CHAPTER III

RANGE BOUND BIDDING FOR BANDWIDTH OPTIMIZATION

3.1. Introduction

When multiple secondary users try to get the available channels of spectrum, appropriate channel allocation is done through channel auctions. In this process, bidding by the secondary users is the mechanism usually followed by quoting their bid prices, where highest bidders will get the channels. In the context of fulfilling the QoS, it is assumed that the high priority users bid for the channels at higher prices while the low priority users bid for lesser prices. There are multiple proposals of this type in the literature, which are described in this chapter.

An innovative method of bidding called range-bound bidding is proposed in the thesis work. The proposed method is to fulfil the QoS requirement and is linked to bidding prices. This proposed 'range bound bidding' is presented here and the results are compared with other bidding methods available in the literature.

Offering QoS to SUs is a demanding task as they need to utilize the channels only in the absence of PUs and the occupancy of PUs is random. Offering very large data rates in the order of several hundreds of Mbps to some applications like 5G wireless communication systems is a real challenge.

Sometimes, PUs exhibit interest in leasing their spectrum to SUs for revenue or cooperation from SUs in transmitting PUs data. In such scenarios the SUs need not be bothered about unexpected handoffs as they are getting the spectrum with the willingness from owners of those bands only. In this perspective, linking of spectrum price to priorities of SU applications is an important point to be considered. The bidding system model is shown in Figure 3.1.

The PUs, owners of channels and the SUs, who are in need of channels, inform the auctioneer about their agreeable selling and buying prices respectively. With the help of appropriate auction mechanism, the auctioneer will assign the free channels of PUs to SUs. After getting the channel, the obtained spectrum will be distributed to the end users.

Generally, the SUs should be willing to pay for the channel. In the actual scenario, many SUs are competing for the channels. If there are N free channels at a time instant, then the top N bidders only will get the channels. To win a channel, a SU needs to bid at highest among all competitors, when only one free channel is available. But it is not possible to know bid amounts offered by its competitors. In this process, unknowingly he/she may offer very high bid value to get the channel, but it will result in more loss to himself/herself. To overcome this problem, the bidders may opt to offer multiple bids and ignore the high bid values whenever he/she got a channel for low bid value itself. But it will lead to confusion during channel allocations.

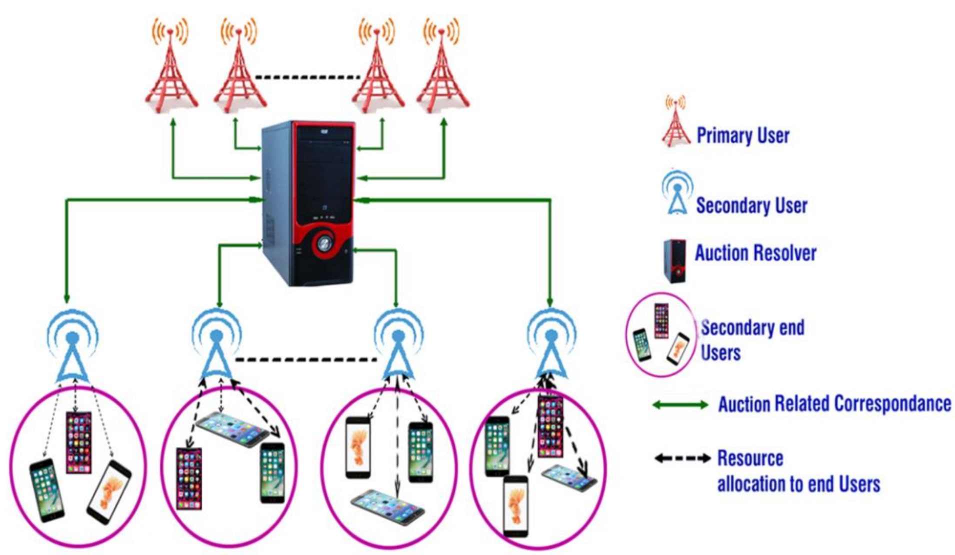

Figure 3.1. System Scenario

To solve the above said problems, two novel auction methods are proposed in this work, which eliminate the ambiguity of how much to bid at and also to avoid unnecessary multiple auctions by the same bidder. In addition to this, the pricing of channels takes into consideration, the demand and supply situation.

3.2. Related Work from Literature

Various types of auction mechanisms are proposed by researchers, for cognitive radio networks in the literature. In (Zhang, Y., Lee, C., Niyato, D. & Wang, P., 2013), the authors have proposed the following methods:

(a) Forward auction: Suitable for one seller (PU) and multiple buyers (SUs) scenarios and the competition is among buyers.

(b) Reverse auction: Appropriate for multiple sellers and one buyer situations and the competition is among sellers.

(c) Double auction: Applicable for multiple sellers and multiple buyers scenarios and is a two way competition.

(d) English auction: Suitable for one seller and multiple buyers. It is open cry and ascending bid values, in which the buyers will announce their willingness to pay as bid values in increasing manner after hearing other's bidders decisions to get the channel.

(e) Dutch auction: Appropriate for multiple sellers and one buyer cases. It is a method of open cry and descending bid values, in which the competing PUs will announce their bid values to SU in terms of their willingness to give channel at their least possible price.

(f) Sealed bid auctions: Here all competitors will submit their bids in closed form. Initially it is proposed for one seller and multiple buyers scenario. The buyer who bid for largest amount will be declared as winner and he/she needs to pay only the k^{th} bid amount when all the bids are arranged in descending order.

    This can be extended to multiple sellers and multiple bidders scenario also. If the competitors are buyers, then the winners will start from highest bid SUs and number of winners is same as number of available free channels. On the other hand, if bidders are PUs then the winners will be announced from PUs that correspond to least bid values and the number of winners are same as number of SUs.

The most frequently used payment rules are based on VCG (Vickrey Clarke Grooves) and GSP (Generalized Second Price Auction) methods.

- VCG (Vickrey Clarke Grooves), in which the winner needs to pay the externality he causes:

Suppose there are two channels and three SUs. Let the bids of SUs for channels are given in rupees per minute as shown in Table 3.1

Table 3.1. Bid values of 3 SUs corresponding to two channels

	Channel 1	Channel 2
SU1	20Rs	40 Rs
SU2	15Rs	35 Rs
SU3	25 Rs	12 Rs

Now from Table3.1, it is clear that SU3 is the winner of channel 1 and SU1 is the winner of channel 2 as they opt for highest bid among three SUs with respect to those channels. So channel assignment is as follows:

Channel 1---------------> SU3

Channel 2---------------> SU1

SU1 has to pay the externality he/she causes, that is the difference between social welfares of primary owner with and without SU1s contribution from others. So, social welfare of primary owner from others in the presence of SU1 = P_1= Rs 25.

Social welfare of primary owner from others in the absence of SU1= P_2=Rs25+Rs 35= Rs 60 (since when SU1 is not present SU2 will be the winner of channel 2).

Therefore, SU1 should pay $P_1 \sim P_2$, which is Rs25 ~ Rs60= Rs 35.

Similarly SU3 needs to pay the externality it causes. In its absence actually next higher bidder is SU1, which is already assigned with channel 2. So SU2 will be assigned to channel 1 in the absence of SU3. So, Social welfare of primary owner from others in the presence of SU3 = P_1= Rs 40.

