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Paired Bid-Based Double Auction Mechanism for RAN Slicing in 5G-and-Beyond System

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Abstract—Network slicing has been widely deemed as a promising technology that enables the sharing of infrastructure resources for 5G-and-beyond mobile networks. Infrastructure Providers (InPs) abstract physical network into multiple isolated network slices, each of which can be operated as a virtual network by different Mobile Virtual Network Operators (MVNOs). However, the asymmetric information between resource supply of InPs and usage requirement of MVNOs challenges the resource allocation when enforcing slicing in the radio access network (RAN). In this paper, we propose a paired bid-based double-auction mechanism for a slicing-based RAN to improve resource allocation efficiency. We construct a market model in which the MVNOs and the InPs submit respective bids and ask Network Slice Broker (NSB) for slice transactions, and the NSB determines the winner pairs and corresponding payments to clear the slice market by maximizing social welfare. Numerical results validate the effectiveness of our proposed mechanism on improving the overall network resource allocation efficiency without collecting full information on the competitive strategies and utility functions of the MVNOs and InPs.

Index Terms—RAN slicing, infrastructure provider, mobile virtual network operator, network slice broker, double auction

I. INTRODUCTION

Forthcoming 5G-and-beyond mobile network explores network slicing to achieve network resource sharing and efficiency improvement through employing Network Function Virtualization (NFV) and Software Defined Network (SDN) techniques [1]. Therefore, the traditional mobile network can be separated into multiple network slices as independent virtual networks without intervening with each other. Moreover, network resources are capable of being scheduled for inter/intra network slices to enable network slice flexible for dealing with the changeable traffic demands [2]–[4].

The new paradigm of network resource sharing in 5G-and-beyond system introduces network economics with a new business model into resource allocation among multiple slices. Specifically, there are two logical business roles in a sliced network, i.e. Infrastructure Provider (InP) who utilizes his infrastructure and resources to enforce network slice and

Mobile Virtual Network Operator (MVNO) who lease network slice to serve his users [5].

However, due to the openness and sharing nature of sliced radio access network (RAN), MVNO and InP have opposite appeal on resource allocation when enforcing RAN slicing, to increase respective benefit [6]. Moreover, no matter acting as an MVNO or an InP, the disorder of competition among counterparties or colleagues will certainly result in inefficient resource utilization.

Most solutions for RAN slicing refer to three different types of business models which are B2B (InP-to-MVNO), B2C (MVNO-to-User Equipment (UE)), and B2B2C (InP-to-MVNO-to-UE) [7]. The work in [8] proposes a hierarchical auction model for B2B2C, and shows that the large number of UEs leads to high computation complexity in B2BC as well as B2C. Thereafter, the work in [9] considers a hierarchical match game for B2B. However, the proposed algorithm considers little dynamic pricing between InP and MVNO. To the best of the authors' knowledge, other studies rarely consider the competition in resource allocation facing to open RAN scenario of the future 5G-and-beyond system.

To address the aforementioned difficulties, in this paper we propose a multi-tenant based network slice market model to study the resource allocation for RAN slicing. Inspired by the work in [3], by employing high level slicing, we consider network slices as some data flows which come from the same MVNO and afford certain services with specific QoS requirements. Hence, the resource allocation on the RAN side can be modeled as the slice transaction in a slice market, which allows the MVNO to act as a tenant, leasing network slices from multiple InPs, and to only require network slices meet the desired QoS instead of paying attention to the specific physical resource allocation for UEs. Intuitively, the proposed slice market model complies with the slicing strategy of 5G-and-beyond as underlying physical resources become transparent for services.

