Direction of Arrival of Narrowband Signals Based on Virtual Phased Antennas

M. Ammad Uddin[1,2], D. Le Jeune[2], A. Mansour[2], el-H.M. Aggoune[1]
[1]Sensor Networks and Cellular Systems Research Center, University of Tabuk, Saudi Arabia
[2]Lab STICC, ENSTA Bretagne, Brest, France.
mohammad.ammad-uddin@ensta-bretagne

***Abstract*— Data collection from field sensors by using Unmanned Aerial Vehicle (UAV) is the application taken in consideration in this paper. All the sensor nodes are kept location unaware to reduce their cost and energy utilization. The issue addressed in this paper is localization of sensor nodes by UAV to collect data in efficient way. ULA of multiple antennas are used to measure the Angle of Arrival (AoA) of incoming signals. However, the drawbacks of mounting such multiple antennas on an Unmanned Aerial Vehicle (UAV) outweigh the benefits. The challenge is to affix multiple antennas and receivers on an UAV, increase its weight which ultimately decrease its payload capacity, flight time, speed and agility. In this paper, we are proposing a new method to estimate the AoA, called Virtual Phase Array (VPA) antenna system. A single moving antenna installed over an UAV taking snapshots every fixed time periods forms an antenna array virtually. This VPA has enable us to introduce two new concepts of adaptive staring precision and multiple frequency use. All these became reality only because number and spacing between antenna elements can be adjusted, which is not easy to implement in physical antenna array especially when antenna is onboard. The proposed system is evaluated by simulation model. Suggested modifications and additions in classical MUSIC algorithm make it possible to operate the virtual antenna system with the same precision as the physical antenna may have, but adding more flexibility, ease of use, cost economy, more reliability and better throughput.**

***Index Terms*— Array antenna system, direction of arrival, narrowband signal, virtual phased array antenna**

I. Introduction

AGRICULTURE field is taken as a case study, in this research paper. Large number of heterogeneous sensors are installed in a crop field to monitor various parameters related to the plant health, soil and atmospheric conditions. All these sensors are location unaware and left unattended in the field. As farm field is in very remote area and no fixed infrastructure is available for communication, so an Unmanned Aerial Vehicle (UAV) is used as a mean of communication and to harvest desired data from these field sensors. Adverse environmental factors are another challenge where rain, dust storm, growing follicles of plants, may cause hurdles in data communication. Considering all these challenges, we proposed an UAV data routing protocol for crop health monitoring in EUSIPCO 2016 [1]. Dynamic clustering of heterogeneous field sensor nodes and runtime Cluster Head (CH) selection criteria was introduced in that article. As mentioned before, all field sensors are location unaware. In this case, it is the responsibility of UAV to estimate the location of multiple sensors deployed on the ground to collect data from all of them efficiently. The success and efficiency of above mentioned dynamic data collection scheme lies in accurate estimation of CHs locations. We have taken this particular example in consideration, and proposing a Virtual Phase Array (VPA) antenna system which will mitigate many challenges, a typical physical antenna system is facing, which restrict it to be installed in small size UAV such as: heavy weight, big size, energy demanding, etc.

The accurate estimation of Angle of Arrival (AoA) of a signal is very important in many applications such as: those involving Radar [2], Sonar [3], Emergencies and surveillance [4], and cellular systems [5]. To find AoA, one should use a set of multiple antennas which is either fixed to form an array, or rotating in case of radar, except some exception like multi cell static radar in aircrafts. An array of antenna system can be used to detect many parameters of the incoming signal including range, frequency, polarization and the most important is AoA. Array antenna system not only improves the resolution of AoA of incoming signal, but also makes it possible to identify multiple sources that are emitting these signals. AoA can be described as the direction in terms of angle (azimuth θ and elevation Φ), created by multiple plane wave signals (narrowband or wideband) incident on a single or array of antennas.

