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Truthful Auction Analysis and Design in Multiunit Heterogenous Spectrum Markets With Reserve Prices

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***Abstract*—We consider a practical multiunit heterogeneous spectrum market in which each buyer may request multiple channels with different bid prices at different geographical regions and each channel is associated with a reserve price indicating the desired revenue of the seller. The degree-of-freedom brought by multiunit trading and (reserve and bid) price diversity in such a market can be exploited to break the truthfulness of the two most popular schemes adopted by secondary spectrum auctions, namely Myerson's Optimal Mechanism (MOM) and Vickrey-Clarke-Groves (VCG), via bidder self-collusion. In this paper, we conduct a thorough analysis on the root causes of untruthfulness in MOM and VCG, and prove the fundamental theories addressing when MOM and VCG are truthful and when their truthfulness is broken by bid rigging. Particularly, we demonstrate how self-collusion is exploited in MOM and VCG to improve the untruthful bidders' utility. The critical findings provide a guidance for us to design a Self-collusion Resistant Auction (SIRI) in multiunit heterogeneous spectrum markets with reserve prices. The economic properties of SIRI are proved via rigorous theoretical analysis.**

***Index Terms*—Truthfulness; self-collusion; reserve price; multiunit heterogeneous spectrum market.**

I. Introduction

In this paper, we consider the truthfulness of spectrum auctions in a multiunit heterogeneous secondary spectrum market that covers multiple non-overlapping geographical regions. In such a market, a seller can supply multiple channels at each region with diverse reserve prices to guarantee its revenue and each buyer may demand one or more channels at each region with diverse bids. Spectrum reuse is allowed at non-adjacent regions, as the cellular networks do. This model is more practical and flexible than those taken by most existing research [1]–[12] that do not fully explore the heterogeneity of secondary spectrum markets and tackles spectrum reuse based on conflict graphs determined by the physical communication models. The major reasons lie in two aspects: i) in practice bid and reserve price variate at different geographical regions with different population density and degree of wealth; and ii) spatial channel reuse can not be guaranteed if conflict graphs are determined by communication models in a dynamic environment due to node mobility and other factors.

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However, the degree-of-freedom brought by multiunit trading and (bid/reserve) price diversity may be exploited via *self-collusion* to break the truthfulness of the two most popular schemes adopted by secondary spectrum auctions, namely Myerson's Optimal Mechanism (MOM) [13] and Vickrey-Clarke-Groves (VCG) [14]. A buyer can easily perform self-collusion by manipulating its bid prices on different channels and/or at different regions to win the auction and improve its utility, causing truthfulness violations. Such a "single member" collusion is easy to launch but hard to detect compared to multi-member collusions as colluding with another bidder requires the two to trust each other and secure the post-auction benefit distribution ahead of time. As a result, self-collusion is more detrimental and insidious compared to multi-member collusions. However, in spectrum markets, only a few efforts have been done for self-collusion resistance [11], [15]–[18]. Specifically, among the most three popular auction mechanisms, self-collusion in McAfee [19] is studied by [15]–[17], self-collusion in Myerson's optimal mechanism (MOM) [13] is investigated by [11], [18], but self-collusion in Vickrey-Clarke-Groves (VCG) [14] has not been paid attention to in literature yet. Therefore, to effectively avoid market manipulation in spectrum markets, more studies are needed to fill the gap in self-collusion.

Therefore in this paper we investigate the vulnerabilities of MOM and VCG to untruthfulness caused by self-collusion in our multiunit heterogeneous spectrum market with reserve prices as they serve as the bases for many mechanisms targeting different spectrum markets. Our major activities and contributions in this paper are summarized as follows:

- We extend traditional MOM and VCG to our multiunit heterogeneous spectrum market with reserve prices and establish fundamental theories to answer the following questions: when are MOM and VCG truthful and when are they not truthful? particularly, when are they vulnerable to self-collusion? We present the conditions under which YES answers or NO answers are provided.
- We use both toy examples and rigorous theoretical analysis to identify the root causes of MOM and VCG's

untruthfulness. Our findings indicate that both MOM and VCG suffer from untruthfulness due to the degree-of-freedom brought by multiunit trading and (bid/reserve) price diversity. What's more, self-collusion can be easily performed in both MOM and VCG by rigging the bid prices on different channels and/or at different locations to help improve utility.

- We employ our foundational theories and findings to design an auction scheme termed **SIRI** for the multiunit heterogeneous spectrum market with reserve prices and prove that **SIRI** possesses the economic properties of truthfulness (and self-collusion resistance) and individual-rationality.

The rest of the paper is organized as follows. Related work is briefly summarized in Section II. Preliminaries, the auction model, and the cheating model are detailed in Section III. Rigorous theoretical analysis on the truthfulness of VCG and MOM in our multiunit heterogeneous spectrum market with reserve prices are presented in Sections V and IV, respectively. Our truthful (and self-collusion resistant) auction scheme **SIRI** is proposed and analyzed in Section VI. This paper is concluded in Section VII.

II. Related Work

In the secondary spectrum market, the existing auction mechanisms are mainly designed based on the three classical auctions, including VCG for maximizing social welfare, MOM for maximizing auction revenue, and McAfee for facilitating bilateral auction.

Multiunit Spectrum Auction: In [1]–[3], [12], McAfee-style multiunit double auctions were developed to simultaneously achieve truthfulness, individual-rationality and budget-balance, with a sacrifice in social welfare and/or revenue; particularly, homogeneous channels were considered in [12], heterogeneous channels were taken into account in [1], and price discount was provided for multiunit channel purchase in [2], and the signal to interference and noise (SINR) was used to measure users' preference to channel allocation in [3]. Multiunit single-side spectrum auctions have been proposed by [4]–[9] to maximize social welfare or revenue, which differ in their approaches to determine winners and payments with different computational complexity. But, [4], [5] did not consider price diversity for spectrum bidding, [6] did to consider diverse available locations of channels, and [7]–[9] only studied homogeneous channels.

Collusion in Spectrum Auction: To prevent collusion among bidders, deterministic mechanisms were explored in [20]–[23], and probabilistic t-truthful spectrum auctions were proposed in [24], [25] targeting small-group collusions. In [26], group truthfulness is ensured by a group-buying auction scheme consisting of a rule to form group and a rule to computer payment. To improve the ability of collusion resistance, a K Nearest Neighbor (KNN) learning-based algorithm was proposed by [27], where however, the performance of collusion resistance is only evaluated via simulations without rigorous proof. Nevertheless, it has been claimed that collusion can not be completely avoided unless a trivial posted-price auction is taken [28].

Self-Collusion in Spectrum Auction: Previous works show that McAfee may become vulnerable to self-collusion when extended to heterogenous bids or multiunit trading. The reason is that when a bidder has more than one bid, or a bidder participates in multiple bid groups due to spatial channel reuse and multiunit requests, its bids become the boundary bids via manipulation, thus successfully affecting auction outcomes. To tackle this issue, [15], [16] implemented a bid-independent buyer-seller matching algorithm after buyer grouping and before winner determination. In [17], the bidder groups are sorted according to group size rather than group bid, so that cheating on bid cannot change the sorted group sequence and the clearing price. Self-collusion of MOM in the single-unit heterogeneous spectrum market has been investigated in [11], [18], but an in-depth analysis under a practical spectrum market setting is missing. Self-collusion in VCG under any setting has never been addressed, to our best knowledge.

Different from the most existing works that directly or indirectly apply the traditional auction mechanisms, this paper considers a multiunit heterogeneous spectrum market, intends to reveal the root causes of untruthfulness and self-collusion in MOM and VCG, and set up fundamental theories for bid rigging prevention. By exploiting the critical theories established in our theoretical analysis, we propose an effective auction mechanism that is truthful and self-collusion resistant.

III. Preliminaries and Models

A. Preliminaries

An auction is a game-based resource allocation method composed of two steps: winner determination and payment (clearing price) computation. In this subsection, we outline the major economic properties and basic concepts that are related to our spectrum auction design. (1) **Price Diversity:** In a spectrum auction, price diversity reflects the price fluctuations of channels in frequency, space, and/or time domains. (2) **Single-unit & Multiunit:** If each buyer requests only one channel, the auction is single-unit; if each buyer demands one or more channels, the auction is multiunit. (3) **Individual-rationality:** An auction is *individually-rational* if no winner obtains a negative utility. (4) **Incentive-compatibility:** An auction is *incentively-compatible* if no bidder can improve its received utility via untruthful bidding. Incentive-compatibility is also called "truthfulness" or "strategy-proof". (5) **Self-collusion:** It is a cheating behavior that involves only one bidder but at least two bids of this bidder. Self-collusion helps illegally improve the bidder's utility and thus results in untruthfulness. (6) **Reserve Price:** A seller can commit not selling the channel after the auction if the winning buyer's payment is lower than the reserve price. (7) **Social Welfare:** It is the sum of all bidders' bid values, indicating the resource allocation efficiency of an auction. (8) **Efficiency:** An auction is *efficient* if it maximizes the social welfare. (9) **Optimality:** An auction is *optimal* if it maximizes the auction revenue, subject to the individual-rationality and incentive-compatibility constraints.

Remarks: (i) Self-collusion is a special cheating behavior of a bidder rigging its bids to win different channels. Therefore an auction that is vulnerable to self-collusion is not truthful, and a truthful auction must be self-collusion resistant. (ii) The reserve price of a channel is different from the bid value on the channel of a seller. Usually, a bid value is the seller's valuation on the channel, while the reserve price reflects the seller's desirable revenue from selling the channel. Thus, even though the bid value of a channel is 0, the seller can increase its revenue by setting a positive reserve price in the auction [29], [30]. (iii) Because efficiency and optimality can not be achieved simultaneously [29], [30], auction designers have to decide which objective to achieve. Intuitively, a selfish seller prefers an optimal auction to increase its revenue; while a public auctioneer may choose an efficient auction for resource utilization improvement.

B. Auction Model

Before introducing our auction model, the main notations are presented in Table I.

TABLE I
NOTATIONS & DEFINITIONS

Notations	Definitions
$\mathcal{K}$	Set of local regions
$\mathcal{M}$	Set of channels of spectrum access provider (seller)
$A = \{a_{ik}\}$	Seller' reserve prices for each channel i at region k
$\mathcal{N}$	Set of spectrum access requesters (buyers)
$B_j = \{b_{ijk}\}$	Buyer j's bid for channel i at region k
$Q_j = (q_{j1}, ..., q_{jK})$	Buyer j's demand on channel i at region k
z_{ik}	Binary constant to indicate availability of channel i at region k
x_{ijk}	Binary variable to indicate channel assignment
p_j	Buyer j's payment for all assigned channels
u_j	Buyer j's utility

We consider a network that can be divided into a set of non-overlapping local regions denoted by $\mathcal{K}$ ($|\mathcal{K}| = K, K \geq 1$). In this network, a spectrum access service provider called "seller" exists to supply a set of orthogonal channels represented by $\mathcal{M}$ ($|\mathcal{M}| = M, M \geq 1$). Assume that there are $M_k \in [0, M]$ available channels at region $k \in [1, K]$. Formally, if channel i is available at region k, we set $z_{ik} = 1$; otherwise, $z_{ik} = 0$. There also exists a set of buyers $\mathcal{N}$ ($|\mathcal{N}| = N, N \geq 1$) requesting spectrum access services from the seller.

In order to obtain a positive revenue, the seller has a reserve price for each channel at each location, which is expressed as

$$A = \begin{pmatrix} a_{11} & a_{12} & \dots & a_{1K} \\ a_{21} & a_{22} & \dots & a_{2K} \\ \vdots & \vdots & \ddots & \vdots \\ a_{M1} & a_{M2} & \dots & a_{MK} \end{pmatrix};$$

where a_{ik} ($i \in [1, M], k \in [1, K]$) is the reserve price of channel i at region k.

To obtain channels, all buyers submit their bids to the seller at the beginning of the auction. A buyer j could submit different bid prices for different channels at different regions, i.e., buyer j submits a bid matrix B_j.

$$B_j = \begin{pmatrix} b_{1j1} & b_{1j2} & \dots & b_{1jK} \\ b_{2j1} & b_{2j2} & \dots & b_{2jK} \\ \vdots & \vdots & \ddots & \vdots \\ b_{Mj1} & b_{Mj2} & \dots & b_{MjK} \end{pmatrix};$$

in which b_{ijk} ($i \in [1, M], j \in [1, N], k \in [1, K]$) represents buyer j's bid price for channel i at region k. Correspondingly, we use $\mathcal{B} = \{B_1, B_2, \dots, B_N\}$ to denote the set of all buyers' bids. Besides, buyer j also reports its demands $Q_j = (q_{j1}, q_{j2}, \dots, q_{jK})$, where q_{jk} ($j \in [1, N], k \in [1, K]$) is the number of requested channels at region k.

