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Research Article

Dynamic Contract Incentives Mechanism for Traffic Offloading in Multi-UAV Networks

Nan Zhao [ID], Pengfei Fan, and Yiqiang Cheng

Hubei University of Technology, Wuhan 430068, China

Correspondence should be addressed to Nan Zhao; nzhao@mail.hbut.edu.cn

Traffic offloading is considered to be a promising technology in the Unmanned Aerial Vehicles- (UAVs-) assisted cellular networks. Due to their selfishness property, UAVs may be reluctant to take part in traffic offloading without any incentive. Moreover, considering the dynamic position of UAVs and the dynamic condition of the transmission channel, it is challenging to design a long-term effective incentive mechanism for multi-UAV networks. In this work, the dynamic contract incentive approach is studied to attract UAVs to participate in traffic offloading effectively. The two-stage contract incentive method is introduced under the information symmetric scenario and the information asymmetric scenario. Considering the sufficient conditions and necessary conditions in the contract design, a sequence optimization algorithm is investigated to acquire the maximum expected utility of the base station. The simulation experiment shows that the designed two-stage dynamic contract improves the performance of traffic offloading effectively.

1. Introduction

Recently, due to their flexible deployment and low cost, Unmanned Aerial Vehicles (UAVs) have been widely used in wireless networks [1, 2]. The rapid mobility of the UAVs can effectively increase network capacity and coverage of the Base Station (BS) [3]. In addition, owing to the low deployment cost of the UAVs, the multi-UAV network is considered as a compelling technology for traffic offloading in the traditional cellular networks [4, 5].

In the typical wireless cellular networks, when major events or emergent situations occur, the traffic demands will increase rapidly in certain areas. Due to the limited communication coverage and power of the BS, it is difficult for users to obtain a sufficient communication service in the hotspot areas. In this case, considering their flexibility and the low cost, the BS may need the UAVs to offload certain wireless traffic. However, the UAVs may consume certain energy when participating in traffic offloading. Without any incentive, the selfish UAVs may not be willing to offer their help [6, 7]. In this work, we will focus on designing a powerful traffic offloading incentive mechanism to address the problem.

Currently, the traffic offloading incentive problem has been investigated in wireless networks [8–14]. Most research works are performed under the complete network information. However, due to the shadowing and fading effects of the transmission channel and the mobility of the UAVs, it is challenging to obtain the complete network information. Moreover, the UAVs may often belong to different network operators. Due to their selfishness, the UAVs may be reluctant to share their communication information with others. Then, the asymmetric information issue arises between the BS and the UAVs [15–17]. Therefore, this paper concentrates on the contract theory-based mechanism to solve the asymmetric information problem in the multi-UAV networks.

Contract theory [18] is an economic concept, which investigates how to design the mutually agreeable contract between the economic entities under the information asymmetric scenario. Currently, contract-based methods are widely applied in many fields [19–32]. However, most works were designed for one-shot incentive. Nevertheless, in certain scenarios, due to the instability of offloading demand, the BS may repeatedly request the UAVs to perform traffic offloading. Under this circumstance, contracts between the two

sides are often repeated over time. Moreover, considering the mobility of the UAVs and the dynamic condition of transmission channels, the network environment may change randomly. Therefore, in order to adapt to the dynamic network environment, this paper proposes a long-term contract theory-based traffic offloading incentive mechanism. Our contributions are summarized as follows.

(i) *New Solution Technique.* As far as we know, this is the first long-term dynamic contract design for traffic offloading in the multi-UAV networks

(ii) *Feasibility of Contracts.* In order to capture the dynamic characteristics of the UAVs in traffic offloading, the dynamic contract mechanisms are designed under both the two information scenarios. Under the symmetric information scenario, the contract only needs to introduce the individually rational (IR) constraint to ensure that the UAVs can achieve the nonnegative utility when participating in traffic offloading. Moreover, under the asymmetric information scenario, the incentive-compatible (IC) constraint is considered to ensure that the UAVs can achieve their maximum utilities when choosing the contract item related to their communication information. In order to obtain the optimal traffic offloading-reward scheme, a sequence optimization method is proposed

(iii) *Performance Analysis.* Simulation results show the effectiveness of the dynamic contract incentive mechanism. By breaking the information asymmetry, the proposed method can increase the BS's long-term utility in traffic offloading

The key notations summarized in this paper are shown in Table 1. The rest of this paper is organized as follows. In Section 2, we present the system model and problem formulation. In Section 3 and Section 4, the dynamic contract incentive mechanisms are investigated under both the two information scenarios. Simulation results are given in Section 5. Conclusions and future works are presented in Section 6.

2. Related Works

In recent years, the incentive problem has been investigated in wireless networks. In [8], Kang and Sun explored the incentive mechanism to stimulate WIFI access points to provide higher quality services for mobile network operators. Zhang et al. proposed a service-based incentive mechanism to facilitate the cooperation of multiple cellular networks [9]. In [10], Hou et al. studied a social-aware incentive mechanism for mobile data offloading. Noreen and Saxena investigated a game-theoretic incentive mechanism for mobile data offloading [11]. In [12], Yao et al. studied a location-aware incentive mechanism for traffic offloading in heterogeneous networks. Mansouri et al. [13] proposed an incentive framework for mobile data offloading with price competition. In [14], Liu et al. designed an offloading incentive mech-

TABLE 1: Key notations.

Symbol	Physical meaning
N	Number of UAVs
$h(\text{RT}_i, D_i)$	UAV's channel (RT_i to D_i) gain
p_{ti}, p_i	UAV's transmit power and accept power
$p_i^1, p_i^2/p_k^2$	UAV's received power in stage 1 and stage 2
c_i, α_i, C_i	UAV's per cost, transmission cost, total cost
θ_i	UAV's private information
$\theta_i^1, \theta_i^2/\theta_k^2$	UAV's private information in stage 1 and stage 2
$f_i^1(\theta_i^1), f_k^2(\theta_i^1)$	Probability density function of θ_i^1
$F_i^1(\theta_i^1), F_k^2(\theta_i^1)$	Probability distribution function of θ_i^1
E_i	UAV's energy consumed by movement
w_i	The reward of UAV
$w_i^1, w_i^2/w_k^2$	UAV's reward in stage 1 and stage 2
$U_{\text{UAV}_i}, U_{\text{UAV}_i}^1, U_{\text{UAV}_k}^2$	UAV's total, stage 1 and stage 2 utility
n_0	Noise power
ρ_i	Profit per transmission capacity
π	BS's total profit
$U_{\text{BS}}, U_{\text{BS}}^1, U_{\text{BS}}^2$	BS's total, stage 1 and stage 2 expected utility

anism combined with anchoring effect and loss aversion in the Internet of Things. However, most of the above works were performed under the complete network information scenario. Practically, an asymmetric information problem may exist between the BS and the UAVs. Therefore, an effective mechanism should be adopted to solve the asymmetric information problem in the multi-UAV networks.

