Cellular UAV-to-device communications: Joint trajectory, speed, and power optimisation

Yaqin Liu | Fanyi Wu | Jianjun Wu

Department of Electronics, Peking University, Beijing, China

Correspondence
Yaqin Liu, Department of Electronics, Peking University, Beijing 100871, China.
Email: yaqin.liu@pku.edu.cn

Abstract
Unmanned aerial vehicles (UAVs) are envisioned to provide a variety of sensing applications in the cellular systems, which is known as the cellular Internet of UAVs. This paper considers a cellular Internet of UAVs, in which the sensory data collected by UAVs can be transmitted to the base station by cellular communications, or to the corresponding mobile devices directly by overlaying UAV-to-device communications. The authors first propose a joint sensing and transmission protocol to schedule UAV sensing and transmission, and then investigate the energy utility (EU) maximisation problem by jointly optimising the trajectory, speed, and transmit power of UAVs in the system. As this problem is non-convex and difficult to be solved, the authors decouple it into three subproblems, i.e. trajectory optimisation subproblem, speed optimisation subproblem, and transmit power optimisation subproblem. Then, the authors propose a joint trajectory, speed, and transmit power optimisation algorithm to obtain the suboptimal solution of the original problem. Simulation results show that the authors’ proposed algorithm can efficiently improve the EU in the system as compared with other benchmark schemes.

1 INTRODUCTION
Owing to the advantages of flexible deployment, broad coverage, and low operational cost, unmanned aerial vehicles (UAVs) are regarded as promising facilities to provide sensing services in the next generation wireless communication networks [1]. Recently, UAVs have been found applications in aerial photography [2], air quality index monitoring [3], precision agriculture [4], and autonomous target detection [5]. Among these sensing applications, the unmanned aircraft systems (UASs) work over the unlicensed band [6], i.e. 2.4 and 5.8 GHz in the Industrial, Scientific and Medical (ISM) Bands. However, the Quality of Service (QoS) for the sensing services cannot be guaranteed due to the opportunistic channel access in the unlicensed band. Therefore, a more reliable network is needed.

To this end, the 3rd Generation Partnership Project (3GPP) suggests to adopt terrestrial cellular networks to support the UAV sensing services [7], which is also referred to as the cellular Internet of UAVs [8–10]. In the cellular Internet of UAVs, UAVs can transmit their collected sensory data to the base stations (BSs) via cellular links, namely, UAV-to-network (U2N) communications [11], or to the corresponding mobile devices (MDs) directly, namely, UAV-to-device (U2D) communications [12]. Furthermore, due to the limitation of onboard batteries, the energy of a UAV is limited [13]. Since the energy consumption of a UAV is jointly affected by its trajectory, speed, and transmit power, it is crucial to study them.

This paper considers a cellular Internet of UAVs consisting of multiple UAVs performing sensing tasks, in which UAVs transmit their collected sensory data in either U2N or U2D mode. To avoid the mutual interference between these two modes, the U2D mode works as an overlay to the U2N mode. Since the UAVs are energy-limited, we aim to maximise the energy utility (EU) of the UAVs by optimising their trajectories, speeds, and transmit powers, in which EU is defined as the sum data rate of all the UAVs with unit power consumption.

However, it is challenging to investigate the EU maximisation problem in our network. First, a UAV’s sensing and transmission are coupled with each other [14], which makes this problem
difficult to be solved. Specifically, it risks in obtaining invalid sensory data when a UAV is far from the sensing target, while the transmission quality is low when the UAV is far from the BS or its MD. Secondly, the power consumption of each UAV is jointly determined by its trajectory, speed, and transmit power. Since a UAV’s trajectory, speed, and transmit power are coupled, it is complicated to optimise the power consumption for the UAVs. To tackle with this issue, we decompose the original problem into three subproblems, i.e. trajectory optimisation, speed optimisation, and transmit power optimisation subproblems. By this means, we can find the suboptimal solution of the original problem by solving these three subproblems sequentially.

In the literature, several works have investigated the cellular Internet of UAVs. Authors in [15–18] focused on the U2N communications. To be specific, in [15], the authors considered a cellular-controlled UAV network in which multiple UAVs performed cooperative sensing and transmission, and jointly optimised the trajectories, sensing locations, and scheduling for the UAVs to minimise the completion time for services. Authors in [16] proposed a new cooperative non-orthogonal multiple access (NOMA) scheme applied to the uplink communication from a UAV to BSs to mitigate the severe uplink interference. The work [17] designed the transmit beamforming at a multi-antenna UAV to deliver its messages to a set of BSs, which aimed to maximise its uplink sum-rate and in the meanwhile suppress the interference. In [18], the authors studied the decentralised UAV trajectory design problem in cellular UAV networks by leveraging multi-agent reinforcement learning.

Besides, authors in [19–21] focused on the UAV-to-UAV (U2U) communications, where UAVs can communicate with each other. Specifically, in [19], the authors studied a cooperative Internet of UAVs where the sensory data collected by the source UAV can be transmitted to the relay UAV, and optimised the transmission mode and the trajectory of UAVs to minimise the task completion time. In [20], the authors evaluated the exchanged control packet loss rate, throughput, and outage probability in a cellular network in which multiple UAVs worked cooperatively. Authors in [21] considered a cellular network where the UAV transmissions can be supported by U2N and U2U transmissions, and formulated a joint UAV speed optimisation and subchannel allocation problem to maximise the uplink sum-rate of the network.

Furthermore, some works on the energy-efficient designs for the UAVs have been studied. Authors in [22] introduced an energy-efficient rechargeable UAV deployment strategy to support seamless coverage in urban areas. In [23], the authors studied a heterogeneous UAV network where the UAVs are adopted as aerial BSs, and proposed an approach for the resource allocation and 3D deployment of the UAV-BSs to optimise their coverage and power consumption.

In the aforementioned works, the direct communications between UAVs and MDs, namely, the U2D communications, is rarely considered. However, it is a considerable practical scenario in the cellular Internet of UAVs. Although there exist a work on the U2D communications [12], the energy consumption of UAVs is not considered. Actually, this is rather critical in practice, as trajectories of UAVs are constrained by their energy. Therefore, different from [12], we study the U2D communications for the energy-limited UAVs in our paper.

The main contributions of this paper are summarised as follows:

1. We investigate overlaying U2D communications for energy-limited UAVs, and design a joint sensing and transmission protocol to schedule UAV sensing and transmission.

2. We formulate the EU maximisation problem by jointly optimising UAVs’ trajectory, speed, and transmit power, and propose a joint trajectory, speed, and transmit power optimisation algorithm to obtain the suboptimal solution of this problem.

3. Simulation results show that our proposed scheme outperforms the uniform acceleration (UA) scheme, the fixed sensing location (FSL) scheme, and the sequential convex optimisation (SCO) scheme, and the gap between our proposed scheme and the simulated optimal scheme is less than 3%.

