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Joint UAV channel modeling and power control for 5G IoT networks

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Abstract

This paper studies the communication problem between UAVs and cellular base stations in a 5G IoT scenario where multiple UAVs work together. We are dedicated to the uplink channel modeling and the performance analysis of the uplink transmission. In the channel model, we consider the impact of 3D distance and multi-UAVs reflection on wireless signal propagation. The 3D distance is used to calculate the path loss, which can better reflect the actual path loss. The power control factor is used to adjust the UAV's uplink transmit power to compensate for different propagation path losses, so as to achieve precise power control. This paper proposes a binary exponential power control algorithm suitable for 5G networked UAV transmitters and presents the entire power control process including the open-loop phase and the closed-loop phase. The effects of power control factors on coverage probability, spectrum efficiency and energy efficiency under different 3D distances are simulated and analyzed. The results show that the optimal power control factor can be found from the point of view of energy efficiency.

Keywords: Unmanned aerial vehicle (UAV), Internet of Things (IoTs), Three-dimensional (3D) distance, Power control, Energy efficiency

1 Introduction

In recent years, with the penetration of new information technology and communication technology in mass production and living areas including natural disaster monitoring, search and rescue, agriculture and forestry protection, power line inspection, forest fire protection, etc., the demand for unmanned aerial vehicles (UAVs) has shown a rapid development trend. At the same time, due to the support of 5G cellular networks for vertical industries and the support of massive Internet-of-Things (IoTs) services, the integration of UAVs and 5G network has obtained great attention. The combination of UAVs and 5G is expected to create a lot of new applications and unprecedented business opportunities [1, 2].

In many IoT scenarios based on UAVs, multiple UAVs are usually required to work together, and different UAVs are equipped with different sensing and camera equipment to collect data, images and videos of the target area. For example, in forest firefighting application, multi-type (multi-rotor, composite wing) UAVs are used to carry professional firefighting equipment, cameras and infrared thermal imaging equipment to conduct real-time detection of forest fires. According to the returned data, AI algorithm is used to perform thermal analysis of images. The on-site video and analyzed fire situation maps are returned to the command center in real time to assist in command decision making.

Obviously, UAVs are used to implement new IoT services based on 5G having significant advantages, such as rapid and flexibility deployment, aerial line-of-sight (LoS) communication can achieve wider service coverage, and the UAV's procurement cost is gradually reduced. However, mobile cellular networks have been designed consistently to serve ground users. Ground UEs have the characteristics of easy charging, long standby time, low-to-medium-speed movement on the ground and complicated wireless propagation environments. There are many key differences between UAV and ground UE. For example, although the UAV and the ground BS are basically LoS communication links with fewer obstructions, since the BS antenna is usually tilted downward to cover the ground UE, the path loss becomes more serious as the UAV height increases. Moreover, unlike the ground UE, the airborne energy of the UAV is very limited, and the UAV needs to continuously fly in any direction in three-dimensional space (3D).

Therefore, the integration of UAV and 5G network still faces a series of problems that need to be resolved. The first is that networked UAVs that support 5G cellular network communication are not yet mature and costly. It is impossible to require all UAVs to support 5G communication in scenarios that require a large number of UAVs to work together. Secondly, UAV energy consumption directly affects the UAV's endurance time and ultimately determines whether UAV-based IoT services can be truly realized. Traditional IoT devices generally have low energy consumption, and standby time can be as long as several years. However, as a new type of IoT device, UAVs have very high energy consumption. On the one hand, due to the continuous increase of the UAV's payload weight, the mechanical energy consumption of the UAV itself is also getting higher and higher. Another important reason is that the 5G module integrated in the UAV needs to consume a large amount of communication energy when it communicates with the ground 5G base station. In addition, the UAV communication environment is very different from the ground communication environment. The wireless channel is dominated by LoS links, and direct propagation is the main mode of UAV wireless signals, which is completely different from the propagation mode of terrestrial communications, which is reflection. Moreover, UAVs can move at a faster speed in 3D space. These make the relevant 5G new radio interface technologies must have significant differences when the 5G base station communicates with the UAV (as the aerial UE) and the terrestrial UE, respectively.

In the UAV cellular network, 5G networked UAVs can work on low-altitude platforms (LAP) and high-altitude platforms (HAP). The UAV in the LAP communicates directly with the ground base station to realize a variety of UAV-based IoT services, which can be widely used in different applications in different fields and has a higher cost-effectiveness. The UAV in HAP can integrate 5G network and satellite communication to build an air–space–ground integrated network, forming a new IoT network integrating satellite, air and ground networks and realizing the vision of seamless global coverage of 6G network in the true sense [3–5].