Array geometry is another important factor in AoA estimation accuracy (resolution), which may composed of a set of antennas organized in a particular formation such as: Uniform Linear Array (ULA), Uniform Circular Array (UCA), Concentric Circular Arrays (CCAs), Uniform Rectangular Arrays (URAs), L-shaped array, V-shaped array, Displaced Sensor Arrays (DSAs), Parallel linear arrays and Y-shaped arrays for details see [6][7][8]. Uniform Circular Array (UCA) is proposed in [6] to provide two-dimensional coverage and uniform performance in all azimuth directions at the cost of adding complexity. AoA is estimated using a rectangle geometry with 8 elements is developed in [7]. Despite all these, ULA is the simplest possible array geometry working on narrowband signals, delivers acceptable resolution and accuracy during beamforming and AoA estimation. The strength of ULA is its simple structure, less computational / processing requirements and a good resolution for the AoA estimation.

II. Proposed System

Antenna array system for AoA estimation has been studied since several years. Many algorithms and techniques have been proposed so far, but still have the potential to improve and develop smarter and smaller antennas to make it compatible with rapidly improving WSN and emerging UAV technologies. UAVs are becoming more and more popular in every field such as: agriculture, defense, disaster management, emergencies, sports, etc.

In this research, agriculture is taken as a case study where a large number of different sensors are installed in a crop field to monitor various parameters related to plant health, soil and atmospheric conditions. All these sensors do not have GPS and left unattended in the field. Farm fields are very remote area where communication infrastructures are not available. UAV is used as mean of communication and to harvest data from these field sensors. For this purpose, it is very important for the UAV to have the complete knowledge about the number of connected sensors and their locations to visit all of them individually or in groups for data collection. Here, we are proposing a virtual phase array (VPA) antenna system installed over UAV to estimate the location of sensor nodes scattered on the ground. This VPA antenna could overcome many challenges exist in the classic physical antenna array system, that are described below one by one;

1. The first problem is to carry the physical antenna array system by an UAV which is not feasible due to heavy weight and complex structure. In a conventional way, many physical antennas are collectively used to estimate the AoA of the signal emitted by a sensor. Adding multiple antennas and receivers on UAV increases its weight and results in decreasing its payload capacity, flight time, speed and agility. In this proposed system, ULA of multiple antennas will be replaced by a single moving antenna which will act as a virtual linear array called VLA.
2. Another issue is, adaptive staring mechanism is not possible in conventional ULA system. For example, during UAV flight if more precision is required to stare some suspected object or area, then proposed system will have the ability to increase the staring precision level by adjusting the length of antenna.
3. This ULA will introduce precession capability to improve the throughput of the system. For example, in normal conditions UAV will fly at a high speed with minimum staring precession (with minimum array elements), as soon as it found something suspected or of interest, it can increase its staring precession by sampling more data and increasing virtually the size of antenna.
4. In classical ULA, the total number of detectable targets is limited to total number of antenna elements. In ULA number of antenna elements is virtually adjustable.
5. The proposed system will be capable to operate on multiple frequencies, and inter element spacing of ULA antenna can be adjusted accordingly.
6. Typical challenges of the physical antenna that are limiting its performance such as: mutual coupling induced current gains and inter-channel phases between array elements do not exist in our proposed VLA.

In the proposed system, UAV will be equipped with a single antenna but will act as a linear array of antennas by exploiting the motion of the UAV. The UAV is moving with a constant speed, it can take snapshot of signals at fixed time intervals. Finally, Snapshots are considered as the outcome of physical antenna elements as shown in Figure 1.

III. Virtual Antenna Array

A VPA carrying UAV we name it Synthetic Aperture UAV (SA-UAV) will be capable to accumulate the data that VPA collects in response of impinging signals with different phases at different times. The parameters (e.g. ToA, AoA) of incoming signals can be estimated if the communication

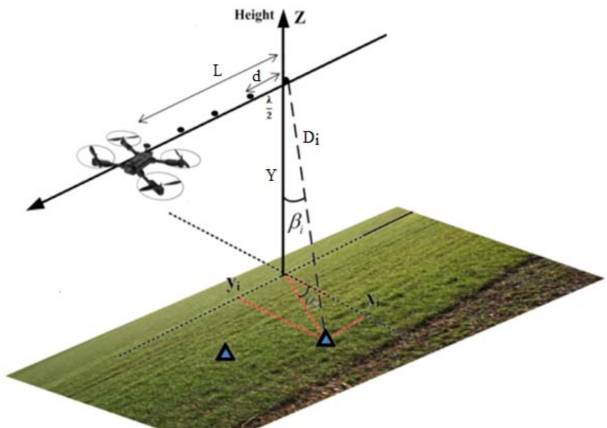

Figure 1: Localization of sensor nodes, using Virtual Phased Array Antenna system

channel during each period of data collection is quasi-stationary. In our proposed system, N target nodes are emitting narrowband signals that are being monitored by UAV at M different places (snapshots) at a fix time period of Δt where $N = M - 1$. UAV will collect MM samples of data between two snapshots. All the received signals are considered to be plane wave as UAV is flying high enough to satisfy far field condition. As shown in Figure 2.

