Fair Profit Allocation in the Spectrum Auction Using the Shapley Value

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***Abstract*—Microeconomics-inspired spectrum auctions can effectively improve the spectrum utilization for wireless networks to satisfy the ever increasing service demands. Considering the spatial reuse, the bidding nodes without mutual interference are grouped as virtual bidders competing for the spectrum bands, which turns a multi-winner spectrum auction into a traditional single-winner auction. To make the participating nodes bid truthfully, strategy-proof auctions are exploited to allocate the vacant spectrum bands. However, how to fairly allocate the profits of the virtual bidder among the winning bidders is still an imperative problem to solve. In this paper, we propose a Shapley Value based profit allocation (SPA) to distribute the profit among the bidding nodes according to their marginal contributions, which are both from helping the virtual bidder to win the auction and from generating the revenue during the auction period. Our simulation and analysis show that SPA can effectively integrate the contributions from the two stages in the spectrum auction and fairly allocate the profit among the winning bidders.**

***Index Terms*—Spectrum Auctions, Shapley Value, Profit Allocation, Coalition**

I. Introduction

In the past few years, the dilemma between the booming growth of wireless services and the limited radio spectrum has pushed the fixed spectrum allocation of Federal Communications Commission (FCC) to the edge, and poured out numerous new techniques which allow the opportunistic access to the under-utilized spectrum bands [1]–[4]. Inspired by the business models in microeconomics, researchers choose the auction as one of the most promising solutions to the problem of allocating vacant spectrum bands to the potential unlicensed users [5]–[7].

Traditionally, the auctions can be classified into several categories by different criteria [8], [9], i.e., open or sealed auction by the bidding manner, first price auction, secondary price auction, Vickery auction [10], or Vickrey-Clarke-Groves (VCG) auction [11] by the pricing manner, and single item or combinatorial auction by the number of auctioned goods [12], [13]. Different auction mechanisms have different characteristics (e.g., incentive compatibility, Pareto efficiency, individual rationality, etc. [8], [14]), and they can be applied to different scenarios according to the requirements.

Although the desirable characteristics of various traditional auctions have been well investigated in existing literature [8]–[10], [12]–[14], these auction mechanisms cannot be hammered into the spectrum auction design directly. Unlike common goods in conventional auctions, spectrum is reusable among bidders subject to the spatial interference constraints, i.e., bidders geographically far apart can use the same frequency simultaneously, while bidders in close proximity cannot. Even though interference is a local effect, the spatial reuse of frequency makes the problem of finding the optimal spectrum allocation NP-complete [15], [16], which fails all the optimal allocation based conventional auction mechanisms [17].

To represent the mutual interference between neighboring bidders, Gandhi [18] has proposed the conflict graph and a general framework for wireless spectrum auctions. Based on these concepts, a truthfully bidding spectrum auction, *VERITAS*, is addressed by Zhou in [17]. The notion of critical neighbor is proposed and employed to guarantee the auction strategy-proof. Zhou [17] also provides an efficient allocation algorithm, which assigns bidders with spectrum bands sequentially from the bidder with the highest bid to the one with the lowest bid w.r.t. interference constraints. However, the validity of this algorithm is challenged by a special scenario in [19]. Wu in [19] shows that it is not always appropriate to allocate the spectrum bands to the bidder with the highest bid when the sum of the neighboring bids is much higher than the highest bid. Therefore, he proposes to trim the multi-winner spectrum auction [19] into a traditional single-winner auction by grouping the bidders with negligible interference together as virtual bidders. Similar to [19], the authors in [20] also group the bidders and turn a multi-seller multi-buyer spectrum auction to a McAfee double auction [21].

