A Two-level Auction for C-RAN Resource Allocation

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***Abstract*—In this paper we propose and evaluate an auction-based resource allocation mechanism in a cloud-based radio access network (C-RAN), where the spectrum is managed by several mobile virtual network operators (MVNOs) and the physical resource is owned by the C-RAN operator. Technically, our approach consists of two coupled auctions in a hierarchical way: the lower-level auction between end users and the virtual operators and the higher-level one between MVNOs and the C-RAN operator. The proposed auction-based approach satisfies fundamental economic properties such as truthfulness. We also numerically analyze the auction results in several typical network settings, considering both homogeneous and heterogeneous resource demands.**

***Index terms*—Resource Allocation, C-RAN, MVNO, Auction.**

I. INTRODUCTION

Next generation (5G) mobile networks are promising 25 times the data rate provided by the current generation [1], higher efficiency, enhanced mobility support and seamless management of connected devices. In order to provide such features, and more importantly, a better efficiency in resource utilization as well as reduced CAPEX and OPEX, the cloud-RAN (or Virtual RAN) paradigm has been recently proposed. Indeed, C-RAN shares with cloud computing functionalities like *centralization* to facilitate resource management and *virtualization* to reduce physical resources' costs and maintenance [2]. In this paper, we focus on resource management by proposing an auction-based resource allocation mechanism in a cloud-based radio access network (C-RAN), where the spectrum is managed by several virtual mobile operators (MVNOs) and the physical resource is owned by the C-RAN operator.

Our approach consists of two coupled auctions in a hierarchical way: the lower-level auction between end users and the virtual operators, and the higher-level one between MVNOs and the C-RAN operator. Our motivation of using auction-based resource allocation is both economical and technical. Economically, auctions are well-adapted in markets to maximize the revenue of sellers (or auctioneers). Technically, auctions can increase the efficiency of the resource utilization. We demonstrate that our designed auction mechanism satisfies crucial economic properties, in particular *truthfulness* (players' dominant strategy is to reveal/bid their true valuations) and is computationally efficient. Finally, we perform an extensive numerical analysis, implementing our proposed approach in several, typical mobile network scenarios, measuring the utility (payoff) obtained by all players' involved in the resource allocation process. We show in this way the effectiveness of our scheme in terms of efficient resource allocation, considering both homogeneous and heterogeneous user demands.

Recently, auction theory has been extensively applied in resource allocation in computing and communication systems to increase the system efficiency, but few consider the case of two hierarchical, coupled auctions as in our setting. The work in [3] describes and proposes different auction approaches that can be applied to radio resource allocation (like spectrum and power allocation). The authors in [4] introduce an auction design between a MVNO and the radio service provider that aims to maximize the social welfare for an efficient and fair allocation. The work also suggests a greedy algorithm to reduce the time complexity of the proposed solution. In [5], a 2-level hierarchical combinatorial auction is proposed for 5G networks between the infrastructure provider, MVNO and user equipments (UEs); two models are stated: a single seller-multiple buyer model and a multiple buyers-multiple sellers model. A backward induction method is proposed to solve the winner and price determination problems. In [6] and [7], the Myerson concept of virtual valuation is used to design a truthful auction for spectrum allocation.

This paper is organized as follows. Section II presents the system model, as well as the assumptions we considered in our work. Then, in Section III we formulate our proposed auction-based architecture, and we prove in the following sections key properties ensured by our scheme. Numerical results are illustrated and discussed in Section VI. Finally, Section VII concludes the paper and discusses future research issues.

II. SYSTEM MODEL AND TWO-LEVEL AUCTION

In this section, we first present the system model we consider in our work; then we formulate the two coupled auctions we designed to efficiently allocate network resources in such scenario.