Different from the above incentive methods, contract theory is an effective mechanism to solve the asymmetry network information issue in many areas, such as energy trading [19, 20], spectrum trading [21, 22], cooperative communication [23–25], Internet of Things [26, 27], and device-to-device communication [28, 29]. In addition, contract theory-based incentive mechanism has also been investigated in traffic offloading. In [30], Li et al. proposed an incentive mechanism based on contract theory for delayed traffic offloading in cellular networks. Du et al. designed a contract-based incentive mechanism to investigate the mobile traffic offloading and resource allocation issue in SDWN-based HetUDNs [31]. In [32], Hu et al. formulated a spectrum trading contract for UAV-assisted cellular networks. However, most works designed the contract mechanism for a one-shot static incentive. Nevertheless, in the practical scenarios, due to the dynamic characteristic of offloading demand and network environment, a long-term dynamic contract mechanism should be considered in multi-UAV networks.

3. System Model and Problem Formulation

In this paper, a typical multi-UAV network is considered, as shown in Figure 1. The network is composed of one BS and N UAVs. Since the traffic sharply increases in the hotspot areas, the BS can employ the UAVs to participate in traffic
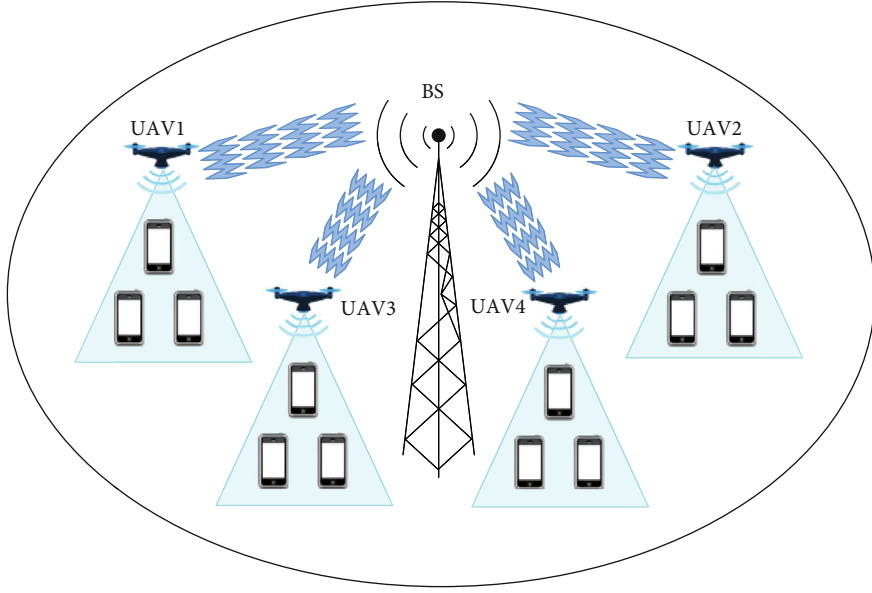
FIGURE 1: The typical multi-UAV network.

offloading. Moreover, considering the selfishness of UAVs and the uncertainty of transmission conditions, it is necessary to design a dynamic contract incentive mechanism to motivate UAVs for traffic offloading efficiently.

3.1. Unmanned Aerial Vehicle.

Let $h(\mathrm{TR}_i, D_i)$ be the channel gain between the ith UAV's transmitter TR_i and the corresponding hotspot areas D_i. In order to obtain the received power p_i at the corresponding hotspot area D_i, the ith UAV needs to offer the transmit power $p_{ti} = p_i/h(\mathrm{TR}_i, D_i)$. Then, the transmission cost of the ith UAV for traffic offloading can be defined as

$$\alpha_i = c_i p_{ti} = c_i \frac{p_i}{h(\mathrm{TR}_i, D_i)}, \quad 1 \le i \le N, \tag{1}$$

where c_i is the unit cost for i^{th} UAV.

Here, we define $\theta_i = c_i/h(\mathrm{RT}_i, D)$ as the private information of the ith UAV, which can describe the ability of traffic offloading of each UAV. When θ_i increases, it means that the ith UAV has a higher transmission cost or the poorer condition of a wireless channel. Since the private information θ_i is a random variable, we assume that θ_i is distributed in a positive interval $\Theta \in [\theta_L, \theta_H]$ with a probability density function $f_i(\theta_i)$ and the corresponding distribution function $F_i(\theta_i)$.

Since the UAVs may consume the energy when participating in traffic offloading, the UAVs need to go back to their own initial locations to recharge the battery. Assume that the cost E_i is consumed by the position movement of UAVs. Then, the total cost of the ith UAV in traffic offloading can be obtained as

$$C_i = E_i + \alpha_i = E_i + \theta_i p_i, \quad 1 \le i \le N. \tag{2}$$

Thus, the ith UAV's utility U_{UAV_i} can be defined as the reward w_i received from the BS minus the total cost C_i, that is

$$U_{\mathrm{UAV}_i} = w_i - C_i = w_i - E_i - \theta_i p_i. \tag{3}$$

3.2. Base Station.

With the UAVs participation in traffic offloading, the achievable profit of the BS can be defined as

$$\pi = \sum_{i=1}^{N} \int_{\theta_L}^{\theta_H} \left[\rho_i \log \left(1 + \frac{p_i}{n_0} \right) \right] dF_i(\theta_i), \tag{4}$$

where n_0 is the noise power, $\rho_i > 0$ is the profit per transmission capacity. For the convenience of the following analysis, the noise power n_0 is normalized to be 1.

Then, by subtracting the UAV's total reward from the achievable profit π, the BS's expected utility U_{BS} can be obtained, which is given by

$$\begin{aligned} U_{\mathrm{BS}} &= \pi - \sum_{i=1}^{N} \int_{\theta_L}^{\theta_H} w_i dF_i(\theta_i) \\ &= \sum_{i=1}^{N} \int_{\theta_L}^{\theta_H} [\rho_i \log (1 + p_i) - w_i] dF_i(\theta_i), \quad 1 \le i \le N. \end{aligned} \tag{5}$$

3.3. Problem Formulation.

This work studies the two-stage contract incentive mechanism under the dynamic asymmetric information scenario. Since the UAV's private information is unknown to the BS, the designed contract not only needs to break the information asymmetry, but also should attract the UAVs to perform traffic offloading.

Based on the revelation principle [18], in order to reflect the UAV's private information of two stages, the BS needs to design one contract item for each type of UAV at each stage. Here, the two-stage contract is defined as $\{w_i^1, p_i^1 ; w_i^2, p_i^2,$
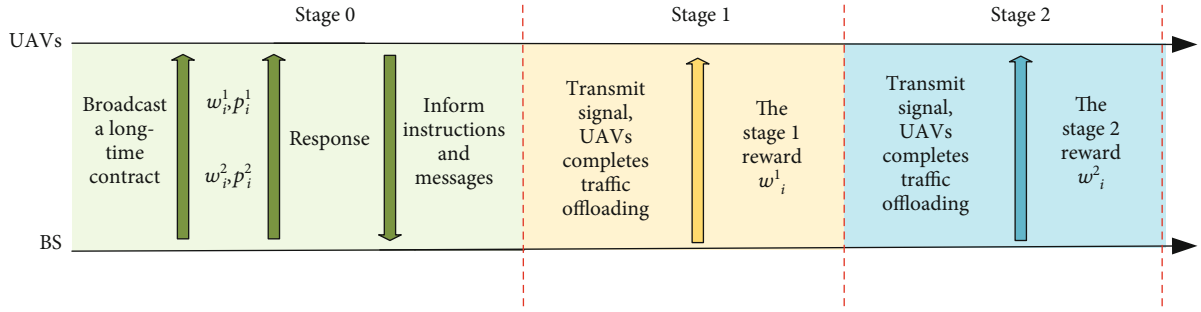
FIGURE 2: Timing with a two-stage contract design.

