A DoA Estimation Based Robust Beam Forming Method for UAV-BS Communication

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Abstract—High data rate communication with Unmanned Aerial Vehicles (UAV) is of growing demand among industrial and commercial applications since the last decade. In this paper, we investigate enhancing beam forming performance based on signal Direction of Arrival (DoA) estimation to support UAV-cellular network communication. We first study UAV fast moving scenario where we found that drone’s mobility cause degradation of beam forming algorithm performance. Then, we propose a DoA estimation algorithm and a steering vector adaptive receiving beam forming method. The DoA estimation algorithm is of high precision with low computational complexity. Also it enables a beam former to timely adjust steering vector value in calculating beam forming weight. Simulation results show higher SINR performance and more stability of proposed method than traditional method based on Multiple Signal Classification (MUSIC) DoA estimation algorithm.

Index Terms—Unmanned Aerial Vehicle (UAV), Cellular network, Direction of Arrival (DoA), receiving beam forming, steering vector

I. INTRODUCTION

UAVs are playing essential roles in completion of a growing number of civil tasks in recent years. As some examples, in safety field, fire departments rely on UAV’s live video functionality for monitoring on fire zone during and after extinguishing operation; in rescuing missions, UAVs fly across the disastrous area to transmit videos, using which ground rescuers can quickly evaluate damage and spot survivors. Other application fields include industrial construction, products inspection, personal use for bird-eye viewing and so on. Successfully completing these tasks require wide-band communication with UAVs — according to 3GPP release 15 [1], [2]. Up rate of UAV uplink data transfer should be as high as 50Mb.

While a single ground device cannot satisfy the communication requirement over long duration, cellular network provides a much faster and more robust link [3], [4]. In such condition, beam forming is one of the most suitable techniques. On one hand, the Air-Ground (AG) channel between UAV and Base Station (BS) is subject to Rician fading — conventional ground channel is Rayleigh fading, as contrast [5] — whose small angular spread and correlated multi-path components make beam forming more applicable than other techniques like MIMO; on the other, applying beam forming also resolves the serious inter-cell uplink interference problem caused by aerial users [6]–[8].

For the above reasons, beam forming between BS and UAVs has become a hot research topic. However, current beam forming schemes will frequently experience low performance in long term Air-Ground connection. In LTE system, beam forming is realized based on Channel State Information (CSI) estimation by using pilot signal. Precision of CSI estimation, in this case, suffers from inter-cell pilot contamination effect [9], the phenomenon that non-orthogonal pilots used by neighbour cells will interfere with each other, and fade as a result. In future 5G network, pilot contamination will cause more serious imprecision of CSI information. First, pilots collisions will happen much more frequently due to the smaller cell radius and dense user population [10]–[12]. What’s more, with significantly less blockage in AG channel, aerial user signal can travel to more neighbour cells with lower attenuation than in ground case. Interference power is then magnified. Consequently CSI estimation will be further unreliable; beam forming performance will inevitably decay.

beam forming based on DoA estimation, on the other hand, is recently shown to reach higher performance compared to current pilot based schema [13]–[15]. The performance margin is especially remarkable in massive MIMO communication scenario [16], [13]. DoA based beam forming, despite having promising prospective in Air-Ground communication, has not been given enough research attention yet, and therefore can be unreliable. One remarkable challenge it faces is the target’s mobility which affects some essential parameters like DoA estimation precision.

This paper proposes a method that provides high performance receiving beam forming, to enhance data transmission from UAV to BS. We first investigate UAV’s mobility and provide its influence on beam forming process. To address this problem, we investigate specific UAV-BS communication attributes, from which we want to extract information to provide solutions. We then propose an algorithm to compute UAV’s signal DoA using UAV flying status information. In the proposed algorithm a prediction method is designed, which keeps the BS informed about the DoA change during DoA estimation interval, increasing DoA knowledge precision. Meanwhile, beam forming algorithms, benefiting from narrowed DoA error range, will experience increased performance. Finally, we illustrate that the prediction process enables real time steering vector update unachievable in traditional pilot-assisted DoA estimation beam forming. Thus, we proposed a steering vector adaptive beam forming method. This method is applicable to most benchmark beam forming algorithms. The benefits includes low computational cost and increased beam directivity. Simulations were done on both robust and non-robust beam forming methods. The results show more precise DoA estimation and higher SINR gain obtained by proposed method, compared to conventional DL and LCMV beam forming combined with MUSIC algorithm. The main
contribution of this paper is summarized as follows:

- A DoA estimation approach is proposed taking advantage of UAV autopilot information, with high accuracy and low computational cost than conventional algorithms.
- The proposed algorithm has a prediction process designed to enable tracking of DoA variations, leading to higher DoA estimation precision and SINR performance of beam forming.
- A real time steering vector adaption approach is proposed to increase beam forming performance.

The rest of the paper is organized as: Section II describes the problem of UAV motion on conventional DoA based beam forming methods; Section III introduces the proposed algorithm. Some simulation work and their results are shown in Section IV to testify performance of the proposed algorithm. Section V concludes the whole paper.

II. PROBLEM FORMULATION

A. DoA Estimation Error

In a typical UAV-ground communication scenario, DoA estimation error is generated both from algorithm execution error and UAV’s mobility. During the time margin between two consecutive estimations, the drone’s position changes continuously in response of its movement. DoA will then deviate from the last time’s estimated result. Fig. 1 illustrates this phenomenon. X and y is horizontal and vertical distance from UAV to BS, respectively. Two consecutive DoA estimations are done on \( t_{n-1} \) and \( t_n \), with a time margin \( \Delta t = t_n - t_{n-1} \). During \( \Delta t \), the assumed signal DoA, \( \gamma \), remains the same. As UAV moves in track, the real signal DoA, \( \eta \), is constantly varying. An estimation error, \( \theta \), is then caused, equaling to the difference between assumed and real angle, \( \theta = \gamma - \eta \). As similar problems exist in ground vehicular communication, work has been done to predict the target’s motion to offset the angle variation. But these optimization methods presuppose that a highly predictable ground vehicle’s heading realized by confined routes like roads or rails. However, a UAV’s heading is much more flexible and often has not a pre-defined track. For this reason, it’s not suitable to apply these algorithms directly on UAV communication.

Fig. 1. DoA error due to UAV mobility

B. Beam Forming and Beam Directivity

DoA error will affect beam forming performance. Conventional beam formers’ performance decreases significantly with even a minor DoA error [17], [18]. To suppress such sensitivity, robust beam forming methods are developed. Nevertheless, for all these algorithms, the optimum SINR value degrades if DoA error range goes larger. Take the widely studied Diagonal Loading (DL) beam former as an example. The coefficient, known as DL-factor, is the key parameter that enables robustness of this beam former. A large quantity of algorithms have appeared to map DL-factor with a certain DoA error range over the last two decades [17], [19]–[21]. The main purpose of them is selecting DL-factor to trade off between DoA error robustness and a close to optimum performance. Fig. 2 shows a plotting of DL beam former output SINR vs DL-factor, under DoA estimation error of 1°, 2°, 3°, 4°, 5°, respectively. The superscript \((\cdot)°\) denotes angle in degree. Input SNR is set as 10dB. DL-factor ranges from 0 to 800 with a step size 1. Comparing these five curves it’s clear that to resist increased DoA error a larger DL-factor is needed, but the optimum SINR will decrease as a consequent. This means once DoA error range is broadened, the upper limit of algorithm gain inevitably decreases to any type of DL beam forming method. A similar situation applies to other beam forming methods, such as Capon and Robust Minimum Variance methods. Thus, a precise DoA estimation is crucial to beam forming performance.

