Position-based Beamforming Design for UAV communications in LTE networks

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Abstract—**Unmanned Aerial Vehicles (UAVs) have demonstrated exceptional capabilities in many real-world applications such as remote sensing, emergency medicine delivery and precision agriculture. LTE networks are regarded as key candidates to offer high performance broadband wireless services to support UAV applications and safe deployment. However, the unique features of aerial UAVs including high-altitude manipulation, three-dimension (3D) mobility and rapid velocity changes, pose challenging issues for optimising LTE wireless communications to support UAVs, especially under the severe inter-cell interference generated by UAVs in the sky. To deal with this issue, we propose a novel position-based robust beamforming algorithm to improve the performance of LTE networks to serve UAVs. For obtaining optimal weight vectors that could tolerate Direction-of-Arrival (DoA) estimation errors, we propose a hybrid method to integrate the channel information and UAV flight information to accurately estimate the DoA angle range. In order to validate the performance of the proposed robust beamforming algorithm, we conduct comprehensive simulation experiments under practical configurations. The results show that the proposed robust beamforming algorithm outperforms benchmark Linearly Constrained Minimum Variance (LCMV) beamforming and GPS-based beamforming algorithms.**

1. Introduction

Unmanned Aerial Vehicles (UAVs) have been widely used in human society to provide various convenient services, such as disaster management, agriculture, healthcare weather forecast, boarder control and oil pipeline patrol. For example, UAVs are used to frequently deliver the medicines to remote areas [1]. Compared with ground vehicles, UAVs provide higher efficiency and the lower cost for task accomplishment. Wireless communication plays an important role in UAV system. Ground control centre needs reliable communication links to send control command to UAV to ensure the task is safely conducted. The UAVs need to send the flight state and environment information captured by cameras and sensors to the ground control centre for decision making [2]. Owning to their merits of wide deployment, high speed and secure links, LTE wireless communications have been regarded as the most potential candidates to offer high broadband wireless services and out-of-sight control for UAV applications. Different from the ground devices, that consume large amount of downlink broadband, the UAV system requires high broadband for the uplink transmission to upload the data captured. For enhancing the uplink transmission, due to the limitations of the battery and size, it is difficult to deploy large amount of antenna or increase the transmission power to improve the uplink signal received by the Base Stations (BS). Recently, receiving beamforming has been considered a promising technology for LTE communication to support uplink UAV communications [3] [4]. Through adaptively adjusting the antenna radiation patterns, the array elements at BS could be combined constructively to form the specific antenna beam targeting to the UAVs, enhancing the signal reception.

The accurate Direction-of-arrival (DoA) estimation plays an important role for beamforming algorithms to achieve the optimal antenna response. In this area, traditional beamforming algorithms suffer from serious performance degradation due to the inaccurate DoA estimation caused by non-ideal channel conditions. To address this issue, tremendous research efforts have been made to design high-performance robust beamforming algorithms, e.g. Diagonal Loading [5], Robust Capon Beamforming [6], and robust LCMV [7]. Through the introduction of noise factors in the variance function of the input signal, robust beamforming algorithms are able to improve the DoA error tolerance through broadening the main-lobe of antennas, however, at the cost of degraded output power and SINR, and cannot satisfy the high-broadband requirements of UAV applications. Therefore, how to enhance the design of robust beamforming becomes urgent and important for LTE networks to realize stable UAV communications. To address these issues, we propose a novel robust beamforming algorithm to efficiently cancel the inter-cell interference and boost the system throughput for LTE-enabled UAV communication system. The major contributions of this work are summarised as follows:

- A new robust beamforming optimisation problem is formed and solved with the aim of maximizing the output SINR under the constraint of strong interference.

- To make the optimal beam weight vector tolerate to DoA errors, we propose a hybrid method to integrate the channel information and UAV flight information to accurately estimate the DoA angle range.
- To evaluate the performance of the proposed algorithm, extensive simulation experiments are conducted in standard LTE Toolbox under practical network configurations. The results show that the proposed algorithm outperforms the benchmark robust LCMV and GPS-based beamforming algorithms in terms of DoA estimation error and output SINR.