II. SYSTEM MODEL

A. Network Model

We consider a fully sharing RAN of 5G-and-beyond system based on the 3GPP specifications [10] [11], where multiple

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MVNOs without owning network infrastructure act as tenants to lease a bundle of virtual network resources from various InPs for specific QoS services. These bundled resources could include spectrum, radio power, time-slot, all of which are capable of being shared and orchestrated on demand when enforcing RAN slicing for the mobile network. Moreover, from MVNOs' perspectives, the shared resource of RAN acts as a basic transmission bearer that supports to establish some data flows for specific services from UEs to the CN. Inspired by the works in [2] and [12], we consider the shared resource is transmission resource, and further assume the transmission resource in this work is referred to as time-slot and the PRB for data transmission would vary dynamically in each time-slot. Nevertheless, our proposed PBDA is general and is not limited to the system model based on time-slot.

In addition, we assume that a Network Slice Broker (NSB) is deployed with the master operator-network manager (MO-NM) system at the InPs side to monitor some crucial measurements of shared RAN by dedicated interface (e.g., Type 1 and Type 2), and interacts with the Sharing Operator-Network Manager (SO-NM) system in the MVNOs side to assist MVNOs for managing the shared RAN via open Application Programming Interfaces (APIs) [5]. Hence, the NSB receives on-demand resource requests from MVNOs and then supervises InPs to configure appropriate transmission resource for corresponding service.

Fig. 1. The multi-tenant system based on sliced network

As shown in Fig. 1, we consider a set $\mathcal{M} = \{m|m = 1, 2, \dots, M\}$ of MVNOs in a sliced mobile network, where each operator $m \in \mathcal{M}$ has a set $\mathcal{N} = \{n|n = 1, 2, \dots, N_m\}$ of service types with specific QoS requirement. Meanwhile, denote by $\mathcal{J} \triangleq \{j|j = 1, 2, \dots, J\}$ the set of InPs where InP $j \in \mathcal{J}$ manages V_j BSs, and each BS $v_j \in \{1, 2, \dots, V_j\}$ can provide T_{v_j} amount of transmission resources.

We consider the case where each MVNO $m \in \mathcal{M}$ request $t_{v_j}^m \geq 0$ time-slots from BS v_j for the service type $n \in \mathcal{N}$. Since each slice can only provides one type of service, we define the slice request vector for MVNO m to InP j with service type n as $\mathbf{S}_m^n \triangleq \{t_{v_j}^m|v_j \in \{1, 2, \dots, V_j\}\}$. Note that BSs can afford multiple slices simultaneously through efficient resource allocation among slices. Hence, a slice may

be deployed on multiple BSs belonging to different InPs, and a BS may also be covered by multiple slices operated by different MVNOs.

As slice request associated with a specific service type has certain QoS requirements, we denote by $c(\mathbf{S}_m^n)$ and $d(\mathbf{S}_m^n)$ the coverage and the data rate of requested slice $\mathbf{S}_m^n$ respectively. As we are only concerned with the BS in the coverage of a slice, thus the coverage of $\mathbf{S}_m^n$ is defined as the number of BSs that allocate time-slots to $\mathbf{S}_m^n$. Moreover, the achievable data rate of $\mathbf{S}_m^n$ can be expressed as:

$$d(\mathbf{S}_m^n) = \min\{t_{v_j}^m B_{v_j} \log_2(1 + \frac{P_{v_j}}{N_0 B_{v_j} + I(B_{v_j})})\}, \quad (1)$$

where B_{v_j} and P_{v_j} represent the bandwidth and transmit power of a shared BS respectively. Besides, N_0 represents the noise power spectral density, and $I(B_{v_j})$ represents the BS's interference caused by neighboring BSs. As the requested slice shares the transmission resource of multiple BSs located at different positions, the achievable rate of entire requested slice is certainly the minimum data rate provided by the BS that contributes the least resource to the slice.

After receiving the slice requests from one of the MVNOs, the NSB requests the responses from InPs. We define the slice response vector for InP j to MVNO m with service type k as $\mathbf{A}_j^k \triangleq \{t_{v_j}^k|v_j \in \{1, 2, \dots, V_j\}\}$. Note that the amount of allocated resource of BS v_j may be different from the requirement. As a result, the data rate and coverage of the slice response (i.e., $d(\mathbf{A}_j^k)$ and $c(\mathbf{A}_j^k)$) could also be different from that of the request. Therefore, we define the service type k as the responding service type to distinguish from the requested service type n .

