VERACITY: Overlapping Coalition Formation-Based Double Auction for Heterogeneous Demand and Spectrum Reusability

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***Abstract*— Spectrum auction is one of the most effective solutions to allocate the spectrum resource following the market rules and has attracted much attention from both academia and industry. However, most of the existing studies assume that the spectrum buyers' demands are homogeneous and the interference relationship is fixed without any change with the variation of spectrum. Furthermore, the economical efficiency of auction outcome has not drawn enough attention. That motivates us to design an auction scheme to jointly consider the multi-demand of buyers, heterogeneous spectrum, and economical efficiency. In this paper, we propose a novel overlapping coalition formation-based double auction, called VERACITY, to address this problem. The auctioneer groups the conflict free buyers into the same coalition and allows a buyer to join multiple coalitions based on the heterogeneous demand. Dynamic overlapping coalition formation implemented by the auctioneer is to find the approximately optimal coalition structure corresponding to the economical efficiency outcome, i.e., maximizing the social welfare. Furthermore, we prove that VERACITY is individually rational, budget balanced, truthful, and economically efficient. Simulation results are presented to show the convergence and effectiveness of the proposed VERACITY.**

***Index Terms*— Double auction, heterogeneous demand, spectrum reusability, overlapping coalition game, economic property.**

I. INTRODUCTION

WITH the exponentially growing demand of spectrum for the bandwidth-hungry wireless devices and applications in the next generation communication systems, the static spectrum allocation policy has imposed restrictions on improving the spectrum efficiency and leads to the artificial shortage of spectrum [1]–[3]. Either in cognitive radio networks [4] or cognitive small cell networks [5], [6], dynamic spectrum access is an effective solution to improve the spectrum utilization [7], [8]. Secondary users (SUs) can sense the spectrum's state of primary users and dynamically access idle channels in a smart manner. However, the spectrum owners may be unwilling to lease their idle spectrum to SUs in a free-charged manner. From the perspective of spectrum owners' profit, the market-driven spectrum trading can encourage them to lease their idle spectrum and bring satisfactory revenue for sellers [9].

Auction is a classical allocation mechanism following the market-driven rules, and brings fairness and efficiency to the players (buyers, sellers and auctioneer) involved in it. Spectrum auction has attracted much attention in recent years and has been widely studied [10]. Unlike the traditional goods (e.g., paints, bonds, cerams) auction, the spectrum spatial reusability and complex interference constraints make the spectrum auction different, i.e., the conflict free bidders can win the opportunities to access the same spectrum simultaneously. These imposed constraints bring challenges to the spectrum allocation in auction and generally searching for the optimal interference-free allocation scheme is an NP-hard problem [11]. On the other hand, the spectrum reusability makes the auction mechanism be redesigned for a specific communication system. Many classical auction mechanisms, i.e. Vickrey-Clarke-Groves (VCG) auction, may lose the truthfulness when directly applied to double spectrum auction considering channel reusability [9], [12]. Truthfulness, also known as the strategy-proof, is a economic property in the auction. Truthfulness can guarantee the reasonable distribution of spectrum resource, i.e., allocating the spectrum to the buyers who value it the most and bringing more revenue to sellers.

There exist efforts as in [9], [11], [13], and [16] on designing the auction mechanism for jointly considering the truthfulness and spectrum reusability. However, most of them ignored the buyers' heterogeneous demand and the heterogeneity of accessing spectrum. To be specific, existing studies [9], [11], [16] assumed that channels are identical objects and buyers' demands are homogeneous; that is to say, buyers

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submit uniform prices for all channels without considering the differences among channels and buyers' preferences. When different channels are allocated for transmission, the interference relationship among buyers needs to be variant based on spectrum-specific interference graph rather than the same one for all channels as in [9], [12], and [13]. Hence, buyers' multi-demand with diversified preferences, termed as heterogeneous demand in this paper, and spectrum heterogeneity need to be integrated into the auction design.

Furthermore, the economical efficiency of auction does not draw enough attention. Apparently, the economical efficiency, i.e., maximizing the payment from all winning bidders, needs to be taken into consideration [11]. To achieve the spectrum reusability, grouping the non-conflicting buyers together and then allocating them with the same spectrum is a general solution. These existing studies [12]–[14] consider the spectrum allocation and pricing scheme separately and yield a relatively low economical efficiency result. It motivates us to incorporate the dynamic buyer group formation into the auction design to obtain high economical efficiency outcome. Considering the spectrum and demand heterogeneity, there are two significant technical challenges to design a dynamic buyer group scheme for double spectrum auction as follows:

- How to make the spectrum auction satisfy the economic properties, especially truthfulness, in the dynamic buyer group progress based on spectrum-specific interference graph?
- How to search the optimal buyer group for maximizing the defined performance metrics such as the economical efficiency?

However, the existing auction schemes may lose the truthfulness in dynamic buyer group considering heterogeneous demand, because the winning buyer groups are selected in a simply random selection. The grouping of the buyers is merely dependent on the interference conditions and without any relationship to the auction process [11]. To this end, we propose an o**VER**lapping co**A**lition formation based double au**C**t**I**on for heterogeneous demand and spec**T**rum reusabilit**Y** (VERACITY). In VERACITY, the auctioneer jointly considers the spectrum allocation and pricing in the process of the buyers' group formation (termed as coalition formation). Moreover, the buyer's heterogeneous demand, i.e., each buyer can require multiple spectrum based on his actual traffic demand and the heterogeneous spectrum, which may lead to the variation of the interference relationship among buyers on different spectrum, are taken into account. We redesign the selection rule of the winning buyer groups to make the auction truthful in the progress of the overlapping coalition formation.

To the best of authors' knowledge, this is the first work to combine the overlapping coalition formation with the double auction, jointly considering heterogeneous spectrum reusability, multi-spectrum demand and economical efficiency.

In short, the main contributions of this paper can be summarized as follows:

- We establish a novel double spectrum auction termed as VERACITY. In it, heterogeneous buyer's demand, spectrum reusability and economical efficiency of the allocation are taken into consideration. Combining it with the coalition game theory, we incorporate the overlapping coalition formation for buyers' group with the auction mechanism.
- To search for the optimal coalition structure (i.e., buyer group formation), we present a dynamic and iterative coalition formation algorithm to jointly consider spectrum allocation and pricing rather doing it separately. Pareto improvement of the every coalition operation in the coalitional formation process can make the algorithm finally converge to a stable and satisfactory coalition structure.
- VERACITY is proved to satisfy the economic properties in terms of *truthfulness*, *individual rationality*, *ex-budget balance* and *economic efficiency* in the dynamic grouping progress. Furthermore, extensive simulations are conducted to present the performance results of VERACITY with the existing auction mechanisms under various networks settings.

The rest of the paper is organized as follows. In Section II, we review the related work. Section III introduces the system model and problem formulation. Section IV presents challenges in the auction design considering heterogeneous demand and spectrum reusability, then the details of VERACITY are presented in Section V. Section VI analyzes the economic properties of the proposed VERACITY. Simulations are performed in section VII. Finally, the conclusions are drawn in Section VIII.

II. Related Work

Recently, the spectrum auction has attracted much attention. VERITAS, proposed by Zhou *et al.* [13], is the first single-side truthful auction considering both spectrum spatial reusability and computation efficiency. Wu and Vaidya [14] designed a truthful auction, named as SMALL, to guarantee that the spectrum sellers can obtain a non-negative utility when they have a reserved price for each spectrum. Zhou and Zheng [9] designed a truthful double auction,[1] called TRUST, considering spectrum spatial reusability, which is a smart extension of the classical double auction McAfee proposed in [15]. Lin *et al.* [16] developed a three stage auction termed as TASG, in which secondary users are grouped as a entity to buy the channel to increase their opportunity for accessing channels. In [11], to maximize the profit of spectrum, Sun *et al*. combined coalition formation with McAfee and designed a coalitional double auction for spatial spectrum (short for "CDAS") allocation in cognitive networks, considering the profit maximization of spectrum. Wang *et al.* [17] developed the TRUMP mechanism to consider both QoS demands and spectrum spatial reuse. Yang *et al.* [18] designed a truthful double auction called PROMISE considering to maximize the profit without the valuation distribution knowledge. Kebriei *et al.* investigated the Nash equilibrium based on the supply-demand function for double-sided bandwidth auction in [23] and [24].

[1]Different from the single-sided auction, double auction, or termed as double-sided auction, is a process of buying and selling goods when potential buyers submit their bids and potential sellers simultaneously submit their ask prices to an auctioneer, then the auctioneer determines the final winning buyers and sellers. A simple example of a double auction is a bilateral trade scenario.

TABLE I
COMPARISON WITH MAIN RELATED AUCTION MECHANISMS

Existing auction designs	**TRUST** [9]	**TAMES** [22]	**SMALL** [14]	**VERITAS** [13]	**TAHES** [21]	**CDAS** [11]	**VERACITY**
Double auction	√	√	×	×	√	√	√
Truthfulness	√	√	√	√	√	√	√
Spectrum Reusability	√	√	√	√	√	√	√
Individual Rationality	√	√	√	√	√	√	√
Heterogeneous Demand	×	√	√	×	×	×	√
Heterogeneous Spectrum	×	√	×	×	√	×	√
Economical Efficiency	×	×	×	×	×	√	√

Some related literature considering the spectrum recall can be found in [19] and [20].

Furthermore, taking the heterogeneous interference relationship into account, Feng *et al.* [21] proposed a truthful double auction, named TAHES, for heterogeneous spectrum. However, these double auction mechanisms assumed that the demands of buyers are homogeneous, i.e., each buyer only needs one channel. Recently, Chen *et al.* [22] proposed TAMES, which is a truthful double auction for multi-demand heterogeneous spectrum. But, in the implementation process of TAMES, it ignores the economic efficiency of the final outcome and just allocates the spectrum for conflict-free buyers in a relatively simple way.

