Energy-Efficient Trajectory Optimization in UAV-Based Internet of Things (IoT) Network with Delay Tolerance

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Abstract. With high flexibility and the ability to achieve better wireless channels, the utilization of unmanned aerial vehicles (UAVs) in internet-of-things (IoT) network has gain great popularity. However, the limitation of the power supply and the movement of the UAV make it necessary to optimize the UAV's trajectory to maximize the ground coverage and prolong the communication duration. In this paper, we consider a scenario where the UAV flies in a circular trajectory in the air and equips the transceiver to collect the data with delay tolerance from a sets of the devices in a certain region. In this way, we formed a UAV-based IoT network. Our aim is to achieve the largest communication coverage by optimizing the altitude and radius of UAV's trajectory under the given transmitting power, so as to achieve the energy-efficient communication coverage. Besides, the situation that the directional antenna is also deployed on the UAV to improve the energy utilization. Then, we model the optimization problem as a joint 2-dimensional optimization problem and propose an exhaustive search (ES) over a 1-D parameter in a certain range. Numerical results are presented showing the optimal altitude and radius in the different cases and the antenna beam angles.

Keywords: Unmanned aerial vehicle · Internet-of-things · Energy-efficiency · Trajectory optimization · Coverage optimization

1 Introduction

With the high mobility and the lower cost compared with the manned aircraft, unmanned aerial vehicles (UAVs) have attracted a lot of attentions and found a wide range of applications during the past few decades [1]. Along with the

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maturity of the technology and the relevant regulations, a worldwide deployment of the UAVs is expected. A good example is that the UAVs can act as mobile aerial base stations (BSs) to provide the downlink and uplink communications for the ground users and boost the capacity of wireless networks [7]. Compared with the traditional network that largely dependent on the fixed infrastructure (BSs) and could be severally disrupted in the case of natural disasters such as floods or earthquakes [2], the UAV-based BSs are easily for deployment and can quickly provide the emergency communications in the disaster area.

One the other hand, Internet of Things (IoT) utilizes the intelligent interfaces to connect devices, vehicles, and other smart objects, in order to provide the smart environments. For some IoT devices, the information generated from them is not delay sensitive (such as temperature sensed by the sensor nodes), and it is not necessary to connect with UAV constantly. Under this delay tolerance network, the devices just communicate with the BS opportunistically.

Fortunately, the UAV provide the ideal platform for such application. Because of the movement of the UAVs, they can dynamically communicate with the target devices in the large area when necessary. However, the UAV's work performance is constrained due to the limited energy supply. In order to fully use the UAV's endurance, we hope that the UAV can work in an energy-efficient way and covers as many devices as possible. Therefore, we are expected to design an optimal trajectory to maximize the effective coverage area under the given UAV endurance.

Accordingly, in this letter, we consider a the delay tolerance IoT network where a UAV flies in a circular trajectory and collects the data from a sets of devices in a certain region (Fig. 1). Our aim is to achieve the largest effective coverage area by optimizing the flying altitude and radius of UAV's trajectory. Besides, the situation that the directional antenna is also deployed on the UAV to improve the energy utilization. Finally, we model the optimization problem as a joint 2-D optimization problem and propose an exhaustive search (ES) over a 1-D parameter in a certain range. Numerical results are presented to show the optimal height and radius in different cases.

For the related work, Zeng et al. [4] provided us an overview of UAV-assisted communications with emphasis on the use cases, network architecture, channel characteristics, and UAV design considerations. The work in [5] considered a scenario where an UAV collects information from a set of sensors located on a straight line and reformulated their design as a dynamic programming (DP) problem to minimize the aviation time of UAV for data collection. In [6], the total amount of data that can be transmitted from the UAV to the uses over the flying duration was formulated and calculated, considering the time-varying channel between UAV and users as LoS Link. The work in [3] took different QoS requirements into consideration and proposed a maximal weighted area (MWA) algorithm for UAV-BSs that maximized the number of covered users using the minimum transmit power. Yang et al. [9] considered the optimal path planning for UAV, which collect data over IoT sensor network. [10] proposed an approach to connect UAVs with IoT to stream sensor data to cloud services was presented, providing an efficient solution for data transmissions. Unlike our paper, these work above not considered the delay tolerance of the data and the effect of the directional antennas on the UAVs.