B. Auction Model

As the BSs of an InP have diverse priority, and the limited resources of each BS cannot satisfy all slice requests from MVNOs as well, the MVNOs could easily fall into disordered competition to pursue as many slices as possible to serve users. Moreover, due to the selfishness nature, each InP intends to maximize own utility without taking the global resource efficiency into account when implementing slicing strategy. Therefore, it is challenging to ensure rational competition in realizing global optimal resource allocation in the sliced network.

Considering auction has been demonstrated an effective tool to address the competitive resource allocation in many fields of wireless communications [13]–[15], we employ double auction model to implement resource allocation in the slice market, where MVNO and InP act as bilateral trading parties with the purpose of leasing network resource to construct network slice for diverse services. Meanwhile, we introduce NSB to supervise the auction. As the slice requests from MVNOs and the slicing strategies from InPs are collected simultaneously, the NSB is capable of facilitating the appropriate resource allocation in a global view, and helping establish an open and efficient slice market for network resource sharing.

Therefore, we model the slice request and slicing strategy to adopt to double auction. The slice request of MVNO evolves to a bid $\mathcal{B} \triangleq \{b(\mathcal{S}_m^n), d(\mathcal{S}_m^n), c(\mathcal{S}_m^n)\}$, which is a combination of cost, data rate, and coverage of requested slice. In particular, element $b(\mathcal{S}_m^n)$ represents the expense that MVNO is willing to pay for slice leasing, which is determined by MVNO's real valuation on the requested slice. Similarly, we let $\mathcal{A} \triangleq \{a(\mathcal{A}_j^k), d(\mathcal{A}_j^k), c(\mathcal{A}_j^k)\}$ denote a bid of an InP, which is a combination of revenue, data rate and coverage of rental slice. Specifically, element $a(\mathcal{A}_j^k)$ represents the benefit that is used to compensate the InP for sharing the transmission resource of BSs to construct a network slice. On basis of the bids from MVNOs and InPs, the NSB will ensure that the slice market operates efficiently by enabling InPs to provide appropriate network slice to qualified MVNOs.

Due to the feasibility of slice deployment, we further consider that the allocated resources to one network slice should be provided by a unique InP, as signaling overhead and management cost would tremendously increase when implementing slicing among multiple InPs [3]. Therefore, in our proposed slice market model, the MVNO and the InP performing a slice transaction should be paired uniquely. Moreover, we define social welfare as the difference between the respective total bids from MVNOs and InPs. Hence, the efficient sliced network resource allocation is to maximize the social welfare of the slice market, which can be formulated as:

$$\max_{\mathcal{S}_m^n, \mathcal{A}_j^k, e_{j-m}^{k-n}} \left(\sum_{m=1}^M \sum_{n=1}^{N_m} b(\mathcal{S}_m^n) - \sum_{j=1}^J \sum_{k=1}^{K_j} a(\mathcal{A}_j^k) \right) e_{j-m}^{k-n}, \quad (2)$$

$$s.t. \quad d(\mathcal{S}_m^n) e_{j-m}^{k-n} \leq d(\mathcal{A}_j^k), \quad \forall e_{j-m}^{k-n} = 1, \quad (3)$$

$$c(\mathcal{S}_m^n) e_{j-m}^{k-n} \leq c(\mathcal{A}_j^k), \quad \forall e_{j-m}^{k-n} = 1, \quad (4)$$

$$\sum_{k=1}^K t_{v_j}^k e_{j-m}^{k-n} \leq T_{v_j}, \quad \forall e_{j-m}^{k-n} = 1. \quad (5)$$

In (2), $e_{j-m}^{k-n} \in \{0, 1\}$ is a binary variable to denote the mapping relationship from a slice request to a slicing response. Specifically, $e_{j-m}^{k-n} = 1$ indicates that the InP adopts slicing strategy $\mathcal{A}_j^k$ to respond to the slice request $\mathcal{S}_m^n$. Constraints (3) and (4) indicate the achieved data rate and the coverage should be greater than the corresponding requirements respectively. Constraint (5) indicates that the available transmission resource of each BS cannot exceed the maximum resource.