Different from the most of the work mentioned above, in this paper, we jointly consider the heterogeneous demand, spectrum reusability and economical efficiency in the design of our scheme. The key is to find a optimal buyers' group, which allows each buyer to join multiple groups based on his actual demand simultaneously. Coalition game [26], [27] provides a powerful tool to analyze the dynamic buyers' partition in the auction and it has been widely applied in the resource allocation and sharing in the heterogeneous networks [28], [29]. Overlapping coalition formation game is a special coalition game [30], in which players can join multiple coalitions rather than one as shown in [11].

To clearly present the difference between the VERACITY and the main related schemes, in Table 1, we provide a comparison in terms of multiple performance metrics. If the auction mechanism considers the corresponding metric, we mark it with "√"; otherwise, with "×".

III. SYSTEM MODEL AND PROBLEM FORMULATION

To begin with, consider a licensed communication system consisting of M spectrum owners, who are also spectrum sellers, and N secondary wireless service providers who are also spectrum buyers in a given geographic region. Denote the sellers' and buyers' set as $\Lambda = \{1, 2, \cdots M\}$ and $\Theta = \{1, 2, \cdots N\}$, respectively. In this paper, we adopt a double auction mechanism to realize the spectrum trading. We consider one round sealed-bid and collusion-free double auction. The auction participants consist of three parties: the auctioneer, spectrum owners (sellers) and secondary wireless service providers (buyers). The potential buyers can be cognitive small cell base stations (i.e. femto-cell and pico-cell), D2D communications pairs or other spectrum utilization devices. The system model is shown in Fig. 1. With the rapid development of cloud-RAN and virtualization techniques, the auction process can be implemented in the cloud center that has powerful real-time computing ability.[2] For convenience, Table II lists the key variables used in this paper.

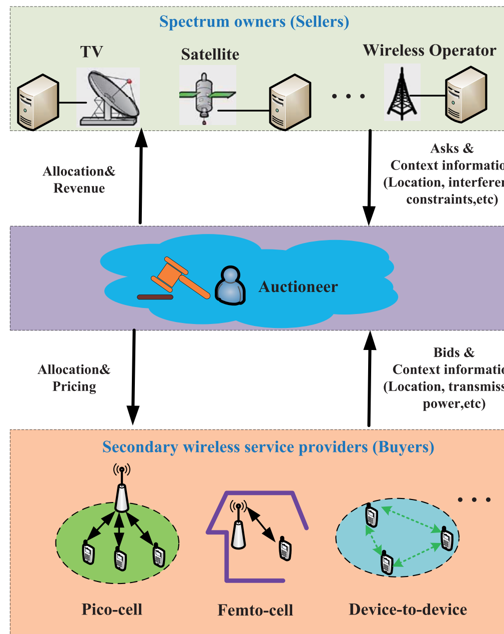


Fig. 1. System model.

Because the spectrum owners' channels[3] are not always fully utilized, they prefer to lease the idle channels to spectrum buyers for profits. Following the widely used assumption such as in [11], communication system operates in time slotted and synchronous manner, thus the spectrum auction can be implemented in every period, consisting of multiple time slots. For a given area and time period, let $K = \sum_{l=1}^{M} n_l$ denote the total available channels from spectrum owners and n_l is the number of channels provided by spectrum owner l. Furthermore, denote the spectrum owner l's available spectrum set as $\mathbf{C}_l = \left[c_{l,1}, c_{l,2}, \cdots, c_{l,n_l}\right]$ and its corresponding ask as $\mathbf{A}_l = \left[a_{l,1}, a_{l,2}, \cdots, a_{l,n_l}\right]$, implying the minimum acceptable payment for leasing spectrum, based on his true valuation profile $\mathbf{V}_l^s = \left[v_{l,1}^s, v_{l,2}^s, \cdots, v_{l,n_l}^s\right]$. Combine all sellers' asks

[2]A promising application scenario is the licensed shared access (LSA)-based system, which is advocated by European Telecommunications Standards Institute Reconfigurable Radio Systems (ETSI RRS) technical standardization committee and provides a universal platform to make secondary users opportunistically access the idle spectrum with the temporary license authorized by the incumbent spectrum holders [31].

[3]In the following, we shall use channel and spectrum interchangeably.

TABLE II
KEY VARIABLES USED IN THIS PAPER

Variables	Explanation
Λ	Sellers' set
Θ	Buyers' set
M	Number of sellers
N	Number of buyers
n_l	Number of channels provided by seller l
K	Total available channels of sellers
$a_{l,j}$	Seller l's ask for spectrum j
γ_j	The ask for spectrum j
$b_{i,j}$	Buyer i's bid for spectrum j
d_i	Buyer i's demand
$v^s_{l,j}$ ($v^b_{i,j}$)	Seller l's (buyer i's) valuation for spectrum j
$p_{i,j}$	Buyer i's payment for spectrum j
$r_{l,j}$	Seller l's revenue for spectrum j
$w^b_{i,j}$ ($w^s_{l,j}$)	Buyer i's (seller l's) winning result for spectrum j
u^b_i (u^s_l)	Buyer i's (seller$l$'s) utility
Υ	Coalition structure (coalition partition)
$\mathbf{\Pi}_j$	The j-th coalition
$\mathbf{\Pi}^{\text{active}}_j$	Active virtual buyer set of the j-th coalition
Φ_j	Coalition bid of the j-th coalition
κ	Charged ratio by the auctioneer

as $\mathbf{A}^{all} = [\mathbf{A}_1, \mathbf{A}_2, \cdots, \mathbf{A}_M] = [\gamma_1, \gamma_2, \cdots, \gamma_K]$ for notation simplicity. Furthermore, denote the inventory state of sellers' spectrum as $\mathbf{W}^s_l = \left[w^s_{l,1}, w^s_{l,2}, \cdots, w^s_{l,n_l}\right]$, where $w^s_{l,j} = 1$ represents that the channel l is sold out; otherwise, $w^s_{l,j} = 0$. We use $\mathbf{R}^s_l = \left[r^s_{l,1}, r^s_{l,2}, \cdots, r^s_{l,n_l}\right]$ to represent seller l's revenue profile.

On the buyers' side, considering the heterogeneous demand, they can report their wanted number of channels to the auctioneer. Therefore, the bid of buy i consists of the spectrum demand $d_i, 1 \le d_i \le K$, implying each buyer may ask for more than one channel, and the bid profile $\mathbf{B}_i = [b_{i,1}, b_{i,2}, \cdots, b_{i,K}], i \in [1, 2, \cdots N]$ representing the maximum prices that the buyer i is willing to pay for channels. We only consider that the buyers are truthful to report their actual demand d_i, because they cannot obtain more profit via misreporting, as shown in [22]. In this paper, we assume that the buyers can accept any g channels if $1 \le g \le d_i$, which is defined as a range request and widely used in [13] and [22]. Without loss of generality, we assume that the buyer i's demand d_i is no more than the total number of spectrum K. Different from the previous works in a complete interference small network such as in [12] and [33], i.e., all spectrum buyers are within in the interference range of each other. In our work, the spectrum can be spatially reused; that is to say, conflict-free buyers can concurrently transmit signals in the same channel to improve the spectrum utilization.

The buyer i's bids are based on his valuation for the available channels and regarded as private information. Denote the buyers' spectrum valuation profile as $\mathbf{V}^b_i = \left[v^b_{i,1}, v^b_{i,2}, \cdots, v^b_{i,K}\right]$. Without loss of generality, if the channel j is not available for buyer i, the corresponding valuation $v^b_{i,j} = 0$. After the auction process, the auctioneer will announce the spectrum' allocation and the payments for buyers. Let $\mathbf{W}^b_i = \left[w^b_{i,1}, w^b_{i,2}, \cdots, w^b_{i,K}\right]$ be the allocation profile of buyer i, where $w^b_{i,j} = 1$ means the channel j is assigned to buyer i and $w^b_{i,j} = 0$ implies the channel j is unavailable for buyer i. Moreover, define the buyer i's payment profile as $\mathbf{P}^b_i = \left[p^b_{i,1}, p^b_{i,2}, \cdots, p^b_{i,K}\right]$, where $p_{i,j} > 0$ is the charged payment for available channel j and $p_{i,j}$ is set as 0 for unavailable channel.

In the following, we present the utility functions of the players involved in the auction. To be specific, the seller l's utility is as follows:

$$u^s_l = \sum_{j=1}^{n_l} \left(r^s_{l,j} - w^s_{l,j} \times v^s_{l,j}\right), \tag{1}$$

and the buyer i's utility is as follows:

$$u^b_i = \sum_{j=1}^{K} w^b_{i,j} \times (v^b_{i,j} - p^b_{i,j}). \tag{2}$$

The auctioneer, who hosts the double auction, plays a critical role. He needs to determine the spectrum allocation scheme, containing the corresponding payment and revenue for winning buyers and sellers respectively, based on the reporting bids and asks. Motivated by the coalitional auction scheme CDAS [11], we incorporate overlapping coalition formation process in the double auction in this paper. However, in our work, different from CDAS, a buyer can simultaneously join multiple coalitions based on his actual demand rather than only one coalition.

The details of our overlapping coalition formation double auction are as follows:

1) **Initialization**: To begin with, the auctioneer collects some essential information such as the maximum available channels K, sellers' and buyers' location, all sellers' asks $\mathbf{A}_l$ and buyers' spectrum demand d_i and bids $\mathbf{B}_i$.

2) **Overlapping coalition formation**: We term the buyers who transmit in the same channel as a coalition. Thus, the maximum number of coalitions, which may include empty coalitions, is K. The auctioneer dynamically places the specific buyers into appropriate coalitions based on the buyer's demand for maximizing the defined performance metric. When the performance metric cannot be improved more, the coalition formation process terminates and the auctioneer will obtain a stable overlapping coalition partition.

3) **Spectrum allocation**: Based on the stable coalition partition, the auctioneer announces the winning buyers with the information of winning spectrum and payments. On the other hand, the sellers will get the corresponding revenue from the sold spectrum.

In the following, we first present the essential definitions related to economical properties in double auction.

Definition 1 (Truthfulness [9])): A double spectrum auction is truthful or strategy-proof if any involved seller or buyer cannot improve his utility via misreporting his ask/bid, i.e., the ask or bid is larger than or lower than his true valuation on spectrum, to the auctioneer.