Let x_{ijk} be an 0-1 binary variable with $x_{ijk} = 1$ indicating that channel i is sold to buyer j at region k. Denote by $\mathcal{G}(\mathcal{K}, \mathcal{E})$ the "adjacent-region graph". For any two regions $k, k' \in \mathcal{K}$, there exists an edge $e(k, k') \in \mathcal{E}$ if and only if k and k' are neighboring with each other. To improve channel utilization while avoiding interference, we set up the following channel allocation constraints (1)-(4):

Within **the same region**, each channel is assigned to only one buyer; that is,

$$x_{ijk} \times x_{ij'k} = 0, \forall i \in [1, M], j \neq j' \in [1, N], k \in [1, K]. \quad (1)$$

Within **any two adjacent regions**, a channel can be used by the same buyer but cannot be used by different buyers, i.e.,

$$x_{ijk} \times x_{ij'k'} = 0, \forall i \in [1, M], j \neq j' \in [1, N], e(k, k') \in \mathcal{E}. \quad (2)$$

The number of traded channels can not exceed the **seller's supply** in each region:

$$\sum_{i=1}^{M} \sum_{j=1}^{N} z_{ik} x_{ijk} \leq M_k, \forall k \in [1, K]. \quad (3)$$

The number of purchased channels is not larger than a **buyer's demand** in each region:

$$\sum_{i=1}^{M} z_{ik} x_{ijk} \leq q_{jk}, \forall j \in [1, N], k \in [1, K]. \quad (4)$$

Let p_j be the payment of buyer j for all its purchased channels in the auction. Then the received utility u_j of buyer j is:

$$u_j = \sum_{i=1}^{M} \sum_{k=1}^{K} x_{ijk} b_{ijk} - p_j. \quad (5)$$

The social welfare W and revenue R of an auction are computed by (6) and (7), respectively.

$$W = \sum_{i=1}^{M} \sum_{j=1}^{N} \sum_{k=1}^{K} x_{ijk} b_{ijk}. \quad (6)$$

$$R = \sum_{i=1}^{M} \sum_{j=1}^{N} \sum_{k=1}^{K} x_{ijk} (b_{ijk} - a_{ik}). \quad (7)$$

We denote the problem of **Multi-unit Heterogeneous Spectrum Auction with Reserve Price** by **MESAP**. We also consider a variant of MESAP, denoted by **v-MESAP**, where the seller does not consider price diversity in the space

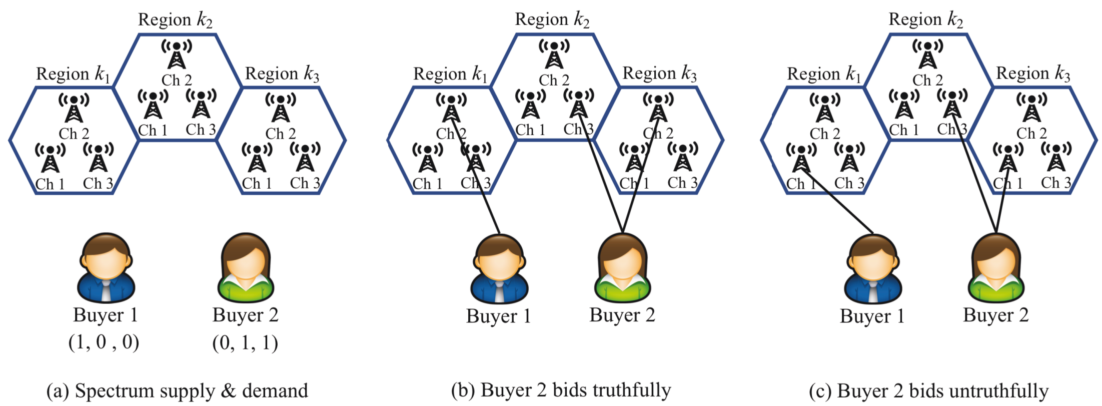

Fig. 1. An example of auction model.

domain and views a channel as one single unit in the whole network. Formally, the reserve price $\hat{A}$ in v-MESAP is defined as $\hat{A} = (\hat{a}_1, \hat{a}_2, \ldots, \hat{a}_i, \ldots, \hat{a}_M)$ with $\hat{a}_i$ being the reserve price of channel i and the revenue $\hat{R}$ is

$$\hat{R} = \sum_{i=1}^{M} \sum_{j=1}^{N} \sum_{k=1}^{K} \hat{x}_{ijk} b_{ijk} - \sum_{i=1}^{M} \hat{y}_i \hat{a}_i, \tag{8}$$

where

$$\hat{y}_i = \begin{cases} 0, & \text{if } \sum_{j=1}^{N} \sum_{k=1}^{K} \hat{x}_{ijk} = 0, \\ 1, & \text{if } \sum_{j=1}^{N} \sum_{k=1}^{K} \hat{x}_{ijk} \geq 1, \end{cases}$$

in which $\hat{x}_{ijk} = 1$ indicates buyer j wins channel i at region k, $\hat{y}_i = 1$ implies that channel i is successfully sold to at least one buyer, and $\sum_{i=1}^{M} \hat{y}_i$ is the total number of sold channels.

Let $\hat{p}_j$ be the payment of buyer j in v-MESAP; then $\hat{u}_j$ and $\hat{W}$ can be respectively defined according to (5) and (6).

Remarks: The consideration of the above two auction models can be justified as follows. (1) Recently, the seller model in v-MESAP has been adopted by almost all existing research [10], [11], [15], [16], [31]–[33], in which spatial channel reuse is considered based on the conflict graph among all buyers determined by the physical communication models. However, in such a model, the seller only cares whether a channel is successfully sold to a buyer – it does not take into account the number of buyers winning the channel. (2) Since price diversity and channel heterogeneity are not fully explored in v-MESAP, we establish a more practical model MESAP, to consider price diversity and channel heterogeneity in both frequency and space domains. In this paper, spatial channel reuse is determined according to the conflict graph defined by neighboring regions, which is more practical, stable, and flexible because (i) conflict graphs determined by communication models may change abruptly, leading to a short period of time to use a purchased channel in a dynamic environment; and (ii) a buyer may want to provide AP-like services to other users and thus purchase a channel for a particular region. (3) From the viewpoints of the type of trading and price diversity, four cases are incorporated in both MESAP and v-MESAP: (i) single-unit trading with a homogeneous reserve price; (ii) single-unit trading with homogeneous bids; (iii) multi-unit trading with homogeneous reserve price and bids; and (iv) multi-unit trading with heterogeneous reserve prices and bids. Thus, we can conduct an in-depth theoretical analysis on self-collusion in VCG and MOM under MESAP and v-MESAP. (4) For a multi-unit heterogeneous spectrum market, combinatorial auctions could be an alternative choice. However, combinatorial auctions cannot support channel reuse due to the following two constraints in resource allocation [29], [34]: (i) any two bundles must be non-overlapping; and (ii) each bundle is assigned to at most one buyer. Moreover, tailoring combinatorial auctions to perform channel reuse is not a trivial problem. We will investigate the self-collusion issues in combinatorial auctions in our future research.

C. Cheating Model

In this paper, we assume that the bids of different buyers are independent and that there is no collusion among the buyers. We also assume that a buyer would like to cheat on its bid matrix B_j only, rather than its demand Q_j, because the buyer's service requirement may not be satisfied with an untruthfully reduced demand and the buyer's payment may be raised with an untruthfully increased demand. Since each buyer j's bid B_j contains $M \times K$ different price values, buyer j is able to manipulate these $M \times K$ price values for utility enhancement. Particularly, if more than one price value is involved in manipulation, the cheating behavior is so-called "self-collusion". This paper intends to conduct a truthfulness analysis on VCG [14] and MOM [13] when they are extended to our multiunit heterogeneous spectrum market with reserve prices.

The auction model and buyers' cheating behaviors can be illustrated via Fig. 1, where there are 3 channels available in regions $\{k_1, k_2, k_3\}$. Buyer 1 demands one channel in region k_1, and buyer 2 demands one channel in both regions k_2 and k_3. Suppose MOM auction is adopted, and the reserve prices and bid prices are shown in Table V. If buyer 2 bids truthfully, she wins channel 3 in k_2 and channel 2 in k_3, and her utility is 3; if buyer 2 manipulates her bid prices, she can win channel 3 in k_2 and channel 1 in k_3, and increase her utility to 5. In Section IV and Section V, we will use toy examples based the network topology of Fig. 1 to analyze the root causes of self-collusion and untruthfulness in both MOM and VCG.

IV. Truthfulness of MOM

Myerson's optimal mechanism (MOM) aims to maximize the seller's revenue in the auction [13]. In MOM, truthfulness can be achieved if the winner determination is a non-decreasing function of each buyer's bid and each winning buyer pays the smallest value with which it can win the auction [29].

A. MOM in MESAP and v-MESAP

MOM in MESAP:

Winner Determination: Calculate

$$X^{\mathrm{o}} \in \arg \max_{X\in\{0,1\}^{M\times N\times K}} R,$$

subject to (1), (2), (3), and (4). The objective function R (see (7)) implies a non-negative marginal revenue of the sold channels, i.e.,

$$b_{ijk} - a_{ik} \geq 0. \tag{9}$$

Clearing Pricing Scheme: Each winning buyer j's payment is its "*critical bid*", computed by $p_j^{\mathrm{o}} = R^*_{\mathcal{B}_{-j}} - R^*_{-B_j}$, in which $R^*_{\mathcal{B}_{-j}}$ is the maximum revenue when buyer j does not participate in the auction, and $R^*_{-B_j} = R^* - \sum_{i=1}^{M}\sum_{k=1}^{K} x^{\mathrm{o}}_{ijk} b_{ijk}$ is the maximum revenue R^* minus buyer j's bid values.

The auction outputs are $\{x^{\mathrm{o}}_{ijk}\}$ and $\{p^{\mathrm{o}}_j\}$.

MOM in v-MESAP:

Winner Determination: Compute

$$\hat{X}^{\mathrm{o}} \in \arg \max_{\hat{X}\in\{0,1\}^{M\times N\times K}} \hat{R},$$

subject to (1), (2), (3), (4), and (9), as the objective function $\hat{R}$ (see (8)) cannot ensure a non-negative marginal revenue of each sold channel.

Clearing Pricing Scheme: The payment of each winning buyer j is $\hat{p}^{\mathrm{o}}_j = \inf\{h : h \geq \sum_{i=1}^{M} \hat{x}^{\mathrm{o}}_{ijk}\hat{a}_i, h + \hat{R}^*_{-B_j} \geq \hat{R}^*_{\mathcal{B}_{-j}}\}$.

Accordingly, the auction outcomes are $\{\hat{x}^{\mathrm{o}}_{ijk}\}$ and $\{\hat{p}^{\mathrm{o}}_j\}$.

VCG vs. MOM:

Similarities: (i) A winner pays its social opportunity cost in VCG and its critical bid in MOM, which are the minimum price for it to win the auction [13], [14], [29]. (ii) There is no method to identify the clearing price of each channel in both VCG and MOM when a buyer successfully purchase multiple heterogeneous channels, because the social opportunity cost and the critical bid are required to be independent of the buyer's bid and demand [29], [35].

Differences: (i) *Objective:* VCG maximizes social welfare for efficiency; MOM maximizes auction revenue for optimality. It is claimed that MOM will become a modified VCG when the seller submits a bid value equal to its reserve price [13], [29], [30]. (ii) *Allocation:* VCG distributes as many channels as possible to the buyers for better channel utilization; MOM assigns each channel for a non-negative marginal revenue [29], [30], [36]. (iii) *Payment:* VCG considers buyers' bids only, but MOM simultaneously takes into account the buyers' bids and the seller's reserve prices [29], [30], [36].

B. When MOM is Truthful?

The truthfulness and self-collusion resistance of MOM in MESAP are proved in Theorem 1.

Theorem 1: MOM in MESAP is truthful and self-collusion resistant.

Proof: When buyer j bids truthfully with B^t_j and untruthfully with B'_j, there are three cases to consider.