Although the resource allocation of network slicing has been defined as a social welfare maximization problem by employing an auction model, it is still a challenge to find the optimal solution, as the objective function is a complicated 0-1 integer programming which also contains two continuous variables in linear part.

III. PAIRED BID-BASED DOUBLE AUCTION MECHANISM

A. VCG-Based Paired Bid

As the essence of social welfare maximization in a double auction mechanism is making the lowest bid goods sold to

buyers who submit the highest bid. It is well-reasoned to employ this situation to determine the winners as long as every participant reveals their true valuations. Therefore, we use natural ordering to filter out the highest bid buyer and lowest bid seller to be a pair, in which the buyer and the seller fulfill the transaction of slice leasing. In order to explain the idea of paired bid, we first transform (2) into the following equivalent objective function,

$$\max_{h_{j-m}^{k-n}, e_{j-m}^{k-n}} \sum_{m=1}^M \sum_{n=1}^{N_m} \sum_{j=1}^J \sum_{k=1}^{K_j} h_{j-m}^{k-n} e_{j-m}^{k-n}, \quad (6)$$

where $h_{j-m}^{k-n} = b(\mathcal{S}_m^n) - a(\mathcal{A}_j^k)$.

Note that (6) is similar to the social welfare maximization of multi-unit reverse auction, which inspires us to employ VCG mechanism to solve the maximization problem of (6). Specifically, VCG mechanism is effective to guarantee the maximization of social welfare as well as the truthfulness of bids in multi-unit reverse auction [16]. Hence, we define h_{j-m}^{k-n} as **paired bid** of participants for the slice transactions. Then the MVNO and the InP who contribute to the paired bid, constitute a pair to compete for the winners to achieve a transaction. For the given paired bid h_{j-m}^{k-n} , the auctioneer derives the optimal solution $\mathbf{E}^*$ that maximizes the objective function,

$$\mathbf{E}^* = \arg \max_{\mathbf{E}} \sum_{m=1}^M \sum_{n=1}^{N_m} \sum_{j=1}^J \sum_{k=1}^{K_j} h_{j-m}^{k-n} e_{j-m}^{k-n}, \quad (7)$$

where $\mathbf{E}$ denotes the set of all feasible values of the decision variables. According to the mechanism of VCG auction, the winner pair is that who achieves the slice transaction corresponding to $e_{j-m}^{k-n} = 1$ where $e_{j-m}^{k-n} \in \mathbf{E}^*$. Then the payment for the transaction can be computed directly as

$$p_{j-m}^{k-n} = V(\mathbf{E} \setminus e_{j-m}^{k-n}) - \sum_{m \neq m^*} \sum_{n \neq n^*} \sum_{j \neq j^*} \sum_{k \neq k^*} h_{j-m}^{k-n} e_{j-m}^{k-n}, \quad (8)$$

where $V(\mathbf{E} \setminus e_{j-m}^{k-n}) = \max \sum_{m=1}^M \sum_{n=1}^{N_m} \sum_{j=1}^J \sum_{k=1}^{K_j} h_{j-m}^{k-n} e_{j-m}^{k-n}$ represents the new maximum of the objective function (7) by excluding the winner pair for starting a new auction, and e_{j-m}^{k-n} represents the new optimal value. Term $\sum_{m \neq m^*} \sum_{n \neq n^*} \sum_{j \neq j^*} \sum_{k \neq k^*} h_{j-m}^{k-n} e_{j-m}^{k-n}$ represents the rest of the original social welfare by subtracting the contribution from winner pair. m^* , n^* , j^* , and k^* represent the corresponding superscripts or subscripts that satisfy $e_{j-m}^{k-n} = 1$.