Social welfare of primary owner from others in the absence of SU3 = P_2= Rs40+ Rs15= Rs 55 (since when SU3 is not present SU2 will be the winner of channel 2, as SU1 is already winner of channel 2).

Therefore, SU3 should pay P_1 ~P_2, which is Rs 40 ~ Rs 55= Rs 15.

The total revenue of primary owner for this example with VCG is Rs 35+ Rs 15= Rs 50.

- GSP (Generalized Second Price Auction), in which the winners need to pay the next bid of their bid values when all bid values are arranged in descending order.

Let us consider the same example of Table 4.1, the winners' declaration is same as VCG, but the payment rule is as follows:

SU1 should pay Rs35 as next highest bid value to Rs40 is Rs 35 for channel 2 and SU3 should pay Rs 20 as next highest bid value to Rs 25 is Rs 20 for channel 1.

The total revenue of primary owner for this example with VCG is Rs 35+ Rs 20= Rs55.

(g) Cooperative auction: As sellers offer price discounts for large amount of commodities, buyers will be grouped to obtain the advantage.

(h) Offline auction: Buyers can make bids at any time before the given time deadline.

(i) Online auction: It is instantaneous bidding.

(j) Anglo Dutch auction: It is a mixture of English and Dutch auctions. In the first step, buyers will made ascending bids (open cry) and when price goes on increasing, some buyers will be dropped. When there are only two buyers left, they will start sealed bid first price auction, which is equivalent to 2 persons Dutch auction.

(k) Waiting line auction: Commodities will be assigned to bidders in the front of queue so that they follow First Come First Serve (FCFS) or First In First Out (FIFO).

In all the above mentioned auction mechanisms, there is a lot of confusion to the bidders regarding how much bid value can make them winners. This may encourage multiple bids by the same bidder and results in chaos in channel assignment.

The authors of (Wang, X., Li, Z., Xu, P., Xu, Y., Gao, X. & Chen, H. H.,2010) presented an auction mechanism which uses game theory and NE (Nash Equilibrium) is its solution. The PU announces a positive reserve bid, which tells how much it needs for its own transmissions and price per unit BW (Bandwidth) to all SUs. Then SUs will calculate their utility function and submit bids, so as to maximize their utility functions. However, it didn't include demand and supply in the finalization of channel price.

In (Khaledi, M. & Abouzeid, A. A., 2013), multiple PUs, multiple SUs and Primary Owner (PO) are considered in the model. Heterogeneous channels are considered instead of identical channels. So each SU bids for each channel with different values and then VCG is used to fix the cost of channel. They analyzed the performance of the system in terms of social welfare (the revenue of the primary owner if top bidders are given chance with their bid values as channel costs), SU utilities (difference between the values of what they bid and what they paid) and PO revenue (amount obtained by primary owner as per VCG). They compared the results of this heterogeneous model with homogeneous model. In the proposed work also heterogeneous channels are considered. The results are compared with respect to GSP.

In (Niyato, D. & Hossain, E., 2008), multiple PUs and one SU service are considered in the model, where SU service is formed by many SUs as a group. Competition exists among PUs to offer channels to SUs, but without getting their own services degraded because of the service given to SUs. Bertrand game (simultaneous game with cost as parameter) is used. NE is found to be inefficient compared to collusion, where there will be some understanding among all PUs and if any PU is deviating from rules, punishment will be given. Here, deviation means a PU reducing its price to attract more demand. But, maintaining coordination among multiple PUs is a difficult issue.

The authors of (Chun, S. H. & La, R. J., 2013) considered multiple PUs and multiple SUs model with SDR (Software Defined Radio) capability. They have first introduced an auction method called Generalized Branco's mechanism (GBM), in which competition among buyers and sellers is a non- cooperative game and a cooperative game respectively. The logic here is that selling of their individual spectrum on their own yields less advantage than joint sale.

In this work a spectrum trading market is considered in which SPs (Spectrum Providers) with their own spectrum bands' EUR (Exclusive Use Right) can be put up for sale for a fixed period to other SPs which are in need of extra spectrum bands or which don't have their own spectrum bands.

SPs will reserve a price to SUs as they have bought EUR with some cost and cannot lend it below their purchased price. These reserved prices are also not fixed and differ from one SP to others. Also, same SP may reserve different prices for different channels.

All the buyers are assumed to be independent. The general steps are as follows:

- Each buyer picks a seller, to whom he wants to participate in auction and he/she will place his/her bid with the selected seller.
- Individual sellers or groups of sellers will decide frequency bands to allot and cost to charge for them.

It can be done as automated trading system that runs periodically, as follows:

a. Each seller group will announce their willingness of lending the channels along with prices with corresponding frequencies. Then interested buyers will choose a seller and frequency bands and offers their willingness to pay as bids.

b. Trading system will assign frequency bands based on bids and charge for them.

c. Based on fixed predefined schemes the trading system will distribute the combined revenue from sales to sellers.

d. Channel allocation and pricing schemes should be such that they encourage and support trading between sellers and buyers.

Buyers benefit depends on the number of frequency bands they are obtaining rather than the specific frequencies they are getting. They may ask for contiguous frequency bands. Performance is measured in terms of profit and payoff to SUs and PUs respectively.

In (Zou, J., Xiong, H., Wang, D. & Chen, C. W., 2013) authors considered a scenario in which multiple SUs use common relay for their simultaneous transmissions and will compete for power levels of their transmissions. Here the time frame is divided into 3 parts. Sensing, Auction for power and Data transmission. Here it operates in two modes. They are:

- Overlay mode: it is opportunistic spectrum sharing i.e it uses the spectrum when PU is absent. Here based on the payment the relay allocates the power.
- Underlay mode: In this mode, PU and SU utilize the channel simultaneously. The transmission powers of SUs should not trouble the transmissions of QoS of PUs.

In their work, they proposed

- A hybrid model of overlay/underlay type spectrum sharing scheme is proposed, where the SUs will be operated in overlay mode if PU is present, else it will be operated in underlay mode. In underlay mode, it should take care of using the power levels such that they should not create harmful interference to PU transmissions.
- Based on biddings for power channel allotment is developed.
- For the proposed auction game, existence of unique NE is proved theoretically.
- In the proposed hybrid overlay/underlay system, the SUs will experience different outage probabilities in different spectrum sharing scenarios.

3.3. Proposed First Auction Technique: Range Bound Bidding-1

3.3.1. Description

From literature it can be understood that in many sealed bid auction strategies there is no limit on bid values, as there is no such predefined bound. It may lead to volatility of prices, which creates ambiguity to SUs while bidding and the situation may suggest SUs to go for multiple bids, in view of dropping the high bid value if a low amount bid gets him the channel, which leads to confusion in channel assignment and hence underutilization of bandwidth.

The situation will be improved if possible bid values are known in advance to all the competing SUs. With this, better scheduling of networks is possible and the SUs, which are having urgent data, can opt for highest known bid value, which will get the channel with improved probability. The SUs, which are having NRT data can go for least available bid value as it doesn't have immediate requirement of a channel. So it can be understood that QoS demands of SUs can be addressed with this auction technique.

Maximum bid value is predefined and all the remaining bid values taken as sub-multiples of the maximum bid is proposed in this auction technique. So with this, SUs can opt for various levels of bids based on their urgencies of channel requirements. The SUs, which are willing to pay maximum bid value will be given more priority during channel allocation and vice-versa. If there exists N free channels and M SUs are in competition and if M > N then the top N SUs will be assigned with N channels when the SUs are arranged in the descending order of their bid values. On the other hand, if M < N, all SUs will be assigned channels.