Based on the aforementioned series of problems that need to be resolved when the UAV and 5G network are integrated, the research content of this paper mainly focuses on the two aspects. One is the wireless channel modeling between UAVs and 5G ground base stations, and the other is UAV's transmission power control when UAVs communicate with 5G ground base stations. Moreover, the characteristics of the wireless channel between UAV and 5G ground base station are an important basis for us to design the UAV power control mechanism.

The main work of this paper is as follows.

(1) We propose the uplink channel model, considering the impact of 3D distance and multi-UAVs reflection on wireless signal propagation.
(2) Based on proposed model, some power efficiency analyses are conducted, and a few interesting results are presented in the paper for gain deeper insights of UAV-BS uplink communications.
(3) An uplink power control mechanism is proposed for maximizing the energy efficiency of UAV-BS uplink communication.

The rest of this paper is organized as follows. The related works are introduced in section II. Section III studies the channel model and system model of communication between UAV and ground base station and gives the variation of uplink coverage probability and energy efficiency with UAV height and power control factor. Section IV presents the entire power control process including the open-loop phase and the closed-loop phase and proposes a binary exponential power control algorithm suitable for 5G networked UAV transmitters. Section V gives the simulation results, and the conclusion is given finally.

2 Previous works

From the current research results, there are mainly two modes of combining UAVs and 5G networks. One is to integrate miniaturized 5G base station modules in UAVs, which serve as aerial base stations to provide communication services for ground UEs. The other is to integrate 5G terminal modules in UAVs. As a new terminal type (aerial UE), UAVs communicate with 5G ground BSs. The first mode is mainly used for temporary coverage enhancement in hot spots, providing emergency 5G services in disaster areas or providing temporary relay services in remote areas that are not covered by 5G ground BSs. This combination model has attracted more attention from researchers and has obtained a large number of research results.

However, from the current and foreseeable future, in more scenarios, 5G networked UAVs are used as aerial end-users rather than as aerial BSs to achieve more and more vertical industry applications. As end-users of the 5G network, the aerial UE is inevitable to be different from the ground UE in many aspects, and these problems urgently need to be resolved in order to realize 5G vertical industry applications based on drones as soon as possible.

A tutorial overview of the recent development of UAV communications was introduced in [6], where the two possible framework forms, namely UAV-assisted cellular network communications and cellular network-connected UAV communications, were discussed, respectively. In addition to showing some recent representative research works, Zeng et al. [6] also discussed a series of problems faced by UAV communication and pointed out some promising directions, including UAV channel model and UAV energy consumption. Fotouhi et al. [7] conducted a more comprehensive investigation on the development of UAV communications. It first introduced the current types of UAVs, then analyzed the challenges and opportunities faced by UAV and cellular network integration communication and studied different ways to reduce UAV communication energy consumption. Finally, the security of UAV communication was discussed. The paper [8] is dedicated to solving the physical layer security problems faced by UAV communication. By jointly optimizing the UAV's movement trajectory and UAV transmission power, a favorable channel is established for the legal link, and a degraded channel is established for the eavesdropping channel, so as to maximize the average security rate. It can be seen that UAV power control is not only very important for UAV communication energy efficiency, but also very important for UAV communication security. For remote IoT applications, the resource allocation problem of air–space–ground IoT uplink communication assisted by UAV relay for the purpose of maximizing energy efficiency was studied in [9]. Aiming at a three-layer heterogeneous network composed of satellites, UAVs and terrestrial cells, a joint UAV hovering height and power control algorithm was proposed in [10] to solve the problem of cross-layer interference. [11] discussed IoT solutions that integrate UAVs and satellites into 5G to overcome the limitations of ground communication infrastructure and better meet the needs of future IoT applications. In order to maximize the transmission rate of UAV, the joint optimization of beamforming and power allocation was studied in [12].

3GPP explored the challenge of UAV as the aerial UE of mobile network in [13]. The results of this research show that due to the dominant LoS link, it will significantly increase the interference in the system, especially in the system composed of multiple UAVs, which will further lead to an increase in the energy consumption of UAV communication. Kandeepan et al. [14] explored the uplink energy problem of terrestrial cellular BS and single UAV communication. UAVs can communicate directly with BS, or they can establish connections with BS through other ground relay nodes to reduce the energy consumption of UAV. Lopez-Perez et al. [15] provide a comprehensive theoretical analysis of the expected performance of the UAV and cellular integrated network, but only the downlink command and control channel is concerned, without considering the performance of the uplink. The uplink performance of a heterogeneous network composed of abundant UAVs and ground BSs was studied in [16], and the conclusion was drawn that when the antenna height difference between UAV and BS is large enough, the effect of fractional power control factor on uplink performance is negligible.