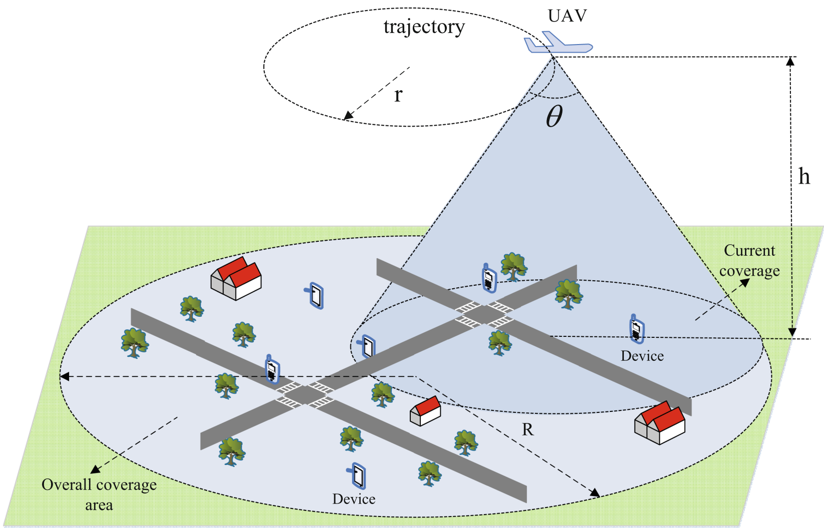

Fig. 1. System model. The UAV-based IoT network. h denotes the UAV flying altitude. θ shows antenna beam angle. R and r are the radius of the efficient overall coverage area and the UAV trajectory, correspondingly.

This work is organized as follows: In Sect. 2, the system model is presented, followed by the problem formulation in Sect. 3. Simulation and discuss are given in Sect. 4. Conclusions are drawn in Sect. 5.

2 System Model and Settings

Here we consider a scenario where a UAV flies in a circular path above the target region and serves as a data gateway over a set of the devices in IoT network. These devices distribute uniformly on the ground and they are expected to transmit the collecting information to the UAV in this system. Let μ denote the set of devices that need to transmit information to the UAV. Without loss of generality, a three-dimensional (3D) cartesian coordinate is considered and (x_i, y_i, z_i) denotes the location of device i in the set of μ. While for the UAV, since its flying trajectory is a circle and the location is time-varying, we denote $(r\cos\frac{v}{r}t, r\sin\frac{v}{r}t, h)$ as the 3D location of the UAV, where r, v and h represent the radius of trajectory, the UAV's speed, and UAV's flight altitude, respectively.

On the other hand, a directional antenna is equipped at the UAV and its beam angle is denoted by θ. According to the directional antenna property, the antenna gain will increase with the decrease of the antenna's beam angle [8]. The relationship between these two parameters can be approximately expressed as:

$$G_a(dBi) = 10Lg(9.7/(\theta_{E,3dB} \times \theta_{H,3dB})) \tag{1}$$

where $\theta_{E,3dB}$ and $\theta_{H,3dB}$ are the elevational angle and horizontal angle of the 3dB gain [11]. What's more, for easily calculation, we make the assumption that the devices can only get the reliable links with the UAV when they are inside the antenna's coverage.

