

SECTOR BASED AoA ESTIMATION ALGORITHM USING TWO-ELEMENT ANTENNA ARRAY

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Abstract

In wireless networks, localization is the process of estimating the spatial coordinates of radio devices. This involves the calculation of both angle and distance of the radio unit relative to a reference point. Normally, an adaptive array system is employed for AoA estimation but with multiple antenna elements forming the array. This adds enormously to the cost of the localization system. This paper investigates the applicability of a 2-element array system for the purpose of AoA estimation. The reference point which can be the base station of a wireless network is equipped with a differential 2-element antenna array system separated by $\lambda/2$. The relative phase of each antenna was varied and the combined output of the two antennas was used to create sum and difference radiation patterns and to steer the antenna radiation pattern to other angular positions. A simple maximum RSSI based AoA estimation algorithm was developed to resolve user AoA. Result of MATLAB simulation show 100% user AoA localization.

Index Terms: Antenna array, Angle-of-arrival, RSSI, Algorithm

I. INTRODUCTION

Localization in wireless networks is becoming very popular due to the versatility of its application in different areas like navigation, environment sensing, home automation, human and animal condition monitoring, Internet of Things (IoT) and recently as a strategy for prompt small cell deployment in heterogeneous networks (HetNet) [1]. Localization is the process of estimating the spatial coordinates of users scattered at unknown positions in space from at least one known location (base station). Two broad categories are range-free and range-based localization. Range-free approach is based on proximity and determines user location using hopcounts or connectivity between network users. The hop-count values between base station (BS) and users are transformed to distance information based on the computed average size of a hop (hop-distance). With this approach, localization complexity increases as the network size increase. The range-based approach requires the knowledge of BS location from where user locations (angle and range) are calculated. Normally an adaptive phased array system is used at the base station to calculate both AoA as well as range of users.

A standard phased array system for AoA estimation comprises of numerous antenna elements each accompanied with a phase shifter as shown in Figure 1.

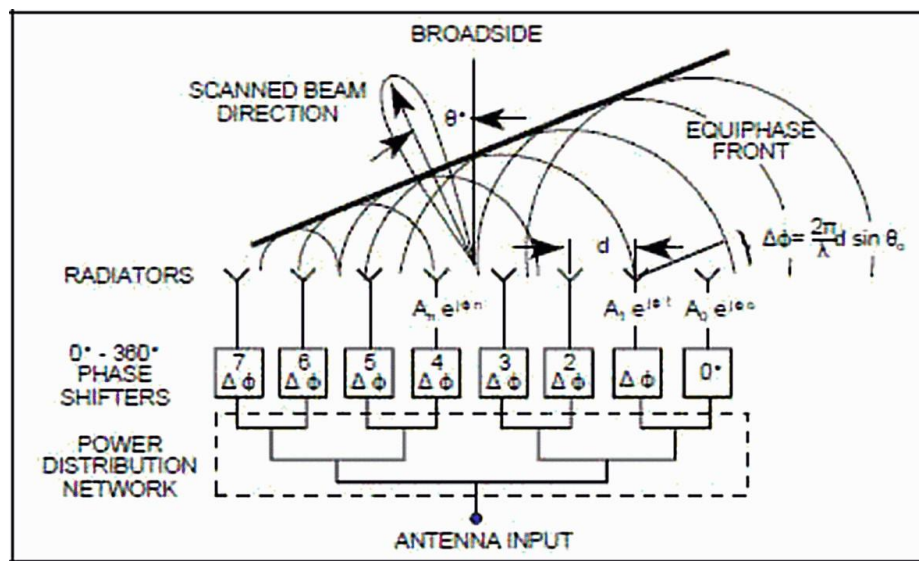


Fig. 1: Standard phased array system

The algorithm for AoA Estimation can be achieved using the conventional technique which is based on Bartlett method (or delay and sum) and capon method (Minimum Variance Distortionless Response (MVDR)). Another approach is by subspace technique which is based on orthogonality of signal to noise subspace. Multiple Signal Classification (MUSIC) and Estimation of Signal Parameter through Rotational Invariance Technique (ESPRIT) are the two widely used subspace based estimation methods [2]. Conventional approach is shown to be simple but of lesser resolution compared to subspace approach which is complex but with high resolution [3]. Conventional approach can also achieve accurate result but with massive antenna elements [4].