When enough number of free channels are existing, then it will be painful to the highest bidder as lowest bidder is also getting the channel but at a very low cost. In order not to suffer the highest bidders, discounts are introduced when sufficient number of free channels is available. 25% discount is offered when at least one channel is left unassigned after channel allocation. The key benefit of this technique is RT SUs can bid for highest bid value without any ambiguity to get the channel before it meets its time deadline.

3.3.2. Model

The SUs are classified into 4 types as SU1s, SU2s, SU3s and SU4s based on their urgency requirements of data channels. Among them SU1s, which needs the channel immediately are defined as highest priority and SU4s, for which channel can be assigned at any time are defined as least priority. The order of priority is decreasing from SU1s to SU4s. The occupancy of PUs is obtained from uniform distribution. The requesting SUs also follow the uniform distribution. For different levels of PU occupancy cost of each channel is obtained with respect to number of channels. The results of proposed auction are compared with GSP auction method.

The demand of channels from various priority SUs is classified into 3 types, namely high, medium and low as shown in Table 3.2.

Table 3.2. Types of Demand from SUs

Parameter	Low demand	Medium demand	High demand
Maximum requesting time of SUs	5	10	15
Maximum number of times each SU is requesting	5	10	15
Number SUs in each priority type	5	10	15

3.4. Simulation Results of the Proposed First Auction Technique: Range Bound Bidding-1

The cost of channel for various types of SUs when the number of channels is increasing is shown in Figure 3.2., which is obtained for the PU occupancy of 25% and medium demand from SUs. The maximum pre defined bid is taken as 100. So, the next three level bids are sub multiples of the maximum bid, that is 50, 33 and 25. The simulation results of Figure 3.2 reveal that the costs of channels for various types of SUs are decreasing with increasing number of channels. It is due to discounts of 25% offer to all SU types when sufficient number of channels is available. For comparing the proposed results with GSP auction results maximum bid of GSP also taken as predefined maximum bid of proposed auction technique, but all the remaining bids of GSP are obtained randomly.

From economic point of view the price of any item should follow supply and demand; when supply is more, cost should be reduced to improve sales and vice-versa. Similarly when demand is more, cost should be increased to have enough stock in hand. In this scenario, it can be observed that the proposed auction is inversely proportional to number of channels, that is supply and GSP auction method is not following any such rule as it is following randomly generated bids and not introducing any discounts.

The results of low and high demands from SUs for the same 25% PU occupancy are shown in Figures 3.3 and 3.4.

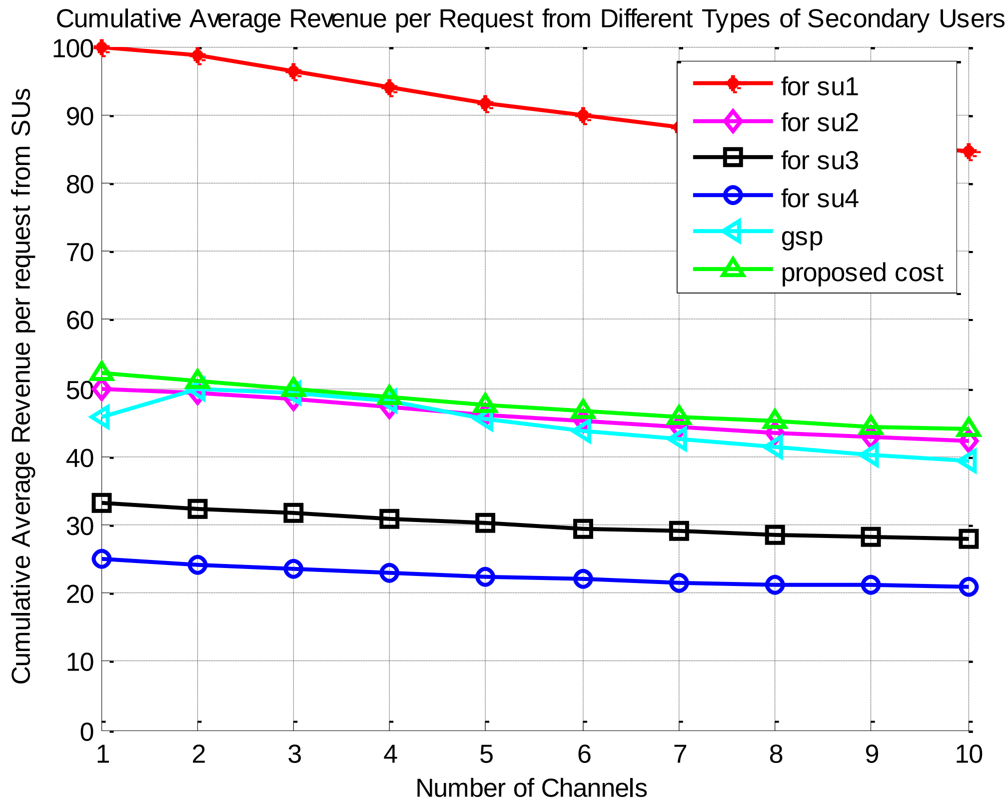

Figure 3.2. Channel allocation cost to different SUs for 25% PU occupancy and medium demand from SUs

It can be observed from Figures 3.2 to 3.4 that the declining rate of channel cost is increasing when demand is decreasing. That means reduction of channel cost is fast for low demand situation. That is supply increase (number of channels) and demand drop causes much reduction of channel cost in the proposed auction technique. There is no such relation in GSP auction method.

The results of channel costs for medium, low and high demand scenarios for 50% channel occupancy is shown in Figures 3.5 to 3.7.

From the figures 3.3 and 3.6, which show the channel cost results for 25% and 50% PU occupancy respectively for low demand case, it is noticed that the average channel cost in the proposed range bound bidding is decreasing at faster rate in 25% PU occupancy compared to 50% PU occupancy counterpart. Due to more available supply in 25% PU occupancy case, it results into less price.

Similarly, the similar conclusions can be drawn after comparing 25% and 50% PU occupancy scenarios for medium and high demand cases.

The effect of discounts can be observed in Figures 3.2 to 3.7. In all graphs the average price of channel is getting reduced as number of channels is increasing from left to right. As is known, when the number of channels are increasing, the last SU types also get channel allotment and finally some channels will be left unassigned, where discount will come into picture. This advantage can be observed for less number of channels in 25% PU occupancy scenario compared to 50% PU occupancy counterpart, as the probability of getting free channels is more in 25% PU occupancy scenario.