How to group bidders to bid truthfully as virtual bidders is the main focus of prior works, while how to fairly split the profit of the virtual bidder among the winning bidders (i.e., the bidders who compose the winning virtual bidder) is not well addressed. Moreover, most previous works assume the traffic demands are static during an auction period, so that as for a certain bidder, the evaluation values of the spectrum bands stay unchanged during the auction period. In fact, since the auction period cannot be arbitrarily short [22], [23], traffic demands are variable and unpredictable even during one auction period. In parallel with that, the values of the spectrum bands fluctuate significantly during the auction period, which makes it impossible for the bidder to determine a fixed evaluation value over the span of the auction period. Thus, the time-varying traffic demands in wireless networks brings more challenges to a fair profit allocation design.

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In this paper, we propose a Shapley Value based profit allocation (SPA) to distribute the profit among the winning bidders according to their marginal contributions. With a joint consideration of bidders' contributions to helping the virtual bidder win the spectrum auction and their contributions to increasing the profit of the virtual bidder during the auction period, SPA maps the profit allocation problem to a cooperative game, and takes use of the Shapley Value to allocate the profit of the winning virtual bidder. By numerical simulations, we show that SPA can effectively integrate the contributions to both stages and fairly allocate the profit among winning bidders in the spectrum auction.

The rest of the paper is organized as follows. In Section II, we introduce the system model and outline the spectrum auction procedure. We describe the challenges to the fair profit allocation among the bidders in Section III. We elaborate on the design of SPA in Section IV, and illustrate the fairness of this scheme by simulation and analysis in Section V. Finally, we conclude the paper in Section VI.

II. Preliminaries

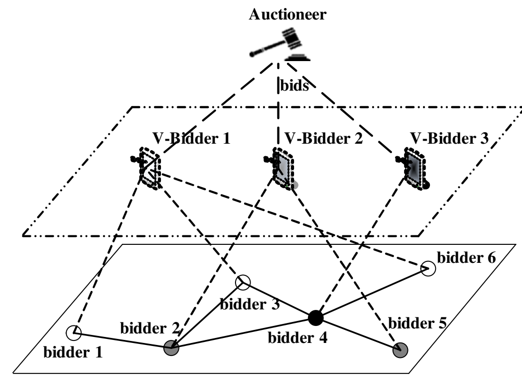
A. System Model

We consider a typical spectrum auction setting, where one auctioneer auctions his unutilized spectrum bands to nodes/bidders located in a geographic region. All the available spectrum bands are supposed to have the same characteristics to different nodes (in the sequel, we use the words nodes and bidders interchangeably), so that the concern of a bidder is the number of spectrum bands he can possibly win and the price per band he needs to pay. Considering the frequency reuse [16], [18], i.e., adjacent nodes must not use the same bands simultaneously while geographically well-separated ones can, we represent the interference relationship among bidders by a conflict graph proposed in [17] and [19]. As shown in Fig. 1, the heavy solid lines stand for mutual interference between corresponding nodes, and the dashed lines denote the bids. Besides, we also assume that there is a common channel[1] for necessary information exchanges between the auctioneer and bidders.

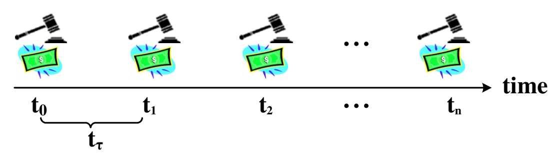
The other notations and definitions related to the spectrum auction are summarized as follows.

- *Bidder Set* **[N]** – $\mathbf{N} = \{1, 2, ..., n\}$ represents the set of n bidders.
- *Virtual Bidder Set* [$\mathcal{V}$] – $\mathcal{V} = \{\mathbf{V}_1, \mathbf{V}_2, ..., \mathbf{V}_v\}$ denotes the set of v virtual bidders. The virtual bidders are defined as a group of bidders without mutual interference, which is the same as the definition in [19], e.g., $\mathcal{V} = \{\mathbf{V}_1, \mathbf{V}_2, \mathbf{V}_3\}$, where $\mathbf{V}_1 = \{1, 3, 6\}$, $\mathbf{V}_2 = \{2, 5\}$, and $\mathbf{V}_3 = \{4\}$ as shown in Fig. 1(a).
- *Bidding Value* [b_i] – b_i indicates node i's bidding value per spectrum band.
- *Bidder's Revenue* [r_i] – r_i represents the amount of monetary gains earned by node i for providing services during an auction period.