Techniques such as MUSIC, ESPRIT [5], Matrix Pencil [6] method or one of their derivatives [7] involves findings of a spatial spectrum of the antenna array and calculating the AoA from the peaks of this spectrum. These calculations are computationally intensive. Matrix Pencil is very efficient in case of real time systems and under the correlated sources. With the conventional approach, AoA estimation is treated as spatial estimation because there is a relationship between the beam pattern and the array excitation. For several m signals impinge on a linear, equally spaced array with n elements each with direction, θ_i , the goal of AoA estimation is to use the data received at the array to estimate, θ_i where $i = 1$ to m . It is generally assumed that $m < n$, but approaches such as maximum likelihood estimation [8] do not place this constraint. Since this paper considers an area based localization, precise accuracy is not a requirement rather complexity and cost is reduced using the minimum possible number of antenna elements in an array. Conventional approach is therefore the most suitable. In this case, the array excitation is used to define different beam positions for AoA estimation.

The rest of this paper is organized as follows; Section II presents a two-element array system and its simulation in MATLAB. Section III presents a model of the azimuth sector positions for AoA classification of users. Section IV is a presentation of the developed AoA estimation algorithm. Section V is the simulation result and discussion while section VI concludes the paper.

II. TWO-ELEMENT ARRAY SYSTEM

Considering two dipole antennas separated by $\lambda/2$ and vertically orientated along z-axis as shown in Figure 2. The aim is to focus the main beam on the direction of plane wave shown (broadside) which is at $\theta^0 = 90^\circ$ from array axis. The field due to antennas 1 and 2 are proportional to their currents and has equal amplitude but different phases at far field so that the excitation current for antennas 1 and 2 is given by E_1 and E_2 with phases β_1 and β_2 respectively. Since both antennas are identical, current is supplied with equal amplitude and so the electric field generated by both elements are assumed to be equal, $E_1 = E_2$. The phase of each antenna comprises of two components, the current phase and the wave propagation phase so that the phase of the fields due to antennas 1 and 2 are given by $\phi_1 = kz_1 \cos \theta^0 + \beta_1$ and that of antenna 2 is given by $\phi_2 = kz_2 \cos \theta^0 + \beta_2$ where $kz_i \cos \theta^0$ is the propagation phase and β_i is the current phase of i^{th} antenna. $z_i = (i-1)d - ((n-1)d/2)$ is the antenna position. $k = (2\pi/\lambda)$ is the wave constant, θ^0 is the angle of arrival of plane wave which is 90° for broadside.

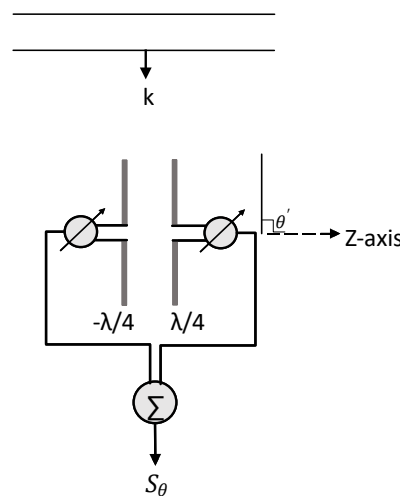


Fig. 2: Two Dipole antenna array system showing plane wave arriving from broadside direction of interest

The weight vector for this array is therefore given by (1).

$$w = \begin{bmatrix} e^{-j(\pi/2)\cos(90)-\beta_1} \\ e^{j(\pi/2)\cos(90)-\beta_2} \end{bmatrix} \quad (1)$$

The array factor, $AF = w^T V(k)$ where $V(k)$ is the steering vector given by Equation (2) for antennas 1 and 2.