$1 \leq i \leq N\}$, where p_i^1 and p_i^2 are the transmission powers of the ith UAV in stage 1 and stage 2, respectively; w_i^1 and w_i^2 are the received rewards of the ith UAV in stage 1 and stage 2, respectively.

The timing diagram of the two-stage contract is shown in Figure 2. The whole incentive mechanism is described as follows.

(i) Contract confirmation in stage 0: at the beginning of the contracting stage, only UAVs know their own private information θ_i^1 of stage 1. The BS broadcasts a two-stage contract $\{w_i^1, p_i^1, w_i^2, p_i^2\}$ to all the potential UAVs. When the UAVs receive the contract, each UAV evaluates and notifies the BS to accept or reject the contract

(ii) Traffic offloading in stage 1: the BS informs each UAV of some communication details, such as the serviced hotspot area and allocated channel. Then, the UAVs go to the corresponding serviced area for traffic offloading. When certain UAVs complete the traffic offloading of stage 1, the BS evaluates the UAV's operation through feedback from the hotspot areas. If the traffic is offloaded successfully, the UAVs will get the rewards w_i^1 according to the contract. If they fail, the UAVs will not receive any reward

(iii) Traffic offloading in stage 2: the second stage of traffic offloading is similar to that of stage 1. After the UAVs complete the traffic offloading work, the BS pays the UAVs the rewards w_i^2 according to the contract

4. Dynamic Contract Incentive Mechanism under Symmetric Information Scenario

In this section, we discuss a two-stage dynamic contract design for traffic offloading under the symmetric information scenario. Here, the BS knows the private information of each UAV precisely.

Considering the two-stage contract design, the total expected utility of the BS can be defined as

$$
\begin{aligned}
U_{\text{BS}} = U_{\text{BS}}^1 + \delta U_{\text{BS}}^2 &= \sum_{i=1}^{N} \int_{\theta_L}^{\theta_H} \left[\rho_i \log \left(1 + p_i^1\right) - w_i^1 \right] dF_i^1 \left(\theta_i^1\right) \\
&+ \delta \sum_{i=1}^{N} \int_{\theta_L}^{\theta_H} \left[\rho_i \log \left(1 + p_i^2\right) - w_i^2 \right] dF_i^2 \left(\theta_i^2\right),
\end{aligned}
$$

(6)

where δ is the discount factor. When δ is greater than 1, it means that the working time of stage 2 is greater than that of stage 1.

Notice that when the ith UAV signs a long-term contract with the BS, it only knows the type of stage 1 θ_i^1. After traffic offloading is realized in stage 1, its private information of stage 2 θ_i^2 can be learned by the ith UAV. Thus, the optimal long-term contract is designed by jointly considering the optimal contract with interim contracting (interim contracting describes the process that the BS offers the contract to the UAVs once the UAVs have already learned their private type information.) in stage 1, and the optimal contract with ex-ante contracting (ex-ante contracting shows the process before the UAVs learn their private type information.) in stage 2.

Moreover, considering that the private information of certain UAV in stage 1 may be different from that in stage 2, we use θ_i^1 and θ_k^2 to indicate the private information in stage 1 and stage 2, respectively.

4.1. Contracting Design in Stage 2. Based on the idea of reverse induction, we first consider the situation of stage 2. The utility of type-θ_k^2 UAV in stage 2 is given by

$$
U_{\text{UAV}_k}^2 \left(\tilde{\theta}_i\right) = w_k^2 \left(\tilde{\theta}_i\right) - E_i - \theta_k^2 p_k^2 \left(\tilde{\theta}_i\right), \quad 1 \leq i, k \leq N, \quad (7)
$$

where $\tilde{\theta}_i$ is the announcement about its private information of the ith UAV in stage 1, $p_k^2(\tilde{\theta}_i)$ and $w_k^2(\tilde{\theta}_i)$ are the transmission power and the obtained reward of the ith UAV in stage 2, respectively.

In order to make sure that type-θ_k^2 UAV obtains a nonnegative utility by selecting the contract item related with θ_k^2, the contract needs to satisfy the following individually rational (IR) constraint

$$w_k^2\left(\tilde{\theta}_i\right) - E_i - \theta_k^2 p_k^2\left(\tilde{\theta}_i\right) \geq 0, \quad 1 \leq i, k \leq N. \tag{8}$$

4.2. Contracting Design in Stage 1.
In stage 1, the ith UAV's utility $U_{\text{UAV}_i}^1$ can be written as

$$U_{\text{UAV}_i}^1 = w_i^1 - E_i - \theta_i^1 p_i^1, \quad 1 \leq i \leq N. \tag{9}$$

Considering that the expected continuation utility of stage 2 is $\int_{\theta_L}^{\theta_H} U_{\text{UAV}_k}^2(\tilde{\theta}_i) dF_k^2(\tilde{\theta}_i)$, in order to make sure that the ith UAV obtains a nonnegative utility by selecting the contract item related with θ_i^1, the contract must satisfy the following IR constraint,

$$\left[w_i^1 - E_i - \theta_i^1 p_i^1\right] + \delta \int_{\theta_L}^{\theta_H} U_{\text{UAV}_k}^2(\theta_i^1) dF_k^2(\theta_i^1) \geq 0, \quad 1 \leq i, k \leq N. \tag{10}$$

4.3. Optimal Contract Design.
In order to achieve the maximum expected utility of the BS in (6), the optimization problem of the two-stage contract design can be defined as follows:

$$\max_{\{w_i^1, p_i^1, w_k^2(\tilde{\theta}_i), p_k^2(\tilde{\theta}_i)\}} U_{\text{BS}}\left(w_i^1, p_i^1, w_k^2(\tilde{\theta}_i), p_k^2(\tilde{\theta}_i)\right)$$

$$\text{s.t.} \quad \begin{aligned} &\text{(IR1)} \quad w_i^1 - E_i - \theta_i^1 p_i^1 + \delta \int_{\theta_L}^{\theta_H} U_{\text{UAV}_k}^2(\theta_i^1) dF_k^2(\theta_i^1) \geq 0 \\ &\text{(IR2)} \quad w_k^2(\tilde{\theta}_i) - E_i - \theta_k^2 p_k^2(\tilde{\theta}_i) \geq 0. \end{aligned} \tag{11}$$

Lemma 1. *In order to ensure that the BS obtains the maximum expected utility, the utility of each UAV in each stage should be zero, that is,*

$$w_i^1 = E_i + \theta_i^1 p_i^1, \quad 1 \leq i \leq N.$$
$$w_k^2\left(\tilde{\theta}_i\right) = E_i + \theta_k^2 p_k^2\left(\tilde{\theta}_i\right), \quad 1 \leq i, k \leq N. \tag{12}$$

Proof. Since the BS's utility in (6) is decreasing in both w_i^1 and $w_k^2(\tilde{\theta}_i)$, the BS can acquire its maximum utility by decreasing both w_i^1 and $w_k^2(\tilde{\theta}_i)$.