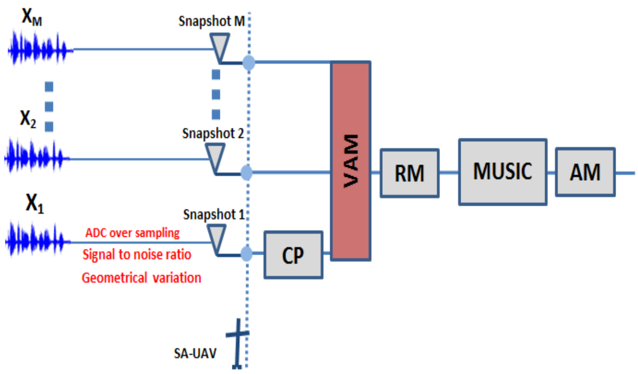

Figure 2: Proposed Virtual Antenna Array system

Signal $x_i(t)$ is transmitted by the target node s_i. Each signal is travelling independently to approach the virtual antenna. All the factors such as: desynchronized UAV and ground sensor clock, Signal to Noise Ratio (SNR) and geometrical variation of antenna for each snapshot, caused an extra deviation in signal phase that will be received at the VPA antenna element. In newly developed system, the calibration phase is introduced during the first snapshot. It is used to estimate the phase difference F_{Offset} between two consecutive samples which is caused by desynchronized clock of devices.

Once the first snapshot has been made, we will consider similar style to gather for the whole data. Data of each snapshot will be fed to the Virtual Antenna Module (VAM) for further processing. VAM produces a steering vector where the response of each signal is stored in the form of a matrix and will be handed over to the Rectifier Module (RM). RM is introduced to rectify the whole data according to the F_{Offset} measured in the calibration phase and makes a covariance matrix R_{AS}. This covariance matrix will pass on to MUSIC algorithm. The output of the MUSIC algorithm (angle θ) will finally be tuned by the adjustment module. The proposed system model and detail description of each module is as follows:

A. Geometrical Variation

The main difference between VPA antenna as compared to Physical Antenna Array (PAA) is that, in VPA all the snapshots are not taken at once. The position of antenna is continuously changing while taking data snapshots, which causes classical MUSIC algorithm inapplicable. First of all, this geometrical variation of antenna is needed to be considered.

Let's suppose N sensor nodes $(n_1, n_2, \cdots, n_N)$ are installed in a field and each Node n_i is making angle $(\theta_1^{n_i}, \theta_2^{n_i}, \cdots, \theta_M^{n_i})$ with M virtual antenna elements of an antenna installed over a UAV (see Figure 3).

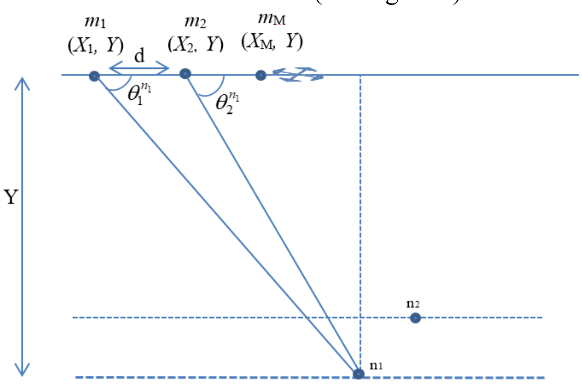

Figure 3: Virtual Antenna Array

UAV is considered as moving in straight path for one antenna length. The X axis corresponds to the UAV trajectory, considered linear.