According to the reference [12], the air-to-ground (A2G) links are either line-of-sight (LoS) or non line-of-sight (NLoS) with some probability. Note that in practice, epically for rural macro-cell (RMa) scenario, the UAV-ground channel is more likely to have the LoS link as compared to the terrestrial ground to ground channel. For simplicity, we assume that the communication link from each device to the UAV is dominated by the LoS channel. The extension to the non-LoS and multi-path channel will be discussed in the urban scenarios in our future work. In addition, for the lower flying speed of UAV, the Doppler shift caused by the mobility of the UAV is also ignored. Therefore, we can conclude that the time-varying channel follows the free-space path model, and the received signal power P_r can be expressed as:

$$P_r(t) = P_T \frac{G_a G_R (\frac{\lambda}{4\pi})^2}{d(t,i)} \tag{2}$$

where $d(t,i) = (r\cos\frac{v}{r}t - x_i)^2 + (r\sin\frac{v}{r}t - y_i)^2 + (h - z_i)^2$ denotes the transmitting distance between the UAV and device i at t time slot. G_R shows the device's antenna gain while G_a is the gain of the antenna equipped on the UAV. P_T is the transmitting power of the devices. Thus, the instantaneous channel capacity in bit/second can be expressed as:

$$R_i(t) = \begin{cases} B\log_2(1 + \frac{P_r(t)}{\sigma^2}) = B\log_2(1 + \frac{\gamma_0}{d(t,i)}) & 0 \le t \le \frac{\alpha r}{v} \\ 0 & \frac{\alpha r}{v} < t \le \frac{\pi r}{v} \end{cases} \tag{3}$$

where $\alpha_{\max} \in (0, \pi)$ is the angle between the line that connects the UAV and the center of its trajectory and the line parallel to the x coordinate in the trajectory. Thus, $\alpha = arctan(\frac{h}{x_i^2 + y_i^2})$. B denotes the channel bandwidth. $\sigma^2 = N_0 B$ is the white Gaussian noise power at the UAV receiver. γ_0 shows the reference received signal-to-noise ratio (SNR) at σ^2. According to the LoS channel property, the SNR will decline with the increase of the communication distance. In some cases, the SNR is too poor to support the data collection and the communication link is outage. Accordingly, in order to guarantee the quality of service (QoS), we set a power threshold P_{th} and the received power P_r must exceed the threshold for the successful transmission. Therefore, the distance between a device and the UAV cannot exceed a distance threshold according to Eq. (3), which is denoted by d_{th}. From the analysis above, we can model the total quantity of information bit uploaded to the UAV from each device as

$$Q_i^T = 2\int_0^T R_i(t)dt = 2\int_0^{\frac{r\alpha}{v}} R_i(t)dt \tag{4}$$

where T is the time period for one hover circle.

3 Problem Formulation and Proposed Solution

In this UAV-based IoT network, there are a set of devices uploading the collecting data to the UAV. However, the total amount of information collected by UAV from different devices is varied because of their different locations. For the movement of the UAV, some devices may be disconnected with UAV intermittently when they are moved out of the coverage of the antenna beam in UAV. To evaluate the effective connection for each device, we set a throughput threshold Q_{th} for the total amount of the transmission information in T, to determine whether the devices are in the UAV's effective coverage. Let $\varepsilon_i \in \{0, 1\}$ be a binary decision variable such that $\varepsilon_i = 1$ when the throughout of device i is more than Q_{th} and $\varepsilon_i = 0$ otherwise. This condition can be written as

$$Q_i^T = \int_0^{\frac{r\alpha}{v}} R(t)dt \geq Q_{th}\varepsilon_i \tag{5}$$

The optimization problem is then formulated as

$$\begin{aligned} &(h^*, r^*) = \arg\max_{h,r} \sum_{i\in\mu} \varepsilon_i \\ &\textit{subject to} \\ &Q_i^T \geq \varepsilon_i Q_{th}, \forall i \in \mu \\ &\varepsilon_i \in \{0, 1\}, \forall i \in \mu \\ &d(t, i) \geq d_{th}^2 \end{aligned} \tag{6}$$

In this network, since the UAV flies in a circular trajectory, the effective overall coverage area is also expected to be a circle. For the given flying altitude, when the radius of trajectory r is too large, the communication hole in which the devices can not connect to the UAV at any time will be formed in the center of the coverage area, causing the communication blind area in IoT network. When r is too small, the effective coverage area is also limited by the antenna beam. On the other hand, if we increase the flying altitude, the communication coverage will be enhanced obviously. However, for the given transmitting power, the higher altitude also causes the large path loss, leading to the lower received SNR and capacity. This phenomenon also restricts the coverage area. Therefore, there exists the optimal flying altitude and hovering circle under the constraint of the throughput in (6). As we can see that (6) is a joint 2-D optimization problem and difficult to solve. The difficulty arises from the coupling between the optimization of height and radius for the large quantity of devices.

