Research on Bandwidth-Oriented Distributed Task Allocation Mechanism for Multi-UAV

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***Abstract*—Bandwidth resources are crucial for the internal communication and task execution of multi-UAV systems. However, traditional allocation models for multi-UAV system are inefficient and result in low utility of UAVs. To overcome this challenge, this paper proposes a novel bandwidth-oriented task allocation model that accounts for the supply-demand relationship between UAVs and tasks for bandwidth resources. To solve this model, this paper presents a Double Auction-based Task Allocation Mechanism, which can achieve distributed allocation of tasks and bandwidth among multi-UAV. The main steps of this mechanism are as follows: (1) each UAV privately submits its bandwidth demand and bids for each task; (2) each task determines the bandwidth price and initial allocation based on the bids, and announces them to each UAV; (3) each UAV selects the task that maximizes its utility, and obtains the final allocation. Furthermore, this paper proves that this mechanism satisfies desirable economic properties such as individual rationality, budget balance, and incentive compatibility. Finally, experimental results show that the proposed mechanism exhibits excellent performance in terms of UAV and task utility, as well as the rate of bandwidth allocation.**

***Index Terms*—Multi-UAV, Distributed double auction, Task allocation, Mechanism design.**

I. Introduction

Unmanned Aerial Vehicles (UAVs) have become increasingly popular and useful in various fields [1], thanks to the rapid advancement of the Internet of Things and Artificial Intelligence. UAVs are well-known for their flexibility and high maneuverability, and have been widely used in various applications such as rescue [2], urban inspection [3]. Multi-UAV cooperation is an effective way to enhance task efficiency, as it can overcome the limitations of individual UAV's resource and capability. However, this also poses a new challenge, which is how to allocate tasks among multi-UAV in a reasonable way. The multi-UAV task allocation problem involves assigning tasks to suitable UAVs based on various factors, such as task requirements and UAV characteristics, and establishing mapping relationships between tasks and UAVs. This is a complex optimization problem that requires considering multiple constraints and objectives.

However, existing models and methods suffer from the following problems. *Firstly*, the common methods to multi-UAV task allocation problem typically employ greedy algorithm [4], genetic algorithm [5], particle swarm algorithm [6]. As the scale of swarms expands, the allocation scheme increases exponentially, resulting in a significant increase in the computational complexity of these algorithms. *Secondly*, as the medium of UAV data transmission, bandwidth resources play a key role in communication systems. Most researches in multi-UAV task allocation simplifies the problem by neglecting the bandwidth resource. Additionally, there is a scarcity of research concerning bandwidth pricing strategy and its allocation rate. *Thirdly*, as a classical method in mechanism design, double auction [7] is widely employed in task allocation. In a double auction, there are three primary entities, including buyers, sellers, and the auctioneer, with the auctioneer serving as the centralized control entity responsible for organizing and conducting the auction process. It is worth noting that the design of effective auction mechanisms can encourage UAVs and tasks to participate honestly in the auction, thus achieving efficient allocation. Therefore, designing an incentive mechanism is a key challenge in the multi-UAV task allocation problem. *Finally*, given the single point of failure and limited flexibility of centralized mechanism in large-scale swarms, it is necessary to design a distributed mechanism for this scenario.

To address these problems, considering the supply-demand relationship of bandwidth resources, we research the bandwidth-oriented task allocation model for multi-UAV. For this model, we propose a Double Auction-based Task Allocation Mechanism (DATAM). The primary contributions of this paper are summarized as follows:

- Considering the supply-demand relationship between UAVs and tasks for bandwidth resources, we introduced a bandwidth-oriented task allocation problem for multi-

UAV and modeled it based on double auction.

- For the proposed model, we designed a DATAM mechanism, enabling the three stages of UAV bidding, winner determination and task determination in a distributed manner. Moreover, we theoretically proved the economic properties satisfied by the proposed mechanism.
- To demonstrate the effectiveness of the mechanism, we conducted various experiments. The results confirmed that the proposed mechanism exhibits superior performance in terms of UAV and task utility, as well as the rate of bandwidth allocation.