In order to reduce complexity, we use natural ordering in reality to determine the winner pair due to the constraint $h_{j-m}^{k-n} > 0$, which guarantees the maximization of (6). We first sequence the MVNOs in descending order according to their bids as $b_1 \geq b_2 \geq \dots \geq b_O$, and sequence the InPs in ascending order according to their bids as $a_1 \leq a_2 \leq \dots \leq a_W$. The subscripts of the sequences are $O = M \times N_m$ and $W = J \times K_j$. Then let H be the greatest index such that $b_H \geq a_H$. The buyer and seller who have the same

index constitute a pair. Therefore, the MVNOs and InPs whose indexes are less than or equal to H are selected as the winner pairs. The members of each winner pair are definitely determined as winner MVNO and winner InP.

B. Bid Strategy Adjustment

In general, the participants of a double auction are price-taking. After receiving the auctioneer's announcement about winners and payments, every winner would compute his utility (i.e., the difference between his bid and the payment). As long as the utility of each winner is positive, the double auction is valid and every participant will accept the auction result. However, in our slice market model, it is difficult for an auctioneer to determine the acceptable result at one time, as the actual resource amount allocated to the MVNO would be less than expectation, which probably leads to negative utility for the MVNO. Hence, in order to guarantee the auction effectiveness, the PDBA mechanism allows each participant to adjust his strategy iteratively when learning the payment of each round.

Given the payment p_{j-m}^{*k-n} determined by (8), each winner InP j solves his utility maximization problem to find the optimal allocation $t_{v_j}^{*k_j}$ of BS v_j for specific slice response A_j^k by solving the following maximization problem:

$$U_j = \max_{t_{v_j}^{k_j}} \left(- \sum_{k=1}^{K_j} \sum_{v=1}^{V_j} a_{v_j} t_{v_j}^{k_j} + \sum_{m=1}^M \sum_{n=1}^{N_m} \sum_{k=1}^{K_j} p_{j-m}^{*k-n} \right), \quad (9)$$

$$s.t. \quad \sum_{k=1}^{K_j} t_{v_j}^{k_j} \leq T_{v_j}, \quad \forall t_{v_j}^{k_j} \in A_j^k, \quad (10)$$

$$t_{basic}^k \leq t_{v_j}^{k_j}, \quad \forall t_{v_j}^{k_j} \in A_j^k, \quad (11)$$

$$\{t_{basic}^k\} \subseteq \{t_{v_j}^{k_j}\}, \quad \forall t_{v_j}^{k_j} \in A_j^k, \quad (12)$$

where a_{v_j} denotes the unit price for network resource on BS v_j , then term $\sum_{k=1}^{K_j} \sum_{v=1}^{V_j} a_{v_j} t_{v_j}^{k_j}$ represents the total cost for A_j^k . Meanwhile, term $\sum_{m=1}^M \sum_{n=1}^{N_m} \sum_{k=1}^{K_j} p_{j-m}^{*k-n}$ represents the total reimbursement from the winner MVNOs for the slice transactions which InP j takes part in. Moreover, constraint (10) indicates that the amount of available resource cannot exceed the maximum capacity of each BS. Constraints (11) and (12) indicate that the allocated resource $t_{v_j}^{k_j}$ needs to satisfy the basic requirements on data rate and coverage of slice response A_j^k . Specifically, denote by t_{basic}^k and $\{t_{basic}^k\}$ the minimum data rate and minimum coverage respectively of service type k . Denote by $\{t_{v_j}^{k_j}\}$ the actual coverage of slice response A_j^k . Apparently, the utility maximization for winner InP is a typical linear programming, and thus simplex method and interior-point method can be efficiently used to find the optimal solution.

