

Geometry Optimization for WiFi-based Indoor Passive Multistatic Radars

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Abstract—Passive multistatic radars (PMRs) are becoming mature in recent times and different kinds of practical systems are being studied and developed. Whereas various issues related to passive radars are still under active research, an important aspect is that the performance of a PMR is greatly dependent on the geometry and physical locations of the transceivers. A PMR designer generally has no control on the position of the transmitters, however, locating the passive receiver to obtain best target detection capabilities remain an interesting research problem. In this paper, we study the optimization of the position of a passive radar receiver in an indoor environment that uses WiFi as an illuminator of opportunity. Furthermore, the proposed technique also provides a method to select a subset of optimal transmitters, among many, for the detection of a target in an indoor area. The subject optimization is performed on a case study where different constraints are applied to find the optimal location of the receiver.

Index Terms—Passive radars, geometry optimization, WiFi, multistatic, Cramer-Rao bound

I. INTRODUCTION

Passive radars rely on existing illuminators of opportunity to perform various sensing operations such as target detection or localization [1]. In a bistatic configuration, a transmitter and a receiver are used to perform target detection whereas in multistatic passive radars, a large number of transmitters and receivers are utilized to perform the operations. Various illuminators of opportunities have been studied and analyzed such as digital audio broadcast (DAB) [4], digital video broadcast (DVB) [5], and cellular signals [6] 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 universally [11].

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 [10]. 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 [9], many recent advances such as through the wall (TTW) sensing have been demonstrated practically on various test-beds [7]. Many researchers have demonstrated to detect motion of either a human or a vehicle through WiFi signals [8] using a two-dimensional (2D) target profiling.

Various modes of direct sequence spread spectrum (DSSS) operation of WiFi for use in passive radars have been studied in [14]. However, 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 [12] optimize the geometry of a passive receiver for outdoor environments using frequency modulation (FM) transmitters where the target can appear only at a discrete number of points in a vertical line. In conventional radars, which are mostly placed in outdoor environments, the optimization of geometry is performed for some sensitive discrete target positions and this is also the case with most of the illuminators of opportunities placed outdoors such as FM towers in [12]. However, using WiFi as an illuminator is not the same because the access points (APs) of WiFi are not generally placed in outdoor environments. On the other hand, the applications based on such passive radars also involve detection of target on some area inside the buildings rather than discrete points [7]. Hence geometry optimization for passive radars in indoor environments results in optimal transceivers' positions in a confined areas of a building.

In this paper, we 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 distinct 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.

The rest of the paper is organized as follows. We define our system model in Section II. After defining our system model in the next section, the paper then goes on to discuss 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. The paper then concludes with a direction of future work at the end.

II. SYSTEM MODEL

We study a special square geometry having an area of 200×200 square feet, as shown in Fig. 1, which depicts a block of building at SEECs-NUST. The access points (APs) represent the 2D coordinates of the transmitters installed in this building. The center of the marked region, which is the area of interest (AoI), is assumed to be at origin, i.e., (0,0) coordinates on the 2D plane, and the position of the APs are evaluated accordingly, where the positions of the APs are given in Table I. For a given AoI, where the target detection is required, the proposed technique selects a transmitter pair from all possible combinations and finds a position where the passive receiver can be placed to optimize the target detection and tracking. In this study, all the transmitters are assumed to have omnidirectional antennas and the passive receiver has a directional antenna with the main beam angle $\alpha = 90^\circ$, which is comprised of its 3-dB beam width with a back lobe angle $\beta = 45^\circ$.

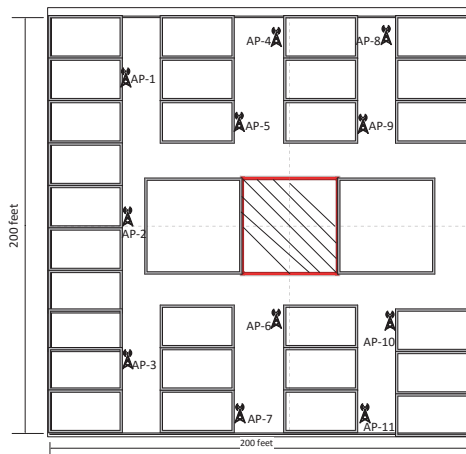


Fig. 1. Layout of the building with installed APs. The hashed area is the AoI

TABLE I
X-Y COORDINATES FOR ACCESS POINTS

AP Number	X ,Y coordinates
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

For the given AoI, the proposed technique evaluates every combination of the available transmitters using two transmit-

ters at a time and searches the entire region available to optimally place the receiver. In this case, there are eleven available transmitters, hence for the given AoI, fifty five combinations are tried and ranked. All the available positions for the receiver on the given geometry are evaluated by satisfying four different constraints, which are described in the next section. We examine the individual effects of three radio frequency (RF) constraints and one signal processing constraint as described in following section.