The remaining sections of this paper are structured as follows: Section II provides an overview of related work on multi-UAV task allocation. Section III presents a formalized expression of the bandwidth-oriented task allocation model for multi-UAV. Section IV introduces a detailed description of the proposed DATAM mechanism. Section V demonstrates the effectiveness of the mechanism through experiments. Finally, Section VI conclude the paper.

II. Related Work

Multi-agent task allocation is a research hotspot in the field of artificial intelligence, and has been extensively studied by researchers in recent years. In this section, we review the related work on two aspects: multi-UAV task allocation and double auction mechanisms.

A. Multi-UAV Task Allocation

Multi-UAV task allocation has been a significant research topic, both in both military and civilian domains. For example, D. Liu et al. [8] addressed the heterogeneous UAV task allocation problem in uncertain environments by proposing a dynamic task allocation algorithm based on multi-agent reinforcement learning, which diminished the load of online computation. In the context of task data dependencies and UAV energy constraints, literature [9] investigated the joint problem of task allocation and bandwidth resource allocation to minimize task latency. However, these methods are not suitable for large-scale swarms. Literature [10] tackled the task offloading problem in UAV-enabled MEC systems via a greedy heuristic-based dynamic scheduling framework. Z. Ning et al. [11] employed an auction algorithm to determine UAV flight trajectories, optimizing for maximum average throughput. They proposed a dynamic task acceptance algorithm to effectively resolve task scheduling problems. However, these literatures do not consider the supply-demand relationship of bandwidth and cannot meet the communication resource demand of UAVs.

B. Double Auction Mechanisms

Double auctions [7], involve “many-to-many” transaction scenarios among multiple buyers and sellers. They have been extensively applied in various fields such as edge computing [12], smart grids [13], and task allocation [14]. For example, X. Li et al. [15] employed a double spectrum auction model to address cross-domain, multi-timeslot wireless spectrum allocation problems, thereby enhancing spectrum reuse. J. Zhu et al. [14] proposed a greedy double auction mechanism for effective job allocation. N. Qi et al. [16] extended the double auctions framework and introduced a group-buying coalition auction approach, encouraging sensors to form coalitions for data collection by UAVs while ensuring economic properties. However, the above methods are centralized and not suitable for distributed scenarios.

Brief conclusion. Unlike the scenarios discussed above, our research primarily focuses on the bandwidth-oriented task allocation scenario for large-scale swarms. To address the proposed model, we design the DATAM-MU mechanism based on double auction, which exhibits excellent performance in terms of UAV and task utility and the rate of bandwidth allocation, while satisfying essential economic properties.

III. Problem Definition

A. System Model

In this section, we present the system model for the application scenario of multi-UAV task allocation problem, as shown in Fig. 1. Let $\mathcal{T} = \{1, 2, \ldots, M\}$ denote the set of M tasks, $\mathcal{U} = \{1, 2, \ldots, N\}$ denote the set N UAVs. In this model, we assume the absence of a centralized control entity within the model. The interaction between UAVs and tasks is conducted in a *distributed double auction*, all within the constraints of finite bandwidth resources. Each UAV $i \in \mathcal{U}$ is considered as a buyer, and each task $j \in \mathcal{T}$ is considered as a seller. In order to meet their bandwidth demands, UAVs must compete with each other for tasks to enhance their own utility.

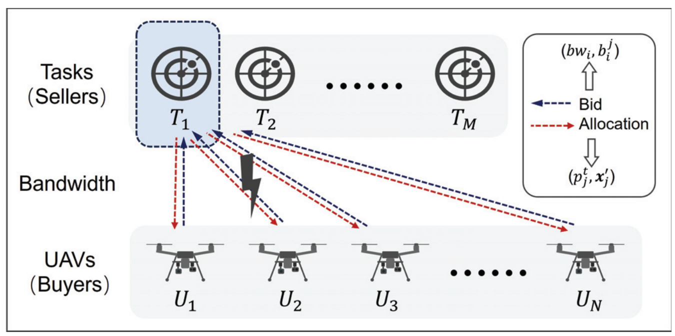


Fig. 1. The schematic diagram for system model.