[1]It is like the common control channel (CCC) proposed in [2], [4], or the common pilot channel (CPC) in [5], [24], [25]



(a) System architecture



(b) Periodical spectrum auction

Fig. 1. Spectrum auction model

- *Charging Price* [$p(i)$] – $p(i)$ is the price charged by the auctioneer for allocating the spectrum bands to winner i for one auction period.
- *Bidder's Profit* [$u(i)$] – $u(i)$ stands for how much node i ends up with, i.e., the payoff of bidder i. It is defined as $u(i) = r_i - p(i)$.
- *Auction period* [t_τ] - A fixed time period t_τ is set w.r.t. the dynamic spectrum access and overhead consideration.[2]

B. Spectrum Auction Procedure

To make the auction strategy-proof [17], [19], the auctioneer employs sealed auction mechanisms [8], [13] (e.g., secondary price auction, VCG auction, etc.) to allocate the spectrum bands and calculate the payments. The periodical spectrum auction can mainly be divided into three phases:

Bidding Phase

Each bidder encloses his identity, location information, and his own bidding value into his bid, which is sealed from the other bidders but open to the auctioneer for allocating spectrum bands and charging prices. Then, bidders submit their bids to the auctioneer.

Grouping Phase

Bidders without mutual interference can be grouped as a virtual bidder, whose bidding value is equal to the sum of the individual bidding values. With the concept of virtual bidders, the multi-winner spectrum auction among bidders can be changed into a conventional single-winner auction[3].

[2]t_τ should not be too long (e.g., months or years) to make dynamic spectrum access infeasible, and it should not be too short (e.g., seconds or minutes) to incur overwhelming overhead in spectrum auction. The typical duration of spectrum auction is hours or days as shown in [22], [23].

[3]Although how to optimally group bidders and allocate spectrum bands considering spatial reuse is NP-complete, many famous approximate algorithms can be embodied as possible substitutions, such as Max-IS [26], Greedy [27], and Greedy-U [27]. The problem of optimal division among bidders is beyond the scope of our paper.

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Opening Phase

At the beginning of current auction period, the auctioneer charges the winning virtual bidder according to the pricing mechanisms of the corresponding auctions. Before the start of the next period, the auctioneer divides the winning virtual bidder's profit among the bidders who compose this virtual bidder.

III. Challenges

By grouping bidders as virtual bidders, spectrum auction inherits the desirable characteristics from conventional auctions. However, due to fluctuant traffic demands of the bidders, how to fairly allocate the overall profit of the virtual bidder among winning bidders poses to be a critical problem. In this section, we first demonstrate that the bidder's evaluation values of spectrum bands change significantly over time by using the AP traffic traces from Dartmouth [28], and then describe the challenges to the design of fairly distributing profit among winning bidders in the spectrum auction.

A. Variable Evaluation Values of Spectrum Bands

As shown in Fig. 1(b) bidders create their bids, the auctioneer forms groups, and the virtual bidders submit their bids at the starting point of each period, i.e., every bidder is enforced to bid according to his evaluation values of the spectrum bands at the time points $\{t_0, t_1, t_2, ..., t_n\}$.

However, the traffic demands of a bidder may fluctuate significantly over time, which leads to the frequent changes of the bidder's evaluation values of the spectrum bands during an auction period. Take the measured WiFi AP traffic traces from Dartmouth [28] for example, we extract the volume of per-AP traffic demand by 5-minute intervals, and set the auction period $t_\tau = 50$ minutes. Figure 2 presents the traffic demands for two randomly selected APs, which can be regarded as two bidders in the spectrum auction. Both of APs are occasionally subjected to burst and spike in traffic demands, which are difficult to predict. Since a bidder's evaluation values of the spectrum bands depend on traffic demands[4], the drastically increasing or decreasing in traffic demands makes it impossible to determine a fixed evaluation value over the span of an auction period. That is to say, the truthful bidding values[5] at the time points $\{t_0, t_1, t_2, ..., t_n\}$ cannot reflect the trend of changes in the bidder's evaluation values of the spectrum bands over the whole auction period.