$$V(k) = \begin{bmatrix} e^{j(\pi/2)\cos\theta} \\ e^{-j(\pi/2)\cos\theta} \end{bmatrix} \quad (2)$$

where θ goes from 0° to 180° . The array output, S_θ is the sum of the signal from each antenna and it is given by Equation (3).

$$S_\theta = \sum_{i=1}^n e^{j(kz_i \cos(90)-\beta_i)} \times e^{-jkz_i \cos\theta} \quad (3)$$

Using Equation (3), a broadside main beam is achieved at $\beta_1 = \beta_2 = 0^\circ$. At far field, the phase of signal incident on the antenna array is a function of the angle of arrival of the plane wave so that if the signals are added together, they may either add constructively or destructively depending on the phases. To receive a signal from any other desired direction, θ^0 , the phases of antennas 1 and 2 are adjusted to pre-calculated values to form a complex weight that multiplies the signal to cancel out the phase change due to propagation of the wave so that

summation of the signal from both antennas will place the main beam in the new desired direction.

A. Two-Element Antenna Array Simulation

Antenna array was simulated in MATLAB for a broadside design such that at same phase between the elements i.e. $[\beta_1, \beta_2] = [0, 0]$, main beam appear perpendicular to array axis. At other pre-calculated phases of $[120, 0]$, $[0, 120]$, and $[180, 0]$ for antennas 1 and 2 respectively phase weights of the individual antenna elements are adjusted to steer the main beam to other selected positions. Figure 3 is simulation result of the two elements at the selected phases showing maximum radiation at desired directions of $\theta = 90^\circ$, $\theta = 135^\circ$, $\theta = 45^\circ$, $\theta = 0^\circ$ (180°) and nulls at $\theta = 0^\circ$, $\theta = 73^\circ$, $\theta = 107^\circ$, $\theta = 90^\circ$ respectively.

