ISTANBUL TECHNICAL UNIVERSITY ★ GRADUATE SCHOOL OF SCIENCE ENGINEERING AND TECHNOLOGY

SPECTRUM SHARING IN COGNITIVE RADIO NETWORK THROUGH MATRIX BIDDING MULTI UNIT COMBINATORIAL AUCTION (CASS)

M.Sc. THESIS

Sheikh Mohammad MOINUDDIN

Department of Computer Engineering

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Thesis Advisor: Asst. Prof. Dr. D. Turgay ALTILAR

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İSTANBUL TEKNİK ÜNİVERSİTESİ ★ FEN BİLİMLERİ ENSTİTÜSÜ

MATRİX BİDDİNG ÇOKLU BİRİM KOMBİNATORİAL AÇIK ARTIRMA ARACILIĞIYLA COGNİTİVE RADYO ŞEBEKE SPECTRUM PAYLAŞIM (CASS)

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FOREWORD

First of all I would like to express my gratitude to my supervisor, Asst. Professor Dr. D. Turgay Altilar for guiding me in the right direction and always taking time for me for discussing topic which related our dissertation and not only that but he always encourage me to do something better. Thanks a lot for your great help and encouragement.

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January 2012 Sheikh Mohammad Moinuddin
(Computer Engineer)

TABLE OF CONTENTS

Page

ABBREVIATIONS

BIOSS	**:** BIOlogically-inspired Spectrum Sharing
CR	**:** Cognitive Radio
CA	**:** Combinatorial Auction
CASS	**:** Combinatorial Auction Spectrum Sharing
DMSS	**:** Demand Matching Spectrum Sharing
FCC	**:** Federal Communication Commission
FSA	**:** Fixed Spectrum Allocation
MB	**:** Matrix Bidding
RKRL	**:** Radio Knowledge Representation Language
SU	**:** Secondary Users
TDMA	**:** Time Division Multiple Access

LIST OF TABLES

Page

LIST OF FIGURES

SPECTRUM SHARING IN COGNITIVE RADIO NETWORK THROUGH MATRIX BIDDING MULTI UNIT COMBINATORIAL AUCTION

SUMMARY

Cognitive Radio (CR) is a promising concept to improve spectrum utilization of the existing spectrum bands. In this thesis, spectrum sharing problem between primary users (licensed) and secondary users (unlicensed), who want to use opportunistically the primary users' spectrum is investigated. One particular form of trading for the spectrum is auction, which is an applied branch of the game theory, and widely known for providing efficient allocation of scarce resources. Sellers use auctions to improve their revenue by dynamic pricing based on demands of buyers. Buyers benefit from auctions since resources would be assigned to those who value them the most. To the best of our knowledge, this thesis is the first in which matrix bidding multi unit combinatorial auction is proposed to share the available spectrum of primary user's among the secondary users.Combinatorial auction (CA) is a good candidate to solve spectrum allocation problem since it focuses on providing complementary and substitutable solutions. In the content of this thesis combinatorial auction allocate the valuable scarce spectrum to the secondary user on the basis of "bid matrix" submitted by secondary users rather than a single bid. Sending bid to the auctioneer as a combination of items is one of the most important feature of CA. Each channel is considered as a virtual channel comprising of multi slots. Submitting "bid matrix" provides secondary user an opportunity to get multiple slots from different channels in an auction. In CASS two important concepts we use one is combinatorial auction and the other one is matrix bidding. We consider that sharing in cognitive radio network is heterogeneous. Because of heterogeneousity the available channels from primary users are different from each other. We also consider multi unit auction not single unit. Because each channel can be divided into multiple units by TDMA mechanism, one secondary user can send bid for multi unit either from same channel or different channel. So the auction in here is a bit different from traditional auction. There are some renowned auction method like single auction, double auction, English auction and Dutch auction. But all these auction methods are focused on single unit not multi unit. Only combinatorial auction emerge for dealing with multi units. The name of this auction method shows that it can handle combination of items. This is the reason behind to choose the combinatorial concept in this thesis. But later we found some issues in combinatorial auction when we a secondary user sends bid to the auctioneer. Combinatorial auction focuses two important points one is complementarity and the other one substituatibiliy issue. But problem arises when the bids are not super-additive. For example, there are two items item1 and item2. One bidder places bid like this fashion b1 ({1}) = \$5, b2 ({2}) = \$4 and b3 ({1,2}) = \$7 and there are no other bidders. The auctioneer has two choice the first one is allocate item1 and item2 separately for gaining revenue (\$4+\$5=\$9) and the other one is allocate item1and item2 together for gaining revenue \$7.

In this regard, combinatorial auction focuses on capturing synergies (complementarities) among items. But in practice, local substitutability (sub additive of the bid price) can occur as well. The scenario which is explained above, one key point is detected is that preference on item. The bidder did not clear his preference in his bid. So the auctioneer has lack of information exactly which item the bidder needed mostly. In this circumstance, we need some comprehensive bidding language like matrix bidding language. Matrix bidding language has a excellent format through which one bidder can show his priority among the items and his preferences. There are some other bidding languages like XOR. We show make a comparison between XOR and matrix bidding. XOR language has much more complexity that matrix bidding language. The details about combinatorial auction and matrix bidding language are given in the thesis.

MATRİX BİDDİNG ÇOKLU BİRİM KOMBİNATORIAL AÇİK ARTIRMA ARACILIĞIYLA COGNITIVE RADYO ŞEBEKE SPECTRUM PAYLAŞIM

ÖZET

Cognitive Radio (CR) mevcut spektrum bantlarının spektrumu kullanımı artırmak için gelecek vaat eden bir kavramdır.Bu tezde, birincil kullanıcıları (lisanslı) ve oportünist birincil kullanıcıların spektrumu incelendiğinde kullanmak istediğiniz ikincil kullanıcılar (lisanssız), arasındaki spektrum paylaşımı sorunu.Spektrum için ticaret belirli bir formu oyun teorisinin uygulamalı bir dalı olan ve yaygın olarak kıt kaynakların etkin tahsisi sağlamak için bilinir müzayede vardır.Satıcılar alıcıların talepleri doğrultusunda dinamik fiyatlandırma ile gelirlerini artırmak için ihaleleri kullanın.Kaynakların onları en değerli olanlar tayin edileceğini yana Alıcılar ihaleleri yarar.Bizim bilgimize göre bu tez ikincil kullanıcılar arasında birincil kullanıcı var en uygun spektrum paylaşmak için önerilen hangi matris teklif çoklu birim kombinatoryal açık artırmada ilk.Kombinatoryal açık artırma (CA) tamamlayıcı ve ikame çözümleri sağlamaya odaklanmaktadır yana spektrum tahsisi sorunu çözmek için iyi bir adaydır.Bu tez Kombinatoryal müzayede içeriği yerine tek bir teklif daha ikincil kullanıcılar tarafından gönderilmiş olan "teklif matrix" temelinde ikincil kullanıcıya değerli kıt spektrum tahsis.Öğeleri bir arada CA en önemli özelliklerden biridir olarak ihaleyi için teklif gönderiliyor.Her kanal çoklu yuva oluşan sanal bir kanal olarak kabul edilir."Teklif matrix" Gönderme ikincil kullanıcı bir açık artırmada farklı kanallardan birden yuvaları almak için bir fırsat sağlar. Matris formatı gibi öğesi prioriity, complimentarity ve substituatibility olarak teklif veren firmanın çok boyutlu bilgi göstermek için bir isteklinin kolaylaştırabilir çünkü Matrix teklifi en kapsamlı ihale dildir.Bu bilgiler çok kazanan teklif karar vermek için bir açık artırma için çok faydalıdır. CASS iki önemli kavram olarak biz bir kombinatoryal ihale ve diğer bir matris teklif olduğunu kullanın. Biz bilişsel radyo ağı bu paylaşım heterojen bir düşünün. Çünkü heterogeneousity primery kullanıcılardan mevcut kanal birbirinden farklıdır. Biz de çok birimi müzayede değil tek ünite düşünün. Her kanal TDMA mekanizma ile birden fazla üniteye ayrılabilir Çünkü, ikincil bir kullanıcı çoklu ünite için de aynı kanal veya farklı kanaldan teklif gönderebilirsiniz. Yani burada açık artırmada geleneksel açık artırma biraz farklı. Bazı tek açık artırma gibi tanınmış ihale yöntemi, çift müzayede, İngilizce ve Hollandaca müzayede müzayede vardır. Ama bütün bu ihale yöntemlerinin tek ünite çok değil birimi odaklandık. Sadece kombinatoryal müzayede çok üniteleri ile uğraşmak için ortaya çıkıyor. Bu ihale yöntemi ile ismi öğelerin birleşimi işleyebilir gösterir. Bu, bu tez içinde birleştirici kavramı seçmek için temel sebebi budur. Spektrum paylaşımı daha verimli hale ihale mekanizmasının diğer bazı avantajları vardır. Birincisi ve en önemlisi, olmayan bir işbirliği mekanizması olduğunu. Dışı kooperatif olduğu gibi, ikincil kullanıcıların aralarında mesaj alış verişi yoktur. Bu nedenle, açık artırma mekanizması hiçbir koordinasyon gecikme vardır. Bencillik ve hile genellikle paylaşımı yöntemiyle gerçekleşebilir. İkincil kullanıcılar kooperatif spektrum paylaşım mekanizması onların değerli bilgileri paylaşmak gerekir. Başka

ikincil hile olabilir çünkü bu çok riskli. Bencillik paylaşımı başka büyük bir sorundur. Tüm ikincil kullanıcı uygun spektrum yakalanan deneyin. Oldukça spektrum tahsis edilmesi de önemlidir. Müzayede mekanizması kıt kaynakların adil dağılımı için en iyi yöntemdir. Ayrıca kaynak kullanımı yanı sıra gelir maksimize. Ama daha sonra biz ikinci bir kullanıcı mezatçı için teklif gönderdiğinde kombinatoryal müzayede bazı sorunlar bulundu. Kombinatoryal müzayede bir tamamlayıcılık ve diğeri substituatibiliy konudur iki önemli nokta odaklanır. Tekliflerini süper katkı değildir Ama sorun doğar. Örneğin, iki öğe item1 ve item2 vardır. Bu moda b1 gibi bir isteklinin yerlerde teklifi b1 ({1}) = $ 5, b2 ({2}) = $ 4 ve b3 ({1, 2}) = $ 7 ve başka isteklilere vardır. Ihaleyi ilk allocate item1and item2 $7 gelir kazanmak için birlikte olduğunu geliri ($ 4 + $ 5 = $ 9) ve diğeri kazanıyor için ayrı ayrı item1 ve item2 tahsis edilir iki seçenek vardır. Bu bağlamda, kombinatoryal açık artırma öğeleri arasında sinerji (tamamlayıcılık) yakalama odaklanır. Fakat uygulamada, yerel ikame (teklif fiyatı alt katkı maddesi) de oluşabilir. Yukarıda, bir anahtar nokta tespit edilir açıklanmıştır senaryo öğe olduğunu tercihtir. İstekli yaptığı teklif onun tercihi açık vermedi. Yani ihaleyi tam isteklinin en çok ihtiyaç duyulan hangi madde bilgi eksikliği vardır. Bu durumda, biz matriks teklif dili gibi bazı kapsamlı ihale dile ihtiyacımız var. XOR gibi bazı diğer teklif dil vardır. Biz XOR ve matris teklifi arasında bir karşılaştırma yapmak göstermektedir. XOR dil bu matrisi teklif dili çok daha fazla karmaşıklık var. Matrix teklif dil tek teklif sahibi öğeleri ve kendi tercihleri arasında onun önceliği gösterebilir hangi aracılığıyla mükemmel bir biçimi vardır. Kombinatoryal ihale ve matris teklif dili hakkında bilgi tez verilmiştir. Kanal özelliklerini analiz için, bağlı ve gerekli minimum iletim gücü geciktirebilir, bu kablosuz bağlantı hata oranı, bağlantı katmanı gecikme ve ikincil kullanıcı talebi kabul edilebilir hata oranı yanı sıra izin verilen maksimum iletim gücü olarak üç spektrum karakteristik parametreleri düşünün. Aslında bu parametreler ikincil kullanıcılar için daha iyi bir kanal seçimi için kabul edilir. İkincil kullanıcının bu üç eşleme faktörlere göre auctioneer için teklif gönderir. İhaleye çıkan ikincil kullanıcı teklifleri ve kullanım şube ve kazanan belirlenmesi için sınır algoritması toplar. En az bir istekliye her bir öğeyi atıyorsanız kombinatoryal müzayede yerine ihale için en önemli üç görev, aynı istekliden birden fazla teklifi kabul edip bir kısmını bu konuda farklı bir teklif almak için birden çok teklifi yeniden birleştirilmesini gelen ihaleyi engelleyen mezatçı önleristekliler tarafından sunulan biridir. CASS olmayan bir kooperatif tayfı paylaşımı yöntemdir. Olmayan kooperatif olduğu gibi, hiçbir koordinasyon gecikme gibi sayısız yararları vardır, ikincil kullanıcıların dürüst davranır ve bencillik ve hiçbir hile yok. Işbirlikçi bir yaklaşım içinde Spectrum paylaşımı gibi sorunlarla karşı karşıyadır. CASS bu sorunların üstesinden bu yana, spektrum adil bir dağılımı sağlar. Oldukça ikincil kullanıcılar birincil kullanıcı uygun spektrum tahsisi bizim tez çalışmasının temel amaçlarından biridir. Son olarak, CASS performansını analiz etmek için, biz diğer iki spektrum paylaşım yöntemleri BIOSS'lar ve DMSS ile simülasyon sonuçları karşılaştırın. İşte, BIOSS kısa ve DMSS algoritma üzerinden gitmek. Bilişsel radyo ağı Spectrum paylaşımı böcek kolonisi görev tahsisi ile büyük benzerlikler vardır. Bilişsel radyo duyuları daha sonra mevcut spektrum bantları ve için çevreyi aynı anda kullanılabilir spektrum bantları kendi paketlerini iletir. Benzer şekilde, bir böcek kolonisi, bireylerin daha sonra kullanılabilir görevleri ve mevcut görevler daha iyi işler için donanımlı bireyler tarafından gerçekleştirilir için feromon çevreyi seziyorum. Biyolojik modelde her görevi daha iyi görevi gerçekleştirirken olasılık ile bu görev için donanımlı bireyler paylaştırılır. Benzer şekilde Bilişsel radyo ağ içinde uygun spektrum bantları oldukça etkin spektrum paylaşımı modeli ile bilişsel radyo paylaştırılmış olmalıdır. Bu benzetme göre, bilişsel radyolar etkili en uygun spektrum bantları paylaşmanızı sağlayan kanal seçimi olasılık tanıtmak olasılık performans görevi kabul eder. BIOSS, böcek kolonilerinde adaptif görev tahsisi modeline dayalı ikincil users.BIOSS arasında herhangi bir koordinasyon ihtiyacı olmadan her lisanssız kullanıcının distributively bu iletişim kurabileceği üzerinde uygun kanalı belirlemek için kılar. Ama BIOSS yöntemi, kanal karakteristikleri ve spektrum paylaşımı için kullanıcı gereksinimleri de sorun var. Congnitive radyo ortamında kullanılabilir spektrum heterojendir ve her spektrum farklı uygulama farklı QoS talep var, farklı characteristics.Different ikincil kullanıcıların sahip olduğu evrenseldir. BIOSS gibi issue.DMSS spektrum karar modeli için bu spektrum karakteristik parametreleri birleştirmek ve lisanssız kullanıcılar spektrum özellikleri ve kullanıcı ihtiyacına göre en uygun spektrum tercih yapmak düşünmüyordu. Biz BIOS'ları CASS ve DMSS daha düşük bir performansa sahiptir ve CASS% 90 kullanımını sağlar olduğu bulundu.