B. Challenges to Fair Profit Allocation

Intuitively, the profit sharing problem among the bidders, who compose the winning virtual bidder, can be carried out in two ways: (i) *No allocation* (NA). That means bidders only cooperate to win the auction, but do not share the profit. Each winning bidder clear his own market individually. (ii) *Proportional allocation* (PA). The profit obtained by the virtual bidder is allocated to the winning bidders proportionally according to their bidding values.

[4]For example, with the same amount of spectrum resource, CDMA system can accommodate more users by lowing the QoS of the individual user to some extent, so that the system's evaluation value of the given resource increases. Similar scenarios can also be found in other accessing technology, such as WiFi, WLAN, etc.

[5]If the spectrum auction is strategy-proof, each bidder will bid truthfully, and the bidding value is equal to the bidder's evaluation value [14], [17].

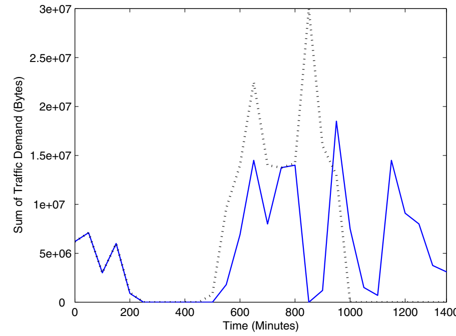

Fig. 2. Traffic demands of two randomly selected APs from Dartmouth Campus WiFi traces.

NA seems reasonable in the sense that even if the winning bidders are using the same spectrum bands, they provide services separately because they are non-interfering nodes. However, the capability of providing services is based on the fact that the virtual bidder is able to beat other virtual bidders and win the spectrum auction, which is definitely determined by the coalition of the participating bidders, i.e., the sum of the bidding values in the group. If the coalition does not exist, the bidder with a low bid may never have a chance to win the auction no matter how many services he can satisfy during the following period.

On the other hand, PA explicitly reflects the coalition relation among the bidders. The higher the node bids, the more profit he is allocated. But this simple method ignores a crucial factor, i.e., the dynamic values of spectrum bands as mentioned in the subsection above. For example, at the beginning of a certain auction period, say t_k, bidder i bids with a high value for the spectrum, while his traffic demands drop drastically during the following auction period, which greatly shrinks his evaluation values of spectrum bands as well as his contributions to the overall profit. According to PA, bidder i may be allocated with more profit than it deserves at the end of this period.

Therefore, a fair profit allocation scheme should give a comprehensive consideration of these two stages in the spectrum auction, i.e., helping the virtual bidder to win the auction and increasing the profit of the virtual bidder by providing services to satisfy the time-varying demands in wireless networks.

IV. The Design of SPA

Taking the two stages of the spectrum auction into consideration, we propose to adopt the contributions of a bidder to the coalition of bidders as a metric for the fair profit allocation. With this evaluation metric, the profit allocation problem can be perfectly matched with the cooperative game in game theory [29], [30], where a group of bidders may enforce the cooperative behavior, hence the game is a competition between coalitions of bidders rather than between individual bidders. In the following section, we first introduce the definition and

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properties of the Shapley Value in cooperative games, and then dwell on the detailed design of SPA.

A. Shapley Value

A cooperative game is such a game that players can conclude a binding agreement as to which outcome will be chosen to implement the possible common interests. The incentive of a player to join this game is not to sacrifice his own interests for the sake of the others, but to cooperate with some others for the purpose of furthering his own interests.

