Project: An Auction Based Channel Allocation in Multi-hop Networks

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Abstract

With the rapid development of cognitive radio network, demand for spectrum accessing increases dramatically. However, if selfish users access the spectrum arbitrarily, it may lead to serious interference problem of the network. In this project, there is a base station in the network which can regular the spectrum accessing of cognitive radio devices. It uses a new kind of auction framework called VARYVER to efficiently allocate the channel. We prove that this VARYVER auction can not only ensure the truthfulness of the auction but also consider the fairness among cognitive radio nodes in our multi-hop network. In addition, some algorithms other than Greedy Algorithm have been proposed to help the base station to wisely allocate the channel. These algorithms perform well in maximizing the throughput of our multi-hop network. Finally, our simulation results compare the performance of these algorithms and show how these algorithms can improve the throughput of the network or better ensure the fairness among cognitive radio nodes. This will help the base station to determine which algorithm to use to allocate the channel under different circumstances.

1 INTRODUCTION

Nowadays, the problem of channel allocation is a hot topic because the scarce of the available frequency spectrum hampers the rapid development of wireless communication technology. Multi-hop network has been studied a lot since it is the only feasible mean of communication in some environment such as large sensor network. It is really close to reality since in large space, source nodes are always far away from their destination. In multi-hop network, if selfish nodes arbitrarily access the channel, serious interference problem will be caused. As a result, an efficient method to efficiently allocate the channel is needed to help all nodes in the network use the channel wisely and let most data arrive its destination.

Auctions are among the best-known market based allocation mechanisms in that it perceived fairness and allocation efficiency. Market-driven spectrum auction can dramatically improve the opportunities for the wireless network to get spectrum. Therefore, we would like to design an auction framework to efficiently allocate the channel.

However, the market manipulation challenges the efficiency and the fairness of the auction game.To avoid this challenge, a truthful spectrum auction is required.

In the former papers, many classical auction systems are made truthful, including the sealed-bid secondary-price [15], k-position [11] [13] and VCG auctions [2] [9]. Unfortunately, spectrum auction is unlike other conventional auction. Spectrum is reusable among bidders subjecting to the spatial interference constraints. Because interference is only a local effect, bidders close to each others cannot use the same spectrum frequency simultaneously but well-separated bidders can. It has been proved in [9] that VCG auction loses its truthfulness. We can also prove secondary-price or k-position auction also lose its truthfulness in our model. Zhou *et al.* [3] uses truthful auction for spectrum trade but its auction cannot deal with the channel allocation problem in multi-hop network. Jain *et al.* [4] has proved that the channel allocation problem in multi-hop network is an NP-hard problem but it doesn't present efficient algorithms to solve the problem. In [1], Kao *et al.* discusses bandwidth allocation in Ad Hoc network based on an auction framework, but it do not discuss efficient algorithms to allocate the channel.

In our project, we consider the channel allocation problem in a multi-hop network. We propose a new kind of auction called **VARYVER**. It is an auction derived from **VERITAS** auction which is introduced in [3]. Our **VARYVER** auction has following two key features. First, Our **VARYVER** auction can ensure the truthfulness of all bidders' bids. Second, Our **VARYVER** auction can ensure the fairness among cognitive radio nodes in our network which means most nodes in our network can get opportunities to use the channel to transmit their data. On the other hand, in channel allocation problem, the algorithm of choosing proper nodes to transmit is also important because an efficient channel allocation algorithm will benefit both bidders and the auctioneer. However, previous works such as [3] [17] always use Greedy Algorithm to solve the channel allocation problem to achieve computationally efficient because it has been proved in [4] that the problem of finding an optimal spectrum allocation is an NP-hard problem. Since our model are set in a multi-hop network which is different from former papers, we introduce several algorithms to solve this problem and compare their performances to find out which algorithm is suitable for our network.

To best of our knowledge, our project has following three contributions:

- We propose the **VARYVER** auction to our multi-hop network. By using the mechanism in the **VARYVER** auction, we can prove that every rational bidder will bid his true value because no bidder can improve its revenue by cheating in the auction.