The rest of this paper is organised as follows. In Section 2, we describe the system model for the cellular Internet of UAVs. In Section 3, we design a joint sensing and transmission protocol to schedule UAV sensing and transmission. In Section 4, we formulate the EU maximisation problem by optimising UAVs’ trajectory, speed, and transmit power jointly, and decompose the problem into three subproblems. Then, we elaborate on the algorithm for solving this problem in Section 5. We introduce the performance analysis in Section 6. Simulation results are presented in Section 7. Finally, we conclude the paper in Section 8.

## 2 | SYSTEM MODEL

As shown in Figure 1, we consider an orthogonal frequency division multiple access (OFDMA) cellular Internet of UAVs, which consists of one BS and $(M + N)$ UAVs. Each UAV first senses its targets, and then transmits the collected sensory data to the BS or its corresponding MD for further processing. Specifically, the system contains $M$ UAVs transmitting the sensory data to the BS, denoted by $\mathcal{M} = \{1, 2, \ldots, M\}$, and $N$ UAVs transmitting the data to their MDs, denoted by $\mathcal{N} = \{M + 1, M + 2, \ldots, M + N\}$. To support their
data transmissions, we assume that there exist two transmission modes:

- **U2N mode**: The UAV transmits its sensory data to the BS through cellular link.
- **U2D mode**: The UAV transmits its sensory data to the corresponding MD directly.

To avoid mutual interference among UAVs in these two transmission modes and ensure the QoS, we assume that the U2D mode works as an overlay to the U2N mode, i.e. the UAVs in these two modes utilise the spectrum resource exclusively. Thus, we divide the spectrum resource in the system into \((M + N)\) orthogonal subchannels to support the OFDMA transmissions of the UAVs. Before the data transmission of each UAV, the BS allocates one available subchannel to it.

In the system, there are \(Q\) targets need to be sensed, denoted by \(Q = \{1, 2, \ldots, Q\}\), and \(Q > M + N\). The sensing targets of each UAV are pre-determined, and we denote the set of sensing targets for UAV \(i\) by \(Q_i\), with \(\bigcup_{i=1}^{M+N} Q_i = Q\) and \(Q_i \cap Q_j = \emptyset, \forall i, j \in M \cup N, i \neq j\). Each UAV should execute its sensing tasks sequentially.

Without loss of generality, we characterise the locations of the BS, UAVs, targets, and MDs by 3D Cartesian coordinates. Specifically, the location of the BS is denoted by \(x_0 = (0, 0, 0)\), with \(H_0\) being its height. The location of UAV \(i\) is denoted by \(x_i = (x_i, y_i, h_i)\). Target \(j\) is located at \(x_{ij}^j = (x_{ij}^j, y_{ij}^j, 0)\). Moreover, the location of MD \(k\) is denoted by \(x_k^D = (x_k^D, y_k^D, 0)\), in which MD \(k\) is the corresponding MD of UAV \(k\), \(\forall k \in N\). Here, we ignore the movements of the MDs, since they are trivial compared with that of the UAVs.

In what follows, we present the models for UAV sensing and transmission, respectively.

### 2.1 UAV sensing

This paper adopts the sensing model in [24] to evaluate the sensing quality of onboard sensors, in which the sensing range of an onboard sensor can be characterised by a cone. To be specific, UAV \(i\) can successfully sense target \(j\) if its sensing range covers the whole circular area with centre \(x_{ij}^j\) and radius \(r\), i.e. the following formula holds:

\[
\sqrt{(x_i - x_{ij}^j)^2 + (y_i - y_{ij}^j)^2} \leq h_i \tan \theta - r,
\]

where \(\theta\) is the maximum sensing angle of the onboard sensor. In addition, we adopt the sensing rate, denoted by \(R_s\), to evaluate the average size of the sensory data collected in unit time.

### 2.2 UAV transmission

As UAVs fly at high altitude, the air-to-ground channels usually contain line-of-sight (LoS) components, whose channel characteristic differs greatly from the terrestrial channels [25–27]. This paper utilises the air-to-ground channel model in [7] for both U2N and U2D transmissions.

#### 2.2.1 U2N mode

Since each UAV can be assigned with a dedicated subchannel, there is no mutual interference among UAVs in the U2N mode. Denote the transmit power of UAV \(i\) as \(p_i^T\). Then, the received signal-to-noise ratio (SNR) at the BS can be expressed as

\[
\gamma_i(x_i, x_0) = \frac{p_i^T 10^{-d_{RN}/10} \zeta_i}{N_\circ},
\]

where \(N_\circ\) denotes the noise power, \(d_{RN}\) is the air-to-ground path loss, and \(\zeta_i\) is the small-scale fading coefficient.

To calculate \(d_{RN}\) and \(\zeta_i\), we consider both the case where LoS component exists and the case where none LoS (NLoS) component exists. To be specific, the probability of the LoS case can be calculated as

\[
P_{LoS,i} = \begin{cases} 1, & p_1 \geq 1, \\ p_1 + e^{-d_i 10^{-x_i^2}} (1-p_1), & p_1 < 1, \end{cases} \]

where \(p_0 = 233.98 \log_{10}(h_i) - 0.95\), \(d_i = \max\{294.05 \log_{10}(h_i) - 432.94, 18\}\), \(p_1 = 10^{-d_i/10}\), and \(d_i = \sqrt{x_i^2 + y_i^2}\). Furthermore, the probability of the NLoS case is given by \(P_{NLoS,i} = 1 - P_{LoS,i}\).

In the LoS case, the path loss from UAV \(i\) to the BS can be calculated by \(P_{LoS,i}[dB] = 30.9 + (22.25 - 0.5 \log_{10}(h_i)) \times \log_{10}(d_{RB}) + 20 \log_{10}(f_i)\), in which \(d_{RB} = \|x_i - x_0\|_2\) is the distance between UAV \(i\) and the BS, and \(f_i[GHz]\) is the carrier frequency. In this case, the small-scale fading \(\zeta_i\) follows Rice distribution with the scale parameter \(\Omega = 1\) and the shape parameter \(K_i[dB] = 5.787 + 4.217 \log_{10}(h_i)\). On the other hand, in the NLoS case, the path loss from UAV \(i\) to the BS can be given by \(P_{NLoS,i}[dB] = 32.4 + (43.2 - 7.6 \log_{10}(h_i)) \times \log_{10}(d_{RB}) + 20 \log_{10}(f_i)\), and the small-scale fading \(\zeta_i\) follows Rayleigh distribution with the scale parameter \(\sigma = 1\).