More specifically, we consider a C-RAN where the physical spectrum resource is owned by the C-RAN operator who sells the spectrum to m virtual mobile operators (MVNOs, indexed from 1 to m), where $MVNO_j$ serves N subscribed users,

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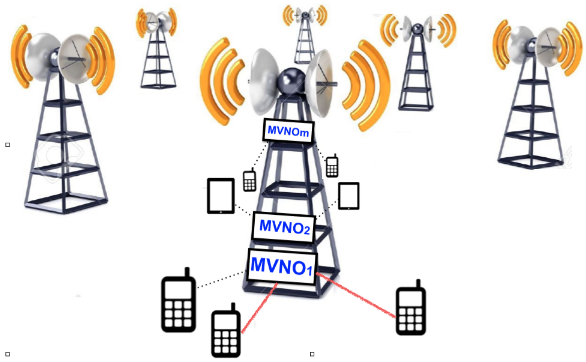

Fig. 1: System model with different cells, owned by a single physical operator, m mobile virtual network operators (MVNOs) and several end users (UEs)

as shown in Figure 1. There are Q resource blocks owned by the C-RAN operator, which are shared among the MVNOs. In our work, we consider the most competitive case where any resource block cannot be used by two users simultaneously.

A. The two-level auction

We develop a two-level auction-based resource allocation scheme, as shown in Figure 2: the higher-level auction runs between the C-RAN operator and the MVNOs; the lower-level auction between each MVNO and the end users it serves.

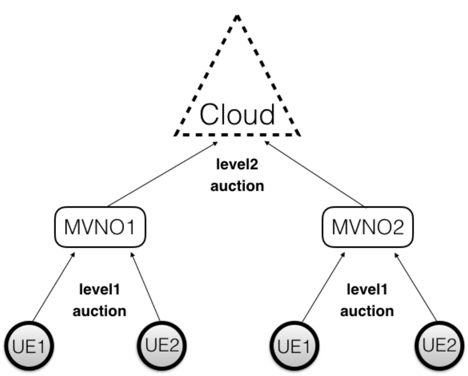

Fig. 2: Hierarchical auction game

More specifically, the agents of the auction are:

- **The C-RAN operator:** Also referred to as *Cloud*, it is the auctioneer at the higher-level auction that initiates the auction over Q resource blocks.
- **MVNOs:** Each $MVNO_j$ ($1 \leq j \leq m$) has two roles: a bidder in the higher-level auction and an auctioneer in the lower-level auction.
- **End users:** End users are bidders in the lower-level auction. They bid for the resource blocks to satisfy their service need. Specifically, the users served by $MVNO_j$ participate to the lower-level auction of this same MVNO.

The commodities of the auctions are the resource blocks. The bids are signals that inform the auctioneer about the bidder demands in terms of resource blocks and the offered price they are willing to pay in order to purchase the commodities.

More in detail, our auction proceeds as below with the notations reported in Table I:

TABLE I: Basic notation used in the 2 coupled auctions

Term	Interpretation
$MVNO_j$	j-th MVNO from a total of m participating in $auction_1$
$UE_{i,j}$	$MVNO_j$ i-th user, from a total of N users, participating in $auction_j$
$B_j = (S_j)$	$MVNO_j$'s bid, where $S_j = P_j$ is the weight and the price to be paid
$b_{i,j} = (d_{i,j}, w_{i,j})$	$UE_{i,j}$'s bid vector, where $d_{i,j}$ is the demand and $w_{i,j}$ the corresponding offered price
R_j	Number of resources allocated to $MVNO_j$
U_j & $u_{i,j}$	$MVNO_j$ & $UE_{i,j}$ utility functions
$\boldsymbol{x_j}$ & $\boldsymbol{p_j}$	Winners and price vectors of $MVNO_j$'s end users. $\boldsymbol{x_j} = \langle x_{1,j}, ..x_{N,j} \rangle$, $\boldsymbol{p_j} = \langle p_{1,j}, ...p_{N,j} \rangle$

1) In the first step, each user associated to $MVNO_j$, denoted as $UE_{i,j}$, submits a bid vector $b_{i,j} = (d_{i,j}, w_{i,j})$ to $MVNO_j$, where:
   - $d_{i,j}$ is an integer indicating the number of resource blocks required by $UE_{i,j}$.
   - $w_{i,j}$ is the price that user $UE_{i,j}$ is willing to pay to purchase $d_{i,j}$. $w_{i,j}$ is always less than or equal to $v_{i,j}$, the true valuation of $UE_{i,j}$ for receiving $d_{i,j}$. $v_{i,j}$ is a private information, only known by the user itself.

