

Unmanned Aerial Vehicle-Based Hybrid Backscatter and Wireless Powered Communications: 3-D Trajectory Design and Resource Scheduling

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Abstract—This paper proposes a hybrid backscatter and wireless powered communications system based on unmanned aerial vehicle (UAV). UAV operates both as a source of radio frequency (RF) signals and an information collector. The system integrates passive information transmission (IT) via backscatter communication (BC) and active IT via wireless powered communication (WPC) to meet the requirements of low-power multi-function communication. At the same time, the system considers the LOS/NLOS channel at variable altitude. By jointly designing the 3D flight trajectory of UAV, the system time slot resources and the active transmit power of ground equipment can maximize the fair rate of ground equipment, and the system also considers various flight restrictions of UAV. Based on the block coordinate descent algorithm, this paper divides the original problem into several sub-problems and processes them separately, and finally obtains an approximate solution through joint iteration. The simulation results show that the hybrid backscatter and wireless powered communications system based on UAV proposed in this paper can significantly improve the fair rate of ground equipment compared with other benchmark schemes.

Index Terms—Backscatter communication (BC), wireless powered communication (WPC), unmanned aerial vehicle (UAV), trajectory design, resource scheduling.

I. INTRODUCTION

WITH the advent of the mobile Internet era, the smart sensor network industry has also ushered in its vigorous development. Large-scale Internet of Things applications need to consider the energy supply of its sensors, which will limited network lifetime. The emergence of wireless energy transmission technology has brought specific solutions to the above-mentioned problems [1]. As an energy technology that has received great attention in recent years, it can serve low-power terminals in the network and provide convenient and reliable energy supply, thereby ensuring the smooth entry of

the Internet of Things into the era of Internet of Everything in the future [2]. As one of the typical applications of wireless energy transmission technology, wireless power communication (WPC) has attracted the interest of many researchers recently. Ju and Zhang [3] proposed a well-known protocol for WPC, called the “Harvest-Then-Transmit (HTT)” protocol. HTT protocol supports active information transmission by devices, but it usually takes some time to collect energy, which will waste some time resources. The author also mentioned the “double long and short distance” problem, which causes users to have fairness problems in throughput performance. Furthermore, Ju and Zhang [4] also designed a user relay assistance protocol for two users. Moreover, in the network model in [5], the author proposed a protocol called Energy Synchronous Mobile Charging in the article, which can solve “double long and short distance” problem. In [6], the author proposed a harvest-then-cooperate mode, which can improve the throughput of IoT network. Furthermore, Kim and Kim [7] summarized WPC through a region-based approach. It should be noted that the HTT protocol has limitations when used on wireless devices far away from energy sources, especially when they send urgent data.

On the other hand, backscatter communication technology has also become a promising communication technology, which is not only energy-saving, but also economical and efficient, and is very suitable for large-scale low-cost IoT devices. Compared with HTT mode, backscatter communication technology consumes less energy and can transmit information in time, but the transmission range is small. Wang et al. [8] proposed dual-site backscatter, which solved the double path loss problem in the single-site backscatter communication link and improved the communication range. Furthermore, Choi and Kim [9] proposed a two-station backscatter network powered by radio frequency energy, and proved in the article that the network can increase the transmission range of WPC. Darsena et al. [10] modeled and analyzed a wireless network based on environmental backscatter, and the results showed that the system can achieve a satisfactory rate under a short communication distance. Moreover, Liu et al. [11] proposed a hardware prototype and theoretical operation principle for tag-to-tag communication, and proved that it can support up to 10kbps through the average ambient TV signal. Unfortunately, the transmission range is not far. In order to solve the limitation of transmission range, Parks et al. [12] designed a new receiver with multiple antennas and new coding technology.

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At the same time, reconfigurable intelligent surfaces (RIS) as an energy-efficient technology has attracted extensive research and discussion among scholars. The author [13] proposed a novel RIS architecture, which can get an improved performance in terms of the achievable rate compared to the conventional architecture. In [14], the author developed the channel estimator for active RIS-aided wireless communications. To increase the coverage of the system, simultaneous transmitting and reflecting reconfigurable intelligent surfaces (STAR-RIS) has been proposed. In [15], the achievable rate about STAR-RIS has been studied.

Considering the advantages and disadvantages of wireless powered communication and backscatter communication, the network system of hybrid wireless powered communication and backscatter communication is proposed [16]. In [17], the author introduced a backscatter assisted dual-hop wireless powered communication network (BADH-WPCN), which can achieve higher throughput. The author [18] introduced the hybrid relay communications, which allows each relay to switch between two radio modes, i.e., the active RF communications and the passive backscatter communications and verified that the hybrid relaying communications can achieve better communication performance. In [19], the author studied the problem of throughput fairness in wireless powered backscatter communications with HTT. In [20], the author studied the transmission scheduling for hybrid backscatter-HTT nodes. In [21], the author designed a new hybrid communication strategy to improve the throughput of the whole system, and its backscatter device can adaptively switch between backscatter mode, active IT mode and energy collection mode. Although the above works [16], [17], [18], [19], [20], [21] proved that hybrid communication has better communication performance, the energy transmitter in their model is fixed. When the channel between the RF signal transmitter and the energy collector is poor or the distance between them is long, the received signal strength will be too low, resulting in poor performance.

UAVs can be deployed flexibly and at low cost, and they can also obtain more reliable line-of-sight (LOS) transmission channel through their mobile characteristics [22], which can solve the above problem. In recent years, UAV-assisted wireless communication has aroused strong interest among researchers. In particular, three ways for UAVs to assist wireless communication were introduced in [23], including assisting in the sending and receiving of system data, cooperative relaying and expanding the coverage of system communication. In the research of UAV-assisted information collection and distribution, Mozaffari et al. [24] considered the two situations of static UAV and mobile UAV. Furthermore, Baek et al. [25] considered UAV-assisted wireless sensor network, and the energy-efficient UAV trajectory and its time slot scheduling factor were designed to maximize the minimum remaining energy between sensors after data transmission. Moreover, Wu et al. [26] studied maximizing the fair throughput of ground users in the presence of multiple users. In terms of the research content of UAV-assisted communication coverage, Alzenad et al. [27] optimized the two-dimensional position of the UAV and its flight height

to obtain the best placement position of the UAV, so that the UAV can cover more ground terminals. In the multi-UAV literature, Mozaffari et al. [28] used the theoretical knowledge of circular stacking to optimize the position of the multi-UAV to achieve greater coverage. Similarly, Mozaffari et al. [29] also studied the optimal deployment of multiple drones. In addition, UAVs can also be used to assist wireless powered communication network. Xu et al. [30] designed UAVs to provide energy transmission services for the Internet of Things terminals in the area. Furthermore, Xie et al. [31] studied an unmanned aerial vehicle (UAV)-enabled wireless powered communication network (WPCN). The system optimized the UAV's trajectory and the wireless resource allocation to maximize the system throughput. Moreover, Tang et al. [32] investigated joint unmanned aerial vehicle (UAV) trajectory planning and time resource allocation for minimum throughput maximization in a multiple UAV-enabled wireless powered communication network (WPCN). Furthermore, Miao et al. [33] investigated the effective deployment of millimeter wave (mmWave) in unmanned aerial vehicle (UAV)-enabled wireless powered communication network (WPCN).

Considering the advantages of UAV in all aspects, therefore, the UAV-enabled hybrid BackCom-HTT communication system is proposed [34]. In [34], the authors studied the problem about maximizing the Energy Efficiency (EE) of all the IoT nodes in the UAV-enabled hybrid BackCom-HTT system and pointed out that the optimized UAV-enabled hybrid backscatter-HTT communication can achieves a much higher EE of all the IoT nodes than other benchmark schemes.