(i) If buyer j wins the auction with both B^t_j and B'_j, the corresponding payments are $p^{\mathrm{o}}_j = (R^*_{\mathcal{B}_{-j}} - R^*_{-B_j})$ and $p'^{\mathrm{o}}_j = (R'^*_{\mathcal{B}_{-j}} - R'^*_{-B_j})$, respectively. Then the utility difference is $u'_j - u_j = \sum_{i=1}^{M}\sum_{k=1}^{K} x'^{\mathrm{o}}_{ijk} b^t_{ijk} - \sum_{i=1}^{M}\sum_{k=1}^{K} x^{\mathrm{o}}_{ijk} b^t_{ijk} + R'^*_{-B_j} - R^*_{-B_j}$. If $\sum_{i=1}^{M}\sum_{k=1}^{K} x'^{\mathrm{o}}_{ijk} b'_{ijk} \geq \sum_{i=1}^{M}\sum_{k=1}^{K} x'^{\mathrm{o}}_{ijk} b^t_{ijk}$, then $u'_j - u_j = (R'^* - R^*) - \sum_{i=1}^{M}\sum_{k=1}^{K} x'^{\mathrm{o}}_{ijk}(b'_{ijk} - b^t_{ijk}) \leq 0$, because $\sum_{i=1}^{M}\sum_{k=1}^{K} x'^{\mathrm{o}}_{ijk} \geq \sum_{i=1}^{M}\sum_{k=1}^{K} x^{\mathrm{o}}_{ijk}$ and the increase of the auction revenue can not be larger than the increase of the bids of a winning buyer's allocated channels. If $\sum_{i=1}^{M}\sum_{k=1}^{K} x'^{\mathrm{o}}_{ijk} b'_{ijk} < \sum_{i=1}^{M}\sum_{k=1}^{K} x'^{\mathrm{o}}_{ijk} b^t_{ijk}$, then $u'_j - u_j = \sum_{i=1}^{M}\sum_{k=1}^{K} x'^{\mathrm{o}}_{ijk}(b^t_{ijk} - b'_{ijk}) - (R^* - R'^*) \leq 0$, as $\sum_{i=1}^{M}\sum_{k=1}^{K} x'^{\mathrm{o}}_{ijk} \leq \sum_{i=1}^{M}\sum_{k=1}^{K} x^{\mathrm{o}}_{ijk}$ and the decrease of the auction revenue can not be smaller than the decrease of the bids of a winning buyer's allocated channels. Thus, $u'_j \leq u_j$.

(ii) If buyer j loses with B^t_j but wins with B'_j, $u'_j = \sum_{i=1}^{M}\sum_{k=1}^{K} x'^{\mathrm{o}}_{ijk} b^t_{ijk} - (R'^*_{\mathcal{B}_{-j}} - R'^*_{-B_j}) = (R'^* - R^*) - \sum_{i=1}^{M}\sum_{k=1}^{K} x'^{\mathrm{o}}_{ijk}(b'_{ijk} - b^t_{ijk}) \leq 0 = u_j$ according to the analysis of (i).

(iii) If buyer j wins with B^t_j while losing with B'_j, we have $u_j \geq 0 = u'_j$.

These three cases imply that buyer j cannot increase its utility by rigging one or more bid values (i.e., $\sum_{i=1}^{M}\sum_{k=1}^{K} x'^{\mathrm{o}}_{ijk} b'_{ijk}$), i.e, buyer j's utility is maximized if and only if it bids truthfully. Therefore, MOM in MESAP guarantees truthfulness and self-collusion resistance. ■

MOM in a single-unit auction with a uniform reserve price and homogeneous bids in v-MESAP is self-collusion resistant and truthful, as proved in Theorem 2.

Theorem 2: In a single-unit auction with a uniform reserve price and homogeneous bids, MOM in v-MESAP is truthful and self-collusion resistant.

Proof: In a single-unit auction with a uniform reserve price and homogeneous bids, buyer j bids a single value b_j for all channels at any location and its payment can be computed by $\hat{p}^o_j = \max\{\hat{a}, (\hat{R}^*_{\mathcal{B}_{-j}} - \hat{R}^*_{-B_j})\}$. There are three cases for each buyer j.

(i) When $(\hat{R}^*_{\mathcal{B}_{-j}} - \hat{R}^*_{-B_j}) \leq b^t_j < \hat{a}$, buyer j loses the auction with b^t_j. Thus, increasing b^t_j to b'_j could help it win a channel. However, if buyer j wins with b'_j, $\hat{u}'_j = b^t_j - \hat{a} < 0 = \hat{u}_j$. Of course if buyer j is still a loser, $\hat{u}'_j = \hat{u}_j = 0$.

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(ii) When $(\hat{R}^*_{\mathcal{B}_{-j}} - \hat{R}^*_{-B_j}) < \hat{a} \le b^t_j$, buyer j wins the auction and pays $\hat{a}$ to the seller. Since $(\hat{R}^*_{\mathcal{B}_{-j}} - \hat{R}^*_{-B_j})$ is a constant, buyer j's payment is always equal to $\hat{a}$ if it wins the auction. Thus, buyer j's utility cannot be enhanced.

(iii) When $\hat{a} \le (\hat{R}^*_{\mathcal{B}_{-j}} - \hat{R}^*_{-B_j}) \le b^t_j$, buyer j is charged a payment of $(\hat{R}^*_{\mathcal{B}_{-j}} - \hat{R}^*_{-B_j})$, which is a constant as the reserve price and each buyer's bids are uniform. Therefore, buyer j needs to pay $(\hat{R}^*_{\mathcal{B}_{-j}} - \hat{R}^*_{-B_j})$ no matter how much it bids (as long as it is a winner) and thus it cannot increase its utility.

These three cases indicate that buyer j cannot improve its utility by cheating on its uniform bid. Thus, MOM is truthful. The self-collusion resistance of MOM under this scenario follows directly from the uniform reserve price and bids. ■

C. When MOM is Untruthful and Vulnerable to Self-Collusion?

Comparing MOM in MESAP and in v-MESAP, we obtain the following two observations: (i) In MESAP, if winning buyer j purchases channel i at region k, it brings a non-negative marginal revenue $(b_{ijk} - a_{ik})$ and contributes to R the same amount. That is, the marginal revenue brought by the winning buyer j purchasing channel i at region k is equal to the increase of the auction revenue. (ii) In v-MESAP, if buyer j is the sole winner on channel i and wins channel i at only one region, i.e., $\sum_{j=1}^{N}\sum_{k=1}^{K} \hat{x}^{o}_{ijk} = 1$, the increase of $\hat{R}$ is $\sum_{j=1}^{N}\sum_{k=1}^{K} \hat{x}^{o}_{ijk} b_{ijk} - \hat{a}_i = (b_{ijk} - \hat{a}_i)$; if there are more than one winner on channel i and/or buyer j wins channel i at more than one region, i.e., $\sum_{j=1}^{N}\sum_{k=1}^{K} \hat{x}^{o}_{ijk} > 1$, the increase of $\hat{R}$ is $\sum_{j=1}^{N}\sum_{k=1}^{K} \hat{x}^{o}_{ijk} b_{ijk} - \hat{a}_i > \sum_{j=1}^{N}\sum_{k=1}^{K} \hat{x}^{o}_{ijk}(b_{ijk} - \hat{a}_i)$. Thus, the increase of $\hat{R}$ is at least equal to the marginal revenue contributed by the winning buyer j purchasing channel i at region k, leading to the possibility of $(\hat{R}^*_{\mathcal{B}_{-j}} - \hat{R}^*_{-B_j}) < \sum_{i=1}^{M} \hat{x}^{o}_{ijk}\hat{a}_i$. As a result, buyer j could improve its utility by winning different channels via self-collusion. In this subsection, we analyze the vulnerability of MOM to market manipulation in v-MESAP when considering multiunit trading and (reserve and bid) price diversity by illustrative examples based on Fig. 1 and identify the root causes.

Table II presents an example of a single-unit MOM with a uniform reserve price in v-MESAP. In this example, buyer 2 wins channel 1 with $\hat{u}_2 = 0$ when bidding truthfully, while winning channel 2 with $\hat{u}'_2 = 2$ by decreasing the bid on channel 1 and increasing the bid on channel 2.

Table III describes a single-unit MOM example with diverse reserve prices and homogeneous bids in v-MESAP. Via reducing the bid from 6 to 5, buyer 2 wins channel 1 instead of channel 2, raising its utility from 0 to 3 in the auction.

In Table IV, an example of multiunit MOM with a uniform reserve price and homogenous bids in v-MESAP is demonstrated. We see that buyer 2 wins the channel at region 3 only while winning the channel at three regions simultaneously by increasing the bid from 3 to 4, improving its utility from 1 to 2.

Finally, Table V illustrates the existence of self-collusion performed by buyer 2 in an example of MOM in v-MESAP.

From these examples, we conclude that in v-MESAP, (i) MOM is vulnerable to self-collusion because of heterogeneous bids; (ii) MOM loses truthfulness due to diverse reserve prices; (iii) MOM is not truthful with multiunit trading; and (iv) MOM cannot achieve truthfulness and self-collusion resistance in v-MESAP.

TABLE II
A SINGLE-UNIT AUCTION EXAMPLE IN V-MESAP WITH HOMOGENEOUS RESERVE PRICE.

Supply & Demand	$Z = \{z_{ik}\}$ $\begin{pmatrix} 1 & 1 & 1 \\ 1 & 1 & 1 \end{pmatrix}$	$\hat{A} = \{\hat{a}_i\}$ $(3,3)$	Q_1 $(1,0,0)$	Q_2 $(0,0,1)$
	Buyer Bid	Payment	Allocation	Utility
Buyer 2 bids B_2	$B_1 = \begin{pmatrix} 4 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}$	$\hat{p}^o_1 = 3$	$\hat{x}^o_{111} = 1$	$\hat{u}_1 = 1$
	$B_2 = \begin{pmatrix} 0 & 0 & \mathbf{3} \\ 0 & 0 & \mathbf{5} \end{pmatrix}$	$\hat{p}^o_2 = 3$	$\hat{x}^o_{123} = 1$	$\hat{u}_2 = \mathbf{0}$
Buyer 2 bids B'_2	$B_1 = \begin{pmatrix} 4 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}$	$\hat{p}^o_1 = 3$	$\hat{x}^o_{111} = 1$	$\hat{u}_1 = 1$
	$B'_2 = \begin{pmatrix} 0 & 0 & \mathbf{1} \\ 0 & 0 & \mathbf{6} \end{pmatrix}$	$\hat{p}'^o_2 = 3$	$\hat{x}'^o_{223} = 1$	$\hat{u}'_2 = \mathbf{2}$

TABLE III
A SINGLE-UNIT AUCTION EXAMPLE IN V-MESAP WITH HOMOGENEOUS BIDS.

Supply & Demand	$Z = \{z_{ik}\}$ $\begin{pmatrix} 0 & 1 & 1 \\ 1 & 1 & 1 \end{pmatrix}$	$\hat{A} = \{\hat{a}_i\}$ $(3,6)$	Q_1 $(1,0,0)$	Q_2 $(0,0,1)$
	Buyer Bid	Payment	Allocation	Utility
Buyer 2 bids B_2	$B_1 = \begin{pmatrix} 7 & 0 & 0 \\ 7 & 0 & 0 \end{pmatrix}$	$\hat{p}^o_1 = 6$	$\hat{x}^o_{211} = 1$	$\hat{u}_1 = 1$
	$B_2 = \begin{pmatrix} 0 & 0 & \mathbf{6} \\ 0 & 0 & \mathbf{6} \end{pmatrix}$	$\hat{p}^o_2 = 6$	$\hat{x}^o_{223} = 1$	$\hat{u}_2 = \mathbf{0}$
Buyer 2 bids B'_2	$B_1 = \begin{pmatrix} 7 & 0 & 0 \\ 7 & 0 & 0 \end{pmatrix}$	$\hat{p}^o_1 = 6$	$\hat{x}^o_{211} = 1$	$\hat{u}_1 = 1$
	$B'_2 = \begin{pmatrix} 0 & 0 & \mathbf{5} \\ 0 & 0 & \mathbf{5} \end{pmatrix}$	$\hat{p}'^o_2 = 3$	$\hat{x}'^o_{123} = 1$	$\hat{u}'_2 = \mathbf{3}$

TABLE IV
A MULTIUNIT AUCTION EXAMPLE IN V-MESAP WITH HOMOGENEOUS RESERVE PRICE AND BIDS.