The rest of this paper is organized as follows. Section. 2 presents the network architecture and system model. Section. 3 proposes a novel position-based robust beamforming algorithm to track UAV positions and enhance the throughput for LTE-enabled UAV communication. The performance of the proposed algorithms is evaluated in Section. 4. Finally, Section. 5 concludes this paper.

2. Network Architecture and Model Description

In this section, we describe a general network architecture for LTE networks to support UAV system and present the system model for beamforming design in Section.3.

2.1. Network Architecture

Fig. 1 shows a holistic network architecture of LTE-enabled UAV communication system, which consists of B_c eNode BS (eNBs) stations with distinct cell IDs c^b, where $c^b \in N_{B_c}$; N_{B_c} denotes the subset of natural numbers with cardinality B_c. There are $N^a_{c^b}$ AUEs served by the c^bth eNB together with $N^g_{c^b}$ GUEs. Compared with the traditional LTE system, the c^bth eNB needs to guarantee normal wireless mobile services for ground GUEs, at the same offers high-performance wireless services for AUEs. The first challenging issue for realizing LTE-supported UAV networks is the serious interferences generated by aerial AUEs. According to the research results published by Qualcomm [9] and Ericsson [10], AUEs produce more uplink interference in the LTE network than GUEs because free space propagation increases the probability that signals could be transmitted and received by neighbour cells. Since both the AUEs and GUEs will coexist and be served by LTE networks, the first requirement for the beamforming algorithm to be designed is the high capability of strong interference cancellation. In addition, onboard data, e.g. HD video, will be transmitted from the AUE to eNB, the beamforming algorithm should be developed to maximise the output throughput and provide high broadband to meet transmission requirements.

The communications between AUEs and BS involves two kinds of wireless channels, Ground to UAV (G2A) and UAV to Ground (A2G) [11], exhibiting different transmission characteristics. For instance, G2A is mainly used to deliver the flight command or task message, requiring the stable and reliable transmission; while the A2G is in charge of high-volume of video delivery, consuming huge channel bandwidth. In this work, the robust beamforming will be designed to improve the performance of the uplink transmission. However, due to its feature of utilizing position information to estimate DoA, the proposed algorithmcan also be applied to the downlink FDD/TDD transmission even if the uplink reference signal is not available in the eNBs.

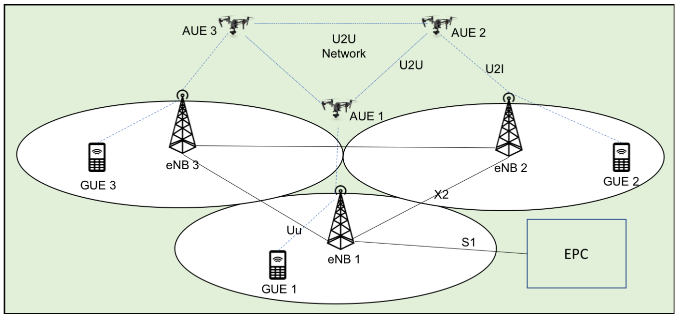

Figure 1. Holistic Architecture of UAV System for HD Video Transmission

2.2. System Model

Let $x_0(t)$ and $x_i(t)$ denote the interesting and the ith interfering signal received by the c^bth eNB; then the receiving signal of antenna system $s(t)$ could be expressed as [13]

$$s(t) = \alpha(\theta_0)x_0(t) + \sum_{i=1}^{N_i} \alpha(\theta_i)x_i(t) + n(t) \tag{1}$$

where N_i denote the number of the interfering sources and $\alpha(\theta_0)$ and $\alpha(\theta_i)$ are the antenna steering vector for the interesting and the ith interfering signals with DoAs of θ_0 and θ_i. For $i \in N_i$, $\alpha(\theta_0)$ and $\alpha(\theta_i)$ are calculated by the following equation