   We define $\boldsymbol{bj} = \langle b_{1,j}, ...b_{N,j} \rangle$, $MVNO_j$ users bids set.
2) In the second step, each $MVNO_j$ submits a bid vector S_j based on the bids received in the lower-level auction, i.e., b_j. We define the m-dimension bid vector $\boldsymbol{S} = \langle S_1, ...S_m \rangle$.
   Based on $\boldsymbol{S}$, the C-RAN operator allocates to $MVNO_j$ R_j resource blocks and charges him $P_j = S_j$. We denote by $\boldsymbol{R} = \langle R_1, ...R_m \rangle$ the allocation set to the m MVNOs participating in $Auction_1$.
3) In the third step, each $MVNO_j$ according to R_j determines the winner vector $\boldsymbol{x_j} = \langle x_{1,j}, .x_{i,j}..x_{N,j} \rangle$, where

$$x_{i,j} = \begin{cases} 1 & \text{if } UE_{i,j} \text{ wins the auction} \\ 0 & \text{otherwise} \end{cases}$$

   The allocation vector a_j is defined as

$$UE_{i,j} : b_{i,j} = (d_{i,j}, w_{i,j}) \quad \longrightarrow \quad a_{i,j} = (d_{i,j}, p_{i,j})$$

   where

$$a_{i,j} = \begin{cases} (d_{i,j}, p_{i,j}) & \text{if } UE_{i,j} \text{ wins the auction} \\ (0,0) & \text{otherwise} \end{cases}$$

The utility functions of the players in the auction are calculated as follows:

- $UE_{i,j}$'s utility:

$$u_{i,j} = v_{i,j} - p_{i,j} \tag{1}$$

- $MVNO_j$'s utility:

$$U_j = \sum_{i=1}^{N} p_{i,j} - P_j \tag{2}$$

- the C-RAN operator's revenue:

$$R_{C-RAN} = \sum_{j=1}^{m} P_j. \tag{3}$$

III. Resource allocation, Winner and price determination

We now illustrate how resources are allocated in both auctions, as well as the winners' determination and the corresponding price each player has to pay.

A. Higher-level auction

In the higher-level auction, the C-RAN operator allocates R_j resource blocks to $MVNO_j$ as follows

$$R_j = \frac{S_j Q}{\sum_{i=1}^{m} S_i + S_0}, \tag{4}$$

where S_0 is a *reserved bid* set by the cloud to avoid low bids. The utility of $MVNO_j$ is

$$U_j = \sum_{i=1}^{N} p_{i,j} - S_j. \tag{5}$$

Each $MVNO_j$ needs to calculate the optimal S_j^* in order to maximize his profit U_j.

B. Lower-level auction

In the lower-level auction, we first derive the optimal strategy for each MVNO. Due to its complexity, we further propose a greedy strategy.

1) Optimal solution: In $auction_j$, we adopt the sealed bid VCG auction where the user either wins all he asked for or nothing, and then pays the *harm* it causes to the other players [8]. We denote by $p_{i,j}^{VCG}$ the VCG price that $UE_{i,j}$ pays:

$$p_{i,j}^{VCG} = \max_{b_{-i,j}} \sum_{k \neq i}^{N} p_{k,j} x_{k,j} - \max_{b_j} \sum_{k \neq i}^{N} p_{k,j} x_{k,j} \tag{6}$$

where b_j denotes the set of all $MVNO_j$'s users bid vectors, while $b_{-i,j}$ indicates the set of all $MVNO_j$'s users bid vectors except for $UE_{i,j}$'s bid: $b_j = (b_{ij}, b_{-i,j})$. Knowing his allocation part, R_j, obtained from $auction_1$, $MVNO_j$ determines the winners by maximizing his profit:

$$max \sum_{i=1}^{N} p_{i,j} x_{i,j} \tag{7}$$

$$s.t. \quad \sum_{i=1}^{K_j = \lfloor R_j \rfloor} r_{i,j}^{k} = d_{i,j} x_{i,j} \tag{8}$$

$$\sum_{i=1}^{N} r_{i,j}^{k} \leq 1 \tag{9}$$

where

$$x_{i,j} = \begin{cases} 1 & \text{if } UE_{i,j} \text{ wins the auction} \\ 0 & \text{otherwise} \end{cases}$$

$$p_{i,j} = \begin{cases} p_{i,j}^{VCG} & \text{if } UE_{i,j} \text{ wins the auction} \\ 0 & \text{otherwise} \end{cases}$$

We denote by $r_{i,j}^{k}$ the k-th resource block $MVNO_j$ owns and allocates to $UE_{i,j}$, such that $1 \leq k \leq K_j$, where we consider K_j to be the integer part of the real number R_j.

Expression (8) ensures that $UE_{i,j}$ wins $d_{i,j}$ or nothing and equation (9) ensures that the resource block k cannot be allocated to more than one user. Using the method in [6], termed *virtual valuation*, and in which the true revelation of the user valuation is the best strategy for him to maximize his own profit, we proceed as follows.

To determine the winners, $MVNO_j$ maximizes the virtual valuation as follows

$$\max \sum_{i=1}^{N} \phi_{i,j}(w_{i,j}) x_{i,j}^{'} \tag{10}$$

$$s.t. \quad \sum_{k=1}^{K_j = \lfloor R_j \rfloor} r_{i,j}^{k} = d_{i,j} {x'}_{i,j} \tag{11}$$

$$\sum_{i=1}^{N} r_{i,j}^{k} \leq 1 \tag{12}$$

where

$$x_{i,j}^{'} = \begin{cases} 1 & \text{if } UE_{i,j} \text{ wins the auction} \\ 0 & \text{otherwise} \end{cases}$$

and

$$\phi_{i,j}(w_{i,j}) = w_{i,j} - \frac{1 - F_{i,j}(w_{i,j})}{f_{i,j}(w_{i,j})} \tag{13}$$

where

$$f_{i,j} = \frac{\partial F_{i,j}(z)}{\partial z} \tag{14}$$

According to the conventional Bayesian approach, we consider that the valuation $v_{i,j}$ of the buyers is drawn from a distribution $F_{i,j}$ known to the seller but not to the other bidders. We assume $F_{i,j}$ to be monotone increasing and $\frac{f_{i,j}}{1-F_{i,j}}$ to be monotone non decreasing, therefore the virtual valuation becomes monotone non decreasing [6].

We can define the virtual price $p_{i,j}^{'}$ as follows:

$$p'_{i,j} = \max_{b_{-i,j}} \sum_{k \neq i}^{N} \phi_{k,j}(w_{k,j}) x_{k,j} - \max_{b_j} \sum_{k \neq i}^{N} \phi_{k,j}(w_{k,j}) x_{k,j} \tag{15}$$

The final allocation $x_{i,j}$ is set to $x_{i,j}^{'}$ and the final price $p_{i,j}$ is set to $\phi_{i,j}^{-1}(p_{i,j}^{'})$.

It is interesting to note that the expected revenue P_E of any truthful mechanism under the Bayesian setting is equal to its expected virtual surplus, $\sum_i x_i \phi(w_{i,j})$. Hence, the expected revenue P_E of Equation (2) becomes

$$P_E = \sum_{i=1}^{N} p_{i,j} = \sum_{i=1}^{N} \phi_{i,j}(w_{i,j}) x_{i,j}^{'}. \qquad (16)$$

2) Greedy algorithm approximation: To avoid the time complexity of the integer linear optimization in the *winner* and *price determination* problems, we propose hereafter a greedy algorithm executed by each MVNO to determine the winners and the corresponding prices to be paid. The greedy algorithm proceeds in 2 phases as follows:

*a) **Winner determination**:*

We first sort, in a decreasing order, a list L of N weights $l_{i,j}$, where $l_{i,j} = \frac{w_{i,j}}{d_{i,j}}$. We start by allocating resources to the users according to the order of the corresponding $l_{i,j}$ value in the sorted list L. In other words, with respect to the order, $UE_{i,j}$ is a winner if $d_{i,j} \leq R_j$, i.e., $x_{i,j}$ is set to 1 and R_j is updated. Otherwise, $x_{i,j}$ is set to 0.

