Chapter 2
Auction Mechanisms

2.1 Overview

According to Wikipedia [1], "An auction is a process of buying and selling goods or services by offering them up for bid, taking bids, and then selling the item to the highest bidder. In economic theory, an auction may refer to any mechanism or set of trading rules for exchange."

There are some common auction forms used in the real world. The English auction is known as the open ascending pricing auction. During a sale an auctioneer calls out a low price and raises it until there is only one interested buyer remaining. The Dutch auction is known as the open descending price auction. The auctioneer calls out a high enough price such that there is no one interested in buying it. Then he gradually lowers the price until one buyer is interested. The price information is made public in both of these types of auctions. There are also sealed-bid auctions where bidders submit their bids and bidders are only aware of their own value. The auctioneer selects those who offer the highest bids as winners. The rule of winners' payment can be flexible. If a winner pays the second-highest bid rather than his own value, then the auction is a Vickrey auction (for a single-object auction).

In this book, to align with the definitions in most of the research works, we assume the spectrum auction is seal-bid.

Generally, there are three types of players in an auction: buyers, sellers, and the auctioneer. If these players are all present, it is a double auction. When the auction is held by a single seller (or buyer), he may act as auctioneer. We assume the buyers and sellers are selfish and rational, which means they behave within the auction framework and try to maximize their individual utilities. They do not submit true values if it brings them any extra benefits. We also assume the auctioneer faithfully executes his duty. Therefore when a seller (or buyer) acts as auctioneer, all participants unconditionally trust him.

An auction consists of two sub-processes: winner determination and payment mechanism. For winner determination, the auctioneer selects some bidders as winners and allocates items (money) to them for exchange. For payment

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mechanism, the auctioneer decides how much a winning buyer should pay for an item and how much a seller should get for a sold item.

2.2 Definitions in Auction Mechanisms

Definition 2.1. Collusion: A ring that some bidders form to bid against outsiders to gain extra benefits by manipulating the auction result.

In the research literature, it is assumed that there is no "Collusion" of bidders. Each bidder plays for himself, which make the auction look like a non-cooperative game.

Definition 2.2. Valuation: Bidders each have a value in mind which represents how much an item is worth to them. The value is their evaluation of the item.

Usually, the value is private information. Some works assume that the value follows some distribution and the distribution is known by the auctioneer. Therefore a buyer is not willing to pay more than a predetermined value to get an item. Likewise, a seller is not willing to sell the item at a lower than the predetermined price (called "reserve price"). This is a required economic property and should be satisfied in the design.

Definition 2.3. Individual Rationality: an auction has individual rational if no buyer pays more than his bid and no winning seller is paid less than his ask.

The Individual Rationality property guarantees that if bidders and sellers submit their true value, they will not receive negative utility, which provides them some incentives to act truthfully. We define the utilities as follows.

Definition 2.4. Utility: for a bidder, the utility is the difference between the true value of all the winning items and the total payment; for a seller, we define the utility as the total income from sales (some work may define it as the difference between the total income and the true value of all the sold items); for the auctioneer, we define the utility as the difference between the total payment from the buyers and the total income of the sellers.

There is an economic property in relation to the auctioneer's utility.

Definition 2.5. Ex-post Budget Balance: a double auction is ex-post budget balanced if the auctioneer's utility can never be negative.

This property ensures the auctioneer has an incentive to set up the auction. In practice the auctioneer can charge a transaction fee. In the research literature, people adopt "Ex-post Budget Balance" for simplicity.

Let us introduce a concept used in both game theory as well as in auction.

Definition 2.6. Dominant Strategy: a dominant strategy is the one that maximize a players utility regardless of what other players' strategies are. Mathematically, if x_i is player i's strategy, for any $x_i' \neq x_i$, and any strategy profile of others x_{-i}, we have $U_i(x_i, x_{-i}) \geq U_i(x_i', x_{-i})$.

Based on “Dominant Strategy”, we define “Truthfulness”:

Definition 2.7. Truthfulness: an auction is truthful if the true value is the players dominant strategy.

When designing auction mechanisms, it is crucial to make them truthful. As the most important property, it has been well accepted in the research literature [21,23] for the following reasons. As the auctioneer does not know the buyers’ private values, truthfulness is the best method to prevent market manipulation, which can hurt the interests of other buyers and sellers. Besides, truthfulness simplifies the strategic decision process for all players, as their true values are the best strategies.

