An Incentive Mechanism for Computation Offloading in Satellite-Terrestrial Internet of Vehicles

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Abstract—With the development of satellite-terrestrial technology and the popularity of Internet of Vehicles (IoV), how to improve the efficiency of mobile cloud computing (MCC) has become the next concern. It is still challenging for cloudlets to motivate vehicle owners to join the process. To this end, we design a satellite-terrestrial IoV based incentive mechanism for computation offloading (IMCO) in mobile edge computing to motivate car owners to perform computation offloading tasks so as to offload some types of computational tasks to the vehicles. By optimizing the MCC model, we integrate the auction theory into the mechanism to ensure individual rationality, budget balance, system efficiency, and truthfulness for both sellers and buyers. Both theoretical derivations and numerical calculation prove that all the desired properties of the mechanism hold.

Index Terms—Computation offloading, incentive, satellite-terrestrial IoV, auction.

I. INTRODUCTION

Along with advances in computing and communication technology, the Internet of Vehicles (IoV), which is gradually replacing conventional Vehicle Ad-hoc Networks, is becoming popular worldwide. Today, the design, implementation, and management of IoV technology relies heavily on modern cloud computing technology. However, considering the limitations such as the size of data and the stability of channel, cloud computing may cause fatal latency [1]. With such a huge amount of data, we need to consider new computing technologies. Mobile edge computing is an emerging paradigm in internet of things (IoT) systems that offloads data processing to the network edge which localizes data processing and enabling services to be functional [2].

However, implementing mobile edge computing for computation offloading still faces several challenges. First, requisitioning a viable and suitable vehicle for computing takes up the owner’s personal resources. Therefore, we need to design a flexible and reasonable incentive mechanism to encourage owners to willingly providing their vehicles as computation resources [3]. Second, the complex physical environment in which cars travel, such as unstable signals and frequent congestion or crashes, places high demands on the stability and capacity of communications. Therefore, we design to adopt satellite-terrestrial networks [4] on IoV [5] to overcome the implementation difficulties. With seamless accessibility to overcome the coverage and distribution limitations of RSUs and BSs, it could provide macroscopic management to improve the overall network efficiency and the resource utilization at a low cost. Third, resource allocations and computation offloading transactions require low time delay or there’s no necessity to conduct it. Therefore, we design costumed algorithms during different stages which guarantee system and computation efficiency [6].

In order to overcome the above challenges, we propose an incentive mechanism for computation offloading (IMCO) which maximizes the motivation of car owners to perform computation offloading tasks while guaranteeing the system’s truthfulness. More specifically, we first investigate the auction theory and integrate it into the vehicle-mounted edge (V-edge) computing for computation offloading, where the problem of resource allocations is redesigned according to demand. To further illustrate the mechanism of IMCO, we design three algorithms for different phases within an auction. By rigorous theoretical analysis, our proposed mechanism is proved to achieve four desirable properties and close-to-optimal performance. Finally, we carry out extensive simulations to verify the performance of our proposed mechanism.

The main contributions of this paper are highlighted as follows.

1) We design a system architecture that effectively performs the information transmission among vehicles and cloudlets based on satellite-terrestrial IoV networks.
2) IMCO solves the problem that remote cloud server is not that sufficient to perform large scale computation tasks and encourages owners to join in computation offloading.
3) We apply the auction theory in economics to mobile edge computing in which computation tasks are offloaded to the car owners. The proposed double auction mechanism, IMCO, can achieve four desirable properties including individual rationality, budget balance, truthfulness, and computational efficiency. Extensive simulations verify that our proposed mechanism outperforms...
the existing solution.

The rest of this paper is organized as follows. Sec. II describes our system model and formulates problems. Sec. III designs the algorithm and the mechanism. Sec. IV presents performance evaluation of our proposed mechanism. Sec. V concludes the paper.

II. SYSTEM MODEL AND PROBLEM FORMULATION

A. System Model

In our system architecture shown in Fig. 1, there are three main parts: the satellite-terrestrial networks (STNs), the vehicles, and the cloudlets. STNs are the integration of satellite networks and terrestrial networks, consisting of one or more satellite systems and land-based stations, which efficiently disseminate information through wireless channels [7]. In the architecture, computational tasks on cloudlets can be offloaded to vehicles within coverage [8], while vehicles are simultaneously free to choose to perform computational tasks from all cloudlets covered by their current locations via STNs.

