# Trajectory Planning Based on K-Means in UAV-Assisted Networks with Underlaid D2D Communications

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**Abstract.** Unmanned aerial vehicles (UAV) has become a popular auxiliary method in the communication field due to its mobility and mobility. The air base station (BS) is one of the important roles of UAV. It can serve the ground terminals (GTs) without being restricted by time and space. When GTs are scattered, trajectory optimization becomes an indispensable part of the UAV communication. In this paper, we consider a UAV-assisted network with underlaid D2D users (DUs), where the UAV aims to achieve full coverage of DUs. Trajectory planning is transformed into the deployment and connection of UAV stop points (SPs), and a K-means-based trajectory planning algorithm is proposed. By clustering DUs, the initial SPs is determined. Then add new SPs according to the coverage, and construct the trajectory. The simulation analyzes the validity of the algorithm from the distribution of DUs and the number of initial cluster centers. The results show that the proposed algorithm is compared favorably against well-known benchmark scheme in terms of the length of the trajectory.

**Keywords:** Unmanned aerial vehicles · Trajectory planning · K-means algorithm

## 1 Introduction

With the rapid development of aviation and electronic technology, unmanned aerial vehicles (UAVs) will play an important role in the field of wireless communication due to its mobility and portability [1, 2]. UAVs can be used as aerial BS to provide reliable wireless communication in scenes of battlefield or disaster area. Different from traditional ground BSs, UAVs can be deployed flexibly and move along a given trajectory which is determined by their aviation characteristics to cover ground terminals (GTs) [3]. Therefore, trajectory planning has become a basic prerequisite to ensure that the UAV successfully completes its mission [4].


S. Shi et al. (Eds.): AICON 2020, LNICST 356, pp. 260–271, 2021.
https://doi.org/10.1007/978-3-030-69066-3_23

Trajectory planning has always been an important research hotspot in the UAV field. However, previous research work is mainly about UAV navigation applications under various environmental constraints, such as obstacle collision avoidance [5]. When faced with communication missions with a wide distribution and a large area, serving as many users as possible or achieving full coverage is one of the goals of UAVs. The authors in [6] study the 3-dimensional (3D) deployment problem of a single aerial BS under the probabilistic line-of-sight (LoS) channel model to realize the offloading of as many GTs as possible from the terrestrial BS. Zeng, Y. et al. [7] design the UAV's trajectory to minimize mission completion time on the basis of ensuring that each GT restores files with a high probability of success.

Due to the limited coverage of a single UAV, multiple UAVs are tried to achieve full coverage. A polynomial-time algorithm with successive vehicle-mounted mobile base stations placement is proposed in [3]. In addition, clustering algorithm is also one of the commonly used methods to place multiple UAVs. In [8], the authors adopt k-means algorithm to classify terrestrial users to be served by multiple UAVs, and GTs that are not covered by the UAVs are supported by the fixed ground BSs. As an effective means to improve spectrum efficiency, device-to-device (D2D) applications are becoming more frequent. There are three mode in D2D communications, i.e., cellular mode, underlay mode and overlay mode. To improve spectrum efficiency, underlay mode is the one with the highest usage. Mohammad Mozaffari et al. [9] investigate the deployment of a mobile UAV in UAV and D2D coexistence networks. In order to completely cover the area, the disk covering problem is computed to obtain the minimum number of stop points (SPs) that the UAV needs. Furthermore, it is often used to relieve cache pressure and expand communication range. Based on [3], authors [10] realize the optimization of the UAV trajectory in the cache network in which the UAV and D2D coexist. This provides a new way to study the trajectory planning, that is, firstly determine the SPs of the UAV, and then construct the trajectory.

In this letter, we assume that ground terminals exist in the form of D2D and a UAV serving as aerial BS. The UAV's task is to cover all D2D users (DUs). We propose a trajectory planning algorithm by utilizing K-means and geometric relationship. In the proposed algorithm, the initial cluster centers obtained by K-means is used as the initial SPs of UAV and then update the number of SPs by judging the positional relationship between DUs and SPs to complete the trajectory planning. Finally, simulation results prove the validity of the algorithm.

