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Channel-Aware Potential Field Trajectory Planning for Solar-Powered Relay UAV in Near-Space

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ABSTRACT The near-space communication relay platform has a broad application prospect and development potential in the field of over-the-horizon communication support. In this paper, we investigate a throughput oriented, real-time path planning method for the high-altitude Solar-Powered UAV (SP-UAV) to ensure high quality communication of long-range mission UAVs. Firstly, based on the spatial distribution, the Channel State Information (CSI) and the potential field theory, we design the channel-aware-aided relay SP-UAV which is capable of adaptively changing its position, while maximizing the total throughput of the communication system. Secondly, in the feedback loop design, a cooperative game theory model is introduced to formulate a feedback-aided strategy for adjusting the weighting factors, which can further improve the whole communication performance. Specifically, to ensure the real-time performance, a low complexity algorithm and the real-time updated system conditions are applied in calculating the planning trajectory of the relay UAV. Simulation results show that compared with the relay UAV with a fixed cruise trajectory, our proposed scheme achieves better network throughput and has good tracking adaptability.

INDEX TERMS Adaptive trajectory planning, channel-aware potential field, relay communication, solar-powered UAV, cooperative game theory.

I. INTRODUCTION

As a relay communication platform, High Altitude Long Endurance (HALE) UAV is a promising technology to improve communication coverage and quality, which is also one of the important research directions in industry and academia in recent years. Solar-Powered Unmanned Aerial Vehicle (SP-UAV), the representative of HALE UAV, can cruise in the near-space for several months (Fig. 1). As a high altitude relay platform, SP-UAV has the potential of high communication capacity, high spectral efficiency, low delay and low path loss, thus it is an ideal relay platform that can be exploited to enhance communication performance. Firstly, benefit by the high altitude, the communication angles of attack are usually large. Therefore the air-to-ground and air-to-air communication links often exist the direct component, then the links to a certain extent can be viewed as Line-Of-Sight (LOS) or Quasi-LOS system, of which the communications are less affected by interference such as path loss and shadowing [1]. Secondly, the environments of mission UAVs are dynamic, therefore the task assignment and control system need to be dynamically adjusted according to the different mission environments [2]. As a relay communication platform, SP-UAV is naturally suitable for the centralized control architecture, which has the advantage that the allocation algorithm is simple to implement and has the potential to obtain the global optimal solution. Specifically, SP-UAV could adjust its altitude, latitude, longitude, flight speed and communication power to guarantee the stability of communication and the effective control of mission UAVs (as shown in Fig. 2). However, how to design the optimal planning path for the relay SP-UAV while meeting the requirements of communication quality, total throughput, control efficiency, real-time, flight speed, etc., is a tradeoff optimization problem.

The first challenge is the tradeoff between the real-time performance and the accuracy requirement. The real-time performance requires that the path planning strategy can

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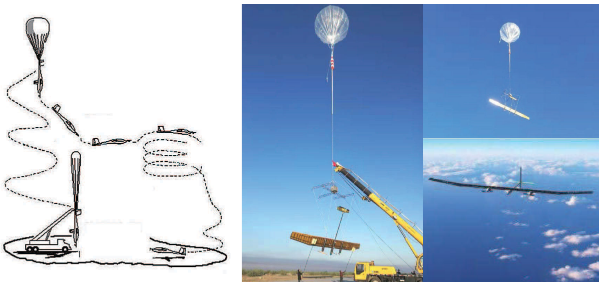


FIGURE 1. Balloon-launched SP-UAV in the near-space [3].

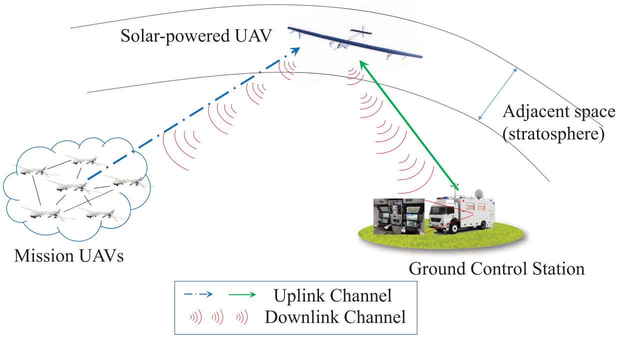


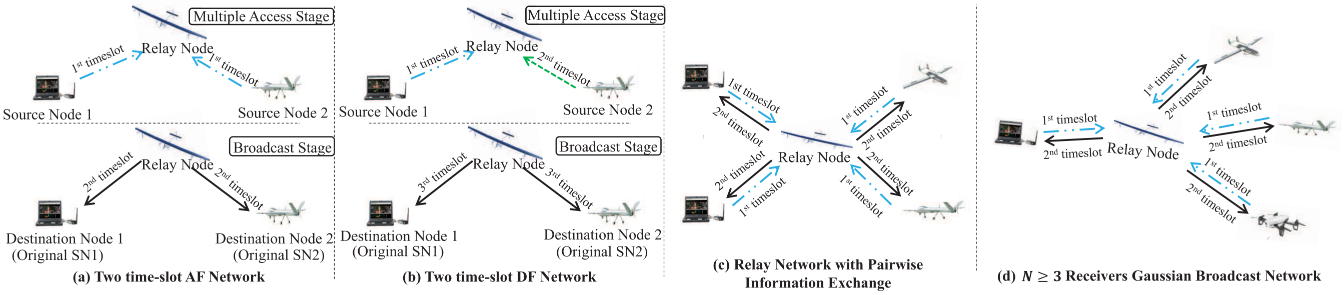
FIGURE 2. SP-UAV as a HALE relay communication platform.

be quickly calculated and implemented, but the existing high-precision and high-efficiency optimization algorithms are often complex and have the high energy consumption, which are not suitable for the UAV with limited energy. Some researchers focus on the iterative algorithms, which are accurate but time-consuming [4]–[8]. Most of them solved the optimization problems and obtained the optimal results by the analogous iterative alternating algorithms, which alternately fixed the trajectory or other related factors. Other researchers investigated the application of heuristic algorithm in path planning, which is feasible but with high computational complexity [9]–[11]. Thereinto, the author of [9] used Particle Swarm Optimization (PSO) algorithm to improve the throughput efficiency. Liu *et al.* in [10] designed a Spatial Refined Voting Mechanism (SRVM) for standard PSO to overcome the defects of local optimal and slow convergence. Rahman *et al.* in [11] proposed an algorithm based on Tabu-search for finding the UAV's position. Most of the above researches focus on the precision and feasibility design, but sacrifice a part of the real-time performance.