If an UAV having VPA onboard want to locate a node n_i where $1 < i \leq (N = M - 1)$, installed in the field, transmitting a plane ware narrowband signal. Y is ordinate of UAV that is same for all nodes. X_k is the abscissa of UAV at time t_k where $1 < k \leq M$, UAV is taking M samples for an array snapshot after fix travel distance:

$d = X_{k+1} - X_k = c_{UAV} \times \Delta t$ where, d is the length of the linear trajectory of the UAV between 2 snapshots, and c_{UAV} is the speed of the UAV for a period of time Δt (time difference between 2 successive snapshots). UAV angle with n_i at the first snapshots is:

$$\tan \theta_1^{n_1} = \frac{X_1}{Y} \quad (1)$$

If we consider first snapshot as reference, the second angle is as:

$$\tan \theta_2^{n_1} = \frac{X_1 - d}{Y} \quad (2)$$

$$\theta_k^{n_i} = \theta^{n_i}(t_k) = \tan^{-1}\left(\frac{X_k - c_{UAV}\, t_k}{Y}\right) \quad (3)$$

As we know, the separation between two antenna elements should be $d = \frac{\lambda}{2}$ and time interval require to cover this distance is $\Delta t = \frac{d}{c_{UAV}}$ second.

Then, we can conclude that UAV will make virtual array by taking snapshots after time interval $\Delta t = \frac{\lambda}{2c_{UAV}}$. UAV having single antenna is moving in straight line at constant height and speed. It can sample the received signals at different times and construct a $M \times 1$ steering vector, or array manifold, for the source S. we can construct observation vector as:

$$A(\theta) = [a_1(t_1), a_2(t_2) \cdots a_{M-1}(t_N)]^T$$

If t_i and $A(\theta)$ are known then virtual phase array can model the physical array of the antennas. Speed of UAV is much higher than required data sampling frequency. We can assume that UAV is making uniform VPA antenna of M elements by moving with a constant speed of $c_{UAV}\ m/sec$ for one antenna length. Array is referenced to the first element and array vector model can be written as:

$$A = e^{j\beta d \sin(\theta)[0:M-1]} \quad (3)$$

$\beta = \frac{2\pi}{\lambda}$, λ is the wavelength, θ is the AoA of the sensor and d is the inter-element spacing.

$$A = e^{j\beta d \sin(\theta)[0:M-1]} = \left[1\ e^{j\beta(v \times t_1)\sin(\theta)}\ e^{j\beta(v \times t_2)\sin(\theta + \Delta\theta_1)}\ e^{j\beta(v \times t_3)\sin(\theta + \Delta\theta_2)} \ldots \ldots e^{j\beta(v \times t_N)\sin(\theta + \Delta\theta_N)}\right] \quad (4)$$

Where, $t_1 = 0$ is the time when UAV will start taking snapshots and t_n is the time when it approaches M^th^ snapshot. $\Delta\theta$ is the change of angle of incedent signal array on snapshot N due to movement of UAV.

B. Sampling

VPA will take M snapshots and within two snapshots $[m_k, m_{k+1}]$ it collects MM samples of data. MM depends on the sampling accuracy Analog to Digital Convertor (ADC) device used. If the ADC over sampling frequency is F_{ADC} Hz then, oversampling of the one virtual array element (number of samples between 2 snapshots of the virtual array) will be:

$$R_{over} = |F_{ADC} \times \Delta t|$$

where Δt is the time between two samples.

A standard Voltage Controlled Crystal Oscillators (VCXO) ADC convertor has an accuracy of:

$$10^{-5} < Freqency\ accuracy < 5 \times 10^{-5}$$

If the communication radio frequency is $F_{radio} = 433$ MHz then

$$4\ kHz < Frequency\ Accuracy < 200\ \text{kHz}$$

and frequency offset is:

$$R\_offset = F\_ADC/\Delta F = (200\ KHz)/(20\ KHz) = 10\ extra\ samples\ per\ phase\ rotation$$

or

$$R\_offset = 2\pi/10\ degree\ phase\ rotation\ per\ sample \quad (5)$$

It means, in above mentioned condition every consecutive data sample may have $\frac{2\pi}{10}$ extra phase difference rather than usual/expected. In physical antenna, as all the snapshots are taken at once and this phase difference is considered as constant and same for all. In case of moving antenna, samples are taken one by one independently and each sample is facing addition R_{offset} separately, that's why it needs to be corrected.

