Truthful Auction Mechanism Design for Short-Interval Secondary Spectrum Access Market

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***Abstract*—Exploitation of short-interval spectrum availability offers an opportunity to better utilize spectrum for wireless communications. One significant class of short-interval secondary spectrum (SiSS) markets involves a primary license holder (PLH) renting out homogeneous spectrum units to a few competing Mobile Virtual Network Operators (MVNOs). This paper presents a design of SiSS market framework with brokerage services that mitigate information asymmetry and host auctions. The novel SiSS auction design is single-round and Vickrey-Clarke-Groves (VCG) auction-based and integrates two innovations. The first is a highly expressive bidding format that allows maximum bidding options to MVNOs in single submission. The second is a virtual bidder by the broker, whose bids are based on PLH's specification of per-unit reserve price, to avoid MVNOs' consideration of undesirable bidding strategies and guarantee that per-unit payment be no less than the reserve price. Such a design exploits the truthfulness of VCG and further achieves individual rationality and budget balance. Numerical experimentation shows that SiSS auction generates in average 31.3% higher per-unit revenue than VCG. For a SiSS market of 200 MVNOs and 500 spectrum units, computation time of clearing auction is within 15 seconds. These designs suit for SiSS applications in time efficiency and economic considerations.**

***Index Terms*—Short-interval, broker, single-round auction, Vickrey-Clarke-Groves, bidding format, virtual bidder, reserve price, truthfulness, individual rationality, budget balance.**

I. Introduction

WITH the development of new wireless broadband access (WBA) technologies such as WiMAX, LTE and LTE-A, high transmission speed and preferable quality of e-services increase the demands for spectrum rapidly [1]. Various global mobile data traffic reports project that worldwide mobile data traffic will increase more than 1X-fold in the coming five to ten years [2]-[4]. In some metropolitan areas, as existing and emerging devices continue to drive mobile data consumption, mobile networks need to prepare for 1000-fold traffic growth [5]. Current static "command and control" policies of spectrum allocations therefore result in inefficient spectrum usage because the underutilized spectrum licenses may still last for years and the clearing and reallocation of licenses has very high costs. The National Telecom & Information Administration (NTIA) of U.S. reported that the reallocation of 95 MHz (1755-1850 MHz) band would cost US$18 billions over ten years [6]. Under the legacy spectrum allocations, how to keep up with the emerging demands by limited spectrum resources becomes a pressing issue.

Secondary spectrum market, an approach to raise network capacity and efficiency of spectrum use, has been developed and adopted by U.S., U.K., New Zealand, and Australia, etc. [7]-[10]. Regulatory bodies such as the FCC of the U.S. and the Ofcom of the U.K., have taken significant steps to remove regulatory barriers and facilitate the development of secondary markets in spectrum usage rights among the wireless application services since 1990s [7][8]. Many countries have looked into the opportunity of exploiting terrestrial TV bands, i.e., TVWS [11]. To quickly increase WBA capacity by 1,000 times while avoiding inefficient clearing and reallocation, the U.S. President's Council of Advisors on Science and Technology (PCAST) proposed in 2012 and have since been advocating the sharing of lowly utilized Federal government spectrum starting with large-scale experimentation by using readily available technologies and systems [12]. Allowing underutilized or unused spectrum to be partitioned or disaggregated, shared, sold, or rented in the secondary market provides ways to mitigate the explosive growth of spectrum demands [10].

In the evolution to next generation wireless networks, emerging dynamic spectrum access (DSA) technologies have been developed to meet access demands by flexible and fine exploitation of spectrum availability over frequency, time and space [13][14]. Cognitive radio (CR) is one of the key technologies. Terminal devices with CR capability can communicate by using various frequencies, transmission power levels and modulation modes based on the external radio environment [15]. With the advancement of DSA technologies, the short-interval spectrum availabilities, which may be tens of minutes, hours, days to a few weeks, therefore become potentially valuable for usage in secondary spectrum markets.

Spectrum utilization and occupancy measurements by Shared Spectrum Company [16] indicate that spectrum resources may be lowly utilized over time in many areas. In

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recent years, measurements of spectrum utilization show that the long-term average utilization of the bands from 30 MHz to 5 GHz is lower than 20% [17]-[20]. However, average spectrum utilization does not reflect the true availability of underutilized or unused spectrum over time of day; detailed analysis of idle duration [21] and characterization of spatial-temporal distributions of underutilized spectrum [22] are needed to determine short-interval availability of spectrum.

A spectrum hole is a range of frequency which idles during a period of time in a specific space. As the emerging WBA technologies support flexible carrier bandwidth from 1.4 to 20 MHz, the measurement efforts in [21] also include search for 2-MHz wide spectrum holes and indicate a significant amount of spectrum holes from 30 MHz to 3 GHz. For example, in the 806-902 MHz band, there were 22 2-MHz holes idle during most of the 87-hour measurement period. Such spectrum holes with bandwidths wider than 1.4 MHz and idle durations longer than a few hours are potentially valuable and suitable for short-interval sharing in secondary spectrum markets.

Researchers have identified the challenges to develop a real-time or short-interval spectrum markets [23]-[26], including precise identification of spectrum hole availability, proper selection of market framework and trading mechanism and efficient exchange of spectrum market information. Kerans *et al.* [27] and Peha and Panichpapiboon [24] addressed the spectrum pricing problem of regulators and wireless service providers (WSPs). For CR-based spectrum sharing, Zhong *et al.* used game-theoretic approaches and designed efficient algorithms to solve the strategy selection problems of opportunistic [28] and energy efficient [29] accesses by secondary users. Alanyali *et al.* [30] characterized guidelines of pricing for profitability under unknown market demands.

Gandhi *et al.* [31] proposed a low complexity auction framework for real-time spectrum trading. Their design may facilitate spectrum trading but are in lack of three desirable economic properties of truthfulness, individual rationality and budget balance. Sodagari *et al.* [32] designed a dynamic, on-line auction among secondary CRs, where CRs submit arrival and departure times and valuations. It achieves anti-cheating property through proper choice of pricing policy and critical value auction. To guarantee individual rationality and exploit channels' spatial reusability, Zhang *et al.* very recently proposed a strategy-proof and efficient multi-channel auction mechanism (SPECIAL) for buyers with diverse demands [33]. Feng *et al.* [34] proposed a mechanism of truthful double auction for heterogeneous spectrums (TAHES), which considers heterogeneity factors in spatial location and frequency and has the three economic properties. But TAHES falls short in clearing price determination when the market has only one seller or one buyer.