Suppose that the bandwidth resource required by UAV i is bw_i, and each UAV competes for bandwidth resources by submitting bid to acquire them. Let the *bid vector* and *valuation vector* for UAV i for all tasks be denoted as $\boldsymbol{b_i} = (b_i^1, b_i^2, \cdots, b_i^M)$ and $\boldsymbol{v_i} = (v_i^1, v_i^2, \cdots, v_i^M)$ respectively, where b_i^j represents the bid made by UAV i for the unit of bandwidth resource provided by task j, and these bids are used to determine the winners in the auction and v_i^j represents the value that UAV i obtain after receiving a unit of bandwidth resource by task j. It is worth noting that these bids and valuations are all about the price per unit bandwidth resource. Additionally, after winning in the auction, UAV i must pay the final price for a unit of bandwidth, denoted as p_i^u.

Suppose that task j has a total bandwidth resource of BW_j and requires a maximum of c_j UAVs. In a single round of the auction, we assume that BW_j and c_j of task j remain constant, and the task attributes are disclosed to each UAV before the auction starts, and then decide whether to allot the task to the UAV according to the bidding information. Additionally, the task will set the price for a unit of bandwidth and broadcast it to all UAVs, denoted as p_j^t.

B. Problem Description

In this section, we use the framework of double auction to formalize the multi-UAV task allocation problem, and focus on designing an incentive mechanism to solve the problem, which enhances the utility of UAVs and tasks while meeting the bandwidth demands of the UAVs. We define the multi-UAV task allocation *matrix* as $X = \{x_{ij}\}_{N\times M}$, where $x_{ij} = 1$ indicates that UAV i is allocated to task j, and 0 otherwise.

Next, we define the utility of UAV i as U_i^u, which is the difference between the value obtained by UAV i after completing task j and the payment. Formally, $U_i^u = \sum_{j=1}^{M} x_{ij} bw_i (v_i^j - p_i^u), \forall i \in \mathcal{U}$. Similarly, we define the utility of task j as U_j^t, representing the payment received by task j after allocation to UAVs. Formally, $U_j^t = \sum_{i=1}^{N} x_{ij} bw_i p_j^t, \forall j \in \mathcal{T}$.

The auction process can be divided into task allocation and payment calculation. In this paper, we propose the following *assumptions* for the auction model: UAVs can bid for any task, whith is not limited by region or capability. There is no collusion among UAVs, that is, the buyers are not know each other's bids and valuations. All UAVs are rational, and their objective is to maximize their utility.

Thus, the constraints for the multi-UAV task allocation problem in this model are as follows: (1) $\sum_{j=1}^{M} x_{ij} \le 1, \forall i \in \mathcal{U}$, (2) $\sum_{i=1}^{N} x_{ij} \le c_j, \forall j \in \mathcal{T}$, (3) $\sum_{i=1}^{N} bw_i x_{ij} \le BW_j, \forall j \in \mathcal{T}$. Among the above constraints, equation (1) ensures that each UAV can only execute one task, equation (2) ensures that the number of UAVs required to execute a task does not exceed the maximum required for that task, equation (3) ensures that the bandwidth resource required by UAVs to execute a task is not more than the total bandwidth resource of that task.

IV. DATAM Mechanism Design

In order to design a practical mechanism, it is necessary to consider the utility and the economic properties. In this section, we introduce the DATAM mechanism which satisfied essential economic properties, such as Individual Rational, Budget Balanced and Incentive Compatible. The truthful mechanism ensures the fairness and efficiency of allocation. This mechanism realizes the matching between buyers and sellers in a distributed manner, consisting of three key phases: (1) the UAV bidding phase, (2) the Winning UAV Determination phase (DATAM-WD), (3) the Task Determination phase (DATAM-TD). In the bidding phase, each buyer broadcasts their bids to the sellers, including bandwidth demands and bids. In the winning UAV determination phase, sellers assess the bids and determine the winning buyer and the their selling prices. During the task determination phase, buyers determine the final seller based on the decisions of the sellers.