According to the definition 1, we can observe that the truthful strategy, submitting the ask/bid equal to the true valuation on spectrum, is a *weakly dominant* strategy for any seller and buyer in a truthful double auction.

Definition 2 (Individual Rationality): A double spectrum auction satisfies the individual rationality if the winning buyers will pay no more than their bids and the winning sellers will obtain the corresponding revenue no less than asks.

The definition 2 guarantees that any player involved in the auction can obtain a non-negative utility.

Definition 3 (Budget-Balance): A double spectrum auction is budget-balanced if the total payment charged from buyers is no less than the revenue paid to the sellers.

Budget-balanced property ensures the auctioneer will not lose money in the auction and has the incentive to implement the auction process.

Definition 4 (Economical Efficiency)[4]: A double auction is economical efficiency if the auctioneer can *approximately* maximize the revenue from the winning buyer groups (coalitions).

IV. Practical Challenges in Auction Design

A. Universally Heterogeneous Interference Graph

Spectrum reuse can drastically improve the spectrum efficiency. In spectrum auction, how to appropriately pick the multiple non-conflicting buyers to one channel is not an easy task for auctioneer. Previous works, such as in [9] and [11], investigated the spectrum reuse in auction, however, they assumed the interference relationship among buyers is homogeneous, i.e., a buyer's potentially conflicting neighbors are generally determined by the physical distance without considering the influence of spectrum's properties. This assumption seems to be impractical in the real-world communication system, because that different spectrum owns its own frequency properties, such as the transmission range, coverage and path loss which is related to the central frequency. That is to say, the interference graph of each channel may be distinct because of the heterogeneous spectrum.

Accordingly, heterogeneous spectrum reusability brings new challenges to the spectrum auction. Recently, the TAHES considered the impact of heterogeneous spectrum and introduced heterogeneous conflict graph (interference graph) to model the interference relationship among buyers [21]. In the following, we shall use interchangeably interference graph and conflict graph. In this paper, we consider a more general interference model introduced by [32] to capture the asymmetric interference relationship among the buyers due to the buyers' heterogeneous transmission powers and locations.

To describe the asymmetric interference relationship among buyers, for a given channel, we adopt generic interference graph consisting of a mixture of directed and undirected edges. Let $G_i = \{V_i, E_i\}$ be the interference graph of channel $i, i \in [1, 2, \cdots, K]$. Each node in the conflict graph represents a buyer and there exists an interference edge between two nodes if the corresponding buyers interfere. The interference edge in the interference graph can be directed or undirected. If an interference edge is directed from buyer i to buyer j, then buyer j's data transmission will be affected by buyer i's co-channel transmission, but buyer i will not be affected by buyer j. If the interference edge is undirected between buyer i and buyer j, then the two buyers can affect each other. Denote the set of neighboring buyers that can cause interference to buyer i on the channel l as $\mathrm{N}_i^l = \{j : (j, i) \in E_l, j \in V_l\}$. Fig. 2 shows a simple example for heterogeneous interference graph with asymmetric interference. For spectrum 1, buyer a is only affected by buyer e if they simultaneously transmit in this channel. Meanwhile, buyer b is affected by buyer a while buyer a is not affected by buyer b when co-channel transmission occurs in spectrum 1. Note that the interference relationship changes in spectrum 2. For instance, buyer a's neighbor is e in the interference graph of spectrum 1, while buyer b is the only one neighbor of buyer a in the interference graph of spectrum 2. The auctioneer can obtain the information of the heterogeneous interference graph based on the context information of both buyers and sellers in the auction's initialization stage.

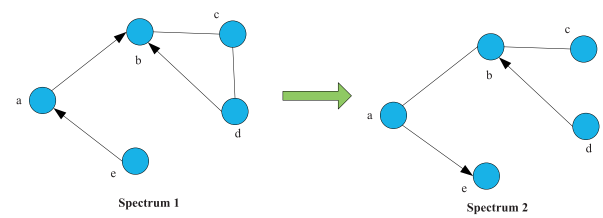


Fig. 2. Heterogeneous interference graph with asymmetric interference.

B. Heterogeneous Buyer's Demand

Different form the most of the existing studies based on the either single-demand auction or homogeneous multi-demand auction, the multi-demand buyers with different spectrum preference make the group formation process more complex. Note that the buyer's spectrum preference is based on the spectrum valuation and reflected by his bid. As pointed out in [22], simply replacing a multi-demand buyer by multiple single-demand virtual buyers may lead to bid manipulation for higher profit. To avoid the collusion and bid manipulation in the auction, similar to TAMES, we generate multiple single-demand brokers for an original multi-demand buyer and each single-demand virtual broker inherits the original buyer's bid profile and heterogeneous interference relationship. Any two virtual brokers cannot be put into the same channel.

V. VERACITY Auction Mechanism

In this part, we will present the details of our proposed VERACITY. The main idea of VERACITY is that a buyer can join multiple coalitions based on the number of his wanted channels (demand); then, the auctioneer can execute a virtual overlapping coalition formation process to find a stable coalition partition to implement the auction. As mentioned before, we generate multiple single-demand virtual buyers to replace one original multi-demand buyer and the virtual buyers have to be separated into different channels. Specifically, we generate one virtual buyer to represent single-demand original buyer.

[4]In our paper, the concept of economical efficiency is approximately maximizing the efficiency. Sine the Impossible Theorem [34] pointed out that no double auction can achieve three properties, containning truthfulness, individual rationality and budget-balance, and maximize auction efficiency simultaneously.

A. Bid of Coalition and Payment

We first give some essential concepts and definitions as follows:

Definition 5 (Coalition): In VERACITY, a coalition Π_k is termed as a set of buyers assigned to the same channel k.

Definition 6 (Coalition Structure)[5]*:* Coalition structure $\Upsilon = \{\Pi_1, \Pi_2, \cdots, \Pi_K\}$ is defined as the overlapping partition/distribution of buyers among all available channels.

Given a coalition structure $\Upsilon = \{\Pi_1, \Pi_2, \cdots, \Pi_K\}$, define the non-empty coalition Π_j's bid as:

$$\Phi_j = \min_{l \in \Pi_j} b_{l,j} \times (|\Pi_j^{\text{active}}| - 1), \tag{3}$$

where Π_j^{active} is the "active" virtual buyers' set in Π_j, obviously, $\Pi_j^{\text{active}} \subseteq \Pi_j$. The operation $|\cdot|$ denotes the cardinality of a set. $\min_{l \in \Pi_j} b_{l,j}$ is the lowest bid of the active buyer set. The design idea of (3) is similar to [14] and [22] and note that coalition bid is independent of winning virtual buyers. This definition of coalition bid may sacrifice some performance to a certain extent, but it can guarantee the truthfulness of the auction, which will be proved in Section VI.

Note that we emphasize the "active" virtual buyers, because there may exist "dummy" virtual buyers, who make no contribution to coalition bid. Therefore, we only care about the active members. In the following subsection, we will explain how to determine the state ("active" or "dummy") of a virtual buyer in a given coalition.

If coalition Π_j can win in the auction, it must satisfy the following inequality:

$$(1-\kappa)\Phi_j \geq \gamma_j, \, j \in \mathbf{C}_l, \tag{4}$$

where channel j is owned by seller l and recall that γ_j is the corresponding seller's ask for channel j. κ is the ratio charged by the auctioneer to host auction and $\kappa\Phi_j$ is the auctioneer's profit from channel j. Specially, if $\kappa = 0$, that means the auctioneer is not profit-driven, for instance, government bodies.

Accordingly, the payment of coalition Π_j is

$$P_{\Pi_j} = \begin{cases} \Phi_j, & (1-\kappa)\Phi_j \geq \gamma_j, \, j \in \mathbf{C}_l, \\ 0, & \text{otherwise.} \end{cases} \tag{5}$$

If $(1-\kappa)\Phi_j \geq \gamma_j$, then, the active buyers can get this channel except the lowest bid one. This principle can guarantee that each buyer truthfully submits his bid. If there are multiple active buyers that have the lowest bid, auctioneer can randomly pick one as the "loser".

Therefore, the payment of virtual buyer i in coalition Π_j can be obtained as:

$$p_{i,j}^b = \begin{cases} \dfrac{P_{\Pi_j}}{|\Pi_j^{\text{active}}| - 1}, & i \in \Pi_j^{\text{active}} \text{ and } i \text{ is not loser}, \\ 0, & i \text{ is defined as loser in active buyer set}, \\ 0, & i \notin \Pi_j^{\text{active}}, i \in \Pi_j. \end{cases} \tag{6}$$

This implies that active virtual buyers in the winning coalition Π_j are charged with a uniform price except the lowest one. The "loser" in the active buyer set and dummy members are charged with 0 since they can not access this channel.

Henceforth, the utility of virtual buyer i in a winning coalition Π_j can be calculated as:

$$u_{i,j}^b = \begin{cases} v_{i,j}^b - \dfrac{P_{\Pi_j}}{|\Pi_j^{\text{active}}| - 1}, & i \in \Pi_j^{\text{active}}, \text{ and } i \text{ is not loser}, \\ 0, & i \text{ is defined as loser in active buyer set}, \\ 0, & i \notin \Pi_j^{\text{active}}, i \in \Pi_j. \end{cases} \tag{7}$$

If the virtual buyer i is not a member of winning coalition Π_j, he has no chance to obtain payoff, hence, $u_{i,j}^b = 0, i \notin \Pi_j$.

Summing up all the virtual buyers' utilities of original buyer i, we can obtain buyer i's utility as:

$$u_i^b = \sum_{j=1}^{K} u_{i,j}^b, i \in \Theta. \tag{8}$$

For a truthful double auction, in (7), $v_{i,j}^b$ is equal to $b_{i,j}$ and we will prove that VERACITY is truthful in Section VI.

