

**Truthful Double Auction Mechanisms for Heterogeneous Spectrums and Spectrum  
Group-Buying**

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THESIS

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To myself:

Be a confident women, never give up yourself when you are in trouble.

Confident is the first trick to be successful.

When you're in trouble, remember that you're always braver, stronger and smarter than you think.

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## **LIST OF ABBREVIATIONS**

CDMA	Code Division Multiple Access
FCC	Federal Communications Commission
ITU	International Telecommunication Union
MAC	Media Access Control
MAHES	Truthful Multi-channel double Auction mechanism for HEterogeneous Spectrums
NTSC	National Television System Committee
OFDM	Orthogonal Frequency Division Multiplexing
RF	Radio Frequency
SAP	Secondary Access Point
SH	Spectrum Holder
SN	Secondary Network
SPTF	Spectrum Policy Task Force
SU	Secondary User
TAHES	Truthful double Auction mechanism for HEterogeneous Spectrums
VBG	Virtual Buyer Group
VCG	Vickery-Clarke-Groves auction
VG	Virtual Group
VSG	Virtual Seller Group

## **LIST OF ABBREVIATIONS (Continued)**

UIC	University of Illinois at Chicago
USA	United States of America

## SUMMARY

Auction has been widely used to spectrum allocation. Most of the previous works supposed that all the spectrums are identical. However, in reality, spectrums are quite different in different locations and frequencies. Recently, some works studied the double auction mechanism for heterogeneous spectrums. But their schemes are based on the assumption of “single-channel request”. To be more realistic, each seller and buyer will bid at least one channel. The previous schemes will not work under multi-channel assumption.

In this thesis, I proposed a truthful multi-channel double auction mechanism for heterogeneous spectrums. Our scheme allows sellers and buyers to sell or buy multi-channels for heterogeneous spectrums. We introduce a novel virtual grouping method to split sellers and buyers. We proved that the proposed scheme satisfies the economic properties: truthfulness, individual rationality and budget balance. Simulation results confirmed that our method achieves high auction efficiency and auction revenue.

Beyond the double auction for heterogeneous spectrums, recent spectrum auction results have shown that small network providers cannot benefit from the auction directly because of the high price asked by the spectrum holders. Therefore, in this thesis, we proposed a truthful group buying-based double auction mechanism for cognitive radio networks. There are two single-round auction in our method. The first one is between secondary users and secondary access point, in which the secondary access point is the seller and the secondary users are the buyers. We call it the outer auction. The outer auction is

## **SUMMARY (Continued)**

based on single-sided buyer-only auction. The other one is between the secondary access points and the spectrum holders, in which the secondary access points are the buyers and the spectrum holders are the sellers. We refer to it as the inner auction. In the inner auction, we apply the double auction mechanism. We proved that our scheme satisfies the economic properties.

At last, we proposed a truthful multi-channel double auction mechanism for spectrum group-buying. Since both sellers and buyers would require to trade multiple channels at the same time. No existing designs can meet multi-channel and group-buying requirements simultaneously. To solve this problem, we introduce a novel group splitting and budget calculation algorithm in the outer auction. We apply a proper winner determination and pricing mechanism in the inner auction. This scheme satisfies the economic properties as well.

## **CHAPTER 1**

### **INTRODUCTION**

Due to the spectrum problem caused by the rapid growth of wireless applications for mobile users, efficient spectrum allocation is the key to improve overall spectrum utilization. In wireless communications, spectrum is one of the most valuable resources (32). Cognitive radio is a new paradigm of designing wireless communications systems which aims to enhance the utilization of the radio frequency (RF) spectrum. The motivation behind cognitive radio is the scarcity of the available frequency spectrum, increasing demand, caused by the emerging wireless application for mobile users (11). A study by the Spectrum Policy Task Force (SPTF) of the Federal Communications Commission (FCC) has shown that some frequency bands are heavily used by licensed systems in particular locations and at particular times, but that there are also many frequency bands which are only partly occupied or largely unoccupied (21). For example, spectrum bands allocated to cellular networks in the USA (43) reach the highest utilization during working hours, but remain largely unoccupied from midnight until early morning. Moreover, spectrum utilization in different locations is highly dynamic. For example, spectrum could be much less utilized in the rural areas compared to the urban areas.

The major factor that leads to inefficient use of the radio spectrum is the spectrum licensing scheme itself. In the traditional long-term and regional lease allocation schemes could only allocate a small part of spectrum to the new wireless applications. Due to this static and inflexible allocation, legacy wireless systems have to operate only on a dedicated spectrum band and cannot adapt the transmission band according to the changing environment. For example, if one spectrum band is heavily used, the

wireless system cannot change to operate on another more lightly used band.

In such case, the long-term and regional lease schemes could have spectrum hole (white space) issue (24), which decreases the utilization efficiency. Spectrum holes (Fig. 1) are defined as frequency bands which are allocated to, but in some locations and at some times not utilized by, licensed users, and, therefore, could be accessed by unlicensed users.

The limitations in spectrum access due to the traditional long-term and regional lease can be summarized as follows (63):

- Fixed type of spectrum usage: In the current spectrum licensing scheme, the type of spectrum use cannot be changed. For example, a TV band which is allocated to National Television System Committee (NTSC)-based analog TV cannot be used by digital TV broadcast or broadband wireless access technologies. However, this TV band could remain largely unused in many locations due to cable TV systems.
- Licensed for a large region: A licensed spectrum is usually allocated to a particular user or wireless service provider in a large region. The allocated spectrum may remain unused in some areas, and other users or service providers are prohibited from accessing this spectrum.
- Large chunk of licensed spectrum: A wireless service provider is generally licensed with a large chunk of radio spectrum (e.g. 60MHz). However, a service provider may require a spectrum with bandwidth of 1.25 MHz to provide temporary wireless access service for a short period to meet a peak traffic load.



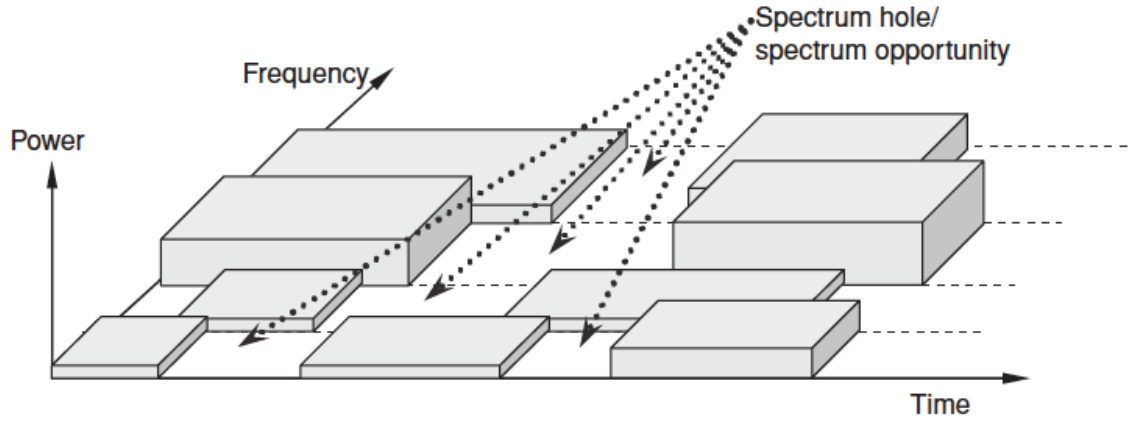


Figure 1: Spectrum hole

- Prohibit spectrum access by unlicensed users: In current spectrum licensing scheme, only a licensed user can access the corresponding radio spectrum and unlicensed users are prohibited from accessing the spectrum even though it is unoccupied by the licensed users.

In order to improve the efficiency and utilization of available spectrum, a number of new spectrum allocation methodologies have been proposed, such as (22; 26; 76). The idea is to make spectrum access more flexible by allowing unlicensed users to access the radio spectrum under certain restrictions.

There are two aspects to allocate a spectrum, technical aspect and economic aspect. Recently, the latter gets more attentions because it considers the incentive issues while the technical aspect does not. With incentives, a well designed spectrum trading mechanism will attract licensed and unlicensed users to join the market, where the spectrum trading is the process of buying and selling spectrums between

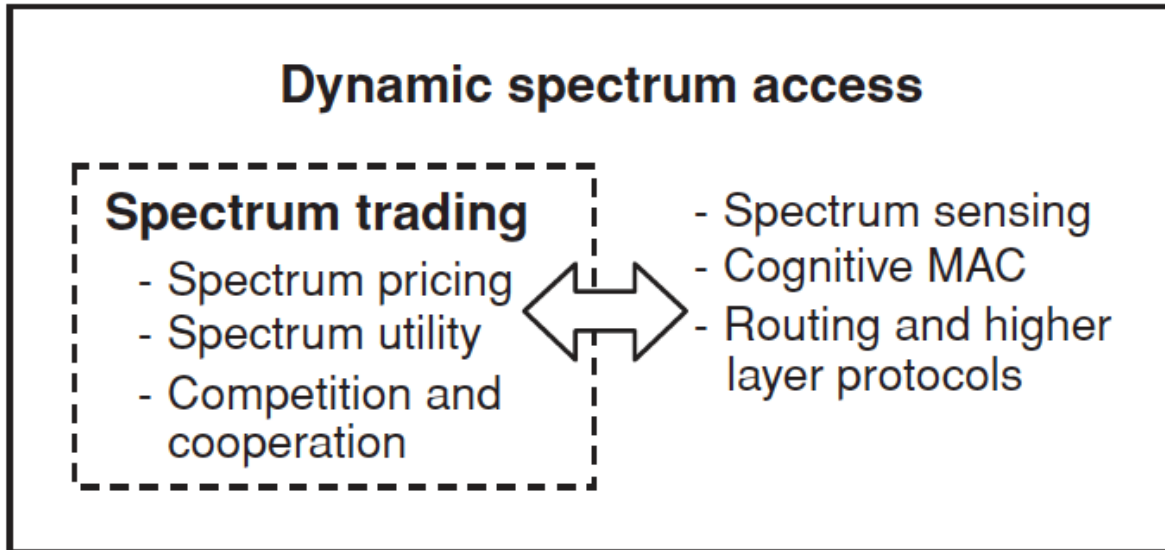


Figure 2: Dynamic spectrum access and spectrum trading

unlicensed and licensed users. In spectrum trading (1), pricing is an important issue for both licensed user (or primary service provider) selling the spectrum and the unlicensed users (or secondary service provider or secondary user) buying the spectrum. While dynamic spectrum access encompasses technical functionalities including spectrum sensing at the physical and MAC layers, channel access, routing, and higher layer protocols, spectrum trading can be regarded as its other component which deals with the economic aspects of dynamic spectrum access (Fig. 2). Spectrum trading can be considered as a component of spectrum management (18) (Fig. 3), and, therefore, it is required to be integrated with other components in a cognitive radio network. In spectrum sharing, spectrum exploration and spectrum exploitation are two major steps (Fig. 4). Spectrum trading is a process between spectrum exploration and exploitation. A spectrum seller has to perform spectrum exploration to identify spectrum oppor-

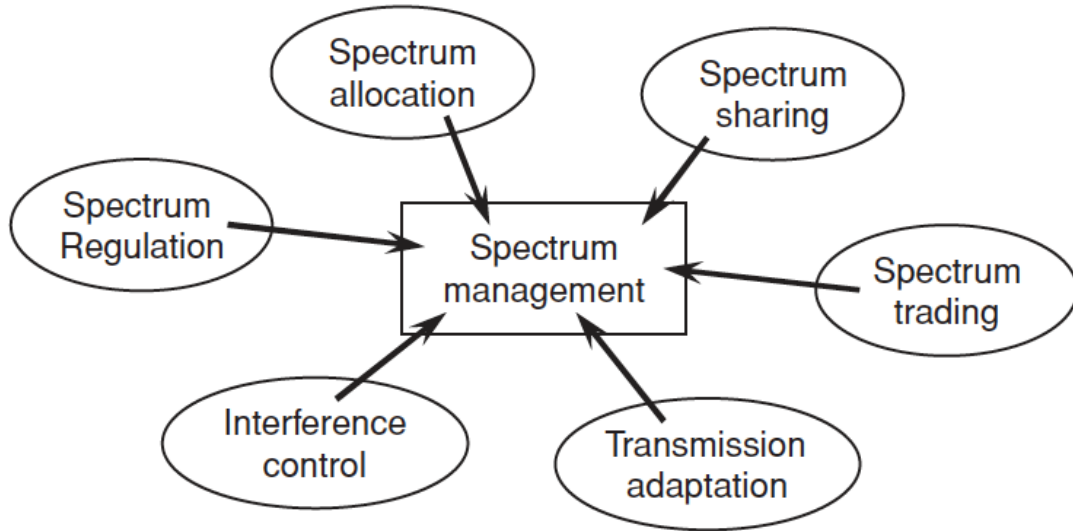


Figure 3: Spectrum management

tunities. Then, these spectrum opportunities can be sold to the spectrum buyer. After obtaining the right to access, the spectrum buyer performs the spectrum exploitation step to utilize the spectrum to achieve its objectives under the constraints defined by the spectrum sellers. For instance, Spectrum-Bridge (4) has already launched an online platform for spectrum owners to sell or lease their spectrums to potential buyers. Extensive works have been worked on allocating a spectrum and most of them cooperate economical tools such as game theory (35; 50; 52; 60), contract theory (16; 23; 34; 69), auction (5; 8; 27; 77; 78), commodity pricing (17) and etc.

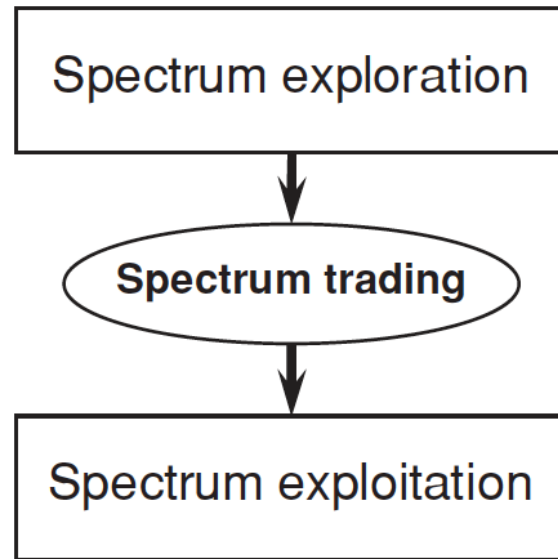


Figure 4: Spectrum exploration, spectrum trading and spectrum exploitation.

### 1.1 The Motivation

In spectrum trading, the objective of a seller is to maximize the revenue/profit, while that of a buyer is to maximize the utility of spectrum usage. However, these objectives generally conflict with each other. The effect can be shown in Fig. 5. As the seller increase the price to achieve higher revenue, the utility of a buyer decreases due to the higher cost. For example, as the spectrum size allocated to an unlicensed user increases, the utility of an unlicensed user increases, but the performance of a licensed user degrades. Therefore, an optimal and stable solution for spectrum trading in terms of price and allocated spectrum would be required so that the revenue and utility are maximized while both the sellers and the buyers are satisfies.

Different techniques can be applied when designing a spectrum trading model to obtain an optimal

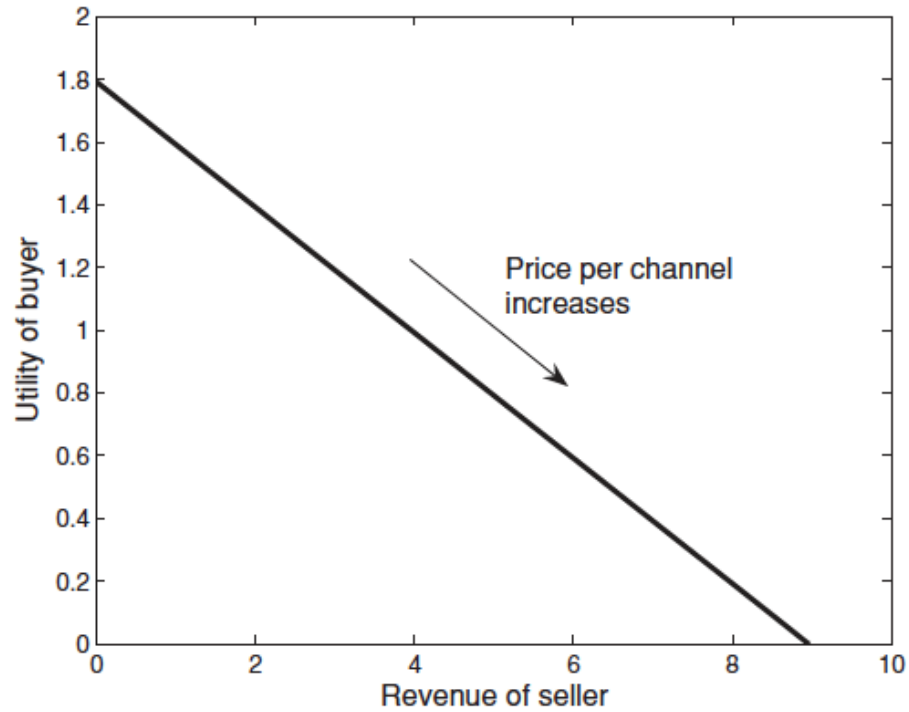


Figure 5: Revenue of a spectrum seller versus utility of a spectrum buyer

and stable solution for the spectrum seller(s) and buyers(s) (46).

- Microeconomic approach
- Classical Optimization approach
- Non-cooperative game approach
- Bargaining game approach
- Auction approach

Among all the spectrum trading methods, auction is an effective and fair way to improve the spectrum utilization. Recently, auction has been a widely used method to allocate the spectrums (13). A good auction mechanism must be truthful, which means that the auction cannot be affected by any market manipulations. A truthful auction satisfies three economic properties: truthfulness, individual rationality and budget balance (45). The spectrum auction is different from the traditional auction in terms of spectrum reusability. The spectrum reusability can significantly improve the spectrum utilization. However, it makes the design of a truthful auction mechanism more challenging (31; 75).

To encourage users' participation and avoid market manipulations, most of the previously proposed auction models are designed to satisfy three major economic properties: truthfulness, individual rationality and budget balance. TRUST (76) satisfies these three properties but only in single-channel auction, where all channels are assumed to be identical. True-MCSA (10) extended their work in multi-channel auctions with an assumption that all channels have the same properties. Therefore, how to ensure the economic robustness for multi-channel auctions for heterogeneous spectrum is still an open problem and it motivates us to propose a truthful multi-channel auction mechanism for heterogeneous spectrums.

Motivated by the group-buying behaviors in the Internet based service such as Groupon (3), Lin et al. (42) proposed a group buying-based spectrum auction, called TASG. In TASG, secondary buyers are grouped together into a secondary network to compete against other secondary networks. The secondary buyers will share the whole channel if their secondary network wins the auction. Yang et al. (65) proposed a new algorithm to compute the budget in the group buying-based auction, which improves the system performance in terms of the number of successful transactions and the number of winning

secondary users. These schemes are based on single-sided buyer-only auction. However, in reality, both buyers and sellers are selfish, which cause competitions among sellers as well as buyers. Therefore, the double auction is essential for spectrum allocation. The group-buying based double auction is still an open problem, this motivates us to propose a truthful group buying-based double auction for both single-channel and multi-channel.

## **1.2 Previous Works**

Recently, auction has been a widely used method to allocate the spectrums (13). So auction has been extensively studied by many researchers (37; 53; 55). There are transmit power auctions (27; 58), spectrum band auctions (7; 36; 49; 51), combinatorial spectrum auctions (66; 72; 73; 74), online spectrum auction (9; 29; 39; 68), two-dimensional spectrum auctions (79) and spectrum pricing (6; 30; 44; 62). However, these schemes do not consider the budget limitations for the buyers. In reality, the buyer may not afford the whole channel. Therefore, the group-buying concept is essential.

Previously, many spectrum auction approaches have been proposed. In (22), Gandhi introduced a general framework for spectrum auction. In (33; 75), spectrum allocation was focused on single-sided buyer-only auction. However, in reality, both buyers and sellers are selfish, which cause competitions among sellers as well as buyers. Therefore, the double auction is essential for the spectrum allocation. In this chapter, we will briefly review different types of double auctions in the existing works.

### **1.2.1 Single-channel Double Auction**

In (76), Zhou introduced a general framework for truthful double spectrum auction called TRUST. TRUST satisfies all the economic properties and enables spectrum reuse. This is the first paper of a

truthful double spectrum auction. In this paper, interference graph is used for grouping. In this paper, it employed bid-independent uniform pricing to maintain economic robust at the substantial cost of efficiency.

In (61), the discriminatory pricing is considered in auction design, and the truthfulness is achieved. In this paper, bidders are charged of varying prices for the same item they purchase.

Recently, Dong et al. introduce the combinatorial auction to solve the spectrum reusability in time-frequency division manner (15). Different from other works using auction mechanisms, they model the spectrum opportunity in a time-frequency division manner. This model caters to much more flexible requirements from buyers and has very clear application meaning.

In (25), the authors also investigated the online problem. They proposed a framework in which buyers can request the usage of one channel with specific frequency band type in a specific area and during some specific time periods.

These schemes are based on the “single channel” assumption, i.e., each buyer can request at most one channel and each seller provides at most one channel. In real world applications, each buyer/seller could request/provide more than one channel.

### **1.2.2 Multi-channel Double Auction**

In (26), the author proposed a truthful multi-channel double auction. This is the first multi-unit double auction approach for wireless spectrum allocation. In this paper, it provides a new clearing price mechanism to assure the strategy-proof property and other essential economic properties.

