Synchronous and Asynchronous Auction Models for Dynamic Spectrum Access

Shamik Sengupta and Mainak Chatterjee

School of Electrical Engineering and Computer Science
University of Central Florida
Orlando, FL 32816-2450
{shamik,mainak}@cpe.ucf.edu

Abstract. Recently, there is an urge to allocate chunks of the spectrum to the wireless service providers on a more dynamic basis rather than the current practice of static allocation. This shift in paradigm is a result of many studies that indicate the improper utilization of the spectrum by the service providers due to the static spectrum assignment. Also, the use of the spectrum has been found to be space and time invariant. In this paper, we investigate the dynamic spectrum allocation policy for optimal use of the spectrum band. We propose a dynamic spectrum assignment strategy based on auction theory that captures the conflict of interest between wireless service providers and spectrum owner, both of whom try to maximize their respective benefits. We compare two different allocation strategies – synchronous and asynchronous. It is demonstrated that synchronous strategy outperforms the asynchronous strategy. Through simulation results, we show how the optimal usage of spectrum band is achieved along with the maximized revenue for spectrum owner and higher probability of winning spectrum for the service providers.

1 Introduction

The presence of multiple wireless service providers in every geographic region is creating a competitive environment where the goal of every service provider is to maximize their profit and continue to enhance their service portfolio. Every wireless service provider buys spectrum from the spectrum owner (for example, Federal Communications Commission in the United States of America) with a certain price and then sells the spectrum to the subscribers (end users) in the form of services. In such a scenario, the aim of each service provider is to get a large share of subscribers and a big spectrum chunk from the spectrum band to fulfill the demand of these subscribers. As capacity of spectrum band is finite, the providers compete among themselves to acquire chunks of spectrum to offer services to a bigger customer base.

The competitive behavior for spectrum was initiated by spectrum auctions in most countries. Though the auctions were very successful in some countries (e.g., United Kingdom, Germany), they were open to criticism in others (e.g., Austria, Switzerland, Netherlands) [4]. Through the Federal Communications Commission (FCC), the spectrum for cellular services was auctioned in the United States. These spectrum allocations are long–term and any changes are made under the strict guidance of FCC.

This kind of static allocation of spectrum has several disadvantages because of being time and space invariant. It has been demonstrated through experimental studies that spectrum utilization is typically time and space dependent [8]. Thus static spectrum allocation may not be the optimal solution toward efficient spectrum sharing and usage. In static spectrum allocation, a large part of the radio bands are allocated to the military, government and public safety systems. However, the utilization of these bands are significantly low. One may argue that spectrum allocated to cellular and PCS network operators are highly utilized. But in reality, spectrum utilization even in these networks vary over time and space and undergo under-utilization. Often times, the usage of spectrum in certain networks is lower than anticipated, while there might be a crisis in others if the demands of the users using that network exceed the network capacity. Static allocation of spectrum fails to address this issue of spectrum sharing even if the service providers (with statically allocated spectrum) are willing to pay for extra amount of spectrum for a short period of time if there is a demand from the users it supports.

1.1 Dynamic Spectrum Access

With the dis-proportionate and time-varying demand and hence usage of the spectrum, it is intuitive that the notion of static spectrum assignment to providers is questionable. Though it might be argued that the implementation and administration is very easy, the fact remains that the current system is ineffective and deprives service providers and their end users. With the transition from 2G to 3G, the demand for bandwidth has been increasing. As a result, to better serve users, each of the service providers needs more spectrum in addition to the already allocated spectrum through static allocation.

As an alternative, the notion of *Dynamic Spectrum Access* (DSA) has been proposed and is being investigated by network and radio engineers, policy makers, and economists [2]. In DSA, spectrum is shared dynamically depending on demand of the service providers. In this new approach, parts of the spectrum band, which are no longer used or under–used, are made open to all the service providers as shown in figure 1. These parts of the band are known as the Coordinated Access Band (CAB) [2]. Whenever the total requested spectrum amount exceeds the spectrum available in CAB, then auction mechanism can be adopted. Spectrum is assigned dynamically from CAB for a certain lease period and again taken back after the lease period expires. Auction model in this case presents a simple way to depict the conflict among the service providers; and if designed properly, an auction will maximize the revenue also for the spectrum owner; thus providing incentive for spectrum owner to design and follow better auctions models. This method of spectrum sharing is efficient and will help service providers, users as well as FCC not to go through any artificial spectrum scarcity. At the same time, as service providers are ready to compete among themselves in a demand–supply world by paying more for the spectrum they need, this will provide FCC a better approach for maximizing its revenue.