1) We set R to R_j, the total resource blocks to be allocated
2) We compute $l_{i,j}$, $\forall\ i \in [1, N]$ such that $l_{i,j} = \frac{w_{i,j}}{d_{i,j}}$
3) We sort the list L in a decreasing order according to $l_{i,j}$ where $[B, I]$ =sort List($l_{i,j}$); B is the sorted list of L and I is the index of the user $UE_{i,j}$ in L, i.e. the first element in the list I is the index of $UE_{i,j}$ having the highest weight $l_{i,j}$ in L.
4) For $t = 1 : N$ we set $k = I[t]$
   - if $d_{k,j} \leq R$, we set $x_{k,j} = 1$ and $R = R - d_{k,j}$
   - else $x_{k,j} = 0$

*b) **Price determination**:*

$UE_{i,j}$ will pay $p_{i,j} = l_{k,j} d_{i,j}$ such that $l_{k,j}$ is the critical weight as described in [6]; if $l_{i,j} \geq l_{k,j}$ $UE_{i,j}$ wins, while he loses if $l_{i,j} < l_{k,j}$. According to the sub-optimal method in [1] we find the critical price $c_{k,j}(i)$ such that if bidder $UE_{i,j}$ bids $l_{i,j} \geq l_{k,j}(c_{k,j}(i))$ he wins, and loses if $l_{i,j} < l_{k,j}(c_{k,j}(i))$. At this point, for the price computation we proceed as follows:

1) We find $c_{k,j}(i)$ $\forall\ i \in [1 : N]$
2) We set the virtual price $p_{i,j}^{\prime}$ to $l_{k,j}(c_{k,j}(i)) d_{i,j}$
3) We find the corresponding $p_{i,j} = \phi_{i,j}^{-1}(p_{i,j}^{'})$.

IV. Analysis of auction properties

It is widely known that it is desirable for auctions to meet the following economic properties: truthfulness, rationality and computational efficiency [4]. In this section we demonstrate that our auction mechanism satisfies these properties.

1) **Truthfulness:** We need to prove that the users are better off by reporting their true valuations. To this end, by Lemma 1 in [4], we can prove the monotone and critical price properties and the truthfulness is proved.
2) **Computational efficiency:** At the lower-level auctions, the VCG auction with the optimal Bayesian mechanism is proved in [6] to respect all of the economic properties except for computational efficiency. In fact, a major concern of the VCG auction is the exponential time complexity due to the ILP optimization problem. We address this limitation by proposing a greedy algorithm that reduces the time complexity to a polynomial. At the higher-level, the weighted proportional fair allocation presents a linear time complexity.

Hence all the properties are satisfied in our auction algorithm.

V. Equilibrium Analysis

In game theory, the solution of a game is characterized by Nash equilibria. According to [9], the set of bids of $MVNO_j$'s users $\boldsymbol{b^*} = (b_{1,j}^*, b_{i,j}^*, ...b_{N,j}^*)$ is a **Nash Equilibrium** if all users' bids $b_{i,j}$ $\forall\ i \in [1; N]$ are **best response** to the corresponding set $b_{-i,j}$. Moreover $b_{i,j}^*$, $UE_{i,j}$'s bid, is considered as **best response** if $UE_{i,j}$, by knowing all other users' bids, will not change his strategy; furthermore, even if user $UE_{i,j}$ gets to know other users bid strategies $b_{-i,j}$, he will not change his bid strategy. We have to prove that:

$$u_{i,j}(b_{i,j}^*, b_{-i,j}) \geq u_{i,j}(b_{i,j}, b_{-i,j}) \qquad (17)$$

$\forall$ possible $b_{i,j}$. Based on that equilibrium in the $auction_j$ game a second equilibrium should exist in $auction_1$: there should exist S_j such as $U_j(S_j^*, S_{-j}^*) \geq U_j(S_j, S_{-j}^*)$.