In (10), a framework for truthful double multi-channel spectrum auctions is proposed. In this paper, it introduced novel virtual buyer group splitting and bidding algorithms, and applied a winner determi-



nation and pricing mechanism to achieve truthfulness and other economic properties. This paper also shows that we can improve the auction efficiency by choosing a proper bidding algorithm and using a base bid.

In (56), it supported flexible spectrum bidding including range bidding and strict bidding. This breaks the “single-channel” assumption. The clearing rule in this paper is able to translate the auction with multi-unit bids into an equivalent auction with single-unit bids. In this paper, the concept of translate-into-one bid is introduced to minimize the network transactions so as to avoid additional transaction overhead.

### **1.2.3 Double Auction for Spectrum Heterogeneity**

In (59), the authors considered the spatial heterogeneity. They designed a double spectrum auction that represented spectrum locality in spectrum markets with a colored graph. But they didn’t mention the frequency heterogeneity. They assumed all interferences among the buyers are the same. However, each seller has different channels and the center frequencies of these channels are different. The low-frequency channels have larger interference than the high-frequency ones. So same buyers will have different interference relationship in different channels. In (19; 25), both spatiality and frequency heterogeneity were considered. In (19), the grouped spectrum buyers according to their non-identical conflict relationships in heterogeneous spectrums to explore spectrum reusability. They also introduced a novel pricing schemes to improve the system efficiency. In (57), we proposed a truthful double auction with multiple items for heterogeneous spectrums called MAHES. Both heterogeneity and multiple items are considered.

TABLE I: COMPARING OF DIFFERENT AUCTION SCHEMES

Existing auction schemes	VCG	TRUST	SPRITE	District	TAHES	MAHES	TASG	Ours
Truthfulness	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Budget balance	No	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Individual rationality	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Spectrum reuse	No	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Multi-unit trading	No	No	Yes	No	No	Yes	No	Yes
spatial heterogeneous	No	No	No	Yes	Yes	Yes	No	No
frequency heterogeneous	No	No	No	No	Yes	Yes	No	No
Budget Limitation	No	No	No	No	No	No	Yes	Yes

#### 1.2.4 Group-buying Based Auction

Lin et al. (42) proposed a group buying-based spectrum auction, called TASG. In TASG, secondary buyers are grouped together into a secondary network to compete against other secondary networks. The secondary buyers will share the whole channel if their secondary network wins the auction. Yang et al. (65) proposed a new algorithm to compute the budget in the group buying-based auction, which improves the system performance in terms of the number of successful transactions and the number of winning secondary users. These schemes are based on single-sided buyer-only auction. We extended their work to double auction. We considered both multi-channel and single-channel double auction for spectrum group buying. Table I shows the summary of the major existing schemes in double spectrum auction.

### 1.3 Overview of Our Approach

In this thesis, at first, we propose a framework for a truthful multi-channel double auction mechanism for heterogeneous spectrums. For convenience, we use MAHES to describe our method in the rest of this thesis. In MAHES, buyers/sellers can request/provide arbitrary number of channels. Each seller locates at different places. All the channels provided by the seller have different center frequencies. The interference relationships among buyers are different at different frequencies. So the buyer grouping mechanism has to consider non-identical conflict relationship to explore spectrum reusability. MAHES also introduces a novel virtual grouping and matching algorithm to solve the multi-channel problem. Our method satisfies the requirement of truthfulness and improves the spectrum utilization.

The main contributions of this method are as follows:

- To the best of our knowledge, MAHES is the first multi-channel double auction mechanism for heterogeneous spectrums. It allows buyers/sellers to request/provide multiple channels under the spectrum heterogeneity condition.
- We propose a novel virtual buyer grouping and matching algorithm, which can successfully solve the multi-channel problem.
- We prove that MAHES guarantees the three economic properties: truthfulness, individual rationality and budget balance.

Second, we consider cognitive radio networks with multiple spectrum holders (SHs) and multiple secondary networks (SNs). Each SN consists of one secondary access point (SAP) and a number of secondary users (SUs). An SAP in each SN acts as a group leader or an agent. The SAP collects bids

from the grouped SUs. In our scheme, there are two types of auctions: single-sided buyer-only auction and double auction. In each SN, SUs submit their bids to the SAP. The SAP decides which SUs can join the group according to their bids. After collecting the money from SUs, SAPs take part in the spectrum auction held by different SHs. The auction between the SAPs and SHs is a sealed-bid double auction. We also refer to it as inner auction. The auction between the SUs and the SAPs is a single-sided buyer-only auction. We refer to it as outer auction. To ensure the truthfulness of the auction, our scheme is based on the “single channel” assumption, i.e. each buyer can request at most one channel and each seller provides at most one channel.

The key contributions of this scheme are as follows:

- To the best of our knowledge, our scheme is the first double auction considering group-buying. It considers the budget of the SUs and avoids market manipulation.
- We prove that our scheme guarantees the three economic properties: truthfulness, individual rationality and budget balance for both inner and outer auctions.
- Our simulation results verify these economic properties.

Third, we extended single-channel group buying-based double auction to multiple channels. We proposed a novel virtual grouping method and channel matching mechanism. Multiple spectrum holders (SHs) and multiple secondary networks (SNs) are considered. Each SH will provide at least one channel. In each SN, there are a secondary access point (SAP) and a number of secondary users (SUs). Each SU may request more than one channel. The SAP acts as a group leader or an agent. Due to the “multi-channel” assumption, we design the steps of virtual buyer group (VBG) splitting, group budget

calculation, winner determination, and pricing to achieve truthfulness and other economic properties. Our scheme consists of two types of auctions: single-sided buyer-only auction and multi-channel double auction. In each SN, SUs submit their bids to the SAP. The SAP splits the SUs into different VBGs and decides which VBGs can join the auction according to their bids. Then SAPs take part in the spectrum auction held by different SHs. We call the auction between the SAPs and SHs as inner auction. The inner auction is a multi-channel double auction. We also call the auction between the SUs and the SAP as the outer auction. The outer auction is a single-sided buyer-only auction. To ensure the truthfulness of the auction, we assume that the buyers and sellers submit truthful number of channels.

The key contributions of this scheme are as follows:

- To the best of our knowledge, our scheme is the first multi-channel double auction for spectrum group buying. It allows buyers and sellers to request and provide multiple channels.
- We propose a novel virtual buyer grouping and bidding algorithm in each SN, which can successfully solve the multi-channel problem.
- We prove that our scheme guarantees the three economic properties: truthfulness, individual rationality and budget balance for both inner and outer auction.

#### **1.4 Outline of the Thesis**

In this chapter, we first show the importance of spectrum allocation in wireless communications. Then we briefly describe the motivation to use spectrum auction in spectrum allocation. Then we review the previous work in spectrum allocation area. We also describe our novel methods those are designed

for solving the spectrum heterogeneity and spectrum group-buying. The rest of the thesis is structured as follows.

- Chapter 2 describes the preliminaries.
- Chapter 3 describes MAHES, a truthful multi-channel auction mechanism for heterogeneous spectrums.
- Chapter 4 introduce group buying-based double auction.
- Chapter 5 introduce truthful group buying-based double auction for cognitive radio networks.
- Chapter 6 introduce a truthful multi-channel double auction mechanism for spectrum group-buying.
- Chapter 7 conclusion and future work.

## CHAPTER 2

### PRELIMINARIES

In this chapter, we introduce the definition of auction theory at first. Then we briefly introduced different types of auction. We also review the economic constraints and some important definitions in auction mechanisms. At last, we briefly describe the special characters of spectrum auction:

- Interference and Reusability
- Super-additive and Sub-additive
- Group Structure

#### 2.1 Auction Theory

An auction is a process used to obtain the price of a commodity with an undetermined value. There are three categories of auction (Fig. 6), supply auction, demand auction and double auction. In a supply auction, multiple sellers offer their commodities to a buyer. In a demand auction, multiple buyers bid for a commodity sold by a seller. In a double auction, multiple buyers bid to buy commodities from multiple sellers.

The components in an auction market are as follows:

- A seller is a market entity who wants to sell the commodity. A seller offers the price (i.e. the asking price) and the amount of commodity to be traded by auction.
- The buyer is an entity who wants to buy the commodity. A buyer submits a bid in terms of price and bidding quantity to buy through the auction.

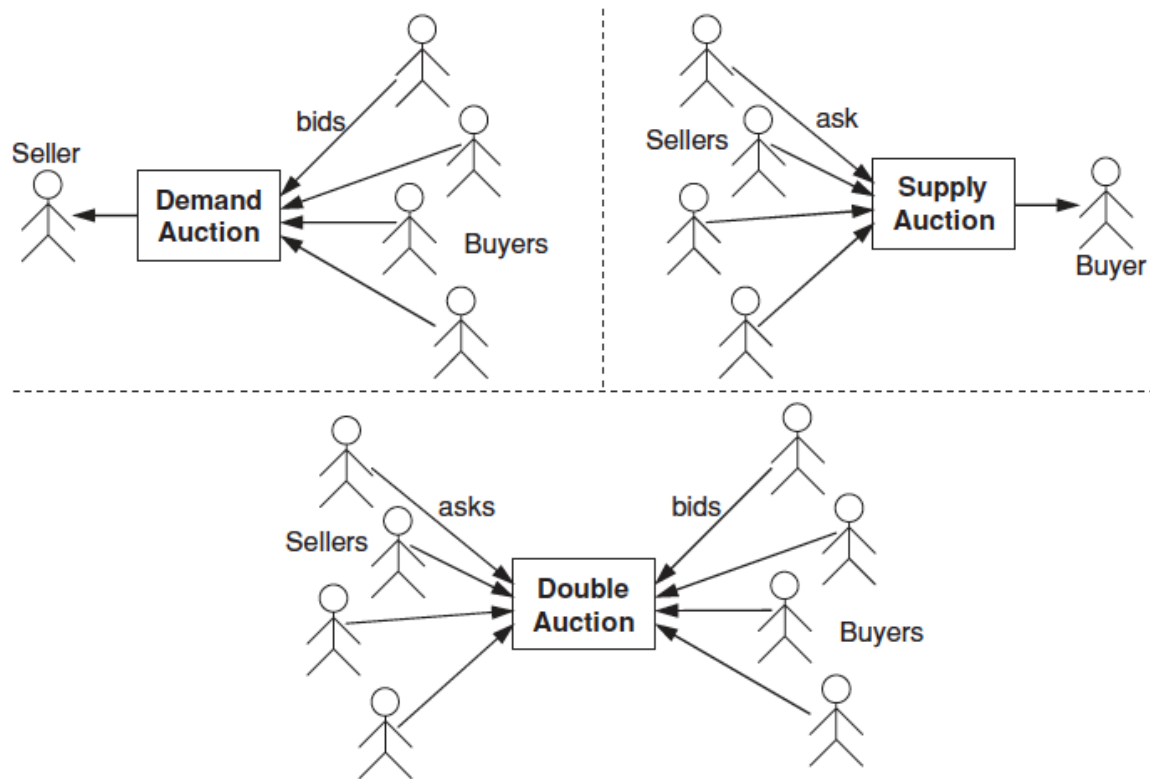


Figure 6: Three types of auction

- The trading/clearing price is the price of each commodity to be traded in an auction market. The trading price has to satisfy the asking price and the bidding price (e.g. it should be higher than or equal to the asking price but lower than or equal to the bidding price) from the seller and the buyer, respectively.



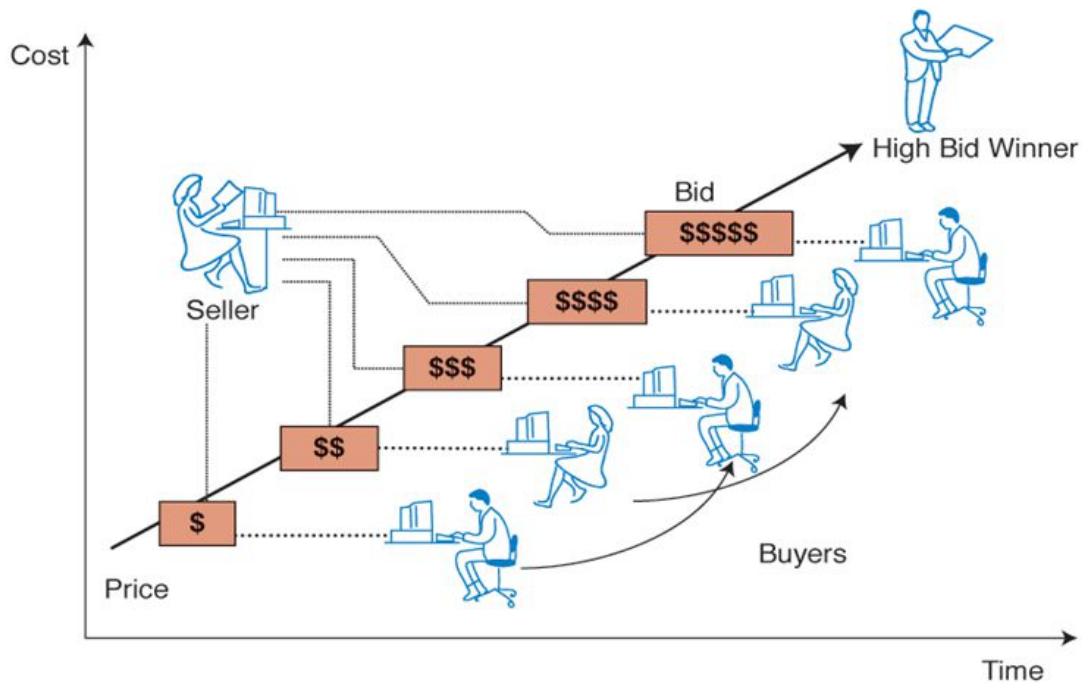


Figure 7: English auction, ascending price

## 2.2 Single-sided Auction

In single-sided auction, there is one auctioneer - which could be a seller or a buyer. If the auctioneer is a seller, we call this case of single-sided auction a supply auction. If the auctioneer is a buyer, we call this case of auction a demand auction. In the single-sided auction, the bidders submit their bids to the auctioneer. Then the auctioneer decides to sell or buy from any bidder. The four major types of single-side auction are the increasing-price auction (English auction), decreasing-price auction (Dutch auction), first-price sealed-bid auction, and second-price sealed-bid auction (Vickrey auction) (64).

In an increasing-price or English auction (Fig. 7), the minimum price is set. Then, a bidder submits

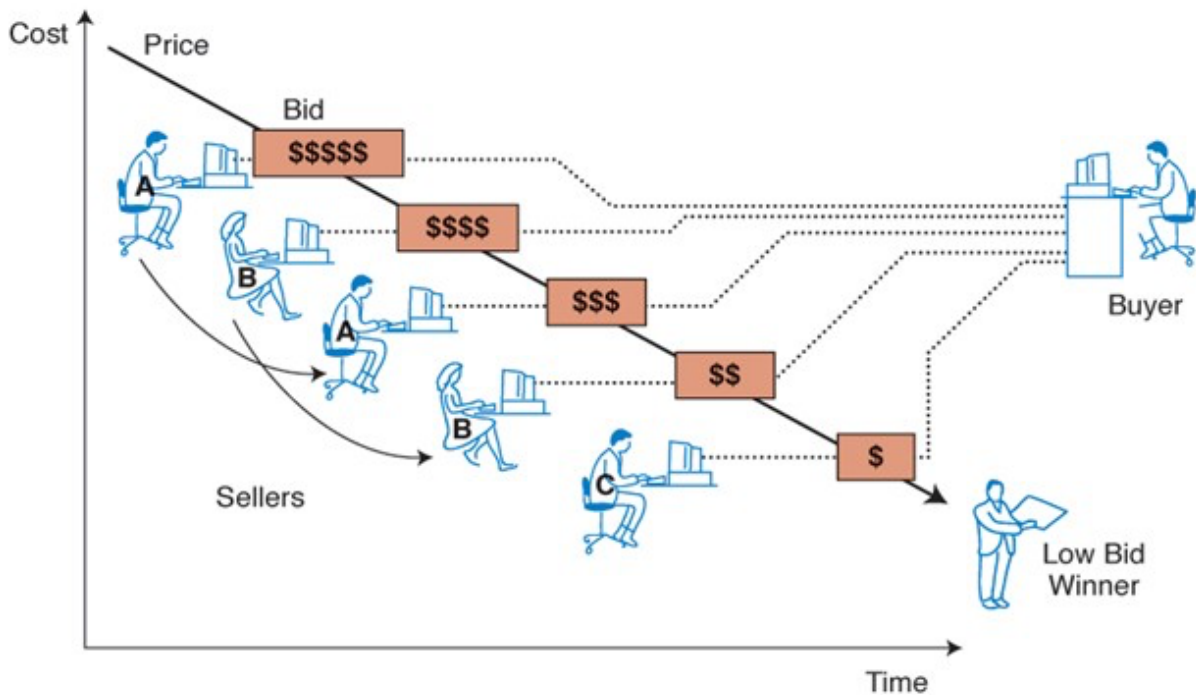


Figure 8: Dutch auction, descending price

a bid to the auctioneer. The bidding price is higher than the minimum price. Each bidder may observe the bids from other bidders and compete by increasing its bidding price. Thereafter, the bidding price is continuously increased until the auction is terminated. There are two cases of auction terminations. The first case is that the auction ends after a limited time duration. The second case is that all the bidders stop submitting bids. The bidder with the highest bidding price wins the auction.

In a decreasing-price auction or Dutch auction (Fig. 8), the maximum price is set. Then, a bidder submits a bid to the auctioneer. The bidding price is lower than the maximum price. The first bidder to accept the price will win the auction. Different from an increasing-price auction, the bidder information

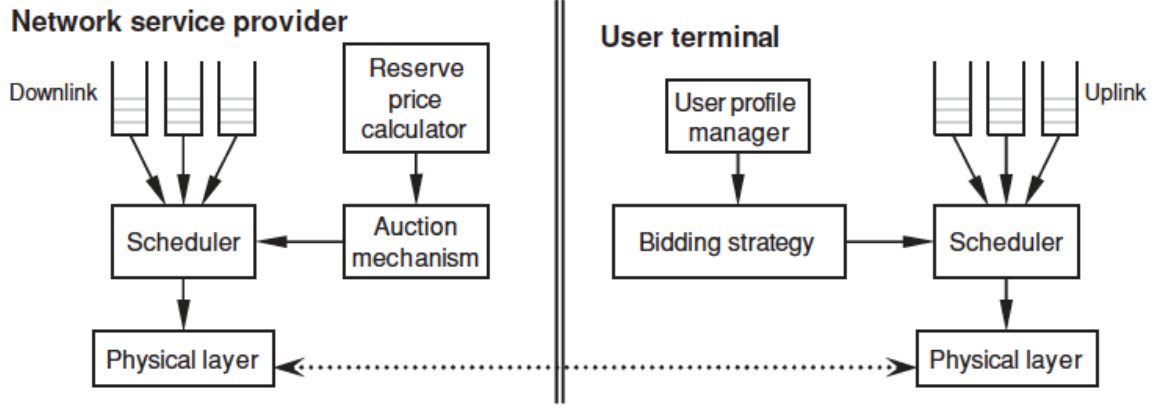


Figure 9: Joint scheduling and spectrum bidding architecture.

does not need to be revealed other than the winning bidder and its bidding price.

In a sealed-bid auction, all bidders submit sealed bids independently. The auctioneer opens the bids and determines the winning bidder whose bidding price is the highest. For the winning bidder, the price to pay the auctioneer could be its bidding price (i.e. first-price auction) or the second highest bidding price (i.e. second-price auction or Vickrey auction).

Spectrum auction may be jointly designed with a resource allocation framework (e.g. scheduling). For example, in (38) joint scheduling and spectrum bidding architecture is proposed (Fig. 9). The downlink and uplink schedulers will use information from the auction mechanism and the user's bidding strategy. Therefore, the user can bid for the spectrum based on the QoS requirement, while the network service provider can charge a price according to the bids from all users.

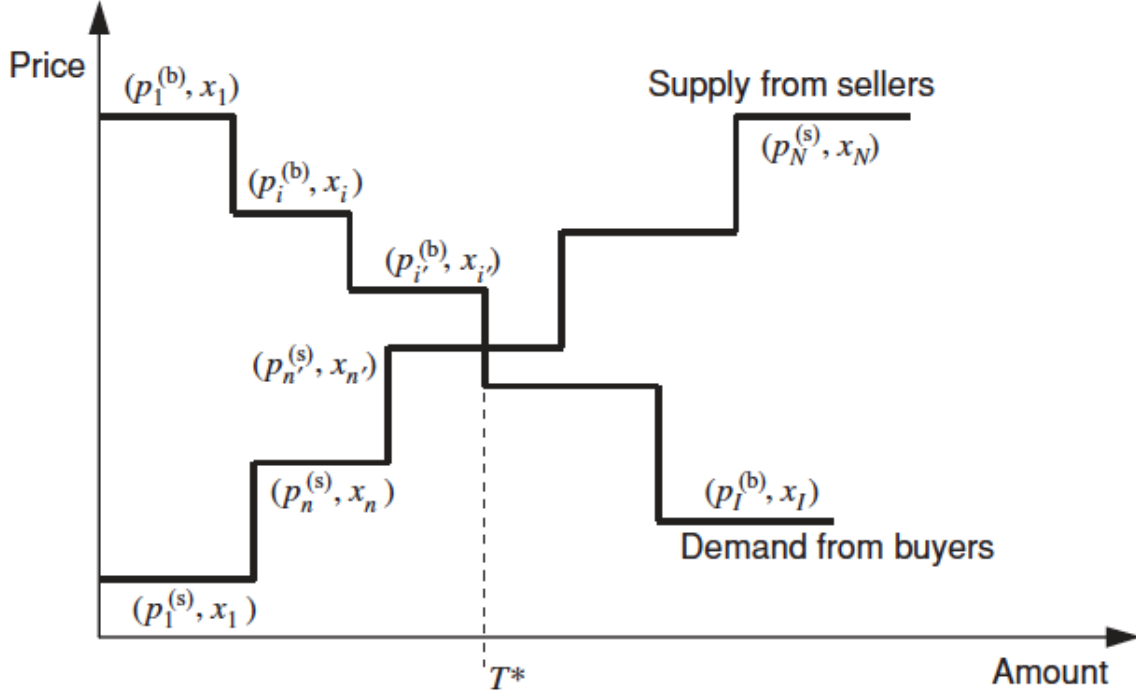


Figure 10: Example of ordered demand and supply in a double auction.