B. Optimization Problem

To make auction more economical efficiency, we expect that the auction results can not only improve the spectrum utilization but also maximize certain economic performance metrics such as the *social welfare*, *satisfactory*, *fairness* and so on. In this paper, we pursue the maximization of the social welfare, which is defined as the summation of winning coalitions' bids as[6]:

$$\mathbf{WF} = \sum\nolimits_j \Phi_j I\left((1-\kappa)\Phi_j - \gamma_j\right), \tag{9}$$

where $I(\cdot)$ is an indicator function defined as follows:

$$I\left((1-\kappa)\Phi_j - \gamma_j\right) = \begin{cases} 1; & (1-\kappa)\Phi_j \geq \gamma_j \\ 0; & \text{otherwise.} \end{cases} \tag{10}$$

The auctioneer is searching for an optimal coalition partition $\Upsilon^* = \left\{\Pi_1^*, \Pi_2^*, \cdots, \Pi_K^*\right\}$, also termed as the concept of core in the collation game theory [26], to achieve maximizing the defined optimization problem:

$$(\text{OP1}) : \Upsilon^* = \arg\max \mathbf{WF}. \tag{11}$$

Remark: Solving this problem by exhaustive search is an inefficient solution. Generally, finding the optimal coalition structure by exhaustive search is NP-hard [11]. Thus, we resort to the coalition game theory to find a suboptimal outcome with a relatively low computational complexity. On the other hand, VERACITY can be flexible to accommodate with different optimization goals; that is to say, we can change the detailed structure of **WF** based on the actual requirements.

[5]In the following, we shall use interchangeably coalition structure and coalition partition.

[6]Generally, the social welfare is defined as the sum value of all winning buyers in traditional auction scenario. In VERACITY, the winning coalition can be viewed as a super-buyer and the coalition's bid is defined in (3). Hence, the social welfare in this paper is defined as the summation of super-buyers' (coalitions') bids.

C. Determination of the Virtual Buyers' State

Given an original buyer i, auctioneer creates d_i virtual buyers (or termed as virtual brokers) set as $\mathrm{VB} = \left[\mathrm{vb}_i^1, \mathrm{vb}_i^2, \cdots, \mathrm{vb}_i^{d_i}\right]$, where vb_i^l denotes the l-th virtual buyer. As mentioned previously, recall that virtual buyers are dispersed among channels and any two virtual brokers are not allowed to place in the same channel. Henceforth, there are $\mathrm{C}_{K_i}^{\min[d_i, K_i]}$ available placement schemes for original buyer i, where K_i is the available number of channels and $K_i \leq K$.[7] $\min[d_i, K_i]$ means the practical number of virtual buyers for the original buyer i.[8] Furthermore, the virtual buyer inherits the characteristics from the original one in the corresponding channel.

For each virtual buyer, his state can be classified into two states: "active" or "dummy". We introduce the state index $F_{i,j}^l$ to reflect the current state of the l-th virtual buyer of original buyer i in coalition Π_j as follows

$$F_{i,j}^l = \begin{cases} 1; & \text{active}, \\ 0; & \text{dummy}. \end{cases} \tag{12}$$

The "active" state means this virtual buyer is a member in the active buyer set, while that "active" state can not guarantee the winning result of that channel. On the other hand, if virtual buyer's state is "dummy", no matter whether the belonging coalition wins or loses in the auction, he loses the auction for this channel.

Given a coalition, the auctioneer needs to utilize the conflict graph to determine the interference relationship among virtual buyers. Then, based on the bids of the virtual buyers, he picks up no interference members, whose bids maximize coalition bid, from available maximum independent sets (MISs), and then makes their state index be 1 ("active"), others' state are set as 0 ("dummy"). If there are multiple MISs with equal and maximum coalition bid, the auctioneer chooses one maximum independent set following the picking rule.

We first present a picking algorithm in Algorithm 1 to select a MIS from any two MISs. Certainly, the auctioneer can easily find the optimal MIS among multiple MISs by Algorithm 1.

Definition 7 (Picking Rule): Given available MISs, the finally selected MIS is determined by the picking algorithm shown in Algorithm 1.

Next, given a channel, we present a simple example to show the "active" buyer determination process in Fig. 3. In Fig. 3, there are 8 virtual buyers. Since an auctioneer only cares about whether the original buyer's virtual broker is located in the given channel, we omit the index of the virtual buyer for clear presentation, i.e., vb_1 is the virtual broker 1 belonging to buyer 1. We can see that there are three MISs yielding the same maximum coalition bid 8. By applying the picking rule, the auctioneer finally selects the MIS $\{\mathrm{vb}_2, \mathrm{vb}_6, \mathrm{vb}_8\}$.

[7]Since the specific buyer may be out of some spectrum seller's licensed coverage, he will be informed by auctioneer that theses channels are not available for him. Hence, the aucually available number of channels K_i satisies $K_i \leq K$.

[8]If demand d_i exceeds the currently available number of channels K_i for buyer i, then, the auctioneer will remove $d_i - K_i$ virtual buyers out of the auction.

Algorithm 1 Picking Algorithm

1. Given bidding profiles of any two maximum independent set MIS_1 and MIS_2 as B_1 and B_2, respectively.
2. Sort the bids in the MISs in decreasing order as $\mathrm{B}_1 = [b_1^1, b_2^1, \cdots b_L^1]$ and $\mathrm{B}_2 = \left[b_2^2, b_2^2, \cdots b_L^2\right]$. i.e., $b_1^1 \geq b_2^1 \geq \cdots \geq b_L^1$, where L is the size of MIS.
3. Set Flag=2; and $l = L$.
4. **While** Flag>1 and $l > 1$ **do**
5. **if** $b_l^1 > b_l^2$
6. Flag=1; Auctioneer chooses the MIS_1, **Break**;
7. **end**
8. **if** $b_l^1 < b_l^2$
9. Flag=0; Auctioneer chooses the MIS_2, **Break**;
10. **end**
11. **if** $b_l^1 = b_l^2$
12. Flag=2;
13. **end**
14. $l = l - 1$;
15. **End While**
16. **if** Flag=2;
17. Randomly select between MIS_1 and MIS_2;
18. **end**

D. Coalition Operations

In the following, we first give a switching rule definition as follows:

Definition 8 (Switching Rule): Given any two coalition partitions $\Upsilon^1 = \left\{\Pi_1^1, \Pi_2^1, \cdots, \Pi_K^1\right\}$ and $\Upsilon^2 = \left\{\Pi_1^2, \Pi_2^2, \cdots, \Pi_K^2\right\}$, the auctioneer prefers to choose Υ^1 if and only if the following condition satisfies:

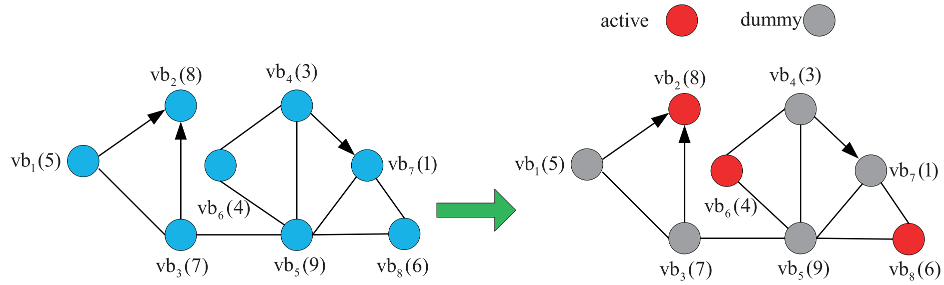
$$\Upsilon^1 \rhd \Upsilon^2 \Leftrightarrow \mathbf{WF}^1 > \mathbf{WF}^2, \tag{13}$$

where the operation $\rhd$ indicates *Pareto improvement* from the perspective of social welfare. $\mathbf{WF}^1$ and $\mathbf{WF}^2$ are the social welfare for coalition partition Υ^1 and Υ^2, respectively.

The auction dynamically changes the coalition partition of buyers to pursue larger social welfare. In classical coalition, there are three simple operations to change the partition: joining, leaving and switching.

- **Joining operation**: a single-member coalition $\Pi_1 = \{i\}$ merges with another coalition Π_2 to a bigger coalition $\Pi_3 = \{\Pi_2, i\}$.
- **Leaving operation**: a coalitional member i leaves the current coalition Π_1 and forms a singleton coalition $\Pi_2 = \{i\}$. The original coalition Π_1 is updated as $\Pi_1 = \{\Pi_1/i\}$. The leaving operation is the opposite of the joining operation.
- **Switching operation**: a coalitional member i leaves the current coalition Π_1 and joins another Π_2. Thus, the original coalitions Π_1 and Π_2 are updated as $\Pi_1 = \{\Pi_1/i\}$and $\Pi_2 = \{\Pi_2 \cup i\}$, respectively.

From the implementation process of both the joining and leaving operations, they can be viewed as special switching operations. For classical coalition formation, the coalitional numbers may change. But, in our proposed auction scheme, the maximum coalitional numbers is fixed as K. Fig. 4 shows the illustration of the overlapping coalition of spectrum buyers.



Available active buyer set	Coalition bid	Win/Lose
$\{vb_1, vb_6, vb_7\}$	2	Lose
$\{vb_1, vb_6, vb_8\}$	8	Lose
$\{vb_2, vb_6, vb_7\}$	2	Lose
$\{vb_2, vb_6, vb_8\}$	8	Win
$\{vb_3, vb_6, vb_8\}$	8	Lose

Fig. 3. A simple example to determine the active buyers in a coalition. There are 8 virtual buyers in that coalition (channel). For a specific vb$_i$(B_i) marked in this figure, where i and B_i denote the buyer' index and bidding price, respectively. The size of MIS is 3 and the partially available coalition bids of these MISs are listed.