From the IR constraint of stage 2 in (8), we can obtain the minimum reward of the ith UAV in stage 2, that is,

$$w_k^2\left(\tilde{\theta}_i\right) = E_i + \theta_k^2 p_k^2\left(\tilde{\theta}_i\right), \quad \leq i, k \leq \text{N}. \tag{13}$$

Similarly, from the IR constraint of stage 1 in (10), the minimum reward of the ith UAV in stage 1 can be obtained as

$$w_i^1 = E_i + \theta_i^1 p_i^1 - \delta \int_{\theta_L}^{\theta_H} U_{\text{UAV}_k}^2(\theta_i^1) dF_k^2(\theta_i^1), \quad 1 \leq i, k \leq N. \tag{14}$$

Then, from (13), we have $U_{\text{UAV}_k}^2(\theta_i^1) = 0$. Therefore, the UAV's reward (14) can be simplified as

$$w_i^1 = E_i + \theta_i^1 p_i^1. \tag{15}$$

This completes the proof.

Thus, by bringing (13) into (6), the BS's expected utility U_{BS}^2 in stage 2 is given by

$$U_{\text{BS}}^2 = \sum_{i=1}^{N} \int_{\theta_L}^{\theta_H} \left[\rho_i \log\left(1 + p_k^2\left(\tilde{\theta}_i\right)\right) - E_i - \theta_k^2 p_k^2\left(\tilde{\theta}_i\right)\right] dF_k^2\left(\tilde{\theta}_i\right). \tag{16}$$

Similarly, by combing (15) with (6), we can also obtain the BS's expected utility U_{BS}^1 in stage 1, that is,

$$U_{\text{BS}}^1 = \sum_{i=1}^{N} \int_{\theta_L}^{\theta_H} \left[\rho_i \log\left(1 + p_i^1\right) - E_i - \theta_i^1 p_i^1\right] dF_i^1\left(\theta_i^1\right). \tag{17}$$

Then, the BS's expected utility U_{BS} (6) can be written as

$$U_{\text{BS}} = \sum_{i=1}^{N} \int_{\theta_L}^{\theta_H} \left[\rho_i \log\left(1 + p_i^1\right) - E_i - \theta_i^1 p_i^1 \right. \\ \left. + \delta\left[\rho_i \log\left(1 + p_k^2\left(\tilde{\theta}_i\right)\right) - E_i - \theta_k^2 p_k^2\left(\tilde{\theta}_i\right)\right]\right] dF_i\left(\theta_i\right). \tag{18}$$

In order to simplify the following analysis, we defined

$$Y\left(p_i^1, p_k^2(\theta_i^1)\right) = \rho_i \log\left(1 + p_i^1\right) - E_i - \theta_i^1 p_i^1 \\ + \delta\rho \log\left(1 + p_k^2(\theta_i^1)\right) - \delta E_i - \delta\theta_k^2 p_k^2(\theta_i^1). \tag{19}$$

Thus, the BS's expected utility U_{BS} can be rewritten as $U_{\text{BS}} = \sum_{i=1}^{N} \int_{\theta_L}^{\theta_H} [Y(p_i^1, p_k^2(\theta_i^1))] dF_i(\theta_i)$.

Then, the optimization problem (11) can be simplified as

$$\max_{\{p_i^1, p_k^2(\theta_i^1)\}} \sum_{i=1}^{N} \int_{\theta_L}^{\theta_H} \left[Y\left(p_i^1, p_k^2(\theta_i^1)\right)\right] dF_i(\theta_i). \tag{20}$$

At this point, we simplify the expected utility optimization problem of BS in (11) to acquire the maximum utility $Y(p_i^1, p_k^2(\theta_i^1))$. Any local optimal solution (denoted as $\{\hat{p}_i^1, \hat{p}_k^2(\theta_i^1)\}$) to maximize the utility $Y(p_i^1, p_k^2(\theta_i^1))$ should satisfy

$$\left.\frac{d\left(Y\left(p_i^1, p_k^2(\theta_i^1)\right)\right)}{dp_i^1}\right|_{p_i^1 = \hat{p}_i^1} = \frac{\rho_i}{1 + \hat{p}_i^1} - \theta_i^1 = 0. \tag{21}$$

$$\left.\frac{d\left(Y\left(p_i^1, p_k^2(\theta_i^1)\right)\right)}{dp_k^2(\theta_i^1)}\right|_{p_k^2(\theta_i^1) = \hat{p}_k^2(\theta_i^1)} = \frac{\delta\rho_i}{1 + \hat{p}_k^2(\theta_i^1)} - \delta\theta_k^2(\theta_i^1) = 0. \tag{22}$$

Then, the second derivative is further calculated as

$$
\frac{\partial^2\left(Y\left(p_i^1, p_k^2(\theta_i^1)\right)\right)}{\partial\left(p_i^1\right)^2}\Bigg|_{p_i^1=\hat{p}_i^1} = \frac{-\rho_i}{\left(1+p\wedge_i^1\right)^2} < 0. \quad (23)
$$

$$
\frac{\partial^2\left(Y\left(p_i^1, p_k^2(\theta_i^1)\right)\right)}{\partial\left(p_k^2(\theta_i^1)\right)^2}\Bigg|_{p_k^2(\theta_i^1)=\hat{p}_k^2(\theta_i^1)} = \frac{-\rho_i}{\left(1+p\wedge_k^2(\theta_i^1)\right)^2} < 0. \tag{24}
$$

From (23) and (24), we can find that the local optimal solutions of (21) and (22) are unique and globally optimal. Therefore, the optimal contract design for traffic offloading under the symmetric information scenario can be obtained as

$$
\begin{cases} p_i^{1*} = \dfrac{\rho_i}{\theta_i^1} - 1, \\[2mm] p_k^{2*}(\theta_i^1) = \dfrac{\rho_i}{\theta_k^2} - 1. \end{cases} \tag{25}
$$

5. Dynamic Contract Incentive Mechanism under Asymmetric Information Scenario

In the previous section, we investigated the dynamic contract design in the case of information symmetry. However, in practical situations, the UAV's private information may not be known to the BS, which causes the information asymmetric problem. Therefore, in this section, we will discuss the two-stage dynamic contract design in the case of information asymmetry.

5.1. Contracting Design in Stage 2. Based on reverse induction, we first consider the situation of stage 2. In stage 2, in order to ensure that the type-θ_k^2 UAV obtains a nonnegative utility by selecting contract $(w_k^2(\tilde{\theta}_i), p_k^2(\tilde{\theta}_i))$, the contract needs to meet the IR constraint in (8).