1. INTRODUCTION

The former strategy of Federal Communication Commission (FCC) is to allocate spectrum causes under-utilization of radio spectrum resources [2]. Day by day the number of wireless applications and wireless devices rapidly growing, that is why needed to assign spectrum to those applications and devices for operation. There are two limitations, which create difficulties for upcoming new wireless application and wireless devices. One limitation is the scarce resource of spectrum and the other one is the fixed spectrum allocation (FSA) strategy of FCC. So the regulatory bodies such as the Federal Communications Commission (FCC) have begun to consider more flexible and comprehensive uses of available spectrum [2].

Cognitive radio technology [4] is emerging in recent years as a revolutionary communication paradigm, which can provide faster and more reliable wireless services by utilizing the existing spectrum band more efficiently [5,6]. A notable difference of a cognitive radio from traditional wireless networks is that users need to be aware of the dynamic environment and adaptively adjust their operating parameters based on the interactions with the environment and other users in the network. So the term, Cognitive radio can formally be defined as follows [3]:

"A Cognitive Radio is a radio that can change its transmitter parameters based on interaction with the environment in which it operates".

The definition of CR as stated above, two important features of CR can be defined as follows [6]:

1. Cognitive capability: This capability refers to the ability of the radio technology to capture or sense the information from its radio environment. Through this capability, the portions of the spectrum that are unused at a specific time or location can be identified. Consequently, the best spectrum and appropriate operating parameters can be selected.

2. Reconfigurability: This feature enables the radio to be dynamically programmed according to the radio environment. More specifically, the cognitive radio can be

programmed to transmit and receive on a variety of frequencies and to use different transmission access technologies supported by its hardware design.

The CR concept was first introduced in [4] by J. Mitola, where the main focus was on the radio knowledge representation language and how the cognitive radio can enhance the flexibility of personal wireless services.

Finally, the CR enables the usage of temporarily unused spectrum which is referred to as spectrum hole or white space [6] shown in Fig.1.1.

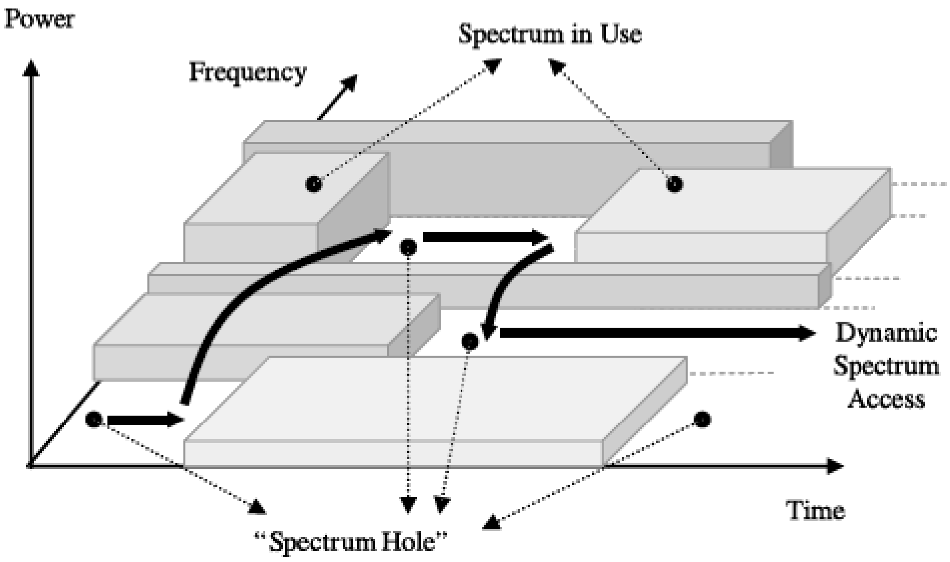

Figure 1.1: Spectrum hole concept [6].

Now we are going to explain our purpose of this thesis.

1.1 Purpose of Thesis

There are two important issues in auction theorem which are not focused in the most of the auction theories.But Combinatorial Auction focuses these two issues:

1. Complementarities.
2. Substitutability.

Complementarities: Bidders may place combination of items. This allows a bidder to express complementarities between items so he does not have to speculate into an item's valuation the impact of possibly getting other, complementary items.

$$\bar{b}(S \cup \acute{s}) \geq \bar{b}(S) + \bar{b}(\acute{S}) \tag{1}$$

Inequality (1) show the complementarities effets for item S and Ś.

Substitutability: Any number of bidder's bid can be accepted.

$$\bar{b}(S \cup \acute{s}) \le \bar{b}(S) + \bar{b}(\acute{S}) \qquad \textbf{(2)}$$

When bids are super-additive there is no problem. However, when some of the bids are not superadditive, this can lead to problems. For example, what happen if bidder 1 bids b1 ({1}) = \$5, b1({2}) = \$4, and b1({1, 2}) = \$7, and there are no other bidders? The auctioneer (primary user) could allocate items 1 and 2 to bidder 1 separately, and that bidder's bid for the combination would value at \$5 + \$4 = \$9 instead of \$7. So, the current techniques focus on capturing synergies (complementarities) among items. In practice, local substitutability (sub-additivity of the bid prices) can occur as well. As a simple example, when bidding for a landing slot for an airplane, the bidder is willing to take any one of a host of slots, but does not want more than one. To handle this situation we need an expressive bidding language, which can help secondary user to place bid to the primary user with a clear valuation of the items. Latter we discuss that expressive bidding language.

In this thesis book, we proposed a combinatorial auction with matrix bid non co-operative spectrum sharing scheme for cognitive radio network. Here two unique points, first one, primary user always tries to maximize revenue and second one, efficient allocation of available unused spectrum of primary user's to the secondary user according to secondary users demand.

1.2 Background

Several researches have already attacked the spectrum sharing problem in CR using different approaches spanning from nature inspired solutions to demand matching and from graph coloring to auctions.

In [9] the proposed model where each secondary user can place bid for only one single unit from multiple homogenous unit. They did not thinking about multi unit sharing. But it is possible in cognitive radio environment one secondary user may win multiple unit. As they did not think about multi unit that's why bidding language is very simple in this model like one SU submit bid its desire band and price for that band. So multiple unit auction we need some expressive bidding language for SUs to submit bid for multiple unit.

In [10] the problem is addressed further as multiple licensed service providers compete with each other to offer spectrum access opportunities to the unlicensed users. By using an equilibrium pricing scheme, each of the licensed service providers aims to maximize its profit under quality of service (QoS) constraint for licensed users with Bertrand game model. Thus unused spectrum is allocated to the unlicensed users. However the coordination among cognitive radios results in large amount of coordination delay.

In [11] BIOlogically-inspired spectrum sharing (BIOSS) algorithm is introduced based on the adaptive task allocation model of an insect colony. Without need for any coordination among the unlicensed users, BIOSS enables each cognitive radio in the same environment distributive share the available licensed or unlicensed spectrum bands over which it can effectively communicate.

However, above-mentioned algorithms do not consider the matching problem between channel characteristics and user requirement for the spectrum sharing. Since the available spectrum holes are heterogeneous, it is true that different spectrum have different characteristics. Meanwhile, different users usually have different QoS demands on various wireless applications.

However, above algorithms do not consider the matching problem between channel characteristics and user requirement for the spectrum sharing. Since the available spectrum holes are heterogeneous, it is true that different spectrum have different characteristics. Meanwhile, different users usually have different QoS demands on various wireless applications.

So it is important for secondary users in spectrum sharing to choose the proper available spectrum those are shared by primary users to fulfill secondary users demand. Thus in heterogeneous cognitive radio spectrum sharing environment sharing can be divided into two steps:

1. Spectrum characterization of the available spectrum in the environment and secondary users (unlicensed) choose the most suitable spectrum according to the spectrum characteristics and secondary user demand.

2. As available spectrum are non contiguous and sub divided into multiple slots, so secondary users have the opportunity to access multiple slots from the same spectrum band or may access multiple slots from available different spectrum.

Thus for accessing multiple unit secondary users submit bid combination of multiple unit to the primary users. Bids are two dimensional (slots, price).

Because pricing can have two different goals: reaching maximum revenue for the network, or allocating efficiently the resources. Here price is the amount that the secondary users willing to pay for the resource they demand.

In [14] Layer and Semret prove that if players are informed of the other players bids when they submit their own bids, the bid profile's converges after a finite time to a Nash equilibrium that corresponds to an efficient allocation of the resources. But the main drawback of this of this scheme is that the convergence phase can be quite long and that it corresponds to a signalling burst (to sending necessary information to players) which non-negligible part of the available bandwidth. The goal here is to change the sequential (dynamic) bid process of into a one-shot multi bid for each player in order to alleviate the bid-profile signalization overhead.

1.3 Structure of the Thesis

This thesis is organized as follows. In Chapter 2, we will explain spectrum sharing concept in cognitive radio, spectrum sharing challenges and auction games. In Chapter 3, combinatorial auction and in Chapter 4, we will explain about Matrix bidding language. Our system model and spectrum-sharing scenario will be outlined in Chapter 5. Simulation results and analysis are shown in Chapter 6. Finally in chapter 7, conclusion is drawn.

2. SPECTRUM SHARING IN COGNITIVE RADIO NETWORK

2.1 Overview of Spectrum Sharing

Traditional spectrum sharing and management approaches, generally assume that all network users cooperate unconditionally in a static environment, and thus they are not applicable to a cognitive radio network.

In a cognitive radio network, users are intelligent and have the ability to observe, learn and act to optimize their performance. The importance of studying cognitive radio networks in a game theoretic framework is multi-fold.

First, by modelling dynamic spectrum sharing among network users (primary and secondary users) as games, network user's behaviours and actions can be analyzed in a formalized game structure, by which the theoretical achievements in game theory can be fully utilized. Second, game theory equips us with various optimality criteria for the spectrum-sharing problem. To be specific, the optimization of spectrum usage is generally a multi-objective optimization problem, which is very difficult to analyze and solve. Game theory provides us with well defined equilibrium criteria to measure game optimality under various game settings. Third, non-cooperative game theory, one of the most important branches of game theory, enables us to derive efficient distributed approaches for dynamic spectrum sharing using only local information. Game theoretic spectrum sharing schemes are classified into four categories shown in Fig.2.1 [17].

2.2 Game Theory for Spectrum Sharing

Cognitive radio users or secondary users are intelligent users. Using intelligency, secondary users make decision on spectrum usage and operating parameters based on dynamically sensed spectrum. Because of their intelligency, there is no cooperating between the other secondary users. Therefore, it is important to analyze the intelligent behavior of secondary users from a game theoretic perspective.