Survey of potential secondary spectrum markets indicates that although one-to-one negotiation is still the main approach for trading [8]-[10][35][36], auction mechanisms are very often considered when there are multiple competitors [35]. Auctions for trading multiple spectrum units are significant because a minimum contiguous bandwidth for communication often requires multiple standard trading units [37] and a buyer may demand for more than the minimum. Information asymmetry among sellers and buyers regarding spectrum availability, values and opponents' strategy also poses an important challenge to market design [38].

In this paper, we consider one significant class of short-interval secondary spectrum (SiSS) market, where there are one primary license holder (PLH), a few mobile virtual network operators (MVNOs) and a SiSS broker (SB). The trading objects are multiple homogeneous spectrum units. Current examples of trading homogeneous units, either one-to-one or one-to-many, include SpecEx [36] and trading of international bandwidth [39]. Referring to the business models in [36] and [39] and in view of short-interval spectrum availability, we shall propose an auction-based market framework and trading mechanism to address the following design issues:

i) ***Information collection and distribution***: Players can distribute for-rent or renting requests, and collect current and historical market information.
ii) ***Time efficiency***: Execution time of trading procedure should be much shorter than the minimum rental period of spectrum holes.
iii) ***Truthfulness***: For a MVNO who likes to bid, bidding in true valuation leads to highest utility to the MVNO.
iv) ***Individual rationality***: Per-unit revenue to the PLH is not lower than the PLH's per-unit reserve price; payment by each MVNO is not higher than the MVNO's bid offer.
v) ***Budget balance***: Commission to the SB is non-negative.

Considering that time availability of spectrum holes is short, we design a SiSS market framework with brokerage services, which can assist potential players in exploring the possibility of trading and assessing the value of spectrum holes. To efficiently match supplies and demands, the trading mechanism adopts single-round auction and selects the Vickrey-Clarke-Groves (VCG) auction for further design due to its merit of truthfulness. The design, called SiSS auction, supports MVNOs' diverse demands in quantities and exploits the merit of VCG but has no revenue deficiency. The innovations consist of a highly expressive bidding format and a virtual bidder, whose bids are based on PLH's specification of per unit reserve price, to avoid MVNOs' consideration of undesirable bidding strategies and to prevent the opportunity cost-based payment calculation from leading to revenue deficiency. Under such a scheme, SiSS auction has incentives for the PLH and MVNOs to participate and the SB to provide services due to the assured properties of truthfulness, individual rationality and budget balance. Evaluation of computational efficiency demonstrates that the design of SiSS auction suits for SiSS applications.

The remainder of the paper is organized as follows. Section II explains the design challenges of SiSS market and presents a practical SiSS market framework with brokerage services. In Section III, we design a single-round and VCG-based SiSS auction with two innovations. Section IV proves three desirable economic properties of the SiSS auction. Numerical performance evaluations are given in Section V. Finally, Section VI concludes this paper.

II. SiSS Market Design Framework

Consider auction-based SiSS trading, through brokerage by a broker, of homogeneous spectrum units between one

PLH and a few MVNOs. The trading assumes the sharing concept of secondary spectrum access [11] and refers to a baseline business model similar to SpecEx [36]. The PLH provides spectrum holes for short-interval secondary access. Salient design requirements for such a SiSS market include time-efficient and flexible trading and the desirable economic properties of iii) - v). This section identifies design challenges and proposes an overall SiSS market design framework.

A. Design Challenges of the SiSS Market

Challenge 1: To mitigate information asymmetry and facilitate trading on a short-interval basis

Secondary spectrum access markets are of growing interest to many PLHs and MVNOs. In view of time-varying demands for short-interval spectrum access and spectrum availability of tens of minutes, hours to days, spending a long time on trading opportunity search, information exchange and negotiation is not acceptable by PLHs and MVNOs. There needs an online mechanism for players to conveniently collect and distribute spectrum information and to efficiently realize trading.

Challenge 2: To satisfy MVNOs' diverse demands

Many trading mechanism designs have buyers demanding for only one spectrum unit each. However, MVNOs often have diverse demands to meet over time.

Challenge 3: To assure the auction mechanism with desirable economic properties

Besides execution time efficiency, design of an effective auction mechanism should take economic properties such as truthfulness, individual rationality and budget balance into consideration. A truthful auction includes an optimal bidder strategy of bidding as one value and lowers the complexity of bid decision. Individual rationality incentivizes the potential participants to join and is significant to raise the exploitation of spectrum holes. Budget balance makes sure that the outcome of auction gives the SB non-negative service commission. However, many well-known auctions do not assure the properties simultaneously [40]. Loss of any property may easily discourage either the PLH or MVNOs from participation [11].

B. Overall SiSS Market Framework

Fig. 1 depicts the market framework with three types of players: one PLH, multiple MVNOs and one SB. The PLH is a WSP with a spectrum license and provides available spectrum in homogeneous units for renting during a specific time interval. MVNOs are also WSPs but without a spectrum license. MVNOs provide services to subscribers through dynamically renting spectrum from the PLH. The spectrum trading goes through brokerage services provided by the SB. Unlike some of the short-interval cloud resource auctions where market players may come and leave on the fly [41], SiSS assumes that the PLH and MVNOs are fixed within one-round of auction because of the nature of secondary spectrum trading.

The brokerage service consists of 1) information collection and distribution among the PLH and MVNOs to reduce their transaction costs and to close the gap of information asymmetry among them, and 2) a SiSS auction to match supplies and demands and rent available spectrum units out whenever possible with the desirable properties. In the SiSS market,

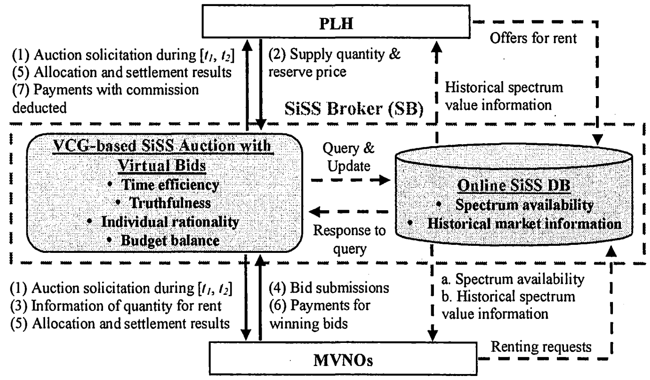

Fig. 1. SiSS market framework with a SB.

significant reduction of transaction costs such as searching for trading opportunity and estimating spectrum prices are indispensable to the success of trading [42]. Entrusted by the PLH and MVNOs, the SB sets up an online SiSS database (OSDB) and is responsible for its maintenance and management for fair trading. The PLH may upload for-rent information onto the OSDB and MVNOs may search for spectrum availability over it. The OSDB also maintains historical market information, which is significant to the PLH and MVNOs for spectrum valuation and price estimation.