$$\alpha(\theta)=[1, \exp\{-j\frac{2\pi}{\lambda}d\sin\theta\}, ..., \exp\{-j\frac{2\pi}{\lambda}d(L-1)\sin\theta\}]^T \tag{2}$$

where L, λ and d denote the antenna number, signal wavelength and distance between two antenna elements. Let $A(\theta) = [\alpha(\theta_0), \alpha(\theta_1), ..., \alpha(\theta_{N_i})]$ and $x(t) = [x_0(t), x_1(t), ..., x_{N_i}(t)]$, then Eq. 1 could be transferred as $s(t) = A(\theta)x(t)^T + n(t)$. Given a beamforming weight vector, ω, the output signal, $y(t)$, is equal to,

$$y(t) = \omega^H * s(t). \tag{3}$$

The aim of this work is to design robust beamforming algorithm to maximise the SINR of output signal, $y(t)$, in the high dynamic UAV scenario.

3. Robust Beamforming Design

3.1. Beamforming Design

By exploiting the navigation information from GPS and inertial measurement unit (IMU), this subsection aims at designing a new robust beamforming algorithm to satisfy the performance requirements of UAV applications. The proposed algorithm is to maximise the output SINR, realise the interference cancellation and combat against the high mobility of the AUEs. As discussed in the previous section, the output signal is shown as

$$y(t) = \omega^H[\alpha(\theta_0)x_0(t) + \sum_{i=1}^{N_i} \alpha(\theta_i)x_i(t) + n(t)] \tag{4}$$

Following Eq. 4, the output SINR, ρ, can be defined by [13]

$$\rho = \frac{E\left\{\left|\omega^H\alpha(\theta_0)x_0(t)\right|^2\right\}}{\sum_{i=1}^{N_i} E\left\{\left|\omega^H\alpha(\theta_i)x_i(t)\right|^2\right\} + E\left\{\left|\omega^H n(t)\right|^2\right\}} \tag{5}$$

According to the Shannon Theorem [14], the throughput, $\mathbb{R}$, is a function of output SINR,

$$\mathbb{R} = B * log_2(1+\rho) \tag{6}$$

where B is the bandwidth of wireless channel. Under the resources restriction, e.g. bandwidth B, the maximisation of the throughput could be guaranteed by maximizing the output SINR, described as $\underset{\omega}{max}(\mathbb{R}) = \underset{\omega}{max}(\rho)$. Let P_0 and P_i denote the signal powers received by BS from the interested and interference UAVs, the maximisation of the output SINR is described as

$$\begin{aligned} &\underset{\omega}{max} \frac{E\left\{\left|\omega^H\alpha(\theta_0)x_0(t)\right|^2\right\}}{\sum_{i=1}^{N} E\left\{\left|\omega^H\alpha(\theta_i)x_i(t)\right|^2\right\} + E\left\{\left|\omega^H n(t)\right|^2\right\}} \\ &= \underset{\omega}{max} \frac{P_0 * E\left\{\left|\omega^H\alpha(\theta_0)\right|^2\right\}}{\sum_{i=1}^{N} P_i * E\left\{\left|\omega^H\alpha(\theta_i)\right|^2\right\} + E\left\{\left|\omega^H n(t)\right|^2\right\}} \end{aligned} \tag{7}$$

To transmit video applications in LTE-enabled UAV system, two aspects should be considered in designing beamforming algorithms, throughput maximisation and interference minimisation respectively. Therefore, the optimisation problem in the above equation can be transferred to the following equation

$$\begin{aligned} &\omega_{opt} = argminE\left[\left|\omega^H R\omega\right|^2\right] \\ &s.t. \quad \begin{cases} \omega^H\alpha(\theta_0) = 1 \\ \omega^H\alpha(\theta_i) = 0, \quad i = 1, 2, ...N_i \end{cases} \end{aligned} \tag{8}$$