As an important application of cooperative game theories, the Shapley Value, first proposed in [30], describes a marginal-contribution based approach to fairly allocate the common transferable gains (e.g., revenue, profits, etc.) obtained by cooperation among the participating players. The Shapley Value is specified by the following 'desirable incentive and organization' properties [31], [32]:

- *Joint efficiency:* The sum of all players' payoff is equal to that of the grand coalition.
- *Zero payoff to the dummy:* If a player fails to contribute anything to the value of any coalition that he joins, then he is called a dummy player. The payoff to a dummy player is zero.
- *Symmetry:* If all players are identical, they share the total payoff equally.
- *Additivity:* The payoff to any given player is equal to the sum of all payoffs that player would receive as a member of all possible coalitions.

B. Details of SPA

In the setting of spectrum auction, the bidders can be regarded as players, the virtual bidder can be considered as the grand coalition, the profit can be mapped to the payoff, and the profit allocation problem can be interpreted as a cooperative game.

Since the losing virtual bidders of the auction cannot obtain any spectrum bands, only the winning virtual bidder is interested in the profit allocation problem. Therefore, we assume the winning virtual bidder of the spectrum auction is $\mathbf{V}_k$, which consists of m bidders, i.e., $\mathbf{V}_k = \{1, 2, ..., i, ..., m\}$, and the size of $\mathbf{V}_k$ is m. In the spectrum auction, the coalition of bidders has double meanings, i.e., cooperating to win the auction and satisfying the time-varying service demands in wireless networks. Correspondingly, the contributions of a bidder may come from both of the two stages.

With those assumptions, we can express the marginal contributions that bidder i makes to the coalition of bidders as

$$\psi_i(\mathbf{S}) = u(\mathbf{S}) - u(\mathbf{S} \setminus \{i\}),\ i \in \mathbf{S},$$

where $\mathbf{S}$ is a coalition of the bidders including bidder i, $u(\mathbf{S})$ is the profit from this coalition, and $u(\mathbf{S} \setminus \{i\}$ is the profit from the coalition without bidder i. For example, given $\mathbf{V}_1 = \{1, 3, 6\}$ as shown in Fig. 1(a), we find that $\mathbf{S} = \{\{1\}, \{3\}, \{6\}, \{1, 3\}, \{1, 6\}, \{3, 6\}, \{1, 3, 6\}\}$. It is obvious that $\mathbf{V}_k$ is also a special coalition, i.e., the grand coalition, in $\mathbf{S}$, and not all the coalitions have non-zero profit.

TABLE I
THE CALCULATION OF ϕ_1 IN THE EXAMPLE

$\boldsymbol{S}$	$\{\mathbf{1}\}$	$\{\mathbf{1} \cup \mathbf{3}\}$	$\{\mathbf{1} \cup \mathbf{6}\}$	$\{\mathbf{1} \cup \mathbf{3} \cup \mathbf{6}\}$
$u(\boldsymbol{S})$	0	2.5	0.5	4.5
$u(\boldsymbol{S} \setminus \{i\})$	0	0	0	1.5
$\psi_i(\mathbf{S})$	0	2.5	0.5	3
$\lvert\boldsymbol{S}\rvert$	1	2	2	3
$w(\lvert\boldsymbol{S}\rvert)$	$\frac{1}{3}$	$\frac{1}{6}$	$\frac{1}{6}$	$\frac{1}{3}$
$w(\lvert\boldsymbol{S}\rvert) \cdot \psi_i(\boldsymbol{S})$	0	0.42	0.08	1

Suppose $\mathbf{S}$ is a coalition with non-zero profit, which the profit of $\mathbf{S}$ can be denoted as

$$u(\mathbf{S}) = \sum_{i \in \mathbf{S}} r_i - p(\mathbf{S}),$$

where r_i the revenue as defined in II-A, and $p(\mathbf{S})$ is the charging price to the coalition $\mathbf{S}$.