Then, considering that the type-θ_k^2 UAV can only obtain its maximum utility when selecting the contract item related with its type, the IC constraint should be satisfied, which can be defined as

$$
w_k^2\left(\tilde{\theta}_i\right) - E_i - \theta_k^2 p_k^2\left(\tilde{\theta}_i\right) \geq w_j^2\left(\tilde{\theta}_i\right) - E_i - \theta_k^2 p_j^2\left(\tilde{\theta}_i\right), \quad 1 \leq i, j, k \leq N. \tag{26}
$$

5.2. Contracting Design in Stage 1. Given that the expected continuation utility for stage 2 is $\int_{\theta_L}^{\theta_H} U_{\mathrm{UAV}_k}^2(\tilde{\theta}_i) dF_k^2(\tilde{\theta}_i)$, the ith UAV's intertemporal utility $U_{\mathrm{UAV}_i}^1$ can be written as

$$
U_{\mathrm{UAV}_i}^1 = \left[w_i^1 - E_i - \theta_i^1 p_i^1\right] + \delta \int_{\theta_L}^{\theta_H} U_{\mathrm{UAV}_k}^2\left(\tilde{\theta}_i\right) dF_k^2\left(\tilde{\theta}_i\right), \quad 1 \leq i \leq N. \tag{27}
$$

Then, in order to make sure that the ith UAV obtains a nonnegative utility by selecting the contract item related with θ_i^1, the intertemporal IC constraint is defined as

$$
\left[w_i^1 - E_i - \theta_i^1 p_i^1\right] + \delta \int_{\theta_L}^{\theta_H} U_{\mathrm{UAV}_k}^2(\theta_i^1) dF_k^2(\theta_i^1)
$$
$$
\geq \left[w_j^1 - E_i - \theta_i^1 p_j^1\right] + \delta \int_{\theta_L}^{\theta_H} U_{\mathrm{UAV}_k}^2\left(\theta_j^1\right) dF_k^2\left(\theta_j^1\right), \quad 1 \leq i, j, k \leq N. \tag{28}
$$

Next, considering that the type-θ_k^2 UAV's utility $U_{\mathrm{UAV}_k}^2(\theta_i^1)$ in stage 2 is independent of θ_i^1, that is, $\int_{\theta_L}^{\theta_H} U_{\mathrm{UAV}_k}^2(\theta_i^1) dF_k^2(\theta_i^1) = \int_{\theta_L}^{\theta_H} U_{\mathrm{UAV}_k}^2(\theta_j^1) dF_k^2(\theta_j^1)$. Then, the IC constraint in (28) can be simplified as

$$
w_i^1 - E_i - \theta_i^1 p_i^1 \geq w_j^1 - E_i - \theta_i^1 p_j^1. \tag{29}
$$

Then, considering the expected continuation utility in stage 2, the ith UAV's intertemporal IR constraint is defined as

$$
\left[w_i^1 - E_i - \theta_i^1 p_i^1\right] + \delta \int_{\theta_L}^{\theta_H} U_{\mathrm{UAV}_k}^2(\theta_i^1) dF_k^2(\theta_i^1) \geq 0. \tag{30}
$$

Therefore, the two-stage contract optimization problem can be given by

$$
\begin{aligned}
&\max_{\left\{w_i^1, p_i^1, w_k^2(\tilde{\theta}_i), p_k^2(\tilde{\theta}_i)\right\}} \quad U_{\mathrm{BS}}\left(w_i^1, p_i^1, w_k^2\left(\tilde{\theta}_i\right), p_k^2\left(\tilde{\theta}_i\right)\right) \\[2mm]
&\text{s.t.} \quad \begin{aligned}
&(\mathrm{IR1}) \quad w_i^1 - E_i - \theta_i^1 p_i^1 + \delta \int_{\theta_L}^{\theta_H} U_{\mathrm{UAV}_k}^2(\theta_i^1) dF_k^2(\theta_i^1) \geq 0 \\[2mm]
&(\mathrm{IR2}) \quad w_k^2\left(\tilde{\theta}_i\right) - E_i - \theta_k^2 p_k^2\left(\tilde{\theta}_i\right) \geq 0 \\[2mm]
&(\mathrm{IC1}) \quad w_i^1 - E_i - \theta_i^1 p_i^1 \geq w_j^1 - E_i - \theta_i^1 p_j^1 \\[2mm]
&(\mathrm{IC2}) \quad w_k^2\left(\tilde{\theta}_i\right) - E_i - \theta_k^2 p_k^2\left(\tilde{\theta}_i\right) \geq w_j^2\left(\tilde{\theta}_i\right) - E_i - \theta_k^2 p_j^2\left(\tilde{\theta}_i\right).
\end{aligned}
\end{aligned} \tag{31}
$$

5.3. Optimal Contract Design. Since the optimization problem in (31) is nonconvex, it is challenging to obtain a global optimal solution. Therefore, a sequential optimization method is proposed to obtain the optimal dynamic contract design.

5.3.1. Optimal Contract Design in Stage 2. Based on the idea of reverse induction, we first consider the situation of stage 2. Since the UAV's utility function $U^2_{\text{UAV}_k}(\tilde{\theta}_i)$ satisfies the following Spence-Mirrlees single crossing condition [33], that is

$$\frac{\partial}{\partial \theta_k^2} \left[-\frac{\partial \left[U^2_{\text{UAV}_k}(\tilde{\theta}_i) \right] / \partial \left[p_k^2(\tilde{\theta}_i) \right]}{\partial \left[U^2_{\text{UAV}_k}(\tilde{\theta}_i) \right] / \partial \left[w_k^2(\tilde{\theta}_i) \right]} \right] = \frac{\partial}{\partial \theta_k^2} [\theta_k^2] = 1 > 0,$$

$$(32)$$

we have

$$\frac{dU^2_{\text{UAV}_k}(\tilde{\theta}_i)}{d\theta_k^2} = -p_k^2(\tilde{\theta}_i) \le 0, \quad (33)$$

which means that the type-θ_k^2 UAV's utility $U^2_{\text{UAV}_k}(\tilde{\theta}_i)$ is decreasing in θ_k^2. So when θ_k^2 takes the maximum θ_H, we have $U^2_{\text{UAV}_k}(\tilde{\theta}_i)|_{\theta_k^2=\theta_H} = \min U^2_{\text{UAV}_k}(\tilde{\theta}_i) = 0$.