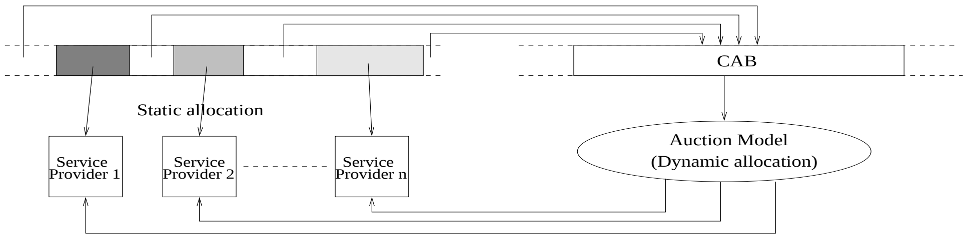


Fig. 1. Virtual merging and coordinated access band

1.2 Contributions of this Work

In this research, we deal with the process of dynamic spectrum allocation where service providers request for additional spectrum lease from the CAB in addition to the already allocated static spectrum. Upon expiry of the lease time, the additional amount of spectrum is returned to the CAB which is made available for reuse. Depending on time interval at which the allocation and de-allocation of spectrum is done form this common pool to the service providers, the spectrum allocation policy can be either *synchronous* or *asynchronous*. In this paper, we define both strategies and compare them. More specifically, the contributions of this paper are as follows.

• We formulate an auction theoretic model to address the DSA policy among the wireless service providers and depict the conflict among these service providers and spectrum owner.

• We devise a "Dynamic spectrum allocator knapsack auction" mechanism with the help of sealed bid, second price auction strategies that is used to dynamically allocate and de-allocate spectrum to competing wireless service providers.

• We investigate both the synchronous and asynchronous allocation policies and compare them in terms of average spectrum allocated, average revenue generated, and probability of winning spectrum after bidding is completed.

• With the help of extensive simulation study, we show that the proposed synchronous allocation strategy encourages the service providers and spectrum owner to participate in the auction. Synchronous allocation and de-allocation of spectrum at a shorter intervals generate average revenue more than the asynchronous allocation and de-allocation strategy. Also the probability of winning spectrum is greater for the synchronous strategy than the asynchronous strategy.

The rest of the paper is organized as follows. In section 2, we discuss the basics of auctions and their types. Our proposed auction methodology is presented in section 3. Synchronous and asynchronous allocation models are also discussed here. In section 4, we compare performances of both these models in regard to the dynamic spectrum access. Simulation model and results are presented in section 5. Conclusions are drawn in the last section.

2 Basics of Auctions

An auction is the process of buying and selling goods by offering them up for bid (i.e., an offered price), taking bids, and then selling the item to the highest bidder. In economic theory, an auction is a method for determining the value of a commodity that has an undetermined or variable price.

Auction types: There are several kinds of existing auction strategies. Depending on whether the bidding strategies of each of the bidders are disclosed in front of the other bidders, open and closed bid auctions are designed. In open auctions [1], [4], bids are open to everybody so that a player's strategy is known to other players and players usually take their turns one by one until winner(s) evolve. This auction game can be best known as the complete information game. Bids generated by players in open bid auction can be either in increasing (e.g., English and Yankee auction) [3], [4] or decreasing order (Dutch auction).

An important perspective of increasing auction is that it is more in the favor of bidders than the auctioneers. Moreover, increasing open bid auction helps bidders in early round to recognize each other and thus act collusively. Increasing auction also detract low potential bidders (bidders with low amount of spectrum request or low value bid) because they know a bidder with higher bid will always exceed their bids.

Closed bid auctions are opposite to open bid auctions and bids/strategies are not known to everybody. Only the organizer (spectrum owner in our case) of the auction will know about the bids submitted by the bidders and will act accordingly. Closed bid auctions thus do not promote collusion. Closed bid auctions are best generalized as the incomplete information game.