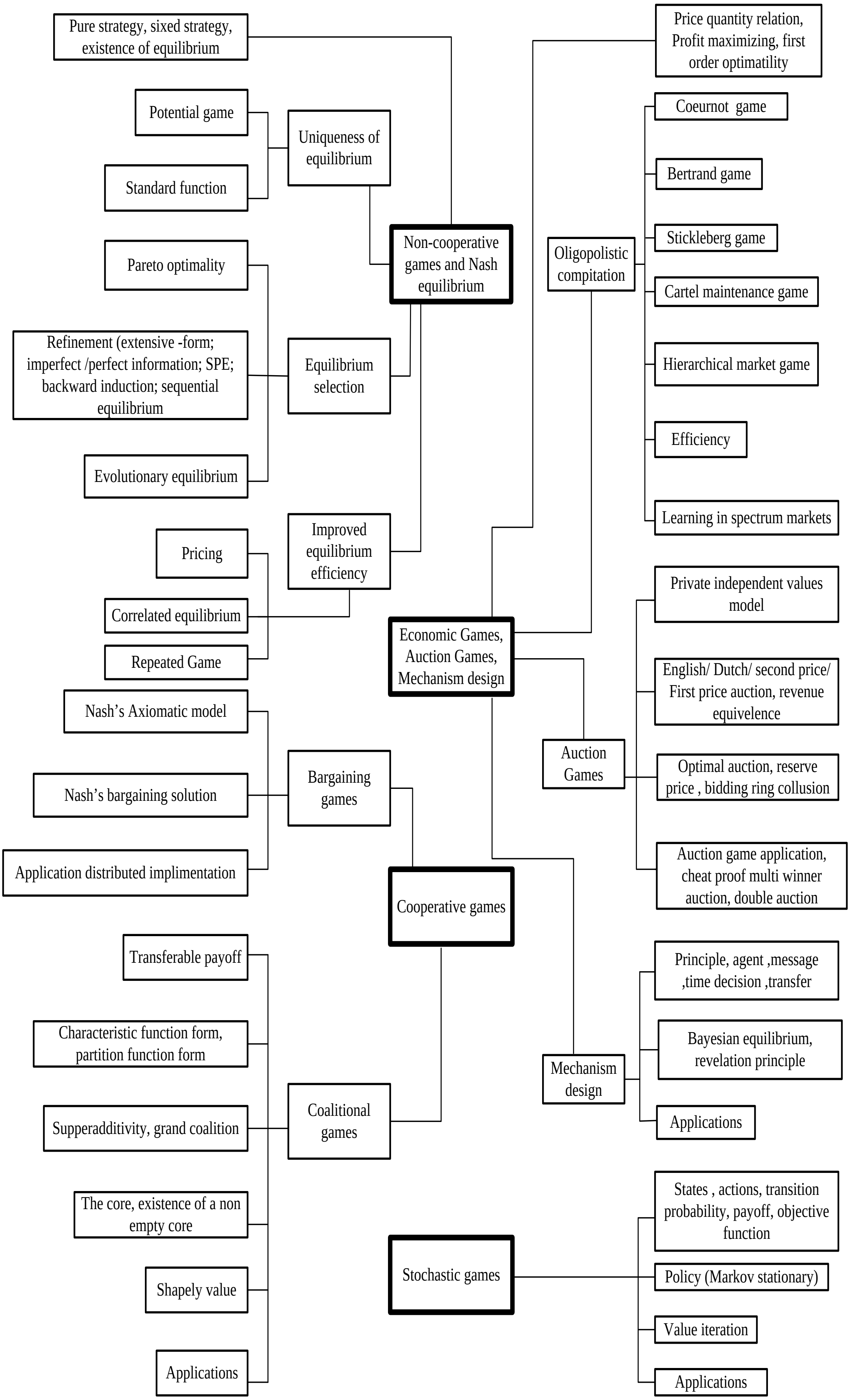

Figure 2.1: Four categories of the game theoretic spectrum sharing approaches [17].

Studying cognitive radio networks in a game theoretic framework is multifold. First, by modeling dynamic spectrim sharing among secondary users as games, secondary user’s behavior and actions can be analyzed in a well format game structure, by which the theoretical achievements in game theory can be fully utilized. Second, game theory equips us with various optimality criteria for the spectrum-sharing problem. Game theory provides us with well-defined quilibrium criteria to measure game optimality under various game settings. Third, non-cooperative game theory, one of the most important branchs of game theory, enable us to derive efficient distributed approaches for dynamic spectrum sharing using only local information. Game theory still rarely uses in engineering and computer science. Here we introduce the most basic game theoretic concepts and then address how these concepts can be leveraged in designing efficient spectrum sharing schemes from a network designer’s perspective. An overall scenario of different game theory approaches is shown in fig.2.1. From the fig.2.1, we can see that there are four main game theoretic spectrum-sharing categories. We first discuss non-cooperative spectrum sharing gaeme in section 2.2.1, because secondary users are mostly assumed to be selfish and only aim to maximizing their own spectrum usage.

2.2.1 Non-cooperative games and Nash equlibrium

Nash equilibrium is a key concept to understand non-cooperative game theory. Nash equilibrium tells us what the equilibrium outcome will be but it does not answer the question “How can we get to the equilibrium?”. This is more important in the context of cognitive radio networks, where players may lack the global information to directly predict the equilibrium. Instead, they may start from an arbitrary strategy, update their strategies according to certain rules, and hopefully converge to the equilibrium. In general, Nash equilibrium oftern suffer from excesisive competition among selfish players in a non-cooperative game and the outcome of the game is inefficient. There are three approaches, namely, usage of pricing, repeated game and correlated equilibrium can improve the efficeiency of Nash equilibrium. Game theory is mathematical tool that analyzes the strategic interactions among multiple decision makers. Three major components in a strategic-form game model, the first one is a finite set of players, the second one a set of actions and the last one payoff/utility. In opportunistic spectrum access, secondary users will choose proper operating parameters to optimize the performance or quality of service (QoS) from sharing the spectrum. In negotiation based licensed spectrum sharing the primary users will announce the available spectrum bands to the secondary users and distributed the bands through auction.pricing, where both primary and secondary users can maximize their profits by leasing and licensed bands. Efficeint spectrum sharing schemes are essential for improving spectrum utilization. However, since users in a cognitive radio network are intelligent and able to observe, learn, and act to optimize their performance, if they belong to different authorities and pursue different goals, fully cooperative behavior cannot be taken for granted. Instead, selfish users will compete for the limited spectrum resources, and only aim to maximize their own benefit. As traditional spectrum sharing approaches only assume cooperative, static, and centralized network settings, new solution based on game theoretic modeling are preferred, which can offer more flexibility in analyzing network user's strategic interactions and achieve efficient dynamic spectrum sharing. In non-cooperative spectrum sharing game with rational secondary users, each user only cares about his/her own benefit and choose the optimal strategy that can maximize his/her payoff function. Such an outcome of the non-cooperative game is termed as Nash equilibrium, which is the most commonly used solution concept in game theory [17].

2.2.2 Economic games, Auction games and Mechanism design

Here we do not go detail on economic games and mechanism design because we focus on auction games. Auction theory is an applied branch of game theory, which analyzes interactions in auction markets and researches the game theoretic properties of auction markets. An auction, conducted by an auctioneer, is a process of buying and selling products by eliciting bids from potential buyers (i.e bidders) and deciding the auction outcome based on the bids and auction rules. The rules of auction or auction mechanisms, determine whom the goods are allocated to and how much price they have to pay. An efficient and important means of resource allocation, auctions have a quite a long history and have been widely userd for a variety of objects including antiques, real properties spectrum resources and so on. There are some auction approaches like English auction, Dutch auction, Second price auction and First price auction. An auction becomes more involved when more than one item are simultaneously sold and bidder bid for packags of products instead of individual products. There is some other game theory such cooperative game and stochastic game [17].

2.3 Spectrum Sharing Challenges

Spectrum sharing in CR network faces a number of new challenges such as radio interference constraints, supporting diverse demands and online multi-unit allocations which are briefly explained as follows [1].

Radio Interference Constraints: Buyers in close proximity interfere with each other and cannot use the same spectrum, while well-separated buyers can reuse the same spectrum. Hence, spectrum auctions need to explicitly account for the impact of interference when determining allocations and prices.

Supporting Diverse Demand: Spectrum auctions need to accommodate diverse demands. These include both traditional long-term spectrum usage using and short-term spontaneous spectrum usage to support bursty traffic. For example, occasional events like sports and conferences will create demand spikes at a specific location for a short-period of time. It is important for these users to obtain and pay for what they need.

Multi unit auction: Spectrum auctions are multi-unit auctions, where multiple identical copies of slots are for sale. Spectrum is divided into a number of channels. Users wish to obtain different amount of spectrum at their desired power level, and may be willing to pay differently depending on the assignment. Hence, we need a new bidding language to allow buyers conveniently express their desire, and do it so compactly. Combinatorial multi unit auction is one of the solutions of multi unit.

Although all of the above mentioned challenges are important we focused on only combinatorial multi unit auction in this thesis. In order to provide a mean to deal with combinatorial multi unit auction we proposed matrix bidding. Matrix bidding is suitable for secondary users to submit their bids for slots in a multiple unit spectrum auction. Combinatorial auction addresses two important issues: providing complementarities and substitutability [8].

2.4 Auction Games

Auction theory is an applied branch of game theory, which analyzes interactions in auction markets and researches the game theoretic properties of auction markets. An auction, conducted by an auctioneer, is a process of buying and selling products by eliciting bids from potential buyers (i.e., bidders) and deciding the auction outcome based on the bids and auction rules. The rules of auction, or auction mechanisms, determine whom the goods are allocated to (i.e. the allocation rule) and how much price they have to pay(i.e., the payment rule). As efficient and important means of resource allocation auctions have quite long history and have been widely used for a variety of objects, including antiques, real properties, bonds, spectrum resources, and so on. For example, the Federal Communications Commision (FCC) has used auctions to award spectrum since 1994, and the United States 700 MHz FCC wireless spectrum auciton held in 2008. The spectrum allocation problem in cognitive radio networks although micro-scaled adn short termed compared with the FCC auctions, can also be settled by auctions.

Auctions are used precisely because the seller is uncertain about the values that bidders attach to the product. Depending on the scenario, the values of different bidders to the same product may be independent (the private values model) or dependent (the independent values model). Almost all the existing literature on aucitons in cognitive radio networks assumes private values. Moreover, if the distribution of values is identical to all bidders, the bidders are symmetric. Last it sis common to assume a risk neutral model, where the bidders only care about the expected payoff, regardless of the variance (risk) of the payoff [17]. A typical auction scenario is shown in fig2.2.

Following assumption for Spectrum sharing: First, buyer (secondary user) bids spectrum with specific but fixed power requirements, and hence focus solely on channel allocation.The seller (primary user) divides its spectrum into a large number of homogeneous channels with equal power limit and transmission bandwidth. So we focus on multiple distinguishable items to be allocated.

These auctions are complex in the general case where the bidders have preferences over bundles, that is, a bidder’s valuation for a bundle of items need not equal the sum of his valuations of the individual items in the bundle.

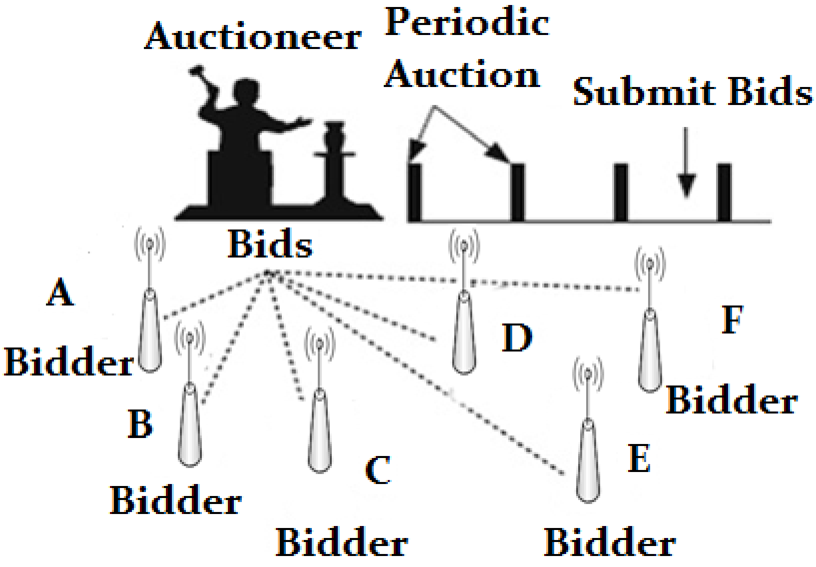

Figure 2.2: A dynamic auction scenario, an auctioneer performs periodic auctions. of spectrum to buyers [1].

3. COMBINATORIAL AUCTION

3.1 Definition of Combinatorial Auction

Combinatorial Auctions (auctions in which bidders may express bids on combinations or bundles of goods) are motivated by the presence of synergy in bidder's valuations for sets of goods. The synergy associated with a set of goods (S) and number of bidder (j) may be defined as $\delta_j(S)$,

$$\boldsymbol{\delta_j(S) = v_j(S) - \sum_{i \epsilon S} v_j(\{i\})} \tag{3}$$

$v_j\,(S)$ is bidder j's value for the set of goods S.