Thus, the type-θ_k^2 UAV's utility $U^2_{\text{UAV}_k}(\tilde{\theta}_i)$ in stage 2 can be written as

$$U^2_{\text{UAV}_k}(\tilde{\theta}_i) = U^2_{\text{UAV}_k}(\tilde{\theta}_i) \Big|_{\theta_k^2=\theta_H} - \int_{\theta_k^2}^{\theta_H} -p_k^2(\tilde{\theta}_i) d\tau$$

$$= \int_{\theta_k^2}^{\theta_H} p_k^2(\tilde{\theta}_i) d\tau. \quad (34)$$

By combining (34) with (7), the reward of the ith UAV in stage 2 can be obtained, that is,

$$w_k^2(\tilde{\theta}_i) = E_i + \theta_k^2 p_k^2(\tilde{\theta}_i) + \int_{\theta_k^2}^{\theta_H} p_k^2(\tilde{\theta}_i) d\tau. \quad (35)$$

Thus, the BS's expected utility U^2_{BS} in stage 2 is given by

$$U^2_{\text{BS}} = \sum_{i=1}^{N} \int_{\theta_L}^{\theta_H} \left[\rho_i \log \left(1 + p_k^2(\tilde{\theta}_i) \right) - E_i - \theta_k^2 p_k^2(\tilde{\theta}_i) \right.$$

$$\left. - \int_{\theta_k^2}^{\theta_H} p_k^2(\tilde{\theta}_i) d\tau \right] dF_k^2(\tilde{\theta}_i). \quad (36)$$

By changing the integration order of (36), the BS's expected utility U^2_{BS} in stage 2 can be simplified as

$$U^2_{\text{BS}} = \sum_{i=1}^{N} \int_{\theta_L}^{\theta_H} \left[\rho_i \log \left(1 + p_k^2(\tilde{\theta}_i) \right) - E_i - \theta_k^2 p_k^2(\tilde{\theta}_i) \right.$$

$$\left. - \int_{\theta_k^2}^{\theta_H} p_k^2(\tilde{\theta}_i) d\tau \right] dF_k^2(\tilde{\theta}_i)$$

$$= \sum_{i=1}^{N} \int_{\theta_L}^{\theta_H} \left[\rho_i \log \left(1 + p_k^2(\tilde{\theta}_i) \right) - E_i - \theta_k^2 p_k^2(\tilde{\theta}_i) \right] dF_k^2(\tilde{\theta}_i)$$

$$- \sum_{i=1}^{N} \int_{\theta_L}^{\theta_H} \int_{\theta_L}^{\theta_k^2} dF_k^2(\tilde{\theta}_i) p_k^2(\tilde{\theta}_i) d\tau_i$$

$$= \sum_{i=1}^{N} \int_{\theta_L}^{\theta_H} \left[\rho_i \log \left(1 + p_k^2(\tilde{\theta}_i) \right) - E_i - \theta_k^2 p_k^2(\tilde{\theta}_i) \right] dF_k^2(\tilde{\theta}_i)$$

$$- \sum_{i=1}^{N} \int_{\theta_L}^{\theta_H} H_K^2(\tilde{\theta}_i) p_k^2(\tilde{\theta}_i) dF_k^2(\tilde{\theta}_i)$$

$$= \sum_{i=1}^{N} \int_{\theta_L}^{\theta_H} \left[\rho_i \log \left(1 + p_k^2(\tilde{\theta}_i) \right) - E_i - \theta_k^2 p_k^2(\tilde{\theta}_i) \right.$$

$$\left. - H_k^2(\tilde{\theta}_i) p_k^2(\tilde{\theta}_i) \right] dF_k^2(\tilde{\theta}_i), \quad (37)$$

where $H_K^2(\tilde{\theta}_i) = F_k^2(\tilde{\theta}_i) / f_k^2(\tilde{\theta}_i)$.

5.3.2. Optimal Contract Design in Stage 1. Similarly, to the case of stage 2, we can find that the UAV's utility of stage 1 $U^1_{\text{UAV}_i}$ satisfies the Spence-Mirrlees single crossing condition (32). Then, we have

$$\frac{dU^1_{\text{UAV}_i}}{d\theta_i^1} = -p_i^1 \le 0, \quad (38)$$

which means that the UAV's utility of stage 1 $U^1_{\text{UAV}_i}$ is decreasing in θ_i^1. Then, we have $U^1_{\text{UAV}_i}(\theta_i)|_{\theta_i^1=\theta_H} = \min U^1_{\text{UAV}_i} = 0$. Thus, the UAV's utility of stage 1 $U^1_{\text{UAV}_i}$ can be written as

$$U^1_{\text{UAV}_i} = U^1_{\text{UAV}_i}(\theta_i) \Big|_{\theta_i^1=\theta_H} - \int_{\theta_i^1}^{\theta_H} (-p_i^1) d\tau = \int_{\theta_i^1}^{\theta_H} p_i^1 d\tau. \quad (39)$$

Then, by combining (27), (34), and (39), the reward of the ith UAV in stage 1 can be obtained, that is,

$$w_i^1 = \theta_i^1 p_i^1 + E_i + \int_{\theta_i^1}^{\theta_H} p_i^1 d\tau - \delta \int_{\theta_L}^{\theta_H} \int_{\theta_k^2}^{\theta_H} p_k^2(\theta_i^1) d\tau dF_k^2(\theta_i^1). \quad (40)$$

Thus, the BS's expected utility U^1_{BS} in stage 1 is given by

$$U^1_{\text{BS}} = \sum_{i=1}^{N} \int_{\theta_L}^{\theta_H} \left[\rho_i \log \left(1 + p_i^1 \right) - E_i - \theta_i^1 p_i^1 \right.$$

$$\left. - \int_{\theta_i^1}^{\theta_H} p_i^1 d\tau + \delta \int_{\theta_L}^{\theta_H} \int_{\theta_k^2}^{\theta_H} p_k^2(\theta_i^1) d\tau dF_k^2(\theta_i^1) \right] dF_i^1(\theta_i^1).$$

$$(41)$$

By changing the integration order of (41), the BS's expected utility U_{BS}^1 in stage 1 can be simplified as

$$
\begin{aligned}
U_{BS}^1 = \sum_{i=1}^{N} \int_{\theta_L}^{\theta_H} & \left[\rho_i \log\left(1+p_i^1\right) - E_i - \theta_i^1 p_i^1 \right. \\
& - \int_{\theta_i^1}^{\theta_H} p_i^1 d\tau + \delta \int_{\theta_L}^{\theta_H} \int_{\theta_k^2}^{\theta_H} p_k^2(\theta_i^1) d\tau dF_k^2(\theta_i^1) \Bigg] dF_i^1(\theta_i^1) \\
= \sum_{i=1}^{N} \int_{\theta_L}^{\theta_H} & \left[\rho_i \log\left(1+p_i^1\right) - E_i - \theta_i^1 p_i^1 - H_i^1(\theta_i^1)p_i^1 \right. \\
& + \delta H_k^2(\theta_i^1) p_k^2(\theta_i^1) \int_{\theta_L}^{\theta_H} dF_k^2(\theta_i^1) \Bigg] dF_i^1(\theta_i^1) \\
= \sum_{i=1}^{N} \int_{\theta_L}^{\theta_H} & \left[\rho_i \log\left(1+p_i^1\right) - E_i - \theta_i^1 p_i^1 - H_i^1(\theta_i^1)p_i^1 \right. \\
& + \delta H_k^2(\theta_i^1) p_k^2(\theta_i^1) \Bigg] dF_i^1(\theta_i^1),
\end{aligned}
$$

$$(42)$$

where $H_i^1(\theta_i^1) = F_i^1(\theta_i^1)/f_i^1(\theta_i^1)$.