Spectrum auctions: Spectrum auction is more close to the multi–unit auctions. Multiple bidders present their bids for a part of the spectrum band, where sum of all these requests exceed the total spectrum band capacity thus causing the auction to take place. Moreover, unlike classic single unit auction, multiple winners evolve in this auction model constituting a winner set. The determination of winner set often depends on the auction strategy taken by the spectrum owner in this case.

Spectrum owner owns the coordinated spectrum band (CAB) and is the seller in the auction model. Service providers on the other hand are the buyers of this additionally created spectrum band. We assume that there are service providers who are already overloaded i.e., they have little or no spectrum left from their static allocation. To attract more users and to make more profit, these service providers request more spectrum from the CAB and advertise a price that they are willing to pay for that amount of spectrum for a certain period. Auction is then held by the spectrum owner depending on these advertised price and the requested amount of spectrum from the service providers in a dynamic basis.

3 Proposed Auction Model for DSA

Good auction design is important for any type of successful auction and often varies depending on the item on which the auction is held. The auctions held in Ebay [6] are typically used to sell an art object or a valuable item. Bidding starts at a certain price defined by auctioneer and then the competing bidders increase their bids. If a bid provided by a bidder is not exceeded by any other bidder then the auction on that object stops and final bidder becomes the winner.

There are two important issues behind any auction design. They are (i) attracting bidders (enticing bidders by increasing their probability of winning), and (ii) maximizing auctioneer's revenue. It is not at all intended that only big companies with high spectrum demand should have a chance at the new spectrum. The goal is to increase competition and bring fresh new ideas and services. As a result it is necessary to make the small companies, who also have a demand of spectrum, interested to take part in the auction. This way, revenue and spectrum usage maximization from the CAB can be made.

3.1 Auction Formulation

The situation described above maps directly to the 0-1 knapsack problem, where the aim is to fill the sack as much as possible maximizing the valuations of the items sacked. Here, we compare the spectrum bands present in CAB as the total capacity of the sack and the bids presented by service providers as the valuations for the spectrum amount they request. We propose this auction procedure as *"Dynamic Spectrum Allocator Knapsack Auction"*.

We formulate the above mentioned knapsack auction as follows. Let us consider that there are n service providers (bidders) looking for the additional amount of spectrum from the CAB. All the service providers submit their demand in a sealed bid way. We follow sealed bid auction strategy, because sealed bid auction has shown to perform well in all–at–a–time auction bidding and has a tendency to prevent collusion. Note that, each service provider has knowledge about its own bidding quantity and bidding price but do not have any idea about any other service providers' bidding quantity and price. We assume that the spectrum band available in CAB is W. Now, if the spectrum requests submitted by some or all of the service providers exceed the spectrum available in CAB then the auction is held to solve the conflict among these providers.

Let, $i = 1, 2, \cdots, n$ denote the bidders (service providers). We denote the strategy taken by service provider i as q_i, where q_i captures the demand tuple of this ith service provider.

$$q_i = \{w_i, x_i\} \tag{1}$$

where, w_i and x_i denote the amount of spectrum and bidding price for that spectrum respectively requested by ith service provider. Auction is best suited when the total demand is more than the supply, i.e.,

$$\sum_{i=1}^{n} w_i > W \tag{2}$$

Our goal is to solve the dynamic spectrum allocation problem in such a way so that earned revenue is maximized from the spectrum owner's point of view, by choosing a bundle of bidders, subject to condition such that total amount of spectrum allocated does not exceed W. Then, formally the allocation policy of the spectrum owner would be,

$$maximize_i \sum_i x_i, \quad \text{such that} \quad \sum_i w_i \leq W \tag{3}$$

3.2 Synchronous and Asynchronous Auctions

Spectrum allocation with the help of proposed sealed bid knapsack auction can be done in two ways. In asynchronous allocation allocation and de-allocation of spectrum from and to the CAB are not done at fixed intervals. On the other hand, in synchronous allocation, allocation and de-allocation of spectrum from and to the CAB are done at fixed intervals.