## 2 System Model and Problem Formulation

We study a UAV-assisted network with underlaid D2D communications, where a UAV acts as an aerial BS to provide wireless connections to terrestrial DUs as shown in Fig. 1. The DUs exist in the form of a homogeneous Poisson Point Process (HPPP) $\varphi_D$ with density $\lambda_D$, which are denoted by the set $\mathcal{N} = \{1, 2, \cdots, N\}$ and at known locations given by $\{\mathbf{w}_n\}_{n \in \mathcal{N}}$, where $\mathbf{w}_n \in \mathbb{R}^{2\times 1}$ denotes the two-dimensional (2D) coordinates of the $n$-th DU. We consider that the DUs are motionless and known for the UAV trajectory planning [7].

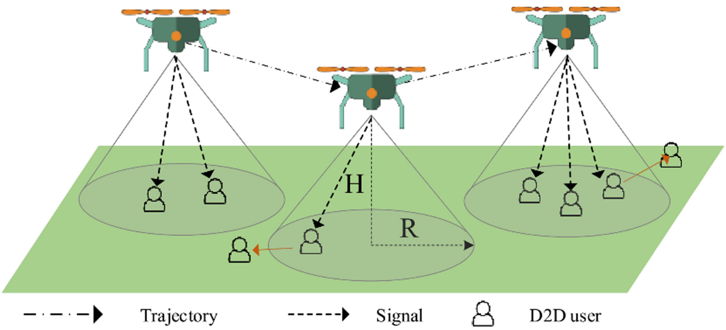



**Fig. 1.** A UAV based wireless communication system, where a UAV acts as a flying BS and GTs appear as D2D pairs.

We aim to design the trajectory of the UAV to achieve the purpose of covering all ground DUs. The trajectory can be discrete into several line segments. The two end-points of each track are the stop points of the UAV. The idea of this paper is to construct the UAV trajectory by finding the right SPs.

Denoting by $\mathcal{M} = \{1, 2, \cdots, M\}$ the set of SPs, UAV can cover multiple DUs at each SP. Therefore, the trajectory planning can be transformed into an optimization problem of the locations of the SPs.

Assume that the UAV starts from the origin and flight height is $H$ in meter. $\mathbf{w}_U[m] \in \mathbb{R}^{2\times 1}$ denotes the horizontal coordinates of SPs. There is no need to go back to the origin after completing the coverage. Therefore, the distance between $m$-th SP and $n$-th DU is written as

$$d_n[m] = \sqrt{H^2 + \|\mathbf{w}_U[m] - \mathbf{w}_n\|^2} \tag{1}$$

Due to the high altitude characteristics of UAVs, we consider that the UAV-DU communication channels are dominated by LoS links. Under the LoS model, UAV-GT link distance is the dominant factor for the air-to-ground (A2G) channel power gain. The average channel power gain from the UAV to $n$-th DU at $m$-th SP can be modeled as

$$\beta_n[m] = \beta_0 d_n^{-\alpha}[m] = \frac{\beta_0}{\left(H^2 + \|\mathbf{w}_U[m] - \mathbf{w}_n\|^2\right)^{\alpha/2}} \tag{2}$$

Where the meaning of $\beta_0$ is the channel power gain at the reference distance which is 1 m, and $\alpha$ is the path loss exponent.

The transmitting power of the UAV is denoted by $P_U$. The received signal-to-noise ratio (SNR) by DU $n$ is given by

$$\gamma_n[m] = \frac{P_U \beta_n[m]}{\sigma^2} = \frac{\gamma_0^U}{(H^2 + \|\mathbf{w}_U[m] - \mathbf{w}_n\|^2)^{\alpha/2}} \tag{3}$$

where $\sigma^2$ denotes the additive white Gaussian noise (AWGN) power and $\gamma_0^U \triangleq \frac{P_U \beta_0}{\sigma^2}$ is the SNR at the reference distance.