Supply & Demand	$Z = \{z_{ik}\}$ $\begin{pmatrix} 1 & 1 & 1 \end{pmatrix}$	$\hat{A} = \{\hat{a}_i\}$ (2)	Q_1 $(1,0,0)$	Q_2 $(1,1,1)$
	Buyer Bid	Payment	Allocation	Utility
Buyer 2 bids B_2	$B_1 = \begin{pmatrix} 7 & 0 & 0 \end{pmatrix}$	$\hat{p}^o_1 = 6$	$\hat{x}^o_{111} = 1$	$\hat{u}_1 = 1$
	$B_2 = \begin{pmatrix} \mathbf{3} & \mathbf{3} & \mathbf{3} \end{pmatrix}$	$\hat{p}^o_2 = 2$	$\hat{x}^o_{123} = 1$	$\hat{u}_2 = \mathbf{1}$
Buyer 2 bids B'_2	$B_1 = \begin{pmatrix} 7 & 0 & 0 \end{pmatrix}$			$\hat{u}_1 = 0$
	$B'_2 = \begin{pmatrix} \mathbf{4} & \mathbf{4} & \mathbf{4} \end{pmatrix}$	$\hat{p}'^o_2 = 7$	$\hat{x}'^o_{121} = 1$, $\hat{x}'^o_{122} = 1$, $\hat{x}'^o_{123} = 1$	$\hat{u}'_2 = \mathbf{2}$

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TABLE V
A MULTIUNIT AUCTION EXAMPLE IN V-MESAP.

Supply & Demand	$Z = \{z_{ik}\}$	$\hat{A} = \{\hat{a}_i\}$	Q_1	Q_2
	$\begin{pmatrix} 1 & 1 & 1 \\ 1 & 1 & 1 \\ 1 & 1 & 1 \end{pmatrix}$	$(2, 5, 1)$	$(1, 0, 0)$	$(0, 1, 1)$
	Buyer Bid	Payment	Allocation	Utility
Buyer 2	$B_1 = \begin{pmatrix} 3 & 0 & 0 \\ 6 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}$	$\hat{p}_1^{\text{o}} = 5$	$\hat{x}_{211}^{\text{o}} = 1$	$\hat{u}_1 = 1$
bids B_2	$B_2 = \begin{pmatrix} 0 & 3 & \mathbf{4} \\ 0 & 0 & \mathbf{5} \\ 0 & 4 & 0 \end{pmatrix}$	$\hat{p}_2^{\text{o}} = 6$	$\hat{x}_{223}^{\text{o}} = 1$ $\hat{x}_{322}^{\text{o}} = 1$	$\hat{u}_2 = \mathbf{3}$
Buyer 2	$B_1 = \begin{pmatrix} 3 & 0 & 0 \\ 6 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}$	$\hat{p}_1^{\text{o}} = 2$	$\hat{x}_{111}^{\text{o}} = 1$	$\hat{u}_1 = 1$
bids B_2'	$B_2' = \begin{pmatrix} 0 & 3 & \mathbf{5} \\ 0 & 0 & \mathbf{3} \\ 0 & 4 & 0 \end{pmatrix}$	$\hat{p}_2'^{\text{o}} = 3$	$\hat{x}_{123}'^{\text{o}} = 1$ $\hat{x}_{322}'^{\text{o}} = 1$	$\hat{u}_2' = \mathbf{5}$

D. Self-Collusion/Untruthfulness Analysis

As indicated in Section IV-C, price diversity and/or multiunit trading lead to self-collusion and truthfulness violation in MOM in v-MESAP. A detailed analysis is presented in this subsection.

Theorem 3: For MOM in v-MESAP, buyer j can improve its utility with B_j' via self-collusion, if the following two conditions are simultaneously satisfied: (i) $(\hat{R}^*_{\mathcal{B}_{-j}} - \hat{R}^*_{-B_j}) < \sum_{i=1}^{M} \hat{x}^{\text{o}}_{ijk}\hat{a}_i \le \sum_{i=1}^{M}\sum_{k=1}^{K} \hat{x}^{\text{o}}_{ijk} b^t_{ijk}$; (ii) $(\hat{p}^{\text{o}}_j - \hat{p}'^{\text{o}}_j) > (\sum_{i=1}^{M}\sum_{k=1}^{K} \hat{x}^{\text{o}}_{ijk} b^t_{ijk} - \sum_{i=1}^{M}\sum_{k=1}^{K} \hat{x}'^{\text{o}}_{ijk} b^t_{ijk})$.

Proof: Condition (i) indicates that buyer j's payment depends on the total reserve price of all allocated channels when it bids truthfully. Condition (ii) indicates that the decrease of the payment is larger than the decrease of the bid values when buyer j wins untruthfully, or that the increase of the payment is smaller than the increase of the bid values when buyer j wins untruthfully.

It is possible that $(\hat{p}^{\text{o}}_j - \hat{p}'^{\text{o}}_j) = [\sum_{i=1}^{M} \hat{x}^{\text{o}}_{ijk}\hat{a}_i - \max\{\hat{R}'^*_{\mathcal{B}_{-j}} - \hat{R}'^*_{-B_j}, \sum_{i=1}^{M} \hat{x}'^{\text{o}}_{ijk}\hat{a}_i\}] > (\sum_{i=1}^{M}\sum_{k=1}^{K} \hat{x}^{\text{o}}_{ijk} b^t_{ijk} - \sum_{i=1}^{M}\sum_{k=1}^{K} \hat{x}'^{\text{o}}_{ijk} b^t_{ijk})$ as long as the difference between $\sum_{i=1}^{M} \hat{x}^{\text{o}}_{ijk}\hat{a}_i$ and $\sum_{i=1}^{M} \hat{x}'^{\text{o}}_{ijk}\hat{a}_i$ is sufficiently large. As a result, $\hat{u}'_j - \hat{u}_j = (\sum_{i=1}^{M}\sum_{k=1}^{K} \hat{x}'^{\text{o}}_{ijk} b^t_{ijk} - \hat{p}'^{\text{o}}_j) - (\sum_{i=1}^{M}\sum_{k=1}^{K} \hat{x}^{\text{o}}_{ijk} b^t_{ijk} - \hat{p}^{\text{o}}_j) = (\hat{p}^{\text{o}}_j - \hat{p}'^{\text{o}}_j) - (\sum_{i=1}^{M}\sum_{k=1}^{K} \hat{x}^{\text{o}}_{ijk} b^t_{ijk} - \sum_{i=1}^{M}\sum_{k=1}^{K} \hat{x}'^{\text{o}}_{ijk} b^t_{ijk}) > 0$. That is, buyer j can increase its utility by winning different channels.

For example, in Table V, $(\hat{R}^*_{\mathcal{B}_{-2}} - \hat{R}^*_{-B_2}) = 1 < (\hat{a}_2 + \hat{a}_3) = 6$ and $(\hat{p}^{\text{o}}_2 - \hat{p}'^{\text{o}}_2) = 3 > (b_{223} - b_{123}) = 1$; thus buyer 2 can enhance its utility from 3 to 5 via self-collusion. Note that conditions (i) and (ii) hold simultaneously for buyer 2 in all other examples presented in Section IV-C. ■

Theorem 4: For MOM in v-MESAP, buyer j cannot enhance its utility by self-collusion if the following two conditions simultaneously hold: (i) $(\hat{R}^*_{\mathcal{B}_{-j}} - \hat{R}^*_{-B_j}) \ge \sum_{i=1}^{M} \hat{x}^{\text{o}}_{ijk}\hat{a}_i$ for B^t_j; and (ii) $(\hat{R}'^*_{\mathcal{B}_{-j}} - \hat{R}'^*_{-B_j}) \ge \sum_{i=1}^{M} \hat{x}'^{\text{o}}_{ijk}\hat{a}_i$ for $B'_j \ne B^t_j$.

Proof: From conditions (i) and (ii), we have $\hat{p}^{\text{o}}_j = (\hat{R}^*_{\mathcal{B}_{-j}} - \hat{R}^*_{-B_j})$ and $\hat{p}'^{\text{o}}_j = (\hat{R}'^*_{\mathcal{B}_{-j}} - \hat{R}'^*_{-B_j})$. Thus, buyer j cannot improve its utility via self-collusion according to Theorem 1. ■

In summary, avoiding self-collusion for MOM in v-MESAP needs to: (i) ensure that the marginal revenue equals the increase of the auction revenue when selling a channel; and (ii) mitigate the diversity of the "*aggregated reserve price*" $\sum_{i=1}^{M} \hat{x}^{\text{o}}_{ijk}\hat{a}_i$ for winning different channels.

V. TRUTHFULNESS OF VCG

The classical Vickrey-Clarke-Groves (VCG) auction proposed for the traditional good market can simultaneously achieve individual-rationality, truthfulness, and efficiency [14]. The efficiency of VCG comes from its clearing pricing scheme, which states that a winning bidder pays its social opportunity cost for its purchased goods. Thus, as long as the winner determination procedure of VCG maximizes the social welfare, its truthfulness can be guaranteed [30]. However, in spectrum markets, the winner determination of VCG becomes NP-hard due to channel reuse, significantly increasing the difficulty in finding optimal solutions. In this section, we extend VCG to our multiunit heterogeneous spectrum markets with reserve prices and investigate whether multiunit trading and (reserve and bid) price diversity affect its truthfulness in MESAP and v-MESAP.

A. VCG in MESAP and v-MESAP

VCG in MESAP:

Winner Determination: Compute

$$X^{\text{v}} \in \arg \max_{X \in \{0,1\}^{M\times N\times K}} W,$$

subject to (1), (2), (3), and (4). That is, $X^{\text{v}} = \{x^{\text{v}}_{ijk}\}$ is an optimal solution to VCG.

Clearing Pricing Scheme: For each winning buyer j, its payment $p^{\text{v}}_j = W^*_{\mathcal{B}_{-j}} - W^*_{-B_j}$, where $W^*_{\mathcal{B}_{-j}}$ is the maximum social welfare when buyer j is removed from the auction ($\mathcal{B}_{-j} = \mathcal{B} \setminus B_j$) and $W^*_{-B_j}$ is the maximum social welfare W^* less buyer j's values, i.e., $W^*_{-B_j} = W^* - \sum_{i=1}^{M}\sum_{k=1}^{K} x^{\text{v}}_{ijk} b_{ijk}$. The price p^{v}_j is the so-called "*social opportunity cost*".

Since each channel has a reserve price, the final winners should be those whose payments can at least cover the reserve prices of the winning channels, to ensure that the seller receives at least the desired revenue. Therefore, if $p^{\text{v}}_j \ge \sum_{i=1}^{M}\sum_{k=1}^{K} x^{\text{v}}_{ijk} a_{ik}$, we set $x_{ijk} = x^{\text{v}}_{ijk}$ for $i \in [1, M]$ and

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$k \in [1, K]$, and $p_j = p_j^{\text{v}}$; otherwise, we set $x_{ijk} = 0$ for $i \in [1, M]$ and $k \in [1, K]$, and $p_j = 0$.

VCG in v-MESAP:

The two steps of VCG in v-MESAP are the same as those in MESAP; therefore $\{\hat{x}_{ijk}^{\text{v}}\}$ and $\{\hat{p}_j^{\text{v}}\}$, and correspondingly $\{\hat{x}_{ijk}\}$ and $\{\hat{p}_j\}$ can be calculated in the same way.

Remarks: (i) Social welfare is the sum of the bidder's values; it does not consider the seller's reserve prices. (ii) The winner determination and pricing procedures of VCG do not consider the seller's reserve price [29], [30], [36]. (iii) By setting a reserve price for a channel, the seller has the right to withhold the channel if the buyer's payment is below the reserve price [13], [29], [30]. (iv) The social opportunity cost of a buyer is the payment of all allocated channels, and the price of each channel cannot be calculated in VCG [29], [35]. Thus, if buyer j wins one or more channels in VCG with payment $p_j^{\text{v}} < \sum_{i=1}^{M}\sum_{k=1}^{K} x_{ijk}^{\text{v}} a_{ik}$ (or $\hat{p}_j^{\text{v}} < \sum_{i=1}^{M} \hat{x}_{ijk}^{\text{v}} \hat{a}_i$), it cannot get any channel from the seller.

TABLE VI

A SINGLE-UNIT AUCTION EXAMPLE UNDER MESAP WITH A HOMOGENEOUS RESERVE PRICE.