In the calculation of beam forming weight vector, DoA information is transformed into a parameter called steering vector, meaning the angle target signal is steered from beam forming antenna array. When DoA accuracy is affected by UAV mobility, so will beam forming steering vector. Traditionally, steering vector could only be updated when DoA estimation is performed. If it is performed very frequently to keep pace with real DoA change — thus keep precise steering vector information — more pilot signal transmission will be required, and so link overhead will significantly increase. Also, transmission interval of pilot information has a lower limit of 10ms in LTE system. Thus, to moving objects steering vector could always be out-dated. To endure with inaccuracy, modern robust beam forming algorithms put a no less than

Fig. 2. Diagonal Loading beam forming output in relate to DoA error
III. DOA ESTIMATION ALGORITHM AND STEERING VECTOR ADAPTIVE BEAM FORMING METHOD

DoA estimation algorithm is designed to measure UAV’s signal arrival angle and also to offset the effect of UAV mobility on estimation accuracy by predicting DoA variation. As a premise, UAV is assumed to carry omni-directional antenna. In fact, due to the limitation of size and power consumption, most normal commercial UAVs are only able to carry one antenna. In calculating the interested DoA, we will first need to receive and process UAV’s flying status information.

Flying status information contains the drone’s current position, heading (rotation angles), and motion vectors in 3-D space, including velocity and acceleration. The generation of it relies on UAV on-board navigator, also called autopilot system, which reads data from multiple sensors and calculates the track of UAV. A complete navigation system comprises an Inertial Measurement Unit (IMU), a GPS receiver and a processor. By integrating IMU and GPS sensor information using Kalman filtering method, an UAV on-board navigator maintains more accurate information than either of these two individual systems [22], [23]. As a standard regulation, UAV flying status information is required to be fed periodically to ground controller, for safety concerns. The type of coordination data containing all UAV sensors’ data is called telemetry message [24]. Telemetry message has an exchange frequency of 4-5 Hz [25]; it is of high QoS priority in 3GPP network (up to $10^{-3}$ Packet Error Loss Rate) [24].

A. Pre-processing

The first step of calculating signal DoA is reading in flying status data from telemetry message. Then, we incorporate the gained vectors together with BS’s position vector. These parameters are in separate coordination frames. The work here is to transform them into an universal one called NED frame. In our specification of the NED frame, $z$ axis is set perpendicular and $x$ and $y$ axis are tangent to earth surface. For simplicity of calculation, BS is set as the origin. Typically, due to differences among individual processors, UAV GPS position output is either in Geodetic or local NED frame, while motion vectors are in either aircraft’s body frame or local NED frame. When data in aircraft’s body frame is presented, rotation angles between body frame and vehicle carried NED frame are also given by UAV on-board processor. If array processor reads a vector that is in Geodetic or aircraft’s body frame, a transformation of it to local NED frame is needed.

In Geodetic frame, position vector is expressed as $\rho = (\gamma, \varphi, h)$, where $h$ is height above earth surface; $\gamma$ and $\varphi$ are longitude and latitude, respectively. A position under Geodetic frame is first transformed into its equivalence in Earth-Centered-Earth-Fixed (ECEF) frame as a transient form and then, into the new NED frame. Set $\rho_{ug}$ and $\rho_{pg}$ as original data of UAV and BS position: $\rho_{ug} = (\gamma_u, \varphi_u, h_u)$, $\rho_{pg} = (\gamma_b, \varphi_b, h_b)$. Meanwhile, using $P_{ue}$ and $P_{be}$ as their positions in ECEF frame, $P_{ue}$ and $P_{be}$ could then be given as [26]:

$$
\begin{align*}
P_{ue} &= (\frac{R_e}{\sqrt{1-e^2\sin^2\gamma_u}} + h_u)\cos\varphi_u\cos\gamma_u \\
&+ (\frac{R_e}{\sqrt{1-e^2\sin^2\varphi_u}} + h_u)\cos\varphi_u\sin\gamma_u \\
&+ (\frac{R_e}{\sqrt{1-e^2\sin^2\gamma_u}} (1 - e^2) + h_u)\sin\varphi_u
\end{align*}
$$

$$
\begin{align*}
P_{be} &= (\frac{R_e}{\sqrt{1-e^2\sin^2\gamma_b}} + h_b)\cos\varphi_b\cos\gamma_b \\
&+ (\frac{R_e}{\sqrt{1-e^2\sin^2\varphi_b}} + h_b)\cos\varphi_b\sin\gamma_b \\
&+ (\frac{R_e}{\sqrt{1-e^2\sin^2\gamma_b}} (1 - e^2) + h_b)\sin\varphi_b
\end{align*}
$$

where $R_e$ is earth ellipsoid long radius, 6378137.0m; $e$ is a constant equaling to 0.08181919.