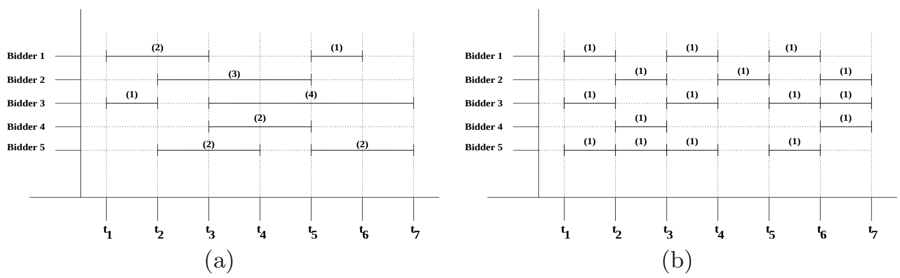


Fig. 2. a)Asynchronous allocation in different intervals of time ; b)Synchronous allocation of spectrum in fixed intervals

Asynchronous allocation: As the name suggests, this allocation procedure of spectrum is asynchronous among the service providers as shown in figure 2(a). Whenever a service provider comes up with a request for spectrum from the CAB, the spectrum owner checks to see if that request can be serviced from the available pool of CAB. If the requested amount of spectrum is available, spectrum owner assigns this chunk to the service provider for the *requested time* (e.g., at time t_1, bidder 1's allocation time is 2 units while bidder 3's allocation time is 1 unit as shown in figure 2(a)) and declines if the spectrum requested is not available at that instant in the available pool. Similarly, if more than one service provider come up with requests for spectrum from the CAB, the spectrum owner checks to see if all the requests can be serviced from the available pool of CAB. If they can be serviced, the spectrum is assigned but if all the requests can not be granted, then the auction model comes into picture. We denote the strategy taken by service provider i as q_i^a, where q_i^a captures the demand tuple of this ith service provider in asynchronous allocation mode.

$$q_i^a = \{w_i, x_i, T_i\} \tag{4}$$

where, w_i and x_i denote the amount of spectrum and bidding price for that spectrum respectively requested by ith service provider and T_i is the duration for which the spectrum amount is requested. The numbers inside the parenthesis in the figure 2(a) denote the duration T_i of the spectrum lease allocated to the corresponding bidders from the CAB. As the decision about whether to allocate or not to allocate spectrum to a service provider is taken instantly in this allocation procedure by looking at the available pool only this allocation procedure is not very effective and may not maximize the earned revenue from spectrum broker point of view. It may easily happen that a service provider B is willing to pay a higher price than a service provider A who is willing to pay a lower price for the same demand and the available pool is such that only one request could be processed. But unfortunately *B's* request came up after *A's* request. In this allocation procedure, as the spectrum owner does not have any idea about the future, *A's* request will be processed and *B's* will be declined (assuming that the available pool does not change at the time of *B's* arrival. Thus revenue could not be maximized in this allocation procedure.

Synchronous allocation: The second allocation procedure that could be taken to encounter the situation presented in asynchronous allocation is to allocate and de-allocate spectrum chunks at fixed intervals (figure 2(b)). All the service providers with a demand from the CAB present their requests to the spectrum broker with their price which they are willing to pay. Spectrum broker takes all the requests, process them using some strategy and then allocate the spectrum bands to the providers at the same time for the *same lease period*. When the lease period expires, all the allocated spectrum chunks are returned to the common pool of spectrum for future use. For example, lease periods for all the bidders are indicated as 1 in the figure 2(b).

4 Performance Comparison

We analyze and compare the performances of synchronous and asynchronous allocation of spectrum with the help of knapsack auction.

Lemma: *Revenue generated in asynchronous allocation through knapsack auction procedure can not be better than revenue generated in synchronous allocation for a given set of biddings.*

Proof: We assume that there are n bidders competing for W amount of spectrum. In asynchronous allocation mode, the bid strategies taken by ith service provider is given by tuple q_i^a, while in synchronous mode, the tuples are represented by, q_i.