- We introduce a new mechanism for auctioneer to allocate the channel

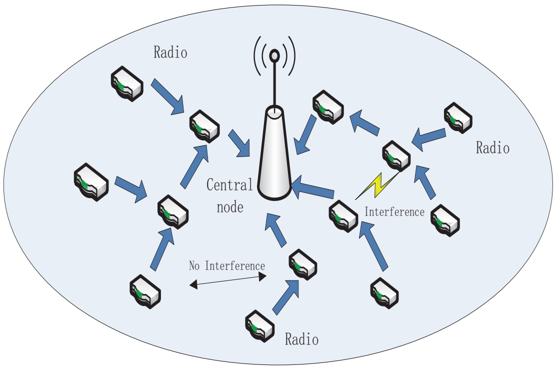

Figure 1: The multi-hop network

which will not only ensure the revenue of bidders with high bid but also consider the fairness in the network. In our network, only the data transmitted to the Central node can be counted as network throughput. In the other word, our **VARYVER** auction is well suited for multi-hop network because it can avoid data congestion of the network to some extent.

- We introduce some algorithms to solve this channel allocation problem to get higher network throughput or better ensure the fairness in our network and our simulation results show which algorithm performs best in our network under different circumstances.

The rest of paper is organized as follows. Section II introduces the system model and all the assumptions throughout our project in detail, and Section III introduces the mechanism of the new **VARYVER** auction and proves its truthfulness. Then, several algorithms for the problem are shown in Section IV. Finally, simulation results and conclusion lays in Section V and Section VI.

2 SYSTEM MODEL

In this section, we describe our system model and assumptions used throughout the project in detail.

We consider a multi-hop network as our model. There is only one Central node which is the destination of all data and only the data being transmitted to the Central node can be counted as the throughput of our network. Every node has the same interference radius R which means when the node use the channel to transmit data, other nodes lay in the interference zone of this node cannot use the channel simultaneously. To simplify our problem, we only discuss the multi-hop network with only one channel.

We call the data transmitter and the data receiver as a data link. We can easily find that in data transmitter's interference zone, no other nodes can receive data while data transmitter is transmitting. In addition, in data receiver's interference zone, no other nodes can transmit data at the same time. Therefore, we can regard the data-link as a whole which has its own interference zone and we only need to consider the interference between data-links. To further clarify our problem, one node in our model can only transmit its data to one other node and the topological structure of our model is stationary. As a result, we can use the transit node in a data-link to represent this data-link, and it is transit nodes submit their bids in the auction. The data-link's interference zone can also to be regarded as the transit node's interference zone.

Since we model our problem in a multi-hop network, we calculate the throughput of our network in a long period of time. This period of time can be split into several parts. At the beginning of each part, each node who attends the auction bids their valuation of the channel. Then, the auctioneer chooses the winners of the auction game, and allocates the channel. After that, the nodes who get the admission to use the channel transmit the data in a time slot. At the end of this time, auctioneer charges the nodes and redistributes the revenue of the network.

Moreover, we need to find out efficient algorithms to help the auctioneer to allocate the channel wisely according to the bids of all the nodes. These algorithms may help to improve the throughput of the network or better ensure the fairness among cognitive nodes in our network.

Then, we introduce a set of notations used to define a truthful spectrum game and efficient algorithms we propose in this project.

Channel bid (b_i) - It represents the bid submitted by bidder i. The set of bids submitted by bidders in the auction game can be represented as $B = (b_1, b_2, ..., b_n)$.

True value for the channel (v_i) - It represents the true value of the bidder i for the channel. In our model, this v_i is known to the bidder i itself only. In addition, it is a general sense that the v is directly related to the capacity of the nodes using this channel. We further assume that every node has the same relation between its capacity and its value.

Charging price (p_i) - This is the price that auctioneer charges the winning bidders. This price might be different among winners of the auction game and must not exceed the price bidder bids.

The length of data buffer (l_i) - Every node has its own length of data buffer. The data buffer of a node is consist of the data generated at the beginning of each time slot and the data it receives from other nodes. Furthermore, we assume that every node has the same data generating rate, and auctioneer knows the initial length of data buffer of every node.

The total weight of vertex set ($w(S)$) - w_i is the weight of vertex i (or node i), and we define $w(S) = \sum_{i \in S} w_i$.

3 VARYVER AUCTION DESIGN

In this section, we will describe the mechanism of our **VARYVER** auction. Moreover, the truthfulness and fairness of this game will also be proved.

3.1 VARYVER Main Algorithm

We start from the main algorithm of the **VARYVER** designed for fairness and truthfulness.