The second problem is how to select the optimization variables for the trajectory optimization of the relay UAV to ensure the whole communication performance. There are many options of the optimization variables [4]–[11], including the selection of user data transmit rate (throughput) in [4], the selection of the lower bound of confidentiality rate in [7], and the selection of Signal-to-Interference-plus-Noise Ratio (SINR) in [9]. But these variables require complex calculations, which increase the energy consumption of the UAV's flight control computer. Therefore, for the HALE SP-UAV relay platform, it is needed to be earnestly analyzed the technical characteristics to find the appropriate input variables. The relay communication designs of [12] and [13] mainly utilize the broadcast characteristics of the wireless channels (Fig. 2), including Network Coding (NC) and Adaptive Modulation and Coding (AMC) technologies. These two technologies guarantee the high reliability and high speed communication by adjusting the communication parameters. More importantly, NC and AMC are relying on CSI or average CSI, which is the most basic parameter of the UAV's communication. Therefore, a promising choice is to adopt the original CSI as the optimization variable for the path planning of relay platform, for the sake of realizing the adaptive adjustment of trajectory and the improvement of communication quality simultaneously. To the best of our knowledge, there are few researches concerning on such multiple combinatorial optimizations and applications of this direction.

The above-mentioned technique challenges motivate us to study the trajectory optimization of the SP-UAV platform as relay communication in near space. The optimization problem is to ensure a high communication performance through optimizing the planning path of the relay UAV. Originally, the Potential Fields have been introduced to enable the mobile agents to derive attracting and repelling forces from a given environment. Afterwards, the combination of potential forces with connectivity targets has been further evolved. In the ad-hoc relay network scenario, the Channel-Aware Potential Field (CAPF) approach is suitable to control the micro as well as macro mobility of the UAV swarm (Chapter 33, [14]). The key point of such channel-aware motion planning is properly determining the path based on the channel quality, in the presence of communication constraints [15]. Inspired by such concept, we need to formulate a channel-aware-based motion strategy for the SP-UAV that tends to improve the whole communication quality, so that the position of the relay UAV can adaptively change with the mission UAVs. As the locations of the mission UAVs change fast, the optimization strategy is preferred to be designed with the low computational complexity, so as to achieve the rapid and timely optimization. To achieve this purpose, we define the entire communication system as an "electric charge model", in which the relay UAV is viewed as an "electron", and the ground-station and the mission UAVs are viewed as "nucleuses". Then, the relay UAV suffers "attractions" from these "nucleuses", which orient it to the direction of the synthetic force. In particular, the magnitude of the "attractions" is determined by the CSIs, while the directions of "attractions" point to these "nucleuses", following the principle of Coulomb's Law [16].

This paper tackles the above-mentioned designs and it is structured as follows. We commence by describing both the system model and channel model of HALE SP-UAV, as well as the problem formulation in Section II. Then the "potential field model" and our proposed channel-aware-based path planning strategy are conceived in Section III, where the adaptive communication technologies are coupled to ensure the communication throughput. Relying on the



(a) Two time-slot AF Network (b) Two time-slot DF Network (c) Relay Network with Pairwise Information Exchange (d) $N \geq 3$ Receivers Gaussian Broadcast Network

FIGURE 3. Multiple UAVs relay communication system. (a-d) rely on [12], [13], [17]–[19], respectively.

previous frame-work, we further develop a feedback design based on the cooperative game theory in Section IV, which realizes a feedback-aided adjustment of the adaptive strategy. Finally, we present our simulation results and evaluate the achievable throughput performance characterizing our proposed schemes in Section V, with our concluding remarks are provided in Section VI.

II. SYSTEM MODEL AND PROBLEM FORMULATION

A. SYSTEM AND COMMUNICATION MODEL

Consider a high-altitude UAV-enabled communication system, which includes a fixed ground control station, mission UAVs beyond the communication scope, and a SP-UAV cruising in the near space that provides relay communication, as shown in Fig. 2.

The communication model adopts the relay network and applies the NC technology to enhance the throughput performance, without occupying extra time-slot resources. The work of [12] and [13] proposed the adaptive Network Coded Modulation (NCM) for two-way relay network associated with multi-carrier system that employs Time Division Duplex (TDD). Fig. 3 (a) and (b) present an abridged general view of a three-timeslot and two-timeslot bi-directional transmission system, which includes two destination nodes and a relay node. This provides the fundamental scenario of the relay SP-UAV system. For multiple mission UAVs, the information exchange between pairs of users can rely on the work of [17] (Fig. 3 (c)), while three-user or even any user case can be based on [18] (Fig. 3 (d)). Explicitly, in the uplink stage, both the mission UAVs and the ground station send their CSIs to the relay UAV, while in the downlink stage, the relay UAV broadcasts the composite signal to the destination nodes.

In the actual mission environments, the trajectories, velocities and spatial distributions of the mission UAVs vary greatly. Due to the unpredictability, it would be beneficial to improve the communication quality if the relay UAV could adaptively adjust its trajectory to support the mission UAVs. However, the environmental information obtained by the sensors is complex and difficult to process. This problem can be solved by CSI-based path planning algorithm, which is benefited by the fact that CSI is the basic information and easy to obtain. We then model the spatial locations in Fig. 4, where the SP-UAV, the Ground Station (GS) and the mission UAVs are denoted by R_0, GS, T_1-T_n, respectively. Take the altitude of the GS as the reference datum, the relay SP-UAV flies at the height of H_0, while the mission UAVs fly at the heights of H_1-H_n. Specifically, the relay node is far away from the GS and the mission UAVs, usually the distances having $D_{RB} >> H_0$ and $D_{RM} >> H_0$. Thus, without changing the nature of the problem, we project the three-dimensional (3D) model onto a two-dimensional plane, see the thumbnail in the upper left corner of Fig. 4. To facilitate the design, we set the initial location of the GS as the origin. The horizontal line between the GS and the initial location of the relay UAV is represented as the X-axis, while the locations of the mission UAVs are T_{11}-T_{n1}, where $1 \ldots n$ represents the identification numbers of mission UAVs.

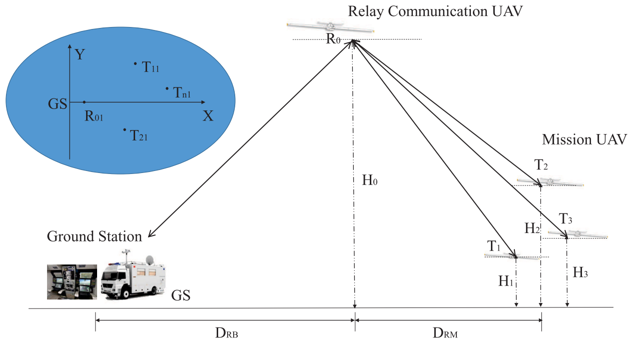


FIGURE 4. Spatial distribution of UAVs and ground station.