We prove the above proposition with the help of counter-example. We arbitrarily decide two time intervals, t_j and t_{j+1} for the asynchronous mode allocation. We assume that first deallocation(s) of spectrum (service providers returning the allocated spectrum to the CAB) and new allocation(s) are happening at time t_{j+1} after time t_j. Moreover, we assume that the asynchronous allocation at time t_j is maximal and provide us with maximum generated revenue from the CAB. Let, m be the number of bidders who were granted spectrum at time t_j. Then, the maximum revenue generated at time t_j can be given by,

$$\sum_{i}^{m} x_i \tag{5}$$

Now, we assume l of m bidders de-allocate at time t_{j+1} and rest $(m-l)$ bidders continue to use their spectrum. Then the revenue generated by these $(m-l)$ bidders is given by,

$$\sum_{i}^{m-l} x_i \tag{6}$$

Moreover, the $(n-m)$ bidders, who were not granted spectrum at time t_j, will also compete for the rest of the spectrum,

$$W - \sum_{i}^{m-l} w_i \tag{7}$$

Now, we need to find, whether the revenue generated in this asynchronous mode at time t_{j+1} can exceed the synchronous mode revenue at the same time by same set of bidders. For simplicity, we assume that the bidders do not change their bidding requests in time intervals t_j and t_{j+1}.

By the property of 0-1 knapsack auction, we know that the revenue generated by a subset (we denote this subset by Q) of $n-l$ set of bidders will be a local maxima, if only the revenue obtained from all the $(n-l)$ set of bidders are considered simultaneously, i.e., synchronous allocation of spectrum to $(n-l)$ interested bidders (note that l is the set of bidders de-allocating their spectrum at time t_{j+1} and are not taking part in auction at time t_{j+1}).

But on the other hand, in the asynchronous mode, $(m-l)$ bidders are already present and thus knapsack auction happens among $(n-m)$ bidders for the spectrum $W - \sum_i^{m-l} w_i$. Then, it can be easily said from the property of 0-1 knapsack auction that, this asynchronous mode will generate the same local maxima as the synchronous mode, if and only if all $(m-l)$ bidders (who are already present from the previous time interval) fall under the optimal subset

Q. If any of the bidders out of $(m - l)$ bidders do not fall under the optimal subset Q, then it is certain that asynchronous mode allocation will not be able to maximize the revenue for that given set of biddings. Let us provide a simple example to clarify the proof.

An illustrative example: Let us consider that 5 bidders are competing for the CAB spectrum. We assume that the capacity of the CAB is 14 and the bid tuples generated by 5 bidders at time interval t_j are $(6, 10, 2)$, $(5, 9, 3)$, $(7, 14, 1)$, $(2, 8, 2)$ and $(3, 9, 3)$ taken arbitrarily. The first number of the tuple denotes spectrum amount requested, while the second and third number denote the price willing to pay for that spectrum request and time duration for which the spectrum request is done respectively. As we can see from the above tuples that bidder 3's request has duration 1, that means, bidder 3 will de-allocate first at time t_{j+1}.

We execute both asynchronous and synchronous knapsack auction. In asynchronous mode, the revenue generated at time t_j is 31 with the optimal subset of bidders given by bidder $2, 3, 4$. Now at time t_{j+1}, bidder 3 exits, while bidders 2 and 4 continue. Then rest of the spectrum left in the CAB is 7 for which the bidders 1 and 5 compete. Then the revenue generated at time t_{j+1} is given by 27 and the bidders granted are $1, 2, 4$.

On the other hand, in synchronous allocation, each of the providers are allocated and de-allocated at fixed time intervals. Then with the same set of bid requests of spectrum amount and price, it is seen that maximum possible revenue generated at time t_{j+1} out of the bidders $1, 2, 4$ and 5 (as bidder 3 is not interested to take part in auction at time t_{j+1}) is 28, while the optimal subset of bidders is given by $Q = \{1, 2, 5\}$. This shows that asynchronous auction may not provide the maxima depending on the bidders de-allocating and requesting.