There are lots of vehicles around one cloudlet, the performance of some vehicles may be too weak to carry out computation-intensive tasks. To lift efficiency, the cloudlet can use auction mechanisms to offload computation tasks to other high-performance vehicles so as to reduce the communication overhead and improve efficiency [9]. Each vehicle will be rated differently from cloudlets based on different factors, such as latency, quality of service, communication overhead, computational capabilities [10]. On the other side, vehicle owners can be rewarded for providing computation resources and compensated for communication costs [11]. As in most real cases in the auction market, both the buyers and the sellers can get benefits from the transactions, that is, car owners can get paid to be incentivized to share its resource [12]. When the computation offloading is applied in the mobile edge computing, every cloudlet bids when it needs extra computational performance, and it submits the offers to the auctioneer [13]. Then, the asks of vehicles are also submitted. The auctioneer, also known as a control center, will allocate vehicles among cloudlets according to the outcome of IMCO, consequently reducing the communication overhead and the latency so that the services will be affordable.

To achieve truthfulness, a sealed-bid auction model is necessary. That is to say, each cloudlet (vehicle) can upload its bid (ask) secretly to the auctioneer so that everyone’s information including buyers’ bids and sellers’ asks is invisible to others. M

For each cloudlet \( c \in C \), \( C = \{c_1, c_2, \ldots, c_n\} \), \( B_i = \{B_i^1, B_i^2, \ldots, B_i^m\} \) is defined as the bid vector, where \( B_i^j \) is the bid for vehicle \( m_j \in M, \in M = \{m_1, m_2, \ldots, m_m\} \). The matrix of bids including all the bid vectors of all cloudlets is denoted by \( B = \{B_1, B_2, \ldots, B_m\} \).

For each vehicle \( m_j \in M \), its ask vector is defined as \( A = \{A_1, A_2, \ldots, A_m\} \), where \( A_j \) is the ask of vehicles \( m_j \in M \).

It is clear that the asks of vehicles are consistent no matter which cloudlets are since the vehicles only care about how much they can get for renting their resources. On the contrary, the offers of cloudlets are variational respecting different vehicles due to the fact that the weights of different tasks are distinct and the performance of different vehicles of different fields are also different.

The auctioneer calculates to determine the winning vehicles \( C_w \in C \) and the winning cloudlets \( M_w \in M \). It also defines a mapping \( \sigma \) between \( C_w \) and \( M_w \). The price \( P_{ij}^c \) is charged from the winning cloudlets \( M_w \in M \), and the reward \( P_{ij}^m \) to \( C_w \in C \). In particular, \( P_{ij}^c \) is denoted as the price charged...
to the cloudlet $c_i$ from vehicle $m_j$ and $P_{ij}^m$ is defined as the payment rewarded to vehicle $m_j$ from cloudlet $c_i$.

### B. Problem Formulation

We concern about the utilities of cloudlets and vehicles in the mechanism. There are two factors that affect the utilities, the evaluation of cloudlets towards the services provided by vehicles and the cost of providing such computation resources. So, we define $V_i^j$ as the valuation toward vehicle $m_j$ rated by $c_i$. $V_i = (V_i^1, V_i^2, \ldots, V_i^m)$. Hence, we can have the utility of $c_i$ and $m_j$ as below.

$$U_i^c = \begin{cases} V_i^j - P_{ij}^c, & \text{if } c_i \in C_w \\ 0, & \text{otherwise} \end{cases}$$  \hspace{1cm} (1)$$

$$U_m^j = \begin{cases} P_{ij}^m - \text{Cost}_j, & \text{if } m_j \in M_w \\ 0, & \text{otherwise} \end{cases}$$  \hspace{1cm} (2)$$

As what Eq. (1) and Eq. (2) express, the utility $U_i^c > 0$ holds only when cloudlet $c_i$ is allocated to the vehicle $m_j$. The higher $U_i^c$ is, the more satisfied the cloudlet will be. On the other side, the utility $U_m^j$ illustrates the profit the vehicle $m_j$ receives which is the difference by subtracting the cost from the received reward.

### C. Desired Properties

As what we have depicted, the auction model has several inputs: $C$, $M$, $B$, and $A$. Correspondingly, the auctioneer adopts an auction mechanism to calculate a series of results: $C_w$, $M_w$, $\sigma$. A well-designed auction mechanism must have the properties as follows.

- **Individual Rationality:**
  $$P_i^c \leq B_i^c, \forall c_i \in C_w$$  \hspace{1cm} (3)$$

$$P_m^j \geq A_j, \forall c_i \in C_w, \forall m_j \in M_w,$$  \hspace{1cm} (4)$$

The formula shown in (3) means that the winning cloudlet is charged less than or equal to its offer. The formula in (4) shows that the winning vehicle is paid more or equal to its ask.