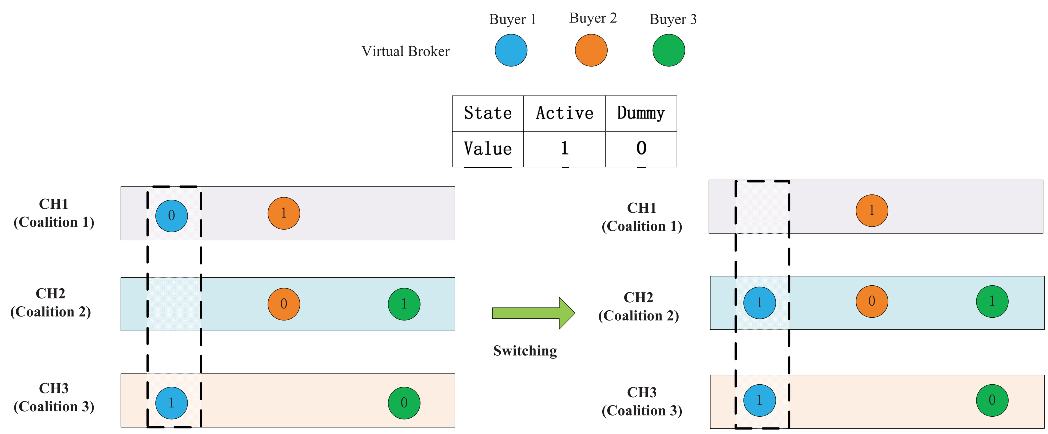


Fig. 4. Illustration of buyers' overlapping coalition formation (the auctioneer moves one virtual buyer of original Buyer 1 from CH1 to CH2, then we can observe that some virtual buyers' states change).

E. Implementation Process of VERACITY

In this subsection, we present of the details of VERACITY in Algorithm 2. In steps 7 and 8, we can resort to powerful computational capacity of the cloud center to obtain the optimal placement. In the limited computational resource scenario for large $\mathrm{C}_{K_i}^{\min[d_i,K_i]}$, we make small changes for the corresponding steps 7 and 8 in Algorithm 2. To be specific, we only calculate the random t_i replacements of $\mathrm{C}_{K_i}^{\min[d_i,K_i]}$ (obviously, $t_i < \mathrm{C}_{K_i}^{\min[d_i,K_i]}$) and switch to the optimal replacement for buyer i among t_i replacements, where t_i is predefined and determined by the system computational capacity. Note that we just need to guarantee the *Pareto improvement* of each switching operation.

F. Revisit the VERACITY From the Perspective of Learning Theory

In the following, we revisit the proposed VERACITY from the perspective of learning theory. Note that VERACITY can be viewed as a centralized-distributed channel selection game. To be specific, each virtual buyer is a smart agent, or termed as a player in game, which has the learning ability to adjust its action. For all agents, their optimization goals, i.e. utility functions, are identical as $U_i(a_i, a_{-i}) = \mathbf{WF}$ and each agent i has finite action set $\mathbf{A}_i$, where each action $a_i \in \mathbf{A}_i$ in it is one of the $\mathrm{C}_{K_i}^{\min[d_i,K_i]}$ available virtual buyer placement schemes, hence that game model falls into the category of exact potential games (EPG)[9] and the potential function is the global objective **WF** defined in (9). Every EPG admits at least one pure strategy Nash equilibrium (PNE) [35]. A PNE denotes a stable overlapping coalition structure in VERACITY for maximizing the potential function.

[9] A game is an exact potential game (EPG) if there exists an exact potential function $\phi : \mathbf{A}_1 \times \mathbf{A}_2 \times \cdots \mathbf{A}_N \to R$. Given any player i, $i \in \Theta$, and any selected two actions a_i and $\overline{a}_i$, $a_i, \overline{a}_i \in \mathbf{A}_i$, the following holds [35]:

$$U_i(a_i, a_{-i}) - U_i(\overline{a}, a_{-i}) = \phi(a_i, a_{-i}) - \phi(\overline{a}, a_{-i}). \quad (14)$$

Algorithm 2 Implement Process of VERACITY

Initialization

1. Spectrum buyers submit their bids, containing wanted channel number and bidding profile, and corresponding context information including location, coverage etc, to auctioneer. And the spectrum sellers send their ask and context information to auctioneer.
2. The auctioneer generates the potential conflict graph based on the collected information.
3. The auctioneer generates d_i virtual buyers for buyer i and randomly distribute them among various channels.
4. Implement the Step 3 for all buyers and obtain an initial coalition structure $\Upsilon^t = \left\{\Pi_1^t, \Pi_2^t, \cdots, \Pi_K^t\right\}$ and the corresponding active buyer sets. Set $t = 0$.

Overlapping Coalition Formation

5. **for** num=1:T **do**
6.   **for** i=1:N
7.   Calculate the available social welfare of the residual $C_{K_i}^{\min[d_i, K_i]}-1$ placements for virtual buyers of buyer i.
8.   Switch to the optimal placement for buyer i for maximize the social welfare and update Υ^t, $t = t + 1$.
9.   **end**
10. **end**

Broadcast the results of auction

11. Obtain the final coalition structure Υ^*, the auctioneer announces the allocation of channels for both sellers and buyers.

In VERACITY, each agent always selects the best strategy at each step, that action updating process is termed as the asynchronous/sequential best response dynamic (ABRD) [36]. The similar idea of best strategy selection also can be found in [37] for tree network formation. We will show the convergence of the ABRD in the next section.

VI. Economic Properties

In this section, we prove the proposed VERACITY is *individually rational*, *ex-post budget balanced*, *truthful* and *economically efficient*.

Lemma 1: VERACITY is individually rational.

Proof: The proof is intuitive. From the perspective of buyer's utility, the winning buyer's payment is not larger than his bid, which guarantees that buyers can obtain a non-negative utility. On the other hand, the winning sellers' revenue from the winning coalition is not less than their ask. Therefore, the proposed VERACITY is individually rational. ■

Lemma 2: VERACITY is ex-post budget balanced.

Proof: It is straightforward to prove that VERACITY is ex-post budget balanced. Because if $(1-\kappa)\Phi_j \geq \gamma_j$ is satisfied, then the channel j is sold and then auctioneer obtains a non-negative utility $\kappa\Phi_j$ from that channel. Combining with Lemma 1, three parties involved in auction can obtain non-negative utility, implying that the VERACITY is ex-post budget balanced. ■

Lemma 3: Buyer's untruthful bidding for one channel has no impact on spectrum allocation results of other channels.

Proof: The dynamic overlapping coalition formation is virtually implemented by auctioneer and no buyer can control it. When the coalition formation converges to a stable state, the winning result of each coalition and the states of players are determined. The winning result of one channel relies on the coalition bid, which is related to the active buyer set in this coalition and independent of the buyers' bids for other channels. Therefore, buyer's untruthful bidding for one channel has no impact on spectrum allocation results of the other channels. That completes the proof. ■

Lemma 4: To report the true valuation is (*weakly*) dominant strategy for buyers, i.e., a buyer cannot misreport the bidding price for one channel to increase his utility gain from that channel.

Proof: Take buyer i's bidding as an example. When buyer i bids truthfully, i.e., $b_{i,j} = v_{i,j}^b$, the winning result is $w_{i,j}^b$ and the utility is $u_{i,j}^b$. On the other hand, if i misreports with untruthful bid, the corresponding winning result and the obtained utility are $w_{i,j}^{b'}$ and $u_{i,j}^{b'}$, respectively. We will prove that $u_{i,j}^b \geq u_{i,j}^{b'}$ always holds.

We discuss two cases if $b_{i,j} \neq v_{i,j}$ in the following:

(1) For $w_{i,j}^b = 0$, there are four possible scenarios as follows:

(i) Buyer i is active and his bid is not the lowest in the active buyer set, but the coalition bid is less than the seller's ask. No matter whether buyer i increases or decreases his bid, the coalition loses in auction. Hence, we can obtain $w_{i,j}^{b'} = 0$ and $u_{i,j}^b = u_{i,j}^{b'} = 0$.

(ii) Buyer i is active but his bid is the lowest among the active buyer set. Assuming that the coalition becomes the winner and the payment is determined by buyer i's bid, i.e., $p_{i,j}^b = b_{i,j}$. If he increases his bid as $b_{i,j} > v_{i,j}^b$, the active buyer set does not change, and the payment $p_{i,j}^{b'}$ is a non-decreasing function of $b_{i,j}$; therefore, $u_{i,j}^{b'} \leq 0$. On the other hand, if he decreases his bid as $b_{i,j} < v_{i,j}^b$, the analysis will be more complex and we will discuss it in the following.

- The original active buyer set does not change and buyer i's bid is the lowest, therefore, $u_{i,j}^{b'} = 0$.
- The active buyer set changes and buyer i is not its member, therefore, $u_{i,j}^{b'} = 0$. Specially, there is no active buyer set in that coalition and active buyer set is an empty set.
- The active buyer set changes and buyer i is its member. We prove that this event will not happen in the following. Recall that the coalition bid is $\Phi_j = \min_{i \in \Pi_j} b_{i,j} \times (|\Pi_j^{\text{active}}| - 1)$, $|\Pi_j^{\text{active}}|$ is equal to the size of the maximum independent set. For notational convenience, denote $S_{\max}$ as the size of the maximum independent set. For a given coalition, $S_{\max}$ is fixed, thus, the coalition bid is determined by the lowest bid in the active buyer set. Without loss of generality, denote the Π_j^1 and Π_j^2, both of them contain buyer i, as the former active buyer set and current active buyer set with the decrease of buyer i's bid, respectively. Let $b_{\min}^1 (b_{\min}^2)$ be the minimum bid in Π_j^1 (Π_j^2) when buyer i is truthful. Let $\Phi^1 = b_{\min}^1 \times (S_{\max} - 1)$ and $\Phi^2 = b_{\min}^2 \times (S_{\max} - 1)$ be the

potential coalition bid related to Π_j^1 and Π_j^2, respectively. If $\Phi^1 = \Phi^2$, that means $v_{i,j}^b = b_{i,j} = b_{\min}^1 = b_{\min}^2$. Φ^1 is always chosen as active buyer set based on the *picking rule* by the auctioneer. In this scenario, buyer i untruthfully submits a smaller bid, and can not make Φ^2 be selected. Therefore, we only focus on $\Phi^1 > \Phi^2$, implying that the following holds:

$$\Phi^1 > \Phi^2 \to v_{i,j}^b = b_{i,j} = b_{\min}^1 > b_{\min}^2.$$

Assuming that buyer i is untruthful and submits a smaller bid, i.e., $b_{i,j} < v_{i,j}^b$, let $\Phi^{1'}$ and $\Phi^{2'}$ be the potential coalition bid related to Π_j^1 and Π_j^2, respectively, where $b_{\min}^{1'}$($b_{\min}^{2'}$) is the minimum bid in Π_j^1 (Π_j^2).
If $b_{\min}^2 < b_{i,j} < v_{i,j}^b$, then $\Phi^{1'} > \Phi^{2'}$ always holds; that is to say, Π_j^1 is still the active buyer set.
Furthermore, if $b_{i,j} < b_{\min}^2 < b_{\min}^1$, then, $b_{\min}^{1'} = b_{\min}^{2'} = b_{i,j}$ and we can get $\Phi^{2'} = \Phi^{1'}$. In this scenario, the auctioneer will choose the active buyer set based on the *picking rule*. Note that $b_{\min}^2$ becomes the second lowest bid in Π_j^2 when buyer i submits a smaller bid and the second lowest bid of Π_j^1 is larger than $b_{\min}^2$. Therefore, the active buyer set is still Π_j^1.
Hence, as previously mentioned, this event will not occur.