Fig. 5 shows a control sequence diagram of the system, where Fig. 5 (a) and (b) separately show the $(k-1)$th and kth moment. Take the starting time of the relay task as the initial moment, and k represents the kth moment. Then the location coordinates of the mission UAVs can be denoted as $T_{1,k}\left(x_{1,k}, y_{1,k}\right) - T_{n,k}\left(x_{n,k}, y_{n,k}\right)$, while that of relay UAV is $R_{0,k}\left(x_{0,k}, y_{0,k}\right)$. Considering the limitation of communication range, the upper distance of the relay node is bounded by D. Let $d_{0,k}$ denote the distance from the SP-UAV to the GS, and $d_{i,k} (i = 1, 2, \ldots, n)$ is the distance from the SP-UAV to the ith mission UAV. Thus we have

$$\begin{cases} d_{0,k} \leq D \\ d_{i,k} \leq D, i = 1, 2, \ldots, n, \end{cases} \quad k \in N_+. \tag{1}$$

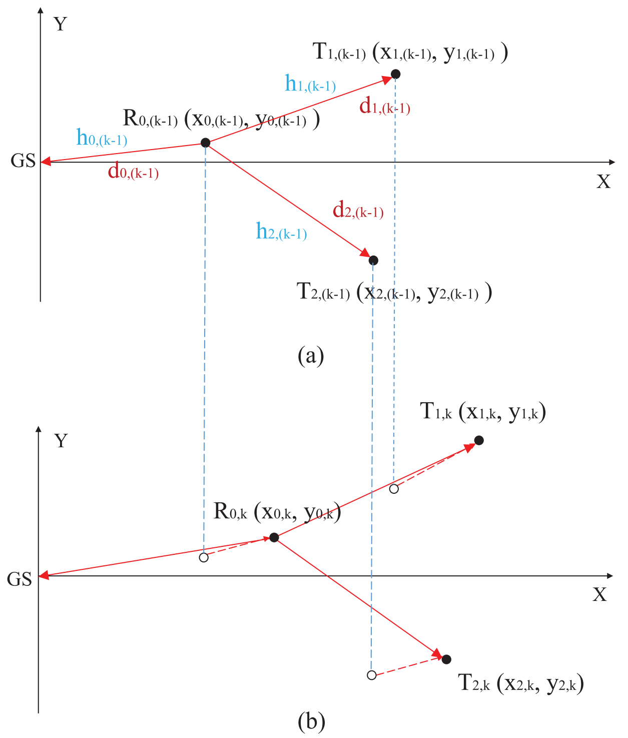


FIGURE 5. Location variations of UAVs at the $(k-1)$th and kth moment.

The relay UAV changes its location according to the CSIs feedback by the GS and the mission UAVs, which are denoted by $h_{0,k}$ and $h_{i,k}, i = 1, 2, \ldots, n, k \in N_+$. Generally, the wireless communication channels are time-varying and change rapidly. Therefore the sampling period of CSI takes the instruction processing cycle of the flight control computer, which is denoted by T_c.

B. PROBLEM FORMULATION

In general, the position change of the relay SP-UAV along with the CSIs of the mission UAVs will result in the improvement of the performance. However, this is an uncertain optimization problem, which involves many uncertain factors and could not be solved by the traditional optimization methods. Firstly, the mission environment of the mission UAVs is uncertain. Secondly, the factors that influence the communication quality of the UAVs are difficult to predict. Finally, there is lack of explicit methods to tell the relay UAV which direction is optimal. Therefore, for the decision making of the relay UAV, it is necessary to model the decision problem abstractly in order to obtain a good decision for the trajectory planning. Commonly, performance of cluster communication networks mainly considers two criteria, Ground Network Coverage (COV) and Throughput (TP) (Chapter 33, [14]), and we mainly consider TP metrics in this context. Thus, we describe our problem as:

- “Based on the current CSI and the location information, the relay node adaptively changes its position according to a strategy, which ensures that the whole communication throughput develops towards a better trend.”

The above description can be expressed mathematically as:

$$\psi_k \geq \psi_{k-1}. \tag{2}$$

where ψ_k denote the summation of transmit rates of each channel at the kth moment.

Without loss of generality, we list the assumptions adopted in this paper:

1) The channel is a non-dispersive and slow-varying Rician fading channel. When the channel is changing faster than it can be estimated and fed back to the transmitter, adaptive techniques will perform poorly.
2) Perfect CSI is available at the relay UAV, GS and mission UAVs using training-based channel estimation. The ideal simplifying assumption that the feedback path does not introduce any error and has no latency may be approximately satisfied by using a low-delay feedback link relying on powerful error control. Additionally, the Doppler Shift is not considered (Chapter 2, [19]).
3) The communication links between the GS and the SP-UAV, as well as between the SP-UAV and the mission UAVs can be approximately viewed as LOS channels. According to Eqs. (2-7), Chapter 2 of [19], when the carrier frequency and the receiving antenna area are fixed, the receiving power is inversely proportional to the square of the distance between the receiving and transmitting antennas. To facilitate our design, we simply map this relation to the channel gain $h_{0,k}$ and $h_{i,k}$, $i = 1, 2, \ldots, n$.
4) The near space is generally between 20km and 100km, and the relay SP-UAV is assumed to fly at a fixed altitude, e.g. 20km. This is because the SP-UAV flies at a low climb rate, thus it has little adjustable altitude in a limited time. Thus the small displacement is negligible for the system of Fig. 4.

Based on the above models and assumptions, we will design our adaptive strategy next.

III. ADAPTIVE TRAJECTORY PLANNING DESIGN

Based on Subsection II.B, the trajectory planning strategy is designed around the following principles: since the movement states of the mission UAVs vary with the environment, the path planning strategy can adaptively choose a direction for the relay node, which is set as “$\overrightarrow{f}_{cal,k}$”, so that the whole communication throughput of the system is most likely to develop towards a better trend. Based on the above guideline, we introduce the concept of “nucleus” to describe the problem. Without loss of generality, it is defined that the strategy starts at the kth moment, and we introduce a set of weighting factors $\omega_i, i = 0, 1, 2, \ldots, n$ to describe the importance of the GS and the different mission UAVs.[1]

Definition 1: Set all the mission UAVs $T_1 - T_n$ and the ground station GS as “nucleuses”, while the relay UAV R_0 is “electron”. Their magnitudes of electric charges are denoted

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[1] The initial ω_i is determined by the expert knowledge rules, and later will be optimized in Section IV according to Game Theory.

by q_1-q_n, q_0 and q, respectively. Then the "nucleuses" have the "electrostatic forces" on the "electron". Specifically, the relay UAV achieves dynamic equilibrium through the attractions that all the nodes apply on it. We then define the force received from the GS as $F_{0,k}$ with the direction $\overrightarrow{f}_{0,k}$, while those from the task drones are denoted by $F_{i,k}$, $i = 1, 2, \ldots, n$, and their directions are $\overrightarrow{f}_{i,k}$.

We then describe the following law to provide the calculation method of the "electrostatic force" for the system.

Coulomb's Law: The magnitude of the attractive or repulsive force between two point charges is directly proportional to the product of the magnitudes of charges, and inversely proportional to the square of the distance between them. The force is along the straight line that connects them. If the two charges have the same sign, the electrostatic force between them is repulsive, while if they have different signs, the force between them is attractive. The scalar form of the mathematical equation is:

$$F = k_e \frac{q_1 q_2}{r^2}, \tag{3}$$

where k_e is the Coulomb's constant, q_1 and q_2 are the signed magnitudes of the charges, and r is the distance between the charges.