5 Simulation Results and Interpretation

We simulate our dynamic spectrum allocator knapsack auction model and show how the synchronous allocation outperforms the asynchronous allocation. The factors that we consider for comparing the performance of the proposed synchronous knapsack sealed-bid auction with the asynchronous auction are the revenue generated by spectrum owner, total spectrum usage, and probability of winning for bidders. We consider the following for the simulation model:

- *Bid tuple:* The bid tuple q_i generated by bidder i in synchronous auction consists of amount of spectrum requested, w_i and the price the bidder is willing to pay, x_i. In asynchronous auction, the duration is also advertised in addition to the above two. Each bidder has a reservation or evaluation price for the amount of spectrum requested and the bid is governed by this reservation price. We assume that the reservation price of each bidder is considered sealed bid and is independent of other bidders' reservation prices.
- *Bidders' strategies:* We follow second price sealed-bid mechanism. We could have chosen the first price bidding policy; the only reason for choosing second price policy is that it has more properties than first price in terms of uncertainty

[5]. After each round of auction, the only information bidders know is whether their request is granted or not. We assume that all the bidders are present for all the auction rounds; bidders take feedback from previous rounds and generate the bid tuple for next round.

We compare the proposed synchronous sealed bid knapsack auction with the asynchronous sealed bid knapsack auction under the second price bidding policy, i.e., bidder(s) with the winning bid(s) do not pay their winning bid but pay the second winning bid. Simulation parameters are shown in table 1.

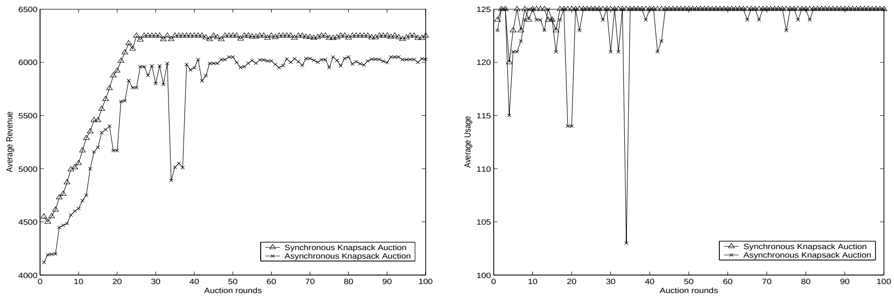
Parameter type	Parameter Value
Total amount of spectrum	125
Minimum amount of spectrum that can be requested	11
Maximum amount of spectrum that can be requested	50
Minimum bid for per unit of spectrum	25
Minimum time requested for spectrum leasing in asynchronous allocation	1
Maximum time requested for spectrum leasing in asynchronous allocation	5
Fixed time for spectrum leasing in synchronous allocation	1

Table 1. Simulation Parameters

Figures 3(a) and 3(b) compare revenue and spectrum usage for both the strategies (synchronous and asynchronous) with increase in auction rounds. The number of bidders considered in this simulation is 15. Note that, both revenue and usage are low at the beginning and subsequently increases with rounds. When auction starts, bidders always act skeptical, thus initial bids are always much lower than the true potential bids of them. With the increase in auction rounds, bidders get an idea of the bids of other bidders and thus try to increase or decrease their bids accordingly.

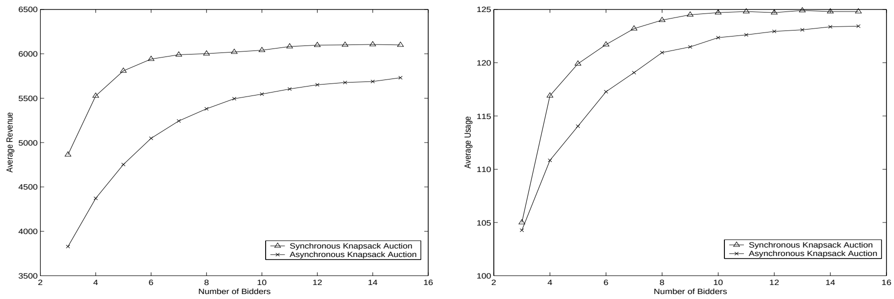
Figures 4(a) and 4(b) show the average revenue and spectrum usage with varying number of bidders for both the auction strategies. We observe that the proposed synchronous knapsack auction generates approximately average 10% more revenue compared to the asynchronous knapsack auction and also reaches steady state faster. The average spectrum usage is also more with the synchronous allocation policy. Figures 5(a) and 5(b) show the average revenue and spectrum usage with increase in capacity in CAB for both the auction strategies. It is clear that with increase in CAB, synchronous strategy provides more revenue and usage of CAB than the asynchronous strategy.