(iii) Buyer i's state is dummy. It implies that buyer i is not included in the active buyer set; that is, any available coalition bid of the maximum independent set, containing buyer i, is less than the coalition bid of the current active buyer set. If buyer i is untruthful and submits a smaller bid, i.e., $b_{i,j} < v_{i,j}^b$, available coalition bids of all maximum independent sets related to buyer i's do not increase. Therefore, buyer i's state is still dummy. On the other hand, if buyer i is untruthful and submits a larger bid, i.e., $b_{i,j} > v_{i,j}^b$, we can discuss the following two scenarios:

- Buyer i's bid is not the lowest in the maximum independent set. Even though buyer i increases his bid, the potential coalition bid of the maximum independent set including buyer i remains unchanged.
- Buyer i's bid is the lowest in the maximum independent set. If buyer i's bid is still the minimum in that maximum independent set, no matter that maximum independent set is active or inactive, buyer i loses in the auction in current coalition. If buyer i's bid is not the lowest bid in that maximum independent set and the state of the that maximum independent set becomes active, the buyer i will obtain a negative utility because the payment is larger than his true valuation $v_{i,j}^b$.

(iv) Buyer i's virtual broker is not a member of current coalition. Untruthful bidding can not help the buyer i to win in the current coalition based on Lemma 3.

(2) For $w_{i,j}^b = 1$, that implies the buyer i is in the winning coalition and his state is active. If buyer i is untruthful, there are two possible scenarios: (i) $b_{i,j} > v_{i,j}^b$ and (ii) $b_{i,j} < v_{i,j}^b$ as follows:

(i) For $b_{i,j} > v_{i,j}^b$, the active buyer set does not change. Since the buyer i's payment $p_{i,j}^b$ is determined by the minimum bid of the active buyer set in coalition j, which is lower than the buyer i's bid due to $w_{i,j}^b = 1$. Thus, we can easily obtain $w_{i,j}^{b'} = 1$ and $p_{i,j}^{b'} = p_{i,j}^b$. Accordingly, $u_{i,j}^b = u_{i,j}^{b'} = v_{i,j}^b - p_{i,j}^b$.

(ii) For $b_{i,j} < v_{i,j}^b$, if $b_{i,j}$ is larger than the minimum bid of the active buyer set, similar to the previous analysis, the payment $p_{i,j}^b$ is independent of $b_{i,j}$; then, the active buyer set does not change and $u_{i,j}^b = u_{i,j}^{b'} = v_{i,j}^b - p_{i,j}^b$. On the other hand, if $b_{i,j}$ is less than the minimum bid of the original active buyer set, we need to analyze the following scenarios:

- The active buyer set does not change. While buyer i's bid is the lowest, therefore, $u_{i,j}^{b'} = 0$.
- The active buyer set changes and buyer i is not in it, therefore, $u_{i,j}^{b'} = 0$.
- The active buyer set changes and buyer i is still in it. That event will not occur in VERACITY, the proof is similar to previous analysis.

In summary, buyer i has no incentive to be untruthful and submits a truthful bid as a (*weakly*) dominant strategy, which completes the proof. ■

Lemma 5: A seller cannot misreport his ask for one channel to increase his utility gain from that channel.

Proof: The proof this part is similar to the Lemma 3 in TAMES [22], so we omit it for brevity. ■

Theorem 1: VERACITY is truthful.

Proof: Based on Lemma 4 and Lemma 5, we can easily conclude that VERACITY is a truthful double auction on both buyers' and sellers' side. That completes the proof. ■

Theorem 2: The overlapping coalition formation process in proposed VERACITY converges to a stable coalition partition in finite steps.

Proof: Given the number of buyers and sellers, the total number of possible coalitional structures with overlapping coalitions is finite. In the implementation process of VERACITY, only the switching rule is satisfied and then auctioneer reallocates the virtual buyers for a given buyer. After that switching operation, the auctioneer obtains a new coalitional structure with higher social welfare than the old one. The Pareto improvement of the switching operations can guarantee that the previously appeared coalitional structure will not be formed in the future. Therefore, the convergence of the overlapping coalition formation process in VERACITY can be guaranteed.

Next, we prove that the final coalitional structure of VERACITY is a stable coalitional structure. Assume that the final coalitional structure Υ^* is not stable. That implies that there exists another coalitional structure that yields higher social welfare by reallocating the buyer i's virtual brokers among channels. Hence, the switch rule is satisfied and the new coalitional structure can be formed, which contradicts with the fact that Υ^* is the final coalitional structure. Thus, the final coalitional structure Υ^* is stable. That completes the proof. ■

Recall that the overlapping coalition formation process in VERACITY can be viewed as ABRD for each buyer from the perspective of learning theory. Therefore, we can present the convergence of VERACITY in another manner as follows:

Lemma 6 [36]: For a potential game, the ABRD converges with probability one to a PNE.

Based on the Lemma 6, we can conclude that the VERACITY can converge to the PNE which is the stable overlapping coalition structure in the sense of coalition game theory.

Lemma 7: VERACITY satisfies the property of economic efficiency.

Proof: Because the overlapping coalition formation converges to a stable coalition structure, which can yield a suboptimal partition of buyers for maximizing the defined social welfare. Hence, VERACITY satisfies the property of economical efficiency. That completes the proof. ■

VII. Numerical Results

A. Simulation Settings

In this section, simulations are conducted to evaluate the performance of the proposed VERACITY. Consider that spectrum sellers and buyers are randomly distributed within 1×1 area, which is similar to [22]. We define the number of contributed channels of each seller and the the number of wanted channels of each buyer are random integer values following the uniform distribution over $[1, 2]$ and $[1, 3]$, respectively. Furthermore, each buyer's bid for an available channel and seller's ask are defined as uniform distribution over $[0, 1]$. From the perspective of the buyer's spectrum availability, if the the distance between the target buyer and seller is less than 0.5 unit, this seller's channles are available for the target buyer. To construct the heterogeneous interference relationship, we set the interference distance of the channel k as $0.1 + (k - 1) \times 0.2/(K - 1)$, implying the minimum and maximum interference distance are 0.1 and 0.3 unit, respectively, with k.

In the following, we will compare the proposed VERACITY with following auction mechanisms:

1) TAMES [22]. TAMES jointly considers the multi-demand and heterogeneous spectrum.
2) Random scheme; in which the auctioneer randomly distributes the buyers among the spectrum and then determines the final winning buyers as the same as VERACITY.

All the simulation results are averaged over 1000 times independent Monte Carlo simulations.

B. Convergence and the Impact of the κ

We present a simple case to show the convergence performance and the impact of κ of the proposed VERACITY in Fig. 5, in which we set $M = 5$ and $N = 15$. For $\kappa = 0$, implying the auctioneer is not a profit-oriented body, we can observe that VERACITY approaches to a stable coalition partition within 30 iterations and the final social welfare is much higher than TAMES. On the other hand, for a profit-oriented auctioneer with $\kappa > 0$, with the increasing of κ, we can find that the achieved social welfare decreases. Because the charged ratio κ by the auctioneer is too high, then the winning condition $(1 - \kappa)\Phi_j \geq \gamma_j$ for channel j is hard to satisfy. In the following, we set $\kappa = 0$ in our proposed VERACITY for fair comparison with TAMES. In Fig. 6, we show the spectrum allocation for winning buyers in VERACITY. The blue dots imply the spectrum (channels) owned by buyers and we plot a line between two dots if adjacent channels are allocated to the same buyer.

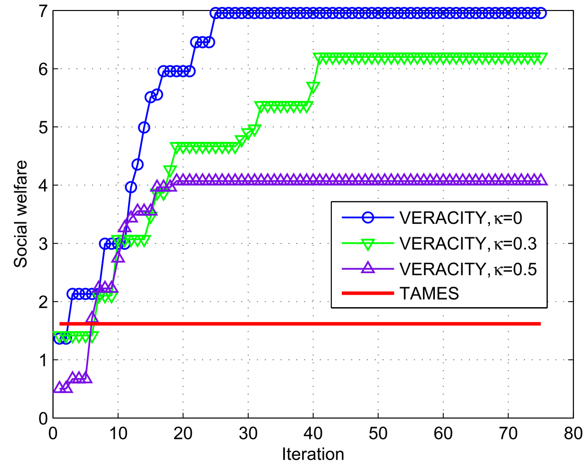


Fig. 5. Convergence of the proposed VERACITY and the impact of κ.