C. Calibration

Due to desynchronized clocks of UAV and sensor nodes, ADC oversampling cause a phase difference between two consecutive data samples. Calibration phase is introduced to estimate this phase difference. Let's suppose $s(k)$ is the k[th] signal VPA received.

$$s(\mathcal{K}) = 2^{j\omega} \quad where\ \mathcal{K} = 1\ to\ R_{over}$$

$$s(\mathcal{K}) = 2^{j(\omega+\mathcal{F})}$$

Where, $\mathcal{F}$ is the frequency offset of sampling frequency.

$$X(\mathcal{K}) = Real(xx(\mathcal{K})) + j\ Imgr(x(\mathcal{K})) = A(k) + jB(\mathcal{K})$$

Where, $s = A + B$ then, A is real and B is imaginary part

$$\Phi = \text{atan}\left(\frac{B(\mathcal{K})}{A(\mathcal{K})}\right) = \omega + \mathcal{F}$$

Where, Φ Is the angle difference because of $\mathcal{F}$.

$$\mathcal{F} = \Phi - \omega$$

$$\mathcal{F} = \text{atan}\left(\frac{B(\mathcal{K})}{A(\mathcal{K})}\right) \quad (6)$$

Average phase difference between two data samples is:

$$\mathcal{F}_{\text{offset}} = \frac{\sum_{k=2}^{R_{over}} \text{atan}\left(\frac{B(k)}{A(k)}\right) - \text{atan}\left(\frac{B(k-1)}{A(k-1)}\right)}{R_{over}-1} \quad (7)$$

Where $R_{over} = |R_{over}|$ considered as an integer.

D. Rectification

Rectification phase is introduced to compensate the phase offset by rectifying the original received signal.

$$Signal\ Rectified\ S_r = e^{-j \times \mathcal{F}_{offset}} \times s(\mathcal{K}) \quad (8)$$

E. Theta adjustment

In our scenario, θ is varying at each sample by the ratio of UAV speed and covered distance. By considering this characteristic, final out put θ value need to be adjusted as:

$$Dx = \frac{c_{UAV} \times M \times dt_{over} \times R_{over}}{Y}$$

Where, c_{UAV} speed of UAV M is the number of virtual antenna elements dt_{over} is covered distance and Y is the Height of UAV. The final adjusted θ is:

$$\theta = \text{atan}\left(\tan\left(\frac{\theta \times \pi}{180}\right) + Dx\right) \quad (9)$$

IV. Virtual Antenna Array in case of UAV Non-Linear Movement

To construct a virtual antenna array, it is assumed that UAV is moving at a constant speed/height and all the snapshots are taken after equal intervals of time in a straight line. UAV is taking its first snapshot $P_1(X_1, Y_1)$ at point A and in a straight line took a second snapshot $P_2(X_2, Y_2)$ at point B. If the latter is not verified because of air pressure or GPS inaccuracies, then the resulting scenario is the one shown in Figure 4.

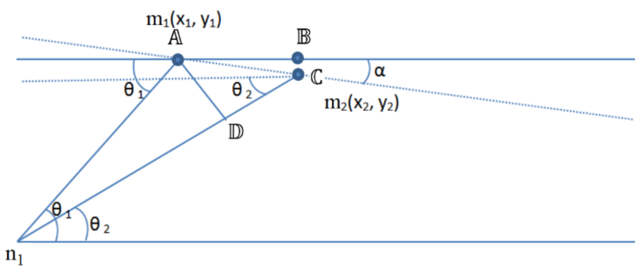

Figure 4: AoA in UAV non-linear movement

UAV is deflected from a straight path, at point B by angle α and it takes second snapshot at point C but separation between two points (A and C) is still λ /2 because snapshots are taken after fix interval of time.Let D_i = distance from n_1 to $m_i = \sqrt{x_i^2 + y_i^2}$

$t_i = \frac{D_i}{c}$ Where c is speed of light and D_i is the i[th] delay observed

Let us consider the relative delay; we consider the origin of the time for the antenna is the time when m_1 received his signal.

The real delay between the two antennas is given by :

$$\tau = \frac{D_2 - D_1}{c} = \frac{\sqrt{x_2{}^2 + y_2{}^2} - \sqrt{x_1{}^2 + y_1{}^2}}{c} \quad (10)$$

$$\tau C \cong dCos(\alpha + \theta) \quad (11)$$

As length of antenna is small and total time required to collect all the data samples is also minute (less than one second), UAV is considered following straight path for one antenna length. In this case, α is considered as negligible.