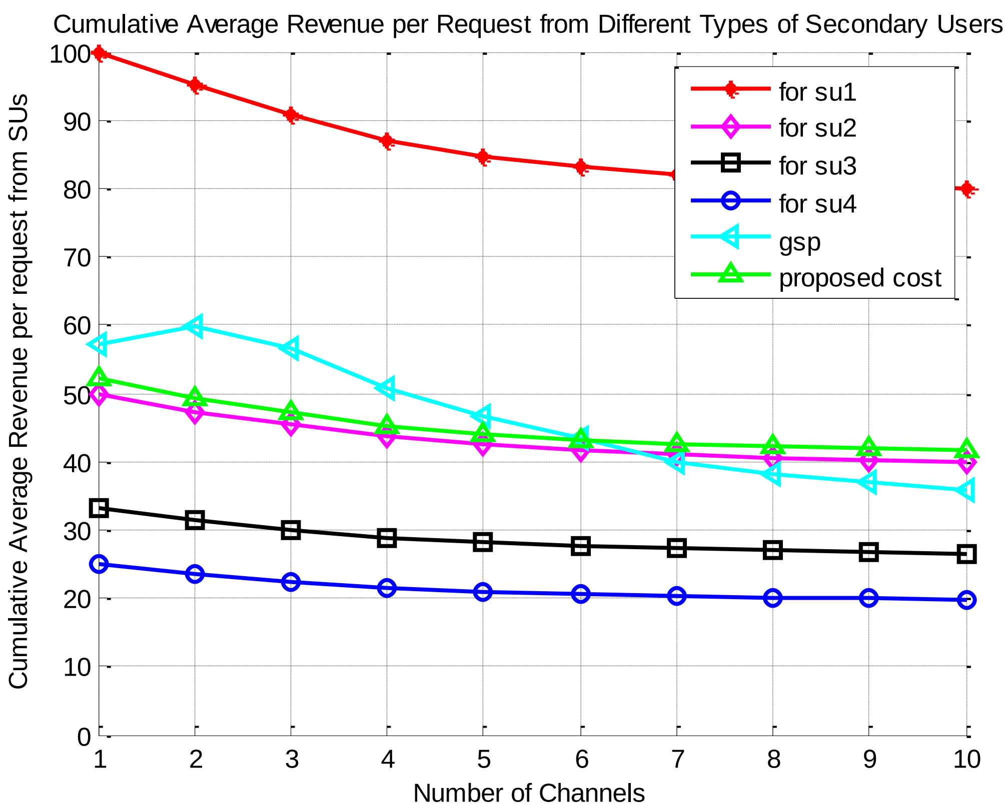

Figure 3.3. Channel allocation cost to different SUs for 25% PU occupancy and low demand from SUs

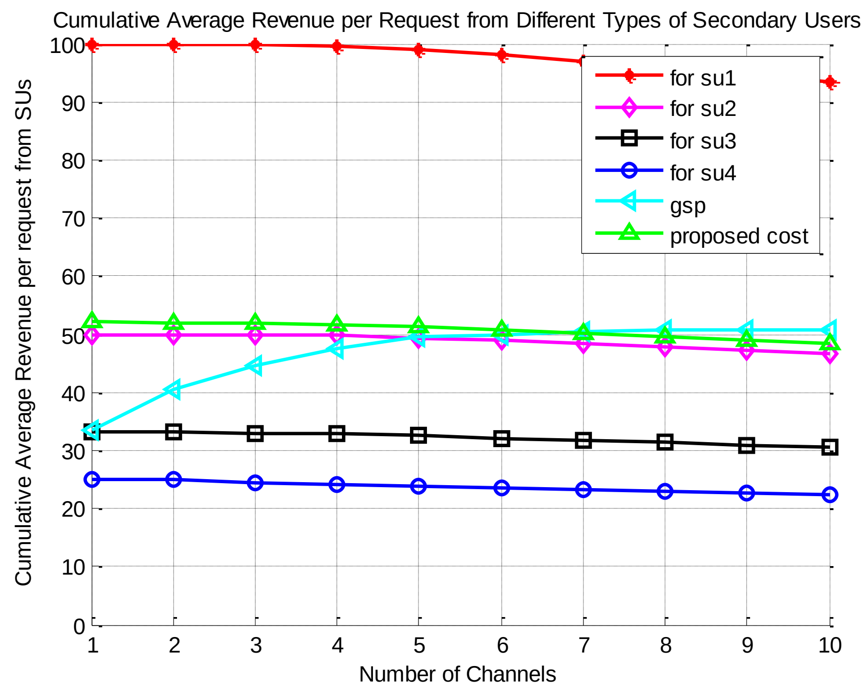

Figure 3.4. Channel allocation cost to different SUs for 25% PU occupancy and high demand from SUs

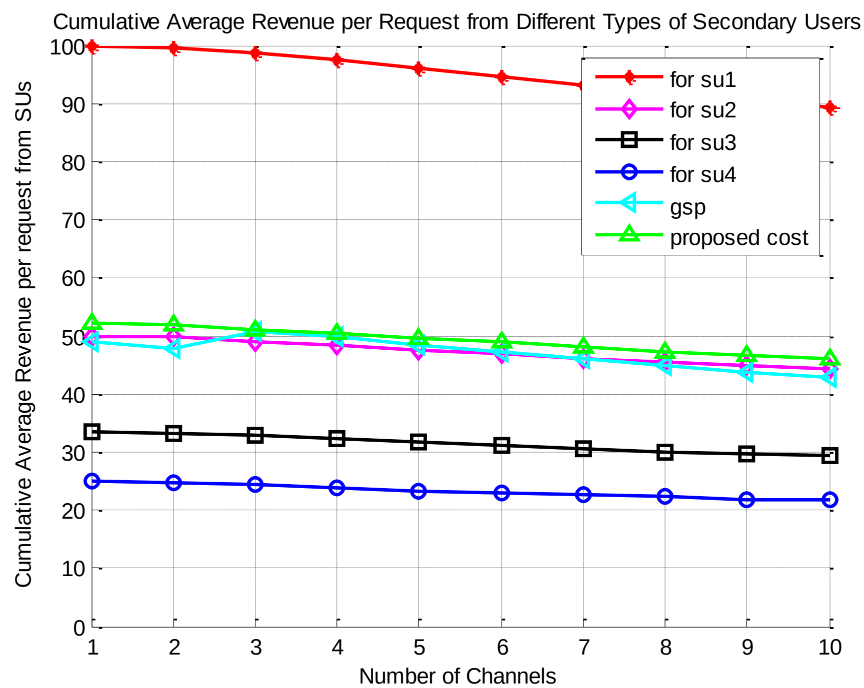

Figure 3.5. Channel allocation cost to different SUs for 50% PU occupancy and medium demand from SUs

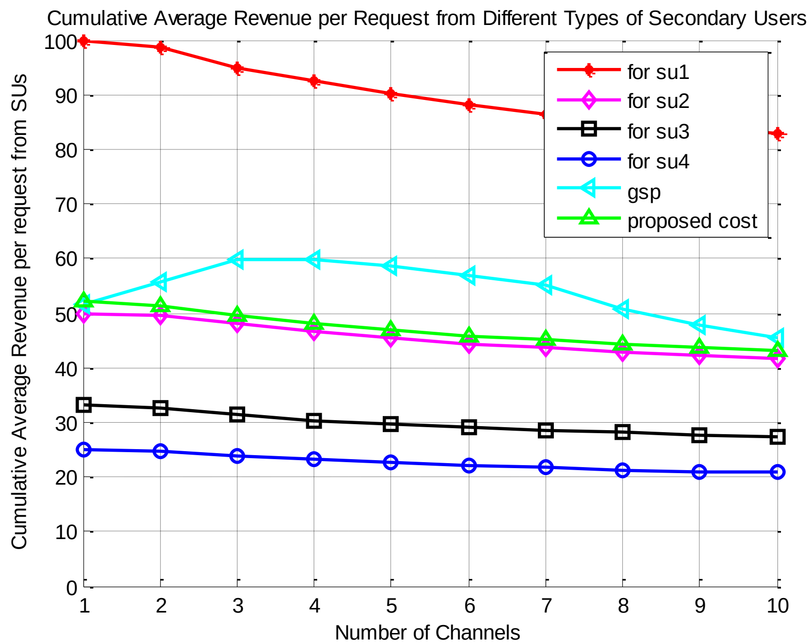

Figure 3.6. Channel allocation cost to different SUs for 50% PU occupancy and low demand from Sus