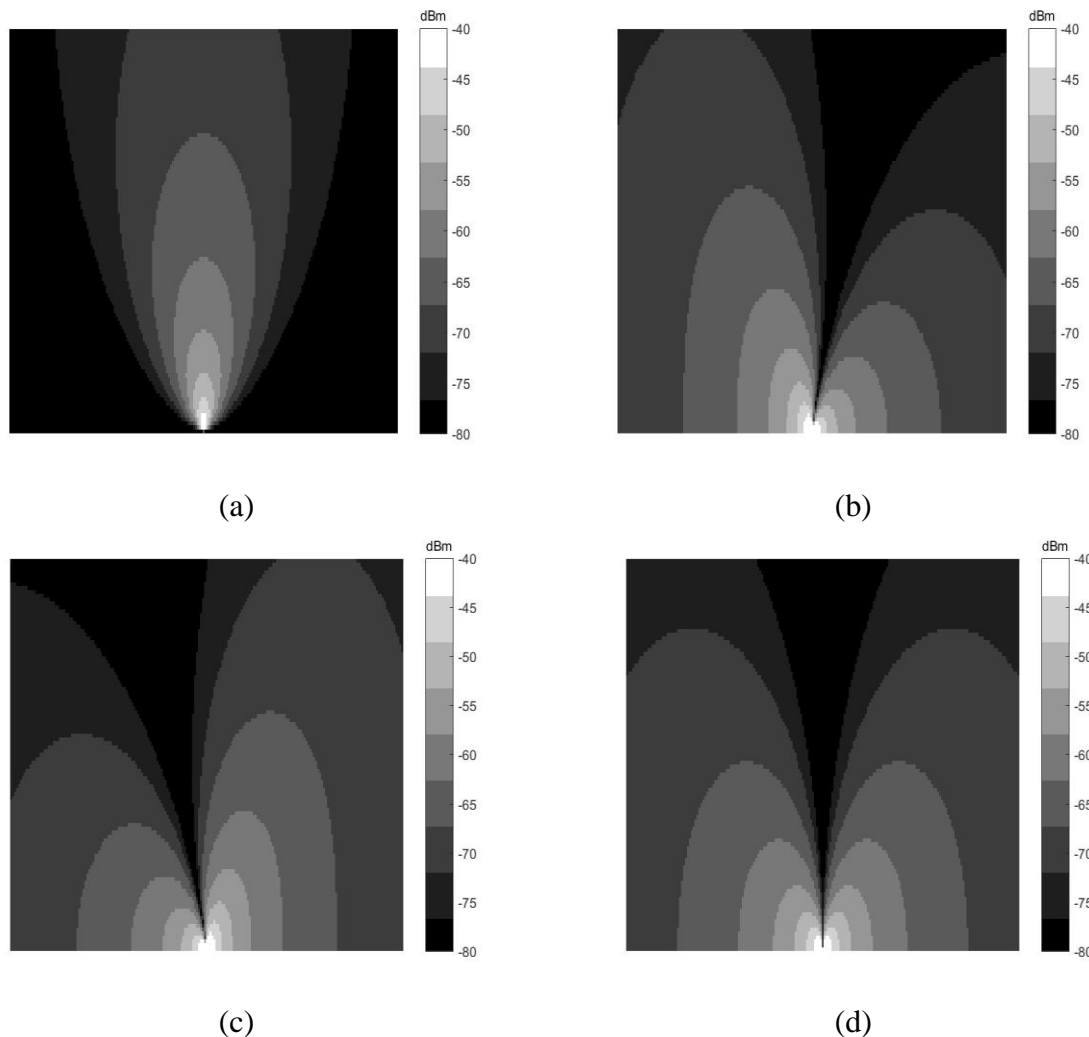


Fig. 3: Beam-forming and beam-steering for (a) $[0, 0]$ (b) $[120, 0]$ (c) $[0, 120]$ phase (d) $[180, 0]$ phases (degrees)

From this simulation result, the (lower, upper) boundary positions are (70, 110), (111, 148), (32, 69) and (149, 180) respectively. These boundary positions are the azimuth edge between beam positions. Therefore at each radial angle, there is only one unique beam with a maximum gain compared with other beam positions forming a boundary of 1° between beams since a 1m grid was modeled. This figure have shown that using only phase difference, beam steering can be achieved with only two antenna elements in an array. Algorithm 1 is the beam-forming and beam-steering algorithm as applied in the simulation.

Algorithm 1 Beam-forming and Beam-steering Algorithm

Input:

Frequency f
 Antenna phase states $\beta = [(\beta_1, \beta_2)_1 : (\beta_1, \beta_2)_j]$ for all j phase combinations
 Maximum radial angle θ_{max}
 Angle θ^0
 Number of elements n
 Element separation distance d

Output:

Array Gain, $G_{j|j \leftarrow 1:4}$
 1: for $\beta_j = 1$ to 4 do . $\beta_j = [\beta_1, \beta_2]$
 2: for $\theta = 0$ to θ_{max} do . path angle 0° to 180°
 3: for $i = 1$ to n do
 4: $z_1 = -\lambda/4$ and $z_2 = \lambda/4$. section II
 5: $w_1 = e^{-j(\pi/2)\cos(90)+\beta_1}$ and $w_2 = e^{j(\pi/2)\cos(90)+\beta_2}$
 6: Compute S_θ using Equation 3 . array output
 7: $G = [G_{j \leftarrow 1} : G_{j \leftarrow 4}]$. array gain per angle for all phase states

III. AZIMUTH LOCATION POSITION MODEL

Azimuth positions for AoA classification of users was created using the angle of array beam with maximum gain at each steered azimuth position when compared with gain at other beam positions. Figure 4 is the resulting AoA localization positions. From this Figure 4, 0(1) position represent the broadside beam position, +I(2), +II(4) and -I(3), +II(5) are two positions right and left of broadside respectively. Two names have been assigned to each azimuth position,