The “Efficiency” property represents the performance of an auction.

Definition 2.8. Efficiency: an auction is efficient if the aggregate of all participants’ utilities are maximized.

It shares a common meaning with “Social Welfare” which describes the aggregate utility of all buyers, sellers and the auctioneer. As the payment among them can be canceled out, “Efficiency” depends only on the determination process of who is the winner. If the items are allocated to those who value them most, then the auction is efficient.

We regard “Efficiency” as the second most important property as we always trade-off between truthfulness and efficiency in auction design. To achieve truthfulness, we compromise efficiency. Usually it is not difficult to design a truthful auction, but it is very challenging to prove that the auction is the most efficient one among all the truthful mechanisms. Very few works have paid attention to making the efficiency as high as possible even though they ensure the truthfulness. Therefore truthful auctions are often designed with possibly very low efficiency.

Besides “Efficiency”, “Time Complexity” is also an easily ignored property in the research literature.

Definition 2.9. Time Complexity: the time complexity of an (auction) algorithm quantifies the amount of it takes to run as a function of size of the input to the problem. An algorithm with low time complexity is computationally tractable.

In practice, we should consider the application scenario of the auction mechanism. If an auction is held frequently or its input size is too large, the mechanism itself should be computationally tractable.

2.3 Research Literature

Traditional auctions can be classified by the number of participants (buyers and sellers), and the number of commodities and their properties (i.e., homogeneous or heterogeneous, super-additive or sub-additive). Here we would like to focus on how auction mechanisms are introduced to the spectrum market and the necessary improvement of rules to accommodate the spectrum trading.

Most early works discussed single-seller multi-buyer auctions with homogeneous channels. Zhou et al. [21] and Jia et al. [10] are two representative works. Zhou et al. [21] proposed VERITAS to support an eBay-like dynamic spectrum market. VERITAS is truthful mechanism and has a polynomial complexity of $O(n^3k)$ with n bidders and k channels. Different from FCC-style spectrum auction which is for the long-term and large geographical regions, it aims for the short-term and small regions. The auction complexity should be low enough to obtain a result quickly. The interference relationship is represented by a conflict graph. Most of the latter works in this area have followed their dead with short-term small-region auctions, and using a conflict graph as pre-knowledge. In [10] a VCG-like auction is used to maximize the expected revenue of the seller given the distribution of the buyers' evaluations. Considering that VCG auctions are usually computationally intractable, they further designed a truthful suboptimal auction with polynomial time complexity. Zhu et al. in [23] extended the meaning of a buyer from a single node to a multi-hop secondary network. They designed a truthful auction for trading homogeneous channels between a seller and multiple secondary networks.

Later, double auction mechanisms (multi-seller multi-buyer) have also been considered in the spectrum market. Zhou et al. [22] proposed TRUST for spectrum trading. It satisfies good properties such as spectrum reusability, truthfulness, budget balance and individual rationality, but it sacrificed one group of buyers (taking its bid as the clearing price) to achieve truthfulness. We believe it is the first to propose the grouping method to tackle the interference relationship. Any two users that might interfere with each other should not be placed in the same group. The conflict graph is then divided into several independent sub-graphs. Although it indeed achieves truthfulness, efficiency is sacrificed, because they can use only random grouping, and the grouping itself affects the efficiency of the auction. For example, who should be grouped together and how many groups should there be? Following the idea of TRUST, Wu et al. [16] improve up on it by only sacrificing one buyer in each group, and at the same time achieving truthfulness. Both works inherited the McAfee mechanism [12], which required homogeneity of channels. Yang et al. [18] were the first to consider the auction with heterogeneous channels. They proposed TASC, a mechanism extending the McAfee mechanism, for a cooperative communication scenario. However, it restricted a unique clearing price for all the channels, which could seriously reduce the system efficiency when the budget and evaluations of the channels varied too much over a big range. Feng et al. [8] and Chen et al. [4] extended this work by considering spectrum reusability and diversity of channel characteristics.