In figure 6, we look at the auction model from the bidders' perspective. Higher revenue requires high participation in number of bidders. We compare the two strategies in terms of the probabilities to win a bid. We observe that the proposed synchronous auction strategy has a significantly higher probability of



(a) (b)

Fig. 3. a)Revenue generated and b)Spectrum usage with auction rounds



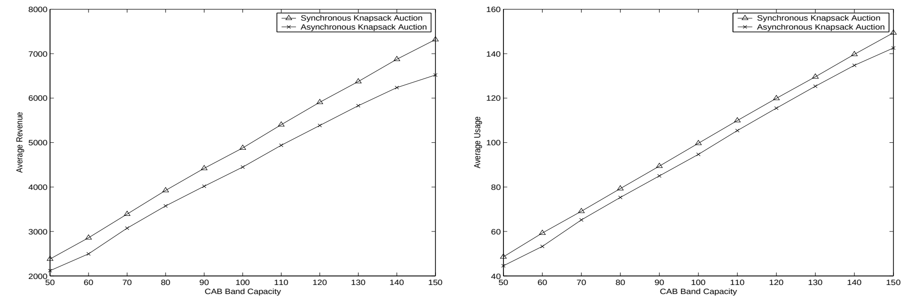
(a) (b)

Fig. 4. a)Revenue generated and b)Spectrum usage with number of service providers

winning compared to asynchronous auction strategy. This implies that providers will be encouraged to take part in the synchronous knapsack auction model thus increasing the competition among the providers and increasing the chance to generate more revenue.

6 Conclusions

In this paper, we proposed an auction mechanism for dynamic spectrum access that is based on the well known knapsack problem. The auction captures the conflict of interest between wireless service providers and spectrum owner. It is such designed that it maximizes the spectrum usage and the revenue of the spectrum owner. Both synchronous and asynchronous auction strategies are studied and compared. Through simulations it was found that it is in the best interest of both service providers and spectrum owner to adopt the synchronous auction. We also showed how the optimal usage of spectrum band is achieved and the revenue is maximized for the spectrum owner. The proposed mechanism yields higher probability of winning for the service providers and thus encourages the providers to participate in the bidding process.



(a) (b)

Fig. 5. a)Revenue generated and b)Spectrum usage with increase in CAB

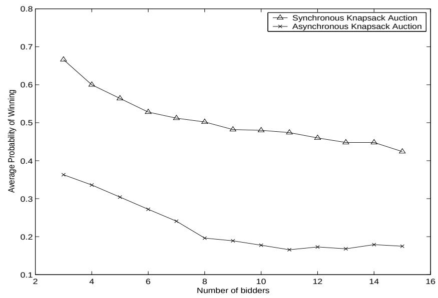


Fig. 6. Average probability of winning spectrum with number of bidders

References

1. R. Bapna, P. Goes, A. Gupta, "Simulating online Yankee auctions to optimize sellers revenue", Proceedings of the 34th Annual Hawaii International Conference on System Sciences, 2001.
2. M. Buddhikot, K. Ryan, "Spectrum Management in Coordinated Dynamic Spectrum Access Based Cellular Networks", Proc. of the First IEEE Intl. Symposium on New Directions in Dynamic Spectrum Access Networks, 2005, pp. 299-307.
3. S. Fatima, M. Wooldridge, N. R. Jennings, "Revenue maximizing agendas for sequential English auctions", Proc. of the Third Intl. Joint Conference on Autonomous Agents and Multi-agent Systems, 2004. AAMAS 2004. pp. 1432 - 1433.
4. G. Illing and U. Kluh, "Spectrum Auctions and Competition in Telecommunications", The MIT Press, London, England, 2003.
5. W. Vickrey, "Couterspeculation, auctions, and competitive sealed tenders", J. Finance, vol. 16, no. 1, pp. 8-37, Mar. 1961.
6. http://www.ebay.com/
7. http://www.ntia.doc.gov/osmhome/osmhome.html
8. http://www.sharedspectrum.com/inc/content/measurements/nsf/NYC_report.pdf