Supply & Demand	$Z = \{z_{ik}\}$	$A = \{a_{ik}\}$	Q_1	Q_2
	$\begin{pmatrix} 1 & 1 & 1 \\ 1 & 1 & 1 \end{pmatrix}$	$\begin{pmatrix} 1 & 1 & 1 \\ 1 & 1 & 1 \end{pmatrix}$	$(0, 1, 0)$	$(1, 0, 0)$
	Buyer Bid	Payment	Allocation	Utility
Buyer 1 bids B_1	$B_1 = \begin{pmatrix} 0 & \mathbf{3} & 0 \\ 0 & \mathbf{4} & 0 \end{pmatrix}$	$p_1^{\text{v}} = 0 < 1$	$x_{112} = 0$	$u_1 = \mathbf{0}$
	$B_2 = \begin{pmatrix} 0 & 0 & 0 \\ 2 & 0 & 0 \end{pmatrix}$	$p_2^{\text{v}} = 1$	$x_{221} = 1$	$u_2 = 1$
Buyer 1 bids B_1'	$B_1' = \begin{pmatrix} 0 & \mathbf{2} & 0 \\ 0 & \mathbf{6} & 0 \end{pmatrix}$	$p_1'^{\text{v}} = 2$	$x_{212}' = 1$	$u_1' = \mathbf{2}$
	$B_2 = \begin{pmatrix} 0 & 0 & 0 \\ 2 & 0 & 0 \end{pmatrix}$			$u_2 = 0$

B. When VCG is Truthful?

We use Theorem 5 to prove that spatial channel reuse does not affect the truthfulness and self-collusion resistance of VCG in single-unit auctions with a uniform reserve price and homogeneous bids , i.e., the seller sets the same reserve price for all channels in all regions and each buyer has the same bid value for all demanded channels at all regions.

Theorem 5: In a single-unit auction with a uniform reserve price and homogeneous bids, VCG is truthful and self-collusion resistant in both MESAP and v-MESAP.

Proof: Let's focus on the truthfulness of VCG in MESAP first. Since VCG under our consideration is a unilateral auction, the seller is assumed to be truthful. As a result, proving this theorem is equivalent to showing that no buyer can improve its received total utility via cheating on its bid price. There are three cases we should consider.

(i) When $\sum_{i=1}^{M}\sum_{k=1}^{K} x_{ijk}^{\text{v}} = 0$, buyer j does not get any channel at the winner determination stage. Note that $W_{\mathcal{B}_{-j}}^*$ is a constant value to buyer j, i.e., $W_{\mathcal{B}_{-j}}^* = W_{\mathcal{B}_{-j}}'^*$. Therefore, to get a higher utility, buyer j has to increase its bid from the truthful value b_j^t to a non-thuthful value b_j' such that $p_j'^{\text{v}} > p_j^{\text{v}}$. Then if $p_j'^{\text{v}} < a$, buyer j's utility $u_j' = u_j = 0$; if $p_j'^{\text{v}} \geq a$, its utility $u_j' = \sum_{i=1}^{M}\sum_{k=1}^{K} x_{ijk}' b_j^t - p_j' \leq \sum_{i=1}^{M}\sum_{k=1}^{K} x_{ijk}'^{\text{v}} b_j^t - p_j'^{\text{v}} = b_j^t - p_j'^{\text{v}} = (W'^* - W^*) - (b_j' - b_j^t) \leq 0$, as $W^* = W_{\mathcal{B}_{-j}}^*$ and $(W'^* - W^*) \leq (b_j' - b_j^t)$. Thus, $u_j' \leq u_j$.

(ii) When $\sum_{i=1}^{M}\sum_{k=1}^{K} x_{ijk}^{\text{v}} = 1$ and $p_j^{\text{v}} < a$, buyer j wins a channel in the winner determination stage but its payment in VCG cannot afford the channel due to reserve price. To increase its utility, buyer j has to increase its bid value in order to get the channel. However, increasing its bid value does not improve p_j^{v}; thus buyer j cannot get the winning channel via cheating on bid.

(iii) When $\sum_{i=1}^{M}\sum_{k=1}^{K} x_{ijk}^{\text{v}} = 1$ and $p_j^{\text{v}} \geq a$, buyer j wins the auction and gets a channel. We argue that buyer j's utility can not be increased by cheating on bid. If a non-thuthful bid is small enough, buyer j may lose the auction, resulting in a 0 utility; if buyer j wins the auction with a non-truthful bid, its utility should remain unchanged as buyer j's clearing price is not related to its bid price.

These three cases indicate that buyer j cannot receive a higher utility by rigging its bid value; thus VCG is truthful in MESAP. A similar analysis can be applied to prove that VCG in v-MESAP is truthful.

In a single-unit auction with a uniform reserve price and homogeneous bids, a buyer can not improve its utility by self-collusion, as winning different channels results in the same utility. ∎

C. When VCG is Untruthful and Vulnerable to Self-Collusion?

Some claims in existing research are worthy of deliberation. For examples, [37] argues that truthfulness of VCG is broken in a unilateral single-unit spectrum auction due to spatial channel reuse, and [15] claims that VCG is not truthful in a bilateral single-unit spectrum auction because of bid heterogeneity. These statements are incorrect as both [37] and [15] employ greedy algorithms for winner determination, which can not always achieve truthfulness as the achieved social welfare may not be optimal (maximized) [30]. VCG is proved to be self-collusion resistant in a bilateral single-unit heterogeneous spectrum auction without reserve price [11].

Theorem 5 indicates that a single-unit VCG with a homogeneous reserve price and uniform bids is self-collusion resistant. In this subsection we use a few toy examples to demonstrate VCG's vulnerability to self-collusion and untruthfulness in MESAP when considering multiunit trading and (reserve and bid) price diversity, and analyze the root causes. Note that all the examples are designed based on the topology illustrated in Fig. 1.

Table VI shows a single-unit auction example of VCG with a homogeneous reserve price. We observe that when the bid prices are heterogeneous, buyer 1 can not get any channel when bids truthfully with B_1; but it can get channel 2 with B_1' by self-collusion (decreasing its bid on channel 1 and increasing its bid on channel 2.

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TABLE VII
A SINGLE-UNIT AUCTION EXAMPLE UNDER MESAP WITH HOMOGENEOUS BIDS.

Supply & Demand	$Z = \{z_{ik}\}$	$A = \{a_{ik}\}$	Q_1	Q_2
	$\begin{pmatrix} 1 & 1 & 1 \\ 1 & 1 & 1 \end{pmatrix}$	$\begin{pmatrix} 3 & 2 & 1 \\ 0 & 1 & 1 \end{pmatrix}$	$(1, 0, 0)$	$(1, 0, 0)$
	Buyer Bid	Payment	Allocation	Utility
Buyer 1 bids B_1	$B_1 = \begin{pmatrix} \mathbf{5} & 0 & 0 \\ \mathbf{5} & 0 & 0 \end{pmatrix}$	$p_1^{\text{v}} = 0 < 3$	$x_{111} = 0$	$u_1 = \mathbf{0}$
	$B_2 = \begin{pmatrix} 4 & 0 & 0 \\ 4 & 0 & 0 \end{pmatrix}$	$p_2^{\text{v}} = 0$	$x_{221} = 1$	$u_2 = 4$
Buyer 1 bids B'_1	$B'_1 = \begin{pmatrix} \mathbf{3} & 0 & 0 \\ \mathbf{3} & 0 & 0 \end{pmatrix}$	$p_1'^{\text{v}} = 0$	$x'_{211} = 1$	$u'_1 = \mathbf{5}$
	$B_2 = \begin{pmatrix} 4 & 0 & 0 \\ 4 & 0 & 0 \end{pmatrix}$	$p_2^{\text{v}} = 0 < 3$	$x_{121} = 0$	$u_2 = 0$

TABLE VIII
A MULTIUNIT AUCTION EXAMPLE UNDER MESAP WITH HOMOGENEOUS RESERVE PRICE AND BIDS.

Supply & Demand	$Z = \{z_{ik}\}$	$A = \{a_{ik}\}$	Q_1	Q_2
	$\begin{pmatrix} 1 & 1 & 1 \end{pmatrix}$	$\begin{pmatrix} 1 & 1 & 1 \end{pmatrix}$	$(1, 1, 1)$	$(0, 0, 1)$
	Buyer Bid	Payment	Allocation	Utility
Buyer 1 bids B_1	$B_1 = \begin{pmatrix} \mathbf{2} & \mathbf{2} & \mathbf{2} \end{pmatrix}$	$p_1^{\text{v}} = 0 < 1$	$x_{111} = 0$	$u_1 = \mathbf{0}$
	$B_2 = \begin{pmatrix} 0 & 0 & 5 \end{pmatrix}$	$p_2^{\text{v}} = 4$	$x_{123} = 1$	$u_2 = 1$
Buyer 1 bids B'_1	$B'_1 = \begin{pmatrix} \mathbf{4} & \mathbf{4} & \mathbf{4} \end{pmatrix}$	$p_1'^{\text{v}} = 5$	$x'_{111} = 1$, $x'_{112} = 1$, $x'_{113} = 1$	$u'_1 = \mathbf{1}$
	$B_2 = \begin{pmatrix} 0 & 0 & 5 \end{pmatrix}$			$u_2 = 0$

Table VII demonstrates an example of single-unit auction with homogeneous bids. We notice that buyer 1 wins when decreasing its bid price from 5 to 3 in B'_1 (buyer 1 is a loser when bids truthfully with B_1) due to the lower reserve price of channel 2. This can be treated as a truthfulness violation because each buyer bids the same price for all channels.

A multiunit auction example of VCG with a homogeneous reserve price and uniform bids is illustrated in Table VIII. One can see that buyer 1 improves its utility by cheating on its bid.

For a general setting, the example shown in Table IX demonstrates the existence of self-collusion for buyer 1 to improve its utility.

These examples indicate that in MESAP, (i) VCG suffers from self-collusion due to bid diversity; (ii) VCG is not truthful with heterogeneous reserve prices; (iii) VCG is not truthful in multiunit auctions; and (iv) in a general setting, VCG is not self-collusion resistant nor truthful. Similar examples can be identified for VCG in v-MESAP. Therefore, we conclude that VCG is vulnerable to bid manipulation in both MESAP and v-MESAP.

TABLE IX
A MULTIUNIT AUCTION EXAMPLE UNDER MESAP.

Supply & Demand	$Z = \{z_{ik}\}$	$A = \{a_{ik}\}$	Q_1	Q_2
	$\begin{pmatrix} 1 & 1 & 1 \\ 1 & 1 & 1 \end{pmatrix}$	$\begin{pmatrix} 5 & 1 & 0 \\ 2 & 2 & 2 \end{pmatrix}$	$(1, 1, 0)$	$(0, 0, 1)$
	Buyer Bid	Payment	Allocation	Utility
Buyer 1 bids B_1	$B_1 = \begin{pmatrix} \mathbf{9} & 6 & 0 \\ 7 & \mathbf{8} & 0 \end{pmatrix}$	$p_1^{\text{v}} = 0 < 7$	$x_{111} = 0$, $x_{212} = 0$	$u_1 = \mathbf{0}$
	$B_2 = \begin{pmatrix} 0 & 0 & 5 \\ 0 & 0 & 1 \end{pmatrix}$	$p_2^{\text{v}} = 0$	$x_{123} = 1$	$u_2 = 5$
Buyer 1 bids B'_1	$B'_1 = \begin{pmatrix} \mathbf{1} & 6 & 0 \\ 7 & \mathbf{1} & 0 \end{pmatrix}$	$p_1'^{\text{v}} = 4$	$x'_{112} = 1$, $x'_{211} = 1$	$u'_1 = \mathbf{9}$
	$B_2 = \begin{pmatrix} 0 & 0 & 5 \\ 0 & 0 & 1 \end{pmatrix}$	$p_2^{\text{v}} = 0 < 2$	$x_{223} = 0$	$u_2 = 0$

D. Self-Collusion/Untruthfulness Analysis

Section V-C indicates that self-collusion and untruthfulness of VCG in both MESAP and v-MESAP are resulted from price diversity and/or multiunit trading. In this section, we report our analysis results.