The design of a SiSS auction needs to achieve time efficiency and three economic properties of truthfulness, individual rationality and budget balance. When the number of MVNOs and the number of trading units are both larger than two, there is no truthful auction that dominates over VCG design in both optimal social welfare and computation efficiency [43][44]. However, VCG does not assure individual rationality and budget balance and therefore may cause revenue deficiency to the PLH and impede the SB from services [45][46]. Revenue deficiency of VCG is rooted in opportunity cost-based payments, which occurs when there is weak market competition or high demand asymmetry among bidders. The SiSS auction design will be single-round for time efficiency, will be VCG-based to exploit the truthfulness property of VCG and will convert the reserve price specified by the PLH to bids of a virtual bidder for achieving individual rationality and budget balance in addition to truthfulness.

Fig. 1 depicts the overall trading procedures presided by the SB. Note that a solid line labeled with a serial number represents the procedural sequence, and a dashed line represents the information flow. Let there be PLH supplies of and MVNO demands for spectrum units during a time period [t_1, t_2]. The SB initiates a round of trading some time ahead of t_1. The procedures are as follows:

1) The SB solicits auction of spectrum during period [t_1, t_2].
2) The PLH provides the SB with supply quantity and reserve price information, which the PLH estimates by referring to both the license holding cost and historical spectrum value information stored in OSDB.
3) The SB converts the reserve price of the PLH to virtual bids and announces the auction quantity to all MVNOs.
4) After receiving the auction information from the SB,

each MVNO first calculates the MVNO's bid offers and then submits them in a required format within a regulation time. MVNOs can query OSDB for historical spectrum value information while calculating the bid offers.
5) When the bid submission time is up, the SB clears the auction via a bid selection and payment calculation process, which should rent as many supply units out as possible to increase the utilization of spectrum. After the settlement, the SB announces auction results to PLH and MVNOs.
6) Winning MVNOs send payments to the SB.
7) The SB takes a fixed rate commission from the winning payments and gives the remaining to the PLH.

Under such a SiSS market framework, OSDB maintenance and management and single-round auction hosting are mandated to the entrusted SB. The OSDB centralizes trading information, mitigates information asymmetry among participants, reduces transaction costs and increases the viability of trading.

III. Truthful SiSS Auction Mechanism Design

This section substantiates the single-round and VCG-based auction in the SiSS market framework with detailed designs. Important notations are defined in Table I. The designs should allow the PLH to contribute and MVNOs to purchase multiple homogeneous units and achieve the objective of allocating spectrum units to MVNOs who value them the most while assuring economic properties of truthfulness, individual rationality and budget balance.

Design innovations include two items:

(a) ***Highly expressive cumulative bidding format (CBF)*** to support MVNOs' diverse demands, allow maximum bidding options for MVNOs, and eliminate the need for multiple-round bidding;
(b) ***Virtual bidder with bids derived from PLH's reserve price*** to avoid MVNOs' consideration of undesirable bidding strategies and guarantee that per-unit payment be no less than the reserve price set by the PLH.

With these innovations, the SiSS auction incentivizes the PLH to put unused or lowly utilized spectrum for rent, and MVNOs to bid true valuation in CBF as an optimal strategy, and the SB to provide brokerage services.

A. Highly Expressive CBF

For a single-round auction of multiple units, a flexible bidding format is highly desirable to support MVNOs' diverse demands and enable MVNOs to specify their bid options via one bid submission. For MVNO-i, who demands for d_i units, the CBF allows the MVNO to submit bids in the format of

$$[1 \text{ unit} : \alpha_i(1),\ 2 \text{ units} : \alpha_i(2),\ ...,\ d_i \text{ units} : \alpha_i(d_i)], \quad (1)$$

where $\alpha_i(j)$ indicates bid offer for j units specified by MVNO-i. The advantages of using CBF are as follows:

1) maximal description of bidding options in one bid submission and diverse bids for units, and
2) flexibility for MVNO-i to bid on and win part of the MVNO-i's demand d_i as compared to all-or-none in the traditional single-bid format (SBF).

TABLE I
Notations for the Truthful SiSS Auction Model

N	total number of MVNOs in the market
i	bidder index, $i = 1, 2, ..., N$, for MVNOs and $i = N + 1$ for the virtual bidder
d_i	the maximal bidding quantity by bidder-i
J	number of spectrum units for rent provided by the PLH
j	spectrum unit index, $j = 1, 2, ..., J$
$\alpha_i(j)$	bid offer for j units submitted by bidder-i
R	per-unit reserve price set by the PLH
S	set of MVNOs and virtual bidder, $S = \{1, 2, ..., N, N+1\}$
x_{ij}	binary decision variable, $x_{ij} = 1$ as j units are allocated to bidder-i, and $x_{ij} = 0$, otherwise
a_i	number of units allocated to bidder-i
$\pi_i(a_i)$	bidder-i's payment for a_i winning units

The use of CBF thus eliminates the need for iterative bid refinement and therefore suits for applications to single-round auction of multiple units.

B. Virtual Bidder with Bids Derived from PLH's Reserve Price

Revenue deficiency of VCG auction may take place when market competition is weak or bidders are highly asymmetric in demands, and leads to low revenues in such cases [45]. The problem is rooted in that payment by a winner is the opportunity cost of winning the bid instead of paying as bid. To be precise, revenue deficiency occurs when there is surplus in supply after removing the MVNO with the most demand from the market. In this case, the MVNO with the most demand can win at least one unit at zero payment because other MVNOs' demands are satisfied and the opportunity cost of winning the one unit is zero. To overcome revenue deficiency of VCG, there have been some extension schemes such as Hobbs *et al.*'s [47] adjustment of the minimum payment to reserve price and iterative allocation and payment calculation by Zhan *et al.* [48]. But both extensions lose VCG merit of truthfulness.

To resolve revenue deficiency while maintaining truthfulness of the VCG-based auction, our design introduces a virtual bidder into the SiSS auction. Once the PLH specifies the quantity, J, and per-unit reserve price, R, for auction to SB, the SB creates a virtual bidder with bid offers based on PLH's specification. The basic ideas are as follows:

i1) The virtual bidder's maximal bidding quantity equals the J units supplied by the PLH, i.e.,

$$d_{N+1} = J. \quad (2)$$

Such a setting makes the total demand excluding the demand of any one MVNO bidder-i, $i \in \{1, 2, ..., N\}$, no less than J units, namely,

$$\sum\nolimits_{i' \in S} d_{i'} - \max_{i \in \{1,2,...,N\}} \{d_i\} \geq J. \quad (3)$$

The undesirable situations that lead to revenue deficiency are therefore avoided after the introduction of a virtual bidder and demand.