It is worth noting that the mechanism determines the winner in a distributed manner, a buyer can be selected by multiple sellers, but a buyer can only select one seller. Therefore, each buyer evaluates the utility obtained from the pool of potential sellers to choose the optimal one. Now, we describe the DATAM-WD and DATAM-TD mechanisms in detail.

A. DATAM-WD Mechanism

In this section, we provide a detailed explanation of the DATAM-WD mechanism, as presented in *Algorithm 1*. In this mechanism, each seller determines the winning buyers based on their bid vectors and bandwidth demand vectors.

Algorithm 1: DATAM-WD Mechanism

Input: Bidding vector $\boldsymbol{b^j} = (b_1^j, b_2^j, \ldots, b_N^j), \forall j \in \mathcal{T}$,
Bandwidth vector $\boldsymbol{bw} = (bw_1, bw_2, \ldots, bw_N)$
Output: Seller's price p_j^t, the winner determines the vector $\boldsymbol{x_j'} = \{x_{ij}'\}, \forall i \in \mathcal{U}$

1 Initialization: $W_j \leftarrow \emptyset$; $W_j' \leftarrow \emptyset$; $x_{ij}' \leftarrow 0, \forall i \in \mathcal{U}$; $count \leftarrow 1$; $sum \leftarrow 0$
2 **foreach** $i \in \mathcal{U}$ **do**
3   **if** $bw_i < BW_j$ **then**
4         $W_j \leftarrow W_j \cup \{i\}$
5   **end**
6 **end**
7 Sort W_j in decreasing order of b_i^j: $b_1^j \ge b_2^j \ge \cdots \ge b_N^j$
8 **foreach** $i \in W_j$ **do**
9   **if** $count \le c_j$ **then**
10   **if** $sum \le BW_j$ **then**
11             $W_j' \leftarrow W_j' \cup \{i\}$
12             $count \leftarrow count + 1$
13             $sum \leftarrow sum + bw_i$
14   **else**
15   break
16   **end**
17   **else**
18   break
19   **end**
20 **end**
21 $p_j^t \leftarrow b_{count}^j$
22 $x_{ij}' \leftarrow 1, \forall i \in W_j'$
23 **return** $p_j^t, \boldsymbol{x_j'}$

The DATAM-WD mechanism first initializes the winning buyers set and the winning decision vector (Line 1). To ensure that the bandwidth demand of each buyer does not exceed the maximum bandwidth resource constraint, buyers whose demands cannot be met are excluded from the set of winning buyers (Lines 2-6). Next, the qualified buyers are sorted in *decreasing order* of their bids (Line 7), which is the core idea of the DATAM-WD mechanism. Based on the task's bandwidth resource and the number of UAVs required, the mechanism *greedily* adds eligible buyers to the set of winning buyers. It selects a maximum of c_j buyers from the sorted list while ensuring that their combined bandwidth demands do not exceed the seller's total bandwidth resourse BW_j (Lines 8-20).

At this point, the selected buyers are marked as winners, and the seller's price p_j^t is set to the bid of the buyer with index $count$ in the set W_j (Lines 21-22).

B. DATAM-TD Mechanism

In this section, we provide a detailed explanation of the DATAM-TD mechanism, as shown in *Algorithm 2*. In this mechanism, each buyer determines the seller's task and the price for bandwidth by receiving the seller's winning decision vector and price for a unit of bandwidth resource.