Theorem 6: For VCG in MESAP, buyer j can become a winner with a positive utility through cheating on a bid or self-collusion, if the following three conditions simultaneously hold: (i) $p_j^{\text{v}} < \sum_{i=1}^{M} \sum_{k=1}^{K} x_{ijk}^{\text{v}} a_{ik}$ with B_j^t; (ii) $p_j'^{\text{v}} \geq \sum_{i=1}^{M} \sum_{k=1}^{K} x_{ijk}'^{\text{v}} a_{ik}$ with B'_j; and (iii) $p_j'^{\text{v}} < \sum_{i=1}^{M} \sum_{k=1}^{K} x_{ijk}'^{\text{v}} b_{ijk}^t$.

Proof: Conditions (i) and (ii) imply that buyer j loses with true bid B_j^t while winning with false bid B'_j. Condition (iii) indicates a positive utility for buyer j with B'_j.

Due to price diversity and/or multiunit trading, $\sum_{i=1}^{M} \sum_{k=1}^{K} x_{ijk}^{\text{v}} a_{ik}$ and $\sum_{i=1}^{M} \sum_{k=1}^{K} x_{ijk}'^{\text{v}} a_{ik}$ are not always equal to each other. In other words, it is possible that $p_j^{\text{v}} < \sum_{i=1}^{M} \sum_{k=1}^{K} x_{ijk}^{\text{v}} a_{ik}$ while $p_j'^{\text{v}} \geq \sum_{i=1}^{M} \sum_{k=1}^{K} x_{ijk}'^{\text{v}} a_{ik}$ for buyer j. As a result, $p_j'^{\text{v}} < \sum_{i=1}^{M} \sum_{k=1}^{K} x_{ijk}'^{\text{v}} b_{ijk}^t$ is possible as long as the difference between $\sum_{i=1}^{M} \sum_{k=1}^{K} x_{ijk}^{\text{v}} a_{ik}$ and $\sum_{i=1}^{M} \sum_{k=1}^{K} x_{ijk}'^{\text{v}} a_{ik}$ is sufficiently large.

For instance, in Table IX, since $p_1^{\text{v}} = 0 < (a_{11} + a_{22}) = 7$, $p_1'^{\text{v}} = 4 > (a_{12} + a_{21}) = 3$, and $p_1'^{\text{v}} = 4 < (b_{112} + b_{211}) = 13$, buyer 1 successfully wins the auction with a positive utility $u'_1 = 9$ via self-collusion. In fact, all the examples in Section V-C demonstrate the co-existence of conditions (i), (ii), and (iii) for buyer 1.

Thus, we conclude that buyer j can manipulate its bids to get a positive utility when the three conditions hold. ■

Theorem 7: For VCG in MESAP, Buyer j cannot improve its utility via cheating on a bid or self-collusion when any of the following two conditions holds: (i) for any $B'_j \neq B_j^t$, $p_j^{\text{v}} < \sum_{i=1}^{M} \sum_{k=1}^{K} x_{ijk}^{\text{v}} a_{ik}$ with B_j^t, and $p_j'^{\text{v}} < \sum_{i=1}^{M} \sum_{k=1}^{K} x_{ijk}'^{\text{v}} a_{ik}$ with B'_j; and (ii) for any $B'_j \neq B_j^t$, $p_j^{\text{v}} \geq \sum_{i=1}^{M} \sum_{k=1}^{K} x_{ijk}^{\text{v}} a_{ik}$ with B_j^t, and $p'^{\text{v}}_j \geq \sum_{i=1}^{M}\sum_{k=1}^{K} x'^{\text{v}}_{ijk} a_{ik}$ with B'_j.

Proof: When condition (i) is satisfied, buyer j is always a loser and gets a zero utility in VCG.

When condition (ii) holds, buyer j is always the winner in VCG. Moreover, for utilities u_j and u'_j, since $W^*_{\mathcal{B}_{-j}} = W'^*_{\mathcal{B}_{-j}}$, we have $u'_j - u_j = \sum_{i=1}^{M}\sum_{k=1}^{K} x'^{\text{v}}_{ijk} b^t_{ijk} - \sum_{i=1}^{M}\sum_{k=1}^{K} x^{\text{v}}_{ijk} b^t_{ijk} + W'^*_{-B_j} - W^*_{-B_j}$. If $\sum_{i=1}^{M}\sum_{k=1}^{K} x'^{\text{v}}_{ijk} b'_{ijk} \geq \sum_{i=1}^{M}\sum_{k=1}^{K} x'^{\text{v}}_{ijk} b^t_{ijk}$, then $u'_j - u_j = (W'^* - W^*) - \sum_{i=1}^{M}\sum_{k=1}^{K} x'^{\text{v}}_{ijk}(b'_{ijk} - b^t_{ijk}) \leq 0$, as $\sum_{i=1}^{M}\sum_{k=1}^{K} x'^{\text{v}}_{ijk} \geq \sum_{i=1}^{M}\sum_{k=1}^{K} x^{\text{v}}_{ijk}$ and the increase of the social welfare can not be larger than the increase of the bids of a winning buyer's allocated channels. If $\sum_{i=1}^{M}\sum_{k=1}^{K} x'^{\text{v}}_{ijk} b'_{ijk} < \sum_{i=1}^{M}\sum_{k=1}^{K} x'^{\text{v}}_{ijk} b^t_{ijk}$, then $u'_j - u_j = \sum_{i=1}^{M}\sum_{k=1}^{K} x'^{\text{v}}_{ijk}(b^t_{ijk} - b'_{ijk}) - (W^* - W'^*) \leq 0$, because $\sum_{i=1}^{M}\sum_{k=1}^{K} x'^{\text{v}}_{ijk} \leq \sum_{i=1}^{M}\sum_{k=1}^{K} x^{\text{v}}_{ijk}$ and the decrease of the social welfare can not be smaller than the decrease of the bids of a winning buyer's allocated channels. That is, $u'_j \leq u_j$.

Thus, as long as either condition (i) or condition (ii) holds, buyer j cannot successfully cheat on a bid and self-collude. ■

Similar conclusions can be drawn for VCG in v-MESAP, which are summarized by the following two theorems (without proof due to similarity).

Theorem 8: For VCG in v-MESAP, when the following three conditions simultaneously hold, buyer j can become a winner with a positive utility via cheating on a bid or self-collusion: (i) $\hat{p}^{\text{v}}_j < \sum_{i=1}^{M} \hat{x}^{\text{v}}_{ijk}\hat{a}_i$ with B^t_j; (ii) $\hat{p}'^{\text{v}}_j \geq \sum_{i=1}^{M} \hat{x}'^{\text{v}}_{ijk}\hat{a}_i$ with B'_j; and (iii) $\hat{p}'^{\text{v}}_j < \sum_{i=1}^{M}\sum_{k=1}^{K} \hat{x}'^{\text{v}}_{ijk} b^t_{ijk}$.

Theorem 9: Buyer j cannot improve its utility via self-collusion in VCG in v-MESAP when any of the following two conditions holds: (i) for any $B'_j \neq B^t_j$, $\hat{p}^{\text{v}}_j < \sum_{i=1}^{M} \hat{x}^{\text{v}}_{ijk}\hat{a}_i$ with B^t_j, and $\hat{p}'^{\text{v}}_j < \sum_{i=1}^{M} \hat{x}'^{\text{v}}_{ijk}\hat{a}_i$ with B'_j; and (ii) for any $B'_j \neq B^t_j$, $\hat{p}^{\text{v}}_j \geq \sum_{i=1}^{M} \hat{x}^{\text{v}}_{ijk}\hat{a}_i$ with B^t_j, and $\hat{p}'^{\text{v}}_j \geq \sum_{i=1}^{M} \hat{x}'^{\text{v}}_{ijk}\hat{a}_i$ with B'_j.

Therefore, to prevent market manipulation in VCG for MESAP (or v-MESAP), mitigating the diversity in the "*aggregated reserve price*" $\sum_{i=1}^{M}\sum_{k=1}^{K} x^{\text{v}}_{ijk} a_{ik}$ (or $\sum_{i=1}^{M} \hat{x}^{\text{v}}_{ijk}\hat{a}_i$) is a key point. This property is exploited in Section VI to design our truthful and self-collusion resistant auction for MESAP and v-MESAP.

VI. Truthful and Self-Collusion Resistant Auction Design

In this section, we propose a novel auction scheme termed **Self-collusion Resistant Auction (SIRI)** for the multiunit heterogeneous spectrum auction with reserve prices. Our design is motivated by the following observations made in Sections IV and V to prevent market manipulation:

(1) In both MOM and VCG, mitigating the diversity of the aggregated reserve price caused by multi-unit trading and/or price diversity is key to self-collusion resistance.

(2) In MOM, ensuring that the marginal revenue equals the increase of the auction revenue when selling a channel is key to self-collusion resistance.

A. Deducted Bid

In order to prevent self-collusion, we introduce the concept of "*deducted bid*" to remove the impact of reserve price diversity. This is done as follows. In MESAP, we transform B_j to the "*deducted bid*" $\tilde{B}_j$ by computing $\tilde{b}_{ijk} = b_{ijk} - a_{ik}$ to get $\tilde{\mathcal{B}} = \{\tilde{B}_j : j \in [1, N]\}$, and set $\tilde{a}_{ik} = a_{ik} - a_{ik} = 0$ for all $i \in [1, M], k \in [1, K]$ to obtain the "*deducted reserve price*"; in v-MESAP, we set $\tilde{b}_{ijk} = b_{ijk} - \hat{a}_i$ and $\tilde{a}_i = \hat{a}_i - \hat{a}_i = 0$.

By utilizing $\{\tilde{b}_{ijk}\}$ and $\{\tilde{a}_{ik}\}$ (or $\{\tilde{a}_i\}$), we successfully tackle the challenges to guarantee self-collusion resistance and truthfulness in MOM and VCG in the following way: (i) Since $\tilde{a}_{ik} = 0$ (or $\tilde{a}_i = 0$) , the aggregated reserve price for all sold channels $\sum_{i=1}^{M}\sum_{k=1}^{K} \tilde{x}_{ijk}\tilde{a}_{ik} = \sum_{i=1}^{M}\sum_{k=1}^{K} \tilde{x}'_{ijk}\tilde{a}_{ik} = 0$ (or $\sum_{i=1}^{M} \tilde{x}_{ijk}\tilde{a}_i = \sum_{i=1}^{M} \tilde{x}'_{ijk}\tilde{a}_i = 0$). As a result, the conditions for a buyer to perform self-collusion cannot hold according to Theorems 6, 8, and 3. (ii) The auction revenue $\tilde{R} = \sum_{i=1}^{M}\sum_{j=1}^{N}\sum_{k=1}^{K} \tilde{x}_{ijk}(\tilde{b}_{ijk} - \tilde{a}_{ik}) = \sum_{i=1}^{M}\sum_{j=1}^{N}\sum_{k=1}^{K} \tilde{x}_{ijk}\tilde{b}_{ijk} = \tilde{W}$, which implies that VCG and MOM are equivalent with the deducted bids and reserve prices. Therefore in v-MESAP, the obtained marginal revenue equals the increase of the auction revenue when a channel is sold.

Accordingly, the optimization problem is formulated by (10), in which the objective (10a) is to maximize the "*deducted social welfare*" $\tilde{W}$. The constraints (10b), (10c), (10d), and (10e) respectively correspond to (1), (2), (3), and (4) of the auction model in Section III-B.

$$\max \quad \tilde{W} = \sum_{i=1}^{M}\sum_{j=1}^{N}\sum_{k=1}^{K} \tilde{x}_{ijk}\tilde{b}_{ijk}; \tag{10a}$$

$$\text{s.t.} \quad \tilde{x}_{ijk} \times \tilde{x}_{ij'k} = 0, \forall i \in [1, M], j \neq j' \in [1, N], k \in [1, K]; \tag{10b}$$

$$\tilde{x}_{ijk} \times \tilde{x}_{ij'k'} = 0, \forall i \in [1, M], j \neq j' \in [1, N], e(k, k') \in \mathcal{E}; \tag{10c}$$

$$\sum_{i=1}^{M}\sum_{j=1}^{N} z_{ik}\tilde{x}_{ijk} \leq M_k, \forall k \in [1, K]; \tag{10d}$$

$$\sum_{i=1}^{M}\sum_{k=1}^{K} z_{ik}\tilde{x}_{ijk} \leq q_{jk}, \forall j \in [1, N], k \in [1, K]; \tag{10e}$$

$$\tilde{x}_{ijk} \in \{0, 1\}. \tag{10f}$$

B. Design of SIRI Auction

The proposed auction consists of two stages: *winner determination* and *payment calculation*.