Similarly, each winner MVNO m is willing to find the optimal $t_{v_j}^{*n_m}$ by solving the following maximization problem:

$$U_m = \max_{t_{v_j}^{n_m}} \left(\sum_{n=1}^{N_m} \sum_{j=1}^J \sum_{v=1}^{V_j} b_{v_j} t_{v_j}^{n_m} - \sum_{j=1}^J \sum_{k=1}^{K_j} p_{j-m}^{*k-n} \right), \quad (13)$$

$$s.t. \quad t_{v_j}^{n_m} \leq t_{basic}^k, \quad \forall t_{v_j}^{n_m} \in S_m^n, \quad (14)$$

$$\{t_{v_j}^{n_m}\} \subseteq \{t_{basic}^k\}, \quad \forall t_{v_j}^{n_m} \in S_m^n, \quad (15)$$

where b_{v_j} denotes the unit revenue for the attained network resource on BS v_j , then term $\sum_{n=1}^{N_m} \sum_{j=1}^J \sum_{v=1}^{V_j} b_{v_j} t_{v_j}^{n_m}$ represents the total revenue by providing service through the attained network resource. Term $\sum_{j=1}^J \sum_{k=1}^{K_j} p_{j-m}^{*k-n}$ represents the total payments for all slice transactions. Constraints (14) and (15) indicate that the minimum data rate and minimum coverage of actual service type provided by slice response A_j^k should be greater than the requests respectively. As the maximization problem (13)~(15) is also linear programming, each winner MVNO is capable of efficiently obtaining his optimal solution.

C. Implementation of PBDA Mechanism

As the winner MVNO and InP have no idea about the global resource usage of the network when determining the respective optimal strategy to maximize the utility, the required resource of the optimal slice request strategy (i.e., $t_{v_j}^{*n_m}$) could deviate from the available resource of corresponding optimal slice response strategy (i.e., $t_{v_j}^{*k_j}$). Hence, the winner MVNO and InP cannot reach an agreement on resource allocation for slice at one time. Specifically, the gap between $t_{v_j}^{*n_m}$ and $t_{v_j}^{*k_j}$ affects the participant's satisfaction for slice transaction, and probably poses negative impact on social welfare of slice market as well if the actual allocated resource differs greatly from the requirement. Therefore, it is desirable to design an iterative algorithm to narrow down the gap by helping the winner MVNO and InP adjust their optimal strategies gradually, and eventually accomplish the resource allocation that every participant is satisfied.

The main idea for implementing PBDA mechanism is shown in Fig. 2. We employ a polynomial-time greedy algorithm to obtain an approximate optimal solution for helping the NSB determine the winner pairs and the corresponding payments on slice transaction. Then, we employ gradient descent method to make NSB find a feasible solution for resource allocation, which guarantees the utilities of all winning participants positive. Once the NSB obtains the feasible solution, the NSB terminate the PBDA mechanism, otherwise the NSB informs InPs and MVNOs to resubmit their new bids and the asked iteratively. Due to the length of the article, the details of the algorithm are omitted accordingly, and the subsequent simulation results will verify the effectiveness of the mechanism and algorithm.

Fig. 2. The flow chart of implementing the PBDA mechanism

IV. PERFORMANCE EVALUATION

A. Simulation Scenario and Settings

We consider a representative network scenario of $M=2$ MVNOs, one of which has 4 slice requests, and the other has 2 slice requests. Please note that it is reasonable to set the number of different MVNOs as 2 for a certain area (such as Vodafone and O2 in UK). Meanwhile, the network has $J = 4$ InPs, with 6, 7, 12, 12 BSs respectively, and each InP owns number of BSs thus to cover the considered area. As we assume that each BS has the same transmit power, the dimension of the vectors reflects the coverage of slice request or slice response. Moreover, we use two vectors to represent the bids of MVNOs and InPs. The final bids of MVNO (or InP) submitted to the broker is the inner product of R_M and B_M (or the inner products of P_J and A_J). The main system parameters used in the simulations are summarized in Table I.