Auction mechanisms are also integrated into the mechanism design in many research directions of networks. For example, Huang et al. [9] proposed a strategy-proof and privacy preserving auction for spectrum trading. Zhuo [24] and Dong [7] used an auction-based framework to motivate third-parties to lease their unused resources to service providers for dynamic cellular offloading. Li [11] and Wang [15] studied auction mechanism in cloud computing scenarios. In [11], cloud providers can buy/sell their Virtual Machines' capabilities on the open market as well as job scheduling and resource pricing. In [15], the authors made optimal capacity segmentation in cloud platform. Resources are priced in the pay-as-you-go style, or auctioned on the spot market, or by subscription, such that users' various types of demands are well satisfied. Wang [14] and Zhang [19] proposed auction in online fashion to satisfy continuously arriving demands.

2.4 Our Starting Points

Spectrum is a special commodity in that two devices using the same spectrum frequency can interfere each other if they are in close proximity. That also means if the devices are far away from each other, they can reuse the spectrum. This is the major difference between spectrum and other commodities. Researchers have extensively exploited the "interference" property in their works [4, 21]. The most frequently used model is Interference Graph, by which they make spectrum allocation and avoid interference as well as encourage spectrum reuse. The "reusability" property is also well utilized [16, 22]. The general method is to randomly allocates buyers into some independent groups such that buyers in the same group do not interfere with each other. The buyers in the same group will win the same channel or lose in the auction.

Our works focus on exploiting other features of spectrum auction, that is the heterogeneous propagation property, the group-buying model and the dynamic spectrum demand property. We do not consider either interference or reusability in the second and the third work for simplicity. The new properties themselves build complete stories.

2.4.1 Auction for Heterogeneous Spectrums

There are many existing works relating to our work that is presented in Chap. 3. However, most of them fail to consider spectrums as non-identical items. In [22], Zhou et al. first address spectrum reusability in their auction design: TRUST. In [17], the authors also consider spectrum reusability for buyers, and they assume buyers can have multiple radios. Recently, in [6], Dong et al. address spectrum reusability in a time-frequency division manner and model the problem as a combinatorial auction. The proposed TAHES scheme also considers spectrum reusability, moreover, TAHES can tackle the case where spectrums are heterogeneous.

In [13], an auction design for heterogeneous TV white space spectrums is proposed. In the paper, the spectrum allocation problem has been defined as an optimization problem where maximum payoff of the central trading entity (called spectrum broker) is the optimization goal. However, [13] is not a double auction scheme and its design goal is different from TAHES. Recently, in [18], Yang et al. proposed a double auction design for cooperative communication with heterogeneous relay selections. However, there is no reusability in their scenario.

Different from our single-round auction model, there have also been works considering spectrum auction in an online fashion [5, 14]. In an online spectrum auction, buyers may arrive at different times and request the spectrum for a particular duration. However, existing online double auction schemes consider only the homogeneous spectrum.

2.4.2 Spectrum Group-Buying Framework

We consider a spectrum group-buying scenario in secondary networks. The auction involves multiple small buyers, one seller, and multiple heterogeneous channels. Single buyers cannot afford a whole channel, nor would they need to use it exclusively. Thus a group-buying model is necessary to enable the function.

From all the state-of-the-art auction mechanism designs, we can see that most VCG-based auctions guarantee truthfulness, and maximize social welfare. However, they have some limitations, such as high computational complexity (exponential running time), and low revenue for the sellers (especially when there are less demands from buyers). Most recent works [10, 23] do not apply the original VCG auctions. Instead, VCG-like heuristic auctions are designed to approximate VCG auction at lower computational overhead. VCG double auction does not satisfy the budget balanced property especially when the demands of the buyers are low. The McAfee mechanism and its successors can work well in auctions with homogeneous items, but cannot be directly applied to those with heterogeneous items.

In summary, none of the existing works provide a feasible tool or solution to tackle the group-buying problem that we are discussing. Consequently, we design new algorithms SAMU and DCP for the two stages, which improve system efficiency significantly.

2.4.3 Flexible Auction

We find that most of previous auction works make the assumption that buyers can claim at most one channel. Therefore these mechanisms cannot satisfy the flexible demands of buyers. To the best of our knowledge, the only mechanism that enables a flexible demand is combinatorial auction. In this model, the authors provide time-frequency flexibility for buyers [6], where each buyer can submit a bid to claim time-channel combinations. The authors in [20] also proposed a simplified combinatorial auction model to make the multi-channel trading without a uniform price for each channel. The major concern regarding combinatorial auction is that in general cases, the problem is NP hard, which means that the mechanism is not suitable for periodic auctions with too many buyers and channels.