### 2.3 Double Auction

In a double auction (48), there are  $I$  buyers and  $N$  sellers. Each buyer  $i$  wants to purchase  $x_i$  items and each seller  $n$  wants to sell  $y_n$  items. The information about  $x_i$  and  $y_n$  are available publicly. In a double auction, a buyer  $i$  reports a price  $p_i^{(b)}$  per unit of the commodity. A seller  $n$  reports a price  $p_n^{(s)}$ . Without loss of generality, we may assume  $p_1^{(b)} > p_2^{(b)} > \dots > p_I^{(b)}$  and  $p_1^{(s)} < p_2^{(s)} < \dots < p_N^{(s)}$ . If two prices are equal, their indexes are interchangeable. Each seller or each buyer can set different prices for different items, where the seller and the buyer sells and buys each item separately.

To determine the trading price in double auction, the demanded quantities from all buyers are arranged according to the ascending order of price. The supplied quantities from all sellers are arranged according to the descending order of price (Fig. 10). At the trading point  $T^*$ , the aggregated demand and supply intersect, and hence  $n'$  sellers will sell  $T^*$  items to  $i'$  buyers.

when a central controller is available in this double auction, an optimization problem can be formulated to obtain the quantity of items to be traded. We call this central controller an auctioneer. Both buyers and sellers submit their bids simultaneously to an auctioneer. Then, the auctioneer matches those bids from the buyers and sellers. This matching process should satisfy two constraints: (1) the number of winning buyers is equal to the number of winning sellers, (2) the utilities of winners are non-negative and the utilities of losers are 0. After matching, the auctioneer decides the winning price. In this thesis, we consider a Vickrey double auction mechanism. The  $k$ th Vickrey double auction sells to the highest  $k$  buyers at the  $k + 1$ th bid of buyers and buys from the lowest  $k$  sellers at the  $k + 1$ th of sellers. Therefore, the number of winning bidders is  $k$  and the winning price is the  $k + 1$ th bids of buyers and sellers.

#### **2.4 Economic Constraints and Definitions in Auction Mechanisms**

To encourage users' participation and avoid market manipulations, most of the previously proposed auction models are designed to satisfy three major economic constraints: truthfulness, individual rationality and budget balance. TRUST (76) satisfies these three properties but only in single-channel auction, where all channels are assumed to be identical. True-MCSA (10) extended their work in multi-channel auctions with an assumption that all channels have the same properties. Therefore, how to ensure the economic robustness for multi-channel auctions for heterogeneous spectrum is still an open problem. Due to the budget limitation, the buyer may not afford the whole channel, the group-buying

concept is proposed. However, the existing methods were based on single-side buyer-only auction. These method cannot avoid market manipulations of the sellers. These open problems motivate our research in this thesis.

### 2.4.1 Economic Constraints

The three economic constraints (45) are defined as follows:

**Definition 1.** *Truthfulness: An auction is said to be truthful if neither the sellers nor the buyers can improve their utilities by bidding untruthfully. For each seller or buyer,  $U^t \geq U$ , where  $U^t$  is the utility if the seller or the buyer bids truthfully, and  $U$  is the utility that the seller or the buyer gets after bidding.*

**Definition 2.** *Individual Rationality: An auction is said to be individually rational if neither the sellers nor the buyers will get a negative utility. That means every seller who wins the auction will be paid more than its bid and every buyer who wins the auction will pay less than its bid,  $u_n^s \geq 0$  for all  $n = 1, \dots, N$ , and  $u_m^b \geq 0$  for all  $m = 1, \dots, M$ .*

The individual Rationality property guarantees that if bidders submit their true value, they will not receive negative utility, which provides them some incentives to act truthfully.

**Definition 3.** *Budget Balance: An auction mechanism is budget balanced if the auctioneer's profit  $\Phi \geq 0$ . The profit of the auctioneer is the difference between the total revenue of buyers and the expense paid to sellers,*

$$\Phi = \sum_{m=1}^M p_m^b r_m^w - \sum_{n=1}^N p_n^s c_n^w. \quad (2.1)$$

This property ensures the auctioneer has an incentive to set up the auction. In practice, the auctioneer can charge a transaction fee.

#### **2.4.2 Definitions in Auction Mechanism**

The basic definitions in the auction mechanism (45) are defined as follows:

**Definition 4.** *Collusion: A ring that some bidders form to bid against outsiders to gain extra benefits by manipulating the auction result.*

In our thesis, 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 5.** *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.*

**Definition 6.** *Utility: For a buyer, 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 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.*

### **2.5 Special Characters of Spectrum Auction**

The special characters of spectrum auction are describes (41) as follows:

#### **2.5.1 Interference and Reusability**

We can refer 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.

To avoid interference, the transmissions can be isolated by spatial domain, temporal domain, frequency domain, or code domain. In the existing research works, researchers focus on spatial and temporal reusability, which do not need to involve extensive knowledge of technical aspects. The “interference and reusability” properties are usually formulated as constraints. Therefore, the auctioneer needs to solve the optimization problems to obtain the winners and their payments. Usually the constraints are based on either spatial or temporal reusability.

- Spatial reuse: is the most frequently used as it enables the non-interfering nodes that transmit at the same channel simultaneously. Usually, we assume a pre-knowledge of conflict graph (Fig. 11), which describes the interference 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.
- Temporal reuse: 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 and channel states. The output of this problem is the channel allocation result in the temporal domain.

### 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

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



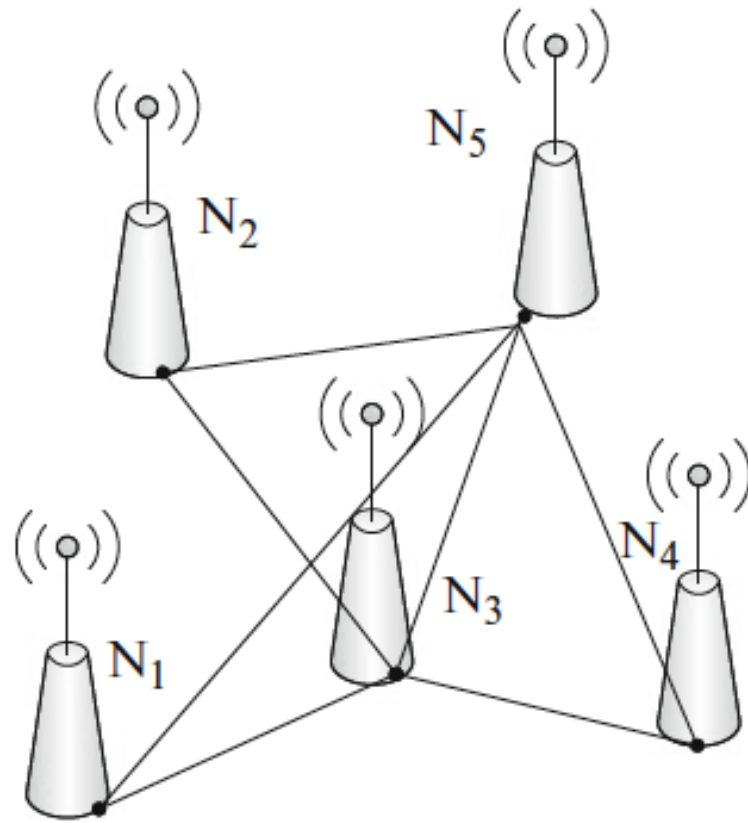


Figure 11: Illustration of conflict graph

always holds, then the super-additive property is satisfied. This property can be explained by the marginally decreasing effect in economics. For example, bidders - usually large telecom companies

- often have super-additive preferences for licenses that are adjacent to each other. When the items are substitutes, this property usually holds. If

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

always holds, we say that the sub-additive property is satisfied. When the items are complements, 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.

### **2.5.3 Group Structure**

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

The group structure can be exogenous or endogenous. 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 Chapter 5, users belonging to the same secondary network are form within the same group and the auction takes this as input. Endogenous means that the group structure is formed in the process of the auction. For example, in (57; 76), the auctioneer randomly divides non-interfering bidders into groups.

## **Statement of Published work**

Chapter Three: A truthful multi-channel auction mechanism for heterogeneous spectrums(Previously published as Wang, A. and Liu, D. (2014) A truthful multi-channel double auction mechanism for heterogeneous spectrums, Wireless Personal Communications, 77(3):1677-1697)

## CHAPTER 3

### A TRUTHFUL MULTI-CHANNEL AUCTION MECHANISM FOR HETEROGENEOUS SPECTRUMS

In this chapter, we propose MAHES, a truthful Multi-channel Auction Mechanism for Heterogeneous Spectrum. At first, we introduce the problem model of MAHES. Then we discuss the challenges when consider the spectrum heterogeneity. After that, we describe our method in three sections:

- Grouping and Matching
- Winner determination
- Pricing Mechanisms

At last, we prove that our method satisfies the economic properties, truthfulness, individual rationality and budget balance. Then we show the simulation results of evaluating the performance of MAHES and study the auction efficiency and auction revenue for spectrum auctions.

#### 3.1 Problem Model

In this thesis, we consider the scenario where  $M$  buyers (unlicensed users) try to buy multi-channel from  $N$  sellers (licensed users). We propose a single round multi-unit double auction method. We suppose that each buyer requests at least one channel and each sellers provides at least one channel. All bids are sealed and private. A third-party acts as an auctioneer. All sellers and buyers submit their bids privately to the auctioneer without knowing of others' offers. The auctioneer decides the winning bids and the payment.

We use  $(s_n, c_n)$  to denote the bid from seller  $n$ , where  $s_n$  is the minimum per-channel payment required by seller  $n$  ( $s_n > 0$ ).  $c_n$  is the number of channels that seller  $n$  will provide ( $c_n \geq 1$ ).  $v_n^s$  is the true valuation of each channel and  $v_n^c$  is the true number of channels that seller  $n$  provided. We use  $p_n^s$  as the per-channel payment received if seller  $n$  wins the auction. For a buyer  $m$ , its bid is denoted as  $(b_m, r_m)$ .  $b_m$  is the maximum per-channel price that the buyer  $m$  wants to pay ( $b_m > 0$ ).  $r_m$  is the number of channels that buyer  $m$  will request ( $r_m \geq 1$ ). Also we use  $v_m^b$  to represent the true valuation of each channel and  $v_m^r$  the true number of channels requested by the buyer  $m$ . Similarly, we use  $p_m^b$  to represent the per-channel price to pay if the buyer  $m$  wins the auction.

Therefore, the utility of the seller  $n$  is:

$$u_n^s = \begin{cases} c_n^w (p_n^s - v_n^s), & \text{if seller } n \text{ wins,} \\ 0, & \text{otherwise,} \end{cases} \quad (3.1)$$

Also, the utility of the buyer  $m$  is:

$$u_m^b = \begin{cases} r_m^w (v_m^b - p_m^b), & \text{if buyer } m \text{ wins,} \\ 0, & \text{otherwise.} \end{cases} \quad (3.2)$$

where  $c_n^w$  and  $r_m^w$  are the number of channels of seller  $n$  and buyer  $m$  ( $1 \leq c_n^w \leq c_n$ ,  $1 \leq r_m^w \leq r_m$ ).

In this report, our model is based on two assumptions. First, both sellers and buyers can submit untruthful prices for each channel (10). Second, independent from the prices, the submitted number of channels must be truthful.

### 3.2 The Challenges

The foremost difficulty in spectrum auction is the spectrum heterogeneity. In reality, different spectrum owners locates in different places, so they are only available to some of the buyers, which is called spatial heterogeneity. At the same time, each seller has different channels and the center frequencies of these channels are different. The low-frequency channels have larger interference than the high-frequency ones. So same buyers will have different interference relationship in different channels. This is called frequency heterogeneity. The details of spectrum heterogeneity are as followed:

#### 3.2.1 Spatial Heterogeneity and Interference Temperature Limit

Spatial heterogeneity is defined as spectrum availability at different locations. Since sellers and buyers are always in different locations, we divide the entire region into several disjoint sub-regions. Each seller can appear only in one sub-region. Therefore, auctions will not influence each other in different sub-regions. In Fig. 14, for example, we separate the entire region into four sub-regions. In each sub-region, we have unique sellers that are not shared by other sub-regions.

In previous work, (76) designed a double auction mechanism that groups buyers together by finding independent sets from an interference graph. An interference graph is a conflict graph that models the interference relationship among the buyers, shown in Fig. 15. In a conflict graph, if two nodes interfere with each other, we draw an edge between them. For example, in Fig. 15,  $B_2$  conflicts with  $B_1$  and  $B_3$ . Since it is possible that we cannot find a common channel in each group, this mechanism is not suitable for the spatial heterogeneity condition. If there is no common channel in the buyer group, the auction will not continue unless we set the group bid to 0. For example, in Fig. 15, by finding the independent sets from an interference graph, the 9 buyers can be grouped into 3 groups,

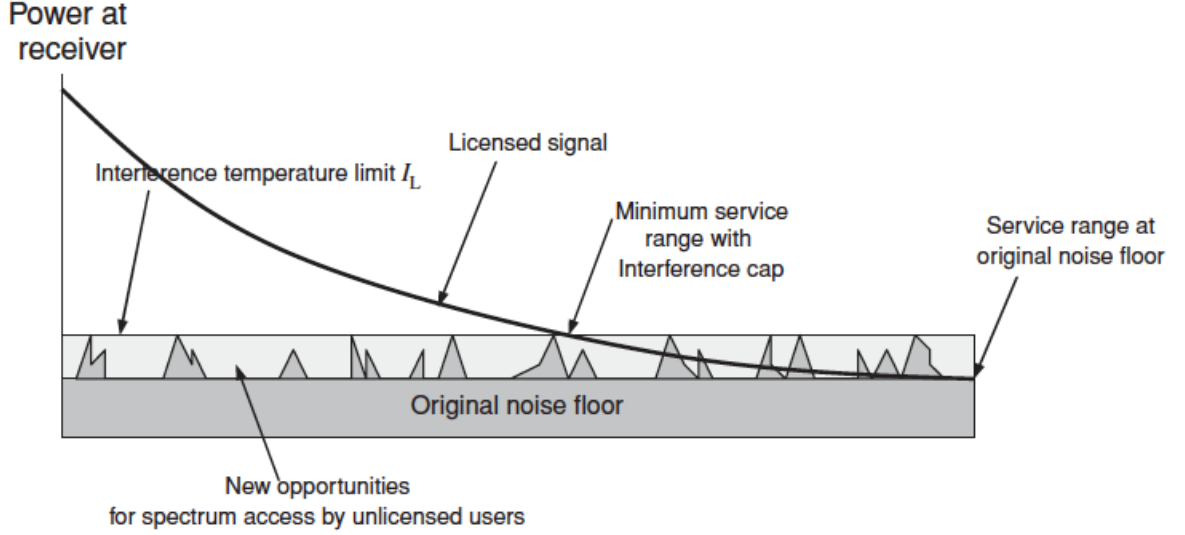


Figure 12: Interference temperature model

$\{B_1, B_3, B_6, B_9\}$ ,  $\{B_2, B_4, B_7\}$  and  $\{B_5, B_8\}$ .  $\{B_1, B_3, B_6, B_9\}$  is an independent set since there are no edges between them. In Fig. 15,  $B_1(L_1)$  means that only  $L_1$  is available to  $B_1$ . So there is no common channel for buyers in each group.

References (19) and (25) considered the spatial heterogeneity in their works. However, besides the location and geographic region, for each seller, we still need to consider the interferences between buyers and sellers. To ensure the QoS of sellers (licensed users), the FCC Spectrum Policy Task Force has recommended a new method in measuring interference (21), called interference temperature (Fig. 12). The concept of interference temperature is defined as follows:

$$I_T(f_c, W) = \frac{P_I(f_c, W)}{KW}$$

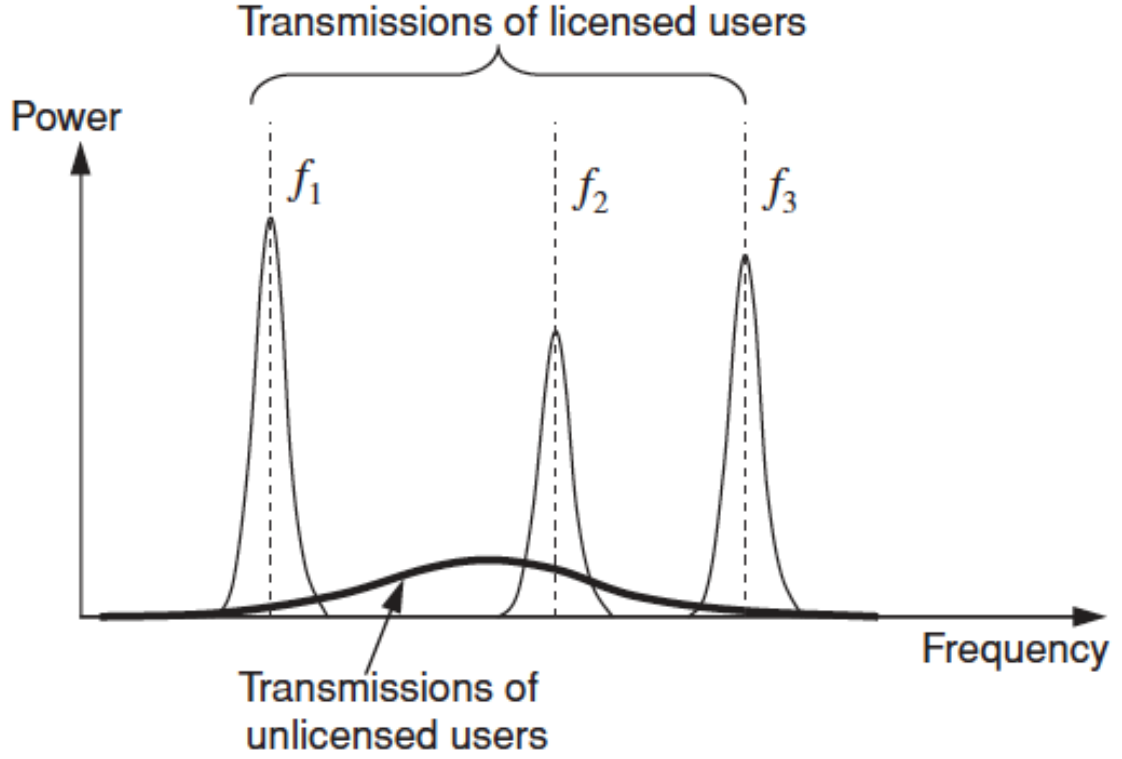


Figure 13: Interference temperature model for licensed users

where  $P_I(f_c, W)$  is the average interference power in Watts for a bandwidth  $W$  Hz centered at frequency  $f_c$  and  $K$  is Boltzmann's constant ( $K = 1.38 \times 10^{-23}$ ) in Joules per Kelvin degree.

Reference (12) introduced two models of interference temperature, an ideal version and a generalized version. In our model, we use the general interference temperature model for licensed users (Fig. 13). It is represented as:

$$I_T(f, W) + \frac{MP}{KW} \leq I_L(f) \quad (3.3)$$



where  $P$  is the transmit power of an unlicensed user over a particular frequency band,  $f$  is the center frequency,  $W$  is the bandwidth of the channel used by the unlicensed user,  $I_L(f)$  is the interference temperature limit, and  $M$  is a multiplicative attenuation factor due to path loss and fading in the link between the unlicensed transmitter and the licensed receiver. This constraint is in terms of the unlicensed transmitter's parameters.

The constraints described above determine the maximum power that buyers (unlicensed users) can transmit. This information will be stored in the database of the auctioneer. When sellers submit their bids, they submit the interference temperature limits to the auctioneer as well at the same time. Similarly, buyers submit their transmitted power to the auctioneer as well as their bids. Most likely, some buyers will not satisfy the transmitted power condition, then their utility will be set to 0. For example, buyer  $m$  locates in the same region as seller  $n$ . If the transmitted power of buyer  $m$  is larger than the maximum power that seller  $n$  can tolerate, buyer  $m$  cannot participate in the auction and its utility will be set to 0.