V. Simulation Model, Results and Analysis

Simulation of the proposed system is conducted in Matlab. A Wi-Fi single antenna operating at 4.3 MHz is mounted over an UAV that is moving with constant speed of 20 m/s. Three targets (sensor nodes) are placed on the ground level with the difference of azimuth angles 20[0] and -60[0] respectively where elevation angle is 0 for all. All the targets are transmitting narrowband signals *a(θ)* periodically from a wave field which incident on the VPA. A VPA antenna installed over an UAV is used to stare and locate the targets that are placed on ground. For simulation, following input parameters are taken:

```
F= 4.3 x 10^8          %Hz radio frequency for
                       transmission
F_ADC= 2 x 10^5        %Hz ADC converter frequency
F_offset= 2 x 10^4     %Hz frequency offset between
                       transmitter and receiver
V=7                    % speed of UAV
dt=λ /(2*v)            % time difference between 2
                       snapshots (2 virtual antennas)
R_over= F_ADC*dt       %oversampling of the virtual
                       array= number of samples
                       %between 2 snapshots of the
                       virtual array
M =20                  %Number of snapshots for 6
                       degree accuracy
y = 100                % Height of UAV
dt_over=1/fADC         time between 2 ADC samples
```

Some simulation results are shown below.

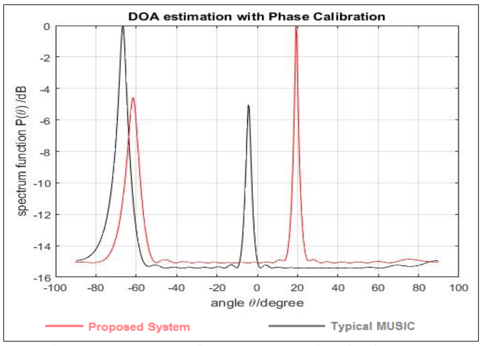

Figure 5: Proposed system VS classical MUSIC

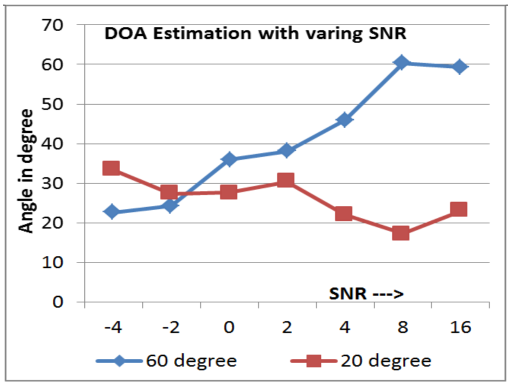

Figure 6: Effect of increasing SNR on proposed DOA estimation system

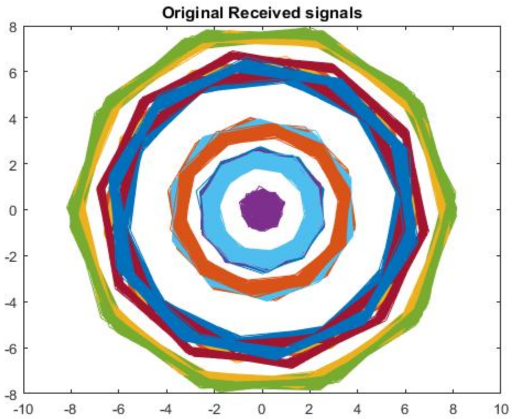

Figure 7: Original received signal on VPA without rectification

As shown in Figure 5, the DOA of two target nodes having angles 20^0 and -60^0 with respect to UAV, is estimated. Directions of both the targets are measured with and without our proposed system. It is analyzed that the proposed system has much better accuracy. Effect of DOA estimation accuracy with increasing SNR is evaluated in Figure 6. It is found that proposed system is working well in low value of SNR up to 4 dB. Original received signal before rectification is shown in Figure 7 and phase offset observed in each signal is shown in Figure 9. It is seen that every snapshot is rotated by almost 36^0 degree angle. This rotation of phases causing major deviation in DOA estimation for that reason, received signal needs special rectification to deal with this issue. Figure 8 is the Received signals after Applying proposed rectification and this figure shows that the problem of rotation of phases due to ADC oversampling is fixed by applying our proposed rectification module. The proposed system is also found working well in the condition when DOA angle is transforming from positive to negative value as shown in Figure 10. In this figure, it is shown that both the angles are measured accurately, especially the angle 0 that actually varies from +2 to -2.