Theorem 1: This theorem is an analogue to "Coulomb's Law". We define $q_i = \omega_i e$, $i = 0, 1, 2, \ldots, n$ correspond to the magnitudes of the charges for GS and T_1-T_n, where e is the unit charge. Explicitly, $q = -e$ is set for the relay node R_0. As the link is viewed as LOS channel, we map the CSI h to the distance r^2. By defining $F_{i,k}$, $i = 0, 1, 2, \ldots, n$ as the ith force, the scalar forms of the mathematical equations are:

$$F_{i,k} = -k_h \frac{\omega_i e^2}{h_{i,k}}, \tag{4}$$

where k_h is a determined constant, the subscript character k is the timeslot, and the negative sign represents all the forces applied on the relay UAV are attractions. The directions of the forces are given by:

$$\begin{cases} \vec{f}_{0,k} = \dfrac{\left(-x_{0,k}, -y_{0,k}\right)}{\sqrt{{x_{0,k}}^2 + {y_{0,k}}^2}}, \\ \vec{f}_{i,k} = \dfrac{\left(x_{i,k} - x_{0,k}, y_{i,k} - y_{0,k}\right)}{\sqrt{\left(x_{i,k} - x_{0,k}\right)^2 + \left(y_{i,k} - y_{0,k}\right)^2}}, \; i = 1, 2, \ldots, n. \end{cases} \tag{5}$$

in which $(x_{i,k}, y_{i,k})$ and $(x_{0,k}, y_{0,k})$ denote the locations of the mission UAVs and the relay SP-UAV, respectively.

A. CALCULATION OF THE SYNTHETIC FORCE

Definition 2: Let $\overrightarrow{F}_{sum,k}$ denote the synthetic force on the relay SP-UAV, and $\overrightarrow{f}_{sum,k}$ denote the direction, as shown in Fig. 6. To simplify the derivation, we set a unit force as $F = -k_h e^2$. According to **Theorem 1**, $F_{i,k}$, $i = 0, 1, 2, \ldots, n$ can be expressed by:

$$F_{i,k} = \omega_i F / h_{i,k}. \tag{6}$$

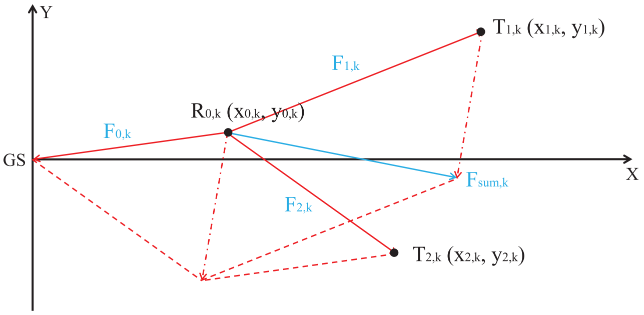

FIGURE 6. Synthetic force on relay UAV.

Then the synthetic force can be obtained by:

$$\overrightarrow{F}_{sum,k} = \sum_{i=0}^{n} \left|F_{i,k}\right| \overrightarrow{f}_{i,k}. \tag{7}$$

By substituting Eqs. (5) and (6) into Eq. (7), the synthetic force $\overrightarrow{F}_{sum,k}$ and its direction $\overrightarrow{f}_{sum,k}$ can be calculated through Eqs. (8) and (9), as shown at the bottom of the next page, respectively.

B. IMPLEMENTATION CRITERIA

Relying on the calculated synthetic force, we need to determine whether to perform the maneuver for the relay SP-UAV. There are two factors associated with the execution. The first is the communication rate. As the communication transmit rate cannot change continuously with the time-varying CSIs, it is actually necessary to discretize the rate to achieve the adaptive transmission [12]. The second factor is the maneuverability of the relay SP-UAV, to avoid the frequent maneuvers in a short period of time. These two factors will be elaborated soon.

We introduce the discrete-rate adaptive communication scheme [12] in Fig. 7. Both the GS and the mission UAVs adopt adaptive M-ary PSK modulations that correspond to the different transmit rates. The threshold of the discrete-rate switching is determined by Signal-to-Noise Ratio (SNR), which is a function of the channel gain h_i [12]. According to the description of our problem in Section II.B, we introduce an evaluation function to design our strategy for ensuring

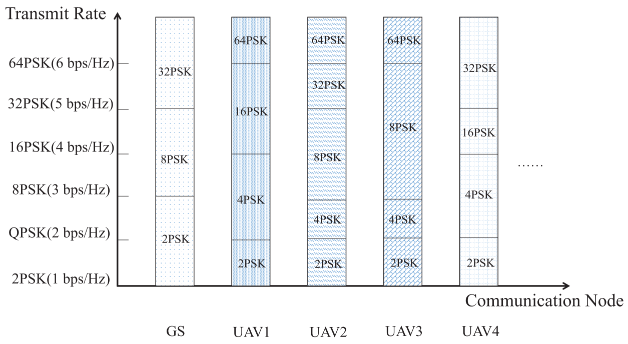

FIGURE 7. Adaptive discrete-rate communication.

the total communication throughput. Considering that the amount of communication traffic handled by the system is determined by summing up the raw data rates of all individual communication connections within the UAVs [14], let ψ_k denote the throughput of the whole system at the kth moment, then we obtain:

$$\psi_k = \sum_{i=0}^{n} C_{i,k}. \tag{10}$$

where $C_{0,k}$ represents the transmit rate between the GS and the SP-UAV, while $C_{i,k}, i = 1, 2, \ldots, n$ is the transmit rate between the SP-UAV and the ith mission UAV.

1) DECISION CRITERIA

If $\psi_k < \psi_{k-1}$, then the relay UAV applies the position change by $\vec{f}_{sum,k}$. For $\psi_k \geq \psi_{k-1}$, the relay UAV does not perform the change. However, considering the maneuverability of the relay SP-UAV in limited time, we introduce another fine-tuning strategy for the $(k+1)$th moment, to avoid the situation where the relay UAV could not achieve a large maneuver.

2) INCLUDED ANGLE JUDGEMENT

Set the moving direction of the current relay UAV as $\vec{f}_k = (x_k, y_k)$. Then we introduce δ_k as the included angle between $\vec{f}_k$ and $\vec{f}_{sum,k}$, which can calculate by:

$$\delta_k = \cos^{-1}\left(\frac{\vec{f}_k \cdot \vec{f}_{sum,k}}{\left|\vec{f}_k\right| \left|\vec{f}_{sum,k}\right|}\right). \tag{11}$$

When $\psi_k \geq \psi_{k-1}$, the direction of the synthetic force may not be the same as the current direction of the flight. To avoid the frequent changes in the direction or the inability of achieving the maneuver at the $(k+1)$th moment, we introduce a boundary $\delta_{\min}$[2] and add the following strategy:

- If $\delta_k > \delta_{\min}$, the relay node will apply the adjustment $\vec{f}_{sum,k}$.
- If $\delta_k \leq \delta_{\min}$, the relay UAV keeps its current flight direction.

C. TRAJECTORY PLANNING ALGORITHM

We then design our adaptive trajectory planning algorithm in **Algorithm 1**, in which $\vec{f}_{cal,k}$ is defined as the moving direction at the kth moment.