*i*2) Bid offers of the virtual bidder are set as:

$$[\alpha_{N+1}(1) = R, \alpha_{N+1}(2) = 2R, ..., \alpha_{N+1}(J) = JR], \quad (4)$$

which correspond to the per-unit valuation of the PLH. As such virtual bid offers are independent of MVNOs' bids, MVNOs with bids lower than R per unit are impossible to win the bids because winner selection adopts the highest bid rule. For MVNO-i who wins a_i units, the payment is at least $a_i \times R$, which is the opportunity cost of not giving the a_i units to the virtual bidder. Any units won by the virtual bidder correspond to those not rented out.

C. Auction Clearing Algorithm

Key steps to clear the allocation include winner selection, payment calculation and settlement between the PLH and SB.

Step 1: Select winning bids

To allocate the J units to MVNOs and virtual bidder for maximal bid offers, an integer programming model of Knapsack problem (KP) is formulated for selecting a maximum bid offer combination [40]. When a MVNO-i^*'s bid for j^* units equals the virtual bidder's bid, selection priority is to MVNO-i^* because the PLH prefers renting out spectrum units rather than holding them to the PLH. Define the equal set

$$S_e \equiv \{(i^*, j^*) \in \{1, 2, ..., N\} \times \{1, 2, ..., d_{i^*}\} | \alpha_{i^*}(j^*) = \alpha_{N+1}(j^*)\}. \quad (5)$$

To capture the priority setting in the (KP) formulation, define the adjusted bids for tie-breaking,

$$\hat{\alpha}_i(j) = \begin{cases} \alpha_i(j) + \varepsilon, & \text{if } (i, j) \in S_e, \text{ where } 1 \gg \varepsilon > 0; \\ \alpha_i(j), & \text{otherwise.} \end{cases} \quad (6)$$

The (KP) formulation is as follows:

$$\text{(KP)} \ \max_{x_{ij}} \sum_{i=1}^{N} \sum_{j=1}^{d_i} x_{ij} \hat{\alpha}_i(j) + \sum_{j=1}^{d_i=J} x_{(N+1)j} \alpha_{N+1}(j). \quad (7)$$

Subject to

Constraint 1: Single bid assignment constraint

A bidder's bid offers for different quantities are different, but one bidder wins at most one bid of a specific quantity j:

$$\sum_{j=1}^{d_i} x_{ij} \leq 1, \forall i \in S. \quad (8.1)$$

Constraint 2: Availability constraint

The total units allocated should be no more than the number available to allocate.

$$\sum_{i \in S} \sum_{j=1}^{d_i} x_{ij} \times j \leq J. \quad (8.2)$$

Step 2: Calculate winning MVNOs' payments

After bid selection by solving (KP), the SB then calculates winning MVNOs' payments. Payment calculation follows that of the VCG auction. Let us first define B_S^J as the objective function value of (KP). Assume that the optimal bid selection of MVNOs is $\{x_{ij}^*\}$, and the number of units allocated to MVNO-i is $a_i = \sum_{j=1}^{d_i} j \times x_{ij}^*$. The payment for the a_i units that MVNO-i wins, $\pi_i(a_i)$, is then

$$\pi_i(a_i) = B_{S \setminus i}^J - B_{S \setminus i}^{J - a_i}, \quad (9)$$

where $B_{S \setminus i}^J$ and $B_{S \setminus i}^{J-a_i}$ are the maximal values of allocating J and $(J - a_i)$ units to bidders in S other than MVNO-i respectively, and $\pi_i(a_i)$ is therefore the opportunity cost of MVNO-i winning a_i units.

Step 3: Calculate PLH's revenue and SB's commission

For each rented spectrum unit, the commission to the SB is the difference between MVNOs' payments and reserve price multiplied by a fixed commission rate which is the sum of rate for PLH, β, and MVNO, γ, namely,

$$\left(\sum_{i=1}^{N} \pi_i(a_i) - \sum_{i=1}^{N} a_i \times R\right) \times (\beta + \gamma). \quad (10)$$

So, the payment from SB to the PLH is MVNOs' payments to the SB minus the SB's commission, i.e.,

$$(1 - \beta - \gamma) \sum_{i=1}^{N} \pi_i(a_i) + (\beta + \gamma) \sum_{i=1}^{N} a_i \times R. \quad (11)$$

TABLE II
COMPARISON RESULTS OF THE ILLUSTRATIVE EXAMPLE

	SiSS auction		VCG auction	
	# of units won	Payment	# of units won	Payment
MVNO-1	3	$18	3	$13
MVNO-2	0	0	0	0
MVNO-3	1	$6	1	$6

D. Illustrative Example and Discussion

Assume three MVNOs to bid for four spectrum units. PLH's per-unit reserve price is \$5. The three MVNOs submit bids in CBF as follows:

MVNO-1: $d_1 = 3$ and $(\alpha_1(1), \alpha_1(2), \alpha_1(3)) = (\$6, \$14, \$23)$;
MVNO-2: $d_2 = 2$ and $(\alpha_2(1), \alpha_2(2)) = (\$6, \$13)$;
MVNO-3: $d_3 = 1$ and $(\alpha_3(1)) = (\$10)$.

The SB creates a virtual bidder with bids of (\$5, \$10, \$15, \$20). The allocation obtained by solving Eqs. (7), (8.1) and (8.2) are $(a_1, a_2, a_3) = (3, 0, 1)$, and individual payments calculated based on Eq. (9) are $(\pi_1(a_1), \pi_2(a_2), \pi_3(a_3)) = (\$18, 0, \$6)$.

Assume that the commission rate $(\beta + \gamma)$ is 3%, the SB can get [(\$18+\$6)−4×\$5]×3% = \$0.12 from this SiSS auction. Revenue to the PLH is \$18+\$6−\$0.12 = \$23.88, which is \$3.88 higher than the reserve price of four units. Comparison with the VCG auction over this example is given in Table II. In the VCG auction, MVNO-1 wins three units and pays \$13, which is lower than \$15, the reserve price of three units.

IV. PROPERTIES OF SISS AUCTION

This section proves the three desirable properties of the SiSS auction design given PLH's specification of a reserve price: *truthfulness*, *individual rationality* and *budget balance*.