TABLE I
SIMULATION PARAMETERS

Notation	Definition	Value
M	the number of MVNOs	2
J	the number of InPs	4
N_M	the vector format of the number of slice requests from each MVNO	[2,4]
V_J	the vector format of the number of BSs deployed by each InP	[6,7,12,12]
R_M	the vector format of unit revenue on allocated resource of BSs	specified
P_J	the vector format of unit price on allocated resource of BSs	specified
B_M	the vector format of requested resource on each BS for slice request	random
A_J	the vector format of allocated resource on each BS for slice response	random

B. Numerical Results

In the first experiment, we investigate the evolution of social welfare (SW for simplicity), total utility of winner MVNOs (TU_M for simplicity), and total utility of winner InPs (TU_I for simplicity) in the iterations. In Fig. 3, we plot the evolution of SW, TU_I and TU_M of PBDA mechanism. We find that at the beginning, some winner MVNOs would attain negative utilities as the actual allocated resources are less than expectation, leading the TU_M to be negative consequently. However, due to the supervision of the NSB for guaranteeing that each participant has positive utility, the winner InPs have to tentatively increase the allocated resources to the slice request of winner MVNOs who have negative utilities, which directly causes a small decrement of TU_I. Meanwhile, as the PBDA mechanism requires the non-negative paired bid ($h_{j-m}^{k-n} \geq 0$) when implementing pairing, this guarantees that the MVNO will give greater valuation than that given by InP for the same allocated resource. Hence, TU_M can increase dramatically as long as the winner InPs increase the allocated resources for some winner MVNOs to compensate their negative utilities.

Fig. 3. The evolution of social welfare, total utility of winner MVNOs, and total utility of winner InPs

In the next experiment, we explore the relationship between the paired bid and payment in the PBDA mechanism. We select a winner pair including one winner MVNO and one winner InP, which produce positive and greatest paired bid. Then we decrease the paired bid of the selected winner pair for repeated experiments, and depict the change of corresponding payment. We present representative three paired bids and corresponding payments, and call them as high, normal, and low paired bid and payment, respectively, as shown in Fig. 4. We observe that the gap between the paired bid and payment diminishes when the paired bid decreases. These numerical results demonstrate the truthfulness property of the PBDA mechanism, as a winner pair cannot affect its final payment through adjusting their paired bid unilaterally. Hence, the rational strategy for every participant is submitting bid truthfully based on respective valuation for allocated resources.

Fig. 4. Relationship between the paired bid and corresponding payment

In the last experiment, we examine the demand and satisfaction of each winner slice. We present the initial request and actual allocation for each winner slice in Fig. 5. Through numerical results, we first validate the effectiveness of the proposed PBDA mechanism, since all six slice requests are responded by InPs. Second, the diversity of demand satisfaction for each winner slice complies with the objective rules in realistic resource allocation. When constructing a single slice, both InP 2 and InP 3 would allocate resources as much as possible, as long as the requirement of the slice is less than their available amount. Hence, the demands of the winner slices related to InP 2 and 3 are completely satisfied. However, when constructing multiple slices simultaneously, InP 1 cannot satisfy the demand of every slice. To maximize the utility, InP 1 has to allocate more resources to the slice that yields the maximized revenue while providing the minimum resource to meet the demands of the rest winner slices. Therefore, the proposed PDBA mechanism guarantees the service quality of slice as satisfying necessary service demand and achieves efficient allocation as enabling limited resources to produce high value as much as possible.

Fig. 5. Demand and satisfaction of each winner slice

V. CONCLUSION

In this paper, we have abstracted the slice resource allocation for RAN slicing as a network slice market, where the MVNOs request network resource to operate virtual sliced networks, and InPs allocate physical network resources to construct the slice. We have proposed a so-called paired bid-based double auction (PBDA) mechanism, which decouples the complicated integer programming problems to multiple linear programming sub-problems. Simulation results have illustrated that the proposed PBDA mechanism can enable MVNOs and InPs to achieve the equilibrium, where the social welfare reaches the maximum, and the network resources are allocated efficiently between virtual network slice and network infrastructure to guarantee the service quality.