BS in local NED frame is set as original point, $p_{bl}(0,0,0)$. Then, UAV position, $p_{ul}$, is computed as:

$$
p_{ul} = (x_{ul}, y_{ul}, z_{ul})^T = R_{en}(P_{ue} - P_{be})
$$

where $R_{en}$ denotes the transformation matrix between ECEF frame and NED frame expressed in [26], the superscript $(\cdot)^T$ denotes transpose of a vector or matrix [26]. Now, we illustrate a transformation of UAV motion vectors from UAV body frame into our local NED frame. Let $\psi, \theta, \phi$ denote rotation angles of UAV body frame, which are also known as Yaw, Pitch, and Roll angles in navigation field. Let $v$ be the speed and $\mu$ be acceleration in NED frame. Then, the transformation between these two forms (body frame and local NED frame) of speed $v$ and acceleration $\mu$ is given as:

$$
v = Rv_b
$$

$$
\mu = R\mu_b
$$

where $R$ is the standard frame transformation matrix, which can also be found in [26].
B. DoA Estimation And Prediction

DoA of the coming signal is the angle between signal’s propagation direction and receiver’s antenna array. Using UAV and BS’s position vectors, this angle could be computed. Assume that BS’s linear antenna array lay along x axis, the DoA is calculated as:

\[ \text{DoA} = \arccos \frac{x_{ul} - x_{bl}}{\sqrt{(x_{ul} - x_{bl})^2 + (y_{ul} - y_{bl})^2 + (z_{ul} - z_{bl})^2}} \] (6)

where \( x_{bl}, y_{bl}, z_{bl} \) is BS position under local NED frame on x, y, z axis, respectively. As BS is the origin, (6) can be simplified as

\[ \text{DoA} = \arccos \frac{x_{ul}}{\sqrt{x_{ul}^2 + y_{ul}^2 + z_{ul}^2}} \] (7)

To address the problem demonstrated in Section 2, motion of UAV will deteriorate precision of DoA estimation angle, the proposed method manages to predict DoA variation during estimation interval. Prediction is implemented by utilizing UAV position as well as motion vectors to first calculate an estimated UAV movement in the previously built local NED coordination frame, then transforming this position information into a DoA estimation. Here, the \( n \)th time prediction of UAV position is denoted as \( p_n(a_n, \beta_n, \gamma_n) \), \( n \leq N \). Set UAV acceleration vector as \( a = (a_x, a_y, a_z) \), and the \( n \)th time UAV velocity vector as \( v_n = (u_n, v_n, w_n) \). Note that \( p_0, v_0 \) and \( a \) are the initial value of all vectors and are deducted from raw data read from telemetry message. We now able to set the status transition matrix in the following form:

\[
\begin{bmatrix}
\alpha_n \\
\mu_n \\
\beta_n \\
v_n \\
\gamma_n \\
w_n \\
\end{bmatrix} =
\begin{bmatrix}
1 & \tau & 0 & 0 & 0 & 0 \\
0 & 1 & 0 & 0 & 0 & 0 \\
0 & 0 & 1 & \tau & 0 & 0 \\
0 & 0 & 0 & 1 & 0 & 0 \\
0 & 0 & 0 & 0 & 1 & \tau \\
0 & 0 & 0 & 0 & 0 & 1 \\
\end{bmatrix}
\begin{bmatrix}
\alpha_{n-1} \\
\mu_{n-1} \\
\beta_{n-1} \\
v_{n-1} \\
\gamma_{n-1} \\
w_{n-1} \\
\end{bmatrix} +
\begin{bmatrix}
0.5\tau^2a_x \\
\tau a_x \\
0.5\tau^2a_y \\
\tau a_y \\
0.5\tau^2a_z \\
\tau a_z \\
\end{bmatrix}
\]