Algorithm 2: DATAM-TD Mechanism

Input: The winner determines the vector $\boldsymbol{x'_j}$, Seller's price $p_j^t, \forall j \in \mathcal{T}$
Output: Buyer's price p_i^u, The allocation vector $\boldsymbol{x_i} = \{x_{ij}\}, \forall j \in \mathcal{T}$
1 Initialization: $x_{ij} \leftarrow 0, \forall j \in \mathcal{T}$
2 $r \leftarrow \sum_{j \in \mathcal{T}} x'_{ij}$
3 **if** $r = 0$ **then**
4     $x_{ij} \leftarrow 0$; $p_i^u \leftarrow 0$
5 **else**
6   **if** $r = 1$ **then**
7   **foreach** $j \in \mathcal{T}$ **do**
8   **if** $x'_{ij} = 1$ **then**
9                 $j^* \leftarrow j$; $x_{ij^*} \leftarrow 1$; $p_i^u \leftarrow p_{j^*}^t$
10   break
11   **end**
12   **end**
13   **else**
14         $max \leftarrow 0$
15   **foreach** $j \in \mathcal{T}$ **do**
16   **if** $x'_{ij} = 1$ **then**
17                 $U_i^u \leftarrow bw_i(x'_{ij} v_i^j - p_j^t)$
18   **if** $U_i^u > max$ **then**
19                     $max \leftarrow U_i^u$; $j^* \leftarrow j$
20   **end**
21   **end**
22   **end**
23         $x_{ij^*} \leftarrow 1$; $p_i^u \leftarrow p_{j^*}^t$
24   **end**
25 **end**
26 **return** $p_i^u, \boldsymbol{x_i}$

The DATAM-TD mechanism first initializes the seller's decision vector to 0, indicating that the set of sellers is initially an empty set (Line 1). The mechanism then computes the number of winners r that the buyer is assigned (Line 2). The main part of the mechanism is to determine the seller and the payment. If $r = 0$, it means the buyer has not been assigned any winners, and both the price and decision vector are set to 0 (Lines 3-4). However, if the buyer has been assigned winners, they choose a seller based on different strategies. Specifically, if the buyer has only one seller (i.e. $r = 1$), they choose that seller (Lines 5-13). If the buyer has multiple sellers (i.e.$r > 1$), it can select the seller that maximizes its utility (Lines 14-24). To ensure that there is no direct relationship between the final price and the bids of both buyers and sellers, we use the seller's bid as the payment for the buyer, ensuring that the final price are independent of the bids made by both parties, thereby encouraging honest bidding during the auction.

C. Proof of Economic Properties

After a detailed description of the DATAM mechanism, we then prove the economic properties of the mechanism.

Theorem 1: DATAM is Individually Rational.

Proof: In the DATAM mechanism, for a UAV, if UAV i loses the auction, then $p_i^u = 0$ and $x_{ij} = 0$. Since $v_i^j > 0$, the UAV's utility $U_i^u = x_{ij} bw_i (v_i^j - p_i^u) = 0$. Conversely, if $x_{ij} = 1$, then since no UAV would pay more than its own bid, i.e., $b_i^j \geq b_{count}^j = p_i^u$, the UAV's utility $U_i^u = bw_i(v_i^j - p_i^u) = bw_i(b_i^j - p_i^u) \geq 0$. For a task, the task's utility $U_i^t = \sum_{i=1}^{N} x_{ij} bw_i p_j^t \geq 0$. Thus, all UAVs and tasks can achieve non-negative utilities in the auction, demonstrating that the DATAM mechanism is individually rational. ■

Theorem 2: DATAM is Budget Balanced.

Proof: In the DATAM mechanism, the payment p_i^u made by each UAV is equal to the price p_j^t of the task. Therefore, we can deduce that $\sum_{i \in \mathcal{U}} x_{ij} bw_i p_i^u = \sum_{i \in \mathcal{U}} x_{ij} bw_i p_j^t, \forall j \in \mathcal{T}$. This shows that the total amount paid by all UAVs for the tasks is equal to the total revenue collected by the tasks. Thus, the DATAM mechanism is budget-balanced. ■

Theorem 3: DATAM is Incentive Compatible.