In this paper, we propose a the hybrid backscatter and wireless powered communications system based on UAV. Compared with literature [16], [17], [18], [19], [20], [21], this paper introduces UAV to improve the channel conditions and shorten the communication distance. Different from the research in [34], we consider UAV as transmitter and receiver at the same time. Compared with the receiver fixed at a position, the receiver position of our system is more flexible. The system can improve the fairness of information rate of ground equipment and obtain greater throughput when the UAV is close to the ground equipment and this part of the throughput accounts for the majority of the total throughput. In addition, the active transmission mode considered in this paper also follows the HTT protocol, but the difference is that during the whole flight mission cycle, the ground multi-functional equipment can flexibly switch between wireless powered communication and backscatter communication modes according to its own power storage and the channel between UAV and multi-functional equipment, which can fully combine WPC mode and BC mode for higher performance compared with literature [34]. More importantly, this paper considers the more realistic LOS/NLOS channel with variable flight altitude and studies the 3D path design of UAV, which is often difficult to be optimized. This optimization can improve the performance of the system. Furthermore, this paper study the problem about maximizing the fair rate of ground equipment by jointly designing the 3D flight trajectory of UAV, the system time slot resources and the active transmit power of ground equipment.

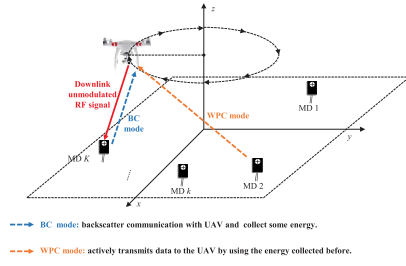


Fig. 1. The hybrid backscatter and wireless powered communications system.

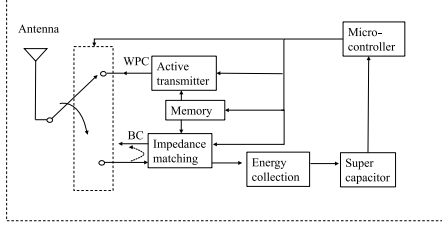


Fig. 2. The structural diagram of the ground multifunctional equipment.

Therefore, the main contributions of this article are summarized as follows:

- A hybrid backscatter and wireless powered communications system based on UAV is proposed where UAV operates both as a source of radio frequency (RF) signals and an information collector to improve the channel conditions and shorten the communication distance.
- A new communication mode of UAV integrating WPC and BC is proposed, in the whole flight cycle of the UAV, the ground multi-functional equipment can flexibly switch between wireless powered communication and backscatter communication modes according to its own power storage and the channel between UAV and multi-functional equipment for higher performance.
- In the hybrid backscatter and wireless powered communications system based on UAV, the LOS/NLOS channel model is considered according to the actual scenario, and the overall performance of the system is improved by optimizing the flying height of the UAV.
- By jointly designing the 3D flight trajectory of UAV, the system time slot resources and the active transmit power of ground equipment maximize the fair rate of ground equipment.

II. SYSTEM MODEL

A. Network Model

The system model is shown in Fig. 1, in which the UAV acts as a signal transmitter and a signal receiver to fly in a fixed area. The structural diagram of the ground multifunctional equipment is shown in Fig. 2. During the whole flight mission cycle, the ground equipment MDs can flexibly switch between wireless powered communication and backscatter communication modes [21]. Specifically, in the backscatter communication (BC) mode, the UAV flies over the area and downlink transmits unmodulated RF signals. On the one hand, the ground equipment modulate the data to the carrier signal

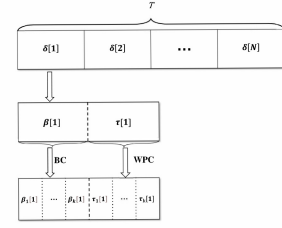


Fig. 3. Time slot diagram.

by adjusting the impedance and passively reflects it to the UAV. On the other hand, the ground equipment can also collect and convert the carrier signal into energy and store it in super capacitor. In the wireless powered communication (WPC) mode, the UAV stops transmitting signals to the ground equipment, and the ground equipment actively transmits data to the UAV by using the energy collected before.

As shown in Fig. 1, the two-dimensional position coordinates of MD are $\{\mathbf{b}_k \in \mathbb{R}^2 | k \in \{1, \dots, K\}\}$. Suppose that the 3D coordinates of UAV in the n th time slot are $(\mathbf{u}[n], h[n])$, where $\mathbf{u}[n]$ is the horizontal coordinate of UAV, specifically (u_x, u_y) , $h[n]$ is the flight altitude of UAV. Then in the n th slot, the distance between the UAV and the ground equipment can be expressed as $d_{uk}[n] = \sqrt{h^2[n] + q_{uk}[n]}$, where $q_{uk}[n] = \|\mathbf{b}_k - \mathbf{u}[n]\|^2$, $\|\cdot\|$ is used to represent the Euclidean distance between vectors. There is a speed limit for UAV, the maximum speed of UAV in two-dimensional plane direction and height direction is v_l and v_h respectively.

B. Physical Layer Model

Suppose that the flight cycle of the UAV is T . Considering that the UAV trajectory is continuous and involves infinite variables in solving the problem, the model is simplified and the UAV flight trajectory is discretized into N points. The flight cycle of UAV is discretized into N equal time slots, i.e., $\delta[n] = \frac{T}{N}, \forall n = 1, 2, \dots, N$, where $\delta[n]$ is each sub-slot. Assuming that the value of N is sufficiently large relative to the number of ground equipment, i.e., $N \gg K$, the UAV can be considered to remain stationary during a flight time slot [30]. During the whole flight mission cycle, the ground equipment MDs can flexibly switch between active communication and passive reflection communication modes according to the channel conditions and the power storage of ground equipment. In order to ensure the flexibility of ground equipment communication mode, in each time slot, the time slot is divided into two stages, BC stage and WPC stage. As shown in the time slot model diagram in Fig. 3, in order to ensure that each ground equipment has the opportunity to conduct backscatter communication and active transmission with the UAV in each time slot, the two stages in a time slot are divided into K sub time slots, $\beta_k[n]$ represents the time when MD k performs backscatter communication in the n th time slot and $\tau_k[n]$ the time when MD k conducts active transmission in the n th time slot. And the communication mode between ground equipment and UAV follows TDMA

transmission protocol. Meet $\sum_{k=1}^K \beta_k[n] + \sum_{k=1}^K \tau_k[n] = \frac{T}{N}, \forall n, 0 \leq \beta_k[n] \leq \beta[n], 0 \leq \tau_k[n] \leq \tau[n], \forall n, k$.

We use a 3D channel model as in [35], [36], [37]. Due to the influence of ground obstacles, the channel conditions of UAV and ground equipment will change with the change of their relative positions. Path loss is:

$$\Omega_{uk}[n] = \begin{cases} \Omega_{uk,LOS}[n] = \left(\frac{4\pi f_c d_{uk}[n]}{c}\right)^2 10^{\frac{\eta_{LOS}}{10}} \\ \Omega_{uk,NLOS}[n] = \left(\frac{4\pi f_c d_{uk}[n]}{c}\right)^2 10^{\frac{\eta_{NLOS}}{10}} \end{cases} \quad (1)$$

where f_c is the carrier frequency, η_{LOS} and η_{NLOS} are the additional loss of LOS and NLOS respectively. Channel between UAV and ground equipment is either line-of-sight (LOS) or non line-of-sight (NLOS) with some probability. And the LOS probability is given:

$$\varphi_{LOS} = \varphi_k[n] = \frac{1}{1 + ae^{-b\left(\frac{180}{\pi} \arctan\left(\frac{h[n]}{\sqrt{q_{uk}[n]}}\right) - a\right)}} \quad (2)$$

where a and b are constant values that depend on the environment.