Based on the SNR, we can express the data rate in the U2N transmission of UAV \(i\) as

\[
r_i^N = \log_2(1 + \gamma_i(x_i, x_0)).
\]

Considering the QoS requirement, the data rate of UAV \(i\) should be no less than the sensing rate, i.e. \(r_i^N \geq R_s\). Otherwise, the transmission is regarded as failed, and we define \(r_i^N = 0\). We assume that the channel state information (CSI) is unknown, as the highly dynamic channels makes it difficult to perform channel estimation. Thus, we calculate the expected data rate rather than the instantaneous rate. We can calculate the expected data rate of UAV \(i\), defined as \(R_i^N = \mathbb{E}(r_i^N)\), as follow.
Proposition 1. The expected data rate of UAV $i$ in the U2N mode is given by

$$R_i^N = \int_0^{+\infty} r \times \left( P_{IaS_i} \times f_{IaS_i}R_i^N (r) + P_{ILaS_i} \times f_{ILaS_i}R_i^N (r) \right) \times u(r - R_i) dr,$$

(5)

with \( f_{IaS_i}R_i^N (x) = \frac{2\ln 2}{A^2} (K_i + 1) \times (2^x - 1) \times \exp(-\frac{K_i+1}{A^2} (2^x - 1)^2 - K_i \frac{2\ln 2}{A^2} (2^x - 1)^2 - x) \)

1) \( 2^x \times \exp(-\frac{K_i+1}{A^2} (2^x - 1)^2 - K_i \frac{2\ln 2}{A^2} (2^x - 1)^2 - x) \)

1) \( f_{ILaS_i}R_i^N (x) = \frac{\ln 2}{A^2} (2^x - 1) \times \exp(-\frac{2\ln 2}{A^2} (2^x - 1)^2 - x) \)

1) \( A_{ILaS_i} = \frac{P_{IaS_i} R_{IaS_i}}{N_0}, \quad A_{ILaS_i} = \frac{P_{IaS_i} R_{IaS_i}}{N_0}, \quad \text{and} \quad n(x) \text{ is the unit step function.} \)

Proof. See Appendix A.1. \( \square \)

2.2.2 U2D mode

Due to the overlay property, the UAV in the U2D mode is not interfered by other UAVs. The received SNR at MD $i$ can be expressed as \( \gamma_i(x, x^D) \), where \( \gamma_i(x) \) is given in (2). Then, the data rate in the U2D transmission of UAV $i$ is given by

$$R_i^D = \log_2(1 + \gamma_i(x, x^D)).$$

(6)

Likewise, the data rate of the U2D communication link should be no less than the sensing rate, i.e. \( R_i^D \geq R_s \). Otherwise, the transmission is failed. Therefore, the expected data rate, defined as \( R_i^D = E[R_i^D] \), can be calculated as follow.

Proposition 2. The expected data rate of UAV $i$ in the U2D mode is given by

$$R_i^D = \int_0^{+\infty} r \times \left( P_{IaS_i} \times f_{IaS_i}R_i^D (r) + P_{ILaS_i} \times f_{ILaS_i}R_i^D (r) \right) \times u(r - R_i) dr,$$

(7)

where \( f_{IaS_i}R_i^D (x) \) and \( f_{ILaS_i}R_i^D (x) \) can be obtained by the similar method in Proposition 1.

3 Joint Sensing and Transmission Protocol

In this section, we design a joint sensing and transmission protocol to schedule UAV sensing and transmission in the cellular Internet of UAVs. We define the time unit in the system as time slot [28]. As illustrated in Figure 2, the UAVs conduct sensing and transmission in a sequence of time slots. For each UAV, its time slots can be classified into three types: empty time slot, sensing time slot, and transmission time slot. We define an indicator \( \xi_i(t) \) to characterise time slot $t$ for UAV $i$, whose values are \( \xi_i(t) = 0, 1, 2 \) if the UAV is in the empty time slot, sensing time slot, and transmission time slot, respectively. At the beginning of each time slot, the UAV sends a beacon to the BS over the control channel [21], which contains its current location and time slot indicator. By this means, the BS can obtain the full knowledge of the UAVs in the system, and optimise the trajectory, speed, and transmit power for these UAVs.

In what follows, we elaborate on these three types of time slots.

3.1 Empty time slot

In empty time slot, each UAV moves towards a sensing point to collect the sensory data for its current task. During this flight, the UAV performs neither sensing nor transmission. According to the information in the UAV beacon, the BS optimises the trajectory and speed for the UAV, and sends the results back to the UAV over the control channel. Afterwards, the UAV moves towards its sensing point along the designed trajectory with the determined speed. Furthermore, the power consumption of a UAV in empty time slot is only for propulsion. According to [29], the propulsion power of UAV $i$ in time slot $t$ can be calculated as

$$P_{i,prop}^t = \mu_1 \|v_i(t)\|^3 + \frac{\mu_2}{\|v_i(t)\|} \times \left( 1 + \frac{\|a_i(t)\|^2}{g^2} \right),$$

(8)

where \( \mu_1 = 9.26 \times 10^{-4}, \mu_2 = 2250, \) and \( g = 9.8. \) Besides, \( v_i(t) = (v_i^x(t), v_i^y(t), v_i^z(t)) \) is the velocity of UAV $i$, and \( a_i(t) = (a_i^x(t), a_i^y(t), a_i^z(t)) \) is its acceleration, with \( v_i(t) = x_i(t) - x_i(t - 1) \) and \( a_i(t) = v_i(t) - v_i(t - 1). \) Moreover, the speed of UAV $i$ is the magnitude of its velocity, i.e. \( v_i(t) = \|v_i(t)\| \).

3.2 Sensing time slot

After arriving at the sensing point, the UAV switches to a sensing time slot. In sensing time slot, the UAV hovers on the
sensing point and continuously senses its target with the sensing rate \( R_i \). To guarantee the sensing quality, the sensing process is required to last for \( T_0 \) time slots. Besides, in every sensing time slot, each UAV consumes its power for both hovering and sensing, which are fixed on \( p^{fh} \) and \( p^s \), respectively.

### 3.3 Transmission time slot

As the sensing process is finished, the UAV remains at the sensing point and transmits the collected sensory data to the BS or its corresponding MD. The reason lies in that, in practice, the UAV will spend more time and power if it moves to another location for data transmission [30, 31]. The BS optimises the transmit power for the UAV according to the information in UAV beacon, and sends the result back to the UAV over the control channel. As such, the UAV transmits the collected sensory data with the optimised transmit power. For the sake of QoS, the transmission process should also last for \( T_0 \) time slots. Moreover, in transmission time slot, UAV \( i \) consumes its power for hovering as well as transmission. The hovering power \( p^{fh} \) is constant, while the transmit power \( p^t_i(t) \) is variable with time slot \( t \).

After the UAV completes the data transmission for the current task, it will immediately start to execute the next sensing task. Each UAV should repeat the aforementioned procedure until all its tasks are completed.

### 4 PROBLEM FORMULATION AND DECOMPOSITION

In this section, we investigate the EU maximisation problem in the system. Since this problem is quite complicated, we further decompose it into three subproblems.