Algorithm 1 Trajectory Planning Algorithm

```
Input: $h_{0,k}$-$h_{n,k}$, $T_{0,k}(x_{0,k},y_{0,k})$-$T_{n,k}(x_{n,k},y_{n,k})$, $\vec{f}_k(x_k,y_k)$
Output: $\vec{f}_{cal,k}$
Initialize the CSIs and $T_{0,k}(x_{0,k},y_{0,k})$-$T_{n,k}(x_{n,k},y_{n,k})$;
Determine the data transmit rates $C_{0,k}$-$C_{n,k}$;
Calculate the throughput of this cycle $\psi_k = \sum_{i=0}^{n} C_{i,k}$;
Calculate the direction of the synthetic force $\vec{f}_{sum,k}$;
if $\psi_k < \psi_{k-1}$ then
    Set $\vec{f}_{cal,k} = \vec{f}_{sum,k}$;
else
    Calculate the included angle $\delta_k$;
    if $\delta_k \geq \delta_{\min}$ then
        Set $\vec{f}_{cal,k} = \vec{f}_{sum,k}$;
    else
        Set $\vec{f}_{cal,k} = \vec{f}_k$;
    end
end
return $\vec{f}_{cal,k}$.
```

In each control period of **Algorithm 1**, the relay UAV receives its required information through the communication links, then implements the algorithm to generate the maneuvering command. Of particular note that the optimization of system throughput is an evolutionary process, in other words, the algorithm leads the whole system's throughput to a better trend over a period of time.

$$\vec{F}_{sum,k} = \left\{ \left[\sum_{i=1}^{n} \frac{\omega_i (x_{i,k} - x_{0,k})}{h_{i,k}\sqrt{\left(x_{i,k} - x_{0,k}\right)^2 + \left(y_{i,k} - y_{0,k}\right)^2}} - \frac{\omega_0 x_{0,k}}{h_{0,k}\sqrt{{x_{0,k}}^2 + {y_{0,k}}^2}} \right], \left[\sum_{i=1}^{n} \frac{\omega_i (y_{i,k} - y_{0,k})}{h_{i,k}\sqrt{\left(x_{i,k} - x_{0,k}\right)^2 + \left(y_{i,k} - y_{0,k}\right)^2}} - \frac{\omega_0 y_{0,k}}{h_{0,k}\sqrt{{x_{0,k}}^2 + {y_{0,k}}^2}} \right] \right\} F, \tag{8}$$

$$\vec{f}_{sum,k} = \left\{ \left[\sum_{i=1}^{n} \frac{\omega_i (x_{i,k} - x_{0,k})}{h_{i,k}\sqrt{\left(x_{i,k} - x_{0,k}\right)^2 + \left(y_{i,k} - y_{0,k}\right)^2}} - \frac{\omega_0 x_{0,k}}{h_{0,k}\sqrt{{x_{0,k}}^2 + {y_{0,k}}^2}} \right], \left[\sum_{i=1}^{n} \frac{\omega_i (y_{i,k} - y_{0,k})}{h_{i,k}\sqrt{\left(x_{i,k} - x_{0,k}\right)^2 + \left(y_{i,k} - y_{0,k}\right)^2}} - \frac{\omega_0 y_{0,k}}{h_{0,k}\sqrt{{x_{0,k}}^2 + {y_{0,k}}^2}} \right] \right\}. \tag{9}$$

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[2] The maneuverability of relay UAV is constrained by its maximum turning angle [10]. Explicitly, we define the half of the maximum turning angle as $\delta_{\min}$.

IV. COOPERATIVE-GAME-BASED FEEDBACK STRATEGY DESIGN

The above strategy is designed from the forward direction, which does not consider the feedback gain of the execution result. However, from the perspective of information theory, feedback information can bring the positive benefits to the strategy. The above optimization strategy is a typical multi-user decision model. In particular, game theory can provide ideas for the players who face a dilemma whether to cooperate or conflict with each other [20]. It takes into consideration the impact of decision uncertainty, therefore is feasible to be applied on the study of the decision-making process among multiple rational decision-makers with mutual influence. Explicitly, it provides us with an accurate quantitative analysis perspective to study the scenario of conflict, the cooperative competition and the mutual influence decision-making [21]. To be specific, we regard all mission UAVs as an unmanned system network. When they are intended to be deployed in challenging missions to accomplish predefined goals and requirements, one of the prerequisites for these networked agents is team cooperation and coordination [22]. Based on the above analysis, in this section, we introduce a cooperative game model to investigate the feedback gain of the network, relying on the game characteristics of competition and cooperation among the multi-UAVs. This design is very important for the integrity of the strategy design. Specifically, we use the ideas and the basic elements of Game Theory to reconstruct the above problem.

A. MODELING UAV NETWORK AS A COOPERATIVE GAME

Under the premise of certain relay resources, each mission UAV tries its best to improve its transmit rate. However, once the whole throughput increases, it means that the GS could get more task information and allocate tasks more reasonably in a certain period of time, which will benefit all mission UAVs. Meanwhile, when the system's throughput get optimized, the improvement means an increase in transmit rates of some mission UAVs. In terms of limited resources and system effectiveness, cooperation among players must be strengthened. Therefore, compared with the non-cooperative game, the cooperative game is more advantageous. Cooperative game theory does not discuss how rational players achieve the process of cooperation, but directly discusses the results of cooperation and the distribution of benefits. Furthermore, in a coalition game, the players form coalitions to improve the system utility [23]. To be specific, the moving strategy of the relay UAV mainly studies how game players form the cooperative alliances to optimize the whole throughput of the system, and analyzes how each cooperated player allocates the additional throughput gains brought by the cooperation. Additionally, while each mission UAV is eager to increase its transmit rate, it must comply with the mandatory rules from the relay UAV.

Based on the above analysis, we propose to introduce the coalitional cooperative game theory into the adaptive algorithm to impose constraints on the players in the system, so as to optimize the benefits of the system, and try not to reduce the benefits of any players.

According to [24] and [25], by regarding the relay UAV as the principal part, we define the elements of the game process:

Modeling Elements:

- **Game Players**: $N = \{0, 1, 2, \cdots, n\}$, respectively denote the GS and the mission UAVs T_1-T_n;
- **Coalition Players**: $S = N$, demonstrates all the game players are in a coalition;
- **Strategy Space**: $\Omega = \{\omega_i, i = 0, 1, 2, \ldots, n\}$, describe the weighting factors of the ground station and different mission UAVs;
- **Utility Function**: $u(S)$, denotes the coalition's utility function;
- **Information**: complete information, which means all the elements of the game are common knowledge;
- **Strategy-making Time**: all the players determine the strategies simultaneously, in other words, the game is static.

It is important to note that the game process does not actually occur in the system, it is only simulated in the flight control computer of the relay UAV. Therefore, according to the game elements and utility function of the cooperative game, we propose a feedback-aided algorithm with adaptive adjustment of the weighting factors.

Before introducing the algorithm, we analyze the relay dilemma firstly. Suppose that there are two mission UAVs in a relay system, and the relay UAV attempts to maximize the whole throughput. Fig. 8 demonstrates the results of the game. It can be observed that when the weighting factors change, the transmit rates of the different mission UAVs present diverse states.