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Algorithm 1 Winner Determination

1: **Input**: $\mathcal{M}$, $\mathcal{N}$, $\mathcal{K}$, $\tilde{\mathcal{B}} = \{\tilde{b}_{ijk}\}$, $\mathcal{E}$.
2: **Output**: $\{\tilde{x}_{ijk}\}$.
3: Set $\tilde{\mathcal{B}'} = \tilde{\mathcal{B}}$, $Sell(i,k) = 0$, and $Buy(j,k) = 0$;
4: **while** $\tilde{\mathcal{B}'} \neq \emptyset$ **do**
5:     Select a bid $\tilde{b}_{ijk} = \arg\max_{\tilde{\mathcal{B}'}}\{\tilde{b}_{i'j'k'}\}$;
6:     **if** $\tilde{b}_{ijk} \geq 0$, $Sell(i,k) < M_k$, $Buy(j,k) < q_{jk}$, and channel i is not assigned at region k or k's conflicting regions in $\mathcal{E}$ **then**
7:         Set $\tilde{x}_{ijk} = 1$;
8:     **end if**
9:     Update $Sell(i,k)$ and $Buy(j,k)$;
10:     $\tilde{\mathcal{B}'} = \tilde{\mathcal{B}'} \setminus \tilde{b}_{ijk}$;
11: **end while**
12: **return** $\{\tilde{x}_{ijk}\}$.

1) Winner Determination: The winners are iteratively determined in a greedy way until no channel can be sold where the pseudo-code is presented in Alg. 1. Denoted by $Sell(i,k)$ and $Buy(j,k)$ the number of distinct channels sold at region k and the number of distinct channels purchased by buyer j at region k, respectively, which can be used to check the constraints (10d) and (10e). As shown in Alg. 1, in each iteration, a maximum bid $\tilde{b}_{ijk}$ is selected. Regarding a non-negative bid, if channel i is not assigned to any buyer at region k and k's conflicting regions in graph $\mathcal{E}$, and the supply and demand constraints are not violate, buyer j gets channel i at region k. Then, update $\tilde{x}_{ijk}$, $Sell(i,k)$ and $Buy(j,k)$, and remove $\tilde{b}_{ijk}$ from $\tilde{\mathcal{B}'}$.

2) Payment Calculation: The "*deducted payment*" $\tilde{p}_{ijk}$ is introduced to represent the payment paid by buyer j for channel i at region k, thus the total payment of buyer j is

$$\tilde{p}_j = \sum_{i=1}^{M}\sum_{k=1}^{K} \tilde{p}_{ijk}.$$

To compute the payments, the critical neighbor of each winner should be identified first, in which the winner will become the loser if his bid is smaller than his critical neighbor's bid. Different from the most existing works where each winner has only one critical neighbor, in MESAP and v-MESAP, one winner may have more than one critical neighbor because there may be a critical neighbor in every channel at every region. To ensure truthfulness as well as to resist self-collusion in such complicated situation, we find the critical neighbor of buyer j with respect to each bid $\tilde{b}_{ijk}$ if $\tilde{x}_{ijk} = 1$. The key idea is that without the participation of buyer j, his critical neighbor (e.g. buyer j') can win channel i at region k or k's conflicting region. If such a critical neighbor j' can be found, we set $\tilde{p}_{ijk} = \tilde{b}_{ij'k}$; otherwise, $\tilde{p}_{ijk} = 0$. The corresponding pseudo-code is presented in Alg. 2.

By now, we have the solutions $\{\tilde{x}_{ijk}\}$ and $\{\tilde{p}_j\}$. For $\forall i \in [1,M], \forall j \in [1,N]$, and $\forall k \in [1,K]$, we set $x_{ijk} = \tilde{x}_{ijk}$ in MESAP and $\hat{x}_{ijk} = \tilde{x}_{ijk}$ in v-MESAP. Then, if $\sum_{i=1}^{M}\sum_{k=1}^{K} x_{ijk} \geq 1$ (or $\sum_{i=1}^{M}\sum_{k=1}^{K} \hat{x}_{ijk} \geq 1$), we set $p_j = \tilde{p}_j + \sum_{i=1}^{M}\sum_{k=1}^{K} x_{ijk}a_{ik}$ for MESAP (or $\hat{p}_j = \tilde{p}_j + \sum_{i=1}^{M} \hat{x}_{ijk}\hat{a}_i$ for v-MESAP). Finally, **SIRI** outputs $\{x_{ijk}\}$ and $\{p_j\}$ for MESAP and $\{\hat{x}_{ijk}\}$ and $\{\hat{p}_j\}$ for v-MESAP.

Algorithm 2 Payment Calculation for $\tilde{p}_{ijk}$

1: **Input**: $\tilde{b}_{ijk}$, $\mathcal{M}$, $\mathcal{N}$, $\mathcal{K}$, $\tilde{\mathcal{B}} = \{\tilde{b}_{ijk}\}$, $\mathcal{E}$.
2: **Output**: $\tilde{p}_{ijk}$.
3: Set $\tilde{p}_{ijk} = 0$, $\tilde{\mathcal{B}'} = \tilde{\mathcal{B}}$, $\tilde{\mathcal{B}''} = \tilde{\mathcal{B}} \setminus \tilde{b}_{ijk}$, $Sell(i,k) = 0$, and $Buy(j,k) = 0$;
4: **while** $\tilde{\mathcal{B}''} \neq \emptyset$ **do**
5:     Select a bid $\tilde{b}_{i'j'k'} = \arg\max_{\tilde{\mathcal{B}''}}\{\tilde{b}_{i''j''k''}\}$;
6:     **if** $\tilde{b}_{i'j'k'} \geq 0$, $Sell(i',k') < M_{k'}$, $Buy(j',k') < q_{j'k'}$, and channel i' is not assigned at region k' or k''s conflicting regions in $\mathcal{E}$ **then**
7:         Set $\tilde{x}_{i'j'k'} = 1$;
8:     **end if**
9:     Update $Sell(i',k')$ and $Buy(j',k')$;
10:     **if** $j' \neq j$, $i' == i$, and ($k' == k$ or $e(k',k) \in \mathcal{E}$) **then**
11:         $\tilde{p}_{ijk} = \tilde{b}_{i'j'k'}$;
12:     **end if**
13:     $\tilde{\mathcal{B}''} = \tilde{\mathcal{B}''} \setminus \tilde{b}_{i'j'k'}$;
14: **end while**
15: **return** $\tilde{p}_{ijk}$.

C. Economic Property Analysis

Theorem 10: **SIRI** is individually-rational in both MESAP and v-MESAP.

Proof: For each winning buyer j, $\tilde{p}_{ijk} = 0$ or $\tilde{p}_{ijk} = \tilde{b}_{i'j'k'}$. Since $\tilde{\mathcal{B}''} = \tilde{\mathcal{B}} \setminus \tilde{b}_{ijk}$, we have $\tilde{b}_{ijk} \geq \tilde{p}_{ijk}$ according to line 5 of Alg. 1 and line 5 of Alg. 2. Thus, $p_j = \tilde{p}_j + \sum_{i=1}^{M}\sum_{k=1}^{K} x_{ijk}a_{ik} \leq \sum_{i=1}^{M}\sum_{k=1}^{K} x_{ijk}b_{ijk}$ in MESAP, and $\hat{p}_j = \tilde{p}_j + \sum_{i=1}^{M} \hat{x}_{ijk}\hat{a}_i \leq \sum_{i=1}^{M}\sum_{k=1}^{K} x_{ijk}b_{ijk}$ in v-MESAP. Accordingly, we have $u_j = \sum_{i=1}^{M}\sum_{k=1}^{K} x_{ijk}b_{ijk} - p_j \geq 0$ and $\hat{u}_j = \sum_{i=1}^{M}\sum_{k=1}^{K} \hat{x}_{ijk}b_{ijk} - \hat{p}_j \geq 0$. Therefore, **SIRI** is individually-rational in both MESAP and v-MESAP. ■

Lemma 1: The winner determination in **SIRI** is monotonic, i.e., buyer j can still win the auction with b'_{ijk} if he wins with b_{ijk} ($b'_{ijk} \geq b_{ijk}$).

Proof: Note that $b'_{ijk} \geq b_{ijk}$ means $\tilde{b}'_{ijk} \geq \tilde{b}_{ijk}$. From line 5 of Alg. 1, this lemma is proved. ■

Lemma 2: In **SIRI** auction, $\tilde{p}_{ijk}$ is the critical price of buyer j in channel i at region k; that is, buyer j cannot win channel i at region k if $\tilde{b}_{ijk} < \tilde{p}_{ijk}$.

Proof: According to Alg. 1 and Alg. 2, we can conclude that $\tilde{x}_{ijk} = 1$ if $\tilde{b}_{ijk} > \tilde{b}_{i'j'k'}$ and $\tilde{b}_{ijk} > 0$ and that $\tilde{x}_{ijk} = 0$ if $\tilde{b}_{ijk} < \tilde{b}_{i'j'k'}$ or $\tilde{b}_{ijk} < 0$. Thus, this lemma can hold. ■

Theorem 11: **SIRI** is truthful and self-collusion resistant in MESAP.

Proof: When buyer j bids with truthful bids $\mathcal{B}^t_j$, we have the deducted bids $\tilde{\mathcal{B}}^t_j$, the payment p^t_j, the set of assigned channels Ch^t_j, and the utility u^t_j. When buyer j bids with untruthful bids $\mathcal{B}'_j$, we correspondingly obtain $\tilde{\mathcal{B}}'_j$, p'_j, Ch'_j, and u'_j. Moreover, in MESAP,

$$p^t_j = \tilde{p}^t_j + \sum_{i=1}^{M}\sum_{k=1}^{K} \tilde{x}^t_{ijk}a_{ik} = \sum^{Ch^t_j}(\tilde{p}^t_{ijk} + a_{ik}),$$

and

$$p'_j = \tilde{p}'_j + \sum_{i=1}^{M}\sum_{k=1}^{K} \tilde{x}'_{ijk} a_{ik} = \sum^{Ch'_j} (\tilde{p}'_{ijk} + a_{ik}).$$

If buyer j bids untruthfully, there are five cases for consideration.

(i) $Ch^t_j = Ch'_j$. From Lemma 1 and Lemma 2, we have $u^t_j = u'_j$.

(ii) $Ch^t_j \subset Ch'_j$. In this case, $\Delta Ch_j = Ch'_j \setminus Ch^t_j \neq \emptyset$; that is, there is at least one channel at a region such that $x^t_{ijk} = 0$ and $x'_{ijk} = 1$. Thus, we have $u'_j = u^t_j + \Delta u_j$, where Δu_j is the utility received from channels in ΔCh_j. According to Lemma 1 and Lemma 2, there must be $\Delta u_j \leq 0$. Hence, $u'_j \leq u^t_j$.

(iii) $Ch^t_j \supset Ch'_j$. So, $\Delta Ch_j = Ch^t_j \setminus Ch'_j \neq \emptyset$, and $u^t_j = u'_j + \Delta u_j$. In ΔCh_j, all channels are obtained due to truthful bidding, and thereby $\Delta u_j \geq 0$ from Theorem 10. Thus, $u^t_j \geq u'_j$.

(iv) $Ch^t_j \cap Ch'_j = \cap(Ch_j) \neq \emptyset$. Let $\Delta Ch^t_j = Ch^t_j \setminus Ch'_j$ and $\Delta Ch'_j = Ch'_j \setminus Ch^t_j$. Accordingly, $u^t_j = \Delta u^t_j + \cap(u_j)$ and $u'_j = \Delta u'_j + \cap(u_j)$, in which Δu^t_j, $\Delta u'_j$, and $\cap(u_j)$ are the utilities corresponding to ΔCh^t_j, $\Delta Ch'_j$, and $\cap(Ch_j)$, respectively. Theorem 10, Lemma 1, and Lemma 2 indicate that $\Delta u^t_j \geq 0$, $\Delta u'_j \leq 0$, and $\cap(u_j) \geq 0$. As a result, $u^t_j \geq u'_j$.

(v) $Ch^t_j \cap Ch'_j = \cap(Ch_j) = \emptyset$. From Theorem 10, Lemma 1, and Lemma 2, we have the similar conclusion: $u^t_j \geq 0$ and $u'_j \leq 0$, implying that $u^t_j \geq u'_j$.

From the aforementioned five cases, we can conclude that our proposed auction is truthful and self-collusion resistant in MESAP. ■

By using the proof process similar to that in Theorem 11, we can obtain the following theorem.