3 System model

3.1 5G UAV IoT network with UAVs-aided

Since UAVs can carry a variety of IoT devices, perform flight missions at a certain height and have many excellent features such as wide coverage, flexible networking and fast mobility, UAVs are anticipated playing a significant role in the future 5G IoTs network. They can be widely used in agriculture, forestry and plant protection, smart cities, wildlife protection, earthquake and fire disaster relief, industrial IoT applications, etc. [17].

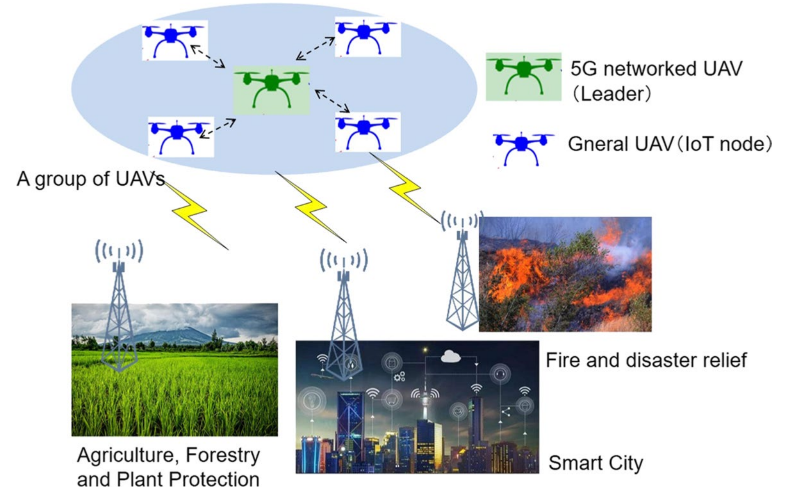

Fig. 1 The scenarios of 5G-enabled IoTs with UAVs-aided

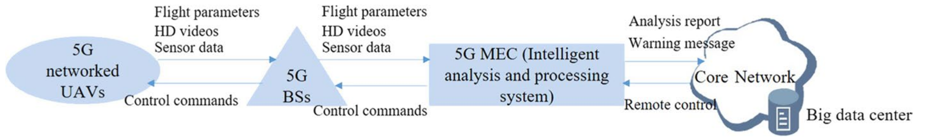

Fig. 2 The application deployment architecture of UAVs-aided 5G IoTs

These applications require multiple UAVs to form a UAV group to coordinate the completion of the scheduled flight tasks. Due to the cost of 5G connected UAVs and the shortage of 5G spectrum, we think it is impossible to require all UAVs to support directly communication with 5G network. In the scenario studied in this paper (shown in Fig. 1), at least one of the UAV group is a 5G connected UAV (called the leader), and the other UAVs only serve as IoT nodes. In addition to carrying IoT equipment, the leader UAV is also responsible for communication with the ground 5G network. Other UAVs transfer the collected IoTs information to the 5G network through the leader UAV.

In order to reduce the bandwidth pressure on the 5G network backhaul link and meet the needs of real-time analysis and decision making, UAV-assisted 5G IoT applications need to deploy intelligent analysis and processing systems on 5G edge servers (such as mobile edge computing). 5G MEC can help IoT applications filter useless or redundant information locally, use AI algorithms to intelligently analyze the received images and videos, make real-time decision making and processing and upload early warning and other information in time to enhance the system's efficiency. The applications deployment architecture of UAVs-aided 5G IoTs and message flow is shown in Fig. 2.

For example, in the application of fire disaster relief scenarios, multiple UAVs equipped with corresponding IoT devices such as infrared high-temperature detectors, smoke detectors and multi-spectral cameras patrol the fire area to collect various data such as the fire source, the area of the fire and the direction of the fire movement. The 5G networked UAV transmits these data to nearby 5G base stations and performs intelligent analysis and decision making in the MEC. Then, the decision-making results can be quickly transmitted to the UAV through control commands, so the UAV is scheduled to perform corresponding operations in time. MEC filtered images, videos and other information and analysis reports generated by AI are transmitted to the big data center of the core network through the 5G backbone network. The rear commanders can also issue remote control commands through the big data center to overall dispatch the front firefighting work.

3.2 Channel mode

Generally, the height of the transmitter and/or receiver in the UAV communication system is much higher than that of in the traditional ground communication system, and the working environment of the UAV communication system is also very different from the ground cellular communication. Therefore, although the existing channel model of the traditional cellular communication system can be used for UAV communication in principle, we still need to develop a specific channel mathematical model for UAV communication system in order to more accurately characterize the unique propagation of UAV communication surroundings. In most cases, the communication between the UAV and the ground base station usually occurs in the airspace. Therefore, we can study the channel characteristics of UAV-BS based on the traditional free space path loss model [18, 19].