		Mission UAV 1	
	ω	1	∞
Mission UAV 2	1	(4,4)	(0,8)
	∞	(8,0)	(4,4)

FIGURE 8. Matrix representation of the relay dilemma.

B. FEEDBACK-AIDED ADAPTIVE SCHEME

Based on the above definitions, we then consider how to design the utility function. In general, it consists of the revenue and the cost. As the goal of our optimization is to maximize the throughput, we set the throughput as the revenue. Meanwhile, we implement a discrete rate adaptive communication scheme in the algorithm, which shows the relationship between CSIs and transmit rates, thus we take the whole CSIs as the cost. Then we have:

$$u(S) = \sum_{i=0}^{n} \ln(C_i) - \sum_{i=0}^{n} \ln(h_i), \tag{12}$$

where $\sum_{i=0}^{n} \ln(C_i)$ denotes the revenue, and $\sum_{i=0}^{n} \ln(h_i)$ is the cost, while C_i and h_i are the same as the previous definition.

Considering that the cooperative game aims at maximizing the utility, Eq. (12) can be converted into:

$$u(S) = \sum_{i=0}^{n} \ln(\frac{C_i}{h_i}). \tag{13}$$

Observing Eq. (13), due to the uncertain mathematical relation between the different transmit rates and the CSIs, it is hard to obtain closed-form solutions. However, according to our proposed algorithm in Section III, it can be concluded that when one channel link benefits from the current strategy, the performance of the other channel links may be affected. Therefore, when all channels in the system contribute equally to the utility function, the whole system can get the maximum utility. To achieve this goal, we propose to find a compromise among the different mission UAVs.

At the kth moment, we calculate all the values of $\ln(\frac{C_i}{h_i})$. Without loss of generality, we assume that the Ith value is the maximal among them. Then we can calculate $\omega_{i,k}$ by:

$$\omega_{i,k} = \begin{cases} 1, & i = I \\ \dfrac{h_{i,k} C_{I,k}}{h_{I,k} C_{i,k}}, & i \neq I. \end{cases} \tag{14}$$

where $\omega_{i,k}$ denotes the weighting factors of the GS and different mission UAVs at the kth moment.

According to Eq. (14), in each control period, the algorithm calculates a new set of weighting factors and replaces them back into the algorithm, then the whole communication throughput can be further optimized. The detailed steps are shown in Fig. 9 and **Algorithm 2**. Explicitly, the weighting factors of the $(k-1)$th moment affect the moving direction of the relay UAV in the $(k-1)$th period, which will determine its location at the kth moment. Then, the location has an important influence on the CSI and the transmit rate of each channel at the kth moment, which will further determine the weighting factors of this period. Benefits by this character, it is believed that the algorithm will obtain gains by adding the feedback.

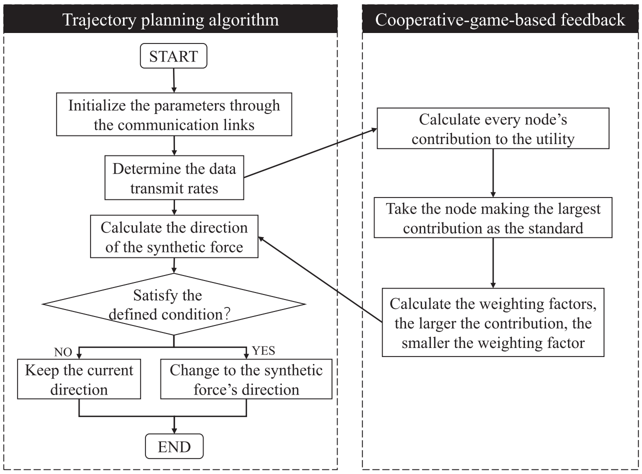


FIGURE 9. **Logic diagram of cooperative-game-based adaptive algorithm.**

Algorithm 2 Cooperative-Game-Based Feedback Trajectory Planning Algorithm

```
Input: $h_{0,k}$-$h_{n,k}$, $T_{0,k}(x_{0,k},y_{0,k})$-$T_{n,k}(x_{n,k},y_{n,k})$, $\overrightarrow{f}_k(x_k,y_k)$
Output: $\overrightarrow{f}_{cal,k}$
Initialize the CSIs and $T_{0,k}(x_{0,k},y_{0,k})$-$T_{n,k}(x_{n,k},y_{n,k})$;
Determine the data transmit rates $C_{0,k}$-$C_{n,k}$;
Calculate the weighting factors $\omega_{0,k}$-$\omega_{n,k}$;
Calculate the direction of synthetic force $\overrightarrow{f}_{sum,k}$;
if it satisfies the defined condition then
    Set $\overrightarrow{f}_{cal,k}$=$\overrightarrow{f}_{sum,k}$;
else
    Set $\overrightarrow{f}_{cal,k}$=$\overrightarrow{f}_k$;
end
return $\overrightarrow{f}_{cal,k}$.
```

V. SIMULATION RESULTS AND PERFORMANCE ANALYSIS

The above-mentioned strategy provides the basis for our adaptive relay auxiliary communication. In this section, a range of representative numerical results are presented for validating our theoretical analysis. Our emphasis is on the improvement of the communication system's throughput. Before presenting the analysis, we unify the simulation parameter settings as follows.

- *Common Parameter Settings:*
  - Processing cycle: Set the instruction processing cycle of the flight controller as $T_c = 10ms$.
  - Relay communication UAV setting: Fixed cruising speed (far lower than mission UAVs) and altitude.
  - Mission UAVs settings: For demonstration purposes, set fixed loop trajectories and flight speeds for the mission UAVs.
  - Communication throughput: Calculate by Eq. (10), Section III.
  - CSIs: Generate according to Assumption 3), Section II.
  - Bandwidth: Set $B = 1$, corresponding to the unit of transmit-rate bit/s.
- *Scenario 1 Settings (5 mission UAVs with the thoroughly distinct paths):*
  - Mission UAVs' number: 5.
  - Mission UAVs' paths: Rectangle or roundness, with clockwise or anticlockwise.
  - Simulation execution time: 1.6 millions control periods.
  - Weighting factors: Set $\omega_i = 1, i = 0, 1, 2, \ldots, 5$.

TABLE 1. Discrete-rate adaptive communication (according to CSIs) [12].

Discrete-rate Area	Range of $SNR(h)$	C(bit/s)
0	$0 <= SNR(h) < 1.8$	0
1	$1.8 <= SNR(h) < 3.6$	2
2	$3.6 <= SNR(h) < 7.2$	4
3	$7.2 <= SNR(h) < \infty$	8

TABLE 2. Discrete-rate adaptive communication (according to CSIs) [12].