By utilizing the Lagrange Multiplier [15], the optimization function is formed as,

$$Ł(\omega^H, \lambda) = \omega R_n \omega + \lambda(\omega^H A(\theta)F) \tag{9}$$

where $F = [1, 0, ..., 0]$. After a series of derivation, the beamforming weight vector is a function of parameter λ,

$$\frac{\partial Ł(\omega^H, \lambda)}{\partial \omega^H} = R_n\omega + \lambda A(\theta) = 0 \tag{10}$$

$$\omega = -\lambda {R_n}^{-1} A(\theta) \tag{11}$$

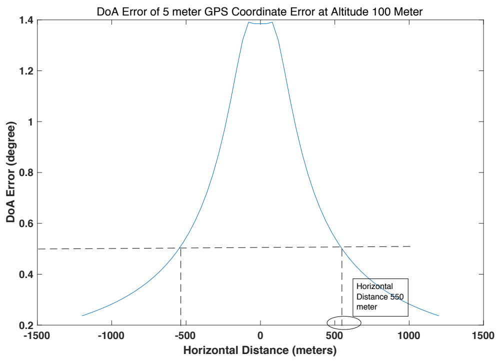

Figure 2. Position-based DoA Estimation Error by Varying the Horizontal Distance from UAV to BS

The parameter λ in Eq. 11 could be obtained by solving the optimisation constraint $\omega^H A(\theta) = F$,

$$\lambda = -[A(\theta)^H {R_n}^{-1} A(\theta)(\theta]^{-1} F \tag{12}$$

Finally, the optimal beamforming weight is calculated by,

$$\omega = [A(\theta)^H {R_n}^{-1} A(\theta)]^{-1} {R_n}^{-1} A(\theta) F \tag{13}$$

3.2. DoA Estimation

To obtain the optimal performance of beamforming design, one of the key issues is to calculate the DoA angle, θ, in the steering vector, $A(\theta)$. However, for UAV communications, accurately estimating the DoA information is a challenging task due to the high UAV mobility and dynamic channel condition. For UAV system, the same level of GPS error would cause different DoA estimation error. In order to investigate the relationship between the GPS coordination error and the DoA estimation error, we conduct a simulation experiments with 5 meter in the vertical position coordination. The results are illustrated in Fig. 2. It can be seen that same amount of 5m position error produces 1.4^o DoA error when UAV locates 20 meters away from BS, and has 0.3^o DoA error when UAV is at around 900 meters from BS.

In addition, the DoA error $\Delta\theta$ is closely related to the UAV flight status. The same moving direction, speed and acceleration would result in different DoA errors when the UAVs are operated at different distances from the BS. When the UAV is near to the BS, communication system would experience the large scale of DoA errors, while if UAV is far from the BS, small DoA error would be introduced to the steering vector. The relationship between the DoA estimation at the kth moment and the position and movement information is given by the following equation,

$$\theta_k = \arctan(\frac{\sqrt{{x_k}^2 + (z_k - z_k^b)^2}}{y_k}) \tag{14}$$

where (x_k, y_k, z_k) is the three-dimensional position information of UAV device at the kth moment. Let the speed, accelerate and time interval at kth and $(k-1)th$

transmission moments are denoted as $(v^x_{k-1}, v^y_{k-1}, v^z_{k-1})$, $(a^x_{k-1}, a^y_{k-1}, a^z_{k-1})$, and τ, the position update could be calculated in the following equation,

$$\begin{bmatrix} x_k \\ y_k \\ z_k \end{bmatrix}^T = \begin{bmatrix} x_{k-1} \\ y_{k-1} \\ z_{k-1} \end{bmatrix}^T + \tau * \begin{bmatrix} v^x_{k-1} \\ v^y_{k-1} \\ v^z_{k-1} \end{bmatrix}^T + \tau^2 * \begin{bmatrix} a^x_{k-1} \\ a^y_{k-1} \\ a^z_{k-1} \end{bmatrix}^T \quad (15)$$