III. PROBLEM FORMULATION

A. Backscatter Communication Mode

The transmitting power of UAV is P_t . Therefore, in the n th time slot, the signal power received by the ground equipment MD k is $P_{r1,k}[n] = \frac{P_t}{\Omega_{uk,LOS}[n]} \varphi_{LOS} + \frac{P_t}{\Omega_{uk,NLOS}[n]} (1 - \varphi_{LOS})$. Within a time slot, the channel between the ground equipment and the UAV remains unchanged. Therefore, the backscattered signal power received by the UAV is $P_{r2,k}[n] = \frac{P_t \Gamma_k}{\Omega_{uk,LOS}^2[n]} \varphi_{LOS} + \frac{P_t \Gamma_k}{\Omega_{uk,NLOS}^2[n]} (1 - \varphi_{LOS})$. Where $\Gamma_k \in [0, 1]$ is the reflection coefficient of ground equipment MD k . Therefore, the backscatter channel capacity of the device MD k in the n th slot can be expressed as:

$$C_{ku,bcs}[n] = \log_2 \left(1 + \frac{P_{r2,k}[n]}{\sigma_0^2} \right) \text{ [bps/Hz]}. \quad (3)$$

where σ_0^2 is the channel noise power, and the throughput of MD k in the backscatter communication phase can be expressed as:

$$R_{bcs,k} = \sum_{n=1}^N \beta_k[n] \log_2 \left(1 + \frac{P_{r2,k}[n]}{\sigma_0^2} \right) \quad (4)$$

B. Wireless Powered Communication Mode

When the device MD k is not awakened for communication, it can collect and convert the downlink RF signal transmitted by the UAV into energy. The duration of the device MD k not being awakened within a time slot is $\beta[n] - \beta_k[n]$. Therefore, this portion of energy can be expressed as: $E_1 = P_{r1,k} \eta (\beta[n] - \beta_k[n])$, where η is the energy conversion efficiency of the ground equipment circuit. In addition, in backscatter communication mode, the Γ_k portion of the power of the signal received by the device MD k is used for backscatter communication, and the $(1 - \Gamma_k)$ portion of the power can be converted into energy. Therefore, this portion of energy can be expressed as: $E_2 = P_{r1,k} \eta (1 - \Gamma_k) \beta_k[n]$.

Consequently, the energy collected by the ground equipment MD k in the n th time slot is:

$$\begin{aligned} E_k[n] &= E_1 + E_2 \\ &= P_{r1,k} \eta (\beta[n] - \Gamma_k \beta_k[n]) \end{aligned} \quad (5)$$

The ground equipment has certain initial energy E_0 . The ground equipment can use the energy collected in this part and certain initial energy for active data transmission. This paper does not consider the circuit loss in active information transmission and backscatter communication. Assume the signal power of active transmission of ground equipment MD k is $\{P_k[n] | n = 1, \dots, N, k = 1, \dots, K\}$, the signal power of active transmission received by UAV is: $P_{r3,k} = \frac{P_k[n]}{\Omega_{uk,LOS}[n]} \varphi_{LOS} + \frac{P_k[n]}{\Omega_{uk,NLOS}[n]} (1 - \varphi_{LOS})$. Therefore, the channel capacity of the active transmission of the MD k in the n th slot can be expressed as:

$$C_{ku,wpc}[n] = \log_2 \left(1 + \frac{P_{r3,k}[n]}{\sigma_0^2} \right) \text{ [bps/Hz]} \quad (6)$$

Therefore, in the whole cycle T , the average throughput of the MD k can be expressed as:

$$\begin{aligned} R_k &= \frac{1}{T} (R_{bcs,k} + R_{wpc,k}) \\ &= \frac{1}{T} \left(\sum_{n=1}^N \beta_k[n] \log_2 \left(1 + \frac{P_{r2,k}[n]}{\sigma_0^2} \right) + \sum_{n=1}^N \tau_k[n] \log_2 \left(1 + \frac{P_{r3,k}[n]}{\sigma_0^2} \right) \right) \end{aligned} \quad (7)$$

C. Uplink Fair-Throughput Maximisation

The joint design of the UAV's horizontal trajectory $\{\mathbf{u}[n] | n = 1, \dots, N\}$, the UAV's vertical height $\{h[n] | n = 1, \dots, N\}$, the ground equipment MDs' active transmit power $\{P_k[n] | n = 1, \dots, N, k = 1, \dots, K\}$ and the system time slot variables $\{\beta_k[n] | n = 1, \dots, N, k = 1, \dots, K\}$, $\{\tau_k[n] | n = 1, \dots, N, k = 1, \dots, K\}$ is formulated as

$$(P1): \max_{\{\mathbf{u}[n], h[n], \beta_k[n], \tau_k[n], P_k[n] \text{ for } \forall n, k\}} R_{\text{fair}} \quad (8)$$

$$\text{s. t. } R_{\text{fair}} \leq R_k = \frac{1}{T} \left(\sum_{n=1}^N \beta_k[n] \log_2 \left(1 + \frac{P_{r2,k}[n]}{\sigma_0^2} \right) + \sum_{n=1}^N \tau_k[n] \log_2 \left(1 + \frac{P_{r3,k}[n]}{\sigma_0^2} \right) \right), \forall k, \quad (8a)$$

$$\sum_{k=1}^K \beta_k[n] + \sum_{k=1}^K \tau_k[n] = \frac{T}{N}, \forall n, \quad (8b)$$

$$0 \leq \beta_k[n] \leq \frac{T}{N}, 0 \leq \tau_k[n] \leq \frac{T}{N}, \forall n, k, \quad (8c)$$

$$\|\mathbf{u}[n+1] - \mathbf{u}[n]\| \leq \frac{T}{N} v_l, n = 1, \dots, N-1, \quad (8d)$$

$$\|h[n+1] - h[n]\| \leq \frac{T}{N} v_h, n = 1, \dots, N-1, \quad (8e)$$

$$\mathbf{u}[1] = \mathbf{u}[N], \quad (8f)$$

$$h[1] = h[N], \quad (8g)$$

$$P_k[n]\tau_k[n] \leq E_0 + \sum_{i=1}^n E_k[i] - \sum_{i=1}^{n-1} P_k[i]\tau_k[i], \forall n, k, \quad (8h)$$

$$P_{\min} \leq P_k[n] \leq P_{\max}, \quad (8i)$$

The optimization problem aims at maximizing the fair rate of MDs on the ground, as shown in (8) and (8a). Among them, constraints (8b) and (8c) limit the value range of time slot resource variables. Constraint (8d) and (8e) respectively constrain the horizontal and vertical speed of the UAV. Constraint (8f) and (8g) shows that the UAV has to come back to its origin after completing the whole work. Constraint (8h) shows that the energy required for active transmission of each time slot of the ground equipment does not exceed the current energy. Constraint (8i) limit the value range of active transmit power of ground equipment.

IV. A BCD ALGORITHM AIDED JOINT DESIGN

For the problem (P1), it is a non convex problem due to the non convex nature of some constraints, so it can not be solved by the common convex optimization methods. Based on this, we propose an algorithm, based on block coordinate descent method, which divides the UAV's horizontal trajectory $\{\mathbf{u}[n]|n = 1, \dots, N\}$, the UAV's vertical height $\{h[n]|n = 1, \dots, N\}$, the ground equipment MDs' active transmit power $\{P_k[n]|n = 1, \dots, N, k = 1, \dots, K\}$ and the system slot variable $\{\beta[n]|n = 1, \dots, N\}$, $\{\tau[n]|n = 1, \dots, N\}$, $\{\beta_k[n]|n = 1, \dots, N, k = 1, \dots, K\}$, $\{\tau_k[n]|n = 1, \dots, N, k = 1, \dots, K\}$ into four sub problems for processing.