#### 4.1 Problem formulation

We define the EU in the system as the sum data rate of all the UAVs with unit power consumption. For simplicity, we assume that all UAVs start to perform tasks synchronously. Denote the time slot that UAV \( i \) completes all its tasks by \( T_i \). Then, the total power consumption of UAV \( i \) is given by

\[
p_i = \sum_{\xi_i(t)=0}^{T_i} p_i^{ph}(t) + \sum_{\xi_i(t)=1}^{T_i} (p^{fh} + p^s) + \sum_{\xi_i(t)=2}^{T_i} (p^{fh} + p^t_i(t)).
\]

(9)

As such, the EU in the system can be expressed as

\[
EU = \frac{\sum_{i=1}^{T_i} R_i^N(t) + \sum_{i=1}^{T_i} R_i^D(t)}{\sum_{i=1}^{\sum_i}} p_i.
\]

(10)

The aim of this paper is to maximise the EU in the system by jointly optimising the trajectory, speed, and transmit power of the UAVs. Let \( x'_j \) be the sensing point where UAV \( i \) senses its \( j \)th target, and \( \tau'_j \) be the time slot that UAV \( i \) starts to sense its \( j \)th target. Then, the EU maximisation problem can be formulated as

\[
\begin{align*}
\max_{\{x'_j, \tau'_j, 0 \leq b_j(t) \leq b_{max}, \forall i \in M \cup N, \ v_i \leq v_{max}, \ \forall i \in M \cup N, \ \|a_i(t)\| \leq a_{max}, \ \forall i \in M \cup N, \ \tau'_j + 2T_i - 1, \ \sum_{i=\tau'_j}^{\tau'_j+2T_i-1} v_i(t) = 0, \ \forall i \in M \cup N, j \in Q, \ \ p^t_i(t) \leq p_{max}, \ \forall i \in M \cup N. \end{align*}
\]

Constraints (11b), (11c), and (11d) are the flying altitude, speed, and acceleration constraints for each UAV due to space and mechanical limitations, respectively. Constraint (11e) implies that a UAV’s speed is zero when performing sensing and transmission. Constraint (11f) is the transmit power constraint for each UAV.

#### 4.2 Problem decomposition

Since objective function (11a) is non-convex with respect to \( p^t_i(t) \), problem (11) is a non-convex optimisation problem which is difficult to be solved. Therefore, we further decompose it into three subproblems: trajectory optimisation subproblem, speed optimisation subproblem, and transmit power optimisation subproblem.

1. **Trajectory optimisation subproblem**: According to Section 3, each UAV’s hovering power and sensing power are constant. Therefore, for any given transmit power, we can maximise the EU in the system by minimising the propulsion power consumption of UAVs. Moreover, the propulsion power consumption is influenced by UAVs’ trajectories. Since their trajectories are independent with each other, we can design them in parallel. Specifically, the trajectory optimisation subproblem for UAV \( i \) can be expressed as

\[
\begin{align*}
\min_{\{x'_j\}} \sum_{i=1}^{T_i} p_i^{ph}(t) \quad \text{s.t.} \quad b_{min} \leq b_i(t) \leq b_{max}, \ \forall i \in M \cup N. \quad (12a)
\end{align*}
\]


(2) Speed optimisation subproblem: Given the trajectory of a UAV, we can optimise its speed between two successive tasks independently to minimise the propulsion power consumption. To be specific, the speed optimisation subproblem for UAV \( i \) between its \( j \)th and \((j + 1)\)th task can be given by

\[
\min_{\left\{ v_i(t) \right\}} \sum_{t = t_i^j + 2 \Delta t}^{t_{i+1}^j - 1} p_{i}^\text{prop}(t) \\
\text{s.t.} \quad v_i(t) \leq v_{\text{max}}, \quad \forall i \in \mathcal{M} \cup \mathcal{N},
\]

\[
\|a_i(t)\| \leq a_{\text{max}}, \quad \forall i \in \mathcal{M} \cup \mathcal{N},
\]

\[
\tau_i^{j+2 \Delta t} - 1 \sum_{t = \tau_i^j}^{\tau_i^{j+1} - 1} v_i(t) = 0, \quad \forall i \in \mathcal{M} \cup \mathcal{N}, \quad j \in \mathcal{Q}.
\]

(3) Transmit power optimisation subproblem: Given the trajectory and speed of a UAV, the propulsion power consumption is determined, and thus, we can maximise the EU by optimising the transmit power. Since different UAVs’ transmit power are independent with each other, the maximum EU in the system can be achieved when the EU of each UAV is maximised. The transmit power optimisation subproblem for UAV \( i \) is given by

\[
\max_{\left\{ p_i^T(\cdot) \right\}} EU_i \\
\text{s.t.} \quad p_i^T(t) \leq p_{\text{max}}, \quad \forall i \in \mathcal{M} \cup \mathcal{N}.
\]

5 | JOINT TRAJECTORY, SPEED, AND TRANSMIT POWER OPTIMISATION ALGORITHM DESIGN

In this section, we propose a joint trajectory, speed, and transmit power optimisation algorithm to obtain the suboptimal solution of problem (11), in which subproblems (12)–(14) are solved sequentially. In what follows, we elaborate on the algorithms to solve these subproblems.

5.1 | Trajectory optimisation algorithm

Since the propulsion power consumption of a UAV increases monotonously with the length of its trajectory, we aim to minimise the total length of the UAV’s trajectory when it completes all of its sensing tasks. Specifically, when UAV \( i \) moves from sensing point \( x_i^j \) to the next sensing point \( x_i^{j+1} \), the shortest trajectory is the line segment between \( x_i^j \) and \( x_i^{j+1} \). As such, the UAV’s optimal trajectory can be determined by its optimal sensing points. Therefore, the trajectory optimisation problem is equivalent to finding a set of sensing points to minimise the length of the trajectory.

Denote the set of all available sensing points for UAV \( i \) sensing its \( j \)th target by \( S_j^i \). According to (1), \( S_j^i \) is a conical area which can be depicted as

\[
\sqrt{(x - x_j^{i})^2 + (y - y_j^{i})^2} \leq (h - r \cot \theta) \times \tan \theta.
\]

As such, problem (12) can be converted into the following problem:

\[
\min_{\left\{ x_j^i \right\}_{j=1}^{Q_i}} \sum_{j=1}^{Q_i} \| x_j^i - x_j^{i-1} \|_2 \\
\text{s.t.} \quad \forall x_j^i \in S_j^i,
\]

where \( x_0^i \) is the initial location of UAV \( i \). Since objective function (16a) and constraint (16b) are convex, problem (16) is a convex optimisation problem. Therefore, we can efficiently solve it by standard convex optimisation techniques, e.g. CVX [32, 33].