First, unlike other normal auction games, we choose the winners of the game base on both the length of data buffer of node i - l_i and the bids of node i - b_i instead of just base on the bids of nodes. Specifically, we use $w_i = b_i \cdot l_i$ as the weight of the node to determine the winners of the **VARYVER** auction game.

THEOREM 1. *By using $W = (w_1, w_2, ..., w_n)$ to determine the winners of the **VARYVER** auction, we ensure the fairness of the network.*

Proof. In every time slot, there is always some data coming to nodes. If nodes which haven't got the opportunity to use the channel for long time, they must have long length of data buffer, which will result in the increasing w of these nodes. Therefore, the nodes which may not get a high value from the channel will also get some opportunities to win the auction or use the channel.

Moreover, the fairness of the multi-hop network is extremely important because only when most nodes get opportunities to transmit data, most data can be successfully transmitted to the destination. Otherwise, it may cause serious congestion of the network. Therefore, if the fairness of the network is ensured, the congestion of the network will be solved.

Then, we propose the **VARYVER** allocation algorithm:

Algorithm 1 VARYVER-winners selection.

```
input: the new weight of every node W;
sort W in descending order W';
while W' ≠ ϕ
i=top(W');
if there is no node in i's interference zone wins the auction then
let i be a winner of the auction;
end if;
W' = W' \ {w_i};
end while;
```

Finally, we introduce the charging mechanism of our **VARYVER** which ensures the truthfulness of the auction game. We charge the winning bidders the boundary bid x_i which means if i bids higher than x_i, it will win the auction game, otherwise it will lose. The boundary bid x_i can be calculated as follow:

$$x_i = \frac{w_m}{l_i}, \tag{1}$$

w_m is the highest weight belonging to a node which lays in the interference zone of i. It can be proved that this x_i will not be higher than b_i which is bid by i. Moreover, [3] has already proved that w_m can be easily got by auctioneer.

To clarify our problem, the winners of the auction game do not always get the opportunity to use the channel. This depends on what algorithm the auctioneer chooses to allocate the channel. In next section, we will propose several algorithms and discuss their performance in our network. This will help the auctioneer to wisely allocate the channel. On the other hand, it is the winner of the auction game who gets revenue from the auction, and someone who gets the opportunity to use the channel may also get revenue from the auction.

We charge node i which uses the channel the critical bid y_i which is defined as $y_i = \frac{w_m}{l_i}$. In this case, w_m is the highest weight belonging to a node m which lays in the interference zone of i but do not interfere with the other nodes which are selected to use the channel. In the other word, if node i didn't exist, node m will be selected to use the channel instead. Then, we redistribute these revenue of the network $R = \sum y_i$ by allocate these revenue to the winners of our **VARYVER** auction. Winner i gets the revenue as follow:

$$r_i = min(b_i - x_i, \frac{(b_i - x_i)R}{\sum_{j \in D} b_j - x_j}), \tag{2}$$

$D = (d_1, d_2...)$ denotes the winners of the auction.

It is obvious that $r_i \geq 0$, $\sum_{i \in D} r_i \leq R$ and $y_i \geq 0$. Therefore, the auctioneer and the nodes who use the channel or win the auction can all get revenue from the auction. In addition, nodes which do not win the auction are willing to cooperate to improve the performance of the network.

3.2 VARYVER Truthfulness

From [3] [5], we can easily get the conclusion that neither Secondary Price Auctions nor VCG-Style Spectrum Auctions can achieve our goal as a truthful auction game. The examples present in [3] are great counter-examples to prove the possible untruthfulness which may occur in above two auctions.

Now, we propose some lemmas and theorems which will prove the main result of this section - truthfulness.

THEOREM 2. *The auctioneer can get the true information about* $L = (l_1, l_2, ..., l_n)$

Proof. As we assume above, the auctioneer knows the initial length of data buffer in every node. In addition, the auctioneer knows which node get the opportunity to transmit their data in every time slot. Furthermore, the value of the channel is directly associated with the capacity one can get from the channel. As the assumption we stated above, every node has the same valuation for a same channel capacity. Therefore, the auctioneer can use the recurrence relations to calculate the length of data buffer of each node in every time slot.

