Dual Trajectory Optimization for a Cooperative Internet of UAVs

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***Abstract*—In this letter, we consider a cooperative Internet of unmanned aerial vehicles (UAVs) in which the UAV collects data from ground sensors (GSs) and transmits the received data to the base station (BS) for further processing. The data at the UAV can either be transmitted directly to the BS via the cellular mode or be transmitted through the other UAV via the relay mode. The objective is to minimize the completion time for all the tasks by joint mode selection and trajectory optimization, which can be decoupled into a series of convex optimization problems. The simulation results show that the relay mode is more likely to be selected when the signal-to-noise ratio (SNR) threshold is higher than 10 dB. Otherwise, the UAV prefers to transmit in the cellular mode.**

***Index Terms*—Unmanned aerial vehicle, mode selection, relay, dual trajectory optimization.**

I. INTRODUCTION

IN RECENT years, UAVs are gaining increasing popularity as various low-cost and high-flexibility UAV applications have been discussed in the 3rd Generation Partnership Project (3GPP) specifications [1]. In these cases, the data from the ground sensors (GSs) needs to be transmitted to the base stations (BSs) for real-time processing [2]. However, it is time-inefficient for one single UAV to ensure quality-of-service (QoS) of data transmission when the GSs are remote from the BS. To tackle this problem, the cooperative Internet of UAVs is considered as a promising solution, where all the UAVs possess the capability of relaying data and accessing network infrastructure.

In this letter, we study a simplified model of the cooperative Internet of UAVs, which contains a source UAV and a relay UAV. The sensory data collected by the source UAV can either be transmitted to the BS directly, or be transmitted through the relay UAV. To minimize the task completion time for the cooperative Internet of UAVs, we need to optimize the data transmission mode and the trajectory of the two UAVs.

Unlike most of the existing UAV relay networks in which UAVs work as fixed infrastructures [3], [4], we study the UAVs as mobile Internet of Things devices that adjust their locations dynamically to collect data from GSs, and consider the quality of both data collection and data transmission for the UAVs. Specifically, in the relay mode, the distance between the two UAVs determines the transmission quality. Therefore, the trajectories of the two UAVs should be designed jointly, which leads to a complicated dual trajectory optimization problem.

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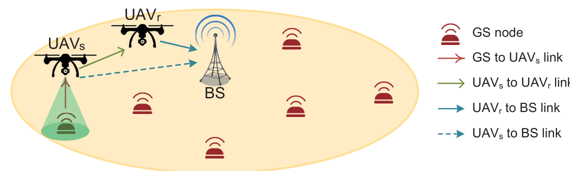

Fig. 1. System model.

II. SYSTEM MODEL

As shown in Fig. 1, we consider a cellular UAV network, which consists of one BS, one source UAV (UAV_s), one relay UAV (UAV_r), and N GSs, denoted by $\mathcal{N} = \{1, 2, \ldots, N\}$. UAV_s needs to collect sensory data from the N GSs in sequence, and upload the received data to the BS. Due to the storage limitation of the UAVs, the data transmission of a GS should be completed before collecting data from the next GS, and thus, a number of iterations of data collection and transmission are required to complete the whole tasks.

A. UAV Data Collection

In this step, UAV_s receives data from a GS. In time slot t, we denote the location of UAV_s by $\boldsymbol{l}_s(t) = (x_s(t), y_s(t), h_s(t))$, and the location of UAV_r by $\boldsymbol{l}_r(t) = (x_r(t), y_r(t), h_r(t))$. The location of the BS is $\boldsymbol{l}_{BS} = (0, 0, H)$, and the location of GS i is $(x_i, y_i, 0)$. The trajectories of UAV_s and UAV_r can be expressed as $\{\boldsymbol{l}_s(t)\}$ and $\{\boldsymbol{l}_r(t)\}$, respectively. Let τ_i be the time when UAV_s collects the data from GS i. To ensure the QoS of UAV data collection, the feasible region for UAV_s to collect data from GS i is assumed to be a conical region, with θ being the top angle, which can be expressed as

$$(x_s(\tau_i) - x_i)^2 + (y_s(\tau_i) - y_i)^2 \leq (z_s(\tau_i) \tan\theta)^2. \quad (1)$$

The sensory data from each GS is considered to be R_s, and the UAV data collection for each GS can be completed in one time slot when (1) is satisfied.