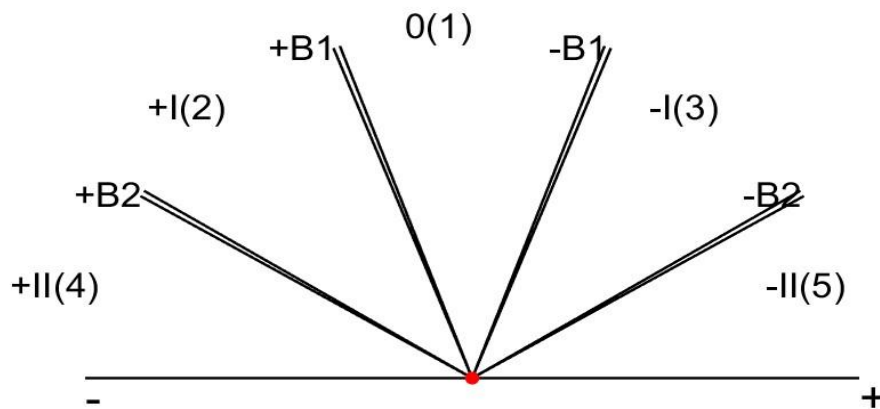


Fig.4: Simulated azimuthal sectors for AoA classification

First is name due to their position off broadside (outside bracket) and second is their numerical numbering (enclosed in a bracket) for easy referencing. A fifth position was created from the bidirectional property of the radiation pattern for (0,180) to form position -

II(5), thereby saving time on phase switching. The peak gain angle in each steered beam position is the center of each azimuth AoA localization positions sector. Boundary positions were also created using the difference between the antenna array gains at beam boundary positions of two beams sharing a boundary. Four boundary positions (+B1(102), +B2(103), -B1(204), -B2(305)) were established where +B1 is the boundary between positions 0 and +I, +B2 is the boundary between positions +I and +II, -B1 is the boundary between positions 0 and -I and -B2 is the boundary between positions -I and -II. The boundary conditions to govern the classification of users into these positions were also defined based on the value of this difference in beam position gain in dB which is calculated in real time by the system depending on the antenna system beam characteristics. If beam of smaller or higher beam-width is generated, the system recalculates the boundary condition to classify users into appropriate positions. This ensures the robustness of the system. Algorithm 2 is a step by step approach to developing the AoA localization positions and creating positions for user location classification.

Algorithm 2 Azimuth Positions For Localization

Input:

Array Gain for four main beam positions, $G_{j|j \leftarrow 1:4}$ Output:

Boundary Conditions, $Bc = [Bc_1, Bc_2, Bc_3, Bc_4]$

- 1: for $j = 1$ to 4 do
 - 2: Find beam peak angles, Pa_j
 - 3: Find beam boundary angles, Ba_j
 - 4: Find gain at beam peak, GPa_j
 - 5: Find gain at boundary angles, GBa_j
 - 6: Compute difference in gain between neighboring beams to obtain Boundary Conditions, Bc
 - 7: Using, Ba_j , segment coverage area into azimuth positions for localization leaving 1° gap between beams for boundary users localization.
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IV. ANGLE OF ARRIVAL ESTIMATION ALGORITHM

Considering a 180° network coverage with all pixel points of 1m distance apart to be occupied with UD's in a FSPL environment. Applying the FSPL environment model, RSS of each UD is calculated at each beam position to obtain a matrix of RSS so that for all beam positions there are four dimensional matrix of RSS values from four main beam positions. The fifth main position is determined using the fourth RSS of the second symmetrical bi-directional beam of (0,180) phase. The AoA of each radio device is the beam position where the highest RSS value for that radio device was measured when compared to measured value at other beam positions. Beam positions four and five were differentiated on the algorithm using the second maximum RSS value. If the second maximum RSS is position +I, then the AoA is position +II but if the second highest RSS is position -I, then the AoA is -II. For the boundary positions classification, if the difference between measured RSS of two beams sharing a boundary fall within the boundary condition for that boundary, then the user is classified as being in that boundary. In this way, each of the UD were classified into one of the nine azimuth position sectors. All UD at each pixel point was correctly classified into azimuth sector where they belong. This figure also show that a thin layer of boundary users exist within the 1m spacing between users. This is an indication that most of the users will be located within the actual sector of the coverage area but if boundary users exist, the system will be able to indicate users that occur in boundary for better decision making. It is also

noticed that more boundary users exist between positions 0 and $+I$ or 0 and $-I$ than between positions $+I$ and $+II$ or $-I$ and $-II$. It should be noted that the estimated AoA is not a precise estimate but a sector estimate and so accuracy is based on the beam width at each beam steered positions. Algorithm 3 is a step by step approach to developing the AoA estimation model.