Discrete-rate Area	Range of $SNR(h)$	C(bit/s)
0	$0 <= SNR(h) < 2.4$	0
1	$2.4 <= SNR(h) < 4.8$	2
2	$4.8 <= SNR(h) < 9.6$	4
3	$9.6 <= SNR(h) < \infty$	8

  - Transmit rates: Adaptive discrete-rate communication scheme as given in Table 1.
- *Scenario 2 Settings (3 mission UAVs with the analogous paths):*
  - Mission UAVs' number: 3.
  - Mission UAVs' paths: Clockwise, rectangle.
  - Simulation execution time: 6 millions control periods.
  - Weighting factors: (1) $\omega_i = 1, i = 0, 1, 2, 3$; (2) $\omega_0 = 1$ and $\omega_i \in (0, 1), i = 1, 2, 3$.
  - Transmit rates: Table 2.
- *Scenario 3 Settings (Game-Theory scheme with the same paths as in Scenario 2):*
  - Mission UAVs' number: 3.
  - Mission UAVs' paths: Clockwise, rectangle.
  - Simulation execution time: 2 millions control periods.
  - Weighting factors: $\omega_{i,0} = 1, i = 0, 1, 2, 3$.
  - Transmit rates: Table 1.
- *Complexity Analysis Benchmarks:*
  - **RUSA** [Alsharoa *et al.*, 2018]: A recursive uniform search algorithm for the non-convex optimization problem, which optimizes the trajectories of UAVs for the fixed associations and UAVs' transmit power levels in [4].
  - **IA** [Li *et al.*, 2018]: An iterative algorithm for the non-convex optimization problem, which optimizes the UAV's trajectory by assuming that the resource allocation is fixed in [5].
  - **TSBA** [Rahman *et al.*, 2018]: A heuristic method for the optimization problem, which bases on Tabu-search and finds the UAV's positions for the throughput maximization in [11].

A. SCENARIO 1 NUMERICAL RESULTS

We plot the adaptive trajectory scheme and the fixed trajectory scheme of the relay UAV in 3D and Top View in Fig. 10. Observe that our proposed algorithm is capable of adaptively tracking the mission UAVs, providing an autonomous path planning design.

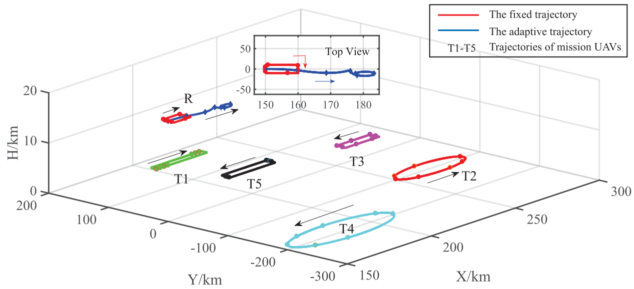
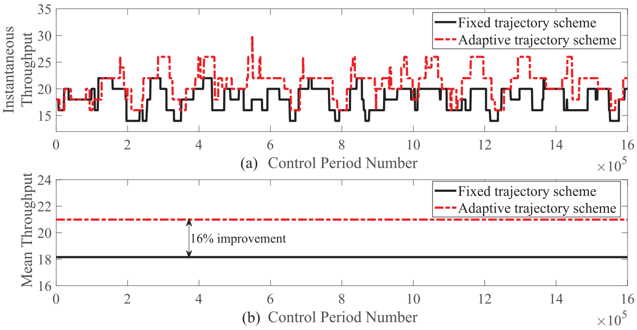


FIGURE 10. Relay UAV's trajectory in 3D and top view.



(a) Control Period Number

(b) Control Period Number

FIGURE 11. Throughput comparison between the adaptive trajectory and the fixed trajectory schemes.

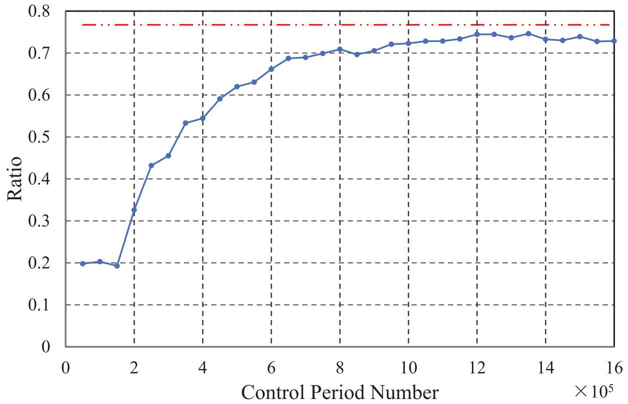


FIGURE 12. Ratio that performance of the adaptive scheme outperforms that of the fixed regime.

We then present the throughput performance of the adaptive trajectory scheme and the fixed regime in Fig. 11. It can be observed that in Fig. 11 (a), the instantaneous throughput of our proposed algorithm is superior to its counterparts operating with the fixed scheme in most of time. We further plot the mean throughput comparison in Fig. 11 (b), which indicates a throughput improvement gain approximately 16% (2.8321 bit/s) under the current simulation settings. Of particular note that the instantaneous throughput of the adaptive trajectory does not always exceed the fixed trajectory, because the communication distances will inevitably increase some time as the mission UAVs constantly change their locations. The phenomenon can be mitigated but not be changed by the adaptive trajectory planning algorithm, therefore the throughput decreases occasionally.

In order to further analyze the effectiveness of the adaptive algorithm, we plot the ratio that the instantaneous throughput of the adaptive scheme outperforms that of the fixed regime in Fig. 12. It can be seen that the advantage rate of our