Proof: To achieve higher utility U_i^u, a UAV may consider submitting a false bid. Let v_i^j be the true valuation, b_i^j the true bid, $\hat{b}_i^j$ the false bid, U_i^u the true utility, and $\hat{U}_i^u$ the false utility. We need to show that for a UAV i, if $\hat{b}_i^j \neq b_i^j$, it's not possible to have $\hat{U}_i^u > U_i^u$. We consider various scenarios:

Scenario 1: If $x'_{ij} = 0$ and $b_i^j = v_i^j$, then $b_{count}^j \geq b_i^j = v_i^j$ and $U_i^u = 0$.

Case 1: UAV i loses task j by submitting a false bid $\hat{b}_i^j < b_{count}^j$, but $\hat{b}_i^j \neq b_i^j$. Hence, the false utility $\hat{U}_i^u = U_i^u = 0$.

Case 2: UAV i wins task j by submitting a false bid $\hat{b}_i^j \geq b_{count}^j$, where $x_{ij} = 1$. With $p_i^u = b_{count}^j$, the false utility $\hat{U}_i^u = bw_i(v_i^j - p_i^j) \leq bw_i(b_{count}^j - p_i^j) = 0$. Hence, the false utility $\hat{U}_i^u \leq U_i^u = 0$.

Scenario 2: If $x'_{ij} = 1$ and $b_i^j = v_i^j$, then $v_i^j = b_i^j \geq b_{count}^j$ and $U_i^u = bw_i(v_i^j - p_i^u)$.

Case 3: If UAV i submits a false bid $\hat{b}_i^j < \min_{j \in \mathcal{T}} b_{count}^j$ and loses all tasks j, i.e., $x'_{ij} = 0, \forall j \in \mathcal{T}$, the false utility is $\hat{U}_i^u = 0$. Hence, the false utility $U_i^u = bw_i(v_i^j - p_i^u) \geq 0 = \hat{U}_i^u$.

Case 4: If UAV i wins task j by submitting a false bid $\hat{b}_i^j \neq b_i^j \geq b_{count}^j$, where $x'_{ij} = 1$, then $p_i^u = b_{count}^j$, and the UAV's payment does not depend on the bid b_i^j. Hence, the false utility $\hat{U}_i^u = U_i^u$.

Scenario 3: If $x'_{ij} = 0$, $x'_{ij'} = 1$, and $b_i^j = v_i^j$, then $v_i^j = b_i^j < b_{count}^{j'}$ and $U_i^u = bw_i(v_i^j - p_i^u)$. Define the payment of task j as p_{ij}^u, the payment of task j' as $p_{ij'}^u$ and the payment of task j' under the false bid as $\hat{p}_{ij'}^u$.

Case 5: If UAV i wins task $j' \neq j$ by submitting a false bid $b_{count}^{j'} \leq \hat{b}_i^j < b_{count}^j$, where $x_{ij'} = 1$, then the false utility $\hat{U}_i^u = bw_i(v_i^{j'} - \hat{p}_{ij'}^u) = bw_i(v_i^{j'} - p_{ij'}^u) \leq bw_i(v_i^j - p_{ij}^u) = U_i^u$.

Case 6: If UAV i wins task $j' \neq j$ by submitting a false bid $b^{j'}_{count} \leq \hat{b}^j_i < b^j_{count}$, where $x_{ij'} = 1$, then the false utility $\hat{U}^u_i = bw_i(v^{j'}_i - \hat{p}^u_{ij'}) = bw_i(v^{j'}_i - b^{j'}_{count}) \leq bw_i(b^{j'}_{count} - b^{j'}_{count}) = 0 \leq U^u_i$.

In all cases, the false utility either remains the same or is less than the true utility. Therefore, UAVs do not have an incentive to submit false bids to increase their utility. Thus, the DATAM mechanism is Incentive Compatible. ■

D. Computational Complexity

In this section, we analysis the computational complexity of the DATAM mechanism.

Theorem 4: The computational complexity of DATAM is $\mathcal{O}(N^2 \log N + M^2)$.