Algorithm 3 Angle of arrival estimation algorithm

Input:

Boundary Conditions, $Bc = [Bc_1, Bc_2, Bc_3, Bc_4]$ Output:

Estimated AoA, θ^0

Neighboring Position, $NP = [NP1, NP2, NP3, NP4]$

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1: for  $j \leftarrow 1 : 4$  do
2:   Measure RSS of all users  $i : m$ 
3: A set of measured RSS at each beam position,  $RSS_{j|j \leftarrow 1:4}$ 
4: Determine beam position with maximum RSS,  $P = \text{argmax}_j RSS_{\beta i, j}$ 
5: Determine beam position with second maximum  $NP$ 
6: Determine Boundary beam RSS difference,  $\{Bd1, Bd2, Bd3, Bd4\}$ 
7: for  $i = 1$  to  $m$  do
8:   if  $P_i = 1$  OR  $2$  AND  $Bd1_i \leq Bc_2$  then  $\theta_i^0 = +B1$ 
9:   else if  $P_i = 1$  OR  $3$  AND  $Bd3_i \leq Bc_3$  then  $\theta_i^0 = -B1$ 
10:  else if  $P_i = 2$  OR  $4$  AND  $Bd2_i \leq Bc_1$  then  $\theta_i^0 = +B2$ 
11:  else if  $P_i = 3$  OR  $4$  AND  $Bd4_i \leq Bc_4$  then  $\theta_i^0 = -B2$ 
12:  else if  $P_i = 2$  then  $\theta_i^0 = +I$ 
13:  else if  $P_i = 3$  then  $\theta_i^0 = -I$ 
14:  else if  $P_i = 4$  AND  $NP_i = 2$  then  $\theta_i^0 = +II$ 
15:  else if  $P_i = 4$  AND  $NP_i = 3$  then  $\theta_i^0 = -II$ 
16:  else  $\theta_i^0 = 0$ 

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. Algorithm 1

V. SIMULATION RESULT

To test the AoA estimation algorithm, twenty randomly distributed users within the network coverage area in a FSPL environment were simulated. User distribution and actual positions are shown in Figure 5.

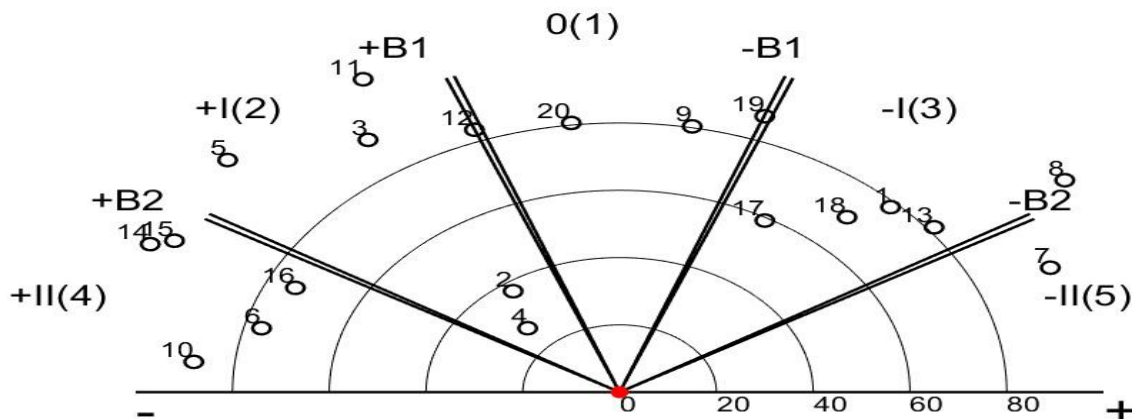


Fig. 5: Actual location of 20 random users before AoA estimation

At each azimuth position, RSS was measured and maximum RSS based AoA estimation model was applied to determine the AoA of each user. Figure 6 shows the estimated AoA of these users and the measured maximum RSS among all beams which were used for estimation.