Theorem 1: *Truthful bidding is an optimal strategy for MVNOs in the SiSS auction.*

Sketch of Proof: In SiSS auction, the creation of a virtual bidder by SB adds to MVNO bidders a bidder with maximal demand of J units and bid offer in the CBF format of Eq. (4) parameterized by the reserve price R unknown to other MVNO bidders. By interpreting R as the per-unit valuation of the virtual bidder, submitting CBF bids in one MVNO's true demand for and valuations of spectrum units is a simple decision strategy that leads to the MVNO's maximum utility in the auction. The detailed proof is given in the Appendix.

Lemma 1: *Per unit bid price of a selected bid in (KP) must be no less than R.*

Proof: Assume that in a (KP) solution $\underline{x}$, $x_{i^*j^*}=1$, $\alpha_{i^*}(j^*) < j^* \times R$, and the virtual bidder gets the allocation of $\sum_{j=1}^{J} x_{(N+1)j} \times j \le J - j^*$ units. It is obvious that re-setting $x_{i^*j^*}=0$, and allocating j^* more units to the virtual bidder leads to a feasible solution to (KP) but with a higher objective function value in Eq. (7) than the original (KP) solution, a contradiction.

Theorem 2: *SiSS auction is individually rational.*

Proof:

i) Rationality of PLH: Revenue of rented out units is no less than their reserve price.

Define (KP-S-J) as the (KP) with J units for allocation to a set, S. Suppose MVNO-i wins a_i units. (KP-$S\backslash i$-J) and (KP-$S\backslash i$-$(J-a_i)$) are the (KP)s with J and $(J-a_i)$ units for allocation to bidders in set $S\backslash i$ respectively. The payment for MVNO-i winning a_i units is $\pi_i(a_i) = B^J_{S\backslash i} - B^{J-a_i}_{S\backslash i}$ (Eq. (9)), where $B^J_{S\backslash i}$ and $B^{J-a_i}_{S\backslash i}$ are the optimal objective function values of (KP-$S\backslash i$-J) and (KP-$S\backslash i$-$(J-a_i)$). According to Lemma 1, the payment of MVNO-i's a_i winning units is

$$\pi_i(a_i) = B^J_{S\backslash i} - B^{J-a_i}_{S\backslash i} \ge a_i \times R. \tag{12}$$

So the payment from SB to the PLH (Eq. (11)) is no less than the reserve price of the units rented out,

$$(1-\beta-\gamma)\sum_{i=1}^{N}\pi_i(a_i) + (\beta+\gamma)\sum_{i=1}^{N} a_i \times R \ge \sum_{i=1}^{N} a_i \times R. \tag{13}$$

ii) Rationality of MVNO: Payment is not higher than the bid offer for units won.

Let $\{x^*_{ij}\}$ be the optimal bid selection of (KP-S-J), B^J_S be the optimal objective function value, and $a_i = \sum_{j=1}^{d_i} j \times x^*_{ij}$. Note that $B^J_S = \alpha_i(a_i) + B^{J-a_i}_{S\backslash i}$. It then follows that

$$\begin{aligned} &\alpha_i(a_i) - \pi_i(a_i) = \alpha_i(a_i) - (B^J_{S\backslash i} - B^{J-a_i}_{S\backslash i}) \\ &= (\alpha_i(a_i) + B^{J-a_i}_{S\backslash i}) - B^J_{S\backslash i} = B^J_S - B^J_{S\backslash i} \ge 0, \forall i. \end{aligned} \tag{14}$$

Corollary 1: *SiSS auction is budget balanced.*

Proof: According to Theorem 2, MVNO-i's payment for a_i winning unit, $\pi_i(a_i)$, is equal to or higher than $a_i \times R$. By substituting inequality (12) into expression (10), it shows that the commission to the SB is non-negative when there are bid offers, i.e., budget balanced:

$$\begin{aligned} &[\sum_{i=1}^{N}\pi_i(a_i) - \sum_{i=1}^{N} a_i \times R] \times (\beta+\gamma) \\ =\ &[\sum_{i=1}^{N}(B^J_{S\backslash i} - B^{J-a_i}_{S\backslash i}) - \sum_{i=1}^{N} a_i \times R] \times (\beta+\gamma) \\ \ge\ &[\sum_{i=1}^{N} a_i \times R - \sum_{i=1}^{N} a_i \times R] \times (\beta+\gamma) = 0. \end{aligned} \tag{15}$$

TABLE III
PARAMETER SETTING FOR NUMERICAL EVALUATION OF SISS AUCTION

Parameter	Value
N	1~10
J	Integers uniformly distributed in [5, 15]
d_i	Integers uniformly distributed in [1, 5]
R	800$/hour
$\alpha_i(j)$	$\alpha_i(0) = 0$; and $\alpha_i(j) = \alpha_i(j-1) + x$ for $j = 1$ to d_i, where $x \sim U[500, 1500]$, $\forall i$

TABLE IV
DEFINITION OF COMPETITION LEVELS AND RATIO OF OCCURRENCE

Competition level	Supply (J) - Total Demand (D) Relation	Ratio of occurrence
Level-1	$J \le 0.5D$	3,956/10,000 ≈ 0.396
Level-2	$0.5D < J < D$	2,937/10,000 ≈ 0.294
Level-3	$D \le J$	3,107/10,000 ≈ 0.311

V. PERFORMANCE EVALUATION

After proving the three properties of SiSS auction, there are still four important performance questions, both economic and computational, to answer about SiSS auction:

1) What advantages does CBF have over SBF?
2) How do SiSS and the VCG auctions compare in revenues for the PLH and in payments for MVNOs?
3) Is the computation of SiSS auction efficient? With the understanding about the performance of SiSS auction under a given reserve price R, it is very natural to ask
4) How will reserve price affect the economic performance?

A test scenario is designed and 10,000 test instances are generated accordingly for numerical evaluation of SiSS auction to address the four questions. The scenario represents trading between one PLH and multiple MVNOs under the design framework described in Section II. Table III lists the parameter settings. The number of MVNOs, N, ranges from 1 to 10, and 1,000 test instances are generated for each N value. In each test instance, the PLH's supply and individual MVNOs' demands are generated from uniform distributions. Under the settings, the probability that a SiSS market is in an under-supply situation is 0.713. The bandwidth per spectrum unit is defined as 2 MHz because it can support the minimum bandwidths required by LTE and WiMAX based services (i.e., 1.4 MHz and 1.75 MHz, respectively) [21]. In specific, the reserve price per spectrum unit, R, is set to 800$/hour by referring to the 15-year license fees of 3G spectrum auction market in Taiwan [49]. For each MVNO's incremental bid in CBF, we randomly generate per-unit offer from the interval [500, 1500] and sum up the per-unit offers to form cumulative offers up to the MVNO's maximum demand quantity.