Then, the BS's expected utility U_{BS} (6) can be obtained as

$$
\begin{aligned}
U_{BS} = \sum_{i=1}^{N} \int_{\theta_L}^{\theta_H} & \left[\rho_i \log\left(1+p_i^1\right) - E_i - \theta_i^1 p_i^1 \right. \\
& - H_i^1(\theta_i^1)p_i^1 + \delta \left[\rho_i \log\left(1+p_k^2(\theta_i^1)\right) \right. \\
& - E_i - \theta_k^2 p_k^2(\theta_i^1) \Big] \Bigg] dF_i(\theta_i).
\end{aligned}
$$

$$(43)$$

In order to simplify the following analysis, we defined

$$
\begin{aligned}
R\left(p_i^1, p_k^2(\theta_i^1)\right) = & \; \rho_i \log\left(1+p_i^1\right) - E_i - \theta_i^1 p_i^1 - H_i^1(\theta_i^1)p_i^1 \\
& + \delta \left[\rho_i \log\left(1+p_k^2(\theta_i^1)\right) - E_i - \theta_k^2 p_k^2(\theta_i^1) \right].
\end{aligned}
$$

$$(44)$$

Thus, the BS's expected utility U_{BS} can be rewritten as $U_{BS} = \sum_{i=1}^{N} \int_{\theta_L}^{\theta_H} [R(p_i^1, p_k^2(\theta_i^1))] dF_i(\theta_i)$. Then, the optimization problem (31) can be simplified as

$$
\max_{\{p_i^1, p_k^2(\theta_i^1)\}} \quad \sum_{i=1}^{N} \int_{\theta_L}^{\theta_H} \left[R\left(p_i^1, p_k^2(\theta_i^1)\right) \right] dF_i(\theta_i). \quad (45)
$$

Similarly, we can have the optimal transmission power of the ith UAV in stage 1 and stage 2, that is,

$$
\begin{cases}
p_i^{1*} = \dfrac{\rho_i}{\theta_i^1 + H_i^1(\theta_i^1)} - 1, \\[2ex]
p_k^{2*} = \dfrac{\rho_i}{\theta_k^2} - 1.
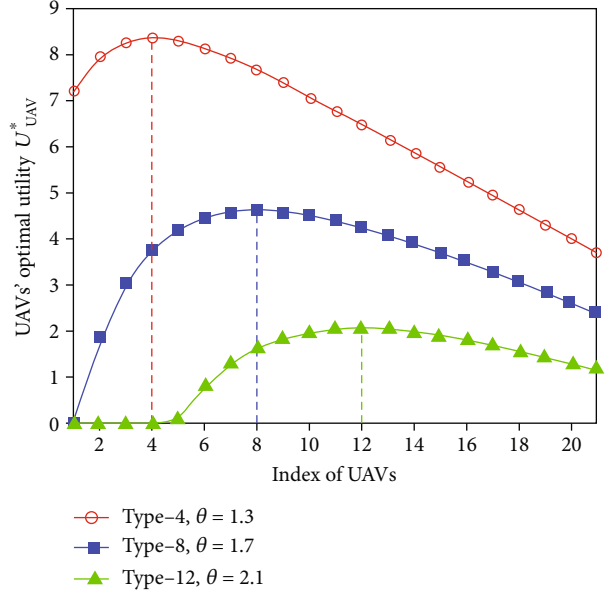\end{cases}
$$

$$(46)$$

FIGURE 3: UAV's optimal expected utility $U_{\text{UAV}_i}^*$ with the different types.

6. Numerical Results and Discussion

In this section, MATLAB simulation experiments are present to verify the proposed incentive mechanism. The experiment environment is composed of one BS and $N = 21$ UAVs. For simplicity, in our experiments, we assume that the type of UAV in stage 1 is the same as that in stage 2, that is, $\theta = \theta_i^1 = \theta_k^2$. The UAV's type θ is assumed to be uniformly distributed in the interval $[1, 3]$. The mobile energy consumption E_i of the UAV is uniformly distributed in the interval $[4, 8]$. In addition, the discount factor δ is set to $\delta = 0.3$. The profit per transmission capacity ρ_i is defined as $\rho_i = 15$.

First, we evaluated the optimal dynamic contract design for the private information discrimination under the asymmetric information scenario. Figure 3 shows the utilities of UAVs with the three types when choosing all contract items provided by the BS. Since the utility of each UAV is a convex function, each UAV can only acquire the maximum utility when selecting a contract related with its type. Through this form of contract design, the type of UAV can be automatically reflected to the BS. Then, the information asymmetric problem can be solved through the dynamic contract design. Moreover, each UAV can obtain the positive optimal utility. The optimal utility of the type-4 UAV is more than that of other types. The type-12 UAV obtains the lowest utility among the three types of UAVs. As the private information θ increases, the transmission cost of the UAV increases, which leads to the low obtained utility.

Figure 4 shows the performance of the UAV's optimal utility with the various discount factors δ. As the private information of each UAV θ increases, its transmission cost increases, resulting in a decrease in the obtained utility. Moreover, while the discount factor δ increases, the time
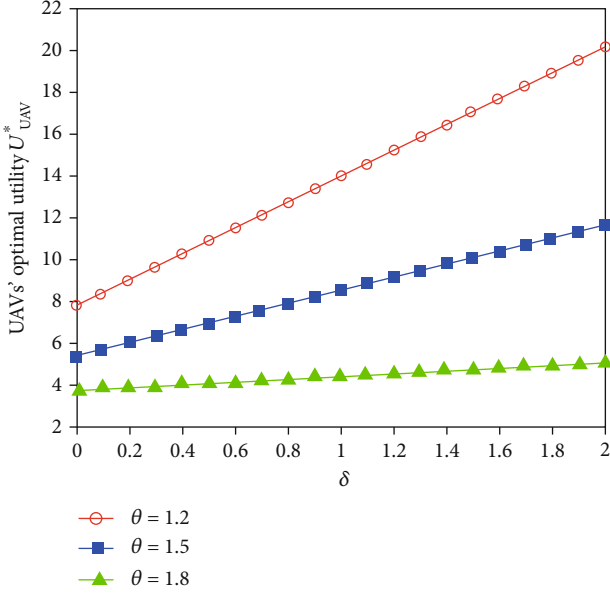
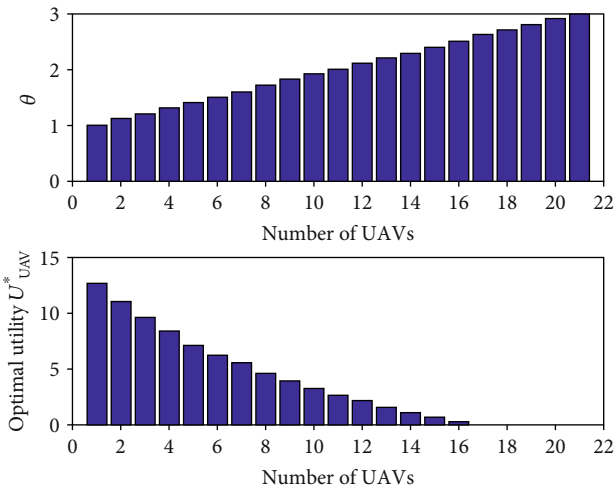FIGURE 4: UAV's optimal expected utility $U^*_{UAV_i}$ vs. the discount factor δ.

FIGURE 5: The optimal utility of each UAV $U^*_{UAV_i}$ with different types of UAVs.