Proof: The DATAM consists of two main parts, DATAM-WD and DATAM-TD. As for the DATAM-WD, the primary time complexity involves sorting the buyers based on their bids and determining the subset of winning buyers. This has a time complexity of $\mathcal{O}(N \log N + N)$. As for the DATAM-TD, its time complexity depends on the number of sellers. This has a time complexity of $\mathcal{O}(M)$. Given that there are M tasks and N UAVs, the total time complexity of the DATAM mechanism is $\mathcal{O}(N^2 \log N + M^2)$. ■

V. Experimental simulation and analysis

In this section, we validate the effectiveness of the DATAM mechanism through experiments. The experimental code is implemented in Python[1], and the computer's processor and memory parameters are as follows: AMD Ryzen 7 5800H with Radeon Graphics (16 CPUs) and 16GB RAM.

A. Experiment Settings

In this section, we introduce relevant data in our experiments. Unless otherwise specified, the parameters for the experiments are set as shown in Table I.

To accommodate large-scale swarm scenarios, we generate the number of UAVs ranging from 70 to 130, with a step size of 10. The total bandwidth resources for each task follow a uniform distribution within the interval $[20, 25]$, and the bandwidth demands for each UAV follow a uniform distribution within the interval $[20/\beta N, 25/\beta N]$. Given that the simulated data is randomly generated, in order to reduce the impact of randomness on experimental results, all experiments in this section are averaged after 200 consecutive executions of the mechanism, and the results are analyzed accordingly.

B. Experiment Results and Analysis

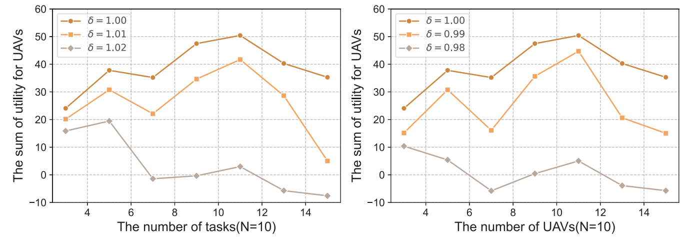
1) Incentive compatibility: As shown in Fig. 2, to validate the incentive compatibility of the DATAM mechanism, we compare the sum utility of UAVs as the number of tasks increases under different valuation ratio factors, $\delta = b^j_i / v^j_i$. We set values of δ as 0.98, 0.99, 1.00, 1.01 and 1.02, representing the UAVs' valuation of bandwidth resources.

We compare the total utility of UAVs when the number of tasks $N = 10$. When $\delta < 1$, it indicates that UAVs submitted

[1]Our code is publicly available at https://github.com/Agentyzu/DATAM.

TABLE I
SIMULATION PARAMETERS

Parameters	Descriptions	Values
M	Number of tasks	[70,130]
N	Number of UAVs	[80,100]
bw_i	Bandwidth demanded by the UAV i	$[20/\beta N, 25/\beta N]$
BW_j	Bandwidth supplied by the task j	[20,25]
c_j	Maximum number of UAVs for task j	[3,5]
δ	Valuation ratio factor	[0.98,1.02]
β	Supply-demand ratio factors	[1,1.4]

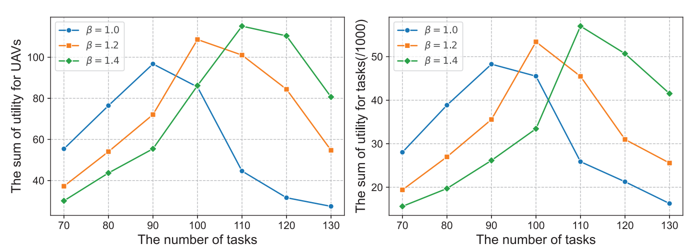


(a) (b)

Fig. 2. The sum of utility for UAVs under different δ values.

bids lower than their valuations. when $\delta > 1$, it indicates that UAVs submitted bids higher than their valuations. When $\delta = 1$, UAVs submitted truthful bids, with their bids equal to their valuations. The results indicate that as the number of tasks M increases, if $\delta \neq 1$, the total utility of UAVs is lower than the utility under truthful bidding. In other words, deceptive bidding does not improve the buyers' utility and can even result in negative utility. This because, when UAVs submit excessively high bids, although some of them become winners, they are ultimately required to pay higher or even more than its valuation, leading to negative utility.