Define the threshold of SNR at the DU is $\gamma_{th}$, the maximum transmitting power of the UAV is $P_U^{\max}$. Then, we have the maximum coverage radius of the UAV.

$$R_C^* = \sqrt{\left(\gamma_0^{U\max}/\gamma_{\text{th}}\right)^{2/\alpha} - H^2} \tag{4}$$

We aim to minimize the number of UAV SPs while each DU is covered by UAV at least once within its communication radius $R_C^*$. This does not rule out the possibility that some DUs will be covered by UAV multiple times. The problem can be formulated as follows

$$(\text{P1}) : \begin{cases} \min_{\{\mathbf{w}_U\}_{m\in\mathcal{M}}} & |\mathcal{M}| \\ \text{s.t.} & \min_{m\in\mathcal{M}} \|\mathbf{w}_U[m] - \mathbf{w}_n\| \le R_C^*, \quad \forall n \in \mathcal{N} \end{cases} \tag{5}$$

where $|\mathcal{M}| = M$ denotes the cardinality of the set $\mathcal{M}$ and the Euclidean norm $\|\mathbf{w}_U[m] - \mathbf{w}_n\|$ is the distance between $n$-th DU and $m$-th SP projected on the ground plane.

Since the coverage of the UAV can be regarded as a disk, so the problem (P1) is also called the geometric disk coverage problem [11]. The goal is to minimize the total number of disks on top of ensuring that each user is covered by at least one disk. Usually, the above problem is an NP problem [3].

## 3 Proposed Solution

To facilitate solving this problem, we propose an efficient heuristic algorithm based on K-means algorithm. The main idea is to take the locations of cluster centers obtained through K-means as the initial UAV SPs, and then determine the coverage of UAV. If the coverage is completed, the UAV trajectory is established according to the minimum path selection principle; otherwise, add new SPs to further coverage and update the UAV trajectory.

### 3.1 K-Means Algorithm

K-means [12] is a cluster-based clustering algorithm. Assuming that there is no label data set as (6), the task of the algorithm is to cluster the data set into $K$ clusters $\mathcal{C} = C_1, C_2, \ldots, C_K$.

$$X = \begin{bmatrix} x^{(1)} \\ x^{(2)} \\ \vdots \\ x^{(m)} \end{bmatrix} \tag{6}$$

In the K-means algorithm, Euclidean distance is used to measure the similarity between data. In other words, the smaller the distance between data, the higher the data similarity. At the same time, the denser the data distribution, the greater the possibility of forming clusters. Therefore, the sum of squared errors (SSE) is used as the objective function to measure the clustering quality, as shown below [4],

$$E=\sum_{i=1}^{K}\sum_{x\in C_i}\|x-\mu_i\|^2 \tag{7}$$

where $\mu_i$ is the center of $C_i$, as shown in formula (8).

$$\mu_i = \frac{1}{|C_i|}\sum_{x\in C_i} x \tag{8}$$

In this paper, $\{\mathbf{w}_n\}_{n\in\mathcal{N}}$ is the no label data set and initial SPs is equivalent to the clusters.

### 3.2 Trajectory Planning Base on K-Means Algorithm

**Select the Initial Cluster Centers.** The two most critical parameters in K-means algorithm are $K$-value and initial cluster centers. For the purpose of better observation of SP selection process, the value of $K$ is increased from 3 until the initial SPs can achieve full coverage. In order to acquire more dispersed initial cluster centers and avoid local optimization of the algorithm, we use formula (9) to confine the distance between the initial cluster centers [13],

$$d_\gamma = \sqrt{\frac{S}{K}} \tag{9}$$

where the area of the research region is denoted by S. In other words, the distance between the initial cluster centers should satisfy $d_{ij} \geq d_\gamma$.