### **3.2.2 Frequency Heterogeneity**

Frequency heterogeneity is defined as different transmission ranges of different frequencies. (19) presents the frequency heterogeneity by assuming that spectrum owner has only one channel with wide range frequencies. That is suitable for CDMA system. In our model, we consider the frequency heterogeneity condition in OFDM system. Each spectrum owner (seller) has multiple channels. Each channel has a different center frequency and its bandwidth is narrow. According to the propagation model rec-

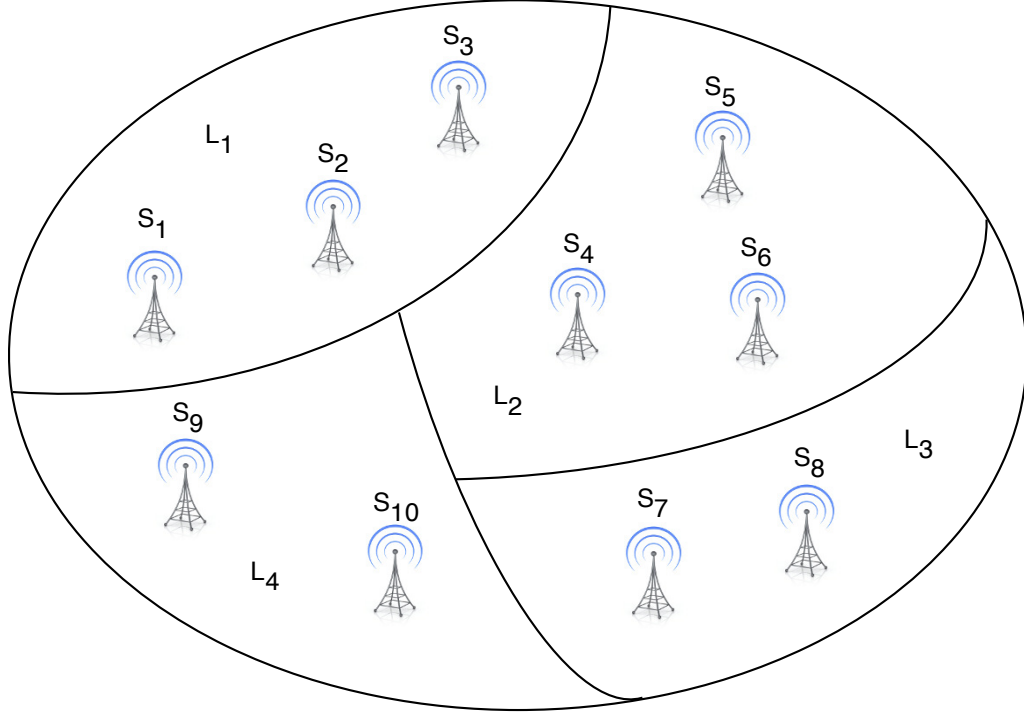


Figure 14: The entire region is separated into 4 disjoint sub-regions.

ommended by ITU, the path loss between two nodes will be affected only by the center frequency. Then, the total path loss  $L$  is defined as follows:

$$L = 10 \log f^2 + \gamma \log d + P_f(n) - 28$$

where  $f$  is the frequency of transmission in megahertz (MHz),  $d$  is the distance in meters (m),  $\gamma$  is the distance power loss coefficient and  $P_f(n)$  is the floor loss penetration factor. For each channel, the path

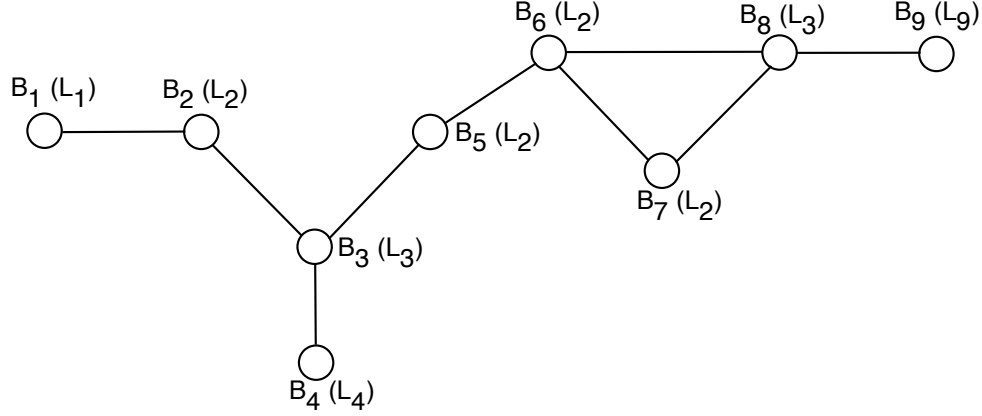


Figure 15: An interference graph of 9 buyers.

loss is different even if the distance between two nodes is the same. So the interference relationships among the buyers are different.

### 3.3 Grouping

In this section, we allocate buyers and sellers into local markets according to their location information. In each local market, we group sellers and buyers into virtual group (VG). In each VG, sellers and buyers only provide and request one channel. We define the VG as a sub-market. In each sub-market, we put buyers into different groups according to the interference relationship.

#### 3.3.1 Grouping Sellers and Buyers into Local Markets

All sellers locate at different geographic locations. The auctioneer groups sellers into different sub-regions according to the geo-location database (20). This seller grouping method is bid-independent. In auctions, bid-independent is very important for grouping. It ensures the truthfulness. Each sub-region is defined as a local market. These local markets are independent to each other. In each local

market, sellers have power requirements for buyers. According to (3.3), each seller has a maximum transmitted power limitation for buyers. The set of maximal powers that buyers can transmit is  $\mathbf{P} = \{P_1, P_2, \dots, P_N\}$ . Without loss of generality, we assume  $P_1 \leq P_2 \leq \dots \leq P_N$ . Each buyer submits its transmitted power and bid at the same time. The set of the transmitted powers of buyers is  $\mathbf{T} = \{T_1, T_2, \dots, T_M\}$ . In Fig.16,  $k$  is the number of sub-regions,  $\mathbf{A} = \{a_{i,j} | a_{i,j} \in \{0, 1\}\}_{M \times k}$ , and  $a_{i,j}$  represents the sub-region  $j$  availability to the buyer  $i$ . If  $a_{i,j} = 1$ , it means sub-region  $j$  is available to buyer  $i$ .  $Q(j)$  is the minimum transmitted power allowed in sub-region  $j$ . In this step, the buyers and the sellers are grouped according to different locations. The grouping procedure is shown in Algorithm 1. In line 8,  $\mathcal{S}$  is the set of buyer groups available to buyer  $i$ . In line 9,  $\mathcal{s}$  is the set of sub-regions available to buyer  $i$ . If there are several sub-regions available to a buyer, we will choose the sub-region which has the highest  $Q(j)$ .

### 3.3.2 Virtual Grouping

After the first step, all buyers are allocated to local markets. Since all local markets are independent to each other, we only need to show the virtual grouping for one local market. The same method is applied to other local markets.

In local market, each seller provides at least one channel to buyers, and each buyer requests for at least one channel. The center frequencies of these channels are different. So we need to split buyers into different virtual buyer groups. In each virtual buyer group, only one channel is requested. The maximum number of channels requested by the buyers is denoted as  $D = \max_{i \in \mathcal{B}(j)}(r_i)$ . Then we can split all the buyers into  $D$  virtual buyer groups, called VBG. The procedure is shown in Fig. 17.

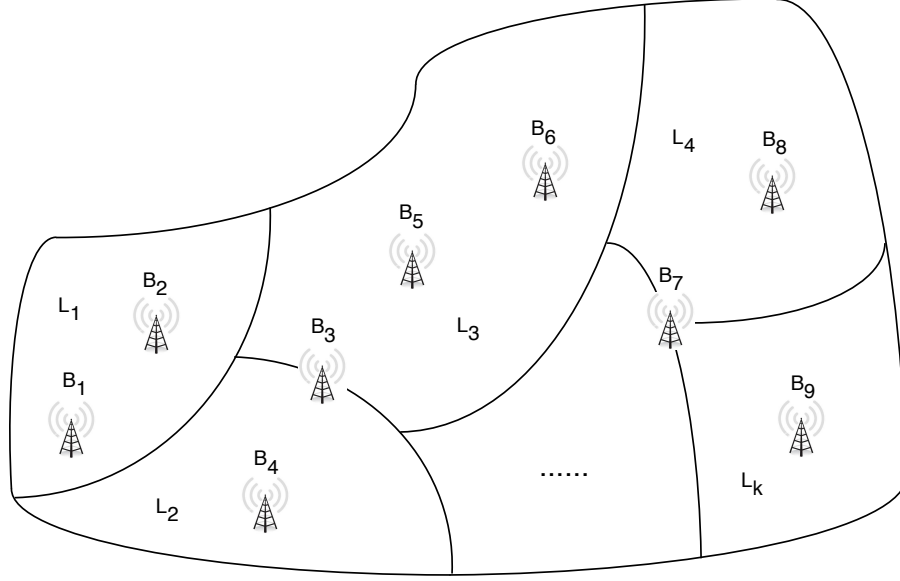


Figure 16: Different sub-regions with buyers.

In Fig. 17, there are 5 buyers, and the maximum number of requested channels is 4. So we split all buyers into 4 virtual buyer groups. Each virtual buyer group requests only one channel. After splitting the buyers, we also split the sellers. This will avoid the complexity caused by the frequency heterogeneity. Similar to splitting buyers, in each virtual seller group, sellers only provide one channel. The maximal number of channels provided by the sellers is donated as  $C = \max_{n \in B(j)} c_n$ . Then we split all the sellers into  $C$  virtual seller groups, called VSG.

After these two steps, we match each VSG with a VBG to generate a virtual group (VG) which contains both buyers and sellers. Here we assume that the channels provided by sellers are always less than the channels requested by buyers, i.e.,  $C \leq D$ . Therefore,  $|VG| = C$ . For example, there are 3 VGs in Fig. 17. The procedure of VG splitting and matching is shown in Algorithm 2. We define each

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**Algorithm 1** Seller-Buyer Grouping
 

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1: //  $B(j)$  represents the set of grouped buyers allocated to sub-region  $j$ 
2: //  $b_i$  represents the buyer  $i$ 
3: loop
4:    $i = 1 \rightarrow M$ 
5:    $S = \emptyset$ 
6:   loop
7:      $j = 1 \rightarrow l$ 
8:      $S = \{B(j) | a_{i,j} = 1 \wedge T_i \geq Q(j)\}$ 
9:      $s = \{j | a_{i,j} = 1 \wedge T_i \geq Q(j)\}$ 
10:    end loop
11:    if  $|S| > 1$  then
12:       $S = \{B(j) | \max_{j \in s} Q(j)\}$ 
13:    end if
14:     $B(j) = b_i \cup B(j), B(j) \in S$ 
15:  end loop

```

---

VG as a sub-market. Each sub-market is independent. We can do double auction in each sub-market at the same time. Every double auction here is a single unit auction for heterogeneous spectrums. We use the same auction mechanism for all the sub-markets. Therefore, we only illustrate the procedure in one sub-market.

### 3.3.3 Buyer Grouping in Sub-markets

Reference (76) groups multiple non-conflicting buyers together. However, it assumes all the channels are the same and the interference relationship between two nodes is always identical. In our model, each channel has a different center frequency. The interference among the buyers will change in different channels. Our grouping algorithm satisfying the following constraints (19):

Interference free constraint: Any two buyers in the same group will not interfere each other in any channels.

---

**Algorithm 2** VG splitting and matching
 

---