In time slot t, let $\boldsymbol{v}_s(t) = (v_s^x(t), v_s^y(t), v_s^h(t))$ and $\boldsymbol{v}_r(t) = (v_r^x(t), v_r^y(t), v_r^h(t))$ be the velocity of UAV_s and UAV_r, respectively, with $\boldsymbol{v}_s(t) = \boldsymbol{l}_s(t) - \boldsymbol{l}_s(t-1)$ and $\boldsymbol{v}_r(t) = \boldsymbol{l}_r(t) - \boldsymbol{l}_r(t-1)$. Due to the space and mechanical limitations, the UAVs have a feasible range of altitude and velocity, which can be expressed as

$$h_{min} \leq h_s(t) \leq h_{max}, h_{min} \leq h_r(t) \leq h_{max}, \quad (2)$$

$$\|\boldsymbol{v}_s(t)\| \leq v_{max}, \|\boldsymbol{v}_r(t)\| \leq v_{max}. \quad (3)$$

B. UAV Transmission

In UAV transmission step, the UAVs transmit the collected data to the BS. It is assumed that the UAV transmission is assigned with a dedicated subchannel, and thus, interference is not considered in the transmission process. Two transmission modes are provided in this network, namely cellular mode and relay mode. The data from each GS is transmitted to the BS by either cellular mode or relay mode.

1) Cellular Mode: In the cellular mode, UAV$_s$ transmits the collected data to the BS directly, and the air-to-ground transmission channel model as presented in [5] is utilized in this mode. The average pathloss from the UAV to the BS can be expressed as

$$PL_{av}(t) = P_L(t) \times PL_L(t) + P_{NL}(t) \times PL_{NL}(t). \quad (4)$$

$PL_L(t)$ is the line-of-sight (LoS) pathloss, $PL_{NL}(t)$ is the non-line-of-sight (NLoS) pathloss, $P_L(t)$ is the probability of LoS connection, and $P_{NL}(t) = 1 - P_L(t)$ is the probability of NLoS connection. The LoS and NLoS pathloss from the transmission UAV to the BS are given by $PL_L(t) = L_{FS}(t) + 20\log(d_{s,BS}(t)) + \eta_L$, and $PL_{NL}(t) = L_{FS}(t) + 20\log(d_{s,BS}(t)) + \eta_{NL}$, respectively. Here, $d_{s,BS}(t)$ is the distance between UAV$_s$ and the BS. $L_{FS}(t)$ is the free space pathloss. η_L and η_{NL} are additional attenuation factors due to the LoS and NLoS connections. The probability of LoS connection is given by $P_L(t) = 1/(1 + a\exp(-b(\phi(t) - a)))$, where a and b are constants depend on the environment, and $\phi(t)$ is the elevation angle.

The signal-to-noise ratio (SNR) at the BS can be expressed as $\gamma^i_{s,BS}(t) = \frac{P_U}{10^{PL_{av}(t)/10}}/\sigma^2$. Therefore, the data rate for GS i from the transmission UAV to the BS is given by

$$R^i_{s,BS}(t) = \log_2\left(1 + \gamma^i_{s,BS}(t)\right). \quad (5)$$

For the sake of QoS, we assume that the SNR for the transmission should be larger than a minimum SNR threshold γ_0, i.e., $\gamma^i_{s,BS}(t) \geq \gamma_0$. Let χ_i be the time when UAV$_s$ starts data transmission for GS i. In order to complete the data transmission, the data rate of the UAV$_s$ to BS link satisfies $\sum_{t=\chi_i}^{\tau_{i+1}-1} R^i_{s,BS}(t) \geq R_s, \forall \lambda_i = 0$, where $\lambda_i = 0$ indicates that the data from GS i is transmitted in the cellular mode, and $\lambda_i = 1$ when the data are transmitted in the relay mode.

2) Relay Mode: The relay mode transmission consists of two phases. In the first phase, UAV$_s$ transmits the collected data to UAV$_r$ via UAV to UAV (U2U) transmission. In the second phase, UAV$_r$ decodes and forwards the received data to the BS via UAV to network (U2N) transmission.