THEOREM 3. *The **VARYVER** spectrum auction is truthful.*

Proof. Since we can get the true information about $L = (l_1, l_2, ..., l_n)$, we only need to consider the truthfulness of bidders bids. We discuss the scenario that $b_i < v_i$ and $b_i > v_i$ respectively.

When $b_i < v_i$, there are following cases:

Case 1: i loses the auction when it bids b_i, but when it bids v_i, it win the auction. As we state above, if someone wins the auction, his revenue must be larger than zero. As a result, bidders bid b_i in this case will get lower revenue.

Case 2: i wins the auction when it bids b_i, but when it bids v_i, it will lose. According to the mechanism of our auction, it is impossible to occur.

Case 3: No matter i bids b_i or v_i, it will win or lose the auction. Therefore, there is no discrepancy between b_i and v_i.

Case 4: i gets chance to use the channel when it bids v_i, when it bids b_i, it won't get this chance. According to our charging mechanism, i's revenue is larger than zero and bidders bid b_i in this case will get lower revenue.

Case 5: i gets chance to use the channel when it bids b_i, when it bids v_i, it won't get this chance. According to our charging mechanism, it is impossible to occur.

When $b_i > v_i$, (we won't discuss cases which are impossible to occur)

Case 1: i wins the auction when it bids b_i, but when it bids v_i, it will lose. As the equation (1) and (2) shown above, in this case, it will result in $r_i < 0$ which is certainly worse than i losing the auction.

Case 2: No matter i bids b_i or v_i, it will win or lose the auction. Therefore, there is no discrepancy between b_i and v_i.

Case 3: i gets chance to use the channel when it bids b_i, when it bids v_i, it won't get this chance. According to our charging mechanism, it will result in $y_i > v_i$ which means i's revenue is smaller than zero.

As we shown above, no bidders cannot improve its revenue by cheating in the auction.

4 Algorithms for channel allocation

This section presents our solutions to efficiently allocate the channel, given the location of each node and the weight of each node. We use three different algorithms to solve the problem, two of which are based on weighted vertex cover problem (WVCP), LP Algorithm and N-LP Algorithm. The third one is Greedy Algorithm. And the comparison among these algorithms we take will be shown by the simulation results.

4.1 Algorithms based on WVCP

The solution is shown in two steps. First, we construct a new graph $G = (V, E)$ according to the relationship between every pair of data-link and transform the problem into an equivalent weighted vertex cover problem. Second, we use two approximate algorithms to solve this problem.

4.1.1 Construction of G

First, for each data-link, we add a vertex i to the graph G and let the weight of i be the weight of the corresponding data-link. Next, for every two data-link i, j, if i interferes with j, we add an edge (i, j) to G. Now the construction of G has been finished. The problem is to choose a subset $S_0 \in V$ so that for every two vertices $i, j \in S_0$, the edge $(i, j) \notin E$, and our purpose is to maximize the total weight of vertex set S - $w(S_0)$.

4.1.2 Transformation to WVCP

Weighted vertex cover problem is described as follow:

Given an undirected graph $G = (V, E)$ and weights $w_i \geq 0, \forall i \in V$.

We call a set S is a vertex cover of G when for every $(i, j) \in E$ we have either $i \in E$ or $j \in E$.

The purpose of the problem is to find a vertex cover S which minimizes $w(S)$.

In our problem mentioned above, the total weight of all vertices is a certain value, so looking for a set S_0 which has a maximum sum of weight is equivalent to looking for a set $S = V - S_0$ which has a minimum sum of weight. And the requirement of S is that for every $(i, j) \in E$, we have either $i \in S$ or $j \in S$, which means that S is a vertex cover of G. Until now, we have transformed our problem into a WVCP. In next step, we will show how we solve this WVCP.

4.1.3 Two Algorithms to Solve the WVCP

The WVCP is known as an NP-hard problem, so we use two different approximate algorithms to solve this problem in a polynomial time complexity. One approximate algorithm based on linear programming was introduced in [7], denoted as LP Algorithm, and has been proved to have a performance guarantee of 2. Another algorithm not using linear programming, denoted as N-LP Algorithm, was introduced in [2] and has the same performance guarantee. We select these two algorithms to solve the WVCP in our work.

To use LP algorithm, we first formulate the problem as an integer program.