The wireless channel propagation model is used to characterize the propagation characteristics of wireless signals between transmitters and receivers in different environments. When there is no obstacle between the transmitter and receiver, there is the line-of-sight transmission path between them. Free space refers to a space filled with a uniform ideal medium. In free space, radio waves propagating does not result in reflection, refraction, scattering and absorption loss, and there is no energy loss. However, when radio waves propagate in free space, their energy will diffuse into space, so the energy of radio waves received per unit area will decline. The longer the distance, the less energy received per unit area.

In order to accurately express the relative position of the UAV and the ground base station, we consider the two-dimensional angle of arrival from the base station to the UAV, which are the horizontal angle and the elevation angle, respectively. The two arrival angles are shown in Fig. 3. When UAV moves up and down in the sky, the height changes accordingly, which is called θ formed between UAV and BS; when the UAV height is constant and only moves left and right on the same horizontal plane, the angle changes accordingly, which is called ϕ.

Different UAV-assisted 5G IoT applications have different communication requirements. For instance, as shown in Table 1, relative to the uplink user data transmission, the UAV command and control data transmission rate requirements are lower, regardless of the downlink and uplink directions. However, compared with the vehicle network service, the reliability requirement of UAV communication (less than 10^{-3} PER, packet error rate) is lower, and the delay tolerance is higher (less than 50-ms delay).

Since the UAV cannot be completely static in the air, it is always hovering or flying, which makes it more difficult to model the wireless channel of UAV communication. When modeling the channel, both the Doppler effect of the UAV flying and the micro-Doppler effect of the UAV vibration should be taken into consideration. Moreover, in the scenario

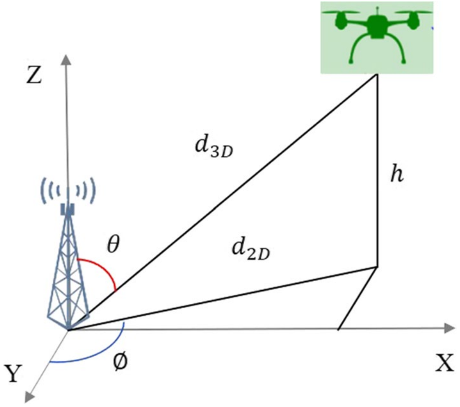

Fig. 3 The UAV-ground propagation path in open airspace

Table 1 The requirements for UAV communication [13]

	Information types	Transmission rate	Reliability	Latency
Downlink	Commands and control data	60–100 Kbps	10–3 PER	50 ms
Uplink	Commands and control data	60–100 Kbps	10–3 PER	–
	Application data	Up to 50 Mbps	–	Similar to ground user

of multi-UAVs communication, the reflection among UAVs must also be considered. The cruise path of the UAV can be a simple circle with a radius of [20].

$$R = \frac{V^2}{11.26 \times \tan(\theta)}, \tag{1}$$

where R is the radius in feet, V is the velocity in knot and θ is the bank angle. Therefore, a UAV (> 100 kg additional payload) should keep a cruising speed at 10 m/s (19.4 knots).

When UAV communicates to the ground base station, the beamforming of the base station should always be aimed at the aerial UAV, and the beam should be as narrow as possible to concentrate the signal energy and enhance the receiving power of the UAV. At the same time, the beam of the base station must be able to follow the movement of the UAV. However, due to the relatively fast UAV's flight speed and large communication delays, traditional DOA estimation methods cannot accurately estimate the current UAV's position in time, and more advanced UAV's position prediction technology is needed to solve this problem.

In order to model the wireless channel between UAV and base station, we consider the three-dimensional (3D) distance between the two, and the calculation method is as follows:

$$d_{\mathrm{3D}} = \sqrt{d_{\mathrm{2D}}^2 + h^2}, \tag{2}$$

where d_{2D} is the two-dimensional distance between the two and h is their relative altitude. It should be noted that the distance later in the paper refers to the 3D distance and is simply denoted by d.

Assuming that there is a Rician fading channel between the UAV and the base station, we can model the channel parameters as a function of the elevation angle θ (as shown in Fig. 3). θ can easily be calculated using h and d_{2D}. In [21], the Rician fading factor is modeled as a non-decreasing function of θ, and the path loss index is modeled as a non-increasing function of θ. This modeling method means that as θ increases (that is, the UAV flies higher or closer to the ground base station), line-of-sight path propagation will become more dominant.

For the frequency non-selective channel of baseband communication, the complex-valued channel coefficient of the wireless channel between the transmitter and the receiver can be expressed as [22, 23]

$$\tau = \sqrt{\beta(d)}\tilde{\tau}, \tag{3}$$

where $\beta(d)$ represents the large-scale path loss, $\tilde{\tau}$ is a complex random variable and generally $\mathrm{E}\left[|\tilde{\tau}|^2\right] = 1.\tilde{\tau}$ explains the small-scale fading owing to multipath propagation caused by other UAVs.