A. 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 *conjecture of inscribed angle* shown in Fig. 2. This conjecture states that ‘the value of intercepted arc formed by the angle (shown as 2α) should be twice as compared to the inscribed angle, α ’. The conjecture implies that the passive receiver is required to be placed at a position such that its main lobe completely illuminates the AoI. For example, the chord A-B 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 at opposite sides of the chord A-B. This approach can be applied directly to calculate the inadmissible area for the receiver when we have to track target on a line or at a particular point. For the indoor geometry at hand, the AoI is not a straight line or a point rather it is a 2D surface or a 3D cubical volume. Therefore, in the proposed approach, the AoI is dissected in vertical and horizontal lines and then circles are drawn using the conjecture of inscribed angle. This is then used to calculate the inadmissible area for the receiver as shown in Fig. 4.

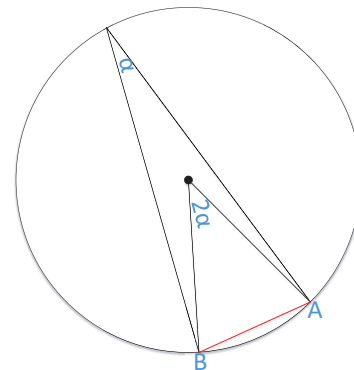


Fig. 2. Conjecture of the inscribed angle to track target at chord A-B

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 the given AoI, this needs to be calculated once. With the help of conjecture 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. 5, where the receiver can be placed anywhere but in the shaded region.

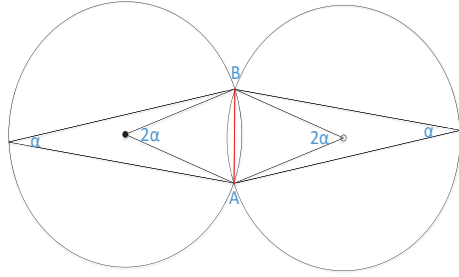


Fig. 3. Conjecture of the inscribed angle to track target at both sides of chord A-B

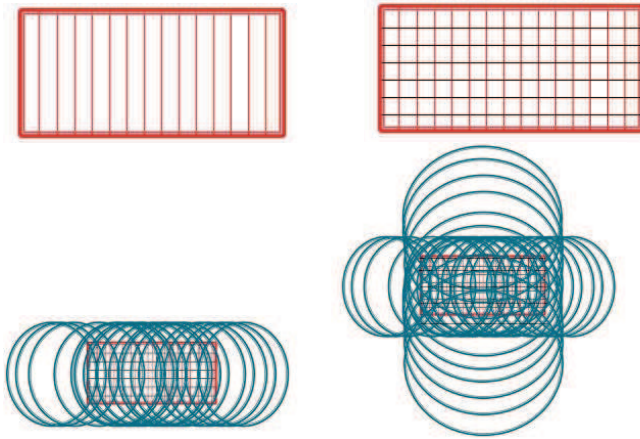


Fig. 4. AoI is dissected into vertical and horizontal lines and for each line the circles are drawn using the conjecture.

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 process can be repeated to all transmitter pairs to check the optimal solution for best detection.

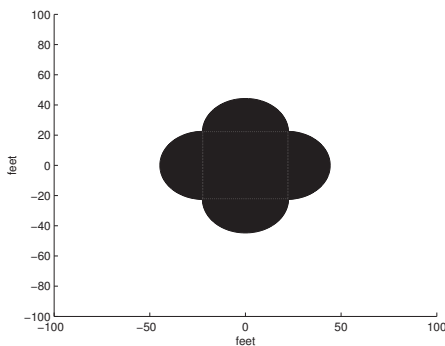


Fig. 5. Illumination of the entire trajectory, the receiver can't be placed in black area