All the simulation results shown above prove that, if an UAV is moving with a constant speed, the single antenna can act us uniform linear array of multiple antenna elements. As shown in Figure 5, both the angles are measured accurately and performance of virtual array antenna system is found outclass.

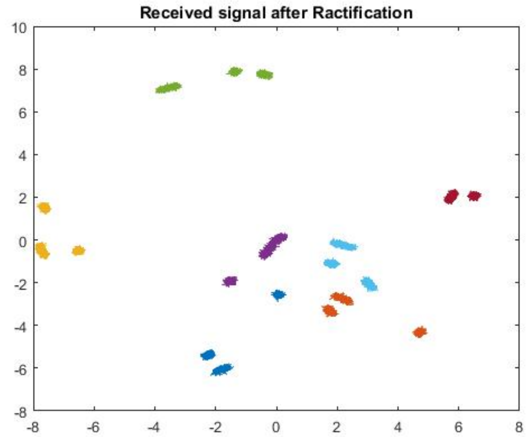

Figure 8: Rectified received signal

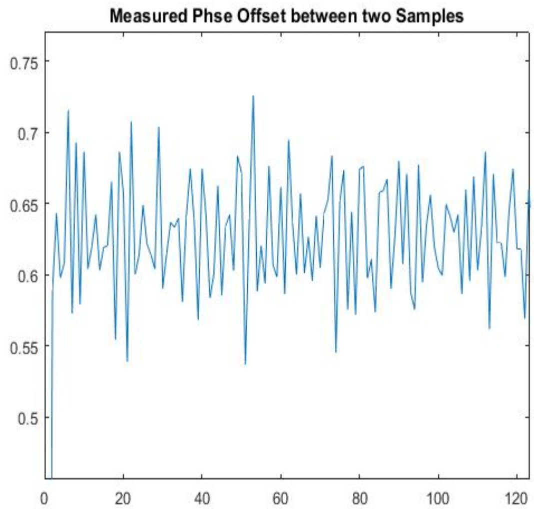

Figure 9: Phase offset observed

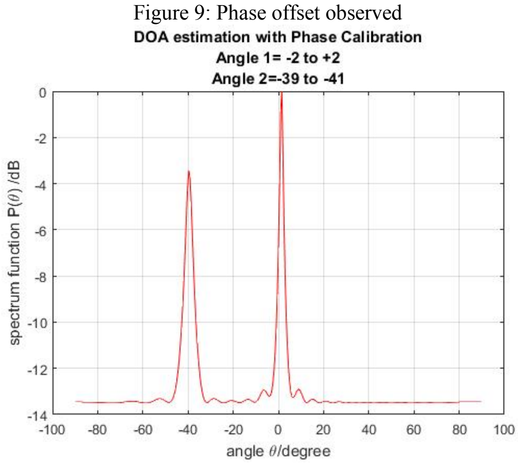

Figure 10: DOA estimation when angle varies from positive to negative value

Classical MUSIC algorithm is not practical in case of single antenna elements and gives very poor performance, if it is used for virtual antenna without suggested modifications. Proposed system will make it possible to use single antenna to work as a virtual phase array of *M* antennas which will add more benefits like ease of use, cost effective, lightweight, energy efficient, flexible, and adaptable.

VI. Conclusion

In this paper, a virtual phase array (VPA) antenna system for DOA estimation of narrowband signal is presented. It is proved mathematically that a single antenna installed on a moving UAV can act as virtual Linear array of multiple antennas and can replace completely the physical array of antennas. The benefit achieved is that, it is a light weight single antenna system that can carry by an UAV very easily and use it for DOA estimation of the signals received from ground sensors. VPA will also provide Adaptive staring capabilities which will help to increase the performance and throughput of the system. By using the proposed system, an UAV can easily estimate the location of sensors installed on the ground and can communication with them more efficiently and precisely. The proposed system is evaluated by using simulation model and found working out class. It has the potential to work better than conventional ULA antenna.

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