```

1:  $B(j)$  represents the set of grouped buyers allocated to sub-region  $j$ 
2:  $i$  represents the buyer in sub-region  $j$ .
3:  $n$  represents the seller in sub-region  $j$ .
4:  $D = \max_{i \in B(j)}(r_i)$  // maximal number of channels requested by buyers in sub-region  $j$ .
5:  $C = \max_{n \in B(j)}(c_n)$  // maximal number of channels provided by sellers in sub-region  $j$ .
6:  $VBG = \emptyset$  //the set of VBGs in sub-region  $j$ .
7:  $VSG = \emptyset$  //the set of VSGs in sub-region  $j$ .
8:  $VG = \emptyset$  //the set of VGs in sub-region  $j$ .
9: loop
10:    $k = 1 \rightarrow D$ 
11:    $VBG_k = \emptyset$  //  $k$ th VBG
12:   loop
13:     for each  $i$ 
14:       if  $r_i \geq k$  then
15:          $VBG_k = VBG_k \cup \{i\}$ 
16:       end if
17:   end loop
18:    $VBG = VBG \cup VBG_k$ 
19: end loop
20: loop
21:    $g = 1 \rightarrow C$ 
22:    $VSG_g = \emptyset$  //  $g$ th VSG
23:   loop
24:     for each  $n$ 
25:       if  $c_n \geq g$  then
26:          $VSG_g = VSG_g \cup \{n\}$ 
27:       end if
28:   end loop
29:    $VSG = VSG \cup VSG_g$ 
30: end loop
31: Sort  $VBG_1, VBG_2, \dots, VBG_D$  in a non-increasing order according to their sizes,
32:  $|VBG_1| \geq |VBG_2| \geq \dots \geq |VBG_D|$ .
33: Sort  $VSG_1, VSG_2, \dots, VSG_C$  in a non-increasing order according to their sizes,
34:  $|VSG_1| \geq |VSG_2| \geq \dots \geq |VSG_C|$ .
35: loop
36:    $v = 1 \rightarrow C$ 
37:    $VG_v = \{VBG_v, VSG_v\}$ 
38:    $VG = VG \cup VG_v$ 
39: end loop

```

---

Common channel constraint: In each buyer group, there is at least one common channel that is available for all buyers.

Buyer grouping is equivalent to finding the independent sets in a conflict graph. So we need to find the independent sets of buyers. Different from (19), each buyer group can bid all the available channels.

The procedure of buyer grouping is as follows:

Step 1: Start from the first available channel.

Step 2: modeling the interference relationship by a conflict graph.

Step 3: Using the existing algorithm to find the independent sets in the conflict graph, such as the algorithms described in (47) and (54).

Step 4: If there exists other available channels, repeat Steps 2 and 3 in each independent set. Otherwise, stop grouping if all channels have been considered.

From the above procedure, it is obvious that all channels are available in each buyer group. The common channel constraint is satisfied. Moreover, according to the grouping procedure, any two buyers will not conflict with each other in any channels. Then the interference free constraint is satisfied. Meanwhile, all buyer grouping procedures in sub-market are bid-independent. Therefore, it ensures the truthfulness in the auction. The process of grouping is illustrated in Fig. 18.

### **3.4 Winner Determination**

After the buyer grouping, the same winner determination procedure of TRUST is adopted.  $S_1, S_2, \dots, S_m$  represent the bids of sellers in one sub-market.  $W_1, W_2, \dots, W_G$  represent the buyer groups in the same sub-market.  $n_g = |W_g|$  is denoted as the number of buyers in  $W_g$ . The group bid  $\beta_g$  is:



$$\beta_g = \min\{b_m | m \in W_g\} n_g \quad (3.4)$$

We sort the bids of sellers in ascending order and the group bids of buyers in descending order:

$$S_1 \leq S_2 \leq \dots \leq S_m.$$

$$\beta_1 \geq \beta_2 \geq \dots \geq \beta_G.$$

After the sorting, we find a maximal  $K$  that  $\beta_K \geq S_K$ . Then the top  $K - 1$  sellers and  $K - 1$  buyer groups are the winners. Algorithm 3 demonstrates this procedure.

---

**Algorithm 3** Winner determination

---

- 1: //  $S_1, S_2, \dots, S_m$  represents the seller bids in one sub-market
  - 2: //  $W_1, W_2, \dots, W_G$  represents the buyer groups
  - 3: //  $\beta_g$  and  $n_g$  represent the group bid and number of buyers in group  $B_g$
  - 4: **loop**
  - 5:    $g = 1 \rightarrow G$
  - 6:    $n_g = |W_g|$
  - 7:    $\beta_g = \min\{b_m | m \in W_g\} n_g$
  - 8: **end loop**
  - 9: Sort  $S_1, S_2, \dots, S_m$  in a non-decreasing order
  - 10:  $S_1 \leq S_2 \leq \dots \leq S_m$ .
  - 11: Sort  $\beta_1, \beta_2, \dots, \beta_G$  in a non-increasing order
  - 12:  $\beta_1 \geq \beta_2 \geq \dots \geq \beta_G$ .
  - 13: Find  $K$ ,  $K = \max\{k | \beta_k \geq S_k\}$
  - 14: Winning buyer groups are:  $W_1, W_2, \dots, W_{K-1}$ .
  - 15: Winning sellers are:  $S_1, S_2, \dots, S_{K-1}$ .
-

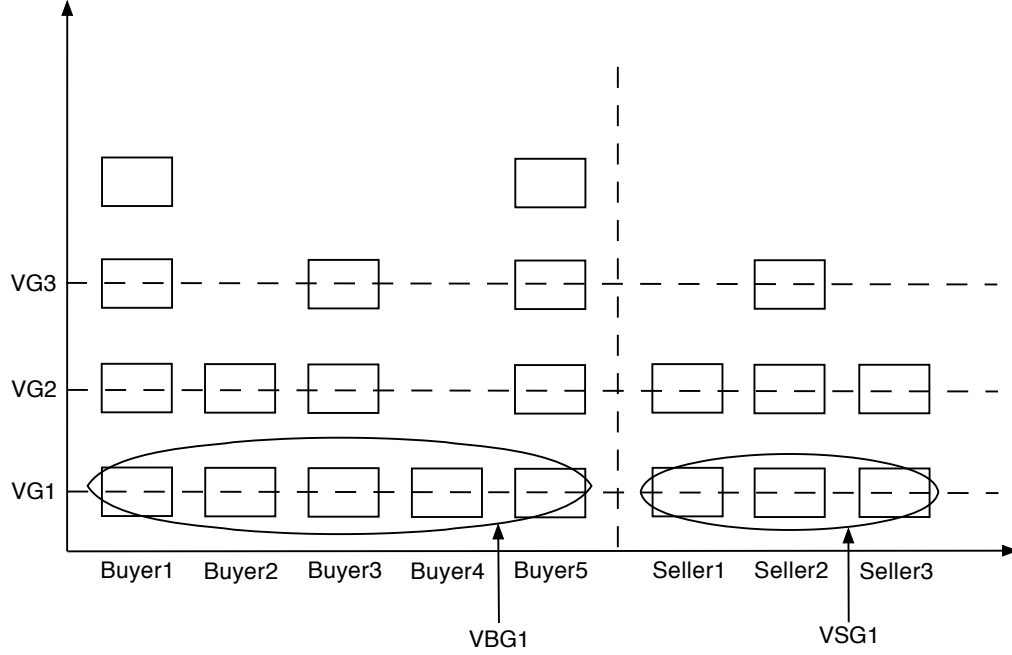


Figure 17: Virtual grouping for 5 buyers and 3 sellers.

### 3.5 Pricing

To ensure the truthfulness, we charge the same price from each winning buyer group, and pay the same price to each winning sellers. In our model, we only consider the uniform pricing. (76) proves that uniform pricing guarantees the individual rationality and truthfulness. We charge each winning group the  $K$ th buyer group's bid  $\beta_K$  and pay each winning seller the  $K$ th seller's bid  $S_K$ . In each winning buyer group, all buyers share the group price equally. The per-channel price for each buyer need to pay in group  $W_g$  is:

$$p_m^b = \beta_K / n_g \quad (3.5)$$

where  $p_m^b \in W_g$ .

For each sub-market, the auctioneer's profit is:

$$\Sigma_c = (K - 1)(\beta_K - S_K) \quad (3.6)$$

The local profit of the auctioneer is:

$$\Psi_l = \sum_{c=1}^C \Sigma_c \quad (3.7)$$

where  $C$  is the total number of sub-markets in each region.

For the whole double auction, the profit of the auctioneer is:

$$\Phi = \sum_{k=1}^L \Psi_k \quad (3.8)$$

where  $L$  is the number of local markets.

### 3.6 Proof of Auction Properties

**Theorem 1.** *MAHES is budget balanced, i.e.,  $\Phi \geq 0$ . MAHES is also individually rational.*

*Proof.* It is easy to prove  $\Sigma_c \geq 0$ , because  $\beta_K \geq S_k$  from (3.6). According to (3.7) and (3.8), it is obvious that  $\Phi \geq 0$ . So MAHES is budget balance.

Since no seller will receive payment less than its bid and no buyer will pay more than its bid according to the winner determination, individual rationality is also guaranteed.  $\square$

Next, we will prove the truthfulness. According to Definition 1, we need to prove that neither seller nor buyer could improve its utility by bidding untruthfully. Before we prove the truthfulness, we need to prove that the winner determination is monotonic and pricing is bid-independent.

**Lemma 1.** *If a buyer wins the auction by bidding  $b_m$ , it also wins by bidding  $b'_m$  ( $b'_m > b_m$ ).*

*Proof.* Case 1: If  $b_m$  is the minimal bid in the buyer group  $W_g$ ,  $b'_m > b_m$ , we have  $\beta'_g > \beta_g$ . If  $\beta_g$  wins the auction, then  $\beta'_g$  will also win the auction. The rank of the buyer group will not be lower than it did before.

Case 2: if  $b_m$  is not the minimal bid in the buyer group  $W_g$ . Then even  $b'_m > b_m$ , the rank of  $W_g$  will not change. If  $\beta_g$  wins the auction,  $\beta'_g$  also wins.

Therefore, the winner determination of buyers are monotonic. □

**Lemma 2.** *If a seller wins the auction by bidding  $s_n$ , it also wins by bidding  $s'_n$  ( $s'_n < s_n$ ).*

*Proof.* If  $s'_n < s_n$ , the rank of the seller  $n$  will not be lower than it did before. So if  $s_n$  wins the auction,  $s'_n$  also wins. Therefore, the winner determination of sellers are monotonic. □

**Lemma 3.** *If the buyer (seller) wins the auction, it will be charged (paid) the same price for different bidding.*

*Proof.* The winning prices for sellers and buyers are  $S_K$  and  $\beta_K$ . For seller  $n$ , if it wins by bidding  $s_n$  and  $s'_n$ , the price paid to it is always equal to  $S_K$ . For buyer  $m$ , if it wins the auction by bidding  $b_m$  and  $b'_m$ , the price charged to it is always equal to  $\beta_K/n_g$ .

Therefore, pricing is bid-independent. □

TABLE II: FOUR POSSIBLE CASES

Case	1	2	3	4
Seller or Buyer lies	Fail	Fail	Win	Win
Seller or Buyer bids truthfully	Fail	Win	Fail	Win

Now we can prove the truthfulness of MAHES.

**Theorem 2.** *MAHES is truthful for buyers.*

To prove MAHES is truthful for buyers, we need to show that any buyer cannot receive higher utility by bidding untruthfully. There are four auction results when the buyer bids truthfully and untruthfully. Table II lists all the possible cases.

*Proof.* Case 1: The buyer is denied for both bidding truthfully and untruthfully. And it will be charged 0. This leads to the same utility.

Case 2: This only happens when the buyer bids lower than its true valuation. And it leads to the result that the rank of the group is lower than the buyer bids truthfully. In this case, the utility is 0 when the buyer lies. The utility is no less than 0 when the buyer bids truthfully. Therefore, the buyer will not gain more utilities if it bids untruthfully.

Case 3: This only happens when  $b_m > v_m^b$ . We use  $\beta'_g$  and  $\beta_g$  to represent the group bid if the buyer bids untruthfully and truthfully. If bidding untruthfully will affect the rank of the buyer groups, the buyer's bid  $b_m$  must be the minimal bid in the group. If it bids truthfully,  $\beta_g = v_m^b n_g$ . The winning price is  $\beta_K$ . The buyer wins the auction if it bids untruthfully, then  $\beta'_g \geq \beta_K \geq \beta_g$ . Then the price

charged to it will be  $\beta_K/n_g$ . The utility is  $v_m^b - \beta_K/n_g \leq 0$ . Therefore, the buyer cannot gain more utility by bidding untruthfully.

Case 4: For both sides, the buyer wins the auction. Then it will be charged the same price. It cannot receive more utilities by lying.

Therefore, MAHES is truthful for buyers. No buyer can improve its utility by bidding untruthfully.

□

**Theorem 3.** *MAHES is truthful for sellers*

*Proof.* Similar to the proof of Theorem 2, we need to check the four cases in Table II.

Case 1: Same as the case of buyers.

Case 2: This only happens when the seller bids higher than its true valuation. For a higher bids, the rank of it is lower than it bids truthfully. In this case, the utility is 0 for lying and non-negative when it bids truthfully. So the seller cannot get more utility if it bids untruthfully.

Case 3: This only happens when  $s_n < v_n^s$ . Let  $S_K$  and  $S'_K$  represent the payment to the seller when it bids truthfully and untruthfully. When it bids truthfully, it loses the auction. Then  $S_K \leq v_n^s$ . It will win the auction if it bids untruthfully. It lowers its bid. Then  $s_n \leq S'_K$ , the seller will be paid  $S'_K$  ( $S'_K \leq S_K$ ). Then we can conclude that  $S'_K \leq v_n^s$ . Therefore, the utility is  $S'_K - v_n^s \leq 0$ . The seller cannot gain more utility by bidding untruthfully.

Case 4: For both sides, the seller wins the auction. It will be paid the same price. Thus, it cannot get more utilities by lying.

Therefore, MAHES is truthful for sellers. No seller can improve its utility by bidding untruthfully.

□

### 3.7 Simulation Setup

In our simulation, sellers and buyers are randomly distributed in a  $100 \times 100$  grids. Each seller can provide at most 3 channels and each buyer can buy at most 5 channels. There are 50–200 buyers and 10–100 spectrum sellers. We split all sellers and buyers into 4 disjoint regions.

In the auction, we randomly generate buyers' bids in  $[0, 6)$ . Due to the spectrum reusability, each channel can be shared by more than one buyers. So we randomly generate sellers' bids in  $[2, 12)$ , which is higher than the buyers' bids. In our simulation, all the results are averaged over 1000 runs.

The performance metrics are auction efficiency ( $\theta$ ), the number of channels traded ( $N_t$ ), the per-channel spectrum efficiency ( $\alpha$ ) and the auction revenue  $\xi$ . The auction efficiency is defined as the number of traded channels out of the total numbers.

$$\theta = \frac{N_t}{\sum_n^N c_n} \quad (3.9)$$

The auction revenue is defined as the bid-weighted sum of all winning buyers' channels minus ones of all winning sellers' channels.

$$\xi = \sum_{m=1}^M b_m r_m^w - \sum_{n=1}^N s_n c_n^w \quad (3.10)$$

Other metrics are defined as follows:

$$N_t = \sum_{n=1}^N c_n^w \quad (3.11)$$

$$\alpha = \frac{\xi}{N_t} \quad (3.12)$$

### 3.8 Auction Efficiency

In this section, we study the auction efficiency, auction revenue and per-channel efficiency of MAHES.

In Fig. 19, we set the number of buyers to a fixed number. As the number of sellers increases, the auction efficiency also increases. The increase of sellers means increasing the supplies. So we can conclude that the increase of supplies will increase the auction efficiency. From Fig. 19, we can find that at the same level of sellers, when we add more buyers, the auction efficiency will decrease. Fig. 19 also shows that the auction efficiency is close to 0.9 when the number of sellers is 100. In Fig. 20, however, we notice that the maximal revenue is not always achieved when the efficiency is optimal. Since more possible transaction pairs appear when more buyers participate in the auction, the admission threshold will be reduced. Therefore, a higher revenue will be achieved when we have more buyers. In Fig. 21, we can find that the per-channel efficiency decreases while increasing the number of sellers. Here the buyer number is still fixed.

In (59), it shows that a simple extension of TRUST for local market is possible if the traded license areas are of some special shapes. Without considering the frequency heterogeneous, the author still found that this extension is problematic. In practice, the traded areas don't need to be of some special shapes. In our algorithm, we also consider the frequency heterogeneous. Thus, the channels are not identical. In TRUST, the grouping algorithm will work only when all the channels are same. Without considering the spacial heterogeneous, TRUST is still not applicable. In order to compare with TRUST, we set all the channels to be same and only consider one local market. In Fig. 22, the degradation performance of our scheme and TRUST are proposed. All the buyers are deployed under either uniform



topology or clustered topology. Even only the multi-unit trading is considered, our scheme still performs much better than TRUST.

Similar to (59), we check the performance of the simple extension of TRUST applied in local market without considering the frequency heterogeneous. According to Fig. 23, we can see that, the efficiency of TRUST extension is really low. By comparing TRUST extension with our algorithm, we can conclude that our algorithm performs much better than TRUST extension.

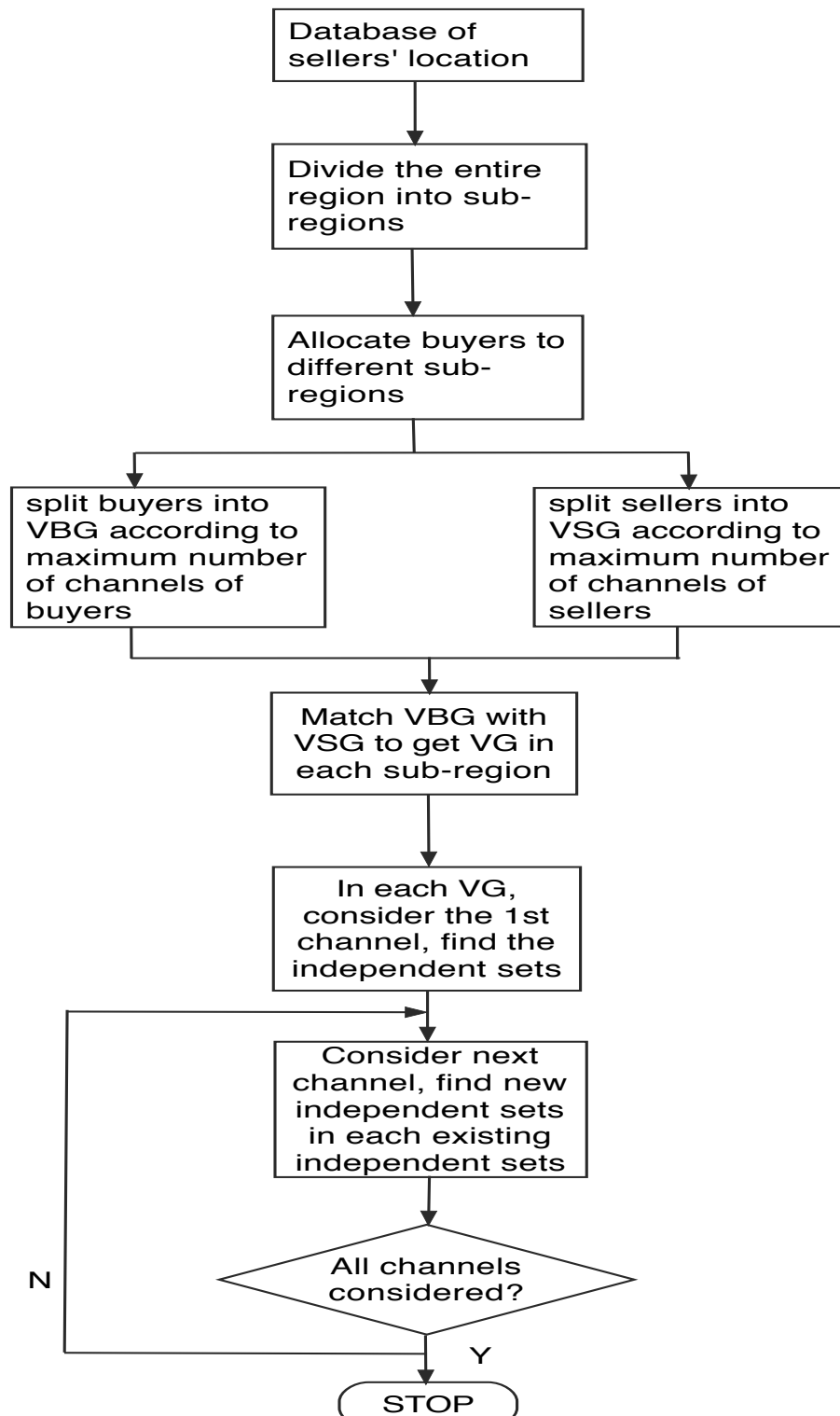


Figure 18: The flow chart of grouping process.

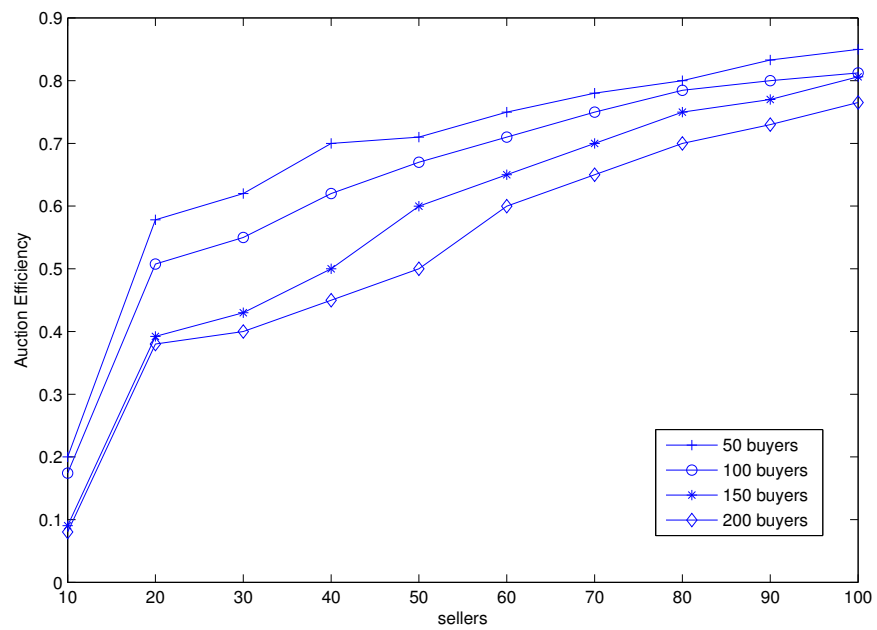


Figure 19: Auction efficiency of MAHES

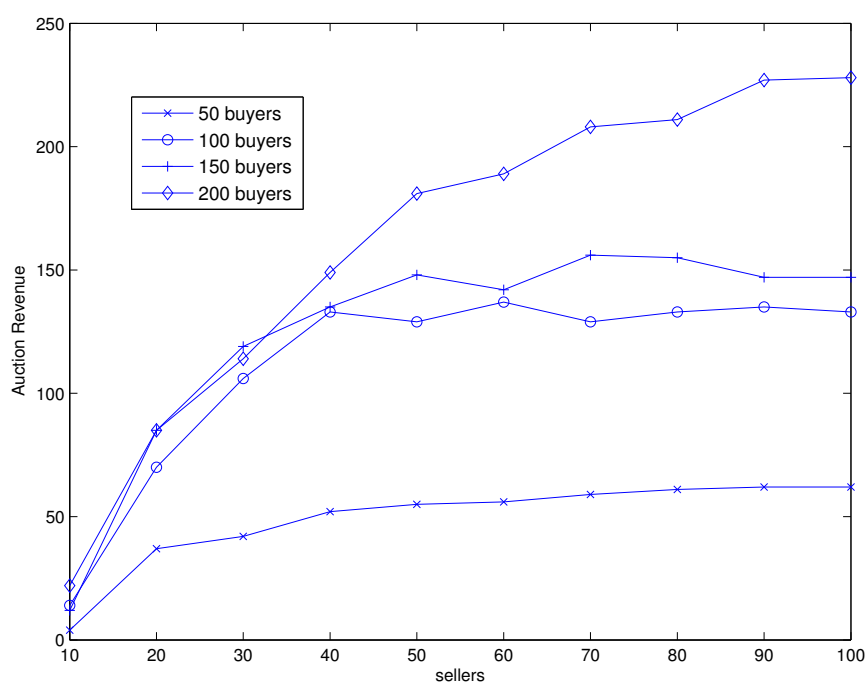


Figure 20: Auction revenue of MAHES

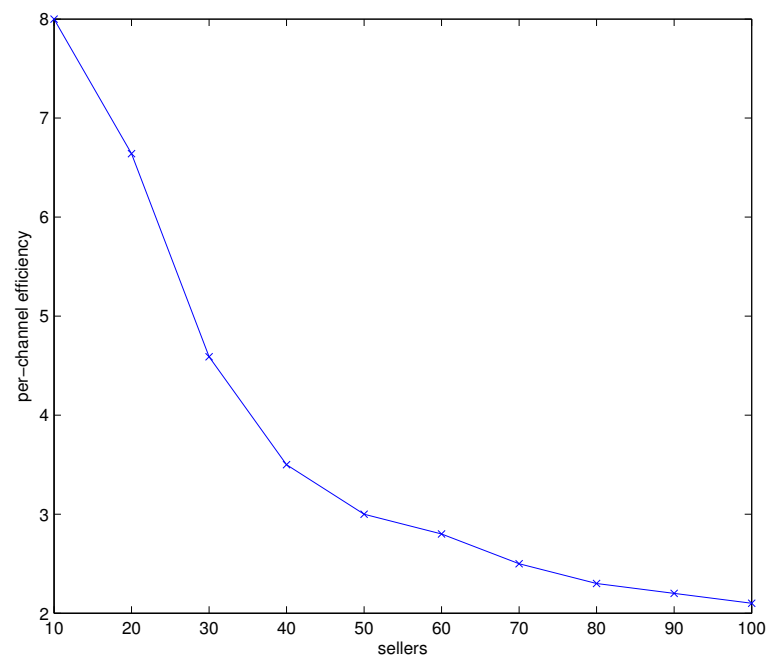


Figure 21: Per-Channel efficiency of MAHES

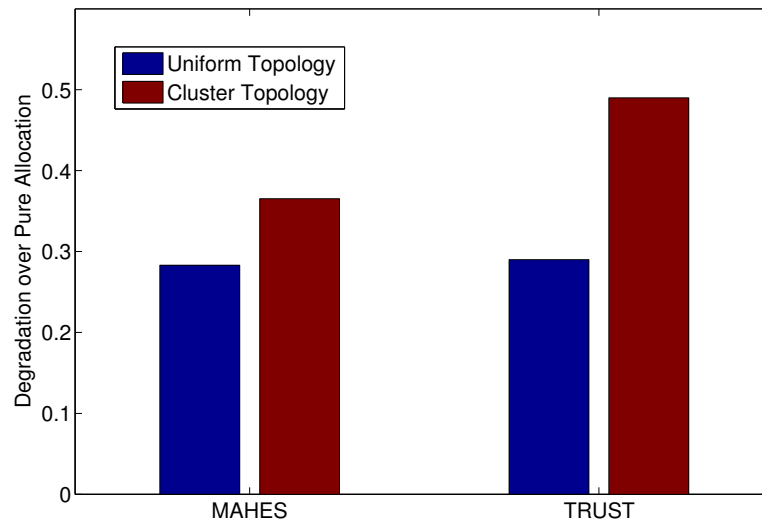


Figure 22: Degradation over pure allocation of MAHES

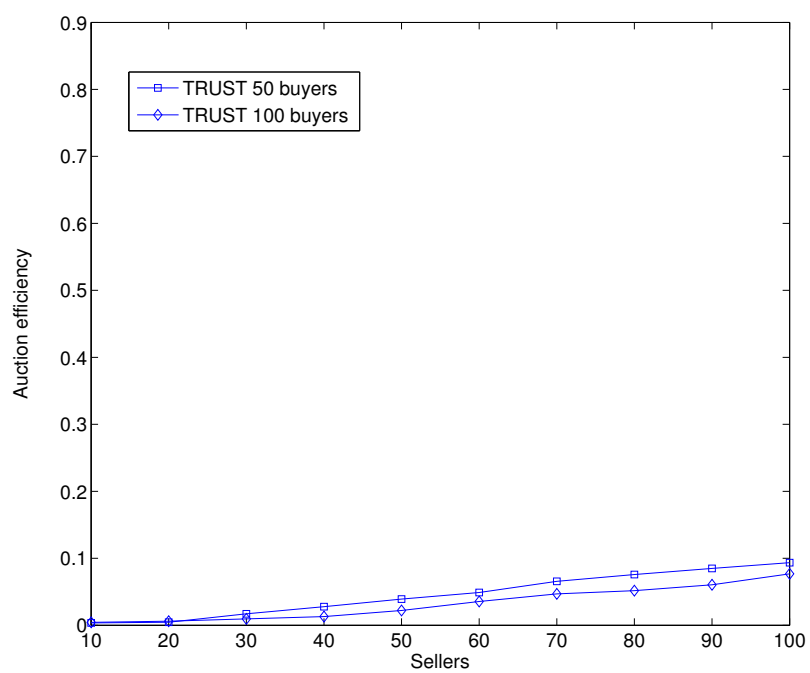


Figure 23: Auction efficiencies of TRUST extension

## CHAPTER 4

### GROUP BUYING-BASED DOUBLE AUCTION

In this chapter, we introduce the motivation for us to design a truthful group buying-based double auction at first. Then we briefly introduce the group-buying concept and the challenges for designing such auction. At last, we describe the three-stage auction framework proposed in this thesis.

#### 4.1 The Motivation

Spectrum auction has been widely used to spectrum allocation. However, recent spectrum auction results have shown that small network providers cannot benefit from the auction directly because of the high price asked by the spectrum holders. For example, in recent German spectrum auction (2) carried out in 2010, there were 41 spectrum blocks to be sold at a total price \$5.5bn. Only three mobile operators got these blocks. In secondary market, secondary users belonging to different networks will compete for unused spectrums from spectrum holders. Therefore, similar cases will happen in the secondary market too. Since individual secondary user has a limit budget, he may not afford a whole spectrum by himself. Motivated by the group buying service on the Internet, secondary users can be grouped together as a super buyer to participate in the spectrum auction to increase their chance to win the auction. Recently, some work studied the group-buying spectrum auction. But their schemes are based on single-sided buyer-only auction. However, in reality, both buyers and sellers are selfish, which cause competition among spectrum holders as well as spectrum buyers. Therefore, the double auction is essential. In our thesis, we consider single-channel and multi-channel double auction for spectrum group-buying. In this



chapter, we will introduce the group-buying concept and the three-stage auction framework. We will also discuss the challenges for group-buying based spectrum auction.

## **4.2 The Concept of Group-buying**

Inspired by the emerging group-buying services on the Internet, e.g. Groupon (3), the buyers can be grouped together to require and share the whole spectrum band sold in the spectrum auctions. In our thesis, we consider the scenario with many secondary users (SUs) who are willing to buy the unused channels from the spectrum holders (SHs). Since any individual SU cannot afford the whole channel, we group the SUs within the same secondary network (SN) together and try to group-buy some channels. The SNs can be viewed as the groups of users taking part in the same deal in Groupon. We assume there is a secondary access point (SAP) in each SN. We consider each SAP as a group leader. The SAP can decide which SUs can join the group and collect money from the grouped SUs. Each SAP also acts as a buyer to take part in the spectrum auction held by the SHs. The SAPs will bid the spectrum in the competition with other groups and major players in wireless industry.

## **4.3 Challenges**

Although spectrum auction has been studied in many works, there are several unique characteristics making the group-buying based spectrum auction challenging (42).

### **4.3.1 Secondary Users Selecting**

In each SN, SUs share both the price and the spectrum. Therefore, the number of grouped SUs in the SN can affect the SUs' satisfaction, which together with payment decides SUs' utilities. The group-buying concept is different from the spectrum reusability design in the existing work (28) (40) (76). In their work, they grouped the buyers together by using conflict graph, which buyers who do not interfere

with each other are randomly selected to form a group. Each buyer in the same group enjoys the whole channel and pays the same amount. Each SU affords a whole channel by himself. In group-buying based scenario, different SUs may have different budgets (the maximum amount of money they can pay) and the evaluations of the whole channel (the benefit if it obtains the whole channel). Therefore, it is challenging for the SAP to make fair, efficient and valid decisions about which SUs should be grouped together.

#### **4.3.2 Truthfulness of the Auction**

A well designed auction should be truthful. A truthful auction will encourage all bidders to participate in the auction and reveal their true valuation for the items they are bidding. A truthful auction can avoid the market manipulation. However, in group-buying based spectrum auction, the budget and evaluation should be both taken into consideration when bidding the channel. Therefore, it is challenging to enforce two-dimensional truthfulness in terms of both budget and evaluation by designing proper auction mechanisms. There are also existing works considering two-dimensional truthfulness. For example, (14) considered bid-based and time-based truthfulness. However, the group-buying based scenario, the two dimensions are coupled together with a connection of the number of selected SUs thus it cannot be simply addressed with existing auction model.

#### **4.3.3 Channel Matching**

The SUs may ask for more than one channel and the SHs may sell more than one channel. In group-buying based auction, the SAP need to decide the number of channels to bid. It is challenging for the SAP to decide the number of channels. The multi-channel assumption brings troubles to our mechanism

design. Although there are recent works considering auction design for multi-channels (67; 70; 71), they cannot be applied in the group-buying scenario directly.

#### **4.4 Three-stage Auction Framework**

In this section, we will introduce a three-stage single-channel auction as shown in Fig. 24. In stage I, all the SUs submit their bids to the SAP within the same SN. Then SAPs compute the budgets for the channels. In stage II, the SHs and the SAPs submit their bids to the auctioneer. The auctioneer decides the winning price and the winning SHs and SAPs. In stage III, the winning SAPs determine the winning SUs and charge them. For multi-channel auction, in stage I, we split the SUs into different virtual buyer groups and determine the virtual group budgets. The stage II is same as single-channel auction. In stage III, the winning virtual groups are determined and charge the SUs in the winning virtual groups.

There are two types of auctions: single-sided buyer-only auction and double auction. In each SN, SUs submit their bids to the SAP. The SAP decides which SUs can join the group according their bids. After collecting the money from SUs, SAPs take part in the spectrum auction held by different SHs. The auction between the SAPs and SHs is a sealed-bid double auction. We also refer to it as inner auction. The auction between the SUs and the SAPs is a single-sided buyer-only auction. We refer to it as outer auction.

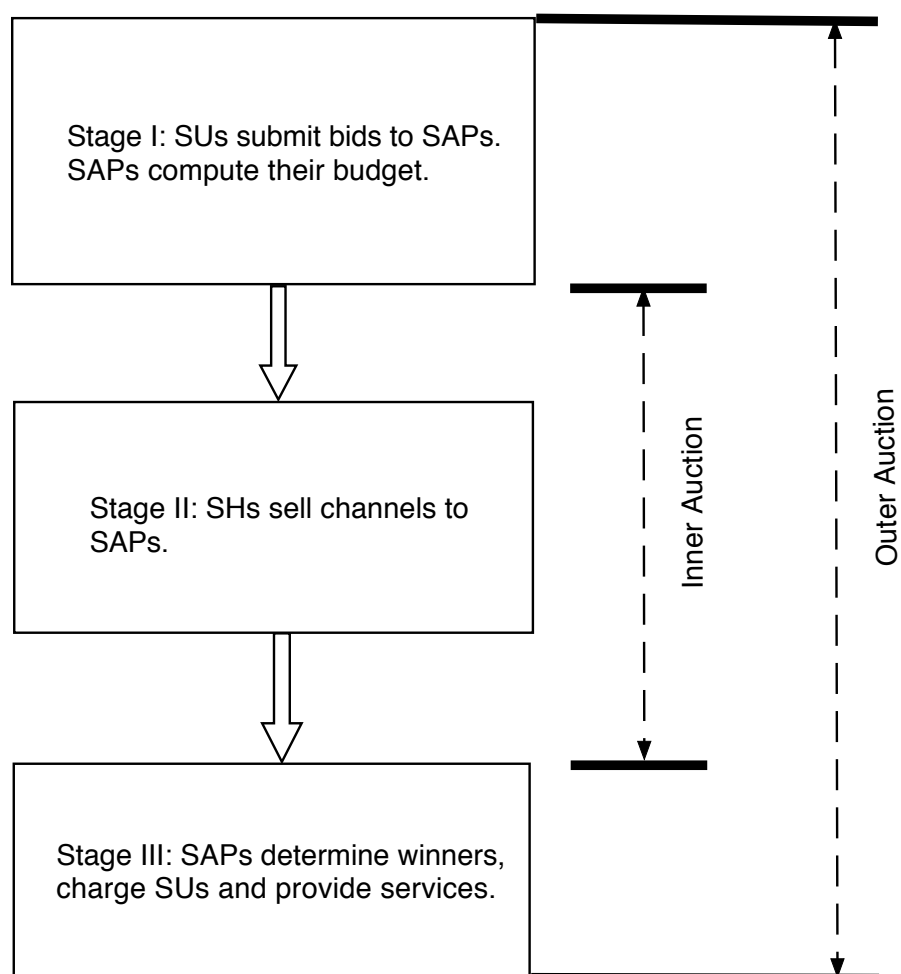


Figure 24: Auction framework

## CHAPTER 5

### TRUTHFUL GROUP BUYING-BASED DOUBLE AUCTION FOR COGNITIVE RADIO NETWORKS

In this chapter, we introduce a truthful group buying-based double auction for cognitive radio networks. At first, we describe the system model of our mechanism. Then we introduce our method in three sections:

- Group budget computation for each SAP
- Winner determination in the inner auction
- Winner determination in the outer auction

After introducing our method, we prove that our scheme satisfies the economic properties, i.e., truthfulness, individual rationality and budget balance for both inner and outer auctions. At last, we show the simulation results of evaluating the performance of our scheme.

#### 5.1 System Model

We consider a static model with  $M$  spectrum holders (SHs) and  $N$  secondary networks (SNs). Each SN is a infrastructure-based network. There is one secondary access point (SAP) in each SN which is available to all the secondary users (SUs). There are  $N_i$  SUs in the  $i$ -th SN ( $1 \leq i \leq N$ ). Each SH has a single channel to sell. The SHs have different reserved prices  $\{c_m\}$  ( $m = 1, \dots, M$ ) for their channels. The reserved price is the minimum price the SH is willing to accept for his channel. The SNs are willing

to buy channels from the SHs. We assume that each SN would like to buy at most one channel and all the channels are homogeneous.

Our scheme consists of two auctions. The inner auction is a double auction which is between the SAPs and the SHs. The outer auction is a single-sided auction which is between the SUs and the SAP in each SN. Both auctions are sealed-bid. In the outer auction, each SU  $s_i^j$  submits a bid  $\{v_i^j, b_i^j\}$  to SAP  $S_i$ .  $v_i^j$  is evaluation for the channel and  $b_i^j$  is the budget. The SU  $s_i^j$ 's true evaluation is  $\tilde{v}_i^j$  and the true budget is  $\tilde{b}_i^j$ . After receiving all the bids from all the SUs in the network, the SAP  $S_i$  computes the budget  $H_i$ . SAPs are also the buyers in the inner auction. They submit their budgets to the SHs to win the channel. If the SAP wins the channel, it will pay  $p_i$  for this channel. After the SAP wins the channel, it needs to select some SUs to form a winner set  $W_i$ . The SUs within the winner set will receive non-negative utilities. Otherwise, the SUs will receive zero utilities. For each SU  $s_i^j$  in the winner set, the SAP  $S_i$  computes the payment  $p_i^j$ . Therefore, the utility of SU  $s_i^j$  is:

$$u_i^j = \begin{cases} \frac{\tilde{v}_i^j}{|W_i|} - p_i^j, & s_i^j \in W_i \\ 0, & \text{otherwise,} \end{cases} \quad (5.1)$$

where  $|W_i|$  is the cardinal number of  $W_i$ .

Also we define the utility of SAP  $S_i$  as:

$$U_i = \begin{cases} H_i - p_i, & \text{if } S_i \text{ wins} \\ 0, & \text{otherwise,} \end{cases} \quad (5.2)$$

Similarly, the utility of each SH is:

$$\Phi_i = \begin{cases} p_m - c_m, & \text{if the channel of } m\text{th SH is sold} \\ 0, & \text{otherwise,} \end{cases} \quad (5.3)$$

where  $p_m$  is the payment to SH  $m$ .

## 5.2 Group Budget Computation for Each SAP

### 5.2.1 Algorithm for Calculating the Budget for SAPs

At first, all SHs submit their information of channels to the auctioneer. Then the SAPs get the information of channels from the auctioneer, such as the bandwidth, frequency and the power limitation. After getting the information, the SAPs pass these information to the SUs in their SN. According these properties of the channel, the SUs can make better evaluations and form their strategies.

Then, we consider the auction in each SN. The SUs submit their two-dimensional bids for channels to the SAP:  $\{(v_i^j, b_i^j)\}$ . In this stage, we use a similar algorithm as in (42) to calculate the budget for the channels  $H_i$ . Since we consider the double auction in our scheme and assume that all the channels provided by different SHs are homogeneous, instead of calculating the budget vector, we only need to calculate the budget for a single channel. After calculating the budget, the winning SUs are selected from all the SUs. The clearing price is also determined from the losers to avoid the untruthfulness. To become a winner, the SU's budget should be no less than the clearing price and its evaluation should be high enough. We will explain the deals by using an example later.

We sacrifice half of SUs with smallest budgets at first. If the number of  $n$  SUs is not even, we sacrifice  $\frac{(n-1)}{2}$  SUs. Then the SAP goes through the remaining SUs and removes those with evaluations small enough. Model in (76) sacrifice only one SU or one group. In (42),  $m$  SUs are sacrificed by using

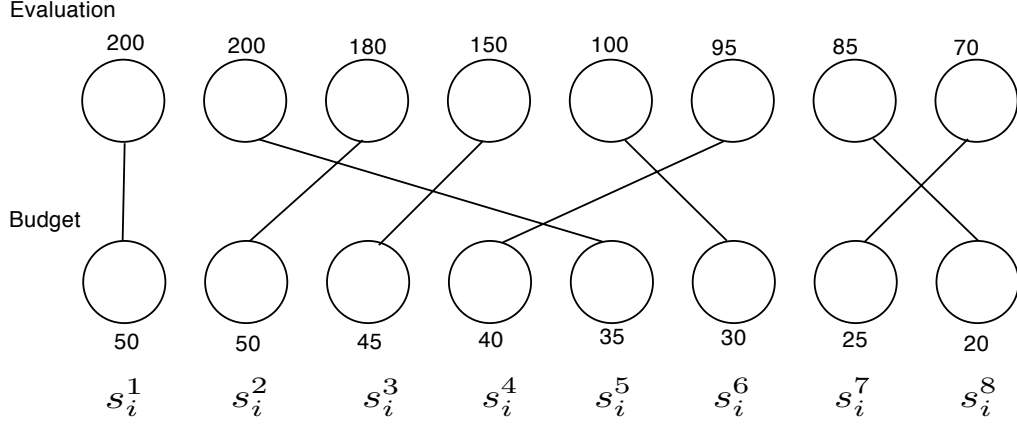


Figure 25: illustration of SAP's budget calculation

SAMU method. It also proved that the system with  $m > 1$  performs better than that with  $m = 1$ . After trying different values of  $m$ , we found the the system performs best if  $m$  is equal to half of the SUs. We will show the simulation result in Section VI. Next, we calculate the budget  $H_i$  of SAP  $S_i$  as its true evaluation. Here  $H_i$  is the maximum amount it can charge those winning SUs. When the SAP submits its budget (true evaluation) to the SHs, the SH cannot charge SAP  $S_i$  more than  $H_i$ . If SH charges  $S_i$  more than its budget  $H_i$ , the individual rationality and budget balance properties will not be satisfied.

### 5.2.2 A Simple Example

In the example shown in Fig. 25, there are 8 SUs in the SN. At first,  $S_i$  sorts the budget. Because we sacrifice half SUs in our scheme, then 35 is the clearing price and  $s_i^5, s_i^6, s_i^7$  and  $s_i^8$  are removed. Then  $S_i$  sorts the remaining 4 SUs by their evaluations. SU  $s_i^4$  is removed as  $95 < 35 * 4$ . Then SAP finds that  $150 > 3 * 35$ . Therefore,  $H_i = 105$ .



$s_i^4$  is willing to participate in the group-buying (though it does not have) and pay 95 units of money to buy the whole channel. If it actually participates the group-buying, there will be 4 SUs in the winner set. It will share  $\frac{1}{4}$  of the whole channel, which is worth  $\frac{1}{4} * 95 < 35$ . Because 35 is the clearing price,  $s_i^4$  has to pay this amount of money if it wants to participate in group-buying. So it is not willing to participate the group-buying at price 35. This shows that the evaluation of a winning buyer should be at least the product of the number of winners and the clearing price.

Now we check the budget if we only sacrifice one SU. Then the clearing price is 20 and remove  $s_i^8$ . Then we still sort the evaluations. We found  $s_i^4$ ,  $s_i^6$  and  $s_i^7$  will be removed and the budget is 80 which is smaller than the budget when we sacrifice 4 SUs. This shows that the system performs better if we sacrifice more than one SU.

### 5.3 Winner Determination in the Inner Auction

After calculating all the budgets of the SAPs, we use the Vickrey double auction to determine the winning SAPs and SHs and the winning price.  $p_1, p_2, \dots, p_N$  represent the bids of SAPs from different SNs.  $c_1, c_2, \dots, c_M$  represent the reserved prices of different SHs.

We sort the reserved prices of SHs in ascending order and the bids of SAPs in descending order:

$$c_1 \leq c_2 \leq \dots \leq c_M$$

$$p_1 \geq p_2 \geq \dots \geq p_N$$

After the sorting, we find a maximum  $K$  that  $p_K \geq c_K$ . Then the top  $K - 1$  SHs and  $K - 1$  SAPs are the winners. Algorithm 5 demonstrates this procedure.

---

**Algorithm 4** Compute Group budget
 

---