The presence of synergistic valuations impedes the generalization of the single-good auctions to efficient multiple-good auctions. When synergy is positive there are complementarities effects; the bidder would like to tell the auctioneer, "I would give you more money if I could be guaranteed to get these goods together". When synergy is negative, substitution effects dominate; the bidder would say, "Here are my prices, but I want to pay less if I get goods that are substitutes". Preferences for a bundle may be referred to as sub-additive, additive, or super-additive when synergy is negative, zero, or positive, respectively. Clearly the auctioneer benefits from taking positive synergy effects into consideration; bidders will promise to pay extra if they are guaranteed certain combinations of goods. Though it is less immediately clear, the auctioneer may benefit if he is willing to consider negative synergy information as well. This is because a bidder will be more willing to bid up to his true value on small bundles if the risk of paying too much for a combined bundle is reduced or eliminated. In addition to the possibility of increased revenue for the auctioneer, taking negative synergies into account can increase the economic efficiency of an auction, a feature desirable in governmental auctions of electricity, radio-spectrum, oil-drilling rights, etc. which constitute an area of major interest in the auction literature.

In a combinatorial auction, the auctioneer collects bids $b_j(S)$ from each bidder j on potentially any subset S of the items in the auction. In an efficient combinatorial auction, the auctioneer then solves a combinatorial optimization problem, the winner-determination problem, which finds an allocation of items to bidders that maximizes the total value of accepted bids. For the most general context, this may be modelled as an Integer Program (IP), related to the set-packing problem, and described, for example, by de Vries and Vohra (2003).

This General Winner-Determination problem (GWD) for the allocation of N items in the set I = {1, 2,.............N} among M bidders in the set J = {1,2,.......M}can be formulated as follows, with binary variables $x_j(S)$that equal 1 if and only if bidder j is awarded bundle $S \dot{\subseteq} I$:

$$\max \quad \sum_{j \in J} \sum_{S \dot{\subseteq} I} b_j(S) x_j(S) \tag{GWD}$$

$$\text{subject to } \sum_{S \dot{\supseteq} \{i\}} \sum_{j \in J} x_j(S) \leq 1 \quad \forall_i \in I \tag{4}$$

$$\sum_{S \dot{\subseteq} I} x_j(S) \leq 1 \quad \forall_j \in J \tag{5}$$

$$x_j(S) \in \{0,1\}, \ \forall S \dot{\subseteq} I, \forall j \in J \tag{6}$$

Constraint set (4) ensures that each item is assigned to at most one bidder, while constraint set (5) prevents the auctioneer from accepting multiple bids from the same bidder, preventing the auctioneer from recombining multiple bids to get a different bid on a subset than the one submitted by the bidder [12].

3.2 Algorithm For Multi Unit Combinatorial Auction

3.2.1 Branch and Bound Algorithm

The idea of Branch and Bound algorithm find optimal allocations in combinatorial auction multi unit search. Let us describe briefly branch and bound search, given a set of bids, combinatorial auction multi unit search systematically compares the revenue from all allocations in order to determine the optimal allocation. This comparison is implemented as depth-first search: we build up a partial allocation one bid at a time. Once we have constructed a full allocation we back-track, removing the most recently added bid from the partial allocation and adding a new bid instead. Sometimes we can safely prune the search tree, backtracking before a full allocation has been constructed. Every time a bid is added to the current location, combinatorial auction multi unit search computes an estimate of the revenue that will be generated by the unallocated goods which remain. Provided that this estimate function o() always provides an upper bound on the actual revenue, we can prune whenever p(π)+o(π)<= p(π_{best}), where π is the best current allocation, p(π)=$\sum_{b\epsilon\pi} P(b)$ and π_{best} is the best allocation observed so far.

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4. BIDDING LANGUAGE

4.1 Matrix Bidding

A bidder in this model specifies her preferences with a value for each item in each of its possible rankings in the final bundle. The bid offered for item (i) by bidder (j) given that it is the kth best item she receives would be denoted b_{ijk}. Bidder j's bid on a bundle S may then be computed as:

$$b_j(S) = \sum_{i \epsilon S} b_{ij} k(i, s) \quad \textbf{(7)}$$

where K(i , S) gives the ordinal ranking of item i among the items in S. For example, K({i, S) = 1 if no item in S has a higher rank than item i. Similarly, K ({i, S) = 2 if exactly one item in bundle S has a higher rank than item i etc. A bidder interprets each matrix bid entry as an incremental bid on an item; the row indicates which item is bid on, while the column tells the ranking of the item within the bundle it brings value to. The matrix bid itself interpreted as a collection of bids on any possible subset, each bid equal to the sum of incremental values for the items. Each bidder submits an ordered list of the items to establish the values of rij and a matrix containing non-negative values of bijk (for simplicity we assume integer values throughout). The matrix of b_{ijk} entries together with the precedence ordering rij referred to as a matrix bid.

The following simple rules summarize how to interpret a matrix bid:

- When an item is awarded to a bidder, the auctioneer receives a single bid from the corresponding row in that bidder's matrix bid.
- Only a single bid may be taken from any column.
- Except for bid entries in the first column, a bid may not be used unless a bid in the previous column and a higher row is also used [13].

4.2 Example of Matrix Bidding

Suppose a bidder is submitting his preferences for the following entertainment choices on a specific date: a ticket to the afternoon baseball game, a coupon for dinner at a nearby restaurant, a day-pass to a water-park (outside of town), and a ticket to a matinee at the local theatre. He reasons that the matinee and baseball game conflict; he cannot go to both, but can make it to dinner after either one. He decides that if he gets any of the other items he will not leave town to go to the water-park. His matrix bid may appear as follows:

Table 4.1: Matrix Bid for four items.

Priority ↑	Football	40			
	Matinee	10	0		
	Dinner	25	25	25	
	Water-park	40	0	0	0

The order r_{ij} is given in the outside column with baseball being priced first, the matinee second and so forth. The first column inside the matrix (always) gives the bid on the good in that row if it is the first (or only) good received. The second column gives the price for each good in the row given that it is the second highest good received etc. If he receives a baseball ticket he is willing to pay 0 for the matinee which he cannot attend due to conflict. If he receives either baseball or matinee in the first column he would being willing to pay 25 for the meal (in the second column). Although the seller is unlikely to give away the matinee ticket, the mathematical formulation does not necessarily rule this out. If the auctioneer gives him the baseball ticket at 40 and the matinee ticket at 0, he is still willing to pay 25 for the dinner, and expresses this with a 25 in the third column; a free matinee ticket does not change his preferences for the dinner. The fourth row shows that he would pay 30 for the water-park pass by itself, but would pay 0 for it if any other items are won. The bid of 30 cannot be accepted with any other bid by the rules outlined above. Another example of matrix bidding, a major TV network has 4 available advertise time slots. X,Y,Z companies have different marketing strategies determining their preference for these time slots in this fashion X need exactly two time slots, are indifferent to which two. Y think slots B and C are more effective because are occurring in the middle of the program than A and D beginning and ending. Z agrees slots B and C superior than A and D. But they are interested in each viewing. The matrix bids these companies submit are:

Table:4.2 Matrix bid of four different time slot.

Bidder X		
priority	A	0
	B	0 30
	C	0 30 0
	D	0 30 0 0

Bidder Y		
priority	A	20
	B	20 6
	C	10 4 0
	D	10 4 0 0

Bidder Z		
priority	A	7
	B	6 7
	C	5 6 7
	D	4 5 6 7

The optimal value for the winner-determination problem is 57: Bidder X receives goods A and D, contributing 30 to the objective function; Bidder Y receives good C for 20 units, while Bidder Z pays 7 units for B. These examples show the ability of the matrix bid format to express several types of preferences. The first example shows the ability to model a precedence relation where certain goods preclude one another while others do not. In the second example the goods are thought of as substitutes by Bidder Y, complements by Bidder Z, and somewhere in between by Bidder X who shows preference for a specific quantity.

5. SPECTRUM SHARING MODEL

5.1 System Model

Our proposed system model is shown in fig5.1. We think a heterogenous environment where different types of channels are available for seceondary user for a very very small period. In fig5.1, it is shown that there K number of channes form primary users are available and each channel are subdivided into multiple solts with TDMA mechanism and N unlicensed users or secondary usrs are trying to accesss those slots.

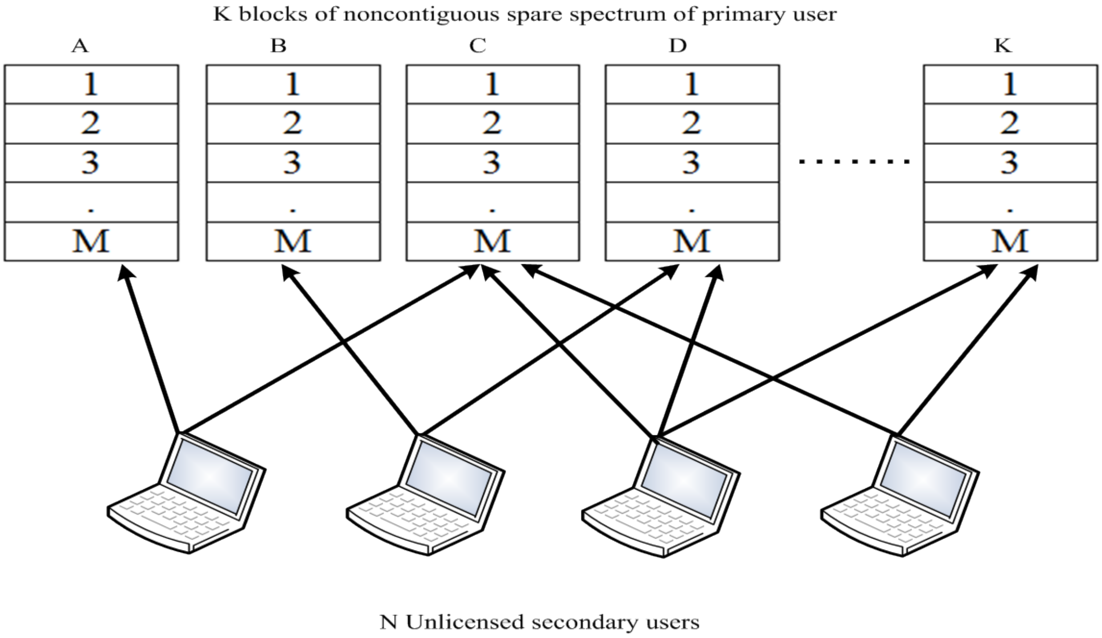

Figure 5.1: Multi unit spectrum sharing scheme to N secondary users**.**

5.2 Oligopoly Market

Spectrum sharing model in fig.5.1 is similar to oligopoly market in economics. In economics an oligopoly market where different manufacturers offer the same good with similar qualities. In this market the manufacturers compete with each other try to achieve their objectives (maximize profit) independently and non-cooperatively through controlling the quantity or the price of supplied product. So price of the market may manipulate by one or all manufacturers. In this market the decision of each manufacturer is influenced by other manufacturer actions and action of one manufacturer may be observed by other manufacturer. Here, manufactures are primary users, consumers are secondary users and goods are frequency spectra (channel) which could be shared for specific times. Here we see that K blocks of non-contiguous spare spectrum (channels) are available for sharing in the cognitive radio environment. These K blocks of non-contiguous spectrum band come from different primary users. Each block is sub divided into M slots and these slots can be utilized by N number of secondary users. As our thoughts focus on multi unit sharing, the above model in fig. 5.1 multiple users share the same spectrum band according to spectrum decision, they access different time slots of the channel to avoid interfering each other. Every available spectrum in sharing environment has its unique characteristics, so it is a heterogeneous channel environment in cognitive radio spectrum sharing. Secondary users have various types of application that’s why they need to select proper channel among the available K channels. For example a secondary user may wish to mainly transmit delay-sensitive traffic like voice or video. Such a secondary user will attach a high demand on available higher bandwidth spectrum and pay high price. Another secondary user may be interested in transmitting delay-insensitive traffic such as email or file transfer. Such secondary user will prefer less demand and prefer low price than former. One more situation may arise like one secondary user may have mixed traffic delay-sensitive and delay insensitive, such secondary user may prefer mixed channel some of from higher bandwidth some of from low bandwidth. Thus spectrum characterization parameters such as wireless link error (E_k) rate, the link layer delay (D_k) and the maximum permissible transmission power (Q_k), etc. Secondary users demand acceptable error rate (e_j), the delay bound (d_j) and the minimum required transmission power (q_j). In [14] authors analyze the above parameters for better channel selection for secondary users. They define $\alpha_{j,k}, \beta_{j,k}, \gamma_{j,k}$ error rate matching factor, delay matching factor, and power matching factor between demand of user j and the characteristic of channel K respectively, which are as follows:

$$\alpha_{j,k} = \begin{cases} \dfrac{E_k}{e_j} & E_k \leq e_j \\ 0 \quad otherwise & \end{cases} \qquad \textbf{(8)}$$

$$\beta_{j,k} = \begin{cases} \dfrac{D_k}{d_j} & D_k \leq d_j \\ 0 \quad otherwise & \end{cases} \qquad \textbf{(9)}$$

$$\gamma_{j,k} = \begin{cases} \dfrac{q_j}{Q_k} & q_j \leq Q_k \\ 0 \quad otherwise & \end{cases} \qquad \textbf{(10)}$$

Taking the matching factor $\beta_{j,k}$ as an example. If the link layer delay D_k of channel K is higher than the maximum delay bound d_j of user j, user j is not permitted to access channel k in term of the delay , thus $\beta_{j,k} = 0$. If D_k is lower than dj , $\beta_{j,k}$ is directly proportional to D_k and inversely proportional to d_j. Each user in the networks tends to access the channel with higher matching factor $\beta_{j,k}$. Thus spectrum with high quality tends to be used by the higher demand user and vice versa. Finally combine all the three matching factor, we introduced overall demand matching factor.

$$\omega_{j,k} = \rho(\alpha_{j,k})^{n1}(\beta_{j,k})^{n2}\ (\gamma_{j,k})^{n3} \qquad \textbf{(11)}$$

ρ is the parameter to adjust the matching factor value and n_1,n_2 and $n_3 \geq 0$ determine the steepness of the matching factor $\alpha_{j,k}$, $\beta_{j,k}$ and $\gamma_{j,k}$ repectively.If n_3=0, then $(\gamma_{j,k})^{n3}$=1, this means power matching factor can be ignored.