5.2 | Speed optimisation algorithm

From constraint (13d), a UAV’s speed is zero when performing sensing and transmission, i.e. the initial and final speed of the UAV along the designed trajectory should both be zero. Therefore, the speed first increases and then decreases when the UAV moving between two sensing points. According to [11], the speed in the acceleration and deceleration processes are symmetric. Therefore, based on Equation (8), the propulsion power consumption in these two processes are equal. Furthermore, due to the symmetry, when the speed in the acceleration process is optimised, we can obtain the optimal speed in the deceleration process simultaneously.

Let \( l \) be the length of the optimised trajectory between \( x_j^i \) and \( x_j^{i+1} \), i.e. \( l = \| x_j^{i+1} - x_j^i \|_2 \), and \( d_i(t) \) be the distance that UAV \( i \) has moved before time slot \( t \). When \( d_i(t) < l/2 \), UAV \( i \) is in the acceleration process, and we optimise its speed in time slot \( t \) by a speed recursive function \( v_i(t) = f(v_i(t - 1)) \), where \( f(\cdot) \) is given in Appendix A.2. Then we update \( d_i(t) = d_i(t - 1) + v_i(t) \). When \( d_i(t) \geq l/2 \), the UAV is in the deceleration process, in which its speed is symmetric to that in the acceleration process.

5.3 | Transmit power optimisation algorithm

Since the U2D mode works as an overlay to the U2N mode, the UAVs in these two modes do not interfere with each other. Thus, we can optimise the transmit power for them separately.
### TABLE 1 Parameters for simulation

| Parameter                                      | Value |
|-----------------------------------------------|-------|
| Number of U2N mode UAVs $M$                     | 5     |
| Number of U2D mode UAVs $N$                     | 5     |
| Number of sensing targets $Q$                   | 40    |
| Maximum flying altitude of UAVs $h_{m_{\text{max}}}$ | 200 m |
| Minimum flying altitude of UAVs $h_{\text{min}}$  | 50 m  |
| Maximum acceleration of UAVs $a_{\text{max}}$    | 12 m/s² |
| Maximum transmit power of UAVs $p_{T_{\text{max}}}$ | 47 dBm |
| Maximum sensing angle of UAVs $\theta$          | 15°   |
| Radius of circular area $r$                     | 13 m  |
| Height of the BS $H$                            | 25 m  |
| Noise power $N_0$                               | $-96$ dBm |
| Carrier frequency $f_c$                         | 2 GHz |
| Sensing/Transmission duration $T_0$             | 10    |
| Hovering power $p_{\text{H}}$                   | 46 dBm |
| Sensing power $p_{\text{S}}$                    | 40 dBm |
| Length of each time slot $\delta$               | 1 s   |

### 5.3.1 U2N mode

Based on Equations (2), (4), and (5), the transmit power of UAV $i$ can be expressed as $p_i^T(t) = g_N(R_i^N(t))$, where $g_N(\cdot)$ is a monotonically increasing function. As such, given the expected data rate, we can find its corresponding transmit power exclusively. Therefore, optimising the transmit power is equivalent to optimising the data rate, and the transmit power optimisation subproblem (14) can be converted to

\[
\max_{\left\{R_i^N(t)\right\}} \sum_{j=1}^{T_i} R_i^N(t) \quad \text{s.t.} \quad p_i^T(t) \leq p_{\text{max}}, \quad \forall i \in \mathcal{M},
\]

(17a)

where

- $B_i = \sum_{t=1}^{T_i} p_i^{\text{pro}}(t) + \sum_{t=1, \xi_i(t) = 0}^{T_i} (p_i^{\text{H}} + p_i^S) + \sum_{t=1, \xi_i(t) \neq 0}^{T_i} p_i^{\text{H}}$. The optimal data rate $R_i^N(t)$ satisfies

\[
\frac{\partial E_{U_i}}{\partial R_i^N(t)} = 0, \quad \forall i \in \mathcal{M}, \quad \xi_i(t) = 2.
\]

According to [11], for any given sensing task, when the maximum EU of UAV $i$ is achieved, the UAV transmits its collected sensory data at a constant rate. Therefore, the optimal data rate will satisfy

\[
R_i^N\left(\tau_i^j + T_0\right) = \cdots = R_i^N\left(\tau_i^j + 2T_0 - 1\right), \quad \forall j \in \mathcal{Q}_i.
\]

(19)

Substituting (17a) and (19) into (18), we can then obtain the optimal data rate by solving the following equation:

\[
\frac{\partial g_N\left(R_i^N(t)\right)}{\partial R_i^N(t)} \times R_i^N(t) - g_N\left(R_i^N(t)\right) = \frac{B_i^j}{T_i^j},
\]

(20)

where

- $B_i^j = \sum_{t=\tau_i^j-1}^{\tau_i^j-2T_i^j} p_i^{\text{pro}}(t) + \sum_{t=\tau_i^j}^{\tau_i^j+T_0-1} p_i^S + \sum_{t=\tau_i^j}^{\tau_i^j+2T_0-1} p_i^{\text{H}}$. Given the UAV’s trajectory and speed, $B_i^j$ can be regarded as a constant, and thus, the right side of
ALGORITHM 1 The Procedure of the Joint Trajectory, Speed, and Transmit Power Optimisation Algorithm

Input: The locations of the BS, targets, and MDs; The initial locations of UAVs; The set of UAVs’ sensing targets \( Q_i, \forall i \in M \cup N \);

Output: The optimal trajectories, speeds, and transmit powers of UAVs;

1: for \( i = 1: (M + N) \) do
2: Solve subproblem (12) to obtain the optimal trajectory of UAV \( i \);
3: Given the optimal UAV trajectory, solve subproblem (13) to obtain the optimal speed of UAV \( i \);
4: Given the optimal UAV trajectory and speed, solve subproblem (14) to obtain the optimal transmit power of UAV \( i \);
5: end for

Equation (20) is a positive constant. Besides, the left side of (20) is a monotonically increasing unbounded function starting from the origin, which can be justified by simulation. Therefore, we can infer that Equation (20) has only one root, denoted by \( R_{i,opt}^N(t) \). Considering the transmit power constraint (17b), the optimal transmit power of UAV \( i \) can be given by

\[
p_{i,opt}^T(t) = \min_{gN} \{ R_{i,opt}^N(t), p_{max} \}. \tag{21}\]

5.3.2 U2D mode

Similarly, the optimal data rate of UAV \( i \) in the U2D mode, denoted by \( R_{i,opt}^D(t) \), can be obtained by solving the equation below

\[
\frac{\partial R_D(R_{i,opt}^D(t))}{\partial R_{i,opt}^D(t)} \times R_{i,opt}^D(t) - g_D(R_{i,opt}^D(t)) = \frac{B_i}{T_0}. \tag{21}\]

The optimal transmit power of UAV \( i \) can then be given by

\[
p_{i,opt}^T(t) = \min_{gD} \{ R_{i,opt}^D(t), p_{max} \}. \]

Based on the above analysis, we summarise the joint trajectory, speed, and transmit power optimisation algorithm in Algorithm 1.