```

1: loop
2:    $i = 1 \rightarrow N$ 
3:   // Let  $B$  be the sorted array of SUs in descending order of budget.
4:   // Let  $N_i$  be the number of SUs in the SN
5:   if  $N_i$  is even then
6:      $m = \frac{1}{2}N_i$ 
7:   end if
8:   if  $N_i$  is odd then
9:      $m = \frac{1}{2}(N_i - 1)$ 
10:  end if
11:  // Let  $E$  be the sorted array of  $B$ 's first  $N_i - m$  elements in descending order of evaluations
12:  // Let the clearing price  $cp$  be the SU  $B_{N_i-m+1}$ 's budget
13:  loop
14:     $l = N_i - m \rightarrow 1$ 
15:    if  $E_l$ 's evaluation is no less than  $l * cp$  then
16:       $H_i = l * cp$ 
17:      // Let  $W_i$  be the winner set with  $E_l$ 's first  $l$  SUs
18:    end if
19:  end loop
20: end loop

```

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**Algorithm 5** Winner determination in the inner auction
 

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1: //  $c_1, c_2, \dots, c_M$  represents the reserved prices of SHs.
2: //  $p_1, p_2, \dots, p_N$  represents the bids of SAPs.
3: Sort  $c_1, c_2, \dots, c_M$  in a non-decreasing order
4:  $c_1 \leq c_2 \leq \dots \leq c_M$ .
5: Sort  $p_1, p_2, \dots, p_N$  in a non-increasing order
6:  $p_1 \geq p_2 \geq \dots \geq p_N$ .
7: Find  $K$ ,  $K = \max\{k | p_k \geq c_k\}$ 
8: Winning SAPs are:  $p_1, p_2, \dots, p_{K-1}$ .
9: Winning SHs are:  $c_1, c_2, \dots, c_{K-1}$ .

```

---

#### 5.4 The Winner Determination and Pricing in the Outer Auction

Assume  $S_i$  wins the auction at price  $p_K$ ,  $p_K \leq H_i$ . SAP  $S_i$  will announce the SUs in the winner set and charge them exactly  $H_i$ . This will ensure that  $S_i$  receives non-negative utility  $U_i = H_i - p_K \geq 0$ . Before the inner auction, the winner set in each SN is determined and the SAP cannot change the group after the inner auction. This will ensure the truthfulness of the algorithm.

For example, in Fig. 25,  $H_i = 3 * 35 = 105$ . We assume that  $p_K = 80$ .  $S_i$  still charges  $H_i$  from the winner set. In section 5.2, we have found the winner set  $\{s_i^1, s_i^2, s_i^3\}$ . For each winning SU in the winner set will be charged  $\frac{105}{3}$  and share  $\frac{1}{3}$  of the whole channel. Now the utility of  $S_i$  is  $U_i = 105 - 80 = 25$ . The utilities of the three winners are  $\frac{200}{3} - 35 = 31.7$ ,  $\frac{180}{3} - 35 = 25$  and  $\frac{150}{3} - 35 = 15$ , respectively.

#### 5.5 Proof of Auction Properties

In this section, we prove that our scheme satisfies the economic properties, i.e., truthfulness, individual rationality and budget balance for both inner and outer auctions.

**Theorem 4.** *The inner auction is budget balanced and individually rational.*

*Proof.* Because  $p_K \geq c_K$ , the auctioneer's profit  $(K - 1)(p_K - c_K) \geq 0$ . Therefore, the inner auction is budget balanced. Since no SAP will pay more than its budget and no SH will receive less than its reserved price according to the winner determination, individual rationality is also guaranteed.  $\square$

**Theorem 5.** *The outer auction is also individually rational.*

*Proof.* Since the bid of an SAP is always smaller than the budget it collects from the winner set and no SU will pay more than its budget according to the clearing price, individual rationality is guaranteed.  $\square$

Next, we will prove the truthfulness. According the definition of truthfulness, we need to prove that neither seller nor buyer could improve its utility by bidding untruthfully. Before we prove the truthfulness, we need to prove that the winner determination is monotonic and bid-independent for both inner and outer auctions.

**Lemma 1.** *If an SU wins the auction by bidding  $\tilde{v}_i^j$  and  $\tilde{b}_i^j$ , it also wins by bidding  $v_i^j \geq \tilde{v}_i^j$  and  $b_i^j \geq \tilde{b}_i^j$ .*

*Proof.* If an SU wins the auction, its budget should be larger than the clearing price. Its evaluation should be larger than the product of the clearing price and the number of winners. Then, a higher bidding value will not change the position of the SU. So the SU is still the winner and pays the same amount. Therefore, the winner determination of SUs is monotonic and bid-independent. □

**Lemma 2.** *If an SAP wins the auction by bidding  $p_i$ , it also wins by bidding  $p'_i$  ( $p'_i > p_i$ ).*

*Proof.* Similar to the proof above, if  $p'_i > p_i$ , the rank the SAP will not be lower than it did before. So if  $p_i$  wins the auction,  $p'_i$  also wins. So the SAP will pay the same amount. Therefore, the winner determination of SAPs is monotonic and bid-independent. □

**Lemma 3.** *If an SH wins the auction by bidding  $c_i$ , it also wins by bidding  $c'_i$  ( $c'_i < c_i$ ).*

*Proof.* If  $c'_i < c_i$ , the rank of the SH  $i$  will not be lower than it did before. So if  $c_i$  wins the auction,  $c'_i$  also wins. The SH will receive the same amount. Therefore, the winner determination of SHs is monotonic and bid-independent. □

Now we can prove the truthfulness of SUs, SAPs and SHs.

**Theorem 6.** *The outer auction is two-dimensional truthful for SUs.*

To prove the outer auction is truthful for SUs, we need to show that any SU cannot receive higher utility by bidding untruthfully. There are four auction results when the SUs bids truthfully and untruthfully. Table II lists all the possible cases.

*Proof.* Case 1: The SU  $s_i^j$  is denied for both bidding truthfully and untruthfully. So its utility is always zero.

Case 2: The SU  $s_i^j$  wins when truthful and fails when untruthful. In this case, the utility is non-negative when the SU bids truthfully and the utility is zero when the SU lies. Therefore, the SU will not gain more utilities if it bids untruthfully.

Case 3: The SU  $s_i^j$  fails when truthful and wins untruthful. There two possible situations that the SU fails when truthful. The first one is its true budget  $\tilde{b}_i^j$  is smaller than the clearing price  $p_c$ . If  $\tilde{b}_i^j < p_c$ , then it has to submit an untruthful budget  $b_i^j > p_c$  to win. The clearing price will not decrease in this case. Therefore,  $s_i^j$  wins and needs to pay at least  $p_c$  which exceeds its real budget. That means  $s_i^j$  cannot afford it, so the utility is zero. The second situation is its true evaluation  $\tilde{v}_i^j$  is smaller than the product of  $p_c$  and the number of winners. If  $s_i^j$  wants to win the auction, it has to submit an untruthful evaluation  $v_i^j \geq p_c(1 + |W_i|)$  to win. Then its profit  $\frac{\tilde{v}_i^j}{1 + |W_i|}$  will be less than its payment  $p_c$ . Then the utility is zero.

