Interference-aware Channel Allocation Algorithm with Game Theoretic Approach for Cognitive Radio Networks

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***Abstract*—In cognitive radio networks, the Secondary Users (SUs) are allowed to utilize unused portions of the licensed spectrum to enhance the performance and efficiency of the channel resource in networks. However, with the increasing number of wireless devices and users competence for the limited channel resource, the channel allocation problem has become an important issue in the cognitive radio networks. Moreover, the interference in communication has become an important factor that affects the efficiency of transmission in cognitive radio networks. In this paper, we proposed an algorithm with game theoretic approach to solve the problem of channel allocations in cognitive radio networks, based on interference aware information between communication pairs. By game theory, the channel allocations of SUs are proposed by their perceived utilities associated with possible actions of neighboring users. The effectiveness of the communication links is determined by the bandwidth of the available channels to the SUs and the heterogeneous interference range between the communication links. Our proposed algorithm can achieve Nash Equilibrium convergence in the game theory.**

Keywords—Cognitive radio networks, channel allocation, game theory, Nash Equilibrium, co-channel interference

I. INTRODUCTION

With the fast growing of wireless devices, spectrum scarcity becomes an important problem for wireless network applications. However, based on the study in [1], there are imbalanced utilization in real application scenarios, such as a large portion of wireless spectrum is underutilized, while other a few portions of spectrum are heavily used. Cognitive Radio (CR) is an efficient technology to solve the scarcity problem by detecting the spectrum hole and allocating the unused channel to Secondary Users (SUs). CR is defined as an intelligent communication system, which periodically scans the radio spectrum, detects the level of occupancy of the spectrum, so that SUs can use the idle channels to communicate. In CR networks, the SUs scan the radio channels to begin with, and later estimate the co-channel interference between neighbors, which is the interference among nodes that share a common channel. Based on these measurements, the SUs choose available channels for the benefit of the network communication. As long as they do not impose harmful interference on licensed users or Primary Users (PUs), the unlicensed users are able to utilize the unused parts of the licensed channel efficiently.

Although SUs are allowed to use the spectrum not occupied by PUs, they are required to leave the channel as soon as a PU appears and pursue the spectrum. Thus as the PU arrives, the SUs need to select another channel. The process of choosing a new channel involves channel information sensing, decision making and switching to a new channel. This process will take a significant amount of time before the communication between SUs begins. Nowadays, a lot of research about CR networks tries to reduce the communication setup time between the base stations and SUs to improve the network throughput. This research can be divided into several categories, such as channel state sensing, channel allocation, cognitive relay transmission, power control, co-channel interference, and so on.

In this paper, we focus on the channel allocation method and try to improve the throughput in the cognitive radio networks. We assume that the cognitive users can acquire the information of available channel bandwidth (BW) and the co-channels interference between neighboring users, by channel overhearing or control channel. Based on the information, we propose a game theoretic method to solve the channel allocation problem with co-channel interference. The channel allocation of each SU is based on its perceived utility associated with each possible action of neighboring users. According to the calculation of utility function, SUs may change their selected channels to get better utility. As a result, we can obtain the better solution of BW allocation by the game theory approach. Moreover, we prove that our channel allocation method based on game theory can achieve Nash Equilibrium (NE). In an NE, no user can improve its utility any more by changing its strategy unilaterally. Although our channel allocation approach is not a global optimal solution, with the simulation results, the network throughput of our proposed algorithm is close to optimal solution.

The rest of the paper is organized as follows. Section II describes related work about channel allocation in cognitive radio networks. Our proposed algorithm is presented in Section III. The simulations and evaluation are shown in Section IV, and finally, Section V concludes this paper.

II. RELATED WORK

As a research topic, channel allocation in cognitive radio networks has been actively discussed by the research community. In this section, we will review some channel allocation schemes.