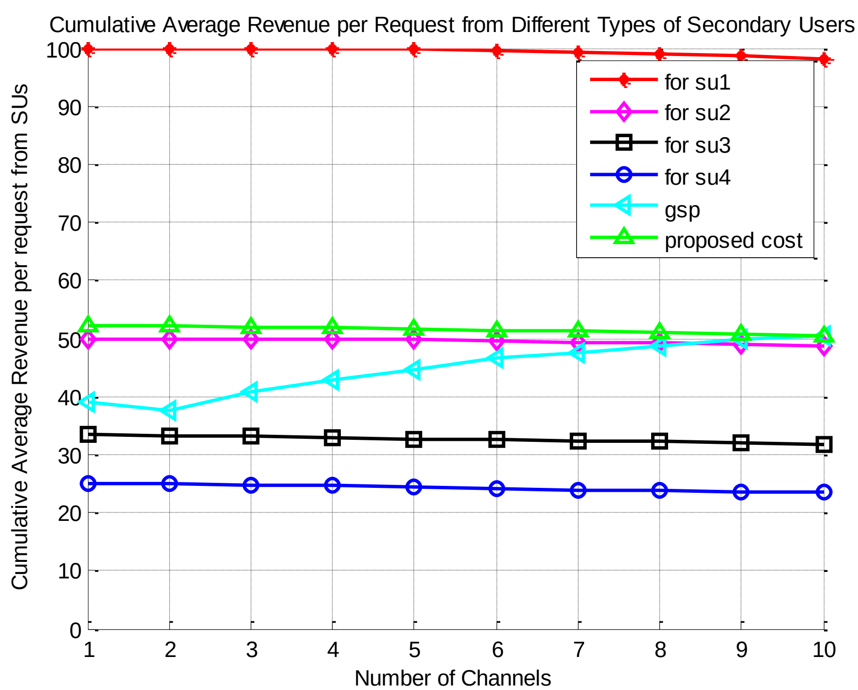

Figure 3.7. Channel allocation cost to different SUs for 50% PU occupancy and High demand from Sus

3.5. Proposed Second Auction Technique: Range Bound Bidding-2

Initially, the competing SUs will opt for channels by offering their willingness to pay in the form of bids in this kind of mechanism. The top N bidders will be assigned channels when there are N free channels and number of bidders is greater than number of channels. On the other hand, if the number of bidders is less when compared to number of available free channels, then, all bidders will be allocated channels.

Here instead of offering discounts, the channel costs are decided such that all assigned channels should pay the same amount equal to the least bid amount of all winners at that instant. The winner determination and channel cost calculation algorithm is shown in Algorithm 3.1.

Algorithm 3.1. Algorithm for Winners Determination and Cost Calculation
Initial state: 1. All competing SUs submit their bids $B=\{b_1, b_2, b_3, \ldots b_k\}$ to the auctioneer. where $b_i \in \{P_{max}, P_{max}/2, P_{max}/3, P_{max}/4\}, \forall i \in N$ 2. Let the free channels available are $C=\{c_1, c_2, c_3, \ldots c_p\}$. 3. Revenue = 0; **Sorting of bidders based on their bid values:** 4. Sort the bid values in non- increasing order of bid values. $B^*=\{b_1^*, b_2^*, b_3^*, \ldots b_k^*\}$, where $b_i^* \geq b_{i+1}^*$ **Winners determination:** 5. M=Min(k,p) 6. For i=1 to M Do 7. Bidder of b_i^* is assigned with c_i 8. End For **Revenue calculation:** 9. $Revenue=M*b_M^*$ 10. Output Revenue.

The motivation behind this type of channel cost decision is to avoid multiple bids by the same bidders, who want to try the channel for low cost. If channel cost is declared as their bid amounts, most of the bidders will go for multiple bids for single channel and when they obtain a channel for low bid value, the bidders will drop the channel obtained for their high bid value leading to instability of the system and thereby underutilization of the spectrum.

Some sort of fine can be imposed when users go for multiple bids, but users may continue with multiple bids provided that the fine amount is less than the benefit they are getting out of multiple biddings. So the proposed range bound bidding auction technique ensures maximum utilization of the spectrum as no multiple auctions and dropouts of SUs happen.

In the general auction mechanisms, there is no upper and lower bounds and whenever an SU is in emergent need of channel he/she has to go for very high bid value and even then there is no guarantee that it will get him/her the channel although free channels are available. On the other hand, some SUs, which have non-real time data for transmission, will go for very small amount of bid, which is a loss to primary owner as he needs to assign the channel whenever finds free channels after all channel assignments. But the proposed auction mechanism is satisfying both the parties.

It is also helpful in predicting the bid values in various scenarios like different levels of supply and demand, which will help the SUs to estimate their bid values and hence their data transmissions.

3.6. Analytical Model of the System

The cognitive radio network contains many channels and many competing SUs. Both PUs and SUs follow uniform distribution with arrival rates λ_p and λs and service rates μ_p and μ_s respectively. In view of realistic situations, where some tasks are real-time, which demand the transmission of data within given time deadline and the other tasks are non real-time, where there is no such time deadlines, the SU traffic is divided into four types. They are SU1s, SU2s, SU3s and SU4s, where SU1s are hard real-time, SU2s and SU3s are soft real-time and SU4s are non-real time applications. The priority order is $SU_k > SU_{k+1}$.

The channel allocation order depends on the priorities of SUs, which inturn depends on their bid amounts. As already discussed maximum bid is defined as P_{max} and all the remaining bids are sub multiples of P_{max}, that is the bid amount to be offered by k^{th} priority SU is P_{max}/k .

Subsequent to bidding, the algorithm to find channel winner SUs and price they have to pay is shown in Algorithm 3.1. 4D Markov chain can be used to model the system, where the state contains 4 dimensions. The state is represented by (N_{s1}, N_{s2}, N_{s3}, N_{s4}), where N_{s1}, N_{s2}, N_{s3} and N_{s4} represents number of SU1s, SU2s, SU3s and SU4s using the spectrum at that time instant respectively.

In (Gelabert, X., Pérez-Romero, J. , Sallent, O. & Agustí., R., 2008) five types of radio access technology (RAT) selection policies are considered in view of TDMA and WCDMA based channel models and data and voice kind of services. To justify the results Markov chains are used. To exemplify different situations, the authors of (Jian Wang, Aiping Huang, Wei Wang, and Tony Q.S. Quek, 2013) used Markov chains. In (El Helou, M., Ibrahim, M., Lahoud, S., Khawam, K. , Mezher, D.& Cousin, B., 2015), they tackled the secondary users, who ruin the performance of the system. Their plan is to provide network parameters like QoS parameters, cost etc. to secondary users so as to take better decisions. But providing the network parameters is a difficult task. To overcome this difficulty, they have initiated reinforcement learning algorithm for getting the network parameters. To meet the objectives of both primary owner and SUs, they used SMDP to get the network parameters. To analyze the proposed model also Markov chains are used. The analysis is carried out for two cases in the thesis.