Accordingly, we propose a solution to simplify this optimization problem. To find the largest coverage area, we only need to find the furthest device that can satisfy the required capacity. Here we utilize exhaustive search (ES) over the altitude and radius of trajectory respectively to find the furthest communication point from the region center. The distance between this point and the center of coverage is regarded as the radius of the largest coverage R. What's more, considering the symmetry of circular region, it is reasonable to just consider

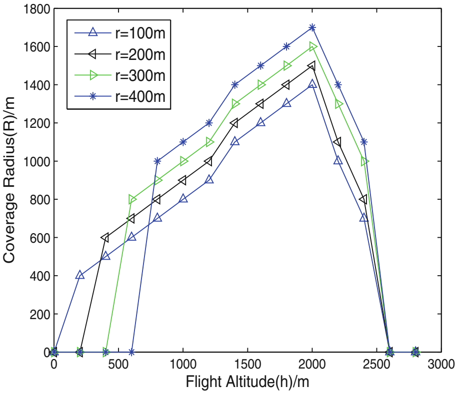

Fig. 2. Maximal coverage vs flight altitude

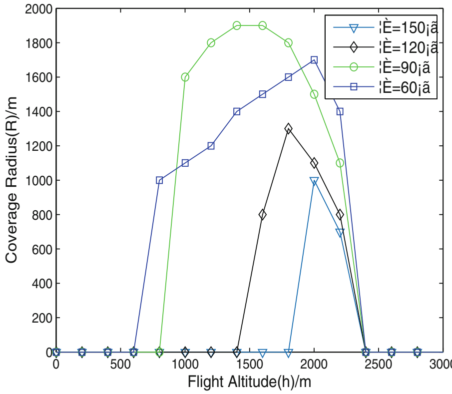

Fig. 3. The effect of beam angle

the device on the x-coordinate whose location is $(x_i, 0, 0)$ and only calculate the capacity when the UAV's location is $(r\cos(vt/r), r\sin(vt/r), h)$.

The process for implementing the ES is as follows:

(1) Initialize the distribution of a set of devices distributed on directivity of the x-coordinate, like $(x_i, 0, 0)$.
(2) Initialize the flight height h and the flight radius r.
(3) Calculate the total capacity (Q_i) of the device i using (5).
(4) Determine whether the device i is in the UAV's coverage by comparing the value of Q_i and Q_{th}.
(5) Update the location of the device until find the furthest device which satisfy the required QoS.
(6) Calculate the coverage radius by $R = x_i$.
7) Update the value of h or r and repeat (1) to (6).

4 Simulation Results and Discussions

In the simulation, we focus on the UAV's maximal coverage and discuss how the parameters affect the size of the coverage area. In the communication system, the communication bandwidth is $B = 1\,\text{Mhz}$ and the noise power spectrum density at the UAV receiver is assumed to be $N_0 = -160\,\text{dBm/hz}$. Therefore, the noise power $\sigma^2 = N_0 B = -100\,\text{dBm}$. The device's transmission power is $P = 0.1\,w(or{-}10\,\text{dB})$. We assume that the carrier frequency is $f_0 = 2.4\,\text{Ghz}$ and the wave length is $\lambda = c/f_0 = 0.125\,\text{m}$.