a) U2U transmission: When UAV$_s$ transmits the data from GS i to UAV$_r$, the received power can be expressed as $P^i_{s,r}(t) = P_U G(d_{s,r}(t))^{-\alpha}$, where G is the constant power gains factor introduced by amplifier and antenna, α is the pathloss coefficient, and $d_{s,r}(t)$ is the distance between the two UAVs. The SNR at UAV$_r$ for GS i is shown as $\gamma^i_{s,r}(t) = P_U G(d_{s,r}(t))^{-\alpha}/\sigma^2$, where σ^2 is the variance of addictive white Gaussian noise with zero mean. The data rate for GS i from UAV$_s$ to UAV$_r$ is given by

$$R^i_{s,r}(t) = \log_2\left(1 + \gamma^i_{s,r}(t)\right). \quad (6)$$

For QoS consideration, the SNR $\gamma^i_{s,r}(t)$ should be larger than a threshold γ_0, i.e., $\gamma^i_{s,r}(t) \geq \gamma_0$. In order to complete the data transmission, the transmitted data is required to be larger than R_s, i.e., $\sum_{t=\chi_i}^{\tau_{i+1}-1} R^i_{s,r}(t) \geq R_s, \forall \lambda_i = 1$.

b) U2N transmission: In the U2N transmission, the air-to-ground transmission channel model mentioned in the cellular mode is utilized. The SNR for UAV$_r$ to BS link is also required to be larger than the minimum SNR threshold, i.e. $\gamma^i_{r,BS}(t) \geq \gamma_0$. The transmission data satisfies $\sum_{t=\chi_i}^{\tau_{i+1}-1} R^i_{r,BS}(t) \geq R_s, \forall \lambda_i = 1$, where $R^i_{r,BS}(t) = \log_2\left(1 + \gamma^i_{r,BS}(t)\right)$ is the data rate of the UAV$_r$ to BS link.

III. Problem Formulation

In this section, we formulate the transmission mode selection and dual trajectory optimization problem. To minimize the completion time for the UAVs to perform data collection and transmission for all the GSs, we design the transmission mode for the data from each GS, and optimize the trajectories of the two UAVs. Since the UAV trajectory for collecting data from multiple GSs are designed jointly, the BS needs to solve the optimization problem offline. We define the completion time for GS i as the time slot when all the data from the GS arrives at the BS, which is denoted by T_i. The completion time minimization problem can be formulated by

$$\min_{\substack{\{\lambda_i\},\{\boldsymbol{l}_s(t)\},\\ \{\boldsymbol{l}_r(t)\}}} \quad T_N, \quad (7a)$$

$$\text{s.t.} \quad (1), (2), (3),$$

$$\gamma^i_{m,n}(t) \geq \gamma_0, \forall \{m, n = s, r, BS, \chi_i \leq t < \tau_{i+1}\}, \quad (7b)$$

$$\sum_{t=\chi_i}^{\tau_{i+1}-1} R^i_{m,n}(t) \geq R_s, \forall \{m, n = s, r, BS, \chi_i \leq t < \tau_{i+1}\}. \quad (7c)$$

Constraints (7b) ensures the QoS for the transmission links, and (7c) is the transmission rate requirements.

Problem (7) cannot be solved directly due to the discreteness of the mode selection variable λ_i. Therefore, we first optimize the UAV trajectory for the cellular mode, and then discuss the impact of utilizing the relay mode for each GS on the completion time. Finally, the mode selection for each GS is performed.

IV. Mode Selection and Dual Trajectory Optimization

In this section, we first propose the UAV trajectory optimization algorithm for the two transmission modes, and then summarize the mode selection and dual trajectory optimization algorithm that solves problem (7).

A. Trajectory Optimization in the Cellular Mode

In the cellular mode, λ_i is fixed at 0, and UAV$_s$ transmits the collected data to the BS directly. The subproblem can be expressed as

$$\min_{\{\boldsymbol{l}_s(t)\}} \quad T_N,$$

$$\text{s.t.} \quad (1), (2), (3), (7b), (7c). \quad (8)$$

In this mode, the trajectory optimization for a single UAV still cannot be solved directly, as constraints (7b) and (7c) are non-convex with respect to $\boldsymbol{l}_s(t)$. In the following, we approximate problem (8) into a convex one.

We denote the feasible location for UAV$_s$ to collect data from GS i by $\mathcal{S}_i$. According to (1), $\mathcal{S}_i$ satisfies

$(x, y, z) \in \{(x - x_i)^2 + (y - y_i)^2 \leq (z \tan\theta)^2\}$, which is a convex region. Similarly, we denote the feasible location for UAV$_s$ to perform data transmission to the BS by $\mathcal{T}$, i.e., constraint (7b) can be satisfied when UAV$_s$ is within the region of $\mathcal{T}$. According to the cellular transmission model given in Section II-B, the region of $\mathcal{T}$ can be approximately expressed as $(x, y, z) \in \{x^2 + y^2 + (z - H)^2 \leq \frac{P_U}{\sigma^2\gamma_0}\}$, which is also a convex region.