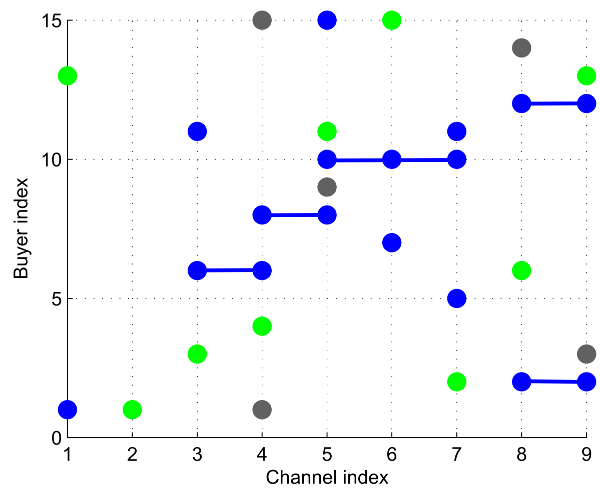


Fig. 6. Spectrum allocation result of the proposed VERACITY, where blue dot means that virtual buyer wins this spectrum, green dot implies the virtual buyer's state is "active" while his bid is the lowest in the active buyer set, and gray dot means the virtual buyer's state is "dummy".

To satisfy the buyer's heterogeneous demand, the auctioneer permits that multi-demand buyer can access multi-channel simultaneously. From the perspective of coalition formation, we view the set of buyers in the same channel as a coalition and multi-demand buyer (player) can join multiple coalition. For instance, in Fig. 6, buyer_10 is assigned 3 channels by auctioneer, implying that he is the co-active-member of coalition_5 (channel_5), coalition_6 (channel_6) and coalition_7 (channel_7). Note that the channels are only allocated to the winning buyers; that is, although a buyer's virtual broker is in that coalition, his state is "dummy" (marked with gray dot) or "active" with the lowest bid (marked with green dot) in the active buyer set, leading to losing the auction in that channel.

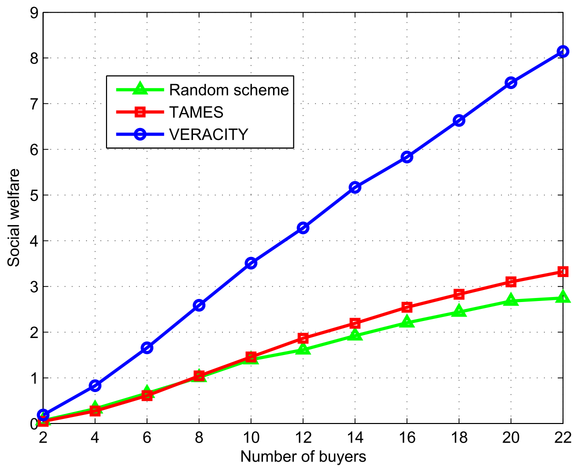


Fig. 7. Social welfare versus the number of buyers.

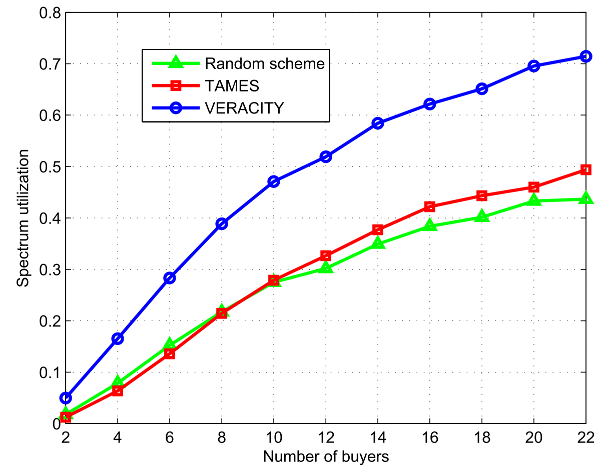


Fig. 8. Spectrum utilization versus the number of buyers.

C. Impact of the Number of Buyers

We vary the number of buyers and fix the number of sellers as $M = 5$. We present the performance comparison in terms of the following metrics:

- **Social welfare**, which is defined in (9) and reflects the revenue from all winning coalitions.
- **Spectrum utilization (channel selling ratio)**, the ratio of number of selling channels to the total number of channels .
- **Average buyer's satisfaction (ABS)**, the ratio of winning virtual buyers to the total demand:

$$ABS = \frac{\sum_{j=1}^{K} \sum_{i=1}^{N} w_{i,j}^{b}}{\sum_{i=1}^{N} d_i}. \tag{15}$$

- **Spectrum Reusability Degree (SRD)**, the ratio winning virtual buyers to the total channels

$$SRD = \frac{\sum_{j=1}^{K} \sum_{i=1}^{N} w_{i,j}^{b}}{K}. \tag{16}$$

- **Average winning buyers per sold channel**, the ratio winning virtual buyers to the sold channels.

In Fig. 7, with the increase of the number of buyers, the social welfare of these three schemes increases. TAMES's performance is close to the random scheme, implying that TAMES only considers simple spectrum allocation for non-conflict buyers and ignores the economic factor. The proposed VERACITY can significantly improve the social welfare especially in dense buyers' deployment scenario. Specifically, the achievable social welfare of the proposed VERACITY is superior to TAMES by about 200% when $N = 16$.

Fig. 8 and Fig. 9 show the comparison of spectrum utilization and average buyers' satisfactory level, respectively. We can see that the spectrum utilization and buyers' satisfactory level go up with the increase of the number of buyers. Note that the spectrum utilization (channel selling ratio) is the winning ratio of the whole coalitions. The more buyers join the auction and it tends to be easier to form a large-size coalition yielding higher coalition bid, which will increase the selling spectrum ratio. On the other hand, more channels sold bring higher social welfare (**WF**). In Fig. 9, we can see that the buyers' satisfactory level tends to be in saturation. The reason is that the more buyer will lose in the auction due to limited spectrum resource in dense buyers' deployment.

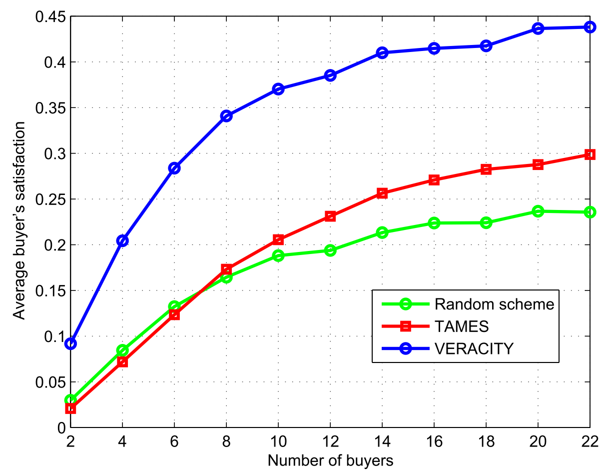


Fig. 9. Average buyer's satisfactory level versus the number of buyers.

Furthermore, we present the average winning buyers per sold channel and the spectrum reusability degree in the Fig. 10 and Fig. 11. Because VERACITY can form more winning coalitions, it increases the reusability degree.

D. Impact of the Number of Sellers

We vary the number of the sellers and fix the number of buyers as $N = 15$. In Fig. 12, we present the comparison of social welfare with the increase of the number of sellers. The achievable social welfare of VERACITY goes up with the increasing number of sellers, while the TAMES and random scheme tend to be in saturation in relatively abundant spectrum resource region. In Fig. 13, we can see that selling channel ratio of these three schemes decreases with the increase of the number of sellers. Because the number of buyers is limited

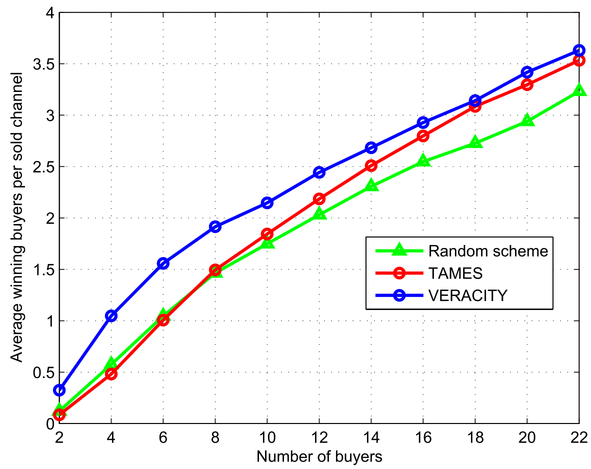


Fig. 10. Average winning buyers per sold channel versus the number of buyers.

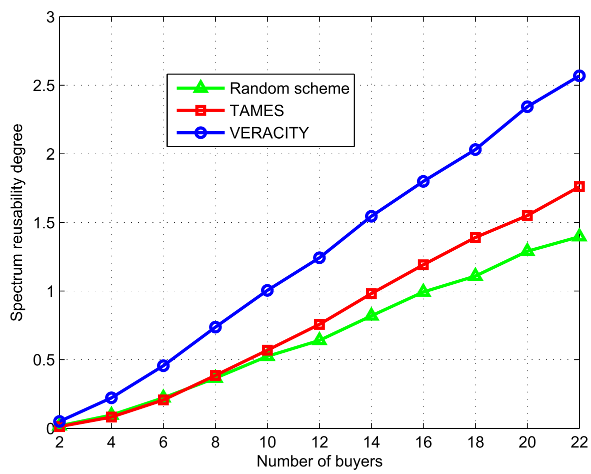


Fig. 11. Channel reusability degree versus the number of buyers.

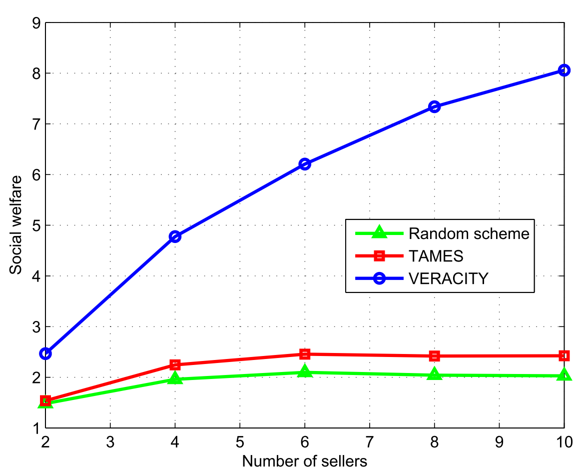


Fig. 12. Social welfare versus the number of sellers.

and their demand is bounded, the abundant spectrum resource leads to more idle channels after auction.