**Stop Point Selection Strategy.** When the initial SPs obtained through K-means cannot achieve full coverage, that is, when there are DUs who cannot effectively communicate with the UAV, it is necessary to determine whether new SPs need to be added according to the users' locations, and if necessary, calculate the locations of SPs.

*Using D2D communication without adding new SP.* As shown in Fig. 2, $DU_2$ is uncovered and $DU_1$ is covered. In this case, $DU_2$ can get the content from $DU_1$ without adding new SP, thereby shortening the trajectory.

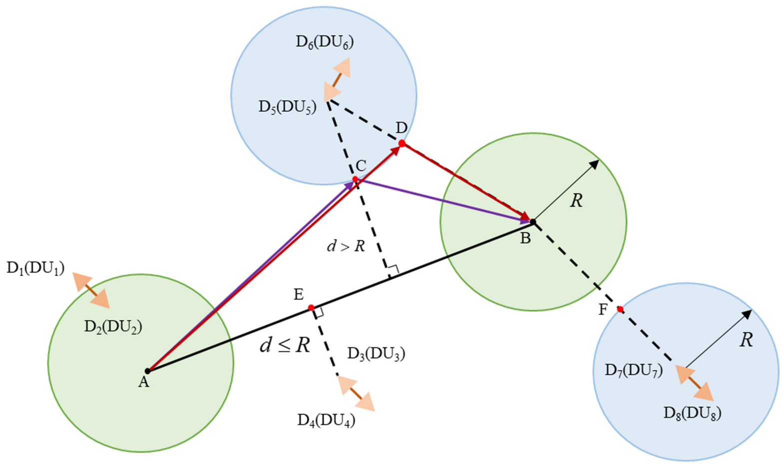



**Fig. 2.** Illustration of stop point selection strategy. Both A and B are stop points and triangles represent D2D users.

*Adding new SP, Trajectory Unchanged.* Both $DU_3$ and $DU_4$ are uncovered in Fig. 2, a new SP is required to add. It can be seen from Fig. 2 that DU3 is closer to AB than $DU_4$, and the distance is less than R. In this case, we only need to find the E, which $D_3E \perp AB$. Namely, E is the newly added SP.

*Adding new SP, Trajectory Changed.* The distance between the 3rd pair and the 4th pair DUs to AB is greater than R. If uncovered users located like the 3rd pair DUs, firstly connect $D_5$ to B, and perpendicular to AB from $D_5$. Then make a circle with $D_5$ as the center and R as the radius, and find the intersection of the above two lines and the circle, i.e., C and D in Fig. 2. Finally, compare the lengths of AC + CB and AD + DB, and the position (C or D) corresponding to the trajectory with the minimum distance is adopted as the new SP. While B is the last SP, there is no need to compare the lengths of the polyline segment. Instead, choose F as the new SP.

**Minimum Path Selection Strategy.** After obtaining all SPs, how to construct the trajectory is also an important issue. In order to make the trajectory length as small as possible, we adopt the minimum path selection strategy, that is, each SP chooses the nearest SP as the next SP.

**Specific Planning Steps.** The procedures of the algorithm are shown in Fig. 3 and specific planning steps are in follows:

Step 1. According to $K$ and $d_\gamma$, determine the initial cluster centers.

Step 2. K-means algorithm is executed through the initial cluster centers obtained in step 1, and then the initial SPs is obtained.

Step 3. Place the UAV at the positions of the initial SPs to determine the coverage. If the full coverage has been completed, turn to step 5, otherwise proceed to step 4.

Step 4. Determine the relationship between uncovered users and the initial SPs, and then calculate the locations of the newly added SPs according to Stop Point Selection Strategy.