A. Time Slot Resource Optimization

By fixing $\{\mathbf{u}[n]|n = 1, \dots, N\}$, $\{P_k[n]|n = 1, \dots, N, k = 1, \dots, K\}$ and $\{h[n]|n = 1, \dots, N\}$, the following sub-problem (P2) optimises the time slot resource:

$$(P2): \max_{\{\beta_k[n], \tau_k[n], \text{for } \forall n, k\}} R_{\text{fair}} \quad (9)$$

$$\text{s.t. } R_{\text{fair}} \leq \sum_{n=1}^N \beta_k[n] A_k[n] + \sum_{n=1}^N \tau_k[n] B_k[n], \forall k, \quad (9a)$$

$$P_k[n]\tau_k[n] \leq E_0 + \sum_{i=1}^n \left(C_k[n] (\sum_{k=1}^K \beta_k[i] - \Gamma_k \beta_k[i]) \right) - \sum_{i=1}^{n-1} P_k[i]\tau_k[i], n = 1, \dots, N \quad (9b)$$

(8b), (8c).

where $A_k[n] = \log_2(1 + \frac{P_{r2,k}[n]}{\sigma_0^2})$, $B_k[n] = \log_2(1 + \frac{P_{r3,k}[n]}{\sigma_0^2})$ and $C_k[n] = P_{r1,k}[n]\eta$ are fixed values. It can be easily deduced that the problem is convex and can be solved by common convex optimization methods, such as interior point method.

B. Equipment Power Optimization

By fixing $\{\mathbf{u}[n]|n = 1, \dots, N\}$, $\{h[n]|n = 1, \dots, N\}$ and $\{\beta_k[n]|n = 1, \dots, N, k = 1, \dots, K\}$, $\{\tau_k[n]|n = 1, \dots, N, k = 1, \dots, K\}$, the following sub-problem (P3) optimises the time slot resource:

$$(P3): \max_{P_k[n], \text{for } \forall n, k} R_{\text{fair}} \quad (10)$$

$$\text{s.t. } R_{\text{fair}} \leq A_k[n] + \sum_{n=1}^N \tau_k[n] \log_2(1 + P_k[n] B_k[n]), \forall k, \quad (10a)$$

$$\sum_{i=1}^n P_k[i]\tau_k[i] \leq E_0 + \sum_{i=1}^n C_k[i], \forall n, k \quad (8i).$$

where $A_k[n] = \sum_{n=1}^N \beta_k[n] \log_2(1 + \frac{P_{r2,k}[n]}{\sigma_0^2})$, $B_k[n] = (\frac{1}{\Omega_{uk,LOS}[n]} \varphi_{LOS} + \frac{1}{\Omega_{uk,NLOS}[n]} (1 - \varphi_{LOS})) \frac{1}{\sigma_0^2}$ and $C_k[i] = P_{r1,k}[i]\eta(\beta[i] - \Gamma_k \beta_k[i])$ are fixed values. It can be easily deduced that the problem is convex and can be solved by common convex optimization methods, such as interior point method.

C. Horizontal Trajectory Optimization

By fixing the height of the UAV $\{h[n]|n = 1, \dots, N\}$, the system time slot variable $\{\beta_k[n]|n = 1, \dots, N, k = 1, \dots, K\}$, $\{\tau_k[n]|n = 1, \dots, N, k = 1, \dots, K\}$ and the ground equipment MDs' active transmit power $\{P_k[n]|n = 1, \dots, N, k = 1, \dots, K\}$, the following sub-problem (P4) optimises the horizontal trajectory:

$$(P4): \max_{\{\mathbf{u}[n], \text{for } \forall n\}} R_{\text{fair}} \quad (11)$$

$$\text{s.t. } R_{\text{fair}} \leq \sum_{n=1}^N \beta_k[n] \log_2 \left(1 + \frac{A_1}{d_{uk}^4[n]} (\varphi_k[n] B_1 + C_1) \right) + \sum_{n=1}^N \tau_k[n] \log_2 \left(1 + \frac{A_2}{d_{uk}^2[n]} (\varphi_k[n] B_2 + C_2) \right), \forall k, \quad (11a)$$

$$\sum_{i=1}^n P_k[i]\tau_k[i] \leq E_0 + \sum_{i=1}^n \frac{A_3}{d_{uk}^2[i]} (\varphi_k[i] B_2 + C_2) (\beta[i] - \Gamma_k \beta_k[i]), \forall n, k \quad (8d), (8f).$$

where $A_1 = \frac{P_t \Gamma_k}{\sigma_0^2 (\frac{4\pi f_c}{c})^4}$, $B_1 = 10^{-\frac{2\eta_{LOS}}{10}} - 10^{-\frac{2\eta_{NLOS}}{10}}$, $C_1 = 10^{-\frac{2\eta_{NLOS}}{10}}$ and $A_2 = \frac{P_k[n]}{\sigma_0^2 (\frac{4\pi f_c}{c})^2}$, $B_2 = 10^{-\frac{\eta_{LOS}}{10}} - 10^{-\frac{\eta_{NLOS}}{10}}$, $C_2 = 10^{-\frac{\eta_{NLOS}}{10}}$, $A_3 = \frac{P_t \Gamma_k}{(\frac{4\pi f_c}{c})^2}$ are constants. By observing this problem, it can be found that it is a nonconvex problem and it is difficult to solve.

Let $\zeta_k[n] = \log_2(1 + \frac{A_1}{d_{uk}^4[n]}(\varphi_k[n]B_1 + C_1))$, $\psi_k[n] = \log_2(1 + \frac{A_2}{d_{uk}^2[n]}(\varphi_k[n]B_2 + C_2))$, $\xi_k[n] = \frac{A_3}{d_{uk}^2[n]}(\varphi_k[n]B_2 + C_2)$. To solve this problem, first let $\nu_k[n] = d_{uk}^2[n]$ and $\eta_k[n] = 1 + ae^{-b\rho_k[n]}$. And introduce constraints:

$$\rho_k[n] \leq \frac{180}{\pi} \arctan\left(\frac{h[n]}{\sqrt{q_{uk}[n]}}\right) - a, \forall k \quad (12)$$

So $\zeta_k[n] = \log_2(1 + \frac{A_1}{v_k^2[n]}(\frac{1}{\eta_k[n]}B_1 + C_1))$, $\psi_k[n] = \log_2(1 + \frac{A_2}{v_k[n]}(\frac{1}{\eta_k[n]}B_2 + C_2))$, $\xi_k[n] = \frac{A_3}{v_k[n]}(\frac{1}{\eta_k[n]}B_2 + C_2)$.

After derivation, it can be known from the verification of Hessian matrix that the expression $\zeta_k[n]$, $\psi_k[n]$, $\xi_k[n]$ are convex functions with respect to $(\nu[n], \eta[n])$, the proof of convex function is in the Appendix. Let $f(v_k[n], \eta_k[n]) = \zeta_k[n]$, $g(v_k[n], \eta_k[n]) = \psi_k[n]$, $\omega(v_k[n], \eta_k[n]) = \xi_k[n]$. Let $f(\nu_k[n], \eta_k[n])$, $g(\nu_k[n], \eta_k[n])$, $\omega(\nu_k[n], \eta_k[n])$ perform a first-order Taylor expansion at $(\nu_{k,0}[n], \eta_{k,0}[n])$ as follows:

$$f^{(1)}(\nu_k[n], \eta_k[n]) = f(v_{k,0}[n], \eta_{k,0}[n]) + f_\nu(v_{k,0}[n], \eta_{k,0}[n]) (v_k[n] - v_{k,0}[n]) + f_\eta(v_{k,0}[n], \eta_{k,0}[n]) (\eta_k[n] - \eta_{k,0}[n]) \quad (13)$$