Let θ^u_{k-1} denote the DoA estimation of Root-MUSIC algorithm at the time $(k-1)$th signal receiving. Due to the UAV mobility, there will be extra DoA error $\Delta\theta_k$ introduced in the steering vector $A(\theta)$ when θ^u_{k-1} is used in beamforming at the time kth. To predict the $\Delta\theta_k$ between to signal receiving, the position information is leveraged to assist Root-MUSIC algorithm to track the UAV position and achieve more accurate DoA estimation. As the BS always has the information of the UAV position for safe operation and hazard management. At the $(k-1)$th time, the DoA angle from position information, θ^g_{k-1} has two parts, calculated by $\theta^g_{k-1} = \theta^r_{k-1} + \Delta\theta^e_{k-1}$. θ^r_{k-1} and $\Delta\theta^e_{k-1}$ represent the real DoA information and the error DoA information at the $k-1$th time. Similarly, we could achieve the DoA angle at the time k, computed by $\theta^g_k = \theta^r_k + \Delta\theta^e_k$. Then the extra DoA error $\Delta\theta_k$, could be computed by $\Delta\theta_k = \theta^g_k - \theta^g_{k-1}$. Combining $\Delta\theta_k$ and θ^u_{k-1}, the DoA information of the Root-MUSIC algorithm is enhanced by the GPS and sensor information, which is calculated by the following equation,

$$\theta^u_k = \theta^u_{k-1} + \Delta\theta_k \quad (16)$$

During calculate the $\Delta\theta_k$, the inherent DoA error of inaccurate position information is eliminated in the $\Delta\theta_k$. At the kth time, $\Delta\theta_k$ could be calculated by $\Delta\theta^{est}_k = \Delta\theta_k + \Delta\theta^e_k - \Delta\theta^e_{k-1}$. For a given spatial position, the DoA errors between two transmission time is similar to each other, $\Delta\theta^e_k \approx \Delta\theta^e_{k-1}$. Then, $\Delta\theta^{est}_k$ could be approximated by $\Delta\theta_k$.

4. Performance validation and analysis

To evaluate the performance of this proposed robust beamforming, we conducted comprehensive simulation experiments and the parameter configuration is summarised in Table. 1, which is set based on the specification of 3GPP TR 36.777 [16]. According to the commercial UAV products [17], GPS signals are generated at the frequency of 5Hz and with the error 10m, following the uniform distribution with the derivation 3 meters [8]. There are three UAVs modeled in the simulation, the interesting UAV ($UAV1$), and two interference UAVs ($UAV2$ and $UAV3$). To capture the characteristics of the real-world LTE-enabled UAV communication, $UAV1$ is allocated in the serving BS and $UAV2$ and $UAV3$ are assigned in the neighbouring BSs to generate the interference signals. Gauss-Markov Random Mobility (GKRM) model [19] is used in the simulation to update the moving speed and direction of UAVs. Due to the physical constraints and inertial force, the speed and moving direction of a UAV remain stable during a relative short time. GKRM model has the feature of avoids sharp motion changes, suitable for modelling the UAV movements. The results are collected and averaged from 100 runs, each lasting 20 resource allocations. In the following, we investigate the effect of high UAV mobility on the performance of GPS-based UAV position prediction and then the performance of different algorithms is analysed in terms of DoA error and receiving SINR.