Moreover, Fig. 14 shows the average buyers' satisfactory level with the increase of the number of sellers. Obviously, VERACITY can provide higher buyers' satisfaction than TAMES. On the other hand, Fig. 15 and Fig. 16

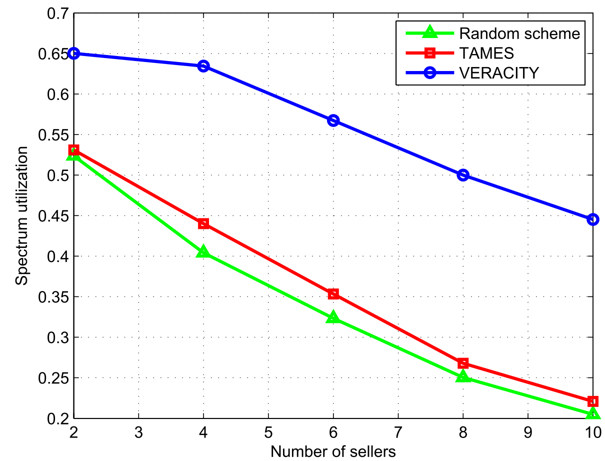


Fig. 13. Spectrum utilization versus the number of sellers.

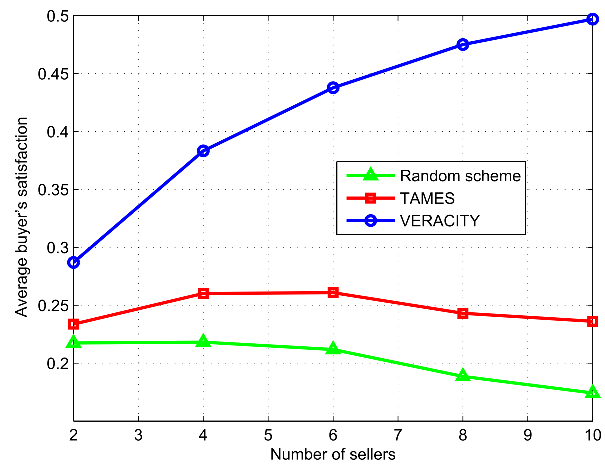


Fig. 14. Average buyer's satisfactory level versus the number of sellers.

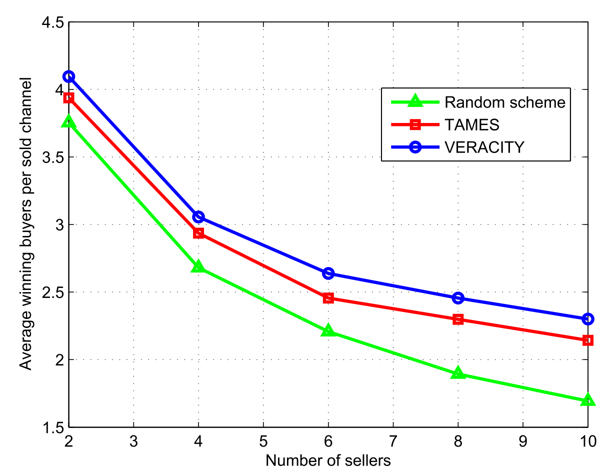


Fig. 15. Average winning buyers per sold channel versus the number of sellers.

present the average winning buyers per sold channel and the spectrum reusability degree versus the number of sellers, respectively. The corresponding performance of these three schemes decreases with increase of the number of sellers due to the relatively abundant spectrum for limited buyers.

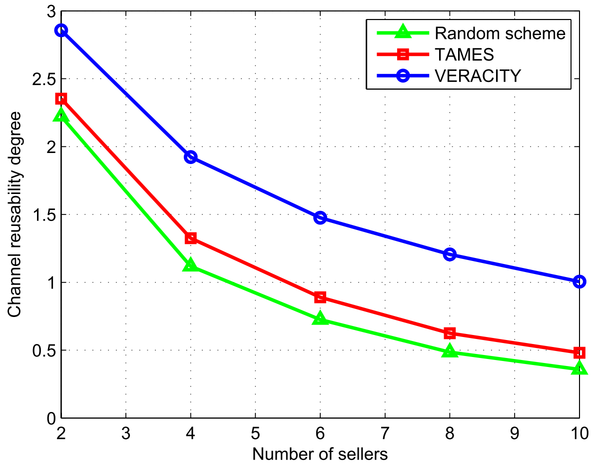


Fig. 16. Channel reusability degree versus the number of sellers.

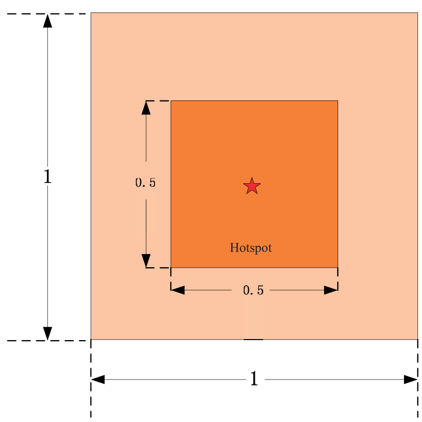


Fig. 17. Illustration of hotspot region in the networks.

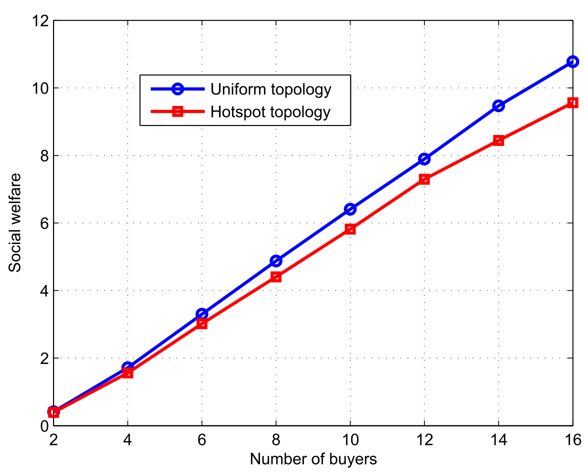


Fig. 18. Social welfare of uniform vs hotspot topologies.

E. Influence of Buyers' Topology

In this section, we investigate the impact of buyers' topology on the performance. We fixed the number of seller as $M = 4$ and we assume that all channels provided by sellers are available for each buyer. Next, we generate two different buyer's topology:

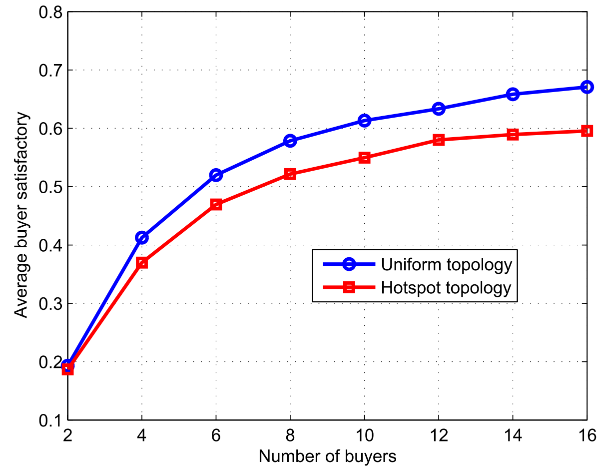


Fig. 19. Average buyers' satisfactory level of uniform vs hotspot topologies.

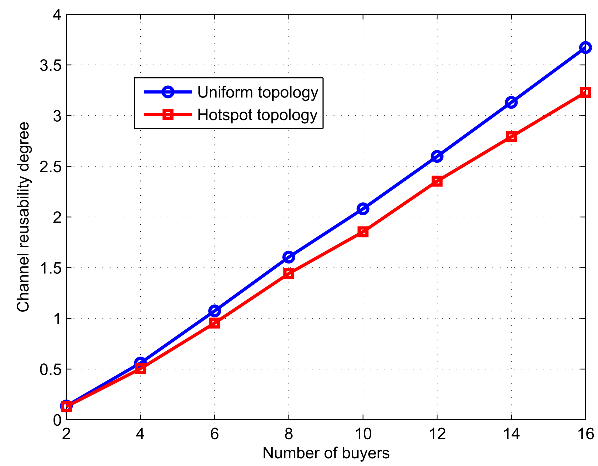


Fig. 20. Channel reusability degree of uniform vs hotspot topologies.

(1). *Uniform topology*; the buyers are randomly placed within the entire area.

(2). *Hotspot topology*; we create one hotspot. There are $\lfloor N/2 \rfloor$ buyers randomly distributed in the hotspot as shown in Fig. 17 and the residual buyers are randomly placed within the entire 1×1 area.

In Fig. 18-20, we present the VERACITY's auction results of uniform versus hotspot topologies from the perspective of social welfare, average buyers' satisfactory and channel reusability degree, respectively. Since the buyers are close to each other and endure severe interference in the hotspot than in the uniform topology scenario, leading to performance degradation in terms of social welfare, average buyers' satisfaction and channel reusability degree.

VIII. CONCLUSION

In this paper, we proposed an overlapping coalition formation based double auction which is termed as VERACITY. It jointly considers the heterogeneous buyers' demand, heterogeneous interference relationship and the economical efficiency. In VERACITY, the auctioneer groups the non-conflicting buyers into the same coalition and allows a buyer to join multiple coalitions based on the actual demand. Dynamic overlapping coalition formation virtually implemented by the auctioneer is to find the optimal coalition structure corresponding to the economical efficiency outcome, i.e., maximizing the social welfare. Furthermore, we proved that VERACITY satisfies good properties including individual rationality, ex-post budget balance, truthfulness and economical efficiency. Compared with the related existing schemes, VERACITY can obtain better auction outcome from the perspective of social welfare, spectrum utilization and buyers' satisfaction.

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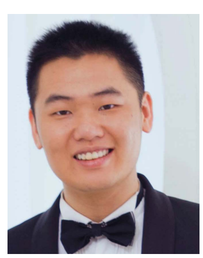

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