6 PERFORMANCE ANALYSIS

In this section, we first present the computational complexity of our proposed algorithm, and then analyse the system performance.

6.1 Computational complexity

In our proposed algorithm, we jointly optimise the trajectory, speed, and transmit power of UAVs. Therefore, we can analyse the computational complexity of this algorithm by analysing those of solving the three optimisation subproblems. For each UAV, the computational complexities of the trajectory, speed, and transmit power optimisations are given as follows:

- The trajectory optimisation subproblem is a convex optimisation problem, which is solved via the standard interior-point method. Based on [34], we can express its computational complexity by \( O(\sqrt{2} |Q_i| \times 3 |Q_i| \times (|Q_i| + 9 |Q_i|^2)) = O(|Q_i|^{1.5}) \).
- The speed optimisation subproblem is solved by recursion method. When optimising the speed of a UAV between two successive tasks, we only need to optimise the speed in the first half of the trajectory. Denote the computational complexity of solving (29) as \( O(C_1) \), where \( C_1 \) is a constant. Then, the computational complexity for optimising the speed between two successive tasks can be given by \( O(\frac{T_0}{2v_{avg,i}^2} \times C_1) \), in which \( v_{avg,i}^2 \) is the average speed of the UAV. Therefore, the computational complexity of speed optimisation is \( O(C_2 \times |Q_i|) \).
- The transmit power optimisation subproblem is solved by finding the solutions of Equation (20) or (21). The computational complexity for solving them is denoted as \( O(C_2) \), where \( C_2 \) is a constant. Thus, the computational complexity for optimising the transmit power is \( O(C_2 \times |Q_i|) \).

In each iteration, these three optimisation subproblems are solved sequentially, and thus, the computational complexity of each iteration is \( O(|Q_i|^{1.5} + \frac{\sqrt{C_1} |Q_i| \times C_2 \times |Q_i|}{2v_{avg,i}^2} = O(|Q_i|^{1.5}) \). The number of iterations is equivalent to the number of UAVs \( (M + N) \). Therefore, the computational complexity of the proposed algorithm is \( O((M + N) \times |Q_i|^{1.5}) \).

6.2 System performance analysis

In this part, we discuss the trend of the EU with \( R_S \) and the major influence factor on the EU in different sensing rate systems.

For the case with low sensing rate, with the increase of \( R_S \), the optimal data rates of the UAVs increase, and then the EU in the system increases, i.e., \( |[\partial EU]/[\partial R_S]| > 0 \). Moreover, as \( R_S \) increases, the increase of the transmit power consumption of the UAVs gradually becomes significant, and thus, the increase of the EU slows down, i.e. we have \( |[\partial^2 EU]/[\partial R_S^2]| < 0 \). On this condition, since the power consumption of the UAVs is almost utilised for propulsion, the propulsion power consumption is the major influence factor on the EU in the system.

For the case with high sensing rate, with the increase of \( R_S \), the optimal transmit power increases significantly, which causes the EU to decrease sharply, i.e. \( |[\partial EU]/[\partial R_S]| < 0 \). Furthermore, considering the transmit power constraint \( p_{max} \), the data rate of the UAVs decreases dramatically with \( R_S \). Thus, the EU in the system decreases with \( R_S \), when it is at a high level, and the transmit power consumption is the major influence factor on the EU in the system.
7 SIMULATION RESULTS

In this section, we present the simulation results on our proposed algorithm. The simulation parameters are based on the existing technical report [7], which are listed in Table 1. In the simulation, we model the cell as a circular area with the BS at the centre and the radius as 1km. The targets and MDs are uniformly distributed on the ground within the cell. Besides, the initial locations of UAVs are uniformly distributed in the cylindrical area whose height is 200 m. Moreover, we assume that the number of sensing targets for different UAVs are identical.

Figure 3 shows the EU versus the sensing rate $R_1$ with the maximum speed of UAVs $v_{\text{max}} = 45$ m/s. Here, we compare our proposed scheme with the following three schemes:

- UA scheme [11]: The UAVs move with fixed acceleration $a_{\text{max}}$, while their trajectories and transmit powers are optimised through the method in [11].
- FSL scheme [15]: The UAVs perform sensing and transmission hovering over the corresponding targets with fixed altitude $H_{\text{FSL}} = 100$ m.
- SCO scheme [35]: The UAVs’ trajectories and speeds are optimised based on linear state–space approximation and SCO techniques.

The optimal scheme is also presented for comparison, in which the maximum EU is obtained by enumeration. For all the schemes, we can observe that the EU increases with $R_1$ when $R_1 \leq 12$ Mbps, since UAVs’ data rates increase. When $R_1 > 12$ Mbps, the EU decreases rapidly with $R_1$, as the transmit power consumption increases sharply with $R_1$. Besides, for each case, our proposed scheme outperforms the UA and FSL schemes, since the trajectory, speed, and transmit power of UAVs are jointly optimised in our scheme. The gap between our proposed scheme and the UA scheme gets smaller with sensing rate $R_1$. The reason lies in that the propulsion power consumption is a major influence factor on the EU for the case with low sensing rate, while the transmit power consumption has more significant impact on the EU for the case with high sensing rate. The simulation curves is consistent with the analysis given in Subsection 6.2. Our scheme also outperforms the SCO scheme. Moreover, for any value of $R_1$, the gap between our proposed scheme and the optimal value is less than 2%, which indicates the effectiveness of our proposed scheme.

Figure 4 illustrates the EU with different maximum speeds of UAVs $v_{\text{max}}$ where the sensing rate is $R_1 = 10$ Mbps. For our proposed scheme, the FSL scheme, the SCO scheme, and the optimal scheme, the EU increases significantly with $v_{\text{max}}$ when $v_{\text{max}} \leq 40$ m/s, since the speed constraint gets loose. The EU remains unchanged when $v_{\text{max}} > 40$ m/s, as the optimal speed of each UAV is below 40 m/s. Besides, the gap between our proposed scheme and the optimal one is less than 3%. In the UE scheme, the EU first increases and then decreases with $v_{\text{max}}$, where the turning point is $v_{\text{max}} = 45$ m/s. This is due to the lack of speed optimisation.

Figures 5(a) and 5(b) show the trajectories of UAV 1 in the U2N mode and UAV 6 in the U2D mode under our proposed scheme, respectively. The trajectory of UAV 1 is denoted by $\{x_{1}^{0}, x_{1}^{1}, x_{1}^{2}, x_{1}^{3}, x_{1}^{4}\}$, and that of UAV 6 is expressed by $\{x_{6}^{0}, x_{6}^{1}, x_{6}^{2}, x_{6}^{3}, x_{6}^{4}\}$. For the UAV in either mode, the projections of its sensing points are close to their corresponding targets, which guarantees the quality of sensing. Besides, we can observe that the UAVs’ flying altitude hardly changes as it performs sensing tasks. The reason lies in that the propulsion power consumption will increase sharply if the UAV changes its flying altitude frequently.