TABLE 1. SIMULATION PARAMETER CONFIGURATION

Parameters	**Values**
Carrier frequency (f_c)	$2.4GHz$
Light speed (c)	$3.0 * 10^8 m/s$
Signal wavelength (λ)	c/f_c
Number of Antenna at BS (N)	8
UAV speed (V)	up to $160km/h$
Flight heights ($h_{AUE(1,2,3)}$)	$0 - 300m$
Flight heights (h_{BS})	$15m$
Number of interfering UAVs (N_i)	2
UAV transmission power (P_s)	$23dbm$
Antenna inter-element distance (d)	$\lambda/2$
Signal-to-Noise-Ratio (SNR)	$10db$
Signal-to-Interference-Ratio (SIR)	$2db$
Root-MUSIC Search Resolution ($Search$)	0.1^o
GPS Error (GPS_e)	$10meters$
Symbol Length (T_B)	$66.7 * 10^{-9}s$
Sampling Interval (T_S)	$0.03255 * 10^{-9}s$
Bandwidth (B)	$5MHz$
Channel Model (h_{los})	RMa Scenario defined by 3GPP specifications in [18]

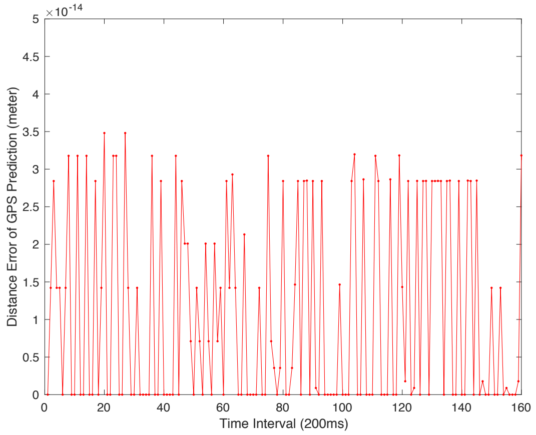

Figure 3. Distance Error of GPS Prediction (T_{GPS}(200ms) $<$ T_{Mov} (800ms))

In Figs. 3 and 4, we investigate the dynamic feature of UAV movement on the performance of leveraging GPS information to track the UAV position. As described in Eq. 15, the UAV position at the ith time is updated by the position, speed and acceleration information at the $(i-1)$th time. Therefore the accuracy of the position prediction is largely depending on the dynamicity of UAV movement. If UAV is in low dynamic model, the GPS and sensor information could be enough to capture the UAV mobility. As shown in Fig. 3, the UAV changes its flight status every 0.8s,

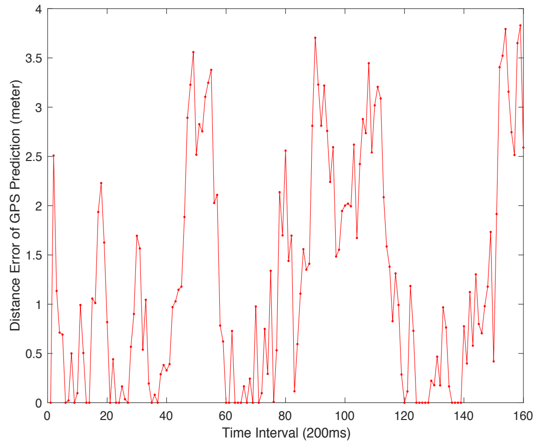

Figure 4. Distance Error of GPS Prediction (T_{GPS}(200ms) $> T_{Mov}$ (50ms))

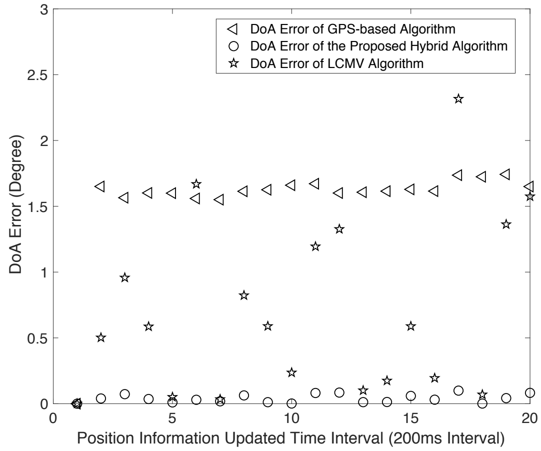

Figure 5. DoA Error of the Interesting UAV

$T_{GPS} = 800ms$. GPS and sensor information is updated every 0.2s, $T_{Mov} = 200ms$. The results show that position-based method could accurately track the UAV movements. However, when UAV is in high dynamic model, there will be an extra distance error in the position-based method. As shown in Fig. 4, the UAV changes its flight status every 0.05s, $T_{Mov} = 50ms$. GPS and sensor information is updated every 0.2s. The results show that up to 4 meters distance error exists in the position updating. The proposed hybrid DoA estimation method is able to reduce the DoA error caused by the high mobility of UAV operation.