Minimize:

$$\sum_{i \in V} w(i) \cdot x_i,$$

s.t.

$$x_i + x_j \geq 1 \quad (i, j) \in E, \qquad x_i \in \{0, 1\} \quad i \in V, \tag{3}$$

$x_i = 1$ means that the vertex i is chosen into the vertex cover set S, while $x_i = 0$ means that the vertex is not chosen.

Then we use constraints $0 \leq x_i \leq 1$ $\forall i \in V$ to replace the constraints $x_i \in \{0, 1\}$ $\forall i \in V$ so that the new problem is a linear program as follow:

Minimize:

$$\sum_{i \in V} w(i) \cdot x_i,$$

s.t.

$$x_i + x_j \geq 1 \quad (i,j) \in E, \qquad 0 \leq x_i \leq 1 \quad i \in V. \tag{4}$$

Then the LP Algorithm is shown as follows:

Algorithm 2 LP Algorithm.

```
input: G = (V, E);
output: Vertex cover S;
solve the linear program to get an optimal solution x';
set S to be empty;
for each i ∈ V do
if x'_i ≥ 0.5 then
add i to S;
end if;
end for;
return S;
```

The N-LP Algorithm is shown as follows in Algorithm 3.

The given weight of i is w_i, while $VW(i)$ denotes the *residual* weight of i. For edge $(i,j) \in E$, $EW(i,j)$ is the *weight* assigned to edge (i,j). S denotes the set of vertex already selected to be in the cover. J denotes the set of edges not covered.

Algorithm 3 N-LP Algorithm.

```
input: G = (V, E);
output: Vertex cover S;
∀i ∈ V, VW(i) = w_i;
∀(i, j) ∈ E, EW(i, j) = 0;
initiate S = φ, J = E;
while J ≠ φ
select (i, j) ∈ J;
M = min(VW(i), VW(j));
EW(i, j) = M;
if VW(i) = M then
k = i; VW(j) = VW(j) − M;
else k = j; VW(i) = VW(i) − M;
end if;
S = S ∪ k;
∀m: (k, m) ∈ E, J = J − (k, m);
end while;
```

4.2 Greedy Algorithm

In Greedy Algorithm, each time we choose node who has the biggest weight and deleted the set of nodes interfering with this node. We do this repeatly until there are no nodes can be chosen.

The Greedy Algorithm is shown as follow:

Algorithm 4 Greedy Algorithm.

input: the new weight of every node W;
sort W in descending order W';
while $W' \neq \phi$
i=top(W');
if there is no node in i's interference zone uses the channel simutaneously **then**
let i use the channel;
end if;
$W' = W \setminus \{w_i\}$;
end while;

It is obvious that Greedy Algorithm is the simplest one among these three algorithms. The auctioneer just need to allocate the channel to the winners of the auction.

5 SIMULATION RESULTS

In this section, we perform several experiments to unveil the performance of the algorithms we discuss before. By comparing the performance of these algorithms, we can choose suitable algorithms for our network under different circumstances. First, we explore the sum of weight of nodes we choose in one time slot. Then, we examine the throughput of the network in a period of 3000 time slots. Moreover, the length of buffer of all nodes is revealed. Finally, we discuss the difference and relation among these three figures.

In all of our simulation works, we randomly generate eighty nodes with different value in our multi-hop network. We let every nodes' interference radius equals to its transmission radius. On the one hand, in transit nodes' interference zone, no other node can receive data at the same time. On the other hand, in receiving nodes' interference zone, no other node can transmit data at the same time. As a result, we can build up an interference table of the random topology. In addition, we assume that every node has the same generating rate of data, and this rate is comparable to the value of nodes for the channel. To simplify our simulation works, we let $v_i = C_i \cdot t$ which means the value of the channel for any node i equals to the amount of bits of data it can transmit through the channel in one time slot.