Case 4: For both sides, the SU  $s_i^j$  wins the auction. Then it will be charged the same price. It cannot receive more utilities by lying.

Therefore, the outer auction is two-dimensional truthful for SUs. No SU can improve its utility by bidding untruthfully. □

**Theorem 7.** *The inner auction is truthful for SAPs.*

*Proof.* Case 1: Same as the case of SUs.

Case 2: The SAP  $S_i$  wins when truthful and fails when untruthful. In this case, the SAP cannot get more utilities if it bids untruthfully.

Case 3: This only happens when  $H_i < p_k$ .  $H_i$  is the budget collected from the SUs. We also can consider it as the true evaluation of the channels.  $p_k$  is the winning price. If SAP  $S_i$  wants to win the auction, it has to bid  $p_i > p_k$ . The winning price  $p_k$  will not decrease in this case. Therefore,  $S_i$  wins and needs to pay at least  $p_k$ . This will make the utility  $H_i - p_k \leq 0$ . The SAP cannot gain more utilities by bidding untruthfully.

Case 4: For both sides, the SAP  $S_i$  wins the auction. Then it will be charged the same price. It cannot receive more utilities by lying.

Therefore, the inner auction is truthful for SAPs. No SAP can improve its utility by bidding untruthfully.

□

**Theorem 8.** *The inner auction is truthful for SHs.*

*Proof.* Similar to the proof of Theorem 7, we need to check the four cases in Table II.

Case 1: Same as the case of SAPs.

Case 2: This only happens when the SH bids higher than its true valuation. For a higher bids, the rank of it is lower than it bids truthfully. In this case, the utility is 0 for lying and non-negative when it bids truthfully. So the SH cannot get more utility if it bids untruthfully.

Case 3: This only happens when  $c_i > c_k$ .  $c_i$  is the reserved price of the SH.  $c_k$  is the winning price. If SH wants to win the auction, it has to bid  $\tilde{c}_i < c_k$ , where  $\tilde{c}_i$  is the untruthful bid. The winning price  $c_k$  will not increase in this case. Therefore, the SH wins and receives at most  $c_k$ . This will make the utility  $c_k - c_i \leq 0$ . The SH cannot gain more utilities by bidding untruthfully.

Case 4: For both sides, the SH wins the auction. It will be paid the same price. Thus, it cannot get more utilities by lying.

Therefore, the outer auction is truthful for SHs. No SH can improve its utility by bidding untruthfully. □

## 5.6 Numerical Results

In this section, we show the simulation results of evaluating the performance of our scheme. The experiment environment is MATLAB. We will show that our scheme is truthful for SUs. Then we verify that SAP increase its budget when it sacrifice about half of SUs, given their uniform distribution of values. Then we evaluate our scheme by the number of transactions, the number of winning SUs and SAPs, utilities of SAPs and SHs.

### 5.6.1 Simulation Setup

The default setting of parameters are  $M = 8$ ,  $N = 10$ ,  $N_i = 100$ .  $\tilde{b}_i^j$  is uniformly distributed within  $[0, 10]$  and  $\tilde{v}_i^j$  is uniformly distributed within  $[0, 50]$ . The bids of SAPs  $p_i$  are uniformly distributed within  $[50, 100]$ . The reserved prices of SHs  $c_i$  are uniformly distributed within  $[40, 80]$ .

### 5.6.2 Evaluation Results

We randomly select an SU  $s_i^j$  to check its truthfulness. We adjust its budget within the range of  $[0, 2\tilde{b}_i^j]$  and its evaluation within the range of  $[0, 2\tilde{v}_i^j]$ . We denote  $U(u)$  and  $U(t)$  as the utilities when

TABLE III: TRUTHFULNESS OF SUS

m	$U(u) < U(t)$	$U(u) = U(t)$	$U(u) > U(t)$
2	0.4650	0.5350	0
4	0.4200	0.5800	0
6	0.3360	0.6640	0

$s_i^j$  bids untruthfully and truthfully. We put the probabilities of the three cases with different  $m$  values in Table III. In this table, we can find that  $U(u) > U(t)$  cannot happen. This verified the truthfulness of SUs. Also we can find that the probability of  $U(u) = U(t)$  will increase when the value of  $m$  increases. That means the number of losers increases.



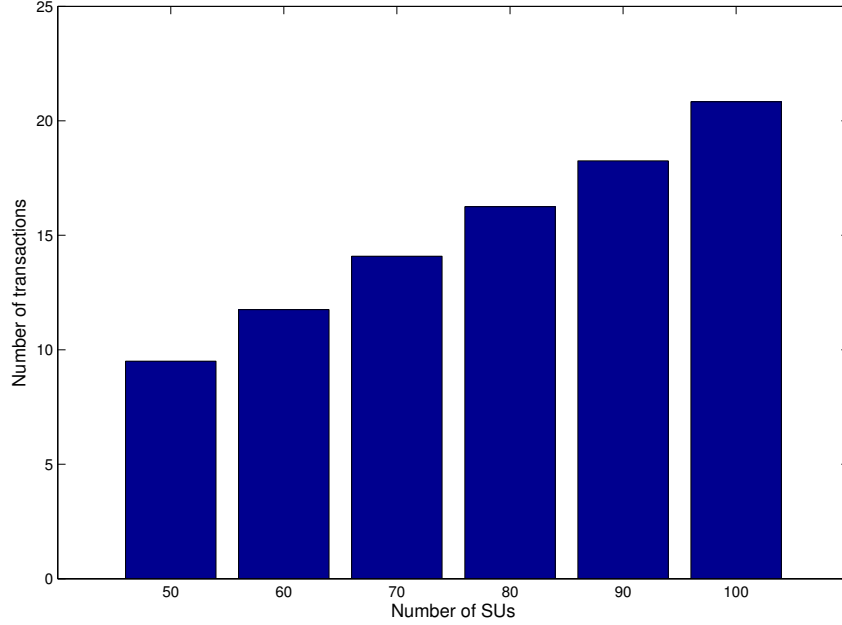


Figure 26: Number of transactions

Fig. 26 shows the number of successful transactions achieved by our scheme. We also notice that this number increases as the number of SUs increases. That is because more SUs may lead to higher budget for each SAP. Fig. 27 shows the average number of winning SUs in the SN. When the number of SUs increases, the number of winning SUs increases.

Fig. 28 and Fig. 29 show the average utility of SAPs and the auction profit. We compared our results with TASG (42). We can find that our scheme improves the performance significantly because the winner determination algorithm and successful transactions in double auctions contribute to the average of the SAPs and the auction profit.

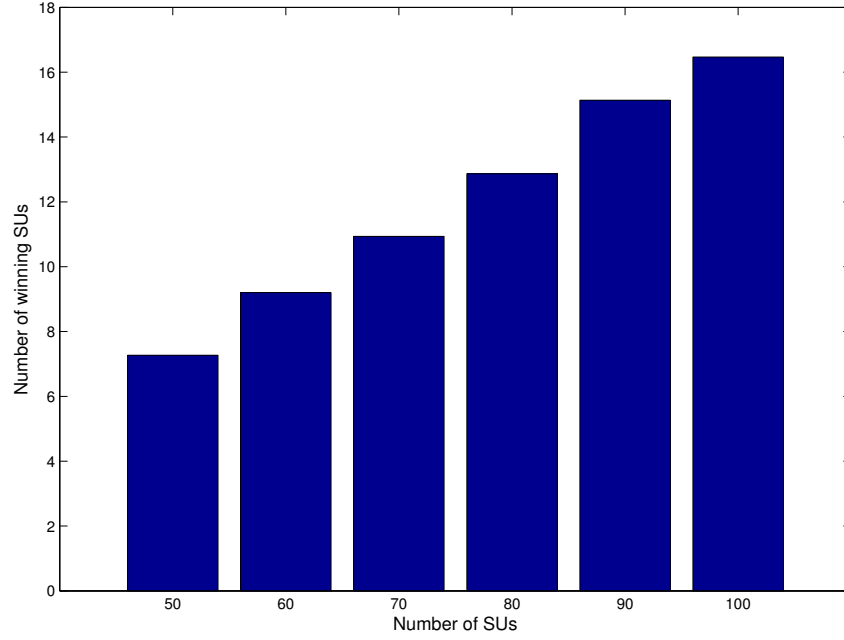


Figure 27: Average number of winning SUs in each SN

Fig. 30 compares the SAP's budget of different  $m$  values. According to the simulation setup, the budget and evaluation are uniformly distributed. When  $m = 1$ , the SAP's budget will be very small. Also we can observe that when we sacrifice about half SUs, the budget is maximum, given their uniform distribution of values.

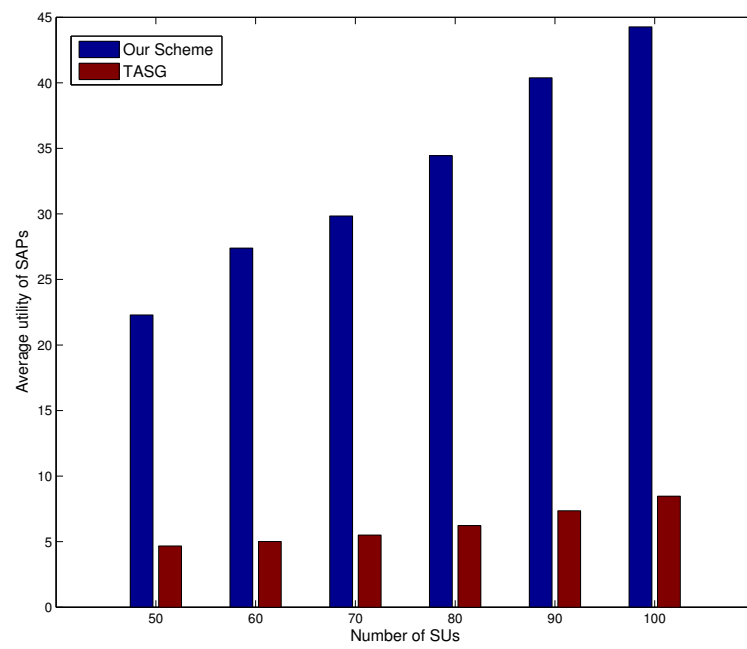


Figure 28: Average utility of SAPs

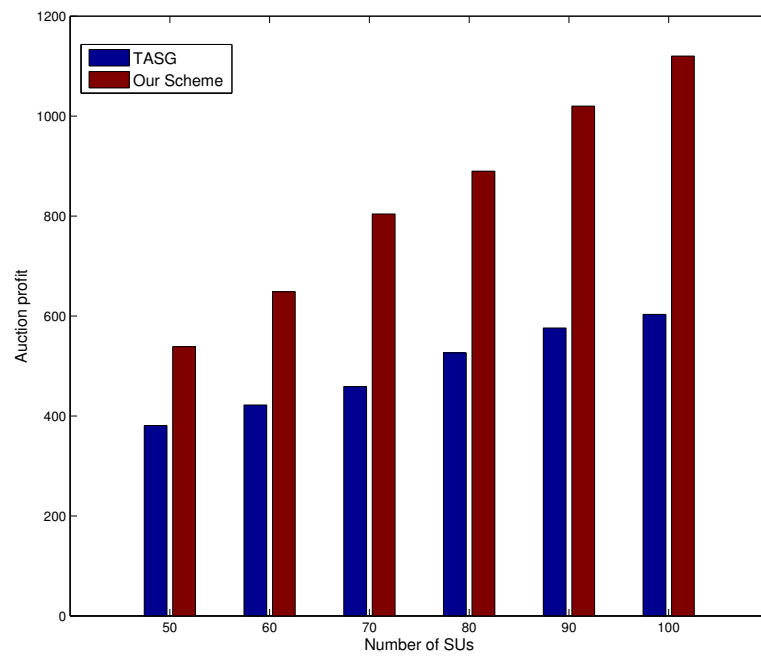


Figure 29: Auction profit

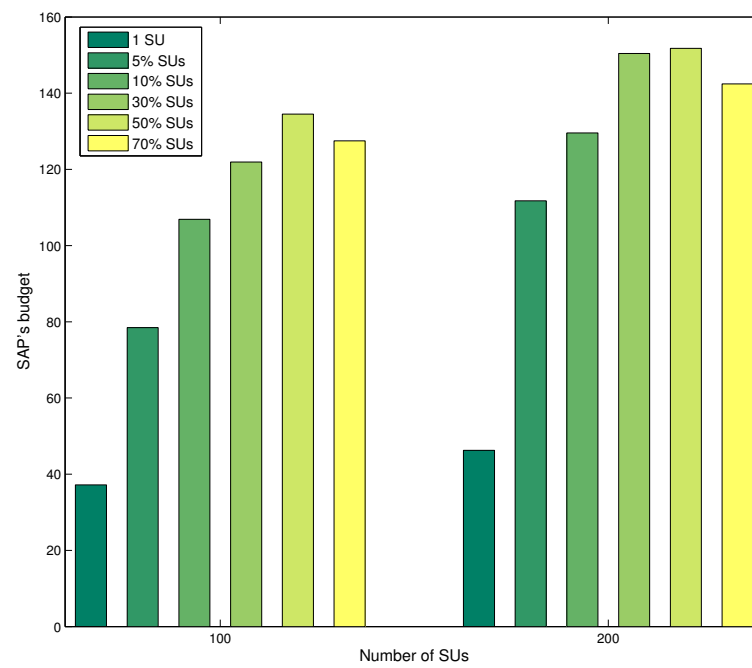


Figure 30: SAP's budget with different  $m$  values

## CHAPTER 6

### A TRUTHFUL MULTI-CHANNEL DOUBLE AUCTION MECHANISM FOR SPECTRUM GROUP-BUYING

In this chapter, we introduce a truthful multi-channel double auction mechanism for spectrum group-buying. At first, we describe the system model of our mechanism. Then we introduce our method in three sections:

- Virtual Buyer Group (VBG) Splitting
- Budget computation for VBGs
- Winner determination in the inner auction
- Winner determination and pricing in the outer auction

After introducing our method, we prove that our scheme satisfies the economic properties, i.e., truthfulness, individual rationality and budget balance for both inner and outer auctions. At last, we show the simulation results of evaluating the performance of our scheme.

#### 6.1 System Model

We consider a static scenario with  $M$  spectrum holders (SHs) and  $N$  secondary networks (SNs). In each SN, there is only one secondary access point (SAP) which is available to all the secondary users (SUs) in the same SN. There are  $N_i$  SUs in the  $i$ -th SN ( $1 \leq i \leq N$ ). We use  $(s_m, c_m)$  to denote the bid from SH  $m$ , where  $s_m$  is the minimum per-channel payment required by SH  $m$  ( $s_m > 0$ ).

$c_m$  is the number of channels that SH  $m$  will provide ( $c_m \geq 1$ ). We assume that all the channels are homogeneous.

Our scheme consists of two auctions. In the outer auction, each SU  $s_i^j$  submits a bid  $\{v_i^j, b_i^j, r_i^j\}$  to SAP  $S_i$ .  $v_i^j$  is the evaluation of each channel,  $b_i^j$  is the per-channel budget and  $r_i^j$  is the number of channels that SU  $s_i^j$  will request ( $r_i^j \geq 1$ ). We assume that the SUs and SHs will submit truthful number of channels.  $\tilde{v}_i^j$  is the true evaluation of each channel and  $\tilde{b}_i^j$  is the true budget for each channel. After receiving all the bids from all the SUs in the network, the SAP splits the SUs into different virtual group. The SAP computes the budgets of the virtual groups  $H_i^k$ . Then, in the inner auction, the SAPs submit their budgets vector to the SHs to win the channel. We define  $W_i$  as the winner set of the virtual groups in the  $i$ -th network. If the virtual group  $k$  wins the auction, it needs to select some SUs to form a winner set  $W_k$ . The SUs will receive non-negative utilities if they win the auction. Otherwise, the SUs will receive zero utilities. In each virtual group, the SAP computes the payment  $p_i^j$  for SU  $s_i^j$ . Therefore, the utility of SU  $s_i^j$  is:

$$u_i^j = \begin{cases} \frac{\tilde{v}_i^j}{|W_k|} - p_i^j, & s_i^j \in W_k \\ 0, & \text{otherwise,} \end{cases} \quad (6.1)$$

where  $|W_k|$  is the cardinal number of  $W_k$

We define the utility of SAP  $S_i$  as:

$$U_i = \begin{cases} \sum (H_i^k - p_i^k), & \text{if } k \in W_i \text{ in the } i\text{-th network} \\ 0, & \text{otherwise,} \end{cases} \quad (6.2)$$

Similarly, the utility of each SH is:

$$\Phi_m = \begin{cases} \sum c_m^w (p_m^w - s_m^w), & \text{if SH } m \text{ wins} \\ 0, & \text{otherwise,} \end{cases} \quad (6.3)$$

where  $p_m^w$  is the payment of sold channels to SH  $m$  and  $c_m^w$  is the sold channel of SH  $m$ .

## 6.2 Virtual Buyer Group (VBG) Splitting

In each SN, we can not directly determine the group budget like TASG. For multi-channel scenario each SU in the SN may request different number of channels. It is hard to determine the group budget and how many channels the SAP should buy. In order to solve this problem, we propose a novel method to compute the budgets of different virtual buyer groups (VBGs). Our basic idea is that we split the SUs in the same SN into several VBGs. In each VBG, only one channel is requested. Then we refer each VBG as a super buyer group to bid for one channel. In this method, a SU may be grouped into different VBGs according to the number of channel he requested. Through the VBG splitting, we convert the multi-channel problem to a single-channel problem. Recall that we denote the bid of SU  $s_i^j$  by  $\{v_i^j, b_i^j, r_i^j\}$ , where  $v_i^j$  is the per-channel evaluation,  $b_i^j$  is the per-channel budget and  $r_i^j$  is the number of channels requested. Assume in the  $i$ -th SN, the maximal number requested channel is  $K_i = \max r_i^j$ . We split all the SUs in the  $i$ -th SN into  $K_i$  VBGs in which each SU request only one channel as follows:

- The  $1^{st}$  VBG consists of buyers in  $i$ -th SN who request their  $1^{st}$  channel.
- The  $2^{nd}$  VBG consists of buyers in  $i$ -th SN who request their  $2^{nd}$  channel.
- ...



TABLE IV: ILLUSTRATION OF VIRTUAL GROUP BUDGET CALCULATION

SUs	$s_i^1$	$s_i^2$	$s_i^3$	$s_i^4$	$s_i^5$	$s_i^6$
Budget	50	50	40	35	30	25
Evaluations	200	160	150	180	90	80

- The  $K_i^{th}$  VBG consists of buyers in  $i$ -th SN who request their  $K_i^{th}$  channel.

Note that, here the “ $i^{th}$  channel” does not mean the channel from seller  $i$  or the channel labeled  $i$ . Instead, it means “the  $i^{th}$  channel requested by some buyers in the buyer group”, which can be bought from any winning seller. Fig. 31 illustrate the VBG splitting procedures. Assume in the  $i$ -th SN, there are three SUs  $\{s_i^1, s_i^2, s_i^3\}$ . The maximal number of channels requested in this SN is 3. Therefore, we split these SUs into 3 VBGs according to the number of requested channels. In  $VBG_1$ , there are three SUs  $\{s_i^1, s_i^2, s_i^3\}$ . In  $VBG_2$ , there are two SUs  $\{s_i^1, s_i^3\}$ . There is only  $s_i^3$  in  $VBG_3$ .