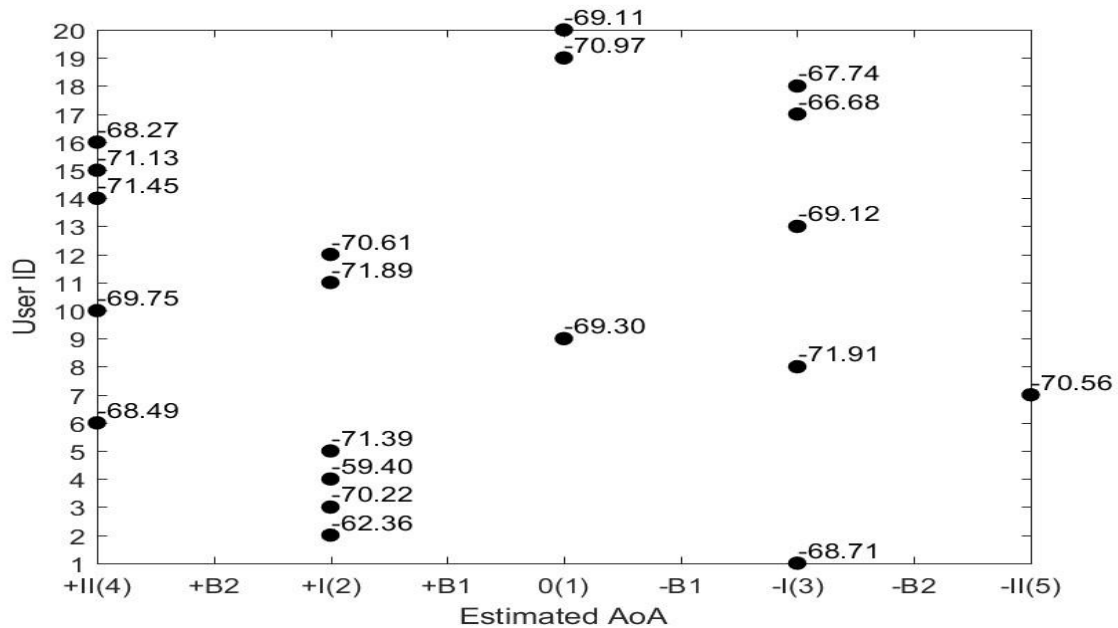


Fig. 6: AoA classification of users after AoA Estimation

Result of Figure 6 shows that all users were correctly classified into their sector angle where they are located. The same process was repeated for twenty other random samples of users with correct AoA estimation achieved.

Since fading and noise is inevitable in any environment and this will cause incorrect measured RSS, normally distributed random error was introduced in the system by generate random numbers between plus and minus multiples of FSPL environment standard deviations ($\sigma = 3.5$). This is to check the effect of these environmental factors on the measured RSS and investigate how this would affect the AoA estimation accuracy. To test this, random users at some points within the network were considered. Different samples and levels of error up to 100 samples and $\pm 20dB$ in FSPL environment were added to measured RSS and still 100% correct AoA estimation for free space environment was obtained. It can therefore be concluded that environment noise in measured RSS will have insignificant effect on the AoA estimation. This AoA estimation system is area based and not point based, therefore, the AoA estimation is based on the sector location and not on a precise angular location. AoA estimation with this system is 100% accurate and robust for it's purpose. Due to it's cost considerations of just two elements and simplicity of algorithm (RSS based), it is cost effective as well.

VI. CONCLUSIONS

This paper presented a simple, robust and cost effective AoA estimation model with only two antenna elements as against multiple elements used in a phased array antenna system for AoA estimation. The system uses a simple RSS based algorithm which was based on the main beam position where maximum RSS was measured compared to other positions was developed and tested with twenty users. Simulation result of 100 samples of 20 users showed 100% AoA estimation. Effect of error in measured RSS up to $\pm 20dB$ was tested and result

indicate no negative effect on AoA estimation. Future work will include experimental verification of the 2-element array system for AoA estimation.

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