Theorem 12: **SIRI** can achieve truthfulness and self-collusion resistance in v-MESAP.

D. Case Study

To better understand the performance of our auction **SIRI**, two illustrative cases are presented.

1) SIRI vs MOM: The network scenario of Table V is used to compare **SIRI** and MOM auctions. As shown in Table V, in MOM, buyer 2 can increase the utility from 3 to 5 by manipulating 2 price values. The deducted bids of buyer 1 and buyer 2 who submits truthful and untruthful bids are:

$$\tilde{B}_1 = \begin{pmatrix} 1 & -2 & -2 \\ 1 & -5 & -5 \\ -1 & -1 & -1 \end{pmatrix};$$

$$\tilde{B}_2 = \begin{pmatrix} -2 & 1 & \mathbf{2} \\ -5 & -5 & \mathbf{0} \\ -1 & 3 & -1 \end{pmatrix};$$

$$\tilde{B}'_2 = \begin{pmatrix} -2 & 1 & \mathbf{3} \\ -5 & -5 & \mathbf{-2} \\ -1 & 3 & -1 \end{pmatrix}.$$

From Algs. 1 and 2, the results of **SIRI** are as follows. (i) **Buyer 2 bids $\tilde{B}_2$:** $\hat{x}_{111} = 1$, $\hat{p}_1 = 2$ and $\hat{u}_1 = 3 - 2 = 1$ for buyer 1; $\hat{x}_{123} = 1$, $\hat{x}_{322} = 1$, $\hat{p}_2 = 3$ and $\hat{u}_2 = 8 - 3 = 5$ for buyer 2. (ii) **Buyer 2 bids $\tilde{B}'_2$:** the results remain the same, which means *buyer 2 cannot obtain a higher utility via manipulation in our auction* **SIRI**.

2) SIRI vs VCG: In the comparison between **SIRI** and VCG, the network scenario of Table IX is adopted, in which buyer 1 enhances the utility from 0 to 9 by cheating under VCG. In **SIRI**, the two buyers' deducted bids when buyer 1 bid truthfully and untruthfully are:

$$\tilde{B}_1 = \begin{pmatrix} \mathbf{4} & 5 & 0 \\ 5 & \mathbf{6} & -2 \end{pmatrix};$$

$$\tilde{B}'_1 = \begin{pmatrix} \mathbf{-4} & 5 & 0 \\ 5 & \mathbf{-1} & -2 \end{pmatrix};$$

$$\tilde{B}_2 = \begin{pmatrix} -5 & -1 & 5 \\ -2 & -2 & -1 \end{pmatrix}.$$

Accordingly, we have the following results. (i) **Buyer 1 bids $\tilde{B}_1$:** $x_{111} = 1$, $x_{212} = 1$, $p_1 = 7$ and $u_1 = 17 - 7 = 10$ for buyer 1; $x_{123} = 1$, $p_2 = 0$ and $u_2 = 5$ for buyer 2. (ii) **Buyer 1 bids $\tilde{B}'_1$: Case 1:** $x'_{112} = 1$, $x'_{211} = 1$, $p'_1 = 8$ and $u'_1 = 13 - 8 = 5$ for buyer 1; $u_2 = 0$ for buyer 2. **Case 2:** $x'_{211} = 1$, $p'_1 = 2$ and $u'_1 = 7 - 2 = 5$ for buyer 1; $x_{123} = 1$, $p_2 = 5$ and $u_2 = 0$ for buyer 2. These results show that *buyer 1's utility is reduced when bidding untruthfully in our auction* **SIRI**.

The above comparison confirms that our auction **SIRI** can resist users' self-collusion behaviors in the multiunit heterogeneous spectrum markets.

VII. Conclusion

In this paper, we rigorously investigate the root causes of untruthfulness of both MOM and VCG in a multiunit heterogeneous spectrum market with reserve prices. We identify the conditions under which untruthfulness (and self-collusion) can/cannot happen in MOM and VCG. Furthermore, based on our fundamental theories, we propose a novel truthful auction scheme **SIRI** and analyze its performance. In our future research, we will target the design of "small-group" collusion resistant auctions in our multiunit heterogeneous spectrum market with reserve prices. We will also consider more robust auctions in practical secondary spectrum markets.

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References

[1] Y. Sun, M. Li, H. Huang, M. Tian, F. Li, and L. Huang, "A double auction mechanism for heterogeneous multi-unit spectrum trading," *Chinese Journal of Electronics*, vol. 25, no. 5, pp. 928–935, Sep. 2016.

[2] S. Chen and M. Huang, "Truthful multi-unit double auctions with quantity discount," in *Chinese Control And Decision Conference (CCDC)*, Jun. 2018.

[3] E. F. Khairullah and M. Chatterjee, "Preda: Preference-based double auction for spectrum allocation in heterogeneous dsa networks," *Computer Communications*, vol. 133, pp. 41–50, 2019.

[4] A. Sultana, I. Woungang, L. Zhao, and A. Anpalagan, "Two-tier architecture for spectrum auction in sdn-enabled cloud radio access network," *IEEE Transactions on Vehicular Technology*, vol. 68, no. 9, pp. 9191–9204, Sep. 2019.

[5] Y. Yang, Q. Zhang, Y. Wang, T. Emoto, M. Akutagawa, and S. Konaka, "Multi-strategy dynamic spectrum access in cognitive radio networks: Modeling, analysis and optimization," *China Communications*, vol. 16, no. 3, pp. 103–121, Mar. 2019.

[6] Y. Chen, X. Tian, Q. Wang, M. Li, M. Du, and Q. Li, "Armor: A secure combinatorial auction for heterogeneous spectrum," *IEEE Transactions on Mobile Computing*, vol. 18, no. 10, pp. 2270–2284, Oct. 2019.

[7] C. Yi and J. Cai, "Ascending-price progressive spectrum auction for cognitive radio networks with power-constrained multiradio secondary users," *IEEE Transactions on Vehicular Technology*, vol. 67, no. 1, pp. 781–794, Jan. 2018.

[8] N. Tadayon and S. A´issa, "Radio resource allocation and pricing: Auction-based design and applications," *IEEE Transactions on Signal Processing*, vol. 66, no. 20, pp. 5240–5254, Oct. 2018.

[9] Q. Deng, Z. Li, J. Chen, F. Zeng, H.-M. Wang, L. Zhou, and Y.-J. Choi, "Dynamic spectrum sharing for hybrid access in ofdma-based cognitive femtocell networks," *IEEE Transactions on Vehicular Technology*, vol. 67, no. 11, pp. 10 830–10 840, Nov. 2018.

[10] W. Li, S. Wang, and X. Cheng, "Truthful multi-attribute auction with discriminatory pricing in cognitive radio networks," in *ACM MobiCom Workshop on CRAB*, Miami, USA, October 2013, pp. 21–30.

[11] W. Li, X. Cheng, R. Bie, and F. Zhao, "An extensible and flexible truthful auction framework for heterogeneous spectrum markets," in *ACM MobiHoc*, Philadelphia, USA, August 2014, pp. 175–184.

[12] T. Jing, C. Zhao, X. Xing, Y. Huo, W. Li, and X. Cheng, "A multi-unit truthful double auction framework for secondary market," in *IEEE ICC*, 2013.

[13] R. B. Myerson, "Optimal auction design," *Mathematics Operations Research*, vol. 6, no. 1, pp. 58–73, 1981.

[14] W. Vickrey, "Counterspeculation, auctions, and competitive sealed tenders," *The Journal of Finance*, vol. 16, no. 1, pp. 8–37, March 1961.

[15] X. Feng, Y. Chen, J. Zhang, Q. Zhang, and B. Li, "Tahes: Truthful double auction for heterogeneous spectrums," *IEEE Transactions on Wireless Communications*, vol. 11, no. 11, pp. 4038–4047, November 2012.

[16] P. Lin, X. Feng, Q. Zhang, and M. Hamdi, "Groupon in the air: A three-stage auction framework for spectrum group-buying," in *IEEE INFOCOM*, Turin, Italy, April 2013, pp. 2061–2069.

[17] F. Wu and N. Vaidya, "A strategy-proof radio spectrum auction mechanism in noncooperative wireless networks," *IEEE Transactions on Mobile Computing*, vol. 12, no. 5, pp. 885–894, May 2013.

[18] W. Li, J. Yu, X. Cheng, R. Bie, and F. Zhao, "An extensible and flexible truthful auction framework for heterogeneous spectrum markets," *IEEE Transactions on Cognitive Communications and Networking*, vol. 2, no. 4, pp. 427–441, 2016.

[19] R. P. McAfee, "A dominant strategy double auction," *Journal of Economic Theory*, vol. 56, no. 2, pp. 434–450, April 1992.

[20] Z. Ji and K. J. R. Liu, "Multi-stage pricing game for collusion-resistant dynamic spectrum allocation," *IEEE Journal on Selected Areas in Communications*, vol. 26, no. 1, pp. 182–191, January 2008.

[21] Y. Wu, B. Wang, K. J. R. Liu, and T. C. Clancy, "Collusion-resistant multi-winner spectrum auction for cognitive radio networks," in *IEEE GLOBECOM*, New Orleans, LO, November 2008, pp. 1–5.

[22] ——, "A multi-winner cognitive spectrum auction framework with collusion-resistant mechanisms," in *DySPAN*, Chicago, USA, October 2008, pp. 1–9.

[23] ——, "A scalable collusion-resistant multi-winner cognitive spectrum auction game," *IEEE Transactions on Communications*, vol. 57, no. 12, pp. 3805–3816, December 2009.

[24] X. Zhou and H. Zheng, "Breaking bidder collusion in large-scale spectrum auctions," in *ACM MobiHoc*, Chicago, USA, September 2010, pp. 121–130.

[25] Q. Wang, Q. Sun, K. Ren, and X. Jia, "Themis: Collusion-resistant and fair pricing spectrum auction under dynamic supply," *IEEE Transactions on Mobile Computing*, vol. 16, no. 7, pp. 2015–2064, 2017.

[26] D. Pang, Z. Deng, G. Hu, Y. Chen, and M. Xu, "Cost sharing based truthful spectrum auction with collusion-proof," *China Communications*, vol. 15, no. 2, pp. 74–87, 2018.

[27] F. Zhao and Q. Tang, "A knn learning algorithm for collusion- resistant spectrum auction in small cell networks," *IEEE Access*, vol. 6, pp. 45 796–45 803, 2018.

[28] A. V. Goldberg and J. D. Hartline, "Collusion-resistant mechanisms for single-parameter agents," in *Proceedings of SODA*, 2005.

[29] V. Krishna, *Auction Theory*, 2nd ed. Elsevier, 2010.

[30] R. L. Zhan, "Optimality and efficiency in auctions design: A survey," in *Pareto Optimality, Game Theory And Equilibria*, ser. Springer Optimization and Its Applications. Springer New York, 2008, vol. 17, pp. 437–454.

[31] W. Wang, B. Liang, and B. Li, "Designing truthful spectrum double auctions with local markets," *IEEE Transactions on Mobile Computing*, vol. 13, no. 1, pp. 75–88, January 2014.

[32] X. Zhou and H. Zheng, "Trust: A general framework for truthful double spectrum auctions," in *IEEE INFOCOM*, Rio de Janeiro, Brazil, April 2009, pp. 999–1007.

[33] Q. Huang, Y. Tao, and F. Wu, "Spring: A strategy-proof and privacy preserving spectrum auction mechanism," in *IEEE INFOCOM*, Turin, Italy, April 2013, pp. 851–859.

[34] P. Cramton, Y. Shoham, and R. Steinberg, Eds., *Combinatorial Auctions*. Boston: MIT Press, 2006.

[35] L. M. Ausubel, *New Economy Handbook*. Academic Press, 2003, ch. 6: Auction Theory for the New Economy.

[36] L. M. Ausubel and P. Cramton, "The optimality of being efficient: designing auctions," Department of Economics, University of Maryland, Tech. Rep. WPS1985, June 1999.

[37] X. Zhou, S. Gandhi, S. Suri, and H. Zheng, "ebay in the sky: Strategy-proof wireless spectrum auctions," in *ACM MobiCom*, San Francisco, USA, September 2008, pp. 2–13.

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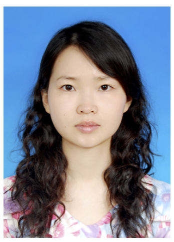

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