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There are many issues we can discuss in the channel allocation that includes the interval of PUs appearance, the interference of transmission power, the channel state information, and the channel sensing method. In [2], the authors studied optimal BW allocation of SUs for throughput efficiency. The optimal BW allocation derived the context of dynamic PU activity, where authors considered both independent and correlated PU channel scenarios while accounting for the effect of channel switch overhead. In [3], the authors proposed a greedy heuristic channel assignment algorithm for finding connected, low interference topologies by utilizing multiple channels. In [4], the authors proposed a novel channel allocation scheme for the QoE (Quality of Experience)-driven multimedia transmission over the cognitive radio networks. A new analytic Markov model combining the On/Off model of PUs and the service queuing model were derived to evaluate the system performance.

In [5-7], the authors assumed that the available channels have the same channel quality. In [5], the authors studied power and channel allocation for cooperative relay in a three-node cognitive radio network, where a cognitive radio relay channel consists of three kind of channels: direct channel, dual-hop channel, and relay channel. In order to maximize the overall end-to-end throughput, the authors used some relay channels that have available spectrum bands at all three cognitive radio nodes to assist the transmission in direct or dual-hop channels. In [6], the authors presented the optimal brute-force search algorithm to solve the corresponding nonlinear integer optimization and proposed two low-complexity channel assignment algorithms. Then the authors designed a distributed medium access control protocol for access contention resolution. In [7], the authors proposed channel assignment algorithms based on the calculation of the appearance probability of the PUs and the unused probability of the available channels.

In [8-9], the authors focused on the channel allocation problem by assuming that different channels have different available BWs. In [8], the authors investigated the performance of cross layer antenna allocation and channel selection approaches for cognitive radio networks. Then, the authors presented the average data rate objection function for multi-band cognitive radio network that accounts for interference constrains at the PUs. In [9], the authors sort the channel quality from high to low and choose the highest quality channel to be used for SUs. In none of the above research, the co-channel interference is considered in their system models or algorithms.

In recent years, some researchers solved the channel allocation problem based on the concept of game theory [10-11]. In [10], in order to avoid co-channel interference, the authors proposed a utility function and formulated as a potential game, to improve the efficiency of channel resource allocation. In their method, the authors calculated the interference of transmission power and the user link gain for the utility function. However, the effective BW of each channel is not considered in the utility function. In [11], the authors proposed a model of channel allocation based on formulating the channel allocation game as a strategic game. According to the proposed model, the authors introduced interference model into the network and designed the utility function. The utility function is calculated by the number of co-channel interferences. The weight of co-channel interference is assumed the same on all channels. However, according to the distance between SUs or the channel transmission power, users have different weights of co-channel interference. If the distance of two communication pairs is close enough, their co-channel interference is high.

III. Interference-aware Channel Allocation Algorithm

We assume that different channels have different available BWs for SUs and there exists heterogeneous co-channel interference between neighboring SUs. Therefore, a SU selecting a lower channel BW with small co-channel interference may be better than selecting a higher BW with large co-channel interference. So the weight of co-channel interference between SUs is also an important role to be considered in channel allocation problem.

A. System Model

We consider a cognitive radio network consisting of a set of N transmitting-receiving pairs of nodes. Each communication pair is denoted as L_u. We assume different pairs of nodes can send packets at different transmission power, so that the interference range of different communication pairs will be different. In Fig.1, we show an example of a cognitive network including seven communication pairs from L_a to L_g, T is the transmitter and will be in charge of the channel selection and R is the receiver. In this system model, we assume that there are K available channels for transmission with different channel BW and $K<N$.