2) The sum of utility for UAVs and tasks: As shown in Fig. 3, to validate the mechanism in large-scale swarm scenarios, we expand the scale of both UAVs and tasks in our experiments. We compare the sum utility of UAVs and tasks as the number of tasks increased under different supply-demand ratio factors, $\beta = \sum_{j \in \mathcal{T}} BW_j / \sum_{i \in \mathcal{U}} bw_i$. We set values of β to be 1.0, 1.2, and 1.4, representing the supply and demand of bandwidth resources.

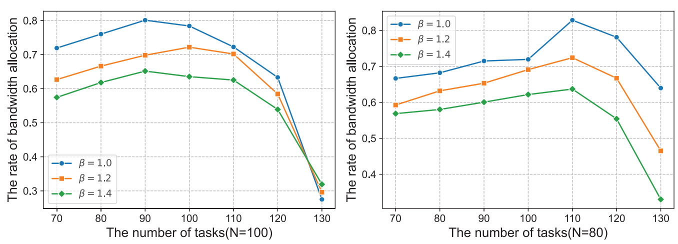


(a) (b)

Fig. 3. The sum of utility for UAVs and tasks under different β values.

We compare the total utility of UAVs under the different number of tasks when $N = 100$. The results indicate that as the number of tasks increases, the total utility of both UAVs and tasks initially increases and then decreases. The reason for this is that with the increase in the number of tasks, there is a greater availability of bandwidth resources from tasks, enabling most UAVs to be allocated tasks, thus increasing the utility for both UAVs and tasks. However, as the number of tasks continues to increase, the competition among tasks becomes more intense, leading to a decline in utility. When β increases, the corresponding peak in the curve is higher, and this corresponds to a larger number of tasks. The reason for this is that the greater abundance of available bandwidth makes it easier for UAVs to compete for more tasks, thus enhancing the overall utility. Tasks can attract more UAVs for execution, further contributing to the increase in total utility.

3) The rate of bandwidth allocation: As shown in Fig. 4, we compare the rate of bandwidth allocation r as the number of tasks increased under different supply-demand ratio factors. The rate of bandwidth allocation is defined as $r = \sum_{i\in\mathcal{U}}\sum_{j\in\mathcal{T}} x_{ij}bw_i / \sum_{j\in\mathcal{T}} BW_i$.



(a) (b)

Fig. 4. The rate of bandwidth allocation under different β values.

We compare the rate of bandwidth allocation under the different number of tasks when $N = 80, 100$. The results indicate that as the number of tasks increases, the rate of bandwidth allocation increases initially and then decreases. The reason for this is that the competition for bandwidth among UAVs intensifies with the increasing number of tasks, resulting in a higher bandwidth allocation rate during this phase. However, when the number of tasks continues to increase, the bandwidth supplied by tasks become more sufficient, yet the bandwidth obtained by UAVs tend to remain stable, resulting in the decrease of the bandwidth allocation rate.

VI. Conclusion

In this paper, we address the problem of bandwidth-oriented task allocation for multi-UAV systems, where the bandwidth resources of tasks and UAVs are heterogeneous. To solve this problem, we propose a distributed DATAM mechanism based on double auction, which allows UAVs to bid for tasks according to their own bandwidth demands and availabilities. Our mechanism has several desirable properties, such as individual rationality, budget balanced, incentive compatibility, which we prove theoretically. Moreover, we conduct extensive experiments to evaluate the performance of our mechanism and compare it with other existing mechanisms. The experimental results show that our mechanism achieves high utility for both UAVs and tasks, as well as efficient bandwidth allocation, demonstrating its effectiveness and superiority.

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