Thus, (8) could be used to compute new position \( p_n \) from UAV motion vector and previous position \( p_{n-1} \). Meanwhile, velocity is also updated with \( p_n \). Using the method introduced above, position of UAV could be maintained by BS. The prediction process uses UAV motion vectors to enable a steering vector update, this information is provided as it exists in current schema, so no further pilot signals are needed. Finally, after calculating new position vector, either updated directly from raw telemetry message data, or from prediction progress, desired DoA value could be derived using (7). For a single time’s DoA calculation, both proposed DoA estimation and prediction have significantly less computation complexity than MUSIC algorithm, which requires matrix operations in the rank of number of samples (typically several thousands \([27]\)). The proposed algorithm requires no assistance of pilot signal. Thus, it adds no additional overhead to the network.

C. An Adaptive Steering Vector Beam former

The non-pilot-assistant attribute and low complexity of DoA prediction enables real time steering vector update for a beamformer. And it is compatible to traditional adaptive beam forming method. Here we also take Diagonal Loading beam former to demonstrate the update progress. The same approach could be applied to other beam forming algorithms. First, using \( \theta \) to denote DoA, and consider an array of \( L \) omni-directional elements, the steering vector could be derived as

\[ s_i = [\exp(j2\pi f \tau), ..., \exp(j2\pi f L\tau)] \] (9)

where

\[ \tau = \frac{rcos(\theta)}{c} \] (10)

is the signal arriving time difference between two neighbour array elements, \( r \) is the distance between array elements; \( c \) is light speed. There are varying algorithms aiming at deciding DL-factor value. However, once DL-factor ; \( \gamma \) is settled, calculating of beam forming weight vector is executed as follows:

\[ \min \ w^H(R + \gamma I_L)w \]

subject to \( sw = 1 \)

where \( I_L \) is identity matrix in the rank of antenna number \( L \); \( R \) is receiving signal covariance matrix. The solution to this constrained optimization problem is:

\[ w = \frac{R^{-1}s_0}{s_0^H R^{-1}s_0} \] (12)

where \( s_0 \) is received signal’s steering vector. \( R \) in conventional beam forming is updated via sampling receiving signal. As only \( R \) is changed in each iteration, real time steering vector can be added without any revision of conventional adaptive beam forming. By altering steering vector, the direction of array main beam also shifts. This way, the centre of the generated beam will be on constant move to track the target UAV.

IV. Simulation Experiments

This part conducts experiments to verify proposed method by comparing its performance with beam forming based on the benchmark MUSIC DoA estimation algorithm \([28],[29]\).

In all experiments, UAV and BS are assumed to be incorporated into the defined NED frame by pre-processing the telemetry data. Antenna array is assumed to lie along the x axis. UAV speed is set to be 160km/h, DoA estimation interval is 200ms. DoA prediction is executed every 20ms between two times’ DoA estimation (Although prediction can be more frequent, ten times execution during each estimation interval is sufficient to manifest algorithm performance). At each estimation point, average DoA value is computed out of 1000 times algorithm execution, both for proposed and MUSIC algorithms. Signal to Noise Ratio (SNR) is set as 10dB. To simulate real world communication environment, two other UAV models are also included to generate interference signals, using the same communication resource as the target UAV. The track of the two UAVs is circle with diameter of 20m and 30m for each. In this way, interference signal arrival angles are constantly changing. The initial distance between interference UAV and BS is 284m and 427m, respectively.
Signal to Interference Ratio (SIR) is 1dB, 2dB, respectively. All key simulation parameters are summarized in Table I.

Considering proposed algorithm accuracy here, we apply the well-adopted GPS multi-variate Gaussian positioning error model. Both vertical and horizontal error is set to have mean 0m. Given study on popular market products [30], [31], the standard variance of vertical and horizontal accuracy is $\sqrt{3}$ and $\sqrt{2}$, respectively. We conducted a specific test on MUSIC algorithm’s error under UAV-BS communication scenario. A wireless AG channel model was built according to 3GPP Release-15 specification, study on ‘enhanced LTE support for aerial vehicles’, published in March 2017. Large scale fading is free space path loss. In terms of small scale fading, we adopt the third alternative of fast fading in the document. SNR is set to 0dB. Three experiments are done relative to different distance values. Algorithm errors with specific settings is summarized in Table II.