In all these works, an assumption is made that the buyers themselves will consume the channels for data transmission, therefore their satisfaction levels are quantitatively analyzed and considered in their utility functions. Usually, the satisfaction level is an input into the auction problem, known as the true evaluation.

However, in our scenario the operators provide services to users to make revenue. Naturally there are no true evaluations for channels at the very beginning and in fact they depend on their users' willingness to pay. We theoretically derive the operators' true evaluations of channels by analyzing the service provision, that is, the pricing mechanism and users' utility maximization.

In summary, none of the existing works provided a feasible auction model to enable flexible demand with polynomial time complexity. Most auction models are polynomial time efficient but they do not support flexible demand. Combinatorial auction supports flexible demand, but they are not computationally efficient. Flexauc preserves good properties of both types and provides flexibility with polynomial time (more specifically, linear time) algorithm. We also show how should the operators determine the best bids in the auction in the three-layered market.

2.5 Special Characters of Spectrum Auction

2.5.1 Interference and Reusability

We can liken interference and reusability to the two sides of a coin. For any pair of nodes in a network, we can set a threshold to distinguish interfering pairs from non-interfering pairs. Then the non-interfering pairs can reuse the spectrum frequency.[1]

Recall that "interference can occur when two sources in close proximity transmit simultaneously at the same frequency". So to avoid interference, the transmissions can be isolated by spatial domain, temporal domain, frequency domain, or code domain. In the research literature of spectrum auction, researchers focus on spatial and temporal reusability, which do not need to involve extensive knowledge of technical aspects, while the other two require a deep understanding of the basis of wireless communication and signal processing.

An auction itself can often be formulated as an optimization problem [6]. The objective function is selected as social welfare or the strong side's utility. The "interference and reusability" properties are usually formulated as constraints. Thus the auctioneer needs to solve the optimization problem(s) to obtain the winners and their payments. Here we focus on the constraints of the optimization problem. Usually they are based on either spatial or temporal reusability.

1. **Spatial reuse**: is the most frequently used as it enables the non-interfering nodes that transmit at the same channel simultaneously. Usually researchers assume a pre-knowledge of conflict graph, which describes the interference relationship of the nodes. We represent that two nodes can interfere with each other by an edge between them in the graph. If there is no edge between them, they can reuse the same frequency band or channel.

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[1] Note that it is a simplified analytical method which are frequently used in studying resource allocation of wireless networks.

If there is only one channel, the auctioneer prefers to allocate it to the non-interfering nodes making total bids most attractive. The allocation problem turns to the maximum weighted independent set problem, which is an NP-hard optimization problem.

If there are multiple channels to trade, the frequently used method is to divide the nodes into several independent sets (groups). Each group can obtain some channel(s) and a random matching is used to map the groups and channels to make the auction truthful. If the matching depends on the bids, the mechanism usually leaves room for untruthful bidding. Typical works using this method include [16, 22].

The conflict graph can also be used as constraints for the optimization problem in resource allocation. Let a_{ij} denote the allocation state of node i on channel j. If $a_{ij} = 1$, then i node gets j channel. Otherwise, it cannot use j channel.

Obviously the sufficient and necessary conditions that the optimization problem should satisfy are: for any edge ik in the conflict graph and any j,

$$a_{ij} + a_{kj} \leq 1 \tag{2.1}$$

holds. The constraints can be further simplified: for any clique C in the graph,

$$\sum_{k \in C} a_{kj} \leq 1 \tag{2.2}$$

holds. "Clique" means the sub-graph which is also a complete graph. Equation (2.2) is a sufficient and necessary condition to guarantee the spectrum allocation is effective and interference-free. Here the term "sufficient" means that any array $\{a_{ij}\}$ that satisfies Eq. (2.2) is an interference-free allocation. The term "necessary" means that any interference-free allocation can be represented by an array $\{a_{ij}\}$ that satisfies Eq. (2.2).

2. **Temporal reuse**: it is relatively less used. Temporal reuse means the interfering nodes transmit in the same channel at a different time. The input of this problem can be the whole period of time (assumed to be [0, 1]) and channel states. The output of this problem is the channel allocation result in the temporal domain, for example, node i_1 uses channel j_1 in the period of [0.3, 0.5]. As no interfering pairs can simultaneously use the same channel, we use the variable $a_{ij} \in [0, 1]$ to denote the time portion of the whole period when channel j is allocated to node i.