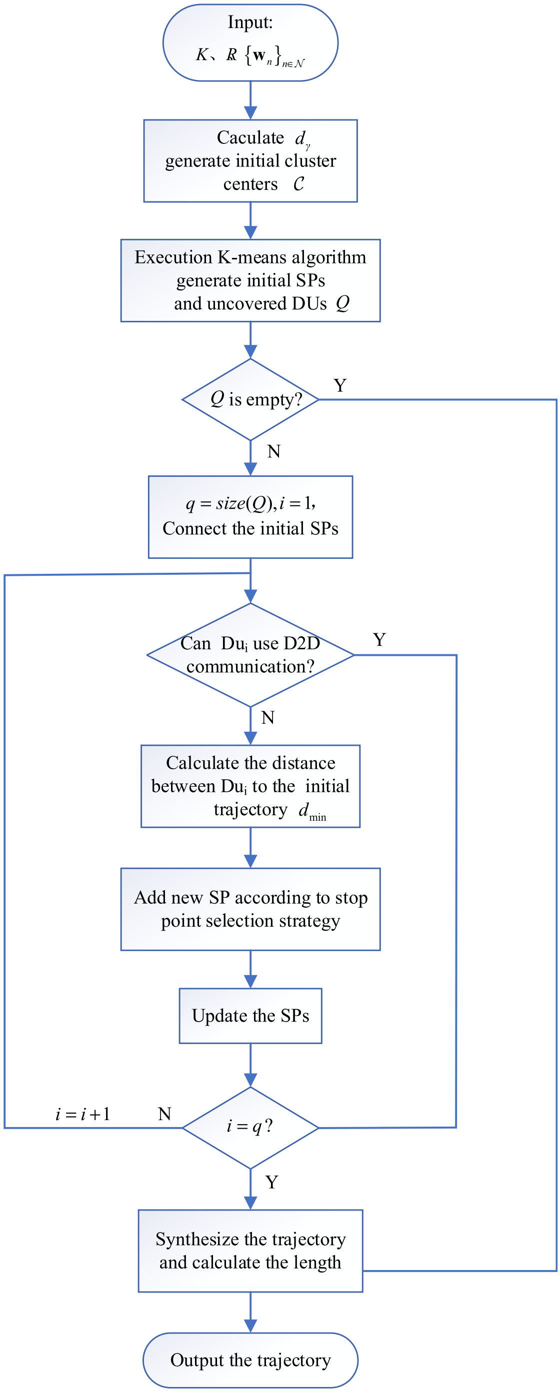



**Fig. 3.** The flow chart of the proposed trajectory planning algorithm

Step 5. Synthesize the UAV trajectory according to the minimum path selection strategy, calculate and compare the changes of the trajectory.

## 4 Simulation and Analysis

In this section, simulation results are illustrated to evaluate the performance of the proposed trajectory design algorithm. The D2D pairs are assumed to distribute in a square region of area 4 $km^2$ and the UAV flight altitude is $H = 100$ m, which generally complies with the rules set by the FAA [14]. According to (4), the maximum coverage radius $R_c^*$ is 430 m. To facilitate calculation, we adopt 400 m as the UAV coverage radius in the simulation. To verify the validity of the strategy,we analysis the influence of distribution of DUs and the number of initial cluster centers on trajectory planning.

### 4.1 Trajectory Planning in Different Distribution Scenarios

The UAV trajectory planning results for four different D2D pair distributions are shown in Fig. 4. Obviously, the initial trajectory obtained through K-means may not be able to achieve full coverage. If there are users who have not been covered, it is necessary to determine whether it is necessary to add a new SP or change the trajectory.

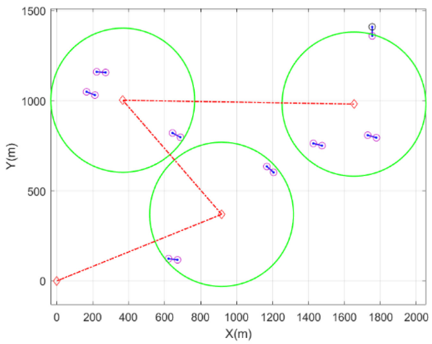
**Case 1: Full Coverage after K-Means.** The first trajectory planning scene is shown in Fig. 4a), only one D2D user has not been covered by UAV in the initial trajectory. Owe to D2D communication, the uncovered user can obtain contents from corresponding D2D user. If the distribution of DUs is shown like Fig. 4b), the initial trajectory can achieve full coverage when $K = 4$.

