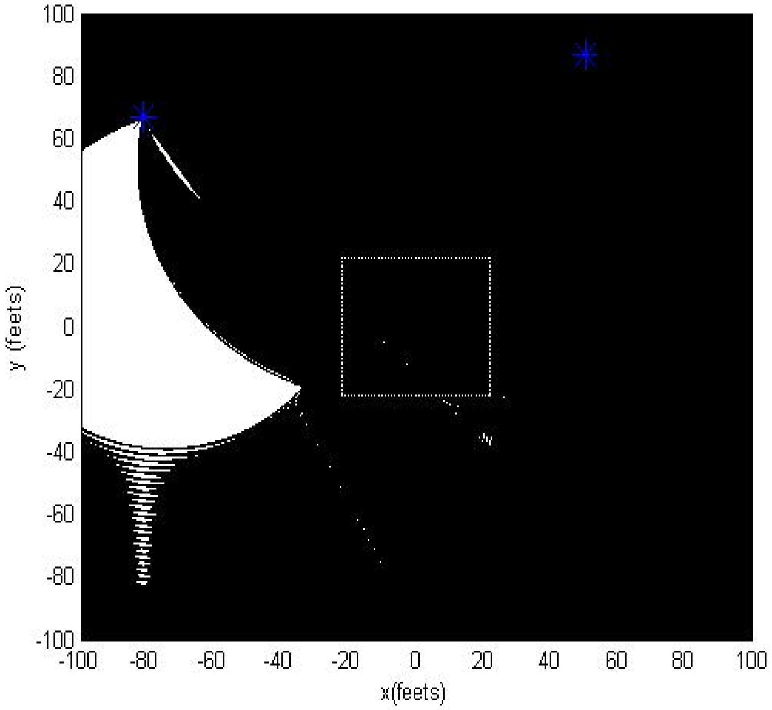

Figure 3.8: Receiver can be placed in the white region

be availed due to other constraint it is shown in Fig. 3.9. Hence it is needed to check by using which pair of transmitter will give least value of CRLB under these constraint it is described in next section.

3.7 The Combined Optimization

The four constraints, evaluated in the previous section, are not independent from one another and they do not have isolated effect on target's detection and tracking. In this case study we have 11 transmitters. Hence for the given AoI, all different combinations of the transmitters are tried and the entire area of 200 × 200 square feet is scanned for the optimal receiver placement.

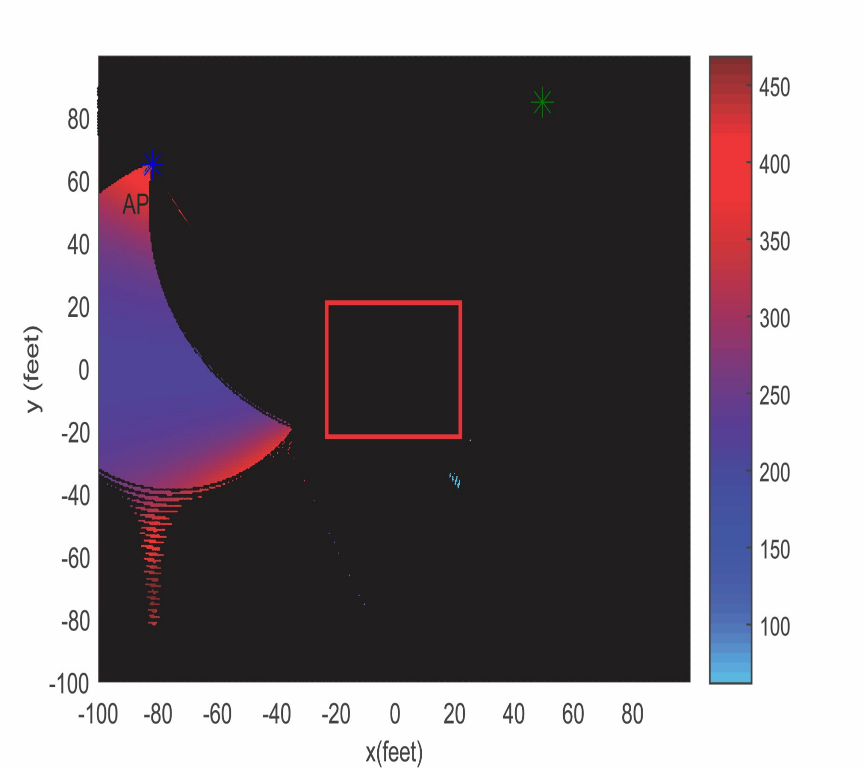

Figure 3.9: CRLB at Admissible Area

For every transmitter pair, all constraints have been tested and finally the combined picture is presented in Fig. 3.10. The black spots signify that there is no optimal position available for the passive receiver in the entire region for that specific transmitter pair. For instance, we cannot use AP-1 and AP-8 to detect the target in the given AoI.