Case 1: $N_{s1}+ N_{s2}+ N_{s3}+ N_{s4}+N_p<N$, where N is total number of channels and N_p is number of primary users utilizing the channels. This means still some free channels are left after channel allocation.

Upon the arrival of a new SU of k^{th} priority type (SUk) where $k \epsilon \{1,2,3,4\}$, there will not be any blocking and the corresponding in-service SUs will be increased by one in the next state. Similarly, when an SU of k^{th} priority type (SUk) leaves the system, then, simply the corresponding in-service SUs will be decreased by one in the next state. It is illustrated in Figure 3.8. For example, let us consider the central state of Figure 3.8, that is (N_{s1}, N_{s2}, N_{s3}, N_{s4}) and when an SU1 arrived, then it will be admitted into the system without checking any condition, as free channels are available. So, the next state becomes (N_{s1}+1, N_{s2}, N_{s3}, N_{s4}). The probability of changing from (N_{s1}, N_{s2}, N_{s3}, N_{s4}) state to (N_{s1}+1, N_{s2}, N_{s3}, N_{s4}) state is λ_{s1} , the arrival rate of SU1s, which is shown on the line connecting from (N_{s1}, N_{s2}, N_{s3}, N_{s4}) state to (N_{s1}+1, N_{s2}, N_{s3}, N_{s4}) state.

Similarly, when an SU1 is leaving the system when it is in state (N_{s1}, N_{s2}, N_{s3}, N_{s4}) then the next state becomes (N_{s1}-1, N_{s2}, N_{s3}, N_{s4}) as one SU1 is left. The probability of changing from (N_{s1}, N_{s2}, N_{s3}, N_{s4}) state to (N_{s1}-1, N_{s2}, N_{s3}, N_{s4}) state is $N_{s1}.\mu_{s1}$, which is shown on the line connecting from (N_{s1}, N_{s2}, N_{s3}, N_{s4}) state to (N_{s1}-1, N_{s2}, N_{s3}, N_{s4}) state, where N_{s1} represents the number of in-service SU1s and μ_{s1} denotes the service rate of SU1s. The remaining part of the Markov chain can be understood in the same manner.

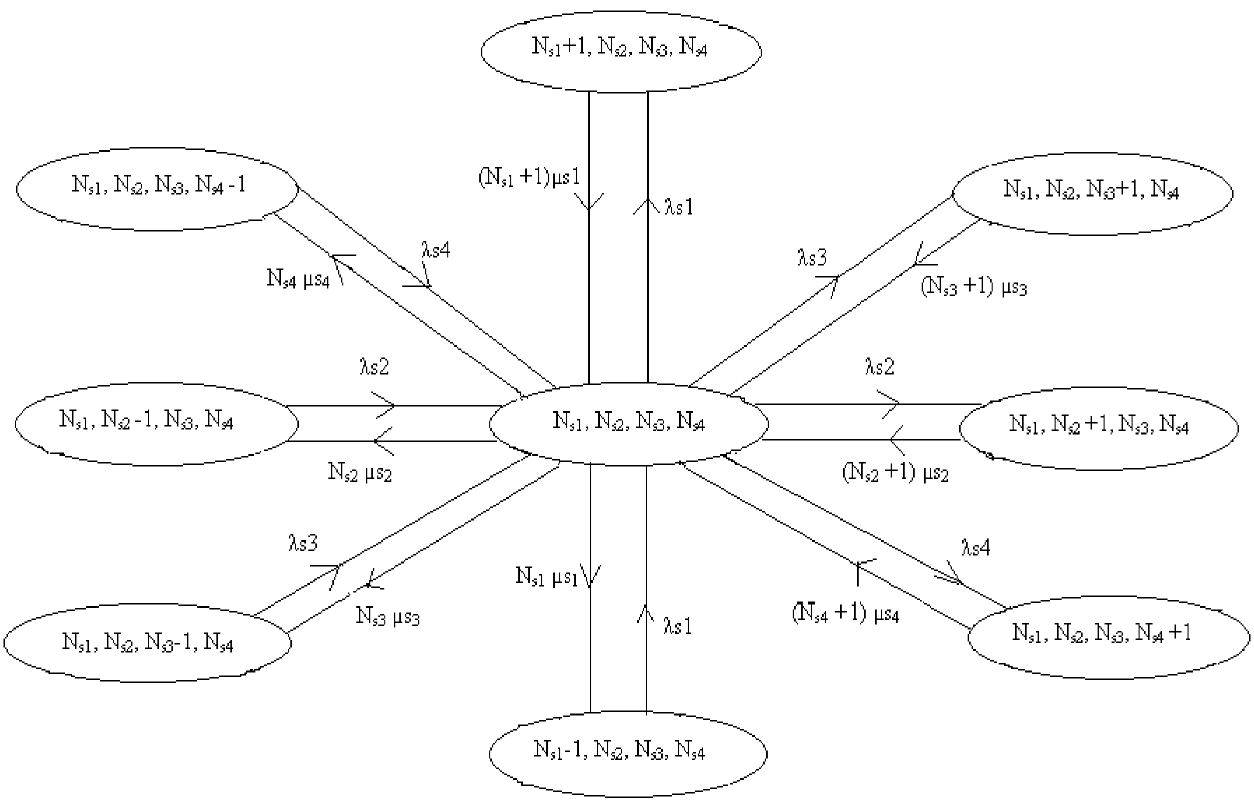

Figure 3.8. Markov Chain for Case-1

Case 2: $N_{s1}+N_{s2}+N_{s3}+N_{s4}+N_p=N$. That is when no free channels are left.

In this scenario, blocking is possible as no free channels are available. Pre-emption is allowed in the model, so when a high priority SU needs a channel then a low priority SU, which is using the channel, should vacate it for the requesting high priority SU. If no low priority SU is utilizing the channel at that time then the requested high priority SU will be blocked. When there are no free channels how blocking of different types of SUs is illustrated in the algorithm shown in Algorithm 3.2.

Blocking of SU1s happen when there are no free channels and pre-emption is not possible, means all the channels are occupied by only PUs and SU1s. So

$$\text{Blocking probability of SU1s } (p_{b1}) = \frac{\sum_{N_A=0} \lambda_{S1}.Q(N_{S1,}\, 0,0,0)}{\sum \lambda_{S1}.Q(N_{S1}, N_{S2}, N_{S3}, N_{S4})} \quad \text{..........(3.1)}$$

Blocking of SU2s occurs when no free channels are available and where pre-emption is not possible, that is all channels are occupied only by PUs, SU1s and SU2s.

$$\text{Blocking probability of SU2s } (p_{b2}) = \frac{\sum_{N_A=0} \lambda_{S2}.Q(N_{S1,} N_{S2}, 0,0)}{\sum \lambda_{S2}.Q(N_{S1}, N_{S2}, N_{S3}, N_{S4})} \quad \text{.........(3.2)}$$

Blocking of SU3s is possible when there are no free channels available and no SU4s are there in the system for pre-emption.

$$\text{Blocking probability of SU3s } (p_{b3}) = \frac{\sum_{N_A=0} \lambda_{S3}.Q(N_{S1,} N_{S2}, N_{S3}, 0)}{\sum \lambda_{S3}.Q(N_{S1}, N_{S2}, N_{S3}, N_{S4})} \quad \text{.................(3.3)}$$

Blocking of SU4s is done when no free channels are left.

$$\text{Blocking probability of SU4s } (p_{b4}) = \frac{\sum_{N_A=0} \lambda_{S4}.Q(N_{S1,} N_{S2}, N_{S3}, N_{S4})}{\sum \lambda_{S4}.Q(N_{S1}, N_{S2}, N_{S3}, N_{S4})} \quad \text{.................(3.4)}$$

Here Q is used to represent the state. If $N_{s1}+ N_{s2}+ N_{s3}+ N_{s4}+N_p=N$, where N is number of channels considered in the system, then no free channels are available, that is $N_A=0$.