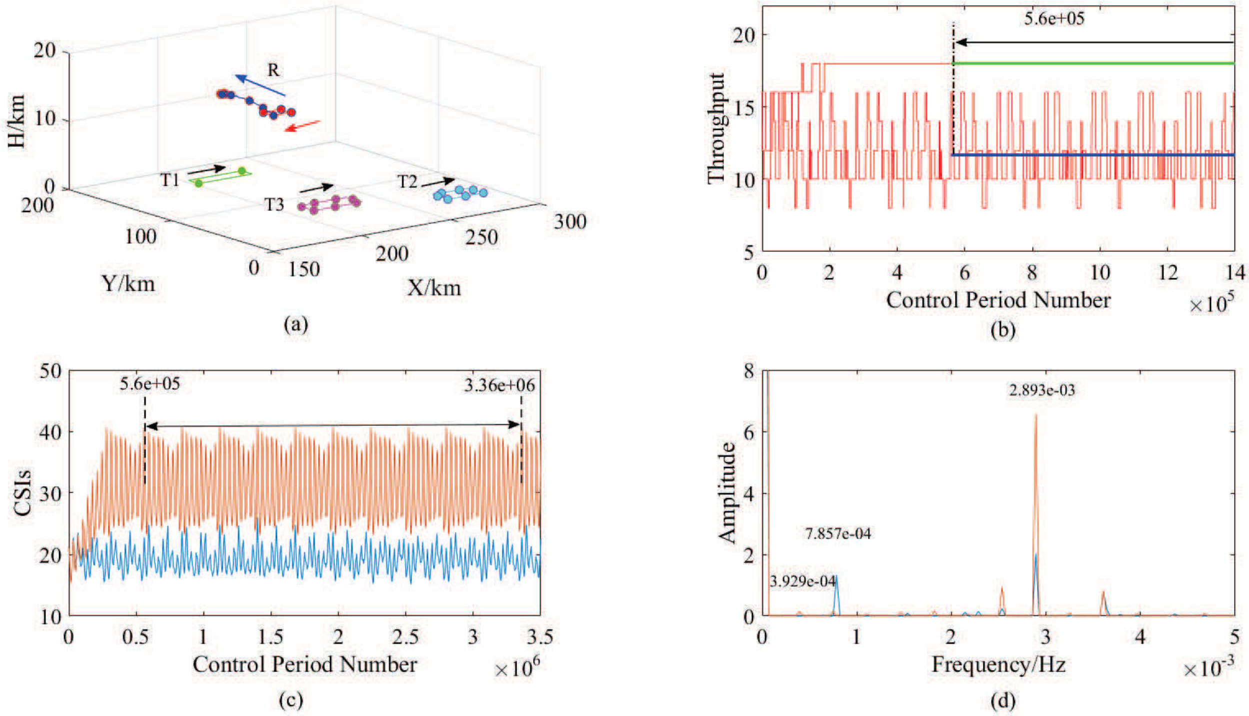


FIGURE 13. **(a) Position changes of each UAV's trajectory in 3D perspective; (b) Instantaneous throughput of the fixed trajectory and the real-time planning adaptive trajectory; (c) Comparison of sum CSIs for two trajectories; (d) FFT results.**

adaptive scheme increases with the increase of the simulation time, but it will approach an upper limit. This is reasonable, because the paths of the mission UAVs are cyclical.

B. SCENARIO 2 NUMERICAL RESULTS

Since the simulation period of Scenario 1 is incomplete, in order to verify the long-term effectiveness and accuracy of the scheme, we take the long-period cruise of three mission UAVs as an example, which is shown in Fig. 13. Fig. 13 (a) depicts the trajectory of the SP-UAV, with the weighing factors $\omega_i = 1, i = 0, 1, 2, 3$. In Fig. 13 (b), we plot the throughput of the adaptive strategy and the fixed scheme. It is worth noting that the system throughput tends to be stable as the trajectories of the mission UAVs appear periodicity. Compared with the average throughput in the stable case, our proposed strategy obtains a 54% improvement (6.3257 bit/s) in the existing simulation settings.

We then confirm the system's periodicity in Fig. 13(c), where the sum of the whole system's CSIs is plotted. We select the data cycles from the 5.6×10^5th to the 3.36×10^6th control periods, which implies the relay UAV enters the periodic steady state. By the FFT of these data in Fig. 13 (d), it can be observed that the longest cycle length of the two trajectories is $2545.18s$. Specifically, the length of the data is 2.8×10^6 control periods (about 28000s), ten times longer than the longest cycle length. Therefore, this part of the data is universal and representative.

To analyze the influence of ω on the throughput of the system, we plot the mean throughput of the fixed scheme and our adaptive scheme in Fig. 14, with the weighing factors $\omega_i = 1, i = 0, 1, 2, 3$ and $\omega_0 = 1, \omega_i \in (0, 1), i = 1, 2, 3$, respectively. Compared to Fig. 13 (b), changing the weighing factors leads to some damage in the throughput, but it still has a performance improvement relative to the fixed trajectory. Setting ω as a variable is more practical for the mission UAVs.

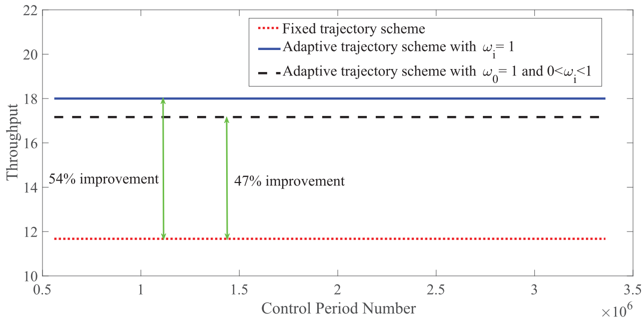


FIGURE 14. **Throughput of the fixed scheme and the adaptive scheme with different weighing factors.**

C. SCENARIO 3 NUMERICAL RESULTS

Next, relying on the same relay communication scenario as scenario 2, we compare the throughput performance of the adaptive scheme and that of the cooperative-game-based adaptive regime in Fig. 15. It can be observed that in Fig. 15 (a), the comparison results of the instantaneous throughput demonstrate the optimization process of our improved algorithm. In the initial control cycles,

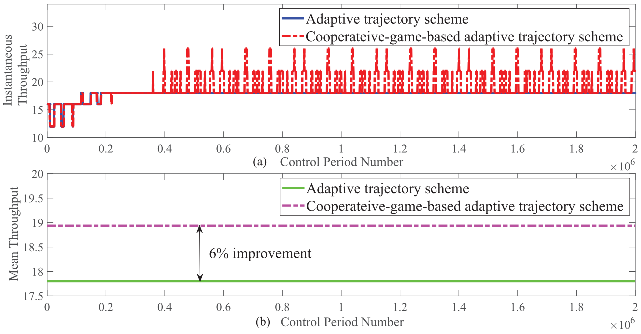


FIGURE 15. **Throughput comparison between the adaptive trajectory and the cooperative-game-based adaptive trajectory.**

the throughput of the two algorithms are the same. With the increase of the control periods, the throughput performance of the cooperative-game-based adaptive algorithm is obviously superior to its counterparts operating with the adaptive algorithm. In addition, by comparing the average throughput in Fig. 15 (b), the cooperative-game-based scheme obtains a 6% throughput improvement in the existing simulation settings, which demonstrates the effectiveness of the feedback-aided optimization.

D. ALGORITHM COMPLEXITY ANALYSIS

We next present the real-time analysis of our proposed schemes. Three benchmarks are selected, as list in the previous simulation settings. According to the time complexity criteria,[3] our adaptive algorithm and feedback-aided adaptive algorithm are $O(1)$ and $O(n)$, respectively. While the corresponding comparison schemes **RUSA** and **IA** are $O(n)$, and **TSBA** is $O(n^2)$. For high altitude SP-UAVs, computing resources are closely related to the energy and must be considered as an important factor. Therefore the above analysis acknowledges that our proposed algorithms may have better real-time performance and energy saving potential than the counterparts.

VI. CONCLUSION

In this paper, we developed a Channel-Aware Potential Field (CAPF)-based adaptive trajectory planning algorithm for the HALE relay SP-UAV, which combines the adaptive communication technique and the potential field theory that adapts to channel variations. The main emphasis of this design is on the CAPF-based path planning, which adjusts the moving direction of the SP-UAV to most possibly orient the whole system throughput towards a better trend. In particular, we introduced a cooperative game theory model to design the feedback-aided strategy that enable the system to autonomically adjust the weighting factors of mission UAVs. Simulation results demonstrated that the proposed scheme is capable of obtaining a higher throughput compared to the benchmark scheme operating without adaptation. By introducing the feedback-aided strategy, the adaptive adjustment of the weighting factors can further improve the system's throughput. It is demonstrated that the designed path planning strategy has good universality, adaptability, real-time performance, as well as a certain level of autonomy.

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