So, the uplink path loss is given

$$\zeta = \tau d^{\alpha}, \tag{4}$$

where the path loss exponent is denoted by α.

Even if the receiver as well as transmitter is at the same distance from each other, their path loss will be different due to possible environmental changes. (The previous free space loss model did not take this into account.) By modifying the path loss index that changes with the environment, a more general path loss model can be constructed [24, 25]. The log-distance path-loss (PL) model is a classical model for $\beta(d)$, where $\beta(d)[\mathrm{dB}] = -\mathrm{PL}_{\mathrm{LD}}(d)[\mathrm{dB}]$ with

$$\mathrm{PL}_{\mathrm{LD}}(d)[\mathrm{dB}] = \mathrm{PL}_{\mathrm{LD}}(d_0) + 10n\log\left(\frac{d}{d_0}\right), \tag{5}$$

where d_0 is the reference distance of the free space path loss (from the transmitter end to the receiver) and d is 3D distance in meters. In different propagation environments, d_0 must be accurately determined.

3.3 System model

On the basis of channel modeling and considering the UAV transmission power control, we give a system model and further study the coverage probability and energy efficiency of the system. In the UAV random access request phase, we use the open-loop power control similar to that in [26]. In the UAV data transmission stage, the UAV uses the slow power control command of the base station to adjust the transmission power. The whole power control procedure is introduced in Section IV. This part only studies the influence of path loss on UAV transmission power. Obviously, greater path loss requires more transmit power. In addition, assume that the UAV transmit power has an allowable maximum value $P_{\max}$. Therefore, the transmission power of the UAV is given as [27]

$$P^{U} = \min\left(P_0\zeta^{\epsilon}, P_{\max}\right), \tag{6}$$

where P_0 is the UAV specific reference transmit power, ϵ is the power control factor and ζ^{ϵ} reflects the compensation for the UAV transmission power caused by path loss and is an important manifestation of open-loop power control.

The signal-to-noise ratio (SNR) of the UAV uplink is

$$\mathrm{SNR} = \frac{p^{\mathcal{U}} \zeta^{-1} g}{N}, \tag{7}$$

where g is the Rayleigh fading and $g \sim \exp(1)$. ζ^{-1} represents the path loss gain, and N denotes the power of additive white Gaussian noise (AWGN) at the receiver.

The coverage probability $p_{\mathrm{c}}(\gamma)$ is defined as

$$p_{\mathrm{c}}(\gamma) = \Pr\left[\mathrm{SNR} > \gamma\right], \tag{8}$$

where γ is the SNR threshold. According to [28], compute the spectral efficiency (SE) as

$$\mathrm{SE}(\gamma_0) = \int_{\gamma_0}^{+\infty} \log_2(1+\gamma) f_{\mathrm{SNR}}(\gamma)\mathrm{d}\gamma, \tag{9}$$

where γ_0 is the minimal working SNR for correct demodulation by the receiver and $f_{\mathrm{SNR}}(\gamma)$ is the SNR's probability density function (PDF). Since $p_{\mathrm{c}}(\gamma)$ is the complementary cumulative distribution function (CCDF) of SNR, $f_{\mathrm{SNR}}(\gamma)$ can be expressed as

$$f_{\mathrm{SNR}}(\gamma) = \frac{\partial(1 - p_{\mathrm{c}}(\gamma))}{\partial \gamma}. \tag{10}$$

The communication energy efficiency (EE) is defined as

$$\mathrm{EE} = \frac{\mathrm{SE}(\gamma_0)}{p^{\mathcal{U}}}, \tag{11}$$

Here, the calculation of $p_{\mathrm{c}}(\gamma)$ and $\mathrm{SE}(\gamma_0)$ can refer to the derivation in our paper [28].

4 Method of UAV power control

In this section, we present the whole power control procedure of the UAV transmitter, including the open-loop stage and the closed-loop stage, as shown in Fig. 4.

(1) UAV transmits the first access detection signal with power P_0; at this time, $\epsilon = 0$.
(2) If the UAV does not receive the confirmation signal from the BS, it adjusts the power control factor, continuously increases the transmission power of the UAV and transmits subsequent access detection signals until the UAV receives the confirmation signal from the BS or the UAV transmission power reaches the maximum value $P_{\max}$.

In order to enable the UAV to access the 5G BS faster, we propose a binary exponential increase algorithm for the power control. Using this algorithm, a UAV transmits signals with a small power when it starts to try to access the channel, and the power increases relatively slowly to avoid a sudden increase to a large power. However, it allows the UAV to quickly increase to a large power after multiple failed attempts to reduce the access delay.