Algorithm 3.2. Algorithm to Depict Blocking Scenario

Initial state:

1. Let the Initial State is (N_{s1}, N_{s2}, N_{s3}, N_{s4}).

Call Handling and Decision Making:

2. Upon arrival of SU_k user
3. If $N_p+N_{s1}+N_{s2}+N_{s3}+N_{s4}< N$, where N is total number of channels.
4. Then admit SU_k user where $k\in\{1,2,3,4\}$.
5. Else if $N_{sl}\neq 0$ & $l>k$
6. Preempt the SU_l user and admit SU_k user.
7. Else Block SU_k user.
8. End.

3.7. Simulation Results of the Proposed Second Auction Technique: Range Bound Bidding-2

Here also, same four priorities of SUS are considered with same probability distributions as explained in 3.4. The system is modelled as discrete event simulation system as the occurrence of each event is observed for every minute and results are obtained by simulating it in MATLAB. Simulations are carried out for 24*60=1440 minutes, which is one day. It also supports pre-emption.

Ideal channels, transmitters and receivers are assumed. The reason for this assumption is that the work is mainly focusing on proving SU1s blocking is very less compared to others, and hence the model is supporting real-time users. So the parameters like bit error rate (BER), channel attenuation and noise are not taken into consideration in the thesis. The system can be treated as queuing model in this scenario.

Simulations are carried out to find average channel costs for all types of SUs, average cost according to the proposed auction mechanism and average cost according to the GSP auction mechanism by changing number of channels from 1 to 10. In addition to costs, blocking probabilities of all types of SUs are obtained for 25% PU occupancy and 50% PU occupancy and for low and high demands from SUs.

The channel costs for 25% and 50% PU occupancy for high demand cases are shown in Figures 3.9 and 3.10. It is observed that the cost reduction rate of 50% PU occupancy situation with respect to number of channels is low compared to its 25% counterpart. This is due to the fact that when number of channels increases, the low level SUs will get more channel winning opportunities in 25% PU occupancy case than 50% PU occupancy case, as in the first case 75% is left for SUs.

The channel costs for low demanding SUs for 50% PU occupancy is shown in Figure 3.11. From Figures 3.10 and 3.11 it is observed that the cost reduction rate of low demand SUs scenario is more compared to its high demand counterpart. It is due to when demand is more, the opportunities reaching the low priority SUs is less and hence probability of cost reduction is less.

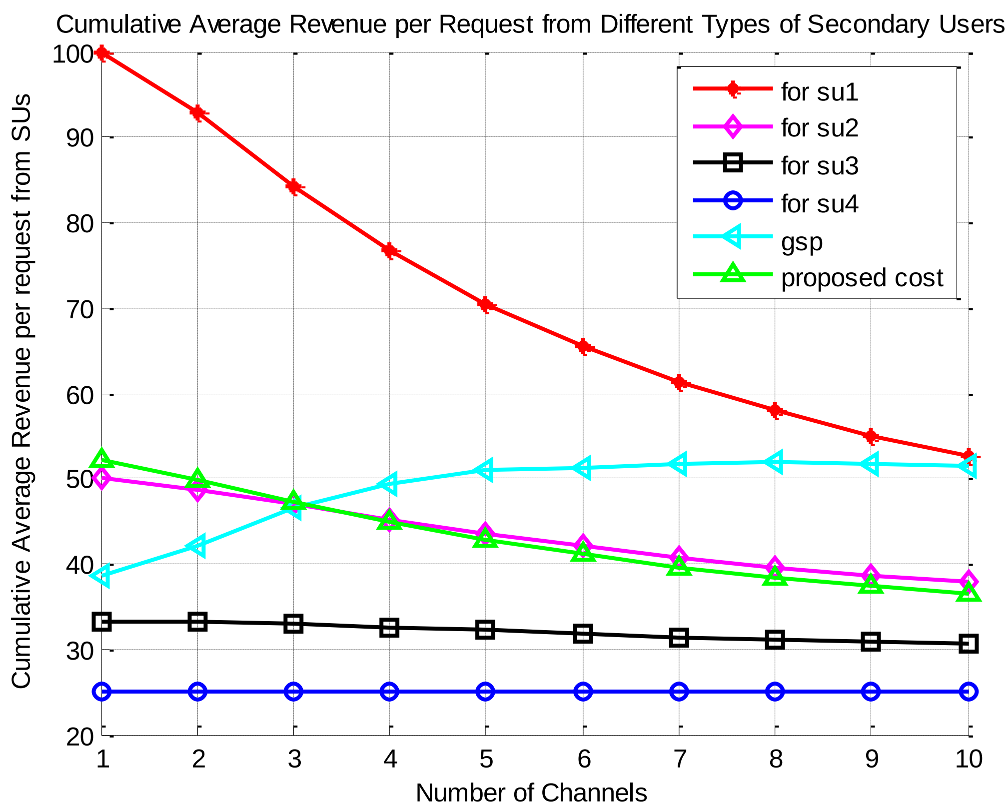

Figure 3.9. Channel allocation cost to different SUs for 25% PU occupancy and high demand from SUs

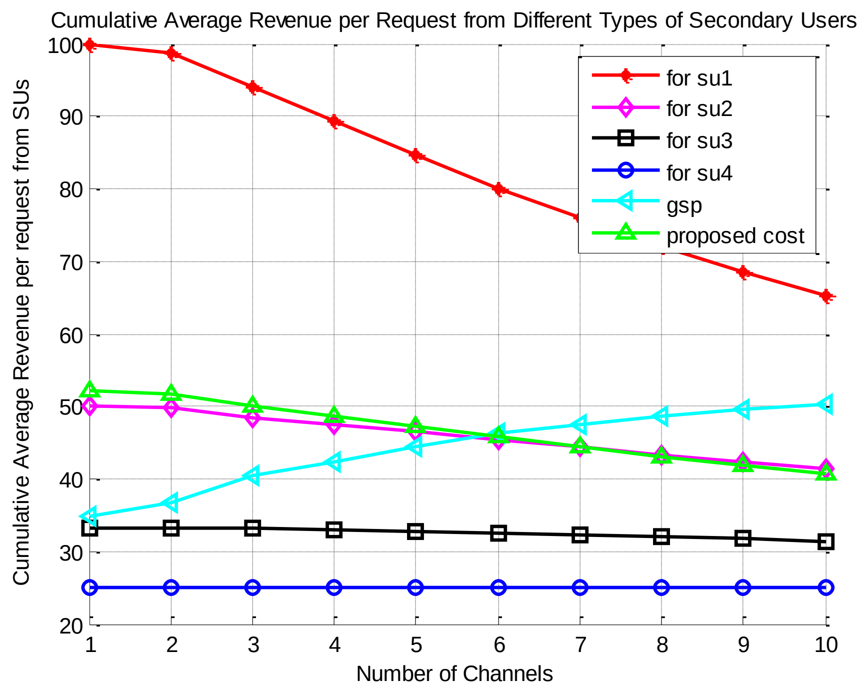

Figure 3.10. Channel allocation cost to different SUs for 50% PU occupancy and high demand from SUs