   However, in this case, Eq. (2.2) is necessary but not sufficient. Figure 2.1 a counterexample showing that an array satisfies Eq. (2.2) but does not make itself an interference-free allocation. We know that $\{a_{ij}\} = \{0.4, 0.6, 0.4, 0.6, 0.4\}$ satisfies Eq. (2.2). However, when making allocation, node 1 occupies the channel in the period of $[0, 0.4]$, node 2 in $[0.4, 1]$, node 3 in $[0, 0.4]$, node 4 in $[0.4, 1]$, and node 5 in $[0, 0.4]$. We find that node 1 and node 5 interfere with each other.

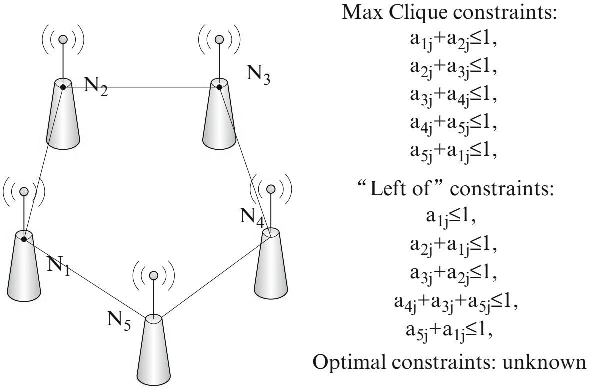

Fig. 2.1 A counterexample of Eq. (2.2)

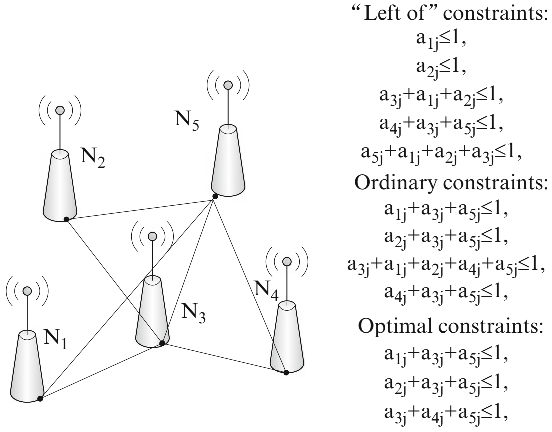

Fig. 2.2 An illustration of the constraints

An alternative method to model the temporal reuse, named "left of" constraint, is sub-optimal [2, 3]. The "left of" constraints are

$$a_{ij} + \sum_{k\in C_i} a_{kj} \leq 1, \forall i, j \tag{2.3}$$

where C_i is the set of node i's "left of" and interfering neighbors. Node k is in C_i if and only if node k is to the left of node i (in a geographic location) and the two nodes form an interfering pair. For ease of understanding, "left of" formulation imposes a topological order among nodes. The advantages of "left of" constraints are three-fold. First, it is less restrictive than ordinary constraint formulation, though it may not be optimal.[2]

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[2] With ordinary constraints' formulation, each node involves any interfering BSs into its constraints. So it is more restrictive than "left of" ones. The optimal constraints are the least restrictive ones which also guarantee an interference-free allocation. These constraints are shown in Fig. 2.2.

A less restrictive formulation can lead to a better result of the optimization problem. Figure 2.2 compares the differences of the constraint formulations. Second, the "left of" formulation can guarantee an interference-free channel allocation for adjacent nodes in the conflict graph. Third, this formulation can be applied to any topologies, but we do not find a general formulation of the optimal constraints.

We have some insight into the formulation of spatial and temporal reusability. First, we can see that temporal reusability is indeed a more generalized model than spatial reusability. If the variables are constraints to the values of only zero or one, it degrades to the spatial reusability. Second, we do not find a generalized formulation of the optimal constraints for the temporal reusability when the model is directly extended. However, what about using two variables b_{ij} and e_{ij} to denote the beginning and end time of node i's channel allocation? Besides, the linear form of the constraints make the optimization problems easier to solve. Are there any non-linear constraints that can well formulate the interference relationship? We believe these points may give rise to future works.