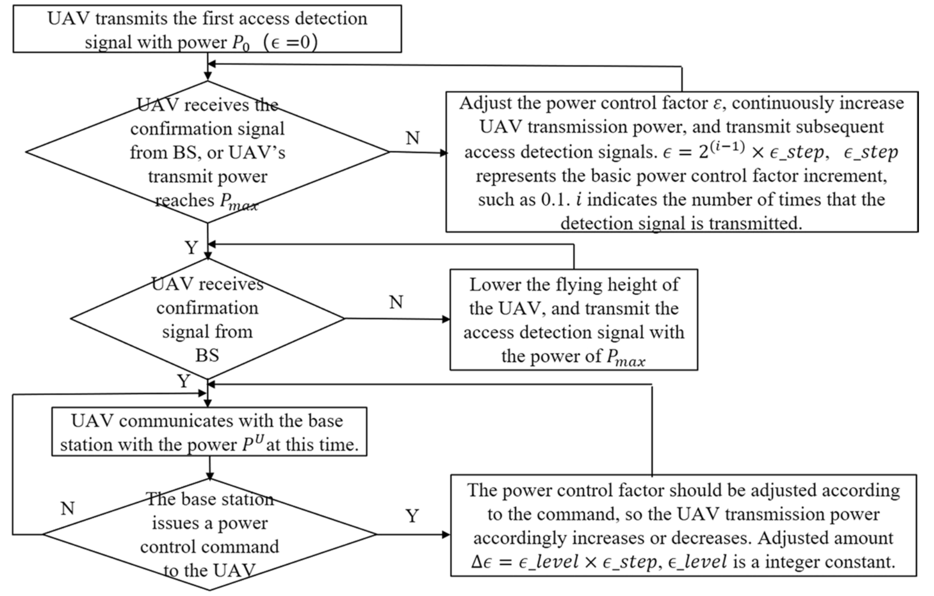

Fig.4 The whole power control procedure of the UAV transmitter

In general, when the access detection signal is transmitted for the ith time, the power control factor of the UAV transmitter is

$$\epsilon = 2^{(i-1)} \times \epsilon\_\text{step} \tag{12}$$

where ϵ_step represents the basic power control factor increment, such as 0.1.

For the robustness of the system, a maximum number of access attempts can be set. When the maximum number is reached, the UAV controller sends 5G access error messages to the UAV's own flight system. Further, error recovery is left to the high-level IoT application system.

(3) If the UAV does not receive the confirmation signal from the BS, and the UAV transmit power reaches the maximum value $P_{\max}$, the UAV's flying height is reduced, and the access detection signal is transmitted at the power of $P_{\max}$ until the UAV receives the confirmation signal from the BS.
(4) If the UAV receives the confirmation signal from the BS, the UAV communicates with the base station with the transmit power P^U at this time.
(5) In order to save communication overhead, the base station then performs a slow closed-loop power control and sends power control commands to the UAV. UAV adjusts the power control factor according to the instruction and increases or decreases the transmission power accordingly. The amount of change for each adjustment is

$$\Delta\epsilon = \epsilon\_\text{level} \times \epsilon\_\text{step}, \tag{13}$$

where ϵ_level is an integer constant.

5 Experimental simulation results and analysis

In this section, we consider multiple UAVs to form a UAV group. As an IoT terminal, the UAV collects various data and information in the target area through different sensors, cameras and other equipment carried. Since most UAVs currently do not have 5G networking capabilities, these ordinary UAVs communicate with ground cellular base stations through 5G UAVs (Leader UAV). The common UAV and Leader UAV communicate through the protocol between UAVs. Leader UAV communicates with cellular base stations through the 5G IoT protocol. The effects of power control on random flight coverage, spectrum efficiency and energy efficiency of pilotless UAV are studied. The simulation parameters are shown in Table 2.

5.1 Coverage probability

The power control factor (ϵ) adjusts the uplink transmit power of the leading UAV to compensate for different propagation path losses. The gain of the propagation of the conversion path ϵ also increases. When the ϵ reaches a certain value, the UAV achieves the maximum transmission power, and the signal is transmitted at P_{max}. When the ϵ is very small, because the transmit power is too small, and the SNR at the BS is too small, the coverage rate is close to 0. With the increase of ϵ, the coverage probability shows a rapid increase. When the UAV is flying closer to the base station, due to the smaller path loss, the probability of coverage can be obtained under the same ϵ. Moreover, when the UAV is operating at the maximum transmit power, the coverage probability becomes a constant. 3D distance is used to calculate the path loss, and the height of the dual UAV can better reflect the actual path loss, thereby achieving precise power control. The coverage probabilities of the power control factor ϵ for various distances d are plotted in Fig. 5. We can see that:

- Even for different d, the transformation trend of the coverage probability $p_{\text{c}}(\gamma)$ with factor ϵ is very similar. When ϵ is small, the SNR at the receiver is small due to the small UL transmit power, so that the receiver cannot demodulate the signal correctly. In this case, the value of $p_{\text{c}}(\gamma)$ is almost zero until ϵ reaches a certain threshold. With the increase of ϵ, the growth rate of $p_{\text{c}}(\gamma)$ accelerates, and there is almost a linear relationship between $p_{\text{c}}(\gamma)$ and ϵ. Within this range, ϵ has a good control effect on $p_{\text{c}}(\gamma)$. It can be seen that when ϵ is large enough, the UL actually transmits data with maximum power, so the coverage probability $p_{\text{c}}(\gamma)$ becomes a constant value.