### 6.3 Algorithm for Calculating the Budget for VBGs

In this stage, we use a similar algorithm as in (42) to calculate the budgets for the VBGs. At first, we sacrifice half of SUs with smallest budget within the same VBG. In (42),  $x$  SUs are sacrificed by using SAMU method. We tried different number of  $x$  and found that we will get the best performance if  $x$  is equal to half of the SUs. This result is true based on the “uniformly distribution” assumption. Next, we calculate the budget  $H_i^k$  of the  $k$ -th VBG as its true evaluation.  $H_i^k$  is the maximum amount it can charge those winning SUs. We will illustrate this procedure by using an example in Table IV

In Table IV, there are 6 SUs in the  $k$ -th VBG. At first, we sort the budget from high to low. According to our scheme,  $s_i^4, s_i^5$  and  $s_i^6$  are removed and 35 is the clearing price. Then we sort the remaining by

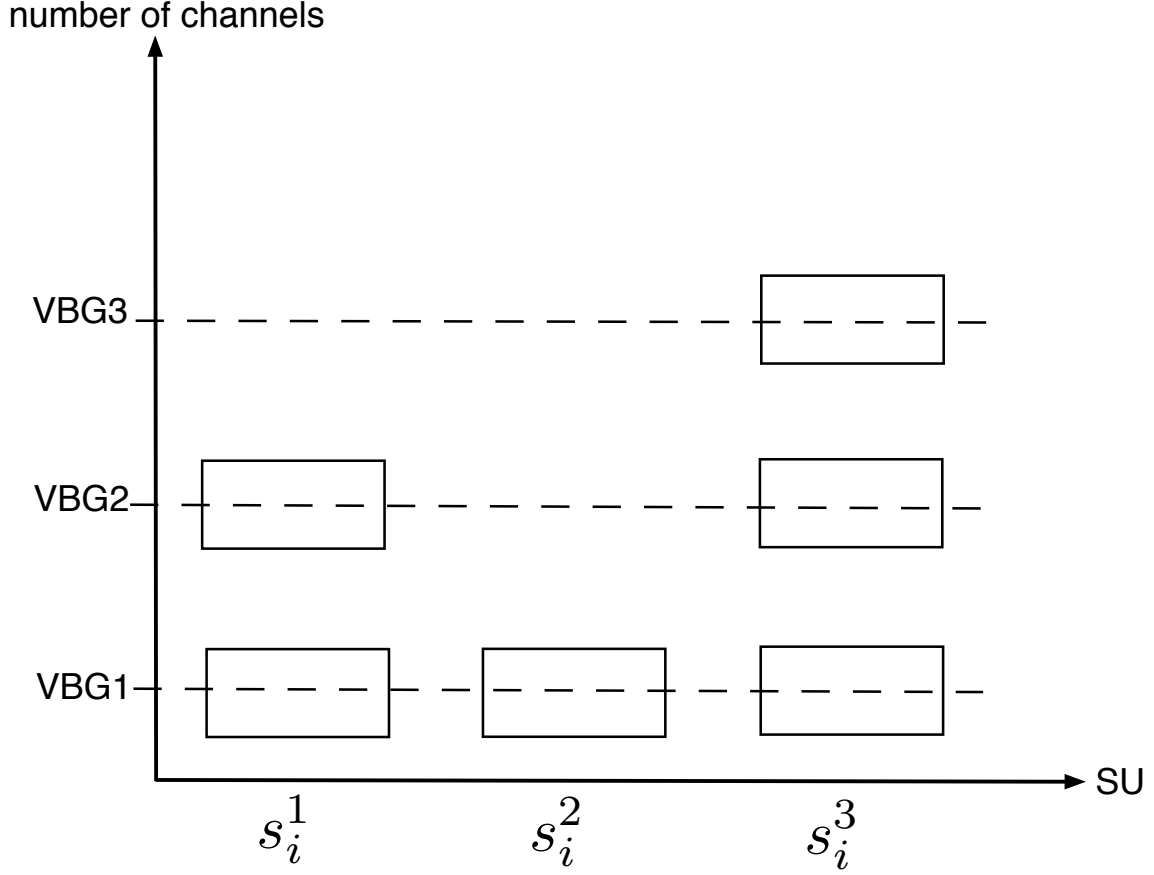


Figure 31: Virtual buyer group splitting

their evaluations. We find that  $150 > 35 * 3$ . Therefore,  $H_i^k = 105$ . If we change the evaluation of  $s_i^3$  to 100. Then  $s_i^3$  will be removed, since  $100 < 35 * 3$ . After removing  $s_i^3$ , we check the evaluation of  $s_i^2$  is 160, which is bigger than  $35 * 2$ . Therefore,  $H_i^k = 70$  in this case. The procedure for VBG splitting and group budget calculation is in Algorithm 6.

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**Algorithm 6** VBG Splitting and Group budget Calculation
 

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1: // Let  $k$  be the maximal number of channels requested in the  $i$ -th SN.
2: Split the SUs into  $k$  VBGs. In each VBG, only one channel is requested.
3: // Let  $N_k$  be the number of SUs in the  $k$ -th VBG.
4: // Let  $B$  be the sorted array of SUs in descending order of budget.
5: // Let  $N_k$  be the number of SUs in the SN.
6: // Let  $m$  be the number of sacrificed SUs.
7: // Let  $E$  be the sorted array of  $B$ 's first  $N_k - m$  elements in descending order of evaluations
8: // Let the clearing price  $p_c$  be the SU  $B_{N_k-m+1}$ 's budget
9: loop
10:    $l = N_k - m \rightarrow 1$ 
11:   if  $E_l$ 's evaluation is no less than  $l * p_c$  then
12:      $H_i^k = l * p_c$ 
13:   end if
14: end loop

```

---

#### 6.4 Winner Determination in the Inner Auction

After calculating all the budgets of VBGs in each SN, SAPs submit these budgets as a bid vector to the auctioneer. The auctioneer determines the winning VBGs and the winning SHs. Recall that our method is based on “homogeneous channels” assumption. Similar to Vickrey double auction, we sort the SHs’ per-channel payment  $s_m$  in non-decreasing order and the VBGs’ budgets  $H_i^k$  are sorted in non-increasing order. Since each SH provides at least one channel, we rewrite each SH’s per-channel payment  $s_m$  as many times as the number of  $c_m$  of channels he bid. We use  $\pi_l$  to represent the budget accumulation of the VBGs. The bid accumulation of the SHs is  $q * s_{m(q)}$ , where  $m(q)$  denote the SH in the  $q$ -th trade. In order to determine the winner set, we need to find the maximum  $l$  that  $\pi_l \geq q * s_{m(q)}$ . We will illustrate the winner determination procedure by using Table V. To achieve truthfulness, the auction winner are the first  $(m(l) - 1)$  SHs. According to our winner determination algorithm, the

TABLE V: WINNER DETERMINATION PROCEDURE

No.	1	2	3	4	5	6
SH	$SH_1$	$SH_2$	$SH_2$	$SH_3$	$SH_3$	$SH_4$
Bid $s_m$	2	4	4	6	6	8
Bid Acc.	2	$2 * 4$	$3 * 4$	$6 * 4$	$6 * 5$	$8 * 6$
VBG	$VBG_1$	$VBG_2$	$VBG_3$	$VBG_4$	$VBG_5$	$VBG_6$
VBG budget	10	8	6	4	2	2
Budget Acc.	10	18	24	28	30	32
Winning SHs	$SH_1, SH_2$					
Winning VBGs	$VBG_1, VBG_2, VBG_3$					

number of channels that each winning SH sells is always the number of channels he bids. For example, in Table II, when  $l = 3$ ,  $\pi_l = 30$  and  $q * s_{m(q)} = 30$ . Thus,  $l = 3$  is the maximum number that  $\pi_l \geq q * s_{m(q)}$ . Then the winners are first ( $l - 1 = 2$ ) SHs and the number of winning VBGs is  $1 + 2 = 3$ . The clearing prices for VBG and SHs are 2 and 6 in this example.

### 6.5 The Winner determination and pricing in the outer auction

Suppose k-th VBG in the i-th SN wins the auction, the clearing price is smaller than the VBG budget. The winning SUs in this VBG will be announced. The SAP will charge them exactly  $H_i^k$ . Before the inner auction, the winner set in each VBG is determined and the SUs will not be charged before the inner auction. This will ensure the truthfulness of the algorithm.

## 6.6 Proof of Auction Properties

In this section, we prove that our algorithm satisfies the economic properties, i.e., truthfulness, individual rationality and budget balance for both inner and outer auctions.

**Theorem 9.** *The inner auction is budget balanced and individually rational.*

*Proof.* Since  $\pi_l \geq q * s_{m(q)}$ , the auctioneer's profit  $\sum (\pi_l - q * s_{m(q)}) \geq 0$ . Therefore, the inner auction is budget balanced. Since no VBG will pay more than its budget and no SH will receive less than reserved price according to the winner determination, individual rationality is also guaranteed.  $\square$

**Theorem 10.** *The outer auction is also individually rational.*

*Proof.* Since the bid of a VBG is always smaller than the budget it collects from the winner set and no SU will pay more than its budget according to the clearing price, individual rationality is guaranteed.  $\square$

Next, we will prove the truthfulness. According to the definition of truthfulness, we need to prove that neither seller nor buyer could improve its utility by bidding untruthfully. Recall that we assume all sellers and buyers provide and request the number of channels truthfully. Now we can prove the truthfulness of SUs and SHs. There are four auction results when users bid truthfully and untruthfully. Table II lists all the possible cases.

**Theorem 11.** *The outer auction is truthful for SUs.*

*Proof.* Case 1: The SU  $s_i^j$  is denied for both bidding truthfully and untruthfully. So its utility is always zero.

Case 2: The SU  $s_i^j$  wins when truthful and fails when untruthful. In this case, the utility is non-negative when the SU bids truthfully and the utility is zero when the SU lies. Therefore, the SU will not gain more utilities if it bids untruthfully.

Case 3: The SU  $s_i^j$  fails when truthful and wins untruthful. There are two possible situations that the SU fails when truthful. The first one is its true budget  $\tilde{b}_i^j$  is smaller than the VBG clearing price  $p_c$ . If  $\tilde{b}_i^j < p_c$ , then it has to submit an untruthful budget  $b_i^j > p_c$  to win. The clearing price will not decrease in this case. Therefore,  $s_i^j$  wins and needs to pay at least  $p_c$  which exceeds its real budget. That means  $s_i^j$  cannot afford it, so the utility is zero. The second situation is its true evaluation  $\tilde{v}_i^j$  is smaller than the product of  $p_c$  and the number of winners. If  $s_i^j$  wants to win the auction, it has to submit an untruthful evaluation  $v_i^j \geq p_c(1 + |W_i^k|)$  to win. Then its profit  $\frac{\tilde{v}_i^j}{1 + |W_i^k|}$  will be less than its payment  $p_c$ . Then the utility is zero.

Case 4: For both sides, the SU  $s_i^j$  wins the auction. Then it will be charged the same price. It cannot receive more utilities by lying.

Therefore, the outer auction is truthful for SUs. No SU can improve its utility by bidding untruthfully. □

**Theorem 12.** *The inner auction is truthful for SHs.*

*Proof.* Similar to the proof of Theorem 11, we need to check the four cases in Table 2.

Case 1: Same as the case of SUs.

Case 2: This only happens when the SH bids higher than its true valuation. For a higher bid, the rank of it is lower than it bids truthfully. In this case, the utility is 0 for lying and non-negative when it bids truthfully. So the SH cannot get more utility if it bids untruthfully.

Case 3: This only happens when  $s_i > s_k$ .  $s_i$  is the reserved price of the SH.  $s_k$  is the winning price. If SH wants to win the auction, it has to bid  $\tilde{s}_i < s_k$ , where  $\tilde{s}_i$  is the untruthful bid. The winning price  $s_k$  will not increase in this case. Therefore, the SH wins and receives at most  $s_k$ . This will make the utility  $s_k - s_i \leq 0$ . The SH cannot gain more utilities by bidding untruthfully.

Case 4: For both sides, the SH wins the auction. It will be paid the same price. Thus, it cannot get more utilities by lying.

Therefore, the outer auction is truthful for SHs. No SH can improve its utility by bidding untruthfully. □

**Theorem 13.** *The inner auction is truthful for VBGs.*

*Proof.* Case 1: Same as the case of SUs.

Case 2: The  $k$ -th VBG in the  $i$ -th SN wins when truthful and fails when untruthful. In this case, the VBG cannot get more utilities if it bids untruthfully.

Case 3: This only happens when  $H_i^k < p_k$ .  $H_i^k$  is the budget collected from the SUs. We also can consider it as the true evaluation of the channels.  $p_k$  is the winning price. If the  $k$ -th VBG in the  $i$ -th SN wants to win the auction, it has to bid  $p_i > p_k$ . The winning price  $p_k$  will not decrease in this case. Therefore, VBG wins and needs to pay at least  $p_k$ . This will make the utility  $H_i^k - p_k \leq 0$ . The VBG cannot gain more utilities by bidding untruthfully.

Case 4: For both sides, the VBG wins the auction. Then it will be charged the same price. It cannot receive more utilities by lying.

Therefore, the inner auction is truthful for VBGs. No VBG can improve its utility by bidding untruthfully.

□

## 6.7 Numerical Results

In this section, we show the simulation results of evaluating the performance of our scheme. The experiment environment is MATLAB. We will show that our scheme is truthful for SUs. We study the auction efficiency of our framework. Then we verify that the VBG increase its budget when it sacrifice about half of SUs, given their uniformly distribution values. Then we compare our scheme with TASG.

### 6.7.1 Simulation Setup

The parameters are  $M = 8$ ,  $N = 10$ ,  $N_i = 100$ .  $\tilde{b}_i^j$  is uniformly distributed within  $[0, 10]$ ,  $\tilde{v}_i^j$  is uniformly distributed within  $[0, 50]$  and  $r_i^j$  is uniformly distributed within  $[1, 5]$ . The reserved prices of SHs  $s_m$  are uniformly distributed within  $[40, 80]$  and the number of channels  $c_m$  is uniformly distributed within  $[1, 3]$ .

### 6.7.2 Evaluation Results

We randomly select an SU  $s_i^j$  to check its truthfulness. We adjust its budget within the range of  $[0, 2\tilde{b}_i^j]$  and its evaluation within the range of  $[0, 2\tilde{v}_i^j]$ . We denote  $U(u)$  and  $U(t)$  as the utilities when  $s_i^j$  bids untruthfully and truthfully. We put the probabilities of the three cases with different  $m$  values in Table VI. In this table, we can find that  $U(u) > U(t)$  cannot happen. This verified the truthfulness of SUs. Also we can find that the probability of  $U(u) = U(t)$  will increase when the value of  $m$  increases. That means the number of losers increases.

Fig. 32 shows the average number of winning SUs in the SN. When the number of SUs increases, the number of winning SUs increase. We compared our scheme with TASG, our scheme will have more



TABLE VI: TRUTHFULNESS OF SUS

m	$U(u) < U(t)$	$U(u) = U(t)$	$U(u) > U(t)$
2	0.4760	0.5240	0
4	0.4580	0.5420	0
6	0.3460	0.6540	0

winning SUs. That is because our scheme increases the chance of each SUs to win the auction by using the VBG method.

In Fig. 33, we compared our auction profit results with TASG. We can find that our scheme improves the performance significantly because the winner determination algorithm and our scheme increase the number of winning SUs. The auction profit will increase if more SUs win the auction.

In Fig. 34, we compares the VBG's budget of different number of sacrificed SUs. Recall that the budget and evaluation are uniformly distributed. When we only sacrifice one SU, the VBG's budget will be very small. When we sacrifice about half SUs, maximum budget will be received. According to this result, we sacrifice half SUs in our group budget calculation step.

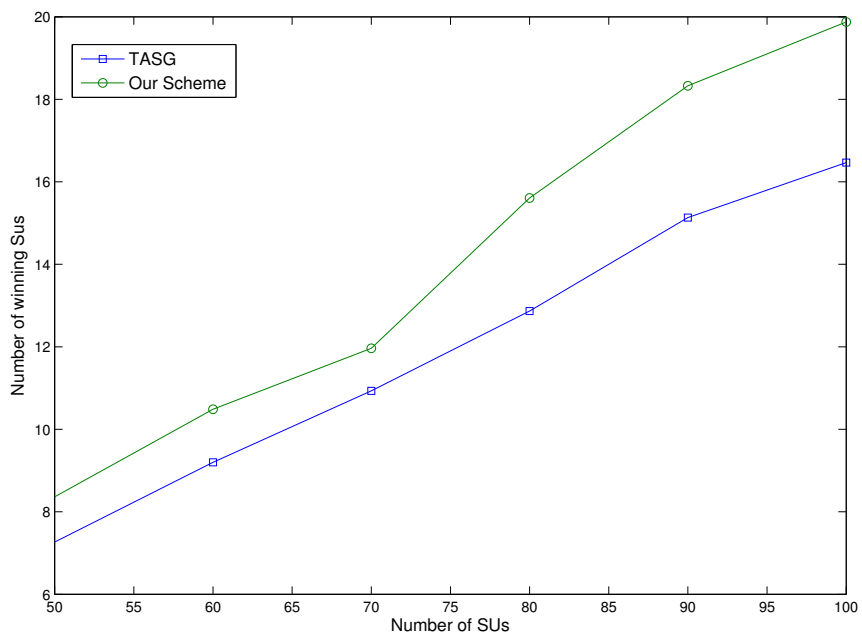


Figure 32: Number of winning SUs in each SN

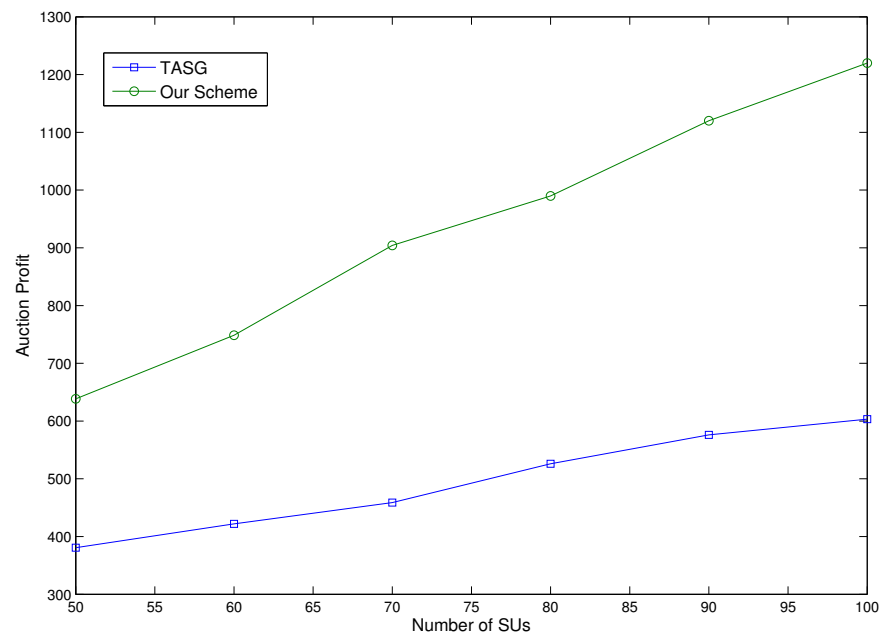


Figure 33: Multi-channel Auction profit

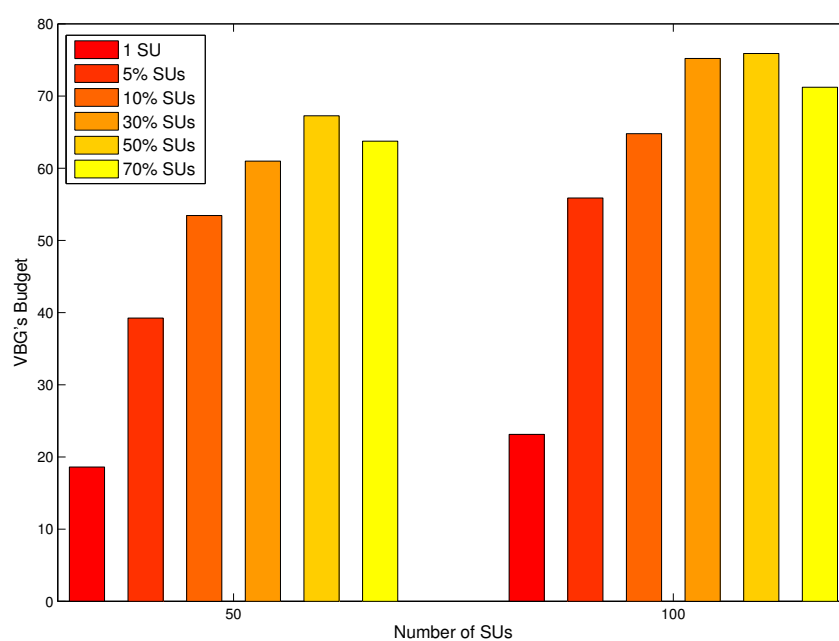


Figure 34: VBG's budget with different number of sacrificed SUs

## CHAPTER 7

### CONCLUSION AND FUTURE WORK

In this thesis, we introduced MAHES, a truthful multi-channel double auction mechanism for heterogeneous spectrums at first. MAHES allows seller and buyers sell and buy multiple channels with different center frequencies. Sellers and buyers in different locations can participate in the auction. MAHES introduced a novel virtual grouping method which can split the buyers and sellers according to the locations and split the buyers into non-conflict groups according to the frequencies. It solves the multi-channel problem of double auctions in heterogeneous spectrums. MAHES also increase the auction efficiency and auction revenue through spectrum reuse. At the same time, MAHES guarantees the economic properties: truthfulness, individual rationality and budget balance. We have shown that MAHES can achieve all the properties. And simulation results confirm that MAHES can provide high auction efficiency and auction revenue.

Second, due to the high price asked in the spectrum auctions, the newly freed spectrums can only be afforded by some largest mobile companies. SUs with limit budget cannot benefit from such auction directly. We studied the group-buying based double auctions for cognitive radio networks. In this thesis, we introduced both single-channel and multi-channel double auction for spectrum group-buying. There are two sealed-bid auctions in our scheme. This inner auction is a double auction and the outer auction is a single-side buyer-only auction. For single-channel auction, we use the Vickrey double auction mechanism to make the winner determination and find the winning price for the inner auction. To find the clearing price in outer auction, we sacrifice about half SUs at first, then find the winner set

according to evaluations. In our simulation results, we have verified that the SAP will get the maximum budget if we sacrifice half of SUs, given the uniform distribution values. The simulation results shows that our scheme can improve the performance significantly, in terms of the average utility of SAPs and the auction profit. For the multi-channel auction, the inner auction is a multi-channel double auction and we proposed a novel virtual group splitting and budget calculation algorithm in the outer auction. We proposed a novel winner determination method for the inner auction. In our simulation results, we have verified that the VBG will get the maximum budget if we sacrifice half of SUs under the uniformly distribution assumption. Comparing our results with TASG, our scheme can improve the performance significantly, in terms of number of winning SUs and the auction profit. At the same time, our schemes guarantee the economic properties: truthfulness, individual rationality and budget balance for both single-channel and multi-channel auctions.

In our future work, we will combine MAHES with group-buying concept. No literatures considered both heterogeneity and group-buying concept. It will be challenging to design a truthful group buying double auction for heterogeneous spectrums. We also can study the group-buying based online double auction in the future. In online auction, the auction is dynamic. In each period, different number of SUs and SHs will participate in the auction. it will be challenging to design a truthful group buying-based double auction in an online manner. Also the discriminatory pricing for group buying-based double auction is still an open problem. To ensure the truthfulness is challenging.

## **APPENDICES**



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