5.3 Spectrum Sharing Scenario

The scenario shows in Figure 5.2. Three channels A, B and C are available for sharing and each channel is sub-divided into 6 slots. Three secondary users X, Y, Z are bidding for accessing the channel. Here, we consider that each channel has different characteristics. Secondary users prioritize the available channels based on its demand and mark one as proffered channel which will improve efficiency of spectrum utilization. Let the secondary user X prefers channel B. Similarly secondary user Y prefers channel C and secondary user Z prefer channel A. Here we consider that each secondary user need total six slots for completing their operation. Channel choices of three users are as follows:

X =(A=2,B=3,C=1),Y=(A=1,B=2,C=3),Z=(A=3,B=1,C=2)

The above mentioned choices can be expressed through matrix bidding language. The table 1 represents X, Y and Z matrix bids.

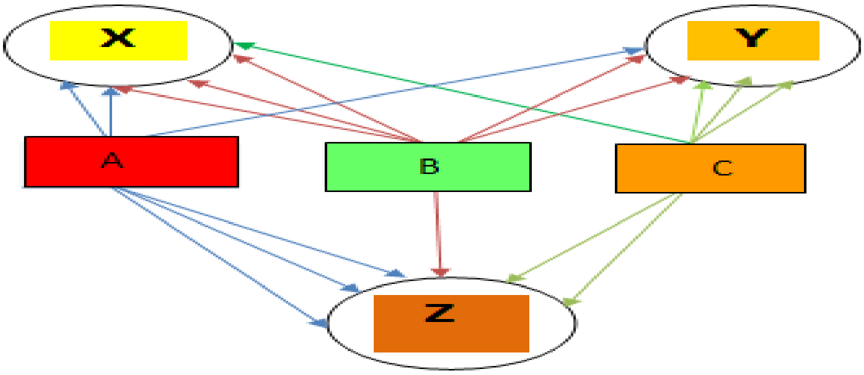

Figure 5.2: Available spectrum slots allocation.

Figure 5.3: Available Spectrum slot auction.

The above scenario we can express through matrix bidding language. When player submit their bids, they will use the trade price.

Explanation about secondary user X’s, matrix bid is given here. X give highest priority to channel B so X’s put price $10 for three slots from channel B, means that X need at exactly three slots from channel B. But slots may any combination such as ({1,2,3},{2,3,4},{3,4,5},{1,4,5}.....). X will not accept less than 3 slots. X put 2nd highest priority to channel A and put price $8 , that means X need exactly two slots from channel A and slots combination({1,2},{2,3}.....).

So the bid of X will be

Bid No.	Price	Ch A	Ch B	Ch C
1	23	3	2	1

Table 5.1: X, Y and Z's Matrix Bid representation.

Secondary user X's Bid		
Channel Priority		Bidding Combination of Slots
CH- B	Slot1	0
	Slot2	0 0
	Slot3	0 0 10
	Slot4	0 0 10 0
	Slot5	0 0 10 0 0
	Slot6	0 0 10 0 0 0
CH-A	Slot1	0
	Slot2	0 8
	Slot3	0 8 0
	Slot4	0 8 0 0
	Slot5	0 8 0 0 0
	Slot6	0 8 0 0 0 0
CH-C	Slot1	5
	Slot2	5 0
	Slot3	5 0 0
	Slot4	5 0 0 0
	Slot5	5 0 0 0 0
	Slot6	5 0 0 0 0 0

Secondary user Y's Bid		
Channel Priority		Bidding Combination of Slots
CH- C	Slot1	0
	Slot2	0 0
	Slot3	0 0 10
	Slot4	0 0 10 0
	Slot5	0 0 10 0 0
	Slot6	0 0 10 0 0 0
CH-B	Slot1	0
	Slot2	0 8
	Slot3	0 8 0
	Slot4	0 8 0 0
	Slot5	0 8 0 0 0
	Slot6	0 8 0 0 0 0
CH-A	Slot1	5
	Slot2	5 0
	Slot3	5 0 0
	Slot4	5 0 0 0
	Slot5	5 0 0 0 0
	Slot6	5 0 0 0 0 0

Secondary User Z's Bid		
Channel Priority		Bidding Combination of Slots
CH- A	Slot1	0
	Slot2	0 0
	Slot3	0 0 10
	Slot4	0 0 10 0
	Slot5	0 0 10 0 0
	Slot6	0 0 10 0 0 0
CH-C	Slot1	0
	Slot2	0 8
	Slot3	0 8 0
	Slot4	0 8 0 0
	Slot5	0 8 0 0 0
	Slot6	0 8 0 0 0 0
CH-B	Slot1	5
	Slot2	5 0
	Slot3	5 0 0
	Slot4	5 0 0 0
	Slot5	5 0 0 0 0
	Slot6	5 0 0 0 0 0

Through Matrix bidding language one secondary user can send multi bid for access resources and also here secondary users behave truthfully. Not only that but also secondary users can shows their preferences on channels.

5.4 Comparison Matrix Bid vs XOR Bid

The following example shows the benefits of matrix bidding over other bidding languages. Let we think about an auction for N = 6 items and a bidder wants to express an additive valuation over the items with a constraint that he cannot consume more than 3 items [13]. A matrix bid expressing this (with arbitrary values given for each item) is as follows:

Table 5.2: Matrix Bid for 6 goods.

Channel	Cost						
	A	22					
	B	18	18				
	C	17	17	17			
	D	16	16	16	0		
	E	14	14	14	0	0	
	F	12	12	12	0	0	0

With this bid, we see that bidder willing to pay same price for each item regardless of what other items he gets. The zeros are shown in the fourth, fifth, and sixth columns of Table 2 which mean that bidder is not interested to pay a positive amount for a fourth, fifth, or sixth item. This matrix bid expressed in XOR language which shown in Table 5.3.

Table 5.3: XOR bid for 6 goods.

(A:22VB:18VC:17)	⊕	(A:22VB:18VD:16)	⊕
(A:22VB:18VE:14)	⊕	(A:22VB:18VF:12)	⊕
(A:22VC:17VD:16)	⊕	(A:22VC:17VE:14)	⊕
(A:22VC:17VF:12)	⊕	(A:22VD:16VE:14)	⊕
(A:22VD:16VE:14)	⊕	(A:22VE:14VF:12)	⊕
(B:18VC:17VD:16)	⊕	(B:18VC:17VE:14)	⊕
(B:18VC:17VF:12)	⊕	(B:18VD:16VE:14)	⊕
(B:18VD:16VF:12)	⊕	(B:18VE:14VF:12)	⊕
(C:17VD:16VE:14)	⊕	(C:17VD:16VF:12)	⊕
(C:17VE:14VF:12)	⊕	(D:16VE:14VF:12)	

Note that if we were to add another item to the auction and maintain the capacity constraint of three items, we would have to add 15 new XOR clauses to the above statement of preferences, while only adding 7 new numbers (one new row) to the matrix bid!In general, additive preferences for n items with a capacity constraint of k takes $\binom{n}{k}$ clauses, each containing k atomic bids in the language of L_{flat} , or a single matrix bid of size $\frac{n(n-1)}{2}$,, verifying that LMB can contain preferences in a single matrix bid that require a sentence of exponential length in L_{flat}.

6. SIMULATION RESULT AND ANALYSIS

In this chapter we explain our simulation to evaluate the performance of non cooperative matrix bid multi unit combinatorial auction in cognitive radio network. Initially for each secondary user we computed demand matching factor $\omega_{j,k}$ and on the basis of $\omega_{j,k}$ each secondary user will put channel priority in its bids. We use MATLAB for computing $\omega_{j,k}$.

Table 6.1: Simulation Parameter for computing demand matching factor.

Symbol	Quantity	Value
K	number of channels	20
N	number of unlicensed user	5~40
M	number of slots	6
e_j	user's acceptable error rate	10^{-8}- 10^{-4}
E_k	Channel's wireless link error rate	10^{-9}-10^{-4}
d_j	User's delay bound	10ms-100ms
D_k	Channel's link layer delay	1ms- 100ms
q_j	Users required transmission power	10mW-40mW
Q_k	Channel's transmission power	10mW-200mW

Computing the $\omega_{j,k}$ each secondary user create its own matrix bid and send to the auctioneer. A sample bid which we used in our simulation shown in Table 6.1. Combinatorial auction finally select the winning bid set. We try to evaluate spectrum utilization. In Figure 6.3 we see that as the number of secondary users increases the percentage of spectrum utilization also increases. We compare our results with two other sharing methods DMMS (Demand Matching Spectrum Sharing) [14] and BIOSS (BIOlogical-inspired Spectrum Sharing) [11]. We took three results CASS1 (Combinatorial Auction Based Spectrum Sharing), CASS2 and CASS3.

Table 6.2: Combinatorial auction Simulation parameters.

No. of Channels
No. of Bids
No. of Slots per Channel
No. of Dummy Channels (optional)

In CASS1 where each secondary user sends bid to auctioneer their first and second best matching channel. We see that CASS1 strategy give 60% spectrum utilization while each secondary user accesses the single channel leaving a number of available channels unused. In CASS2, each secondary user sends bid to auctioneer its all possible matching channels, we examine that CASS2 give 75% spectrum utilization leaving a few available channels unused. In CASS2 each secondary user also gets accesses the single channel. So finally we use CASS3 strategy where each secondary user can access multiple channels and we observe that CASS3 give us 90% spectrum utilization. Subsequent to analyzing spectrum utilization we focus to maximize revenue for single bid combinatorial auction and multi-bids combinatorial auction. Figure 6.2 shows that when each secondary user sends multi-bids rather than single bid, multi-bids strategy always maximizes revenue, increases number secondary users and increases the slot utilization. In the concern of fairness issue, auction is a non-cooperative system, every secondary user behave truthfully when submitting their bid. Auctioneers allocate available channels to the secondary users to find out best possible allocation according to secondary users requests. From the simulation results, we saw that upto 25 secondary users, CASS always shows the better performance than two other methods BIOSS and DMSS. But when number of users are increasing then CASS performance a bit lower than DMSS. The reason behind that when number of users are increasing, a number of secondary users are not getting access to the available channels. Therefore a number of channels are still unused. The performance of BIOSS is low because of imperfect channel selection.

Table 6.3: Sample bid (20 channel and 15 secondary users).

		Channel No																				
Bid No	Price	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	SU
0	100																				5	1
1	100				5																	2
2	50			5																		2
3	20												5									2
4	10						5															2
5	20																			5		2
6	100						5															4
7	15	5																				4
8	16										5											4
9	100																				5	5
10	100										5				5							6
11	100													5								7
12	100											5										8
13	105											5	5							5		8
14	12			5																		8
15	100										5											9
16	102										5				5							9
17	100										5											10
18	102										5				5							10
19	100													5								11
20	20		5																			11
21	120		5											5								11
22	100	5																				12
23	100												5									13
24	60						5															13
25	40					5																13
26	100					5	5															13
27	100																	5				14
28	100						5															15
29	16	5																				15
30	15										5											15
31	40	5									5										5	15

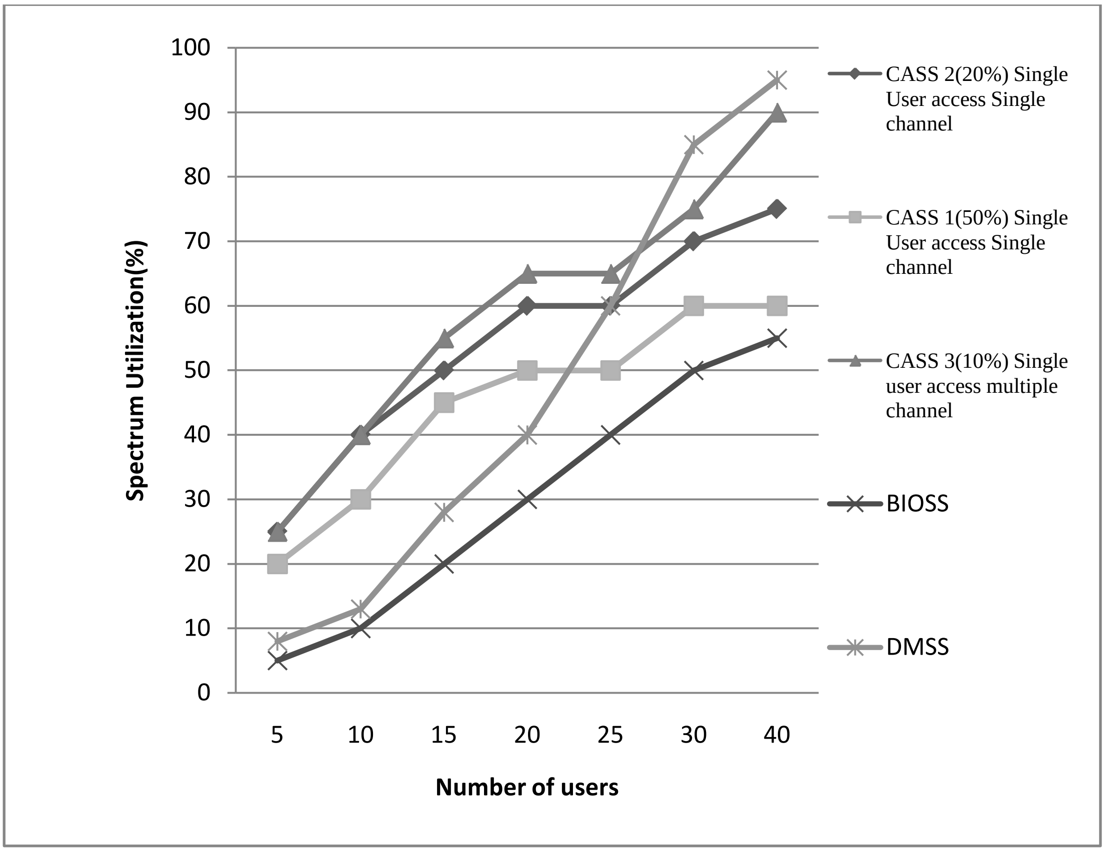

Figure 6.1: Spectrum utilization of CASS, DMSS and BIOS with different number of unlicensed users.