A. Nash Equilibrium for the lower-level auction

Based on the proof of Theorem 1 in [10], we can say that bidding the real valuation is a Nash equilibrium strategy, since with bidding other than $b_{i,j} = v_{i,j}$, $UE_{i,j}$ will not maximize his utility, regardless of all the bids vector $\in b_j^{-i}$. So $b_{i,j}^* = v_{i,j}$ is a Nash equilibrium point since it satisfies (17).

B. Nash equilibrium for the higher-level auction

In [11] the authors prove the Nash Equilibrium of the weighted proportional fair allocation we are using in the $level2$ auction. Nevertheless, in our model we have two games and proving the existence of the Nash equilibrium at this level of the auction requires proving that there exists a S_j^* such as

$$U_j(S_j^*, S_{-j}^*) \geq U_j(S_j, S_{-j}^*) \qquad (18)$$

where S_{-j} denotes the set of weights S excluding $MVNO_j$ weight's S_j. According to [12], the $auction_1$ game has an equilibrium point if $U_j(S)$ depending on the set S of all $MVNO$'s strategies is continuous and concave in all $S_j \in S$. Due to the fact that the expression of U_j is not in closed form, we will consider a numerical example, described hereafter, to simulate and evaluate the existence and uniqueness of the Nash equilibrium, showing that multiple Nash equilibria can indeed exist.

1) Scenario for the Nash Equilibrium evaluation: We consider a game where all the users $UE_{i,j}$ place bids in $auction_j$ by revealing their true valuation independently from the $N-1$ users bids, thus all $b_{i,j} \in \{(b_{i,j}, b_{-i,j})\}$ satisfy (18). We suppose there are 2 virtual mobile operators ($MVNO_1$ and $MVNO_2$), each having N users competing in 2 auctions, respectively, $auction_{j1}$ and $auction_{j2}$. After collecting all the bids, $MVNO_1$ and $MVNO_2$ will place their bids $B_1 = (S_1)$ and $B_2 = (S_2)$ in order to obtain their part of the allocation

(R_1 and R_2, respectively) and consequently pay $P_1 = S_1$ and $P_2 = S_2$. Our goal is to find the couple(s) (S_1^*, S_2^*) satisfying $\forall$ possible S_j:

$$U_1(S_1^*, S_2^*) \geq U_1(S_1, S_2^*) \tag{19}$$

$$U_2(S_1^*, S_2^*) \geq U_1(S_1^*, S_2). \tag{20}$$

In this perspective we simulate this scenario and evaluate the concavity of the utility function U_1 and U_2, and by that evaluate the existence and uniqueness of the Nash equilibrium point. Hence, we fix the cloud capacity Q, the number of users N, and by varying S_1 and S_2 in the interval $]0, S_{max}]$.

VI. Simulation Results

In this section, we simulate the two-level auction using Matlab. Since the fundamental interest of a mobile operator is to maximize its revenue, we first evaluate the payoff of the MVNO and compare the performance achieved by the *Integer Linear Program (ILP)* and the *greedy* algorithm. Then, we analyze in a fine-grained way the MVNO's payoff as a function of its bid and versus the total number of resource blocks with and without consideration of the virtual valuation. Finally, we simulate the Nash equilibrium scenario described in the previous section.