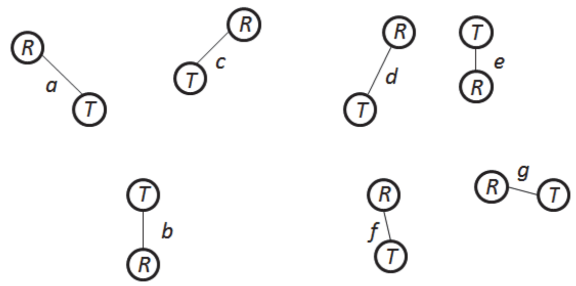
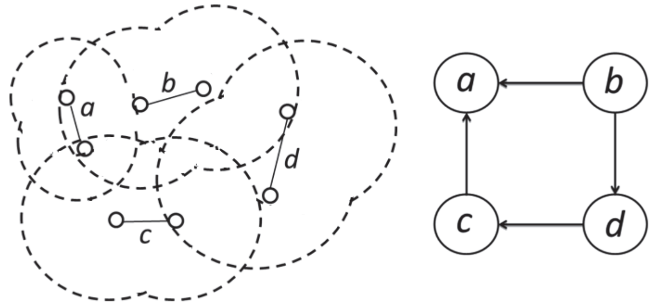


Fig. 1 A snapshot of a cognitive network topology

Due to the transmission interferences, most nodes interfere with each other if they share the same channels. We also assume that the effect of interference among nodes is decided by their location and distances. For example, if the distance of the communication pair L_u and L_v is close enough, they will interfere with each other, when they share a common channel. The co-channel interference will reduce the original BW of the interfered channel. Another example in Fig.2, a dashed circle indicates the interference range of a pair of communication link. Any link u will be interfered by link v if u is within v's interference range and they share the same channel. We assume the interference range of the communication is asymmetric, as the transmission power of nodes is different. As shown in Fig. 2(a), L_a is interfered by L_c but L_c is not interfered by L_a. Therefore, we can describe the co-channel interference by a conflict graph [2]. Conflict graph is widely used to carry out the design of channel allocation algorithm [3]. The conflict graph is shown in Fig. 2(b), there is an edge from L_c to L_a if L_a is interfered by L_c and we use an arrow from c to a to show their relationship.

Notice that, the edges in Fig. 2, are directed as per the asymmetry of the interference range.

We assume that, each communication pair has different BWs of the available channels. If the original BW of channel 1 is 400 Mbit/sec and communication link L_a selects channel 1. The effective BW of channel for L_a is less than 400Mbit/sec if there is co-channel interference. We will show how to calculate the effective BW of each communication link based on game theory in the next sub-section.



(a) (b)

Fig. 2.The network includes 4 pairs of communication links L={a, b, c, d} and the corresponding conflict graph

B. Game Theory Formulation

Game theory is a discipline aimed at modeling scenarios where individual decision-maker has to choose specific actions that have mutual or possibly conflicting consequences. A game consists of a set $P = \{P_1,\ P_2, \ldots, P_n\}$ of players, non-empty strategy sets for each player $P_i \in P$, and a utility set for each player. Let s_i denote the strategy selected by P_i. In our channel allocation model, the communication pairs in the cognitive network can be treated as players, the channels they selected are their actions (strategies) and their preferences are associated with the quality of the channels and the co-channel interference of their neighbors. Then, we will calculate the utility (payoff) value of each player P_i by the utility function U_i. We will give the integrated output and input parameters in detail below.

First, we design our allocation problem as a normal form game in mathematical formulations. The channel allocation game is defined as $\Pi = \{ N\ ,\ \{S_i\}_{i\in N}\ ,\ \{U_i\}_{i\in N}\}$, where N is a finite set of players (decision makers who select channels to transmit), and S_i is the set of all possible strategies associated with player P_i. We define $U : S \rightarrow R$ as the set of utility functions associated with the players and their strategies, where R is the output utility value of the utility function. In our system model, the available communication bandwidth can be reflected by utilities of players, and the allocated channel of each communication pair can be reflected by their strategies. For each player P_i in the game, the utility function $U_i$is a function of s_i, the strategy selected by player P_i, and of the current strategies of its opponents in a set S_{-i}. The utility of player P_i in the channel allocation problem can be thought as the feedback received by player P_i from the network depending on the channel selection in s_i, and the other players' selections in S_{-i}. So the utility function will affect the player's strategy and the total outcome of the game.