The completion time of UAV$_s$ contains the data transmission time and the flight time. The data transmission time is determined by the transmission rate, which is stable during the transmission process for one GS, since the moving distance of the UAV during this period is much shorter than the transmission distance. The data transmission time for GS i approximately equals $\frac{R_s}{R^i_{s,BS}(\chi_i)}$. Therefore, problem (8) can be simplified as a flight time minimization problem. Given the maximum UAV velocity v_{max}, the flight time minimization problem can be converted to UAV trajectory minimization problem, which is expressed as

$$\begin{aligned} \min_{\{\boldsymbol{l}_s(t)\}} \quad & \sum_{i=1}^{N} \|l_s(\chi_i) - l_s(\tau_i)\| + \|l_s(\tau_{i+1}) - l_s(\chi_i)\|, \\ s.t. \quad & \forall l_s(\tau_i) \in \mathcal{S}_i, l_s(\chi_i) \in \mathcal{T}. \end{aligned} \tag{9}$$

Note that the regions of $\mathcal{S}_i$ and $\mathcal{T}$ are all convex, and the objective function is convex with respect to $\boldsymbol{l}_s(t)$. Therefore, (9) is a convex problem, which can be solved by standard convex optimization techniques.

B. Trajectory Optimization in the Relay Mode

In Section IV-A, the UAV trajectory in the cellular mode is optimized. To further reduce the completion time for all the tasks T_N, UAV$_r$ may relay some of the sensory data for UAV$_s$ to the BS. Since the mode selection for different GSs are independent, the dual trajectory optimization in the relay mode can be performed for each single GS, and the problem can be written as

$$\begin{aligned} \min_{\{\boldsymbol{l}_s(t)\}, \{\boldsymbol{l}_r(t)\}} \quad & T_i - T_{i-1}, \forall i \in \mathcal{N}, \\ s.t. \quad & (1), (2), (3), (7b), (7c). \end{aligned} \tag{10}$$

Problem (10) is still non-convex due to the non-convexity of constraint (7b) and (7c). To solve the dual trajectory optimization problem in the relay mode, we first decouple the trajectory optimization for these two UAVs, and propose an algorithm to solve them iteratively.

Given the trajectory of UAV$_r$, the UAV$_s$ trajectory optimization problem can be converted to a trajectory minimization problem similar to problem (9), which is expressed as

$$\begin{aligned} \min_{\{\boldsymbol{l}_s(t)\}} \quad & \|l_s(\chi_i) - l_s(\tau_i)\| + \|l_s(\tau_{i+1}) - l_s(\chi_i)\|, \\ s.t. \quad & \forall l_s(\tau_i) \in \mathcal{S}_i, l_s(\chi_i) \in \mathcal{T}. \end{aligned} \tag{11}$$

Given the trajectory of UAV$_s$, the trajectory optimization for UAV$_r$ is given as

$$\begin{aligned} \min_{\{\boldsymbol{l}_r(t)\}} \quad & T_i - T_{i-1}, \forall i \in \mathcal{N}, \\ s.t. \quad & (1), (2), (3), (7b), (7c). \end{aligned} \tag{12}$$

1) Trajectory Optimization for UAV$_s$: Given the trajectory of UAV$_r$, the trajectory optimization for UAV$_s$ can be solved similarly with problem (9). The only difference is that the region of $\mathcal{T}$ is solved with the U2U transmission model. In the relay mode, $\mathcal{T}$ is defined as $(x, y, z) \in \{d_{s,r}(t)^2 \leq \frac{P_U}{\sigma^2\gamma_0}\}, \chi_i \leq t < \tau_{i+1}$, which is convex. Therefore, (11) is a convex problem and can be solved by standard convex optimization techniques.