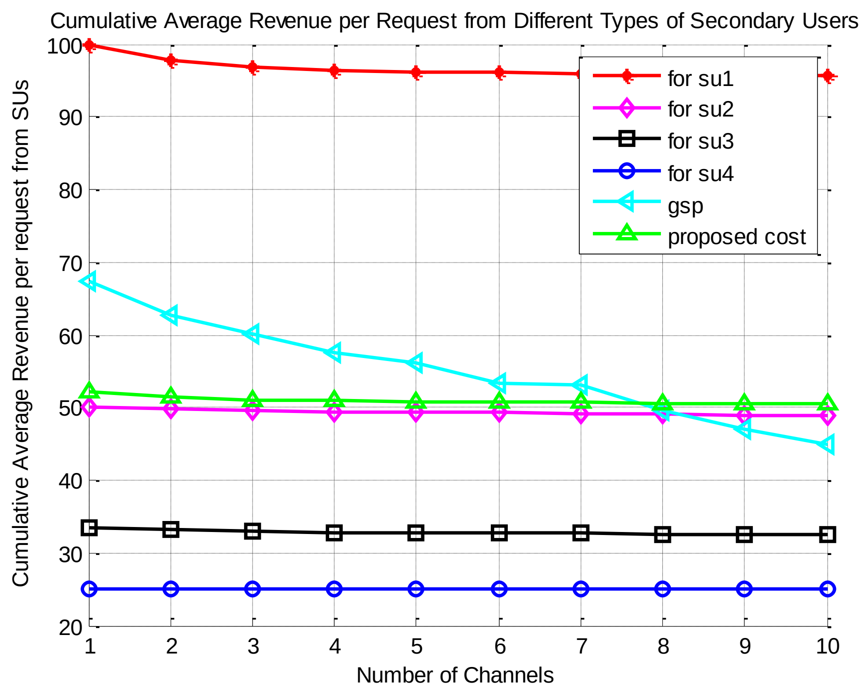

Figure 3.11. Channel allocation cost to different SUs for 50% PU occupancy and low demand from SUs

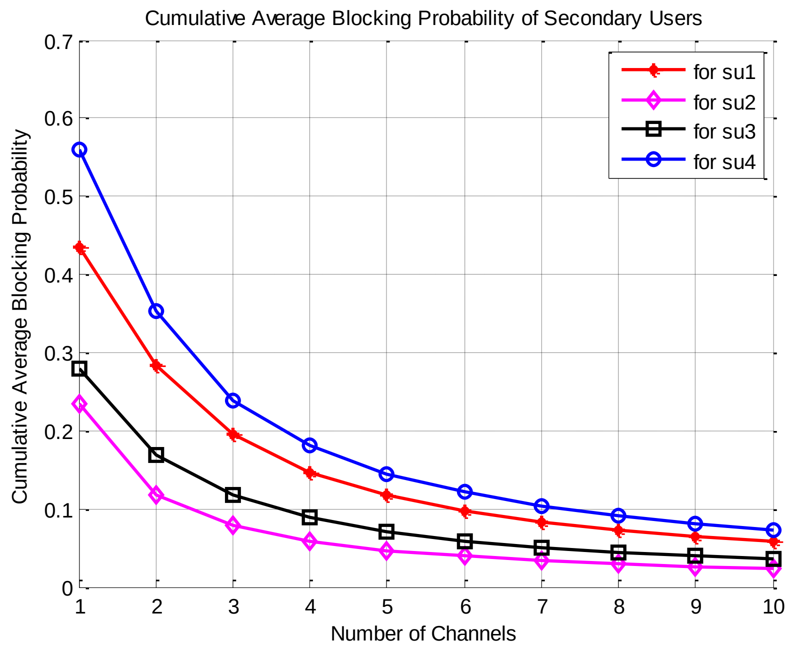

Figure 3.12. Blocking probability of different SUs for 25% PU occupancy and low demand from Sus

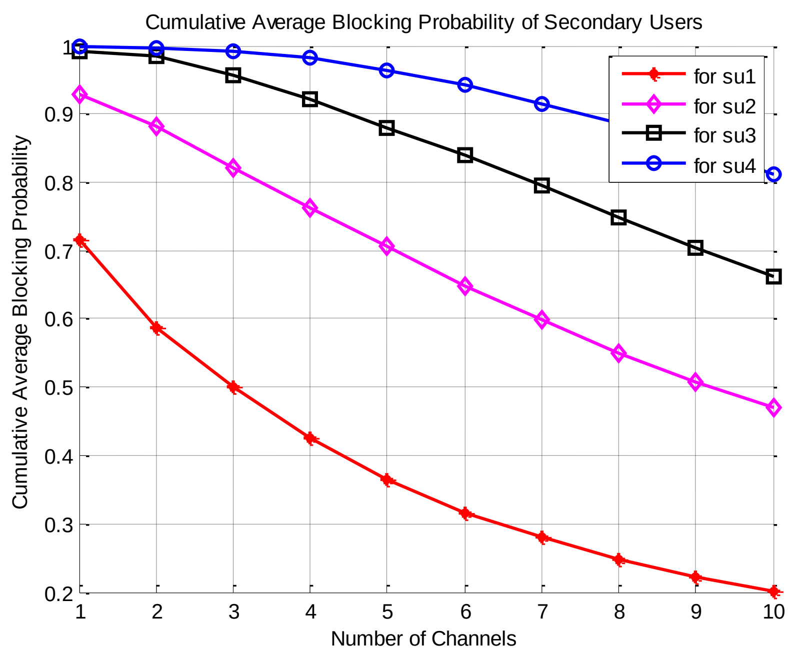

Figure 3.13. Blocking probability of different SUs for 50% PU occupancy and high demand from SUs

The blocking probabilities of all SU types are shown in Figure 3.12 for low demand and 25% PU occupancy. Similarly, the corresponding blocking probabilities for high demand and 50% PU occupancy are shown in Figure 3.13. From Figures 3.12 and 3.13, it is observed that blocking of SU1s is least and blocking of SU4s is highest. Blocking of SU2s and SU3s fall in between. So, the real-time applications can choose SU1 category, that is they have to opt for maximum bid value.

In addition to that, the blocking probabilities of 25% PU occupancy and low demand case are far less compared to 50% PU occupancy and high demand scenario. It is due to reduced supply due to 50% channel occupancy by PUs and increased demand from SUs.

3.8. Summary

In the auction mechanism of SUs two novel range bound bidding auction techniques are proposed to support the real-time users. SU traffic is classified into four types based on time bounds to accomplish their tasks. In both techniques maximum bid value is predefined and the remaining three bid values are derived as sub-multiples of the maximum bid. Based on the urgency level, SUs can opt for bidding. In the first technique, if there is at least one channel left, then discounts are offered to all channel winning SUs. In the second technique, after channel allotment is done, all channel winning SUs need to pay the same amount which is the least bid value among channel winners.

The proposed auction mechanisms of ‘Range-bound bidding’ are compared with existing GSP mechanism. The advantages of proposed range bound bidding auction methods are- alleviating the confusion about the bidding amounts at which channels can be acquired, avoiding multiple bids by secondary users and channel allocation based on demand and supply. Price- linked priority based channel allocations and bandwidth optimization are enabled through these mechanisms.