The 10,000 test instances thus generated include 6,893 under- and 3,107 over-supply situations, which reflect different levels of market competitions. Table IV further defines competition levels and classifies the 10,000 instances accordingly, the larger the level number, the lower the competition. The 3,107 over-supply instances are classified to level-3. Among the 6,893 under-supply instances, there are 3,956 level-1 instances, each with total demand more than double the supply.

In specific, to address question 3, we enlarge the dimension of this test scenario and generate more test instances for analysis. The number of MVNOs and spectrum units range from 50 to 200 and 50 to 500, respectively. For a specific number of MVNOs and spectrum units, the computation time needed is averaged over 10 instances.

A. Advantage of Using CBF

Now we analyze the advantage of using CBF in SiSS auction as compared to using a SBF, where a MVNO makes only one bid offer for the total quantity of the MVNO's demand. In the following analyses, let CBF auction and SBF auction be SiSS auctions using CBF and SBF as bidding formats respectively. Let us first define a significant performance index, spectrum rent-out ratio (ROR), of comparison as follows:

$$ROR \equiv \frac{\text{\# of units allocated to MVNOs}}{\text{\# of units provided by PLH}} = \frac{\sum_{i=1}^{N} a_i}{J}. \quad (16)$$

There are four hypotheses for analyses in this subsection:

H1) CBF auction should lead to a higher ROR than SBF auction because the former has a finer granularity for bid selection and allocation than the latter.

H2) PLH may expect a higher total revenue from CBF auction than SBF auction because the former achieves a higher ROR as hypothesized in H1).

H3) MVNOs in CBF auction would pay more than SBF auction because of higher revenue to the PLH, which implies lower MVNO's surplus.

H4) CBF auction should have a lower variation of MVNOs' winning quantities than SBF auction because CBF has finer granularity in bids and more MVNOs are expected to win.

Figs. 2, 3 and 4 present comparisons between CBF and SBF auctions over numerical experimentation when the $\alpha_i(d_i)$ bid in SBF equals the $\alpha_i(d_i)$ bid in CBF. Fig. 2(a) shows that CBF auction has higher ROR than SBF auction when the number of MVNOs is more than five. Among all the 10,000 instances, Fig. 2(b) shows that CBF and SBF auctions lead to the same ROR in 6,615 instances and that among the other 3,385 instances, CBF auction outperforms SBF auction in 2,088 instances, which means that H1 does not hold for 1,297 instances. The reason is the introduction of virtual bids, which impedes incremental bids lower than reserve price from winning. Let us explain via an example:

Example 1: Assume two MVNOs to bid for four units. The reserve price is $10 and the bids of virtual bidder are ($10, $20, $30, $40). MVNO-1's bids in CBF are ($15, $21) and MVNO-2's bids are ($12, $22). If the auction adopts SBF, MVNO-1 submits $21 for two units and MVNO-2 submits $22 for two units. Auction results are as follows:

CBF auction

MVNO-1 wins 1 unit, MVNO-2 wins 2 units, and the virtual bidder wins 1 unit.

ROR = 3/4 = 75%.

SBF auction

Each MVNO wins 2 units and none for virtual bidder.

ROR = 4/4 = 100%.

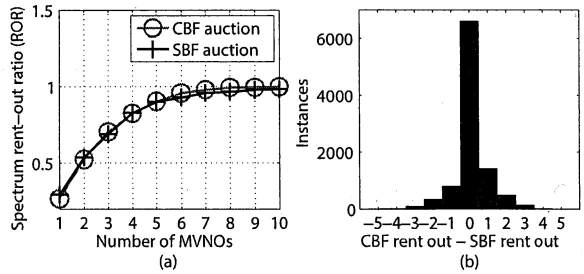

Fig. 2. CBF and SBF auctions: (a) ROR over different number of MVNOs and (b) Histogram of the difference of rent out quantity.

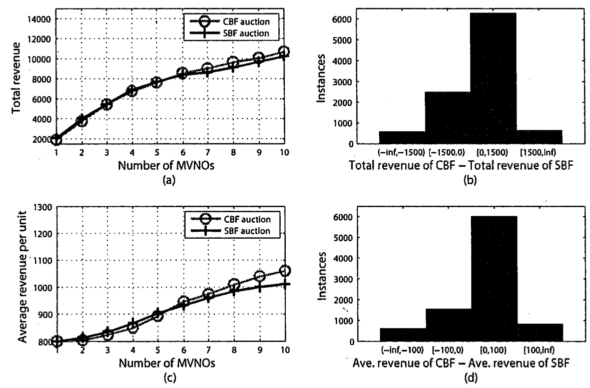

Fig. 3. Comparisons of CBF and SBF auctions: (a) Total revenue over number of MVNOs, (b) Histogram of the difference of total revenue, (c) Average revenue per unit over number of MVNOs and (d) Histogram of the difference of average revenue.

CBF auction has a lower ROR than SBF because MVNO-1's incremental bid of the second unit in CBF is lower than the reserve price and the virtual bidder wins one unit.

Fig. 3(a) shows that total revenue of CBF and SBF auctions both increase with the increase of number of MVNOs. On average, CBF auction leads to higher total revenue when the number of MVNOs is more than six. As depicted in Fig. 3(b), CBF auction has higher total revenue in almost 7,000 instances. Results of per unit revenue shown in Fig. 3(c) and 3(d) are similar to that of total revenue. There are two explanations about why hypothesis H2 does not hold for some instances. The first is that CBF auction may lead to a lower ROR than that of SBF auction as shown in Fig. 2 and hence a lower total revenue. The second is that revenue comes from winners' payments are the opportunity costs instead of bids of winning. Let us consider example 2:

Example 2: This example is the same as Example 1 except that the PLH provides only two units.

CBF auction

MVNO-1 wins 1 unit and pays $22 − $12 = $10 and MVNO-2 wins 1 unit and pays $25 − $15 = $10.

The total payment is $20.

SBF auction

MVNO-1 wins 2 units and pays $21.

The total payment is $21.

Even though the RORs are the same, CBF auction may still leads to lower revenue under the opportunity cost-based

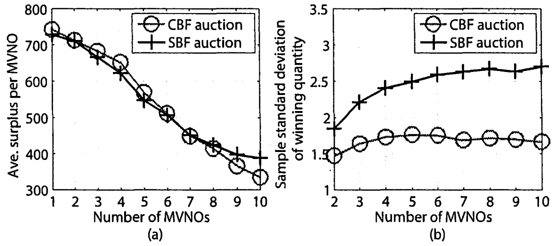

Fig. 4. Comparisons of CBF and SBF auctions: (a) Average surplus per MVNO and (b) Sample standard deviation of winning quantity.