2) Trajectory Optimization for UAV$_r$: In this part, we optimize the trajectory of UAV$_r$ given the trajectory of UAV$_s$. As constraints (7b) and (7c) are non-convex, problem (12) can not be solved directly. Given the data collection time for each GS, the minimum completion time corresponds to the minimum data transmission time. We denote the set of time slots that UAV$_s$ transmits the data from GS i to UAV$_r$ by Ω^i_c, and the set of time slots that UAV$_r$ transmits the data from GS i to the BS by Ω^i_r. The total transmission time for GS i, denoted by t_i, satisfies

$$t_i = |\Omega^i_c| + |\Omega^i_r|. \tag{13}$$

Note that the moving distance of a UAV in t_i is much shorter than the transmission distance. Therefore, the transmission rate in the time slots in Ω^i_c are approximately equal. The transmission time from UAV$_s$ to UAV$_r$ can be written as

$$|\Omega^i_c| = R_s / R^i_{s,r}(t), \forall t \in \Omega^i_c. \tag{14}$$

Similarly, the transmission time from UAV$_r$ to the BS can be approximated by

$$|\Omega^i_r| = R_s / R^i_{r,BS}(t), \forall t \in \Omega^i_r. \tag{15}$$

When substituting (14) and (15) into (13), we have

$$\frac{R_s}{R^i_{s,r}(t_s)} + \frac{R_s}{R^i_{r,BS}(t_r)} = t_i, \tag{16}$$

where t_s and t_r are the time slots when the UAV$_s$ to UAV$_r$ transmission and the UAV$_r$ to BS transmission begin, respectively. As R_s is a constant, the minimum t_i can be obtained when $1/R^i_{s,r}(t_s) + 1/R^i_{r,BS}(t_r)$ is minimized. Therefore, problem (12) can be transferred into

$$\begin{aligned} \min_{\{\boldsymbol{l}_r(t)\}} \quad & \frac{1}{R^i_{s,r}(t_s)} + \frac{1}{R^i_{r,BS}(t_r)}, \\ s.t. \quad & (1), (2), (3), (7b), (7c). \end{aligned} \tag{17}$$

As the convexity of problem (17) is determined by constraints (7b) and (7c), we divide problem (17) into two cases and discuss them separately.

If constraints (7b) and (7c) are both satisfied during the transmission, t_s and t_r are approximately equal. Problem (17) can then be written as

$$\begin{aligned} \min_{\{\boldsymbol{l}_r(t)\}} \quad & \frac{1}{R^i_{s,r}(t)} + \frac{1}{R^i_{r,BS}(t)}, \\ s.t. \quad & (1), (2), (3). \end{aligned} \tag{18}$$

As (18) is a convex problem, it can be solved by the gradient based algorithm [6].

If constraints (7b) and (7c) cannot be satisfied at the same time during the transmission, to achieve the maximum achievable rate, UAV$_r$ moves along the gradient of the transmission rate, i.e.$\nabla R^i_{s,r}(t) = (\frac{\partial R^i_{s,r}(t)}{\partial x_r(t)}, \frac{\partial R^i_{s,r}(t)}{\partial y_r(t)}, \frac{\partial R^i_{s,r}(t)}{\partial h_r(t)})$, at the speed of v_{max}.[1] When constraint (7b) is satisfied, UAV$_r$ stops

[1]Given that $v_{max} \ll d_{s,r}(t)$, the solution of the gradient algorithm will converge close enough to the theoretical optimal solution. Therefore, the step size of the UAV is set as the maximum achievable value, i.e., v_{max}, so that it converges to the final solution with the minimum completion time.

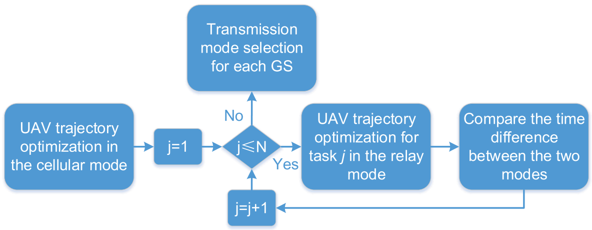

Fig. 2. Mode selection and dual trajectory optimization.

flying and receives the data from UAV$_s$,[2] to reduce the flight time before performing the relay to BS transmission. After receiving all the data from UAV$_s$, UAV$_r$ flies towards the BS in the direction of $\nabla R^i_{r,BS}(t)$ at the speed of v_{max}. Similarly, when the location of UAV$_r$ satisfies (7b), UAV$_r$ stops moving and transmits the data to the BS.

The dual trajectory optimization algorithm in the relay mode is summarized as below. We first find an initial trajectory solution for UAV$_s$ and UAV$_r$ that satisfies all the constraints in (10). We then perform iterations to solve the subproblems. In each iteration, trajectory optimization for UAV$_s$ is performed firstly, with UAV$_r$'s trajectory optimization results given in the last iteration. Afterwards, trajectory optimization for UAV$_r$ is performed given the trajectory of UAV$_s$. The algorithm terminates if the difference of the completion time obtained in the last two iterations is less than a predefined threshold ω.