Table 2 Simulation parameter setting

Parameters	Description
Leader UAV altitude	200–500 m
Leader UAV specific reference transmit power	− 76 dBm
Maximum transmit power of leader UAV	23 dBm
AWGN power at the BS	− 99 dBm
Path-loss exponent (α)	2.09
Channel propagation coefficient related to terrain features	$10^{10.38}$

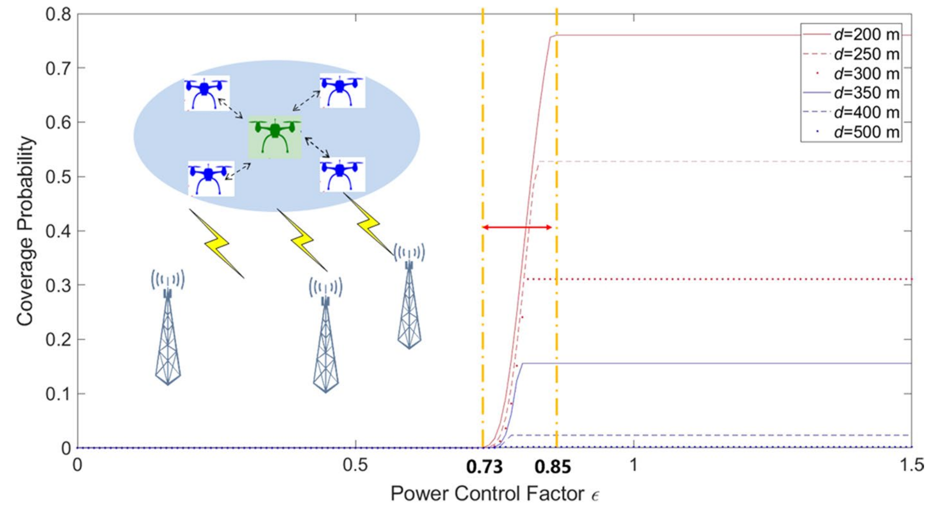

Fig. 5 Coverage probability versus power control factor ϵ

- For a specific ϵ, the smaller d, the larger the corresponding $p_c(\gamma)$, because the smaller d, the smaller the path loss ζ. Similarly, for a specific $p_c(\gamma)$, the smaller d corresponds to the smaller ϵ; this shows that the smaller d, the better the control effect of ϵ on $p_c(\gamma)$. The larger d, the smaller the effective control range of ϵ to $p_c(\gamma)$.
- When ϵ is in the range of 0.73 to 0.85, ϵ has the most obvious effect on $p_c(\gamma)$.

5.2 Spectral efficiency

Considering UAV communications system, the UL spectrum efficiency $\mathrm{SE}(\gamma_0)$ is drawn in Fig. 6. Since SE can be obtained through integration after the coverage difference, the SE and the coverage probability have the same changing trend. When the power control factor ϵ is adjusted to about 0.8, the SE reaches the maximum spectrum efficiency obtainable at various heights.

5.3 Communication energy efficiency

Starting from the UAV's initial reference transmit power, as the transmit power control factor increases, the SNR at the receiver increases accordingly, so the spectral efficiency increases approximately linearly. Since energy efficiency is defined as the ratio of spectral efficiency to transmit power, the trend of energy efficiency changes is basically the same as that of spectral efficiency. When the transmission power reaches the maximum transmission power of the UAV, although the power control factor increases, the UAV still maintains the maximum transmission power operation, and the spectral efficiency and energy efficiency are basically constant, rather than increasing. By adjusting the power control factor to an appropriate value, the optimal SE and EE can be obtained approximately simultaneously.