2.5.2 Super-additive and Sub-additive

Super-additive and sub-additive properties are used in a multi-item auction. Let $V_i(S)$ be any bidder i's evaluation on a set of items S. For any extra item j, if

$$V_i(S \cup \{j\}) \leq V_i(S) + V_i(\{j\}) \tag{2.4}$$

always holds, then the super-additive property is satisfied. This property can be explained by the marginally decreasing effect in economics. When the items are substitutes, this property usually holds. If

$$V_i(S \cup \{j\}) \geq V_i(S) + V_i(\{j\}) \tag{2.5}$$

always holds, we say that the sub-additive property is satisfied. When the items are complements, for example, a set of stamps, this property usually holds.

These two properties cannot be emphasized in one design. They apply in the wireless network area as well as other areas, but as far as we know, relatively less works in spectrum auction exploit these properties. The authors in [6] proposed a combinatorial auction with time-frequency flexibility. Although they do not explicitly mention the super-additive property, their algorithm indeed implies it. In general, combinatorial auctions come with exponential computational complexity. In [6], they assume that bidders can only bid for continuous channels, such that the complexity is reduced to polynomial time. The physical meaning of this assumption is that communication technologies impose minimum bandwidth requirements on frequency bands. More continuous channels provide larger bandwidth, which facilitates service deployment, therefore the super-additive property holds. In our work “Flexauc” which is presented later, we study the sub-additive property in spectrum auction. The property is built on the basis of the elastic demand of the end users and the marginally decreasing effect. Similarly, with the help of this property and the assumption of identical items, we design a linear-time algorithm for the combinatorial auction.

2.5.3 Group Structure

As channels can be shared by non-interfering bidders, researchers usually define bidders who share the same channel as a group.

Note that the group structure can be exogenous or endogenous. The term “exogenous” means that the bidders have been divided into some groups and the group structure are the input of the auction problem. For example, in our work “group-buying framework” which is presented later, users belonging to the same secondary network are form within the same group and the auction takes this as input. The term “endogenous” means that the group structure is formed in the process of the auction. For example, in [16, 22], the auctioneer randomly divides non-interfering bidders into groups.

As far as we know, we are the first to study the exogenous group structure in spectrum auction. Similar to super-additive and sub-additive properties, it is not unique to wireless networks, so our mechanism can be applied to other scenarios with appropriate modification.

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Chapter 3
Truthful Double Auction Mechanism for Heterogeneous Spectrums

In this chapter, we consider the problem of redistribution of spectrums via a double auction and propose truthful auctions mechanism for TV channels.

It is a promising way to enable spectrum owners to lease their spectrums to secondary service providers where there are no interference to the primary users. In return, the spectrum owners can get paid from secondary service providers. An example is the Spectrum Bridge [2] company. It has launched an online platform to allow spectrum owners to lease unused spectrums to buyers. Bands from different sellers are in different frequencies and with various availabilities. Also, there are different preferences from spectrum buyers for different bands. Moreover, the spectrums can be reused. Two buyers that are not conflict with each other may use the same band at the same time.

We can model the spectrum redistribution between spectrum owners and buyers as a *single round multi-item double auction*, where the spectrum owners are the sellers; the secondary service providers are the buyers; the spectrums are the goods.

Although auction has been widely studied, we can not directly apply existing double auction schemes [3, 8, 15, 17, 19, 20] to the new scenario. We face three major challenges here. First, we need to deal with the spatial heterogeneity. The available bands to buyers can be different due to different owners. However, in [3, 8, 15, 17, 19, 20] only the scenario where all spectrums are available to all buyers is considered. Second, there is frequency heterogeneity and spectrum reusability. Due to the reason that the spectrums are from various frequency bands and with different communication ranges (low frequency band have larger transmission rages). Therefore, in different bands, the interference relationships between different buyers can be different. However, existing works usually assume the same conflict range for all frequencies. Third, auction mechanism design under this scenario is challenge. The most critical property: *Truthfulness* (or strategy-proofness) should be preserved. A truthful auction incites all bidders to voluntarily reveal their true valuation for the items they are bidding. Unfortunately, the truthfulness is hard to achieve applying existing schemes when there are heterogeneous items for sale. Besides truthfulness, several other properties are also desirable: (i) *Individual rationality*: The utility of both buyers and sellers is enhanced because of the auction;

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