We give a flowchart to summarize the mode selection and dual trajectory optimization in Fig. 2. We first solve the minimum completion time for all the tasks via the cellular mode as proposed in Section IV-A. Afterwards, we perform the dual trajectory optimization as proposed in Section IV-B, to solve the completion time for each task via the relay mode. Finally, we adopt the transmission mode for each GS according to the solution of the completion time.

V. Simulation Results

In this section, we evaluate the performance of the proposed algorithm. The selection of the simulation parameters are based on the existing 3GPP specifications [1]. We consider the height of the BS as $H = 25$ m, and the data from each GS as $R_s = 20$ Mb. The number of GSs is set as $N = 10$. The noise variance is set as $\sigma^2 = -96$ dBm, and the UAV transmit power is set as $P_U = 23$ dBm. We set the maximum velocity of the UAVs as $v_{max} = 10$ m/s, and the maximum height of the UAVs as $h_{max} = 200$ m. The power gains factor G is -31.5 dB, and the path loss exponent α is 2. As for the parameters of the U2N channel, we set $\eta_{LoS} = 1$, $\eta_{NLoS} = 20$, $a = 12$, and $b = 0.135$.

For comparison, the relay mode scheme and the cellular mode scheme are also performed. In the compared schemes, the transmission mode is fixed when the UAVs collect data from the GSs. We also compare the proposed algorithm with a circular trajectory scheme, where UAV$_r$ moves along a circular trajectory, and the trajectory of UAV$_s$ is the direct link between the locations that it performs data collection.

Fig. 3(a) shows the relation between the SNR threshold γ_0 and the completion time T_N. The locations of the GSs are randomly distributed in an area of 600 m $\times$ 600 m.

[2]When $\boldsymbol{l}_r(t)$ satisfies (7b), the transmission rate does not change significantly in the time slots in Ω^i_s.

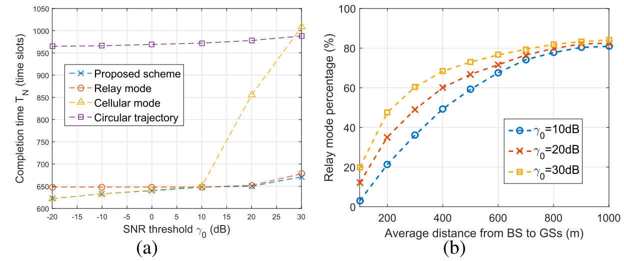

Fig. 3. Simulation result: a) SNR threshold γ_0 vs. Completion time; b) average distance from BS to GSs vs. Relay mode percentage.

The performance of the proposed scheme is similar with the cellular scheme when $\gamma_0 < 10$ dB, and is close to the relay mode when $\gamma_0 > 10$ dB. The reason is that a high SNR threshold requires a short transmission distance, which can be achieved with the relay UAV. However, when the SNR threshold is low, UAV$_s$ tends to perform data transmission in the cellular mode, due to the low latency of the direct link. The completion time with the proposed dual trajectory optimization is over 30% lower than that of the circular trajectory.

In Fig. 3(b), we plot the relation between the percentage of GSs transmitted via the relay mode and the average distance from the BS to the GSs with different values of the SNR threshold γ_0. The sensory data of no more than 20% GSs is transmitted via the relay mode when the average distance from the BS to the GSs is 100 m, since the SNR threshold of the direct link from UAV$_s$ to the BS is easy to be satisfied. The relay mode is more likely to be adopted with the increment of the average distance from the BS to the GSs, due to the increment of transmission channel fading. The percentage of GSs transmitted via the relay mode stays stable at over 80% when the average distance from the BS to the GSs is over 800 m, where most of the transmissions need to be assisted by UAV$_r$. A higher value of γ_0 increases the transmission SNR requirement, which leads to a larger probability of UAV cooperation via the relay mode.

VI. Conclusions

In this letter, we have studied a cooperative Internet of UAVs where one UAV works as a data collector and one UAV works as a relay. We have formulated a mode selection and dual trajectory optimization problem to minimize the completion time for all the tasks, which can be decoupled into several convex optimization subproblems. Simulation results showed that the relay mode is more likely to be selected when the SNR threshold is higher than 10 dB. Otherwise, the UAV prefers to transmit in the cellular mode.

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