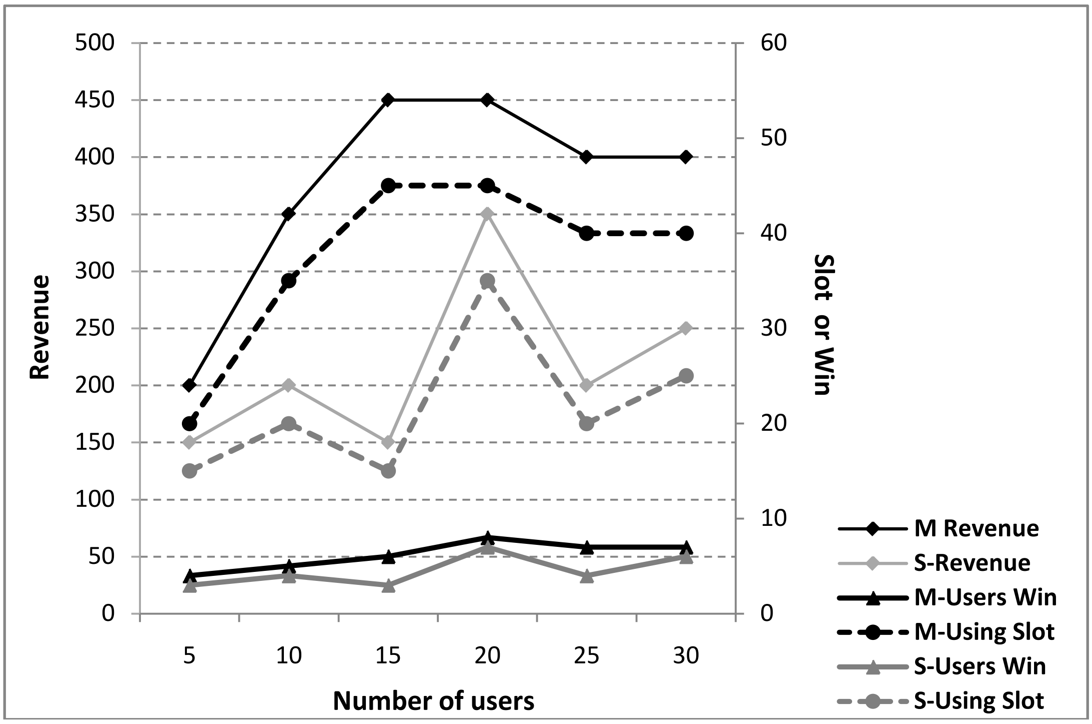

Figure 6.2: Revenue, winning user and slot analysis for single and multi bid CASS.

7. CONCLUSION

In this thesis we proposed a Matrix bid multi units combinatorial auction spectrum sharing scheme for cognitive radio networks. Two vital points in CR networks, first one is primary user always try to maximize revenue and the second one is efficient allocation of available spectrum to the secondary users. We see that our proposed scheme fulfil two aims that maximize revenue of primary users as well as allocate all the available channels to the secondary users. Because of secondary user sends multi bids and no selfishness between them. So there is no coordination delay. Primary user has option to choose best bid for a secondary user from multi bids. Simulation analysis shows that matrix bid multi units combinatorial auction achieves high performance in spectrum utilization where percentage nearly 90%.

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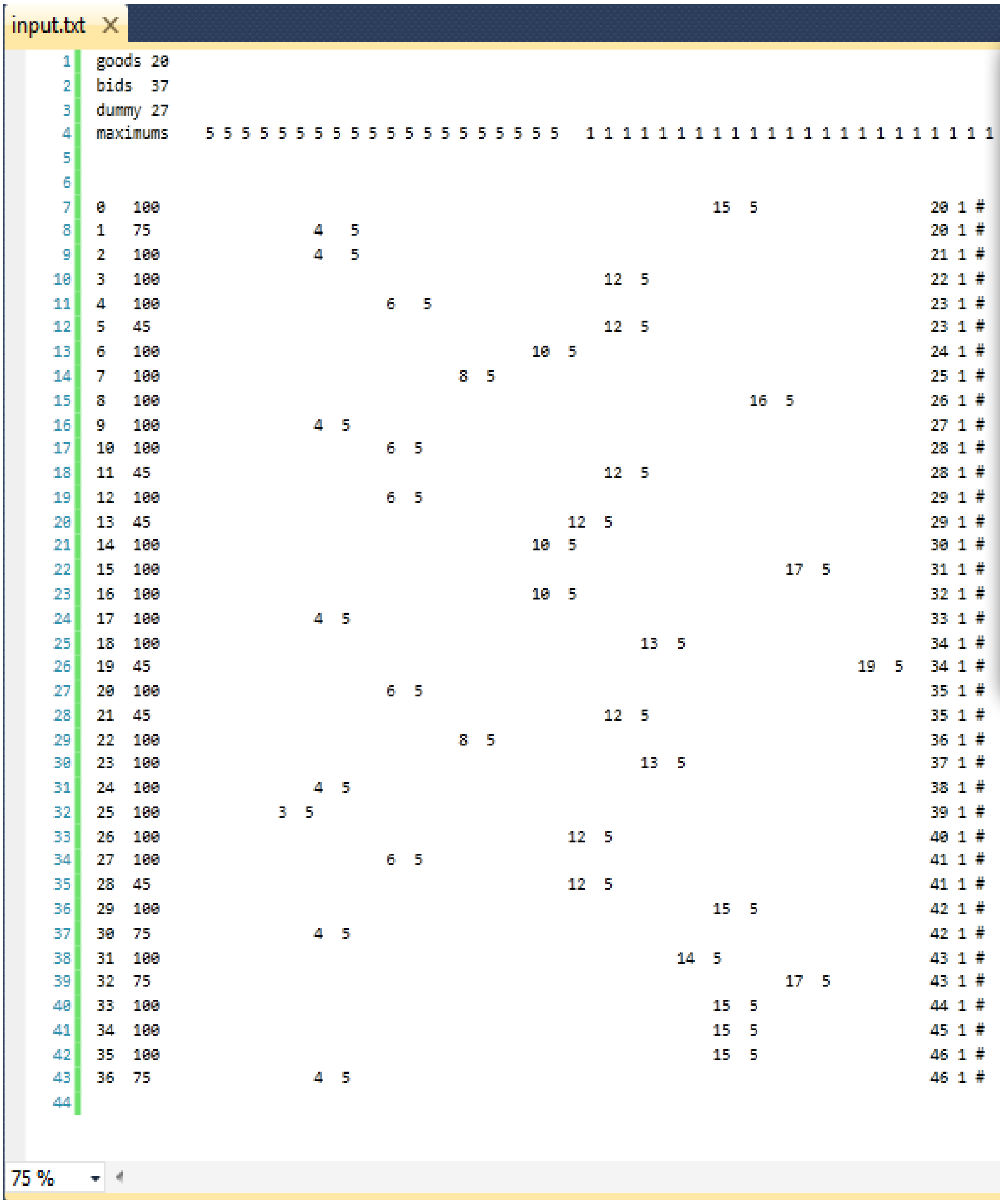
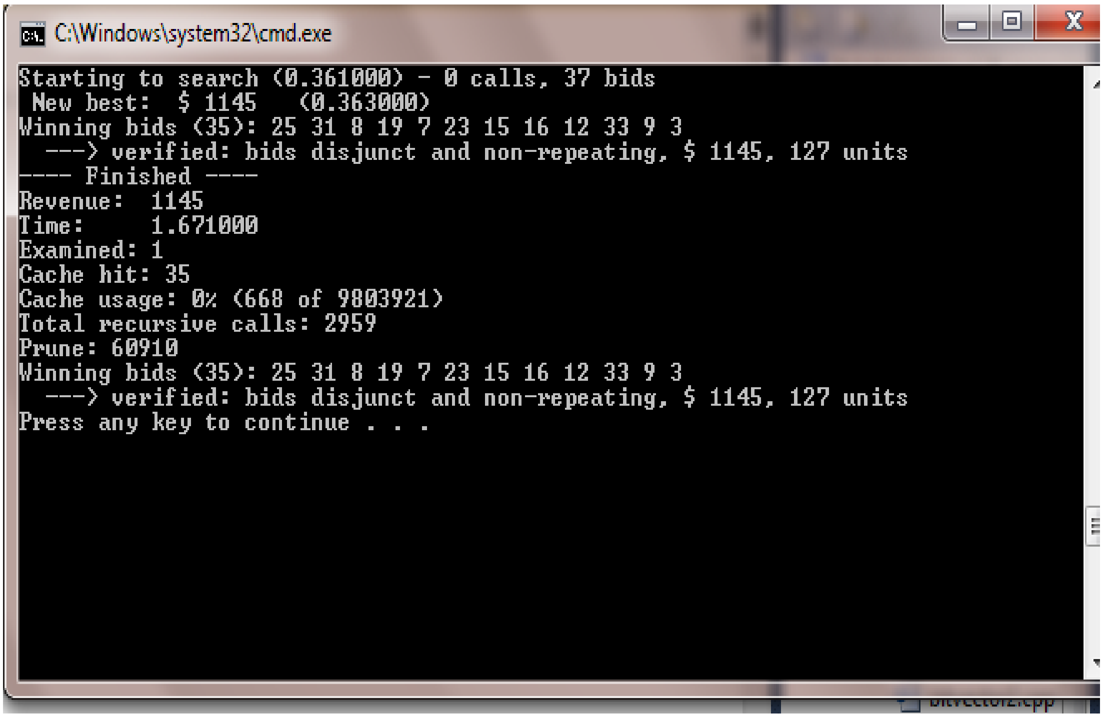
APPENDICES

APPENDIX A: Sample results of our simulation.