- **Budget Balance:**
  $$\sum_{c_i \in C_w} P_{ic}^c \geq \sum_{m_j \in M_w} P_{jm}^m$$  \hspace{1cm} (5)$$

The formula above shows that the total rewards that the auctioneer gives to all winning vehicles are more or equal to the sum of prices that all winning buyers submit to the auctioneer.

- **Truthfulness:** An auction algorithm is said to be truthful if and only if
  $$U_i^c(c_i, B_{-i}) \geq U_i^c(c_i, B_{-i})$$  \hspace{1cm} (6)$$

$$U_m^j(m_j, A_{-j}) \geq U_m^j(m_j, A_{-j})$$  \hspace{1cm} (7)$$

$B_{-i}$ means that the bid vector without the cloudlet $c_i$, and $A_{-j}$ means that the ask vector of all sellers not including $m_j$. Such that a cloudlet cannot improve its utility by taking a bid different from the true valuation of a vehicle and no vehicle can fake the ask different from its cost. $U_i^c$ achieves its maximum only if

$$B_i = V_i, \forall c_i \in C,$$  \hspace{1cm} (8)$$

The $U_m^j$ achieves its maximum only if

$$A_j = C_j, \forall m_j \in M,$$  \hspace{1cm} (9)$$

- **Computational Efficiency:** The outputs of the auction mechanism, i.e., $C_w$, $M_w$, $\sigma$, $P_{ic}^c$ and $P_{jm}^m$ should be calculated in a polynomial time concerning $n$ and $m$.

### D. Technical Challenges

The existing auction algorithms cannot achieve all the properties when they are applied to computation offloading in MCC with cloudlets and vehicles as homogeneous items, i.e., the truthful auction scheme for cooperative communications (TASC) cannot support truthfulness for buyers despite the support of the other desirable properties [14]. To achieve all the desirable properties illustrated before, we propose a truthful double auction mechanism called IMCO.

### III. Mechanism Design

To solve the proposed problem, we propose IMCO in which the auctioneer firstly selects both the winning candidate cloudlets and the vehicles referring to the proposed rules. Then, each vehicle that is one of the winning candidates will be allocated to one winning candidate cloudlet. $P_{ic}^c$ and $P_{jm}^m$ will be determined as well. In addition, IMCO can assign more than one vehicle for a single cloudlet in a temporary state. Finally, the winner’s redundant vehicles will be eliminated to ensure the efficiency of the mechanism.

The IMCO consists of three phases: the winning candidate determination phase, the assignment and pricing phase, and the winner elimination phase.

To be specific, Algorithm 1 is used to filter some unqualified cloudlets and vehicles so as to select the winning candidates. To begin with, Algorithm 1 creates $C^+$ from the original cloudlet set $C$ which consists of bidders whose bids are greater than zero in accordance to $B$. That is to say, a cloudlet can appear several times in regard to the vehicles for which the cloudlet’s offer is larger than 0. Next, $C^+$ is sorted to $C$ in which the bids are sorted in a non-descending sequence. Also, vehicles are sorted in a non-descending list according to ask set $A$, denoted by $M$. Particularly, the $A_{j\beta}$ is the median ask of vehicles in $M$, where $\beta = \left\lceil \frac{B_{po}}{2} \right\rceil$ is to find the minimum value $\alpha$, so that $B_{po+1}^{q\alpha} < A_{j\beta}$ and $B_{po}^{q\alpha} \geq A_{j\beta}$. The $A_{j\beta}$ and $B_{po}^{q\alpha}$ are two standards to identify the winning candidates. For example, if $c_p^i$ is a winning candidate cloudlet in $C_w$, it should satisfy $A_q < A_{j\beta}$ and $B_{po}^{q\alpha} \geq A_{j\beta}$. The vehicle $m_\alpha$ is said to be the winning candidate if and only if and at least one cloudlet from $C$ has a bid for $m_\alpha$. The $\beta$ can be another value which is not necessarily the median value. The value of $\beta$ directly affects the number of $M_w$ so as to affect the number of $C_w$. 

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In the next phase, to protect the system from bidding and asking untruthfully, we closely combine assigning and pricing. Firstly, the control center assigns the winning candidate cloudlets for winning candidate vehicles. There are three situations needed to be discussed. The first situation is that there is only one cloudlet bidding for one vehicle, so the cloudlet is added to the $C_{bf}$ waiting for processing and charged $B_{po}^{\alpha}$. The second situation is that there are two or more cloudlets bidding for one vehicle, the auctioneer would choose the cloudlet with the highest bid from the cloudlet candidates and add it to $C_{bf}$. The last situation is when there are two or more cloudlets that offer the highest bids, the control center will randomly choose one cloudlet among the cloudlets with the highest bid and add to $B_{po}^{\alpha}$. Different from the first situation, the cloudlet is charged for the 2nd highest bid.