Figure 2 shows how the optimal coverage area changes with the flight altitude h when the trajectory radius $r = 100\,\text{m}$, $200\,\text{m}$, $300\,\text{m}$, $400\,\text{m}$ and $\theta = 60^\circ$ respectively. As we can see that the coverage radius R first increases with h gradually and then falls to 0 rapidly from the maximum value. This is because that the altitude of the UAV has a direct affect on the path loss. In the first

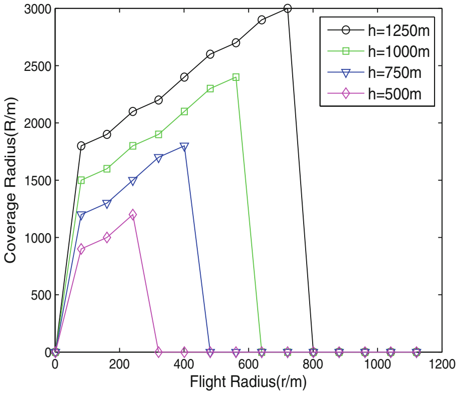

Fig. 4. Maximal coverage vs flight radius

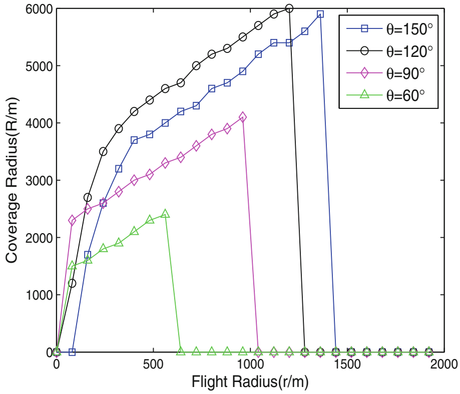

Fig. 5. The effect of beam angle

period, according to $R = h\cos(\frac{\pi-\theta}{2})$, R is in direct proportion to h. However, when the UAV flies too high, the path loss caused by the distance dominate the communication performance and few devices can connect to the UAV. As a result, the coverage will decline to 0 ultimately.

Figure 3 presents the effects of the beam angle when $r = 100\,\text{m}$. By comparing the maximum of different line for $\theta = 60^{\circ}, 90^{\circ}, 120^{\circ}, 150^{\circ}$, We can conclude that the optimal radius is the largest when $\theta = 60^{\circ}$ and there must be an optimal beam angle for a largest covered region. What's more, from the difference between the line for $r = 100\,\text{m}$, $\theta = 60^{\circ}$ in Fig. 2 and the line for $r = 100\,\text{m}$, $\theta = 90^{\circ}$ in Fig. 3, we can find that an optimal beam angle enables the UAV to achieve a bigger coverage with lower flight altitude, which matters a lot on UAV's energy efficiency.

Figure 4 depicts the relationship between the maximal coverage and the flight radius when the flight radius $h = 500\,\text{m}$, $750\,\text{m}$, $1000\,\text{m}$, $1500\,\text{m}$, $\theta = 60^{\circ}$ respectively. As shown in the figure, in a certain range, the increase of the radius can enlarge the coverage. However, there is a limitation for the increase of the flight radius, beyond which the coverage falls to 0. It is because the coverage in this paper is defines as the circular region that can be covered all the time, which is modeled by $(r\cos\alpha - x_0)^2 + (r\sin\alpha - y_0)^2 + (h - z_0)^2 \geq d_{th}^2$.

Figure 5 describes the how the beam able affects the coverage radius when $h = 1000\,\text{m}$, $\theta = 60^{\circ}, 90^{\circ}, 120^{\circ}, 150^{\circ}$. Just like what we do in analysing the beam angle's effects in Fig. 3, we find that there is also an optimal value for the angle. The optimal beam angle can also be determined by ES over a 1-D parameter.

5 Conclusion

In this paper, we consider the scenario that the UAV collect the delay tolerance data from the devices with different transmitting distance and then we formed a UAV-based IoT network. To evaluate the communications performance, we considered the ergodic capacity from UAV to the devices in each UAV flight cycle in order to find the largest coverage area. During the process, we modeled the relationship between the coverage area, the flight altitude, and the flight radius to find the optimal flying altitude and hover radius respectively. What's more, the effects of the directive antenna's beam angle are discussed and presented in the simulations.

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