The color value according to the color bar shows the value of σ_h, i.e., the horizontal range resolution for a specific transmitter pair. From this figure, we can see that for the given AoI, transmitter pair (2,4) provides the optimal value for range resolution where the value of CRLB is least. In a real life scenario, for instance for applications in security, it is possible that the best transmitter pair cannot be utilized because the receiver position is not

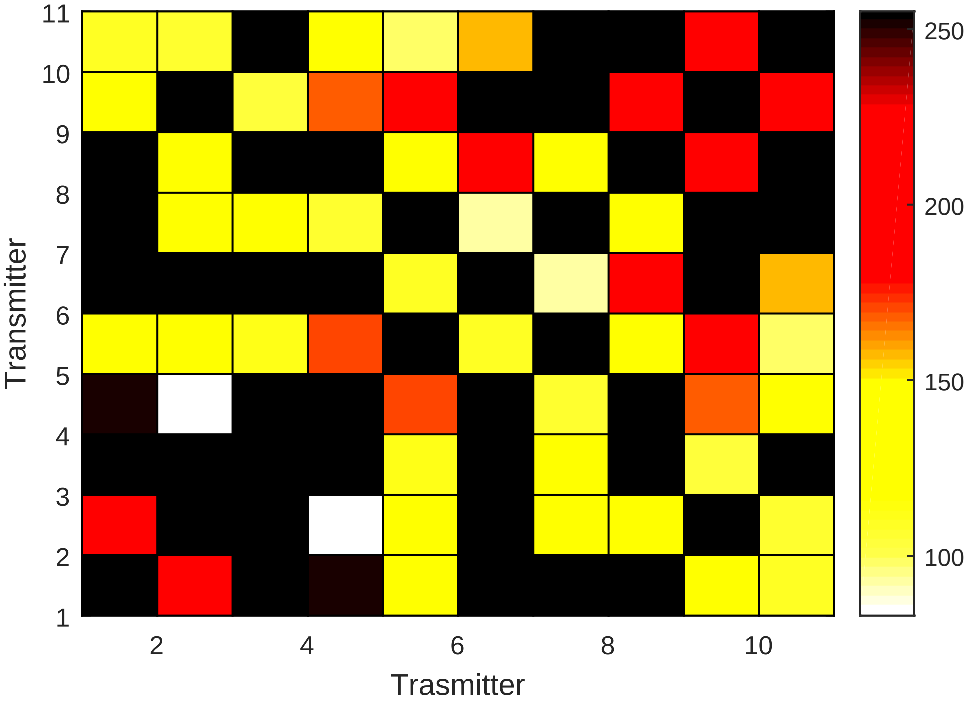

Figure 3.10: A plot of combined optimization

practically realizable. In this case, another transmitter pair can be selected that allows us to place the receiver in a given area and still provides better range resolution.

Chapter 4

Conclusions and Future Work

4.1 Conclusions

In this thesis, We have analyzed an indoor geometry that uses WiFi as an illuminator of opportunity for the detection of a target in an area. Four different constraints have been used that allow us to achieve an accurate target's detection and tracking by adopting the optimal geometry. All of theses constraints are available in literature for conventional outdoor environment in active radars as well as for PMR in outdoor environment. These four constraints have paramount of importance and they all have been tested and optimization based on these constraints improves performance significantly. Theses four constraint have been center point of many research works regarding geometry optimization taking one at a time or more. All the conducted research so far has considered outdoor environment and optimization is performed considering some discrete points of interest or considering a line of interest for target trajectory. We have considered WiFi as illuminator and we have studied an indoor environment for target detection and it is required in room where the target trajectory is area instead of line or a discrete point.

In this work geometry optimization is performed considering four constraints and an area of interest in indoor PMR and then there results are combined which results in optimal position of receiver and then the optimal receiver position is evaluated for all the transmitter pairs to find the best pair for our operation. It is further concluded that not all transmitters are optimal for the said operation, rather a subset of them provides a way to perform the detection.

4.2 Future Work

Topic of Passive radars is one of the emerging field In telecommunications and also in the field of radar technology. Hence there are many possibilities of research is this area future work regarding to our study is mentioned below. In our case study while calculating CRLB the signal processing constraint, we have taken assumption that probability of detecting the target is always one . This assumption can be taken out if the CRLB is calculated considering probability of detection less than unity then this probability of detection will be function of SNR and channel degradations. Another Future aspect regarding this study is about considering more than two transmitter for a PMR. This will improve CRLB and range resolution but the admissible area will become more rare. Aspect of involving 3D plane with respect to all these constraints can be another interesting future extension of this work. Experimental evaluation of the current work on a practical PMR can also be a one of the possible future direction.

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