In the final phase, if one cloudlet in $C_{bf}$ wins at least two vehicles in $M_{bf}$, the auctioneer relies on the efficiency of utilization to decide only one vehicle for a cloudlet. If there are at least 2 equal utilities, the auctioneer will select only one vehicle randomly. After the third phase, there should be a one-to-one mapping relationship between a vehicle in $M_w$ and a cloudlet in $C_w$, since the redundant vehicles can join other auctions.

IV. THEORETICAL ANALYSIS

We analyze IMCO with the attributes that we are interested in, including computational efficiency, individual rationality, budget balance and truthfulness. If and if only those properties are achieved, the auction mechanism can be applied to our proposed scenario.

Theorem 1. IMCO is computational efficiency.

Proof. In Algorithm 1, there are no more than $n \times m$ cloudlet customers in the filtered set of cloudlets with positive valuation $C^+$. The merge sort in Algorithm 1 sorts the cloudlets from $C^+$ into $C$ by taking $O(nm \log(nm))$ time and sorts the vehicles in $M$ by taking $O(m \log(m))$ time. Then when the auctioneer sorts the cloudlets into $C_w$, the number of cloudlets in $C_w$ is $n \times \lceil \frac{1+m}{2} \rceil$. The remain parts of the algorithm, i.e., the following for loops, takes $O(\lceil \frac{1+m}{2} \rceil \times (1+n))$ time. Thus, the time complexity of Algorithm 1 is $O(nm^2 + nm \log n)$.

In the second phase, there exists no more than $\lceil \frac{1+m}{2} \rceil$ cloudlet customers in $C_w$ and vehicles in $M_w$. To find out the subset of $C_w$, the auctioneer needs to take $O(nm)$ time, since the auctioneer has already sorted the cloudlets in non-increasing order, so the auctioneer can save time without sorting again. There are no more than $n$ vehicles, so calculating the winning vehicles only takes $O(n)$ time. The following for loops takes $O(\lceil \frac{1+m}{2} \rceil \times (1+n))$. In the third phase, there exists no more than $\lceil \frac{1+m}{2} \rceil$ cloudlets in $C_{bf}$ and vehicles in $M_{bf}$, since $|C_{bf}| = |M_{bf}|$. The for loop has a time complexity of $O((\lceil \frac{1+m}{2} \rceil \times (n \log nm))$. All in all, since the algorithms in IMCO are sequential execution, so the time complexity of IMCO is $O(nm^2 + nm \log n)$. It means that IMCO is of computational efficiency.

Theorem 2. IMCO is individually rational.

Proof. For the winning vehicle $m_j \in M_w$, the price offered to the vehicle is $P_{po}^m$ which is larger than the ask of $m_j$ on the basis of IMCO. Therefore, vehicles accommodate the demand for the desired property. In the second phase, for every cloudlet $c_{ij} \in C_{bf}$, there are two different situations needed to be discussed. In the first situation, there is only one cloudlet $c_{ij}$ which selects one vehicle $m_j$. The price which the cloudlet $c_{ij}$ needs to submit to the auctioneer is the clearing price $B_{po}^{\alpha}$ which is less than or equal to the price $B_{ij}^q$. In the second situation, there is more than one cloudlet which competes for one vehicle. Suppose that the cloudlet $c_i$ wins the auction, it has the highest bid valued $B_{ij}^q$. The $c_{ij}$ is charged the 2nd highest bid in $C_j$. It is easy to see that $P_{po}^m$ is no more than $B_{ij}^q$. As we illustrate above, both the cloudlets and the vehicles meet the desired property. In the next stage, the auctioneer filters some redundant vehicle. According to the utility of cloudlets, it will not affect the $P_{po}^m$ and $P_{ij}^q$, so it can still have the desired property.

Theorem 3. IMCO is budget-balanced.