**Case 2: Adding Stop Points, Trajectory Remains Unchanged.** As shown in Fig. 4b), four DUs have not be covered by UAV after K-means, of which two users can apply the D2D link, while the other pair of DUs need to add SPs to be covered. Since the distance between the pair of DUs and trajectory of the first stage is less than $R$, the coverage can be achieved by adding a SP to the original trajectory.

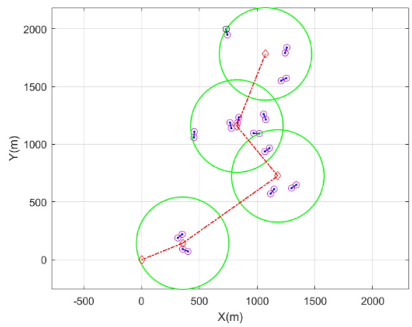
**Case 3: Adding Stop Points, Trajectory Changes.** The case shown in Fig. 4(d) is slightly more complicated than the above. The distances between DUs who have not been covered and UAV's initial trajectory are greater than $R$, which means that the UAV cannot add SPs on the initial trajectory to achieve coverage. Therefore, it is necessary to find locations near the initial trajectory where the distance from the uncovered users is $R$. Due to the addition of new SPs, the UAV's trajectory has changed and the total length of the trajectory has also increased.

## 4.2 Trajectory Planning in the Same Distributed Scenario

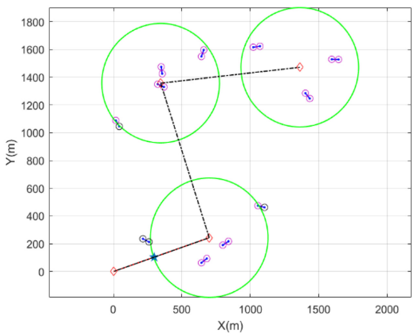
In this subsection, we analyze the influence of the number of initial cluster centers on UAV trajectory planning for the same DUs. In scenarios where the density of DUs is relatively high, the selection of $K$ is vital for UAV trajectory planning.



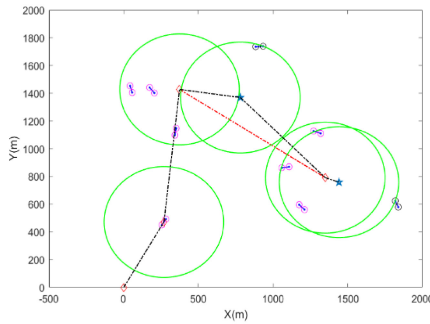

(a) Case 1: $K=3$
$L_i = L_f = 3113.5m$




(b) Case 1: $K=4$
$L_i = L_f = 2622.7m$




(c) Case 2: $K=3$
$L_i = L_f = 2932.8$




(d) Case 3: $K=3$
$L_i = 2670.1m, L_f = 2824.6m$

**Fig. 4.** Comparison of the UAV trajectories with four different distributions of D2D users. Small hollow circles represent D2D pairs, in which pink denotes they have been covered by the initial trajectory, and black denotes conversely. The red dotted line represents the initial trajectory, and the black dotted line represents the final trajectory. Red diamonds represent SPs, and green circles represent the UAV coverage boundary. Stars represent the added SPs. (Color figure online)

We consider a benchmark planning, called "strip-based waypoints", where the UAV's trajectory is devised to realize full coverage [7]. First, obtain the smallest rectangle containing all DUs, and then divide the area into a plurality of rectangular strips with width R. Finally, determine the location of each SP, and the UAV moves along the rectangular strip, as shown in Fig. 5.