FIGURE 6: BS's optimal utility U^*_{BS} with the different distributions of UAV's types.
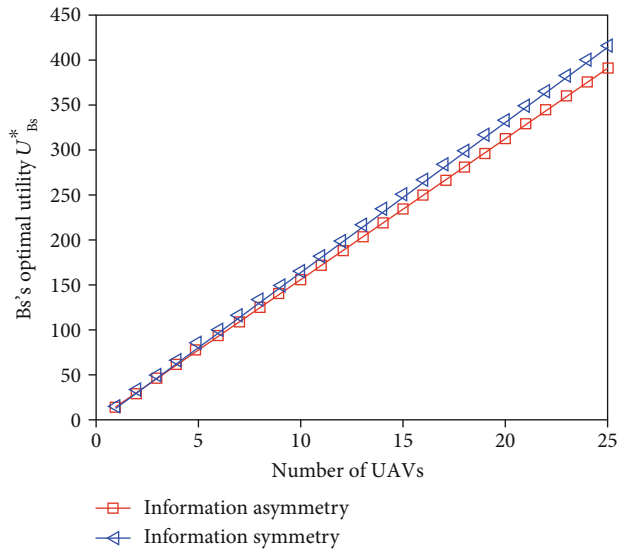
FIGURE 7: BS's optimal utility U^*_{BS} as a function of the UAV's number.

for traffic offloading increases with the increasing utility of each UAV.

Figure 5 describes the relationship between the type of each UAV θ and the corresponding optimal utility $U^*_{UAV_i}$. As the type of each UAV increases, the cost of the UAV increases with the low achieved utility $U^*_{UAV_i}$. In addition, when the type of UAVs increases to a certain extent, the transmission cost of UAVs is too high to obtain no utility.

Next, the performance is considered with the three different distributions of UAVs' types. In case A, all types of UAVs are uniformly distributed in the interval [1, 3] with $f(\theta) = 1/2$. In case B, the probability of the lower type is greater than that of the higher type with $f(\theta) = (8 - \theta)/5$. In case C, the probability of the higher type is less than that of the lower type with $f(\theta) = \theta/9$. Figure 6 shows the BS's optimal utility U^*_{BS}
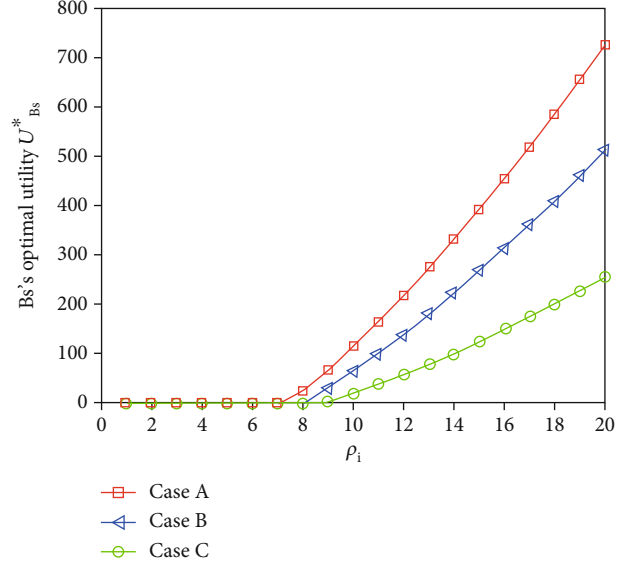
under the above three different distributions of the types. We can find that the BS's utility U^*_{BS} increases with an increase of ρ_i in all the three cases. Moreover, as ρ_i increases, there are similar increase tendencies of the BS's utility in all the three cases. However, when the amount of ρ_i is too small, the UAV may be not willing to participate in traffic offloading, which leads to the zero utility of the BS.

Finally, we study the performance under both the symmetric information and asymmetric information scenarios. Figure 7 shows the BS's optimal utility U^*_{BS} with the different numbers of UAVs. As the number of UAVs increases, the BS's optimal utility U^*_{BS} increases in the two scenarios. In addition, in the case of symmetric information, since the type
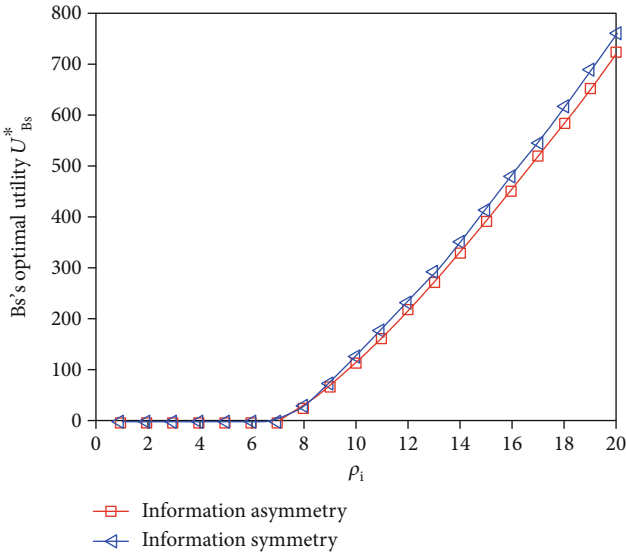
FIGURE 8: BS's optimal utility with the different equivalent profits ρ_i.

information of each UAV is known by the BS, the BS can better select the UAVs for traffic offloading. Therefore, the BS's optimal utility U_{BS}^* under the symmetric information scenario is higher than that in the case of the information asymmetry.

Figure 8 presents the BS's optimal utility U_{BS}^* with the various equivalent profits ρ_i. In the symmetric information scenario, since the BS knows the private information of each UAV, with the increase of ρ_i, the BS's optimal utility under the symmetric information scenario is higher than that in the case of asymmetric information. In addition, when the value of ρ_i is very small, the UAV may be not willing to perform traffic offloading for the BS, which makes the BS's utility close to zero.

7. Conclusions and Future Work

In this paper, a dynamic incentive mechanism is proposed in multi-UAV networks. In order to attract UAVs to participate in traffic offloading, a two-stage dynamic contract is introduced. Traffic offloading with the help of UAVs is regarded as the labour market. The BS designs the contract including the transmission powers and rewards of the UAVs. In addition, based on the feature of network information, two information scenarios are studied. Under the asymmetric information scenario, the designed contract needs to meet the IR constraints. As for the asymmetric information scenario, the optimal contract should satisfy both IR and IC constraints to motivate the UAVs to take part in traffic offloading. A sequence optimization algorithm is proposed to achieve the optimal contract design. The experimental results show that the two-stage dynamic contract design can improve the system performance effectively.

This paper investigates a multi-UAVs incentive mechanism for traffic offloading. For the future work, we will consider how to design the incentive mechanism with multiple BSs and multiple UAVs. The BSs may design contracts and

compete to attract UAVs to participate in traffic offloading for their own hotspot areas. Moreover, the proposed two-stage dynamic contract model will be extended to the multi-stage scenario. In this case, it will be much more challenging to obtain the optimal contract design. Furthermore, a multi-UAV traffic offloading simulator will be considered to make simulation experiments more practical.

Data Availability

No data were used to support this study.

Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

Acknowledgments

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