Proof. After the auctioneer filters all redundant vehicles, only one $c_i \in C_w$ maps to one $m_j \in M_w$. According to the mapping relationship $\sigma(j) = i$, it is easy to see that

$$P_{po}^m \geq B_{po}^{\alpha} \geq A_{j\beta} = P_j^m \quad (10)$$
TABLE I: Computation time.

| m  | 50 | 100 | 150 | 200 | 250 | 300 |
|----|----|-----|-----|-----|-----|-----|
| Time(s) | 0.160 | 0.456 | 0.742 | 1.034 | 1.325 | 1.617 |

That is:

$$\sum_{c_i \in C_w} P_{t_i}^c - \sum_{m_j \in M_w} P_{m_j}^m \geq 0$$  \hfill (11)

Lemma 1. IMCO is truthful for vehicles.

In the second phase, all the winning vehicles are rewarded $A_{j,\beta}$. According to the utility formula (2) of vehicles. Since the cost and the reward are both regarded as constant, the utilities of winning vehicles can be improved. On the contrary, if the ask is higher than its cost, the utility will decrease to 0.

Lemma 2. IMCO is truthful for cloudlets.

In the second phase, cloudlets cannot fake bidding higher than the actual value of the vehicles to compete with the vehicle since the price charging to winning cloudlets is variable. So, the utility of faking cloudlet is below 0. From formula (1), it is easy to obtain

$$U_{t_i}^c = V_{t_i}^j - P_{t_i}^c < 0$$  \hfill (12)

Since there exists competition in the auction, the winning cloudlet cannot improve its utility by increasing its bid, because the price charged to it depends on the 2nd highest bid.

Theorem 4. IMCO is truthful.

Proof. According to the above lemmas, we can get that IMCO is truthful for both vehicles and cloudlets, that is to say, IMCO is truthful.

V. PERFORMANCE EVALUATION

We use datasets to analyze IMCO to find out whether it satisfies the desired properties proved above. Also, we validate the effectiveness of the proposed mechanism. Since there are statistics related to the cost of vehicles and the demands of cloudlets, we use the uniform distribution functions to generate the bids of cloudlets and asks of vehicles in the scope from 0 to 1.

A. Computational Efficiency

We randomly generate different numbers of cloudlets and vehicles to test the running time. The computation time is shown in Table I.

B. Individual Rationality

To verify this property, we present both the winning cloudlets’ bids and the prices, which are shown in Fig. 2. In addition, Fig. 3 shows the asks and the payments of winning vehicles. We can see that the bids are always no less than the price charged to cloudlets and the rewards to vehicles are no less than the asks of vehicles. So, IMCO meets individual rationality. In other words, both the cloudlets and the vehicles can achieve positive utilities. The auctioneer can stimulate vehicles to carry out computation offloading tasks by paying them no less than their asks while the cloudlets can make use of the computation resources of the vehicles.

C. Budget Balance

IMCO is only of budget balance when the total fund that the cloudlets submit to the auctioneer is larger than or equal to the payments which are rewarded to the winning vehicles. We set the number of total cloudlets to 100 consistently. By changing the number of vehicles from 50 to 150, we obtain the total prices and payments. The result is shown in Fig. 4 showing Each time the total number of vehicles increases by 10. It’s clear that the total prices are always larger than the total payments.

D. Truthfulness

We focus on two different cloudlets and mobile vehicles groups which contain both winners and losers. Then, by changing their bids and asks from 0 to 1, we obtain the
Fig. 4: The relationship between the prices and payments of IMCO.

Fig. 5: The utilities of vehicles and cloudlets in the winning set.

changing trends of utilities. The result of those in the winning set is shown in Fig. 5. Fig. 5(a) shows that when the cloudlet offers a truthful bid of 0.42, it has a utility of 0.12. However, no matter how higher a bid the cloudlet selects, the utility still stays the same, unless it reduces the bid under the original price. Fig. 5(b) shows that the utility of mobile vehicles cannot be improved by asking untruthfully. Offering asks lower than 0.25 cannot achieve higher utilities while the utilities are always positive. The result of those not in the winning set is shown in Fig. 6. Fig. 6(a) shows that the utility of the losing cloudlet is always no larger than 0 since it loses the auction. However, even if the losing cloudlet fake its bid, it still cannot make the utility larger than 0. Fig. 6(b) shows that the utility of a losing mobile vehicle can only be 0 or below 0. Overall, IMCO can achieve truthfulness for both cloudlets and mobile vehicles.

VI. CONCLUSION

In this paper, we concentrate on building an incentive mechanism for computation offloading among cloudlets and vehicles based on satellite-terrestrial IoV. To accomplish successful and efficient auction transactions, we propose IMCO which deals with the resource exchange and allocation process from which both the cloudlets and the vehicle owners could benefit. After theoretical analysis and simulations, we prove that IMCO can meet the properties such as individual rationality, budget balance, system efficiency, and truthfulness for both cloudlets and vehicles.

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