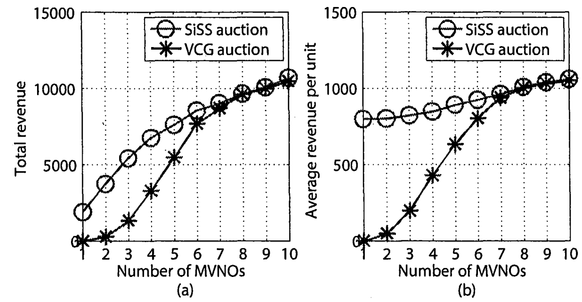

Fig. 5. PLH's revenue comparison between the SiSS and VCG auctions.

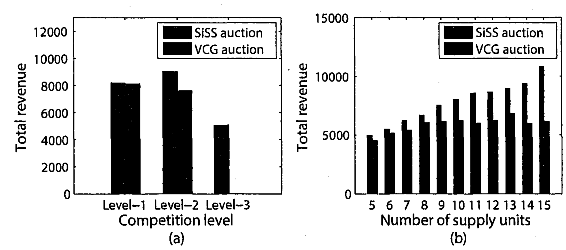

Fig. 6. Comparison of SiSS and VCG auctions: (a) Total revenue over competition levels and (b) Total revenue over number of supply units.

payment calculation scheme.

In consideration of MVNO's surplus, the results shown in Fig. 4(a) are consistent with Fig. 3, where lower revenue to the PLH means higher surplus to MVNOs. When the number of MVNO is less than seven, CBF auction brings higher surplus to winning MVNOs. Fig. 4(b) compares between CBF and SBF auctions the variation of winning quantities among MVNOs, where the sample standard deviation of winning quantity, σ, is define as

$$\sqrt{\frac{\sum_i (\text{\# of units MVNO-}i\text{ wins - Ave. \# of winning units})^2}{\text{\# of MVNOs - 1}}} = \sqrt{\frac{\sum_{i=1}^{N}(a_i - \frac{1}{N}\sum_{i=1}^{N} a_i)^2}{N-1}}. \tag{17}$$

The sample standard deviation results given in Fig. 4(b) confirm that allocations of CBF auction leads to lower levels of variation and the difference enlarges with the increase of number of MVNOs. So compared with SBF auction, CBF auction can prevent monopoly of spectrum by few MVNOs.

B. Comparison of SiSS and VCG Auctions

Design of SiSS auction ensures that per-unit payment be higher than the reserve price and resolves the revenue deficiency problem of VCG auction when the market competition is weak or MVNOs are asymmetric in demand. Fig. 5(a) depicts the PLH's total revenue generated by the SiSS and VCG auctions over number of MVNOs. Results show that total revenue of SiSS and VCG auctions both increase with the number of MVNOs but the SiSS auction has in average of 31.3% higher total revenue than the VCG auction. Over the 10,000 comparisons with the VCG auction, the ratios that SiSS auction has higher, equal, and lower total revenue are 50.7%, 45.85%, and 3.45% respectively. Besides, Fig. 5(b) shows that the SiSS auction ensures per-unit revenue be higher than the reserve price and further maintains it at a lower variation than VCG auction. In the 10,000 instances, the ratios that SiSS auction has higher, equal, and lower per-unit revenue are 53.7%, 45.85%, and 0.45% respectively. The superiority of SiSS auction over VCG auction can be easily observed when the number of MVNOs is less than seven.

Now let us observe how the market competition and amounts of supply affect the PLH's total revenue from the SiSS and VCG auctions. Fig. 6(a) shows that the difference in total revenue between the SiSS and VCG auctions enlarges with the decrease of market competition. The VCG auction even results in zero revenue in level-3. Fig. 6(b) depicts average total revenue of the SiSS and VCG auctions with respect to number of supply units. The superiority of SiSS auction over VCG auction in revenue becomes significant as the amount of supply increases beyond eight units.

C. Analyses of Computation Efficiency

Now we analyze whether the computation time of clearing SiSS auction is feasible when the number of MVNOs and supply units become large. The main computation effort required to solve the SiSS auction problem comes from the calculation of winners' payment. Basically, the more MVNOs bid, the more (KP)s needed to be solved. If we use enumeration to look for optimal solution of (KP), then the computation complexity for enumeration in worst case is $(J+1)^{N+1}$, where $N+1$ means the number of MVNOs and the virtual bidder and J is the amount of supply. The computation complexity for payment calculation is $N(J+1)^N$. So the total time complexity of clearing the SiSS auction is $O(J^{N+1}+NJ^N)$. Dynamic programming has also been adopted for solving a (KP), which is of pseudo-polynomial time complexity [50][51]. Theoretical analysis shows that time complexity of SiSS auction solved by dynamic programming can be reduced to $O((NJ)^2)$.

This paper adopts a commonly available optimization tool suite, IBM ILOG CPLEX [52], for solution. The optimization tool has been reported in the literature to be reliable, efficient, and widely adopted by industries. The CPLEX mixed integer optimizer solves a (KP) by either linear programming-based branch and cut or branch and cut-based dynamic search [53].

To demonstrate that the solution by CPLEX is time-efficient to our application, we consider 50, 100, 150 and 200 MVNOs, who compete for 50 to 500 spectrum units. Based on the survey of large-scale secondary spectrum markets, there are

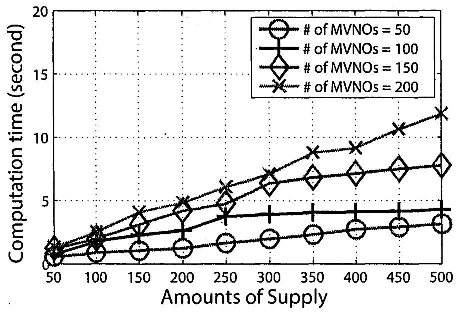

Fig. 7. Computation time over number of MVNOs and spectrum units.

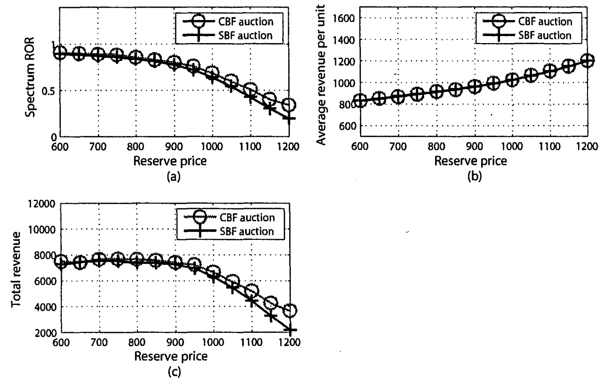

Fig. 8. Effects of reserve price on: (a) Spectrum ROR, (b) Average revenue per unit, and (c) Total revenue.

few countries with more than 50 MVNOs in operation [54]. Fig. 7 shows that the solution can be obtained in few seconds even when there are more than 50 MVNOs. At a fixed number of MVNOs, the computation time needed is approximately a linear function of supplied spectrum units. Similarly, the computation time is a linear function of number of MVNOs given a fixed number of supplied spectrum units. The computation time of less than 15 seconds for all the 10 instances of 200 MVNOs and 500 spectrum units should be efficient enough for SiSS auction application.