B. 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 conjecture of the inscribed angle explained in Fig. 2 is employed again, however, now the back lobe angle $\beta = 45^\circ$ is used instead of α and the chord A-B is replaced by the chord tx-target, where tx-target is the line between the transmitter and the target position. However, this approach is performed in an opposite manner, because the direct signal from the transmitter has to be attenuated and this happens when it is received in the backlobe of the receiver. Therefore, this is achieved by placing the receiver inside of the outer circles in Fig 3 . By observing this constraint, the direct signal from the transmitter is received in the back lobe of the receiver and only echoes from the target are allowed for the main lobe. Once again to achieve this constraint, the AoI is dissected into vertical and horizontal lines and then circles are drawn using conjecture of inscribed angle to calculate the inadmissible area for the receiver as shown in Fig. 4. The shaded region in Fig. 6 cannot be selected for receiver placement for the given AoI in Fig. 1 when transmitter pair AP-1 and AP-8 are selected for detection.

C. Doppler Adjustment

Time difference of arrival (TDOA) [13] is one of the techniques used while tracking objects and for bistatic and multistatic radars employing TDOA, the measured distance is known as bistatic range. It is a relative measurement of distance from the target to the receiver and the transmitter. Bistatic range is linked with this constraint and is used to adjust the error caused by the notion of 'zero Doppler'. The zero Doppler error occurs due to following reasons:

- 1) In a bistatic radar system, the geometry of a transmitter-receiver pair forms an ellipse that provides the bistatic range 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 and hence the target cannot be detected.
- 2) A same base line for the transmitter and the receiver position also results in zero Doppler independent of the target movement.

In this constraint, the geometry is thus adjusted to avoid zero Doppler problem and the shaded region in Fig. 7, for the given AoI, shows the area where the receiver cannot be placed for a specific transmitter pair AP-1 and AP-8.

D. Crammer Rao Lower Bound (CRLB) for Range Resolution

We measured the effects of RF constraints in the previous subsections and they provided a binary decision for the position of the passive receiver, i.e, whether a considered position is admissible or not. The CRLB constraint evaluates the best position for the passive receiver, in all of the admissible region, where highest range resolution can be achieved. In calculating this constraint, at least two independent measurements of

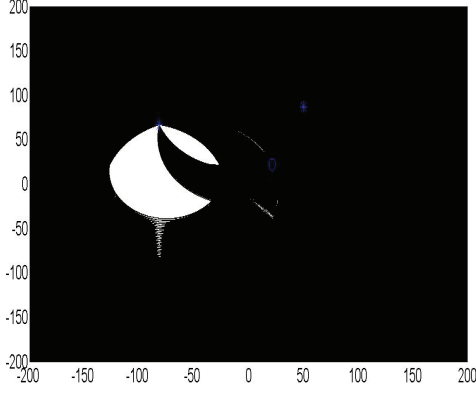


Fig. 6. The constraint of direct signal attenuation. Receiver can be placed in the white region.

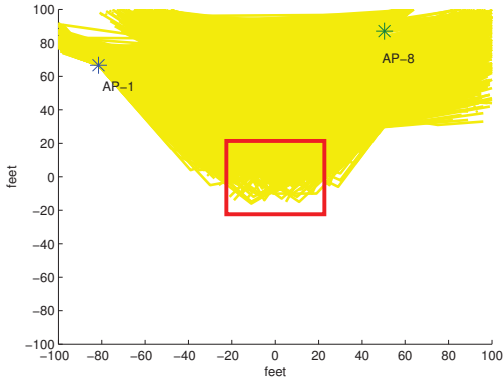


Fig. 7. The snapshot of geometry after Doppler adjustment constraint. White region is admissible

bistatic range are required. These two measurements can lead to actual position of the target and are given as

$$\tilde{R}_{b_n} = R_{b_n} + \epsilon_{r_b}, \quad n = \{1, 2\}, \quad (1)$$

where \tilde{R}_{b_n} is the measured bistatic range and R_{b_n} is the actual bistatic range. The ϵ_{r_b} in (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 [2], [3]. 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

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

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

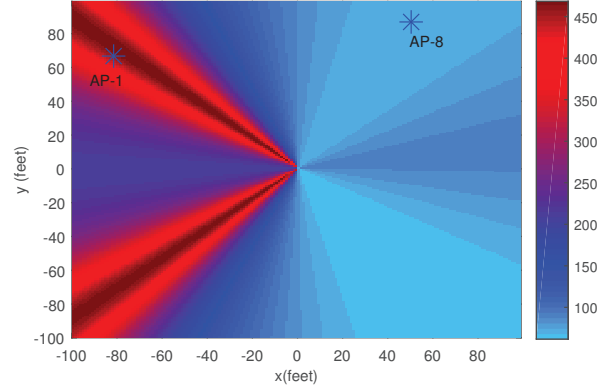


Fig. 8. A CRLB plot obtained by keeping AP-1 and AP-8 as a transmitter pair.