To achieve this, we consider a hierarchical model consisting of a cloud-RAN, which is shared among 2 MVNOs, $MVNO_1$ and $MVNO_2$, both having N subscribed users, where N varies in the range $[20, 100]$. We consider the 3 following scenarios:

1) **Scenario 1:** The N users are *homogeneous*; any given bidder $UE_{i,j}$ can ask for only 1 resource block such as $d_{i,j} = 1, \forall i \in I$ and $j \in \{1, 2\}$. The bid is $b_{ij} = (d_{ij}, w_{i,j})$, where the price $w_{i,j}$, offered to purchase $d_{i,j}$, is generated according to a uniform distribution in $[0, 1]$.
2) **Scenario 2:** The N users are *heterogeneous*: 50% of the users ask for 1 resource block ($d_{i,j} = 1$) and the other 50% ask for 2 resource blocks ($d_{i,j} = 2$). The price $w_{i,j}$ is generated as in Scenario 1.
3) **Scenario 3:** Users are heterogeneous; their demands $d_{i,j}$ are generated according to a *uniform distribution* in $[1, 5]$. The price $w_{i,j}$ is generated as in Scenario 1.

We set the cloud capacity in terms of resource blocks to $Q = 20$, the bids of $MVNO_1$ and $MVNO_2$ to $S_1 = 4$ and $S_2 = 3$, respectively, and the reserved bid $S_0 = 0.5$. We assume that the valuation is generated from a uniform distribution in order to use the virtual valuation concept.

To evaluate the *effect of the number of subscribed users* on MVNOs' payoffs, we increase such parameter from 20 to 100. The results are shown in Figure 3. It can be observed that the 3 scenarios present similar performance when varying N. The payoff increases with N, attends a maximum value at $N = N_c$, and beyond this value the payoff remains constant. More specifically, the gap between the payoff value for small and medium number of users (i.e., $N = 20$ and $N = 30$), respectively, is high and then becomes low, and even null, for large values of N. Furthermore, we observe that the results given by the greedy algorithm are very similar to the optimal one.

Figure 4 compares $MVNO_1$ and $MVNO_2$ payoffs by varying $MVNO_1$'s bid, S_1. We observe that $MVNO_2$'s payoff decreases with S_1; actually, for a given capacity Q and $MVNO_2$'s bid, S_2, the allocation part A_2 will decrease when $S1$ increases (we recall that $R_j = \frac{S_j}{S_j + S_{-j} + S_0}$). This trend is confirmed for the 3 considered scenarios. Conversely, $MVNO_1$'s payoff increases to attend a maximum and then decreases with S_1. We recall that the payoff function is $U_1 = P_E - P_1$, which depends linearly on S_1, since $P_1 = S_1$, and on P_E, which in turn is function of R_1, thus S_1. This explains the form of the curves. As observed before, also in this case, the greedy algorithm exhibits very good performance and provides results which are very close to the optimal solution.

Moreover, Figure 5 shows the revenue generated by $MVNO_1$ when varying the total number of resource blocks Q auctioned between $MVNO_1$ and $MVNO_2$ in $auction_1$. The results show the reservation effect of the virtual valuation on the revenue: without considering the virtual valuation, the revenue decreases when Q increases, while when using the virtual valuation the revenue remains constant when Q increases. These results coincide with those already observed in [6].

Finally, we analyze the scenario described in subsection V-B1. We observe that the equilibrium uniqueness is not always guaranteed. A possible explanation for that is the lack of concavity of the utility function as mentioned in [12]. This problem can be overcome by requiring that the payoff functions of MVNOs and users satisfy concavity requirements under specific conditions on the variable space set.

VII. Conclusion

In this paper we proposed and evaluated an auction-based resource allocation mechanism in the context of cloud-RAN. In such scenario, the spectrum is managed by several virtual mobile operators and the physical resource is owned by the C-RAN operator. Technically, our proposed approach consists of two coupled auctions in a hierarchical way: the lower-level auction between end users and the virtual operators, and the higher-level one between MVNOs and the C-RAN operator. We showed that our proposed auction-based approach satisfies fundamental economic properties, including truthfulness. We evaluated in typical network scenarios the validity of the proposed approach, showing that we are able to allocate resources efficiently, which is a key feature for next generation, 5G mobile networks. We plan to extend our work by enhancing the mechanism so that the solution converges to a unique and efficient Nash equilibrium point.