As for the single-winner strategy-proof auctions, such as secondary price auction, VCG auction, etc. [9], [14], [19], $p(\mathbf{S}) = p(\mathbf{V}_k)$, which means that if non-zero profit coalition $\mathbf{S}$ could be a virtual bidder, it can also win the spectrum auction, and charging price remains the same as that of $\mathbf{V}_k$. This implicitly tells us that for any bidder $\{i | i \in (\mathbf{V}_k - \mathbf{S})\}$, he is not able to contribute to winning the auction any more, but only contribute to increasing the total profit for virtual winner $\mathbf{V}_k$.

Based on the individual bidder's marginal contributions in the coalitions, the Shapley Value can be exploited to calculate a fair division of the overall profit. It can be considered as a weighted average of marginal contributions of a bidder to all the possible coalitions in which it may participate. The mathematical expression of the Shapley Value is given by

$$\phi_i = \sum_{\{\mathbf{S} | i \in \mathbf{S}\}} w(|\mathbf{S}|) \cdot \psi_i(\mathbf{S}),\ \forall i \in \mathbf{V}_k.$$

Furthermore, the coefficient $w(|\mathbf{S}|)$ in the formula above can be calculated as

$$w(|\mathbf{S}|) = (|\mathbf{S}| - 1)!(|\mathbf{V}_k| - |\mathbf{S}|)!/|\mathbf{V}_k|!,$$

where $|\mathbf{S}|$ is the number of bidders in coalition $|\mathbf{S}|$, and $|\mathbf{V}_k|$ is the size of a grand coalition, i.e., m, the number of bidders composing the winning virtual bidder.

With the help of the Shapley Value, we fairly distribute the profit of cooperation adhere to the principle that the profit allocated to a participating bidder in a coalition is determined by his marginal contributions. When joining a coalition, a bidder may generate his contributions from helping the group of bidders to win the auction, or from increasing the the total profit, or from both of them. Note that the marginal contributions that a bidder can produce may be affected by the order in which the bidder joins a certain coalition. However, as mentioned in Section IV-A, the incentive and organization properties of the Shapley Value can guarantee a fair profit allocation among participating bidders, where we considers all orderings with equal probability and weights all bidders equally.

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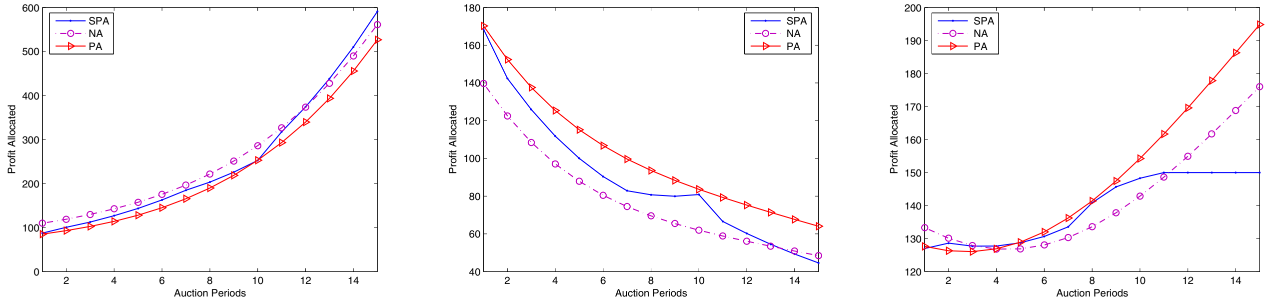

(a) Profit allocated to bidder 1

(b) Profit allocated to bidder 2

(c) Profit allocated to bidder 3

Fig. 3. Performance comparison of *SPA*, *NA* and *PA* in terms of profit allocated to the bidders

C. An Example

To make the proposed SPA better understood, we give an example with the scenario shown in Fig. 1, where $\mathcal{V} = \{\mathbf{V}_1, \mathbf{V}_2, \mathbf{V}_3\}$ and $\mathcal{N} = \{1, 2, 3, 4, 5, 6\}$.