In order to understand how various conditions affect the performance of beam forming methods, we first do an analysis of DoA estimation error of them. The total estimation error of MUSIC method is composed by first imperfection of the algorithm defined as intrinsic error, $E_{\text{INT}}$, and second the error caused by UAV mobility, defined as mobility error, $E_{\text{MOB}}$. Denoting MUSIC method error as $E_M$, it can be expressed as:

$$E_M = E_{\text{INT}} + E_{\text{MOB}}$$

The total estimation error of proposed algorithm also consists of two parts. The first part is introduced on estimation point by imperfect position information; the second part is introduced during prediction period due to both position and motion vectors error. Using $E_{\text{EST}}$ and $E_{\text{PRD}}$ to denote the first and second part of total error, respectively, the proposed method DoA error is:

$$E_P = E_{\text{EST}} + E_{\text{PRD}}$$

where $E_P$ stands for total error of proposed method.

### A. Performance Comparison, UAV Track: Spiral

This group of experiments validate performance of both methods using an upward spiral UAV flight track, widely-applied in real-world scenarios like rescuing and target tracking [32]. Horizontally, the radius is 20 meters. Two types of beam formers are adopted here: Linearly Constrained Minimum Variance (LCMV) beamformer as a representation of non-robust beam forming method, and Diagonal Loading beam former for robust beam forming. For Diagonal Loading approach, at each simulation point, the result will show the maxima of SINR value any type of DL beam former could possibly reach (the value is affected DoA error). The curve of SINR variation relative to DL-factor has a single peak as the DL factor varies from 0 to the positive infinity, so the maxima of SINR could be found by scanning DL factor from 0 and find the first maximum value. Fig. [4] and Fig. [5] show the results of DoA error of both DoA estimation algorithms. We choose the distance as 50m in Fig. [4] to represent the condition of UAV flying near the BS, and 2000m in Fig. [5] for the case of UAV working near the edge of a cell. Other simulation conditions keep the same for both figures.

The max-min DoA error margin at 50m and 2000m distance is $1.053^\circ$ and $0.002^\circ$, respectively for proposed method; $7.843^\circ$ and $0.386^\circ$, respectively for MUSIC method. In terms of average error of whole route, proposed method is $1.039^\circ$ and $0.125^\circ$ lower than MUSIC method, in 50m and 2000m case, respectively. It is obvious that proposed DoA estimation algorithm maintains a much more stable performance than the conventional algorithm. Result of MUSIC algorithm is very turbulent. The curve sometimes goes up dramatically like. This is because, UAV’s movement introduces DoA error, while the specific UAV route affects this error range. For example, when the target object is moving on a specific cone area, its DoA remains the same, therefore no DoA error is produced by mobility. If the track of UAV is perpendicular to the cone, it creates the largest DoA variation. Thus, DoA error can vary dramatically as the drone flies along the circle with constantly changing heading. On the other hand, thanks to prediction progress of proposed algorithm, BS can keep track of the moving UAV. For MUSIC algorithm, increased distance degrades algorithm performance, so that, $E_{\text{INT}}$ increases at each estimation point, e.g. 200ms, 400ms. Meanwhile, UAV movement and position error is less influential with increased distance, leading to decreased $E_{\text{MOB}}$, $E_{\text{EST}}$ and $E_{\text{PRD}}$. Overall, comparing both figures, it can be seen that the range and mean of total DoA error goes smaller at longer distance.