$$g^{(1)}(\nu_k[n], \eta_k[n]) = g(v_{k,0}[n], \eta_{k,0}[n]) + g_\nu(v_{k,0}[n], \eta_{k,0}[n]) (v_k[n] - v_{k,0}[n]) + g_\eta(v_{k,0}[n], \eta_{k,0}[n]) (\eta_k[n] - \eta_{k,0}[n]) \quad (14)$$

$$\omega^{(1)}(\nu_k[n], \eta_k[n]) = \omega(v_{k,0}[n], \eta_{k,0}[n]) + \omega_\nu(v_{k,0}[n], \eta_{k,0}[n]) (v_k[n] - v_{k,0}[n]) + \omega_\eta(v_{k,0}[n], \eta_{k,0}[n]) (\eta_k[n] - \eta_{k,0}[n]) \quad (15)$$

where

$$f_\nu(v_k[n], \eta_k[n]) = \frac{-\frac{2A_1}{v_k^3[n]}(\frac{B_1}{\eta_k[n]} + C_1)}{1 + \frac{A_1}{v_k^2[n]}(\frac{B_1}{\eta_k[n]} + C_1)} \cdot \frac{1}{\ln 2}$$

$$f_\eta(v_k[n], \eta_k[n]) = \frac{-\frac{A_1 B_1}{\eta_k^2[n] v_k^2[n]}}{1 + \frac{A_1}{v_k^2[n]}(\frac{B_1}{\eta_k[n]} + C_1)} \cdot \frac{1}{\ln 2}, \forall k \quad (16)$$

$$g_\nu(v_k[n], \eta_k[n]) = \frac{-\frac{A_2}{v_k^2[n]}(\frac{B_2}{\eta_k[n]} + C_2)}{1 + \frac{A_2}{v_k[n]}(\frac{B_2}{\eta_k[n]} + C_2)} \cdot \frac{1}{\ln 2},$$

$$g_\eta(v_k[n], \eta_k[n]) = \frac{-\frac{A_2 B_2}{\eta_k^2[n] v_k[n]}}{1 + \frac{A_2}{v_k[n]}(\frac{B_2}{\eta_k[n]} + C_2)} \cdot \frac{1}{\ln 2}, \forall k \quad (17)$$

$$\omega_\nu(v_k[n], \eta_k[n]) = -\frac{A_3}{v_k^2[n]}(\frac{B_2}{\eta_k[n]} + C_2),$$

$$\omega_\eta(v_k[n], \eta_k[n]) = -\frac{A_3 B_2}{\eta_k^2[n] v_k[n]}, \forall k \quad (18)$$

Therefore, constraint (11a) and constraint (11b) can be converted to constraint (19) and constraint (20) as follows:

$$R_{\text{fair}} \leq \sum_{n=1}^N \beta_k[n] f^{(1)}(\nu_k[n], \eta_k[n])$$

$$+ \sum_{n=1}^N \tau_k[n] g^{(1)}(\nu_k[n], \eta_k[n]) \quad (19)$$

$$\sum_{i=1}^n P_k[i] \tau_k[i] \leq E_0$$

$$+ \sum_{i=1}^n \omega^{(1)}(v_k[i], \eta_k[i]) (\beta[i] - \Gamma_k(\beta_k[i])) \quad (20)$$

Due to the non convexity of constraint (12), we need to transform it.

Let $\chi_k(q_{uk}[n]) = \arctan(\frac{h[n]}{\sqrt{q_{uk}[n]}})$, $\forall k$. We assume that the horizontal trajectory of the UAV may be very close to the position of the ground equipment, but not equal to the position of the ground equipment, that is, meet $q_{uk}[n] > 0$. After derivation, we can find that the function $\chi_k(q_{uk}[n])$ is convex around $(q_{uk}[n])$. The first-order Taylor expansion of $\chi_k(q_{uk}[n])$ with respect to $q_{uk}[n]$ on $q_{uk,0}[n]$ is formulated as:

$$\chi_k^{(1)}(q_{uk}[n]) = \chi_k(q_{uk,0}[n]) + \chi_{k,q_{uk}[n]}(q_{uk,0}[n]) (q_{uk}[n] - q_{uk,0}[n]), \forall k, \quad (21)$$

where

$$\chi_{k,q_{uk}[n]}(q_{uk,0}[n]) = -\frac{h[n]}{2(q_{uk,0}[n] + h^2[n])(\sqrt{q_{uk,0}[n]})}, \forall k \quad (22)$$

Therefore, constraint (12) can be converted to constraint (23) as follows:

$$\rho_k[n] \leq \frac{180}{\pi} \chi_k^{(1)}(q_{uk}[n]) - a, \forall k \quad (23)$$

To sum up, question (P4) will be restated as question (P5) as follows:

$$(P5): \max_{\{\mathbf{u}[n], \text{for } \forall n\}} R_{\text{fair}} \quad (24)$$

s.t. (19), (20), (23), (8d), (8f).

Because the expression $\zeta_k[n]$, $\psi_k[n]$, $\xi_k[n]$ are convex functions with respect to $(\nu[n], \eta[n])$ and the expression $\chi_k(q_{uk}[n])$ is convex with respect to $(q_{uk}[n])$, we have $f^{(1)}(\nu_k[n], \eta_k[n]) \leq f(\nu_k[n], \eta_k[n])$, $\forall k$, $g^{(1)}(\nu_k[n], \eta_k[n]) \leq g(\nu_k[n], \eta_k[n])$, $\forall k$, $\omega^{(1)}(\nu_k[n], \eta_k[n]) \leq \omega(\nu_k[n], \eta_k[n])$, $\forall k$ and $\chi_k^{(1)}(q_{uk}[n]) \leq \chi_k(q_{uk}[n])$, $\forall k$. Therefore, if the constraints (19), (20), (23) hold, the original constraints (11a), (11b), (12) also hold. We can guarantee that the solution of (P5) is also feasible for (P4). Since (P5) is convex, it can be solved by any convex optimisation tool with a polynomial computational complexity.

D. Vertical Height Optimization

By fixing the horizontal trajectory of the UAV $\{\mathbf{u}[n] | n = 1, \dots, N\}$, the system time slot variable $\{\beta_k[n] | n = 1, \dots, N, k = 1, \dots, K\}$, $\{\tau_k[n] | n = 1, \dots, N, k = 1, \dots, K\}$ and the ground equipment MDs' active transmit power $\{P_k[n] | n = 1, \dots, N, k = 1, \dots, K\}$, the following sub-problem (P6) optimises the vertical height:

$$(P6): \max_{\{\{h[n]\}, \text{for } \forall n\}} R_{\text{fair}} \quad (25)$$

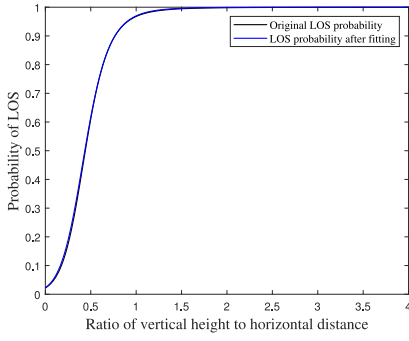


Fig. 4. Comparison between the fitted probability function and the original probability function.

$$\text{s.t. } R_{\text{fair}} \leq \sum_{n=1}^N \beta_k[n] \log_2 \left(1 + \frac{A_1}{d_{uk}^4[n]} (\varphi_k[n] B_1 + C_1) \right) + \sum_{n=1}^N \tau_k[n] \log_2 \left(1 + \frac{A_2}{d_{uk}^2[n]} (\varphi_k[n] B_2 + C_2) \right), \forall k, \quad (25a)$$

$$\sum_{i=1}^n P_k[i] \tau_k[i] \leq E_0 + \sum_{i=1}^n \frac{A_3}{d_{uk}^2[i]} (\varphi_k[i] B_2 + C_2) (\beta[i] - \Gamma_k \beta_k[i]), \forall n, k \quad (25b)$$

(8e), (8g).

where $A_1 = \frac{P_t \Gamma_k}{\sigma_0^2 (\frac{4\pi f_c}{c})^4}$, $B_1 = 10^{-\frac{2\eta_{LOS}}{10}} - 10^{-\frac{2\eta_{NLOS}}{10}}$, $C_1 = 10^{-\frac{2\eta_{NLOS}}{10}}$ and $A_2 = \frac{P_k[n]}{\sigma_0^2 (\frac{4\pi f_c}{c})^2}$, $B_2 = 10^{-\frac{\eta_{LOS}}{10}} - 10^{-\frac{\eta_{NLOS}}{10}}$, $C_2 = 10^{-\frac{\eta_{NLOS}}{10}}$, $A_3 = \frac{P_t \Gamma_k}{(\frac{4\pi f_c}{c})^2}$ are constants.