D. Effects of Reserve Price

Now let us analyze the influence of reserve price, which ranges from \$600 to \$1,200. Before the analyses, there are two intuitively clear properties that with the increase of the reserve price specified by PLH,
P1) spectrum ROR is monotonically non-increasing, and
P2) per-unit revenue is monotonically non-decreasing.
Obviously, there is a question of how the PLH should set the reserve price to maximize the total revenue.

Results of Fig. 8(a) and 8(b) conform to P1 and P2 respectively. Under the scenario setting, Fig. 8(c) shows that the total revenue is almost steady when the reserve price is set lower than \$1,000, the average bid offer per unit of MVNOs, because the variations of ROR and average revenue per unit are small. When the reserve price exceeds \$1,000, the ROR decreases significantly but the average revenue per unit only increases slightly; the total revenue to the PLH therefore decreases with the increase of reserve price. Based on the experimentation, for the PLH, setting reserve price lower than the average value of MVNOs' bids is better than setting higher.

VI. Conclusions

This paper designs a market framework and a novel SiSS auction to exploit availability of spectrum holes for WBA and raise spectrum efficiency. Considered SiSS market is a significant class of one PLH and multiple MVNOs. For the PLH and MVNOs, a SB is mandated to provide brokerage services that mitigate information asymmetry and increase the viability of trading. In the single-round SiSS auction, CBF provides MVNOs with maximal bidding options and allows MVNOs to win part of demands. Introduction of virtual bidder with bids derived from PLH's reserve price avoids PLH's revenue deficiency while incentivizing MVNOs' truthful bids.

This paper has proven that the VCG-based SiSS auction is truthful, individual rational and budget balanced. Numerical experimentation has shown that SiSS auction using CBF has higher RORs and revenues than using SBF on average. Compared with the VCG auction, the SiSS auction generates 31.3% higher revenue and has obvious superior in revenue as the market competition decreases. For large-scale SiSS market with up to 200 MVNOs and 500 spectrum units, computation time of clearing auction is within 15 seconds. The effect of reserve price has also been discussed. The framework and auction designs suit for SiSS applications in both time efficiency and economic considerations.

Appendix A
Proof of Theorem 1

Define the utility of MVNO-i winning a_i units as

$$U_i(a_i) \equiv \text{True valuation of } a_i \text{ units} - \text{Payment for } a_i \text{ units.}$$

Assume that $v_i(j)$ is MVNO-i's true valuation for j units, $j = 1, ..., d_i$. Let $\alpha_i(j)$ be the bid of j units by MVNO-i, $\underline{\alpha}_i \equiv [\alpha_i(j), j = 1, ..., d_i]$, and $\underline{\alpha}_{-i} \equiv [\underline{\alpha}_{i'}, i' \neq i]$. When MVNO-$i$ bids truthfully, that is $\alpha_i(j) = v_i(j), \forall j = 1, ..., d_i$. Let the auction result of allocating J units to S be that MVNO-i wins a_i units and other bidders win $\underline{a}_{-i}$, where $\underline{a}_{-i} \equiv [a_{i'}, i' \neq i]$. MVNO-$i$'s payment for the a_i units is $p_i(v_i(a_i), \underline{\alpha}_{-i}(\underline{a}_{-i})) \equiv B^J_{S\backslash i} - B^{J-a_i}_{S\backslash i}$ (Eq. (9)). Now assume that MVNO-i bids untruthfully with $\alpha_i'(j') \neq v_i(j)$ and other bidders' bids remain $\underline{\alpha}_{-i}$. Let the result now be that MVNO-i wins a_i' units and other bidders win $\underline{a}'_{-i}$. MVNO-i's payment for the a_i' units is $p_i(\alpha_i'(a_i'), \underline{\alpha}'_{-i}(\underline{a}_{-i})) \equiv B^J_{S\backslash i} - B^{J-a_i'}_{S\backslash i}$.

Now, prove that when all the other bidders' bids are unchanged, the utility of truthful bidding by MVNO-i, $U_i(a_i)$, is no less than the utility of any untruthful bidding, $U_i'(a_i')$:

$$\begin{aligned}
&U_i(a_i) = v_i(a_i) - p_i(v_i(a_i), \underline{\alpha}_{-i}(\underline{a}_{-i})) \\
&= v_i(a_i) - (B^J_{S\backslash i} - B^{J-a_i}_{S\backslash i}) = v_i(a_i) + \textstyle\sum_{l=1, l\neq i}^{N+1} \alpha_l(a_l) - B^J_{S\backslash i} \\
&= \alpha_i(a_i) + \textstyle\sum_{l=1, l\neq i}^{N+1} \alpha_l(a_l) - B^J_{S\backslash i} \\
&= \textstyle\sum_{l=1}^{N+1} \alpha_l(a_l) - B^J_{S\backslash i} \geq \sum_{l=1}^{N+1} \alpha_l(a_l') - B^J_{S\backslash i} \\
&= \alpha_i(a_i') + \textstyle\sum_{l=1, l\neq i}^{N+1} \alpha_l(a_l') - B^J_{S\backslash i}
\end{aligned}$$

$$= v_i(a_i^{'}) + \sum_{l=1,l\neq i}^{N+1} \alpha_l(a_l^{'}) - B_{S\backslash i}^{J} = v_i(a_i^{'}) - (B_{S\backslash i}^{J} - B_{S\backslash i}^{J-a_i^{'}})$$
$$= v_i(a_i^{'}) - p_i(\alpha_i^{'}(a_i^{'}), \underline{\alpha}_{-i}(\underline{a}_{-i}^{'})) = U_i^{'}(a_i^{'}).$$

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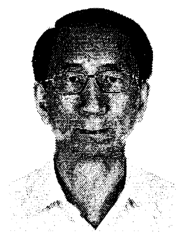

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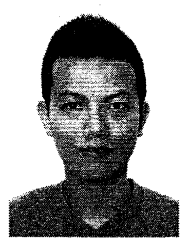

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