Beam forming results are shown in Fig. [6] and Fig. [7]. The red and the blue lines are DL beam forming output SINR of proposed and MUSIC based DL beam forming methods, respectively; the black and the yellow lines are LCMV beam forming output SINR of proposed and MUSIC based DL beam forming methods, respectively. Statistics of the results are summarized in Table IV. The proposed DoA estimation algorithm based DL beam forming show highest performance in both figures. And it also has most remarkable stability, despite the highly dynamic motion of the target. The combination of MUSIC algorithm and DL beam forming reaches higher average SINR than the combination of proposed algorithm and LCMV beam forming. This suggests that robust beamformings are able to keep a high gain within a certain DoA range. But in terms of error range, the latter is much smaller, showing higher stability.

### B. DoA Estimation Performance, UAV Track: Random Walk

To illustrate the suitability of the proposed algorithm in any type of UAV route, in this part, we compare the above two

\begin{table}[h]
\centering
\caption{Simulation Parameters}
\begin{tabular}{|c|c|}
\hline
Parameter & Value \\
\hline
Interested UAV speed & 40m/s \\
Interference UAV speed & 40m/s \\
Interested UAV-BS initial distance & 230m \\
Interference UAV-BS initial distance & 284m, 427m \\
DoA estimation interval & 200ms \\
Number of array elements & 9 \\
Transmission power & 23dBm \\
SNR & 10dB \\
SIR & 1dB, 2dB \\
\hline
\end{tabular}
\end{table}
TABLE II
MUSIC ALGORITHM ERROR-relative to DISTANCE

| Distance(m) | Number of rays | Number of clusters | Average error(degree) |
|-------------|----------------|--------------------|-----------------------|
| 50          | 8              | 10                 | 0.06                  |
| 490         | 10             | 12                 | 0.10                  |
| 2000        | 12             | 15                 | 0.14                  |

TABLE III
PROPOSED METHOD DOA ERROR-relative to DISTANCE, UAV on FIXED position

| Real DoA (degree) | 50 (m) | 300 (m) | 500 (m) | 800 (m) |
|-------------------|--------|---------|---------|---------|
| 60                | 2.443  | 0.439   | 0.258   | 0.163   |
| 45                | 2.342  | 0.374   | 0.232   | 0.150   |
| 30                | 2.089  | 0.336   | 0.205   | 0.125   |

Fig. 4. DoA estimation error, flight track: circle, UAV-BS initial distance: 50m

Fig. 5. DoA error in circle mode, flight track: circle, UAV-BS initial distance: 2000m

Fig. 6. Beam forming SINR performance, UAV-BS initial distance: 50m

Fig. 7. Beam forming SINR performance, UAV-BS initial distance: 2000m

algorithms using an UAV random walk model. The random walk model is built as follows: the starting distance between the drone and the BS is 490m, selected as a medium distance; the value of UAV velocity remains 160km/h; UAV’s direction is composed by an azimuth and a polar angle, which change every 300ms. The azimuth and polar angle is chosen randomly between $0^\circ - 360^\circ$, and $-60^\circ - 60^\circ$, respectively (as most fixed wing UAVs could not fly in a very steep angle vertically, range of polar angle is constrained). The total simulation is 6000ms, so 20 times’ UAV random heading selection are executed. In the experiment, the random walk process recurs 100 times and the average performance is calculated. Fig. 8 shows ten randomly generated tracks of the interested UAV. DoA error results are shown in Fig. 9. From Fig. 9 it is evident that proposed algorithm is able to maintain stability throughout the whole process.

C. Effect of Distance And Real DoA

In this part, we consider the effect of UAV-BS distance and real DoA angle. Here, only performance of proposed algorithm is considered. To test this effect, experiments are done on fixed geographical points decided by angle and distance. As
TABLE IV  
BEAM FORMING PERFORMANCE, UAV track: spiral

|                                | Proposed method (dB) | MUSIC method (dB) |
|--------------------------------|-----------------------|-------------------|
| Max-min margin (DL beam forming, 50m distance) | 0.453                | 39.190            |
| Max-min margin (LCMV beam forming, 50m distance) | 5.379                | 20.575            |
| Average (DL beam forming, 50m distance)         | 18.754               | 15.544            |
| Average (DL beam forming, 2000m distance)      | -2.530               | -4.842            |
| Max-min margin (DL beam forming, 2000m distance) | 0.015                | 0.029             |
| Average (DL beam forming, 2000m distance)      | 18.705               | 18.703            |
| Average (LCMV beam forming, 2000m distance)    | 18.261               | 14.767            |

Fig. 8. Random walk track of interested UAV (showing 10 randomly generated routes)

Fig. 9. DoA error, flight track: random walk, UAV-BS initial distance: 490m

measurements are taken on fixed points, the total error is only manifested by $E_{\text{EST}}$, so that $E_P = E_{\text{EST}}$.