REFERENCES

- [1] H. Zhang, N. Liu, X. Chu, K. Long, A.-H. Aghvami, and V. C. Leung, "Network slicing based 5G and future mobile networks: mobility, resource management, and challenges," *IEEE communications magazine*, vol. 55, no. 8, pp. 138–145, 2017.
- [2] X. Costa-Pérez, J. Swetina, T. Guo, R. Mahindra, and S. Rangarajan, "Radio access network virtualization for future mobile carrier networks," *IEEE Communications Magazine*, vol. 51, no. 7, pp. 27–35, 2013.
- [3] C. Liang and F. R. Yu, "Wireless network virtualization: A survey, some research issues and challenges," *IEEE Communications Surveys & Tutorials*, vol. 17, no. 1, pp. 358–380, 2014.
- [4] Y. Sun, S. Qin, G. Feng, L. Zhang, and M. A. Imran, "Service provisioning framework for RAN slicing: user admissibility, slice association and bandwidth allocation," *IEEE Transactions on Mobile Computing*, 2020. [Online]. Available: <http://dx.doi.org/10.1109/TMC.2020.3000657>
- [5] K. Samdanis, X. Costa-Pérez, and V. Sciancalepore, "From network sharing to multi-tenancy: The 5G network slice broker," *IEEE Communications Magazine*, vol. 54, no. 7, pp. 32–39, 2016.
- [6] U. Habiba and E. Hossain, "Auction mechanisms for virtualization in 5G cellular networks: basics, trends, and open challenges," *IEEE Communications Surveys & Tutorials*, vol. 20, no. 3, pp. 2264–2293, 2018.
- [7] M. Jiang, M. Condoluci, and T. Mahmoodi, "Network slicing in 5G: An auction-based model," in *2017 IEEE International Conference on Communications (ICC)*. IEEE, 2017, pp. 1–6.
- [8] K. Zhu and E. Hossain, "Virtualization of 5G cellular networks as a hierarchical combinatorial auction," *IEEE Transactions on Mobile Computing*, vol. 15, no. 10, pp. 2640–2654, 2015.
- [9] S. A. Kazmi, N. H. Tran, T. M. Ho, and C. S. Hong, "Hierarchical matching game for service selection and resource purchasing in wireless network virtualization," *IEEE Communications Letters*, vol. 22, no. 1, pp. 121–124, 2017.
- [10] 3GPP TS 32.130, "Telecommunication Management; Network Sharing; Concepts and Requirements," Tech. Rep., Release 12.
- [11] 3GPP TR 23.708, "Architecture Enhancement for Service Capability Exposure," Tech. Rep., Release 13.
- [12] F. Fu and U. C. Kozat, "Stochastic game for wireless network virtualization," *IEEE/ACM Transactions on Networking*, vol. 21, no. 1, pp. 84–97, 2012.
- [13] G. Iosifidis, L. Gao, J. Huang, and L. Tassioulas, "A double-auction mechanism for mobile data-offloading markets," *IEEE/ACM Transactions on Networking*, vol. 23, no. 5, pp. 1634–1647, 2014.
- [14] W. Borjigin, K. Ota, and M. Dong, "In broker we trust: A double-auction approach for resource allocation in nvf markets," *IEEE Transactions on Network and Service Management*, vol. 15, no. 4, pp. 1322–1333, 2018.
- [15] D. Zhang, Z. Chang, T. Hämäläinen, and F. R. Yu, "Double auction based multi-flow transmission in software-defined and virtualized wireless networks," *IEEE Transactions on Wireless Communications*, vol. 16, no. 12, pp. 8390–8404, 2017.
- [16] Y. Chen, J. Zhang, Q. Zhang, and J. Jia, "A reverse auction framework for access permission transaction to promote hybrid access in femtocell network," in *2012 Proceedings IEEE INFOCOM*. IEEE, 2012, pp. 2761–2765.