This sub-problem is a non-convex problem, and its solution is the same as the horizontal trajectory sub-problem (P4). For constraint (12), after analysis, we can know that it is a convex constraint. Unfortunately, as far as we know, the current convex optimization solver does not support solving atan function. In order to solve this problem, our method is to fit the atan function. In fact, this atan function is a part of the probability function, so we fit the atan function to make the probability function almost unchanged. We fit the atan function as follows:

$$\gamma_k[n] = \frac{\pi}{2} (1 - e^{-a_1 x}) + a_2, \forall n, k \quad (26)$$

where a_1, a_2 are constant. Therefore, the fitted LOS probability is as follows:

$$\varphi'_{LOS} = \frac{1}{1 + a e^{-b(\frac{180}{\pi} \gamma - a)}}, \forall n, k \quad (27)$$

Fig. 4 shows the comparison between the original function and the function after fitting. We can see that our fitting effect is very good. So the constraint (12) is converted to constraint (28) as follows:

Algorithm 1 The BCD Algorithm for Solving (P1)

Require: mission period T , maximum horizontal flight speed v_l , maximum vertical flight speed v_h , transmit power of UAV P_t , location of MDs $\{\mathbf{b}_k \in \mathbb{R}^2 | k \in \{1, \dots, K\}\}$, backscattering coefficient of MDs Γ_k , energy conversion efficiency η , noise power σ_0^2 , convergence threshold ϵ , additional loss of LOS and NLOS,

Ensure: Optimal $\{\mathbf{u}^*[n]\}$, $\{h^*[n]\}$, $\{P_k^*[n]\}$, $\{\beta_k^*[n]\}$, $\{\tau_k^*[n]\}$ and maximum R_{fair}^* .

- 1: Initialise feasible $\{\mathbf{u}^{(0)}[n]\}$, $\{h^{(0)}[n]\}$, $\{P_k^{(0)}[n]\}$, $\{\beta_k^{(0)}[n]\}$ and $\{\tau_k^{(0)}[n]\}$;
- 2: Initialise $R_{\text{fair}}^{(0)} \leftarrow \min_k R_k^{(0)}$ by substituting $\{\mathbf{u}^{(0)}[n]\}$, $\{h^{(0)}[n]\}$, $\{P_k^{(0)}[n]\}$, $\{\beta_k^{(0)}[n]\}$ and $\{\tau_k^{(0)}[n]\}$ into (8a);
- 3: Initialise $R_{\text{fair}}^{(-1)} \leftarrow 0$ and $i \leftarrow 0$;
- 4: **while** $|R_{\text{fair}}^{(i)} - R_{\text{fair}}^{(i-1)}| > \epsilon$ **do**
- 5: Update $i \leftarrow i + 1$;
- 6: Obtain $\{\beta_k^{(i)}[n]\}$ and $\{\tau_k^{(i)}[n]\}$, by solving (P2) with $\{P_k^{(i-1)}[n]\}$, $\{\mathbf{u}^{(i-1)}[n]\}$ and $\{h^{(i-1)}[n]\}$;
- 7: Obtain $\{P_k^{(i)}[n]\}$, by solving (P3) with $\{\beta_k^{(i)}[n]\}$, $\{\tau_k^{(i)}[n]\}$, $\{\mathbf{u}^{(i-1)}[n]\}$ and $\{h^{(i-1)}[n]\}$;
- 8: Obtain $\{\mathbf{u}^{(i)}[n]\}$ by solving (P5) with $\{h^{(i-1)}[n]\}$, $\{\beta_k^{(i)}[n]\}$, $\{\tau_k^{(i)}[n]\}$ and $\{P_k^{(i)}[n]\}$;
- 9: Obtain $\{h^{(i)}[n]\}$ by solving (P7) with $\{\mathbf{u}^{(i)}[n]\}$, $\{\beta_k^{(i)}[n]\}$, $\{\tau_k^{(i)}[n]\}$ and $\{P_k^{(i)}[n]\}$;
- 10: **end while**
- 11: **return** $\{\mathbf{u}^*[n] \leftarrow \mathbf{u}^{(i)}[n]\}$, $\{h^*[n] \leftarrow h^{(i)}[n]\}$, $\{\beta_k^*[n] \leftarrow \beta_k^{(i)}[n]\}$, $\{\tau_k^*[n] \leftarrow \tau_k^{(i)}[n]\}$, $\{P^*[n] \leftarrow P^{(i)}[n]\}$, $R_{\text{fair}}^* \leftarrow \min_k R_k^*$.

$$\rho_k[n] \leq \frac{180}{\pi} \gamma_k[n] - a, \forall n, k \quad (28)$$

It can be found that the constraint (28) is convex constraint.

Therefore, question (P6) will be restated as question (P7) as follows:

$$\begin{aligned} \text{(P7): } & \max_{\{\{h[n]\}, \text{for } \forall n\}} R_{\text{fair}} \\ \text{s.t. } & (19), (20), (28), (8e), (8g). \end{aligned} \quad (29)$$

It can be deduced that the problem is convex and can be solved by common convex optimization methods, such as interior point method.

E. Joint Design

In order to solve (P1), this paper designs an iterative optimization algorithm based on BCD. The pseudo code is provided in Algorithm 1. The optimization results of the UAV flight trajectory, system time slot resource variables and the ground equipment MDs' active transmit power are alternately updated to obtain the sub-optimal solution. By iteratively solving (P2), (P3), (P5), (P7), we can obtain the approximate local optimal value of (P1). And because R_{fair} is a finite value, the convergence of the iterative algorithm can be guaranteed. Since each sub optimization problem is transformed into a convex optimization problem, it can be solved by conventional

TABLE I
PARAMETER SETTINGS

Parameter name	Parameter value
Horizontal flight speed v_l	$5m/s$
Vertical flight speed v_h	$3m/s$
Noise power σ_0^2	$-100dBm$
The number of discrete points N	100
MD number K	4
Convergence threshold ϵ	10^{-3}
Backscatter coefficient Γ_k	0.6
Energy conversion efficiency η	0.8
Carrier frequency f_c	$7.55 \times 10^2 MHz$
Initial energy of equipment E_0	$5 \times 10^{-4} J$
Additional loss of LOS η_{LOS}	1
Additional loss of NLOS η_{NLOS}	20
Environment constant a	9.61
Environment constant b	0.16
Fitting constant a_1	0.6976
Fitting constant a_2	0.0039
Maximum flying altitude h_{max}	40m
Minimum flight altitude h_{min}	3m
Maximum active transmit power P_{max}	10dBm

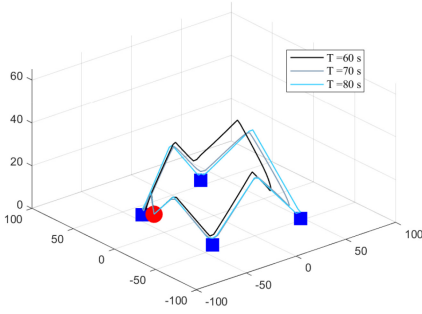


Fig. 5. 3D trajectory diagram of UAV under different flight cycles.

convex optimization tools. Because each round of updating to solve the subproblem is a polynomial complexity, the total BCD algorithm is also a polynomial complexity. Therefore, the total complexity of the algorithm is $O(N_{ite}(KN)^{3.5})$, where N_{ite} denotes the iteration number [38].