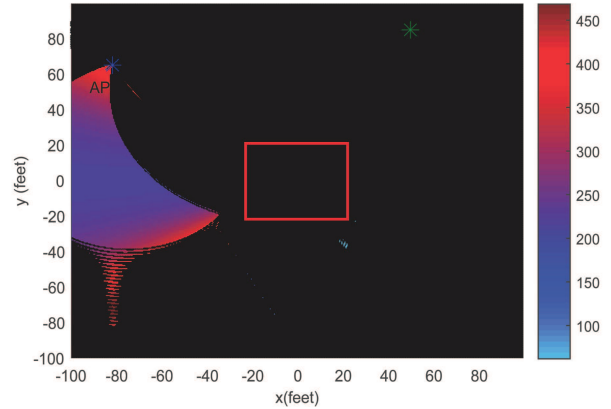


Fig. 9. Combined effect of all constraints for AP-1 and AP-8 as the transmitter pair

parameter of interest taken is $\theta = [x \ y]$. The Fisher information matrix for this parameter is given as

$$\mathbf{I}(\theta) = \frac{1}{\sigma^2} \begin{bmatrix} \frac{\partial^2 \tilde{R}_b}{\partial x \partial x} & \frac{\partial^2 \tilde{R}_b}{\partial x \partial y} \\ \frac{\partial^2 \tilde{R}_b}{\partial y \partial x} & \frac{\partial^2 \tilde{R}_b}{\partial y \partial y} \end{bmatrix}. \quad (3)$$

From the above equation, $(\mathbf{I}(\theta))_{(1,1)}^{-1}$ results in σ_x^2 and $(\mathbf{I}(\theta))_{(2,2)}^{-1}$ results in σ_y^2 , where σ_x^2 and σ_y^2 are the variances in the estimation of x and y coordinates of the target's position, respectively. The accumulated effect on a 2D plane can be well observed by the horizontal range resolution given as

$$\sigma_h = \sqrt{\sigma_x^2 + \sigma_y^2}. \quad (4)$$

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

E. The Combined Optimization

The four constraints, evaluated in the previous subsections, are not independent of one another and they don't have isolated

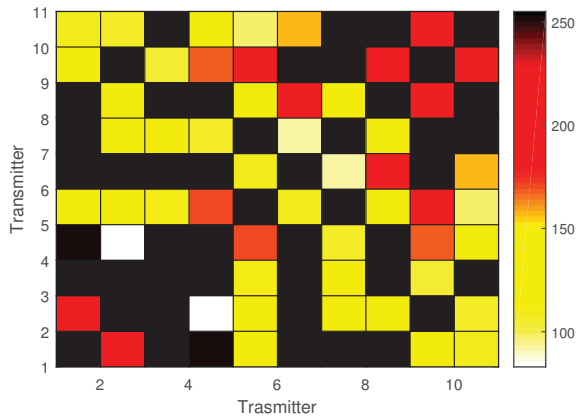


Fig. 10. A plot of combined optimization for transmitter selection

effects on target's detection and tracking. Hence for a specific transmitter pair, e.g., AP-1 and AP-8, an intersection of all admissible regions using RF constraints and CRLB is required, which is shown in Fig. 9. The inadmissible region in Fig. 9 is depicted in black whereas the color map of CRLB is plotted on the admissible region. It can be observed that light-colored positions are most suitable for receiver placement.

1) *Transmitter pair selection:* In this case study, we have 11 transmitters and for the given AoI, all different combinations of these transmitters are tried and the entire area of 200×200 square feet is scanned for the optimal receiver placement. For every transmitter pair, all constraints have been tested and finally the combined result is presented in Fig. 10. The black squares signify that there is no optimal position available for the passive receiver in the entire region for that specific transmitter pair. On the other hand, 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 minimum. In a real life scenario, for instance for applications in security, it is possible that the best transmitter pair cannot be used because the receiver position is not practically realizable. In this case, alternative transmitter pair can be selected that allows the receiver to be placed in a given area while still providing better range resolution.

III. CONCLUSION

In this paper, 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. It is concluded that not all transmitters are optimal for the said operation, rather a subset of them provides a way to perform the detection of a target.

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