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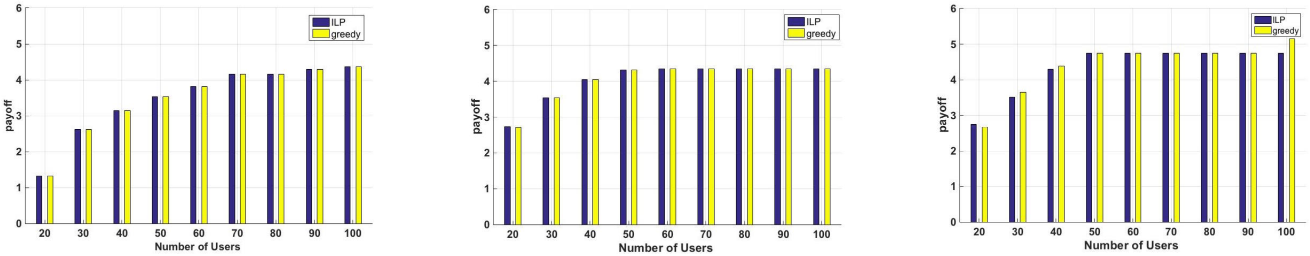
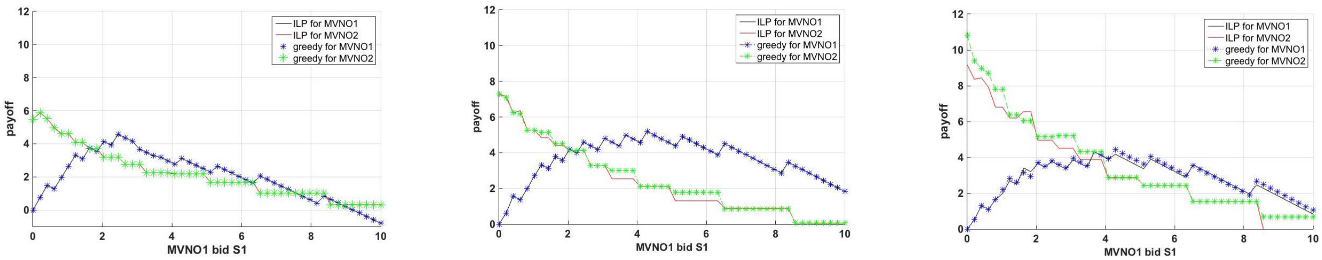


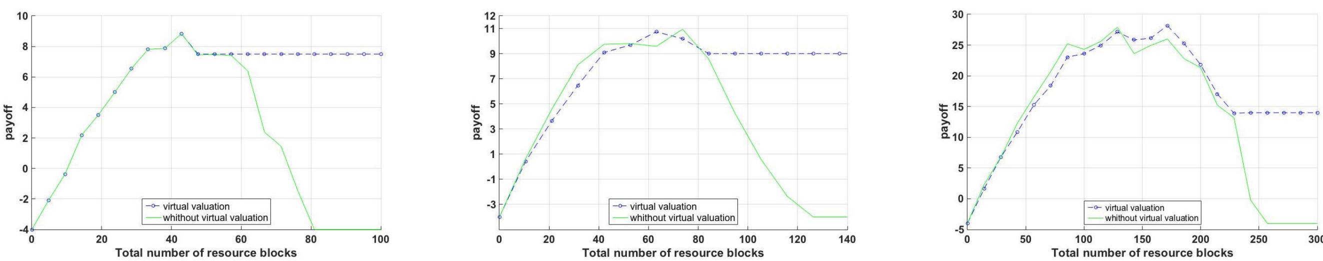
Scenario 1 Scenario 2 Scenario 3

Fig. 3: $MVNO_1$ and $MVNO_2$ payoffs: Increasing the number of users from 20 to 100.



Scenario 1 Scenario 2 Scenario 3

Fig. 4: $MVNO_1$ and $MVNO_2$ payoffs: Optimal and Greedy Algorithm solutions.



Scenario 1 Scenario 2 Scenario 3

Fig. 5: $MVNO_1$ payoff: Increasing the total number of resource blocks auctioned in $auction_1$.

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