Figures 6(a) and 6(b) depict the speeds of UAV 1 in the U2N mode and UAV 6 in the U2D mode, respectively. For the UAV in either mode, when it performs a task, its speed...
FIGURE 6  Speeds of UAVs with $R_i = 10$ Mbps and $v_{\text{max}} = 45$ m/s. $t_1^i$, $t_2^i$, $t_3^i$, and $t_4^i$ are the time slots that UAV $i$ finishes its task 1, 2, 3, and 4, respectively, with $i \in \{1, 6\}$
(a) UAV 1 in the U2N mode.
(b) UAV 6 in the U2D mode.

First increases and then decreases with time, and the speed in the acceleration and deceleration processes are symmetric. Afterwards, the speed remains zero for $2T_0$ time slots, as the UAV hovers on the sensing point for sensing and transmission.

Figures 7(a) and 7(b) show the power consumptions of UAV 1 in the U2N mode and UAV 6 in the U2D mode, respectively. The propulsion power consumption is calculated based on Equation (8). As the speed of the UAV changes over time, the propulsion power consumption is also changed. The power consumption for hovering as well as sensing is constant. Besides, for a certain task, the transmit power consumption is constant, while for different sensing tasks, the transmit power consumptions are also different.

FIGURE 7  Power consumptions of UAVs with $R_i = 10$ Mbps and $v_{\text{max}} = 45$ m/s. $t_1^i$, $t_2^i$, $t_3^i$, and $t_4^i$ are the time slots that UAV $i$ finishes its task 1, 2, 3, and 4, respectively, with $i \in \{1, 6\}$
(a) UAV 1 in the U2N mode.
(b) UAV 6 in the U2D mode.

8  |  CONCLUSION

This paper studied a cellular Internet of UAVs where the U2D communications work as an overlay to the U2N communications. We have designed a joint sensing and transmission protocol to schedule UAV sensing and transmission, and formulated the EU maximisation problem by jointly optimising the trajectory, speed, and transmit power of UAVs in the system. To solve the non-convex problem, we have decoupled it into three subproblems: trajectory optimisation subproblem, speed optimisation subproblem, and transmit power optimisation subproblem, and proposed a joint trajectory, speed, and transmit power optimisation algorithm to obtain the suboptimal solution of this problem. Simulation
results have shown that our proposed algorithm outperforms the UA, FSL, and SCO schemes, and the performance gap between our proposed scheme and the optimal scheme is less than 3%.

REFERENCES

1. Wang, J., et al.: Taking drones to the next level: Cooperative distributed unmanned-aerial-vehicular networks for small and mini drones. IEEE Veh. Technol. Mag. 12(3), 73–82 (2017)
2. Mozaffari, M., et al.: A tutorial on UAVs for wireless networks: Applications, challenges, and open problems. IEEE Commun. Surv. Tutorials 21(3), 2334–2360 (2019)
3. Yang, Y., et al.: Real-time profiling of fine-grained air quality index distribution using UAV sensing. IEEE Internet Things J. 5(1), 186–198 (2018)
4. Aalsalam, B.H.Y., et al.: Autonomous UAV with vision based on-board decision making for remote sensing and precision agriculture. In: Proc. IEEE Aersop. Conf., Big Sky, MT, USA, pp. 1–12 (2017)
5. Kersnoeski, T., et al.: A UAV system for autonomous target detection and gas sensing. In: Proc. IEEE Aersop. Conf., Big Sky, MT, USA, pp. 1–12 (2017)
6. Zhang, H., et al.: Unmanned Aerial Vehicle Applications over Cellular Networks for 5G and Beyond. Springer, Switzerland (2020)
7. 3GPP TR 36.777: Enhanced LTE support for aerial vehicles. Release 15 (2017)
8. Motlagh, N.H., et al.: UAV-based IoT platform: A crowd surveillance use case. IEEE Commun. Mag. 55(2), 128–134 (2017)
9. Bergh, B.V.D., et al.: LTE in the sky: Trading off propagation benefits with interference costs for aerial nodes. IEEE Commun. Mag. 54(5), 44–50 (2016)
10. Hu, Z., et al.: UAV offloading: Spectrum trading contract design for UAV-assisted cellular networks. IEEE Trans. Wireless Commun. 17(9), 6093–6107 (2018)
11. Zhang, S., et al.: Joint trajectory and power optimization for UAV sensing over cellular networks. IEEE Commun. Lett. 22(11), 2382–2385 (2018)
12. Wu, F., et al.: Cellular UAV-to-device communications: Trajectory design and mode selection by multi-agent deep reinforcement learning. IEEE Trans. Wireless Commun. 16(11), 7574–7589 (2017)
13. Zhang, H., et al.: Cooperation techniques for a cellular internet of unmanned aerial vehicles. IEEE Wireless Commun. 26(5), 167–173 (2017)
14. Zhang, S., et al.: Cellular cooperative unmanned aerial vehicle networks with sense-and-send protocol. IEEE Internet Things J. 6(2), 1754–1767 (2019)
15. Mei, W., Zhang, R.: Uplink cooperative NOMA for cellular-connected UAV. IEEE J. Sel. Top. Signal Process. 13(3), 644–656 (2019)
16. Liu, L., et al.: Multi-beam UAV communication in cellular uplink: Cooperative interference cancellation and sum-rate maximization. IEEE Trans. Wireless Commun. 18(10), 4679–4691 (2019)
17. Hu, J., et al.: Reinforcement learning for decentralized trajectory design in cellular UAV networks with sense-and-send protocol. IEEE Internet Things J. 6(4), 6177–6189 (2019)
18. Zhang, S., et al.: Dual trajectory optimization for a cooperative Internet of UAVs. IEEE Commun. Lett. 23(6), 1093–1096 (2019)
19. Hellaoui, H., et al.: Aerial control system for spectrum efficiency in UAV-to-cellular communications. IEEE Commun. Mag. 56(10), 108–113 (2018)
20. Zhang, S., et al.: Cellular UAV-to-X communications: Design and optimization for multi-UAV networks. IEEE Trans. Wireless Commun. 18(2), 1346–1359 (2019)
21. Li, X., et al.: A near-optimal UAV-aided radio coverage strategy for dense urban areas. IEEE Trans. Veh. Technol. 68(9), 9098–9109 (2019)
22. Namvar, N., et al.: Heterogeneous UAV cells: An effective resource allocation scheme for maximum coverage performance. IEEE Access 7(1), 164708–164719 (2019)
23. Al-Hourani, A., et al.: Optimal LAP altitude for maximum coverage. IEEE Wireless Commun. Lett. 3(6), 569–572 (2014)
24. Chandrasekharan, S., et al.: Designing and implementing future aerial communication networks. IEEE Commun. Mag. 54(5), 26–34 (2016)
25. Matolak, D.W., Sun, R.: Air-ground channel characterization for unmanned aircraft system—part I: Methods, measurements, and models for over-water settings. IEEE Trans. Veh. Technol. 66(1), 26–44 (2017)
26. Al-Hourani, A., et al.: Modeling air-to-ground path loss for low altitude platforms in urban environments. In: Proc. IEEE GLOBECOM, Austin, TX, USA, pp. 2906–2904, (2014)
27. Chen, M., et al.: Caching in the sky: Proactive deployment of cache-enabled unmanned aerial vehicles for optimized quality-of-experience. IEEE J. Sel. Areas Commun. 35(5), 1046–1061 (2017)
28. Leishman, G.J.: Principles of Helicopter Aerodynamics, pp. 159–193.Cambridge University Press, UK (2006)
29. Da-Jiang Innovations Science and Technology Co., Ltd. (DJI): ‘Mavic air 2’ Basic helicopter performance. https://www.dji.com/cn/mavic-air-2, Accessed 12 June 2020
30. Say, S., et al.: A hybrid collision coordination-based multiple access scheme for super dense aerial sensor networks. In: Proc. IEEE Wireless Communications and Networking Conf. (WCNC), Doha, Qatar, pp. 1-6 (2016)
31. Boyd, S., Vandenberghe, L.: Convex Optimization. Cambridge University Press, UK (2004)
32. ‘CVX: MATLAB Software for Disciplined Convex Programming, Version 2.1’. http://cvxr.com/cvx/, Accessed 2 March 2019
33. Ben-Tal, A., Nemirovski, A.: Lectures on Modern Convex Optimization: Analysis, Algorithms, and Engineering Applications. SIAM (2001)
34. Zeng, Y., Zhang, R.: Energy-efficient UAV communication with trajectory optimization. IEEE Trans. Wireless Commun. 16(6), 3747–3760 (2017)
35. 3GPP TR 38.901: Study on channel model for frequencies from 0.5 to 100 GHz. Release 14 (2017)