V. SIMULATION RESULTS

In this section, the parameter settings and simulation results of the numerical simulation are given, and the simulation results verify the effectiveness of the low-power multi-function communication system model based on UAVs in this chapter, and verify that the proposed solution algorithm has good convergence.

Generally, $K = 4$ MDs are uniformly distributed within a square area of $100 \times 100m^2$. The maximum horizontal flight speed of the UAV is $v_l = 5m/s$, and the maximum vertical flight speed is $v_h = 3m/s$. The noise power is $\sigma_0^2 = -100dBm$. The convergence threshold is set to be $\epsilon = 10^{-3}$.

The specific simulation parameters are listed in Table I.

Fig. 5 depicts the UAV's 3D flight trajectory diagram under different flight cycles $T = \{60s, 70s, 80s\}$, where the MD position is marked with blue squares, respectively $(-42, 36)$, $(35, 58)$, $(48, -47)$, $(-36, -42)$. The red circle is the starting point of the UAV, and the coordinates are $(-60, 0, 10)$. The transmitting power of UAV is 10 W. Observing Fig. 5, we can

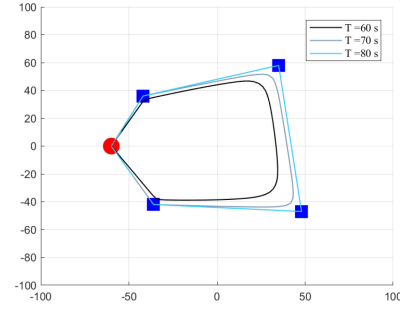


Fig. 6. Horizontal trajectory diagram of UAV under different flight cycles.

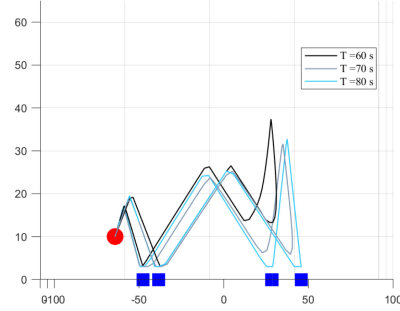


Fig. 7. Height variation diagram of UAV under different flight cycles.

find that the UAV always tries to approach the ground MD on the two-dimensional plane trajectory. In terms of the flying height of the UAV, you can see that the height fluctuates. This is because the system can have higher performance gains by continuously adjusting the height of the UAV.

In order to further study the change curve of UAV flight trajectory with flight period, we study horizontal trajectory diagram of UAV under different flight cycles and height variation diagram of UAV under different flight cycles respectively. Fig. 6 depicts horizontal trajectory diagram, We can clearly see that with the gradual increase of the flight cycle of the UAV, the horizontal flight path of the UAV gradually approaches each ground backscatter device, and finally forms a polygon with the starting point of the UAV and the ground device as the vertex. Fig. 7 depicts height variation diagram, where the flight altitude of UAV changes regularly. When the UAV starts from the starting position, because the distance between the UAV and the ground MD1 is far, the elevation angle between the UAV and the ground MD1 is small, and the probability of the channel between the UAV and the ground MD1 being NLOS channel is high. Therefore, the UAV can increase its flight altitude to increase the probability of LOS channel and reduce the loss of signal transmission. When the UAV approaches MD1 gradually, because the elevation between the UAV and the ground MD1 is large enough, the redundant height of the UAV will increase the transmission distance of the signal and thus increase the loss of the signal. Therefore, at this time, the UAV will gradually reduce its flight altitude until it reaches the lowest level directly above MD1. At this time, the loss of signal transmission will be minimal. When the UAV gradually moves away from the newly arrived MD 1 and rushes to the next MD, the UAV first

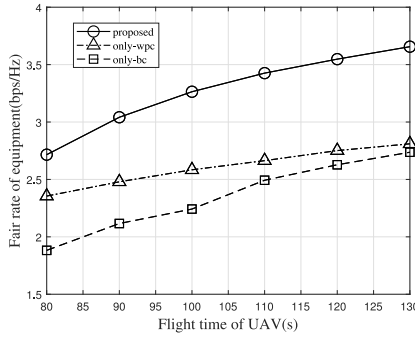


Fig. 8. The relationship between the flight cycle of UAV and the fair rate of the equipment.

increases its flight altitude to maintain a high LOS channel probability with MD1, and then reduces its flight altitude when it approaches the next MD, namely MD2. In this way, the UAV gradually reaches the top of each MDk and finally flies through a cycle. Therefore, we can conclude that in the vertical direction, the UAV drops to its lowest point when approaching ground equipment and gradually rises when moving away from ground equipment. In the horizontal direction, when the flight cycle is sufficient, the UAV moves along a polygon with the starting point and ground equipment as vertices.

Fig. 8 describes the relationship between the flight cycle of UAV and the fair rate of the equipment, in which the transmitting power of UAV is 10 W. We labeled our proposed joint design as “proposed” and compared it with the following benchmark scheme in Fig. 8:

- The scheme is marked as “only-bc” in the diagram. During the entire mission period, only the backscatter communication technology is used to passively transmit data information, that is, the time for active transmission communication of the device is 0. The corresponding MDs position coordinates and other parameters are consistent with the parameter settings in the “proposed” scheme;
- The scheme is marked as “only-wpc” in the diagram. During the entire mission period, only the active transmission of data and information is used. Specifically, each sub slot is divided into two parts, the first part is used to collect energy, and the latter part is used for active information transmission. The corresponding MDs position coordinates and other parameters are consistent with the parameter settings in the “proposed” scheme.

Observing Fig. 8, it can be found that as the flight cycle of UAV increases, the fair rate of the equipment of three schemes all increase. Moreover, it is important that it can be found that the “proposed” scheme proposed in this article is better than the other two schemes which shows the excellence of the “proposed” scheme.

Fig. 9 describes the relationship between the transmitting power of UAV and the fair rate of the equipment, in which the flight cycle of UAV is 110 s. Similarly, we compared our proposed joint design with the other two schemes. Observing Fig. 9, it can be found that as the transmitting power of UAV increases, the fair rate of the equipment of three schemes all

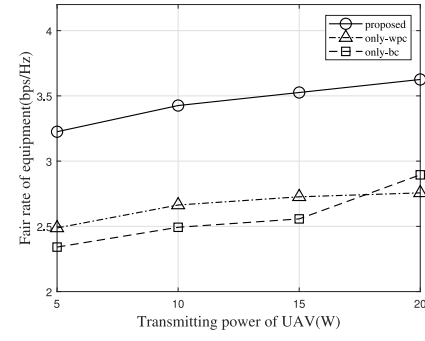


Fig. 9. The relationship between the transmitting power of UAV and the fair rate of the equipment.

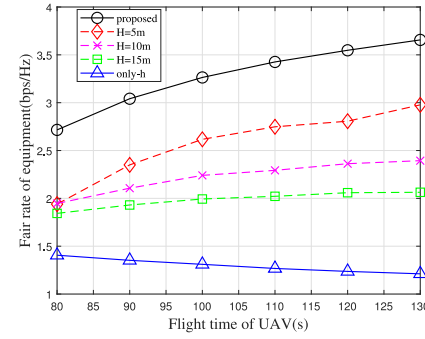


Fig. 10. The relationship between the flight cycle of UAV and the fair rate.

increase. Moreover, it is important that it can be found that the “proposed” scheme proposed in this article is better than the other two schemes which shows the excellence of the “proposed” scheme.