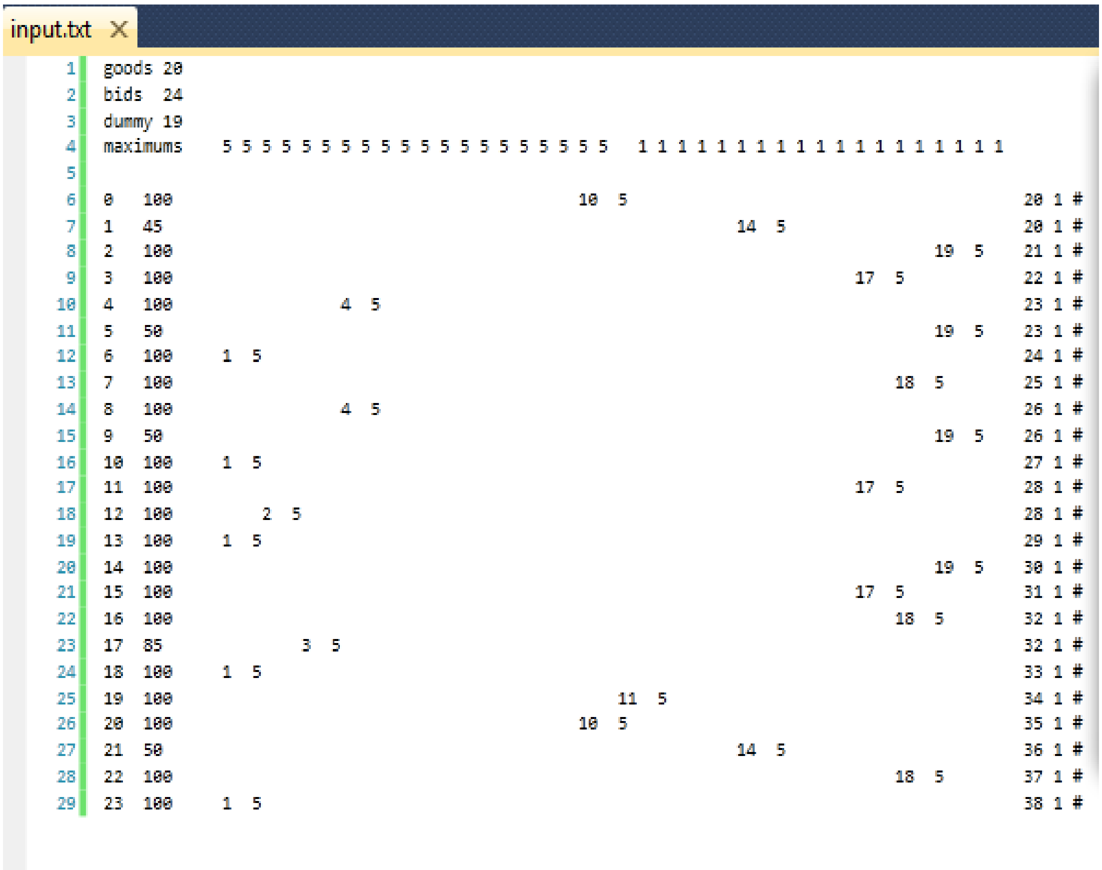
```
goods 20
bids  37
dummy 27
maximums    5 5 5 5 5 5 5 5 5 5 5 5 5 5 5 5 5 5 5 5    1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1


0   100                                                              15   5                   20 1 #
1   75                   4   5                                                                20 1 #
2   100                  4   5                                                                21 1 #
3   100                                                  12   5                               22 1 #
4   100                          6   5                                                        23 1 #
5   45                                                   12   5                               23 1 #
6   100                                          10   5                                       24 1 #
7   100                                  8  5                                                 25 1 #
8   100                                                                  16   5               26 1 #
9   100                  4  5                                                                 27 1 #
10  100                          6  5                                                         28 1 #
11  45                                                   12   5                               28 1 #
12  100                          6  5                                                         29 1 #
13  45                                               12   5                                   29 1 #
14  100                                          10   5                                       30 1 #
15  100                                                                      17   5           31 1 #
16  100                                          10   5                                       32 1 #
17  100                  4  5                                                                 33 1 #
18  100                                                      13   5                           34 1 #
19  45                                                                                19   5  34 1 #
20  100                          6  5                                                         35 1 #
21  45                                                   12   5                               35 1 #
22  100                                  8  5                                                 36 1 #
23  100                                                      13   5                           37 1 #
24  100                  4  5                                                                 38 1 #
25  100              3  5                                                                     39 1 #
26  100                                              12   5                                   40 1 #
27  100                          6  5                                                         41 1 #
28  45                                               12   5                                   41 1 #
29  100                                                              15   5                   42 1 #
30  75                   4  5                                                                 42 1 #
31  100                                                          14   5                       43 1 #
32  75                                                                       17   5           43 1 #
33  100                                                              15   5                   44 1 #
34  100                                                              15   5                   45 1 #
35  100                                                              15   5                   46 1 #
36  75                   4  5                                                                 46 1 #
```

Figure A.1: Input bid file for 20 channels and 30 users.



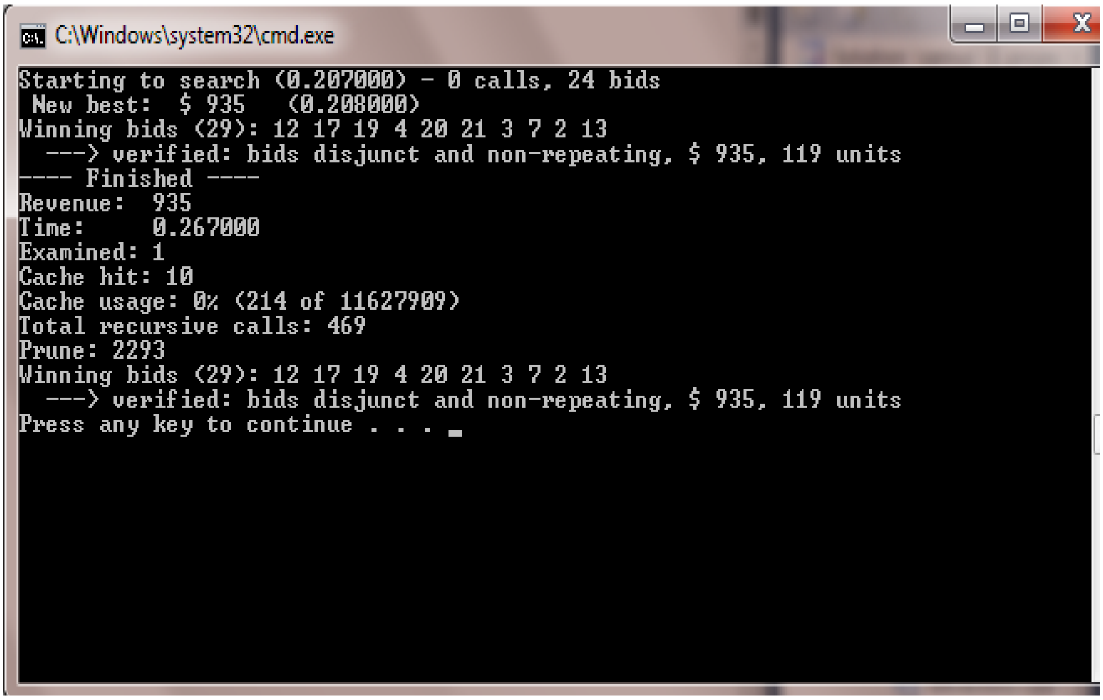
```
Starting to search (0.361000) - 0 calls, 37 bids
 New best:  $ 1145    (0.363000)
Winning bids (35): 25 31 8 19 7 23 15 16 12 33 9 3
  ---> verified: bids disjunct and non-repeating, $ 1145, 127 units
---- Finished ----
Revenue:  1145
Time:     1.671000
Examined: 1
Cache hit: 35
Cache usage: 0% (668 of 9803921)
Total recursive calls: 2959
Prune: 60910
Winning bids (35): 25 31 8 19 7 23 15 16 12 33 9 3
  ---> verified: bids disjunct and non-repeating, $ 1145, 127 units
Press any key to continue . . .
```

FigureA.2: Winning result for 20 channels and 30 users.



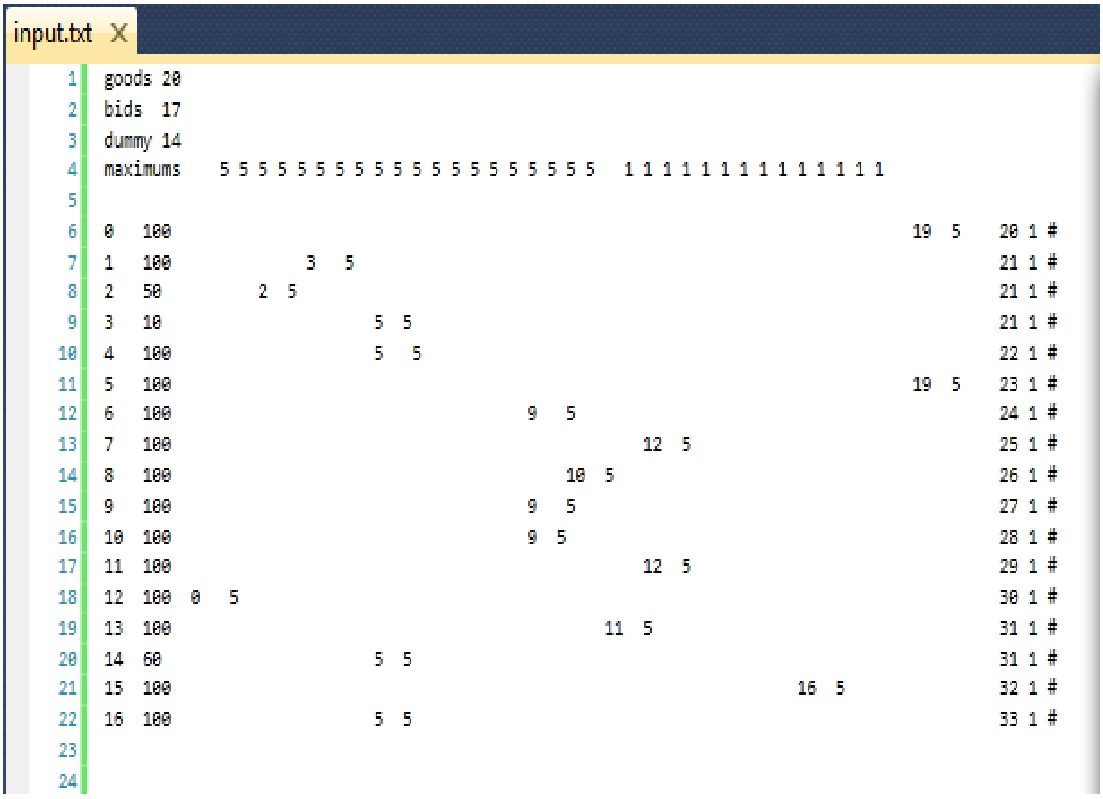
```
goods 20
bids  24
dummy 19
maximums    5 5 5 5 5 5 5 5 5 5 5 5 5 5 5 5 5 5 5 5    1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1

0   100                                         10  5                                        20 1 #
1   45                                                          14  5                        20 1 #
2   100                                                                             19  5    21 1 #
3   100                                                                     17  5            22 1 #
4   100                 4  5                                                                 23 1 #
5   50                                                                              19  5    23 1 #
6   100     1  5                                                                             24 1 #
7   100                                                                         18  5        25 1 #
8   100                 4  5                                                                 26 1 #
9   50                                                                              19  5    26 1 #
10  100     1  5                                                                             27 1 #
11  100                                                                     17  5            28 1 #
12  100         2  5                                                                         28 1 #
13  100     1  5                                                                             29 1 #
14  100                                                                             19  5    30 1 #
15  100                                                                     17  5            31 1 #
16  100                                                                         18  5        32 1 #
17  85              3  5                                                                     32 1 #
18  100     1  5                                                                             33 1 #
19  100                                             11  5                                    34 1 #
20  100                                         10  5                                        35 1 #
21  50                                                          14  5                        36 1 #
22  100                                                                         18  5        37 1 #
23  100     1  5                                                                             38 1 #
```

FigureA.3: Input bid file for 20 channels and 20 users.



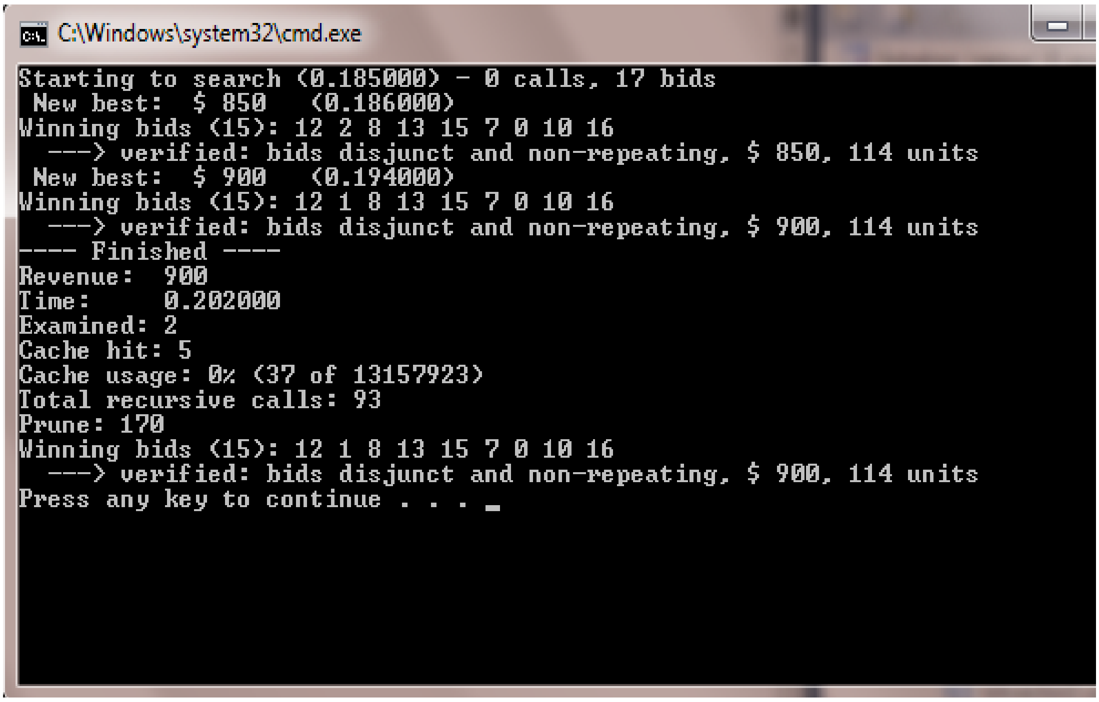
```
Starting to search (0.207000) - 0 calls, 24 bids
 New best:  $ 935   (0.208000)
Winning bids (29): 12 17 19 4 20 21 3 7 2 13
  ---> verified: bids disjunct and non-repeating, $ 935, 119 units
---- Finished ----
Revenue:  935
Time:     0.267000
Examined: 1
Cache hit: 10
Cache usage: 0% (214 of 11627909)
Total recursive calls: 469
Prune: 2293
Winning bids (29): 12 17 19 4 20 21 3 7 2 13
  ---> verified: bids disjunct and non-repeating, $ 935, 119 units
Press any key to continue . . .
```

FigureA.4: Winning result for 20 channels and 20 users.