Table III shows average DoA error for different real DoA, and UAV-BS distance. As for current cellular network system, antenna beams could not reach either too high or too low angle, served range is then assumed to be between $30^\circ$ - $60^\circ$ degrees. From the table we conclude that, proposed DoA method error $E_{\text{EST}}$ drops as distance increases or real DoA angle goes down. However, the influence of distance is much more significant than real DoA angle.

D. Effect of UAV Heading And Position, UAV Track: Straight Line

The averaged performances are discussed in previous sub-sections. In this part, we analyze UAV heading’s effect. This part could be viewed as illustrations of some micro phenomenons of previous results. To do this, we conduct two experiments with fixed UAV speed in each one. The velocity has $45^\circ$ polar angle and $30^\circ$ azimuth angle in the first experiment, and $75^\circ$ polar angle and $225^\circ$ azimuth angle in the second. The initial distance is 490m from the BS. Additionally, fixed DoA estimation error for MUSIC algorithm and position error for proposed algorithm are added. Thus, the figures demonstrate trend of error with respect to distance.

Fig. 10 and Fig. 11 show results of DoA error. Trend of $E_M$ is affected by UAV heading. If MUSIC algorithm has a positive error $E_{\text{INT}}$, and UAV is flying away from BS linear array which causes an accumulating negative error $E_{\text{MOB}}$, total error $E_M$ decreases. This case is shown in Fig. 10. Inversely, in the situation of Fig. 11 both $E_{\text{INT}}$ and $E_{\text{MOB}}$ are positive, so that $E_M$ is increasing. The above analysis reveals that the UAV’s motion could superpose the MUSIC algorithm’s output errors, leading to increased or decreased DoA estimation errors.

The value of $E_P$ caused by a specific position error is influenced by UAV’s real position. Sometimes a large position error causes a small or even no DoA error. To analyze the trend of the proposed method error, we could view the real UAV position and the position error as two 3-D geometrical vectors. When these two vectors are in line with each other, position error leads to no angle error. As directions of two vectors deviates, the angle error increase. To summarize, for a particular position error, how much angle estimation error it will cause depends on the real UAV position. In our simulation, the error vector is set as $(1.5, 1.5, 3)$ at each point. As the drone flies, UAV position changes. In Fig. 10 $E_P$ continues to drop until UAV reaches the position $(185.48, 185.48, 369.60)$. The drone’s flying direction in this case is very close to the error vector, so that $E_P$ goes down to very near to zero. Then, as UAV moves on, these two vectors begin to deviate, and $E_P$ increases. In Fig. 11 as UAV position vector doesn’t change direction dramatically over time, angle error doesn’t change much either.
V. CONCLUSION

In this paper, we have investigated realizing high performance beam forming on UAV-cellular communication. We proposed an algorithm that is able to estimate and predict the DoA variation of UAV’s signal. This algorithm maintains a small error range, and has much less computational complexity than MUSIC algorithm. Taking advantage of UAV’s telemetry message, this algorithm requires no additional overhead to the cellular system. By the contribution of narrowed DoA error range, and non-pilot-assistant attribute, an antenna array’s main beam is able to update steering vector in real time. As proved by simulation results, these advantages can lead to higher and more stable SINR performance compared to traditional beam forming methods.

The proposed DoA estimation algorithm could also serve areas other than beam forming, with a lot of flexibility. Unlike traditional algorithms which rely on array antennas, this algorithm is not constrained by number of antennas. As long as the served UAV is produced under industrial standard, any ground controllers could obtain DoA information via receiving and processing telemetry message.

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