Suppose there is only one vacant spectrum band, and sealed secondary price auction[6] is carried out among the virtual bidders. We also assume $\mathbf{V}_1 = \{1, 3, 6\}$ is the winner of the spectrum auction for a certain auction period, say from t_k to $t_{(k+1)}$, node 1, 3, and 6 bid at t_k with $b_1 = 3$, $b_3 = 2$, and $b_6 = 4$, and the secondary highest price is 4.5 (either from $\mathbf{V}_2$ or from $\mathbf{V}_3$). Moreover, suppose that the revenue earned by providing services from the winning bidders are $r_1 = 3$, $r_3 = 4$, and $r_6 = 2$ for the period from t_k to $t_{(k+1)}$.

Then, we make use of the Shapley Value to calculate the profit allocated to bidder 1 according to his marginal contributions as shown in Table I, where $\phi_1 = (0.42+0.08+1) = 1.5$. In the similar way, we can compute the corresponding profit allocated to bidder 3 and bidder 6 are $\phi_3 = 2$ and $\phi_6 = 1$, respectively.

V. Simulation and Analysis

In this section, we compare SPA with NA and PA to demonstrate the underlying fairness of the proposed scheme in the spectrum auction.

A. Simulation Setup

We set up the simulation with a similar setting to that shown in Fig. 1, where the number of spectrum bands for auction is 1, and the sealed secondary price auction is applied among the virtual bidders. To be simple, we assume the spectrum auction lasts for 15 periods, where $t_\tau = 50$ minutes, the secondary price is fixed at 500, and the winning virtual bidder is composed of three bidders with the starting bidding values of $b_1 = 200$, $b_2 = 400$, and $b_3 = 300$. Without loss of generality, we suppose that the revenue of bidder 1 increases exponentially over time, the revenue of bidder 2 decreases exponentially over time, and the revenue of bidder 3 keeps unchanged.

[6]For the single item auction, VCG is equivalent to the sealed secondary price auction.

B. Results and Analysis

We demonstrate the fairness lying in SPA by comparing it with NA and PA. In Fig. 3, the performance of the three schemes is depicted in terms of the profit allocated to different bidders.

As depicted in Fig. 3(a), we find that the curve of NA scheme shows the impact of revenue increasing during the auction periods upon the profit allocation. On the other hand, the curve of the PA shows the impact of bids at the bidding time (i.e., the starting time point of each auction period) upon the profit allocation, whereas neither of them can successfully combine the two pieces of impact together. On the contrary, SPA can effectively integrate the bidders' contributions from the two stages, and fairly allocate the profit to the bidders. Note that on the curve of SPA, there is a small turning point around the 10-th auction period. In the given simulation scenario, bidder 1 makes less contributions to the group of bidders than bidder 2 does preceding that turning point, but contributes more than bidder 2 after that point. Similar analysis also applies to bidder 2 in Fig. 3(b), except that his profit decreases over time.

In Fig. 3(c), the SPA based profit allocated to bidder 3 saturates after the 12-th period. The reason is that the revenue of bidder 1 increases quickly enough to help the virtual bidder win the auction, and all the contributions bidder 3 can make is to increase the group profit with his revenue, which is a fixed value. Correspondingly, the profit allocated to bidder 3 is fixed according to *Zero payoff to the dummy* property of the Shapley Value. By contrast, both of NA and NA unfairly give bidder 3 more profit than he deserves.

VI. Conclusion

In this paper, we propose SPA, a Shapley Value based profit allocation scheme to distribute the profit among the bidding nodes according to their marginal contributions in the spectrum auction. Considering bidders' contributions both to helping the virtual bidder win the spectrum auction and to generating the revenue during the auction period, we formulate the profit allocation problem as a cooperative game, and leverage Shapley Value to allocate the profit of the virtual bidder among winning bidders. Through numerical simulations, we show that

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SPA can effectively integrate the contributions from those two stages and fairly allocate the profit in the spectrum auction.

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