Fig. 2 shows the comparison of the total weight of chosen nodes in one time slot among the three different algorithms. We do the comparison for thirty five times to make our results more general. Then, we use enumeration method to calculate the maximum weight we can get in each time. The ratio of the weight we can get by using our algorithms to the maximum weight is presented in Fig. 2. From this figure, we can find that LP Algorithm perform best in this

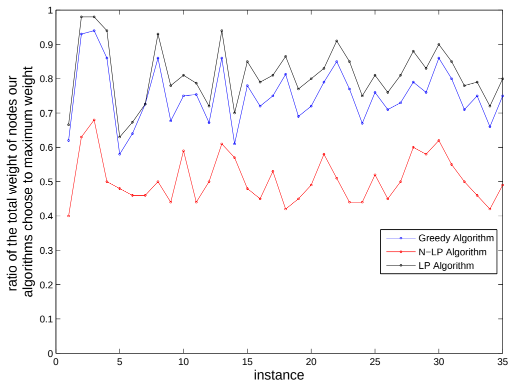

Figure 2: The comparison of the total weight of chosen nodes in one time slot among the three different algorithms

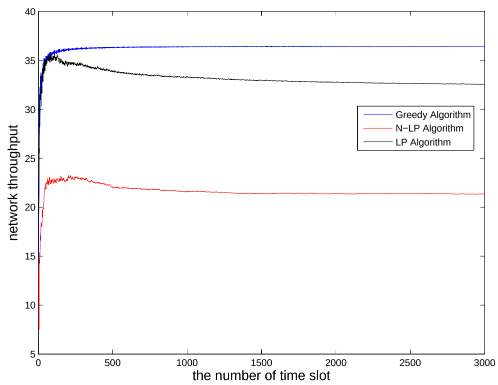

Figure 3: The network throughput in three thousand time slots

experiment, and this algorithm can achieve up to 80 percent of the maximum weight.

In Fig. 3, we run these algorithms for a period of 3000 time slots and examine the throughput of the network. Moreover, after about 300 time slots, the throughput of the network becomes stable. It can be seen that Greedy perform best which means by using the Greedy Algorithm, we can maximize the average amount of data the Central node receives in a time slot.

Fig. 4 presents the buffer status of all nodes in the network in a random time slot. We can find that LP Algorithm and N-LP Algorithm can both ensure the fairness of the network since there is little difference in the length of buffer among all nodes in the same time slot. However, Greedy Algorithm performs

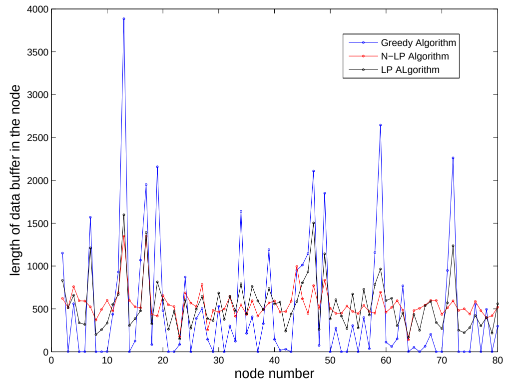

Figure 4: The buffer status of nodes in the network

bad in this aspect, which means that some nodes in the network have a long data buffer and some data congests in these nodes.

Associating the results of Fig. 2 with results of Fig. 3 and Fig. 4, we can conclude the performance of these algorithms in our network. LP Algorithm plays best in maximizing the total weight of the picked nodes in one time slot. However, the Greedy algorithm help our network to get the maximum throughput. Because the weight in our network is defined as $w_i = b_i \cdot l_i = v_i \cdot l_i$, LP Algorithm getting the maximum sum of weight in each time slot doesn't means it can get the maximum throughput in our network. Fig. 4 shows that while using Greedy Algorithm, some nodes are being sacrificed to improve the throughput of the network. Since these nodes do not get an equal chance to use the channel as other nodes, there must be some data congested in these nodes. This is also one of the reason that Greedy Algorithm perform better than LP Algorithm in getting a higher throughput. Finally, we can conclude that when we want to get a higher throughput of the network, we should choose Greedy Algorithm, but when we want to take both fairness and throughput into consideration, LP Algorithm is a better choice.

6 CONCLUSION

In our project, we develop a new kind of auction called **VARYVER** to discuss the channel allocation problem in multi-hop network. The mechanism of this **VARYVER** action not only ensure the truthfulness of every bidders' bids but also consider the fairness among nodes in our network. In addition, we introduce several algorithms to help auctioneer to efficiently solve the channel allocation problem. By comparing the behaviors of these algorithms in simulation results, we find that Greedy Algorithm is better to get a high throughput of the network, while LP Algorithm is a better choice when we consider both the throughput and the fairness among cognitive nodes of the network.

In the future, we would like to extend our problem to multi-channel rather than single channel in our project. In addition, we can also consider a multi-hop network with several Central nodes in it.

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