In Fig. 5, we investigate the DoA error, $\Delta\theta$, of UAV1 for different beamforming algorithms. $\Delta\theta$ is defined as the absolute difference between real DoA and estimated DoA, $\Delta\theta = |\theta^t - \theta^e|$. We could see that the proposed hybrid method shows a significant gain over the robust LCMV approach in [20] and the GPS-based algorithm. Compared with the other two approaches, the proposed method could much smaller DoA estimation error.

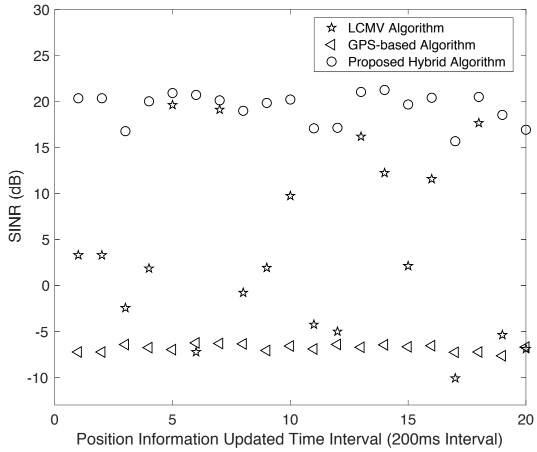

Figure 6. Ouput SINR Comparisons of Different Beamforming Algorithms

In Fig. 6, we investigate the performance of the output SINR for three algorithms. In order to clearly show the performance gains, the real DoA values are used by optimal beamforming algorithm to calculate the optimal beamforming performance. Fig. 6 shows that the proposed algorithm outperforms the other two approaches, nearly reaches the theoretical values of the accurate DoA estimation. Due to the significant reduction of DoA error, the proposed robust beamforming has least-error position information for calculating the steering vector in Eq. (2) and beamforming weight vector Eq. (13), achieving good SINR output. In addition, as shown in Fig. 6, LCMV algorithm with small DoA error can occasionally achieve good SINR performance at the resource allocation time of 3th, 14th, 20th, but could not provide stable SINR output. The reason for this phenomenon is that when UAV is operated in vertical direction of BS, slight DoA error is introduced between two resource allocation slots and good performance of the receiving SINR could be achieved, however, when UAV changes its flight status according to the mission requirements, the large scale of DoA error would be involved, which results in low receiving SINR. In this case, the hybrid DoA estimation method proposed in this work can be used to reduce the DoA error and achieve good and stable receiving SINR.

5. Conclusion

In this paper, we proposed a new position-based beamforming algorithm to improve the performance of LTE networks to support UAV communications. The beamforming algorithm was designed with the aim of the system throughput maximization under the constraints of the interference cancellation. In addition, we observed that the performance of the optimal beamforming algorithm is affected by accuracy of DoA estimation. This is a serious issue in the high dynamic UAV communication environment. Therefore, a new DoA estimation method was designed in this work, which combines the channel information and UAV flight information to accurately estimate the DoA angle. Through the complementary consideration of these two aspects, the proposed algorithm is able to enhance the receiving SINR. We conducted comprehensive simulation experiments to validate the performance of the proposed algorithms. The results showed that the proposed algorithm outperforms the optimal LCMV and GPS-based beamforming algorithms. In addition, the proposed algorithm can be deployed in current and future cellular system to enhance the communication quality of UAVs and mitigate their strong interference to other ground and aerial users.

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