It can be seen in Fig. 7 that with the increase of ϵ, the energy efficiency has a similar development trend with $p_c(\gamma)$ and $\mathrm{SE}(\gamma_0)$. However, for different d, the value of energy efficiency is different. The greater the 3D distance between the UAV and the base station,

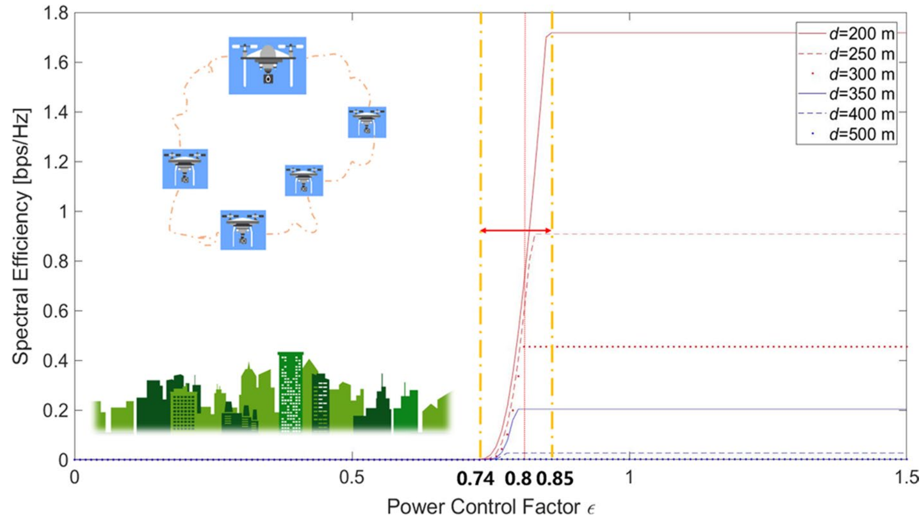

Fig. 6 Spectral efficiency versus ϵ

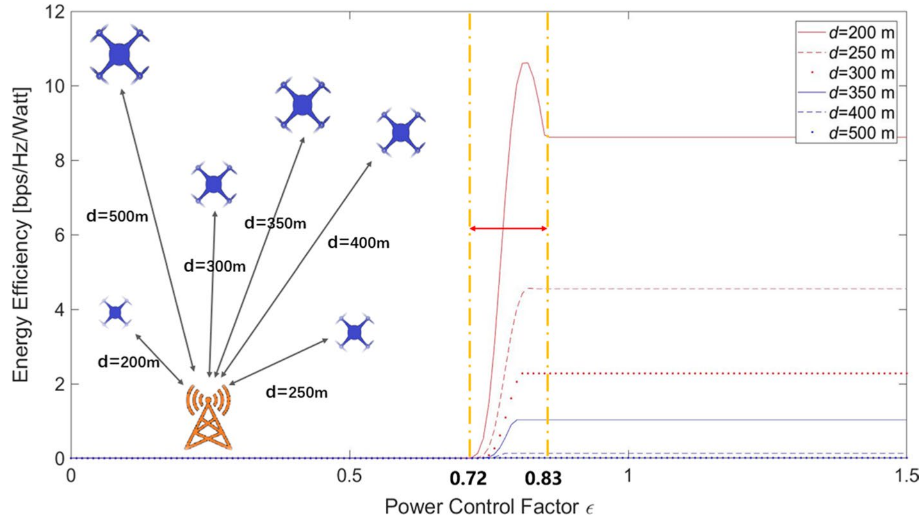

Fig. 7 Communication energy efficiency versus ϵ

the lower the energy efficiency. Moreover, for a relatively small d, for example, $d = 200$ m, the energy efficiency reaches the maximum of 10.898 bps/Hz/W when $\epsilon = 0.81$.

6 Conclusion

The integration of UAVs and 5G networks can realize a variety of promising IoT applications in the future. In these IoT applications, different drones can carry different IoT devices, such as various sensors and cameras. UAVs need to transmit all kinds of information, videos, images, etc. obtained by UAVs to the cellular network through the uplink from UAVs to ground cellular base stations. This poses a serious challenge on the UAV's communication capabilities and energy consumption. Based on the 5G IoT scenario, this article studies the uplink transmission in the case of multi-UAV coordination. Given the channel model considering the 3D distance and multi-UAVs reflection, the UAV's uplink power control is studied, and the power control factor is used to adjust the UAV's transmit power to compensate for the propagation path loss under different 3D distances from the UAV to the cellular base station.

Abbreviations

IoT: Internet of Things; UAV: Unmanned aerial vehicle; 3D: Three-dimensional; BS: Base station; LoS: Line of sight; LAP: Low-altitude platforms; HAP: High-altitude platforms; DL: Downlink; UL: Uplink; PL: Path loss; SNR: Signal-to-noise ratio; AWGN: Additive white Gaussian noise; SE: Spectral efficiency; PDF: Probability density function; EE: Energy efficiency; CCDF: Complementary cumulative distribution function.

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Authors' contributions

In this paper, XF conceived, designed and wrote the study. TD did the simulation work. All authors read and revised the manuscript.

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Availability of data and materials

The author keeps the analysis and simulation datasets, but the datasets are not public.

Declarations

Competing interests

The authors declare that they have no competing interests.

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