APPENDIX A

A.1 | Proof of Proposition

According to [7] and [36], in the LoS case, the small-scale fading $\zeta_i$ obeys Rice distribution with the scale parameter $\Omega = 1$, whose probability density function (PDF) is

$$f_{\text{LoS}\zeta_i}(x) = 2(K_i + 1)x \times e^{(K_i + 1)x^2 - K_i} \times I_0\left(2\sqrt{K_i(K_i + 1)x}\right), \quad x \geq 0. \quad (A.1)$$

Here $I_0(\cdot)$ is the modified Bessel function of the first kind with order zero. Moreover, in the non-LoS (NLoS) case, the small-scale fading $\zeta_i$ follows Rayleigh distribution with the scale parameter $\sigma = 1$, whose PDF is given by

$$f_{\text{NLoS}\zeta_i}(x) = \sigma x e^{-x^2/\sigma^2}, \quad x \geq 0. \quad (A.2)$$

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Based on (2) and (4), the data rates in the LoS and the NLoS cases can be, respectively, expressed by
\[ r_{\text{LoS},i} = \log_2 (1 + A_{\text{LoS},i}) \] and \[ r_{\text{NLoS},i} = \log_2 (1 + A_{\text{NLoS},i}) \], with \( A_{\text{LoS},i} = \frac{p_T}{10} \cdot \frac{10^{-PL_{\text{LoS},i}}}{N_0} \) and \( A_{\text{NLoS},i} = \frac{p_T}{10} \cdot \frac{10^{-PL_{\text{NLoS},i}}}{N_0} \), whose PDFs are
\[ f_{r_{\text{LoS},i}}(r) = f_{r_{\text{NLoS},i}}(r) \times \frac{2r \ln 2}{A_{\text{LoS},i}}. \] (A.3)
\[ f_{r_{\text{NLoS},i}}(r) = f_{r_{\text{NLoS},i}}(r) \times \frac{2r \ln 2}{A_{\text{NLoS},i}}. \] (A.4)

Therefore, the PDF of the data rate is
\[ f_{r_i}(r) = P_{\text{LoS},i} f_{r_{\text{LoS},i}}(r) + P_{\text{NLoS},i} f_{r_{\text{NLoS},i}}(r). \] (A.5)

Considering the Quality of Service (QoS) requirement, the expected data rate is given by
\[ R_i = \int_0^{+\infty} r \times f_{r_i}(r) \times u(r-R_i) \, dr, \] (A.6)
in which \( u(\cdot) \) is the unit step function. Then, the proof ends.

**A.2 Speed recursive function derivation**

When unmanned aerial vehicle (UAV) \( i \) moves at the optimal speed, it can achieve the minimum propulsion energy consumption. Define the propulsion energy consumption for UAV \( i \) to move distance \( \Delta l \) as \( \Delta E_{\text{pro}}^i \). Then, we have
\[ \Delta E_{\text{pro}}^i = P_{\text{pro}}^i(t) \times \frac{\Delta l}{v_i(t)}. \] (A.7)

Thus, the optimal speed can be obtained when \( \frac{d\Delta E_{\text{pro}}}{dt} = 0 \).

Furthermore, since the UAV flies directly towards its sensing points, we have \( \|a_i(t)\| = v_i(t) - v_i(t-1) \). Substituting (8) and (28) into \( \frac{d\Delta E_{\text{pro}}}{dt} = 0 \), the optimal speed should satisfy the following recursive equation:
\[ \mu_1 g^2 v_i(t)^4 + \mu_2 v_i(t-1) v_i(t) - \mu_2 (g^2 + v_i(t-1)^2) = 0. \] (A.8)

Given \( v_i(t-1) \), Equation (29) has only one positive real root, which can be solved by the quartic equation root formula. Then, we can obtain the optimal speed \( v_{i}^{\text{opt}}(t) \) through recursion.

Considering constraints (13b) and (13c), the speed of UAV \( i \) in time slot \( t \) is set as
\[ v_i(t) = \begin{cases} v_{i}^{\text{opt}}(t), & \text{if } v_{i}^{\text{opt}}(t) \leq v_{i}^{\text{max}}(t) \leq v_{i}^{\text{max}}(t), \\ v_{i}^{\text{min}}(t), & \text{if } v_{i}^{\text{opt}}(t) < v_{i}^{\text{min}}(t), \\ v_{i}^{\text{max}}(t), & \text{otherwise}, \end{cases} \] (A.9)

where \( v_{i}^{\text{min}}(t) = v_i(t-1) - a_{\text{max}} \) and \( v_{i}^{\text{max}}(t) = \min\{v_i(t-1) + a_{\text{max}}, v_{i}^{\text{max}}(t)\} \).