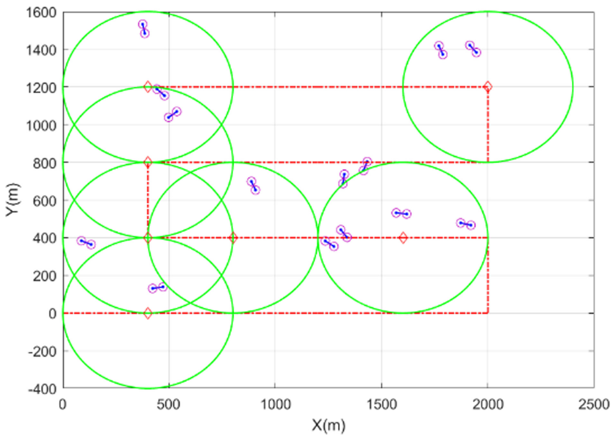
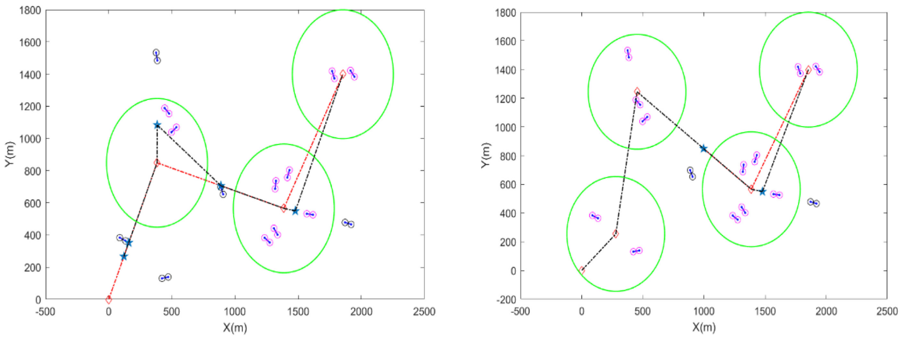



**Fig. 5.** Strip-based waypoints, $L = 8000\,\text{m}$

From Fig. 6 and Fig. 7, we can clearly observe the influence of $K$ on the UAV trajectory. As $K$ increases, the total length of the initial trajectory and the final trajectory of the UAV increases. Compared with the benchmark scheme, the K-means-based UAV trajectory planning algorithm we proposed has obvious advantages. Regardless of the number of SPs or the length of the trajectory, our proposed algorithm is smaller than the benchmark scheme.




(a) $K$=3 (b) $K$=4

$L_i = 2929.7m, L_f = 3044.3m$ $L_i = 3493.4m, L_f = 3559.9m$

**Fig. 6.** Comparison of the UAV trajectories with $K$=3, 4. The meaning of all shapes is consistent with Fig. 3.

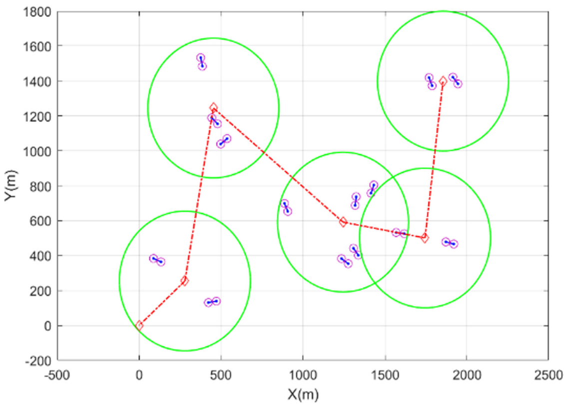



**Fig. 7.** $K=5$, $L_i = L_f = 3822.9\,\text{m}$

## 5 Conclusion

This letter proposed a trajectory planning algorithm based on K-means for a UAV-assisted network with underlaid D2D communications. In our algorithm, the initial stop points are obtained through the K-means algorithm and then determine the coverage. If the coverage is not complete, then D2D communication is selected or the trajectory is changed by adding the new stop points. Compared with the known benchmark planning, the proposed design algorithm has good advantages in terms of trajectory length.

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