Fig. 10 describes the relationship between the flight cycle of UAV and the fair rate, in which the transmitting power of UAV is 10 W. We labeled our proposed joint design as “proposed” and compared it with the following benchmark scheme in Fig. 10:

- The scheme is marked as “only-h” in the figure. Compared with the proposed “proposed”, the horizontal trajectory of the UAV is not optimized in the iterative algorithm. The specific simulation parameters are consistent with the parameter settings in the “proposed” scheme. The horizontal trajectory of the UAV is set as a polygonal track with $(-60, 0)$, $(-5, 60)$, $(50, 0)$, $(-5, -60)$ as the vertices;
- The scheme is marked as “H=5m”, “H=10m”, “H=15m” in the figure. Compared with the proposed “proposed”, the height of the UAV is not optimized in the iterative algorithm. The horizontal flight path of UAV is optimized under three scenarios of fixed flight height of 5m, 10m and 15m. The simulation parameters are consistent with the parameter settings in the “proposed” scheme.

Observing Fig. 10, it can be found that as the flight cycle of UAV increases, the “proposed” scheme, the “H=5m” scheme, the “H=10m” scheme and the “H=15m” scheme increase and the “only-h” scheme slowly decreases. This is because the horizontal trajectory of the “only-h” scheme is too bad, resulting in a slow decline in the fair rate of the equipment

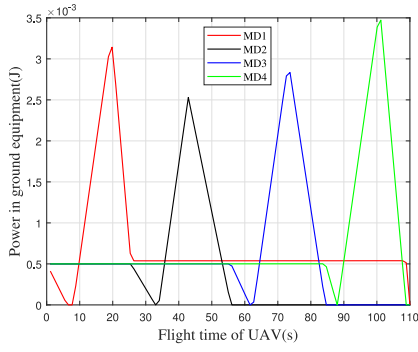


Fig. 11. Change of electric quantity of ground equipment.

even if the flight cycle increases. Moreover, it is important that it can be found that the “proposed” scheme proposed in this article is better than the other two schemes which shows the excellence of the “proposed” scheme.

Fig. 11 describes the change of electric quantity of ground equipment where $T = 110s$. In short, the power of ground equipment fluctuates throughout the flight cycle of the UAV. Specifically, when the UAV is far away from the ground equipment, the loss of backscatter communication mode will be large due to the impact of double path loss. Therefore, the communication mode between ground equipment and UAV is considered as active information transmission, and the ground equipment consumes its own energy. When the distance between the UAV and the ground equipment decreases gradually, the performance of the backscatter communication mode gradually increases. The communication mode between the UAV and the ground equipment is converted from active information transmission to backscatter communication. At the same time, the ground equipment collects energy, and the energy stored by the ground equipment gradually increases. When the UAV gradually moves away from the arrived ground equipment and flies to the next ground equipment, as the distance between the UAV and the newly arrived ground equipment gradually increases, the communication mode between the UAV and the ground equipment changes from the backscatter communication mode to the active information transmission communication mode, and the storage power of the ground equipment continues to decline. Therefore, we can conclude that when the distance between the UAV and ground equipment is close, the ground equipment and UAV engage in backscatter communication, while the ground equipment collects some energy, resulting in an increase in the energy collected by the ground equipment’s battery. When the distance between the UAV and ground equipment is far, the ground equipment actively transmits information to the UAV through wireless powered communication. At this time, the energy stored by the ground equipment gradually decreases.

Furthermore, it can be seen from Fig. 12 that our algorithm has good convergence performance.

VI. CONCLUSION

This paper proposes a hybrid backscatter and wireless powered communications system based on unmanned aerial

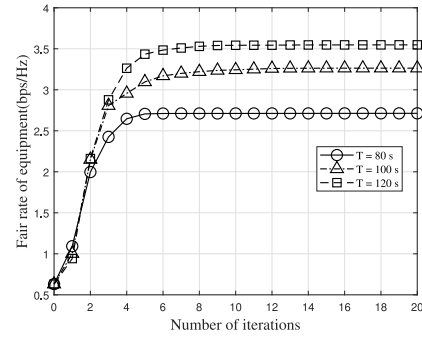


Fig. 12. Convergence graph of the proposed BCD aided joint design.

vehicle (UAV). UAV operates both as a source of radio frequency (RF) signals and an information collector. The system integrates passive information transmission (IT) via backscatter communication (BC) and active IT via wireless-powered communication (WPC) to meet the requirements of low-power multi-function communication. At the same time, the system considers the LOS/NLOS channel at variable altitude. By jointly designing the 3D flight trajectory of UAV, the system time slot resources and the active transmit power of ground equipment can maximize the fair rate of ground equipment, and the system also considers various flight restrictions of UAV. Based on the block coordinate descent algorithm, this paper divides the original problem into several sub-problems and processes them separately, and finally obtains an approximate solution through joint iteration. The simulation results show that the hybrid backscatter and wireless powered communications system based on UAV proposed in this paper can significantly improve the fair rate of ground equipment compared with other benchmark schemes.

APPENDIX

Prove that function $\zeta_k[n] = \log_2(1 + \frac{A_1}{v_k^2[n]}(\frac{B_1}{\eta_k[n]} + C_1))$ is convex function. Let f represent $\zeta_k[n]$, and abbreviate $v_k[n]$ and $\eta_k[n]$ as v and η . First, we calculate the first partial derivative of function f with respect to v and η :

$$f_v = \frac{-2A_1B_1\eta - 2A_1C_1\eta^2}{v^3\eta^2 + A_1B_1v\eta + A_1C_1v\eta^2} \frac{1}{\ln 2} \quad (30)$$

$$f_\eta = \frac{-A_1B_1v}{v^3\eta^2 + A_1B_1v\eta + A_1C_1v\eta^2} \frac{1}{\ln 2} \quad (31)$$

Then we calculate the second partial derivative of function f with respect to v and η :

$$f_{v\eta} = f_{\eta v} = \frac{2A_1B_1v^3\eta^2}{(v^3\eta^2 + A_1B_1v\eta + A_1C_1v\eta^2)^2} \frac{1}{\ln 2} \quad (32)$$

Because

$$f_{vv} = \frac{(2A_1B_1\eta + 2A_1C_1\eta^2)(3v^2\eta^2 + A_1B_1\eta + A_1C_1\eta^2)}{(v^3\eta^2 + A_1B_1v\eta + A_1C_1v\eta^2)^2} \frac{1}{\ln 2} > 0 \quad (33)$$

$$f_{\eta\eta} = \frac{A_1B_1v(2v^3\eta + A_1B_1v + 2A_1C_1v\eta)}{(v^3\eta^2 + A_1B_1v\eta + A_1C_1v\eta^2)^2} \frac{1}{\ln 2} > 0 \quad (34)$$

and $f_{vv}f_{\eta\eta} - f_{v\eta}f_{\eta v} > 0$. Therefore, the sequential principal minor of the Hessian matrix of function $\zeta_k[n]$ are greater

than 0, so the Hessian matrix is positively definite, and therefore function $\zeta_k[n]$ is a convex function with respect to variable $(v_k[n], \eta_k[n])$.

Similarly, it can be concluded that the sequential principal minor of the Hessian matrices of functions $\psi_k[n]$ and $\xi_k[n]$ are greater than 0, indicating that the Hessian matrix is positively definite. Therefore, functions $\psi_k[n]$ and $\xi_k[n]$ are also convex functions with respect to variable $(v_k[n], \eta_k[n])$.

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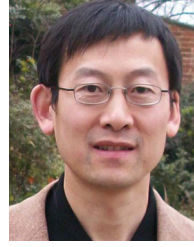


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