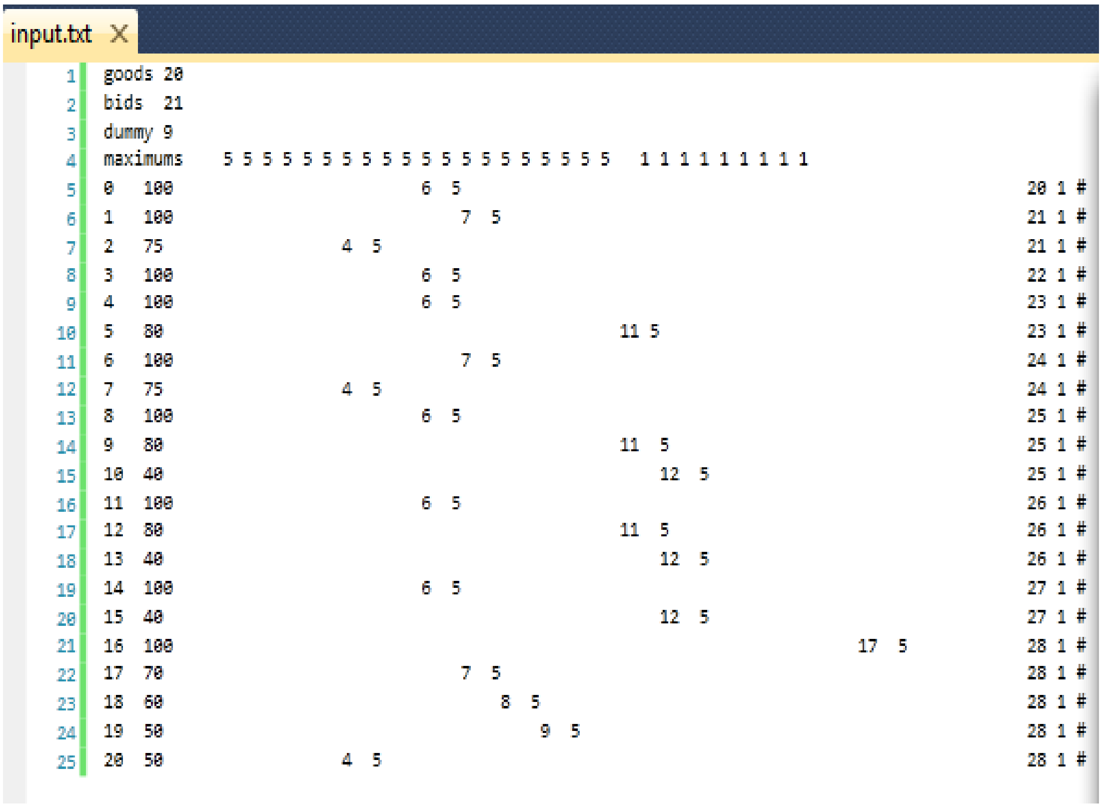
```
goods 20
bids  17
dummy 14
maximums    5 5 5 5 5 5 5 5 5 5 5 5 5 5 5 5 5 5 5 5  1 1 1 1 1 1 1 1 1 1 1 1 1 1

0   100                                                                            19  5    20 1 #
1   100              3   5                                                                  21 1 #
2   50          2  5                                                                        21 1 #
3   10                      5  5                                                            21 1 #
4   100                     5   5                                                           22 1 #
5   100                                                                            19  5    23 1 #
6   100                                    9   5                                            24 1 #
7   100                                                12  5                                25 1 #
8   100                                        10  5                                        26 1 #
9   100                                    9   5                                            27 1 #
10  100                                    9  5                                             28 1 #
11  100                                                12  5                                29 1 #
12  100  0   5                                                                              30 1 #
13  100                                            11  5                                    31 1 #
14  60                      5  5                                                            31 1 #
15  100                                                                16  5                32 1 #
16  100                     5  5                                                            33 1 #


```

FigureA.5: Input bid file for 20 channels and 15 users.



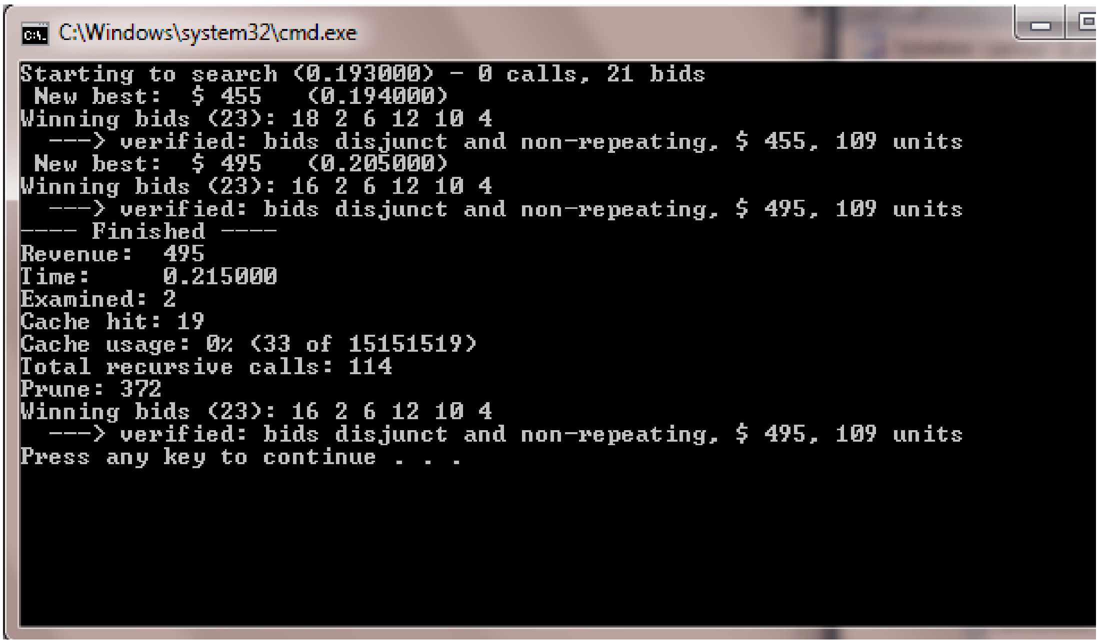
```
Starting to search (0.185000) - 0 calls, 17 bids
 New best:  $ 850   (0.186000)
Winning bids (15): 12 2 8 13 15 7 0 10 16
  ---> verified: bids disjunct and non-repeating, $ 850, 114 units
 New best:  $ 900   (0.194000)
Winning bids (15): 12 1 8 13 15 7 0 10 16
  ---> verified: bids disjunct and non-repeating, $ 900, 114 units
---- Finished ----
Revenue:  900
Time:     0.202000
Examined: 2
Cache hit: 5
Cache usage: 0% (37 of 13157923)
Total recursive calls: 93
Prune: 170
Winning bids (15): 12 1 8 13 15 7 0 10 16
  ---> verified: bids disjunct and non-repeating, $ 900, 114 units
Press any key to continue . . . _
```

FigureA.6: Winning result for 20 channels and 15 users.



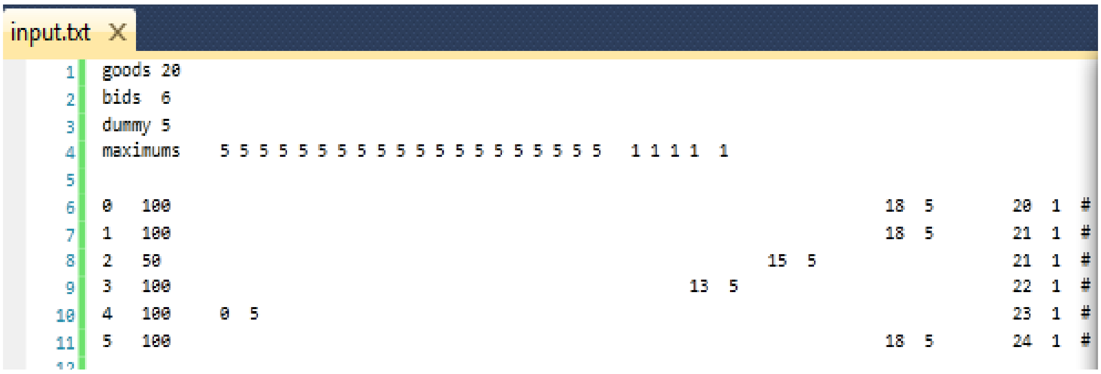
```
goods 20
bids  21
dummy 9
maximums    5 5 5 5 5 5 5 5 5 5 5 5 5 5 5 5 5 5 5 5   1 1 1 1 1 1 1 1 1
0   100                         6  5                                                        20 1 #
1   100                             7  5                                                    21 1 #
2   75                  4  5                                                                21 1 #
3   100                         6  5                                                        22 1 #
4   100                         6  5                                                        23 1 #
5   80                                              11 5                                    23 1 #
6   100                             7  5                                                    24 1 #
7   75                  4  5                                                                24 1 #
8   100                         6  5                                                        25 1 #
9   80                                              11  5                                   25 1 #
10  40                                                  12  5                               25 1 #
11  100                         6  5                                                        26 1 #
12  80                                              11  5                                   26 1 #
13  40                                                  12  5                               26 1 #
14  100                         6  5                                                        27 1 #
15  40                                                  12  5                               27 1 #
16  100                                                                     17  5           28 1 #
17  70                              7  5                                                    28 1 #
18  60                                  8  5                                                28 1 #
19  50                                      9  5                                            28 1 #
20  50                  4  5                                                                28 1 #
```

Figure A.7: Input bid file for 20 channels and 10 users.



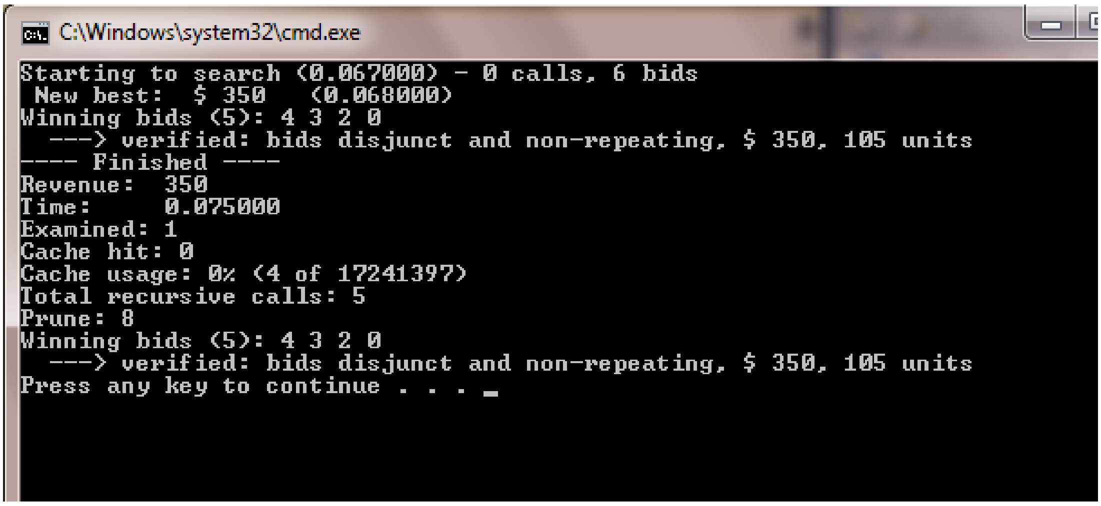
```
Starting to search (0.193000) - 0 calls, 21 bids
 New best:  $ 455   (0.194000)
Winning bids (23): 18 2 6 12 10 4
  ---> verified: bids disjunct and non-repeating, $ 455, 109 units
 New best:  $ 495   (0.205000)
Winning bids (23): 16 2 6 12 10 4
  ---> verified: bids disjunct and non-repeating, $ 495, 109 units
---- Finished ----
Revenue:  495
Time:      0.215000
Examined: 2
Cache hit: 19
Cache usage: 0% (33 of 15151519)
Total recursive calls: 114
Prune: 372
Winning bids (23): 16 2 6 12 10 4
  ---> verified: bids disjunct and non-repeating, $ 495, 109 units
Press any key to continue . . .
```

Figure A.8: Winning result for 20 channels and 10 users.



```
goods 20
bids  6
dummy 5
maximums    5 5 5 5 5 5 5 5 5 5 5 5 5 5 5 5 5 5 5 5   1 1 1 1  1

0   100                                                                         18  5        20  1  #
1   100                                                                         18  5        21  1  #
2   50                                                              15  5                    21  1  #
3   100                                                     13  5                            22  1  #
4   100     0  5                                                                             23  1  #
5   100                                                                         18  5        24  1  #
```

Figure A.9: Input bid file for 20 channels and 5 users.



```
Starting to search (0.067000) - 0 calls, 6 bids
 New best:  $ 350   (0.068000)
Winning bids (5): 4 3 2 0
  ---> verified: bids disjunct and non-repeating, $ 350, 105 units
---- Finished ----
Revenue:  350
Time:      0.075000
Examined: 1
Cache hit: 0
Cache usage: 0% (4 of 17241397)
Total recursive calls: 5
Prune: 8
Winning bids (5): 4 3 2 0
  ---> verified: bids disjunct and non-repeating, $ 350, 105 units
Press any key to continue . . . _
```

Figure A.10: Winning result for 20 channels and 5 users.

CURRICULUM VITAE

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International Conference:

- Moinuddin S.M., D. T. Altilar, "**Spectrum Sharing in Cognitive Radio Network through Matrix Bidding Multi Unit Combinatorial Auction**" to appear in the Mosharaka International Conference on Communications and Electronic Systems, Dubai, December. 2011.