In order to determine a final result of the game in finite time, there must exist a convergence time for the channel allocation algorithm, after which no player would deviate anymore, such as NE.

Definition: For arbitrary player $P_i \in N$, A strategy profile for the players, $S = [s_1, s_2, \ldots, s_N]$, is a NE if and only if

$$U_i(s_i\ , S_{-i}) \geq U_i(s_i'\ , S_{-i}), s_i \text{ and } s_i' \in S_i. \quad (1)$$

Equation (1) means that any player P_i, changing its strategy from s_i to s_i', will not get higher output utility value of the utility function. Therefore, we will propose a utility function to satisfy the NE. The proposed utility function U considers channel BWand co-channel interference of neighbor. In Table 1, we will explain the important notations of the utility function$U$.

Table 1 Summary of important notations

Notation	Description
$\boldsymbol{U_i(s_i\ , S_{-i})}$	The utility function of player P_i with strategy s_i and the strategies for other players are $S_{-i} = \{s_j \mid 1<j \neq i<N\}$.
$\boldsymbol{Qs_i}$	The channel BW of the current player P_i selects strategy s_i.
$\boldsymbol{Vs_i = (v_1, v_2, \ldots, v_k)}$	The current channel selection vector of player P_i under strategy s_i. For the jth element in Vs_i, v_j= 1 if player P_i selects channel j, otherwise v_j =0.
$\boldsymbol{Cs_i = (c_1, c_2, \ldots, c_k)}$	The current selected channel BW vector of player P_i under strategy s_i. For the jth element in the vector Cs_i, c_j is the BW of channel j if player P_i selects channel j, otherwise c_j = 0.
$\boldsymbol{W_{ji}}$	The weight of co-channel interference from player P_j to player P_i if P_i and P_j select the same channel.
$\boldsymbol{P_j \in N^-(P_i)}$	The set of neighbors that will co-channel interfere to player P_i
$\boldsymbol{P_j \in N^+(P_i)}$	The set of neighbors which will be co-channel interfered by player P_i

The utility of player P_i is evaluated by the channel BW obtained from the selected channel minus the co-channel BW interfered by its neighbors, who select the same channel with P_i and the co-channel BW of the neighbors interfered by player P_i. We introduce two subtractions in the utility function including the co-channel BW interfered by neighbors who select the same channel and the co-channel BW of the neighbors interfered by current player, so that the two interferences can be considered to achieve balance in games. According to the above definitions, each player P_i will use utility function (2) to calculate its utility on a strategy s_i.

$$U_i(s_i, S_{-i}) = Qs_i - \sum_{P_j \in N^-(P_i)} Cs_i \cdot Vs_j \times W_{ji} - \sum_{P_j \in N^+(P_i)} Vs_i \cdot Cs_j \times W_{ij}. \quad (2)$$

We give an example as shown in Table 2. We assume each transmitter of the communication links will exchange BW of its available channels and the weights of co-channel interference, through the control channel periodically. There are four players and four available channels. And the distance of communication links are calculated by the Signal to Noise Ratio (SNR) of the packets.

Table 2 Available BW of channels 1, 2, 3, and 4 for players P_a, P_b, P_c, and P_d

	1	2	3	4
P_a	400	300	200	100
P_b	300	200	100	400
P_c	400	200	200	100
P_d	200	400	100	300

Our assumption of the conflict graph of four communication links is shown in Fig. 2(b). For example, if player P_a selects channel 1, then Qs_a = 400, Vs_a is (1, 0, 0, 0) and Cs_a = (400, 0, 0, 0). In Fig. 2, we have $P_j \in N^-(P_a) = \{P_b, P_c\}$ and $P_j \in N^+(P_a) = \{\}$. In other words, P_a is interfered by P_b and P_c but P_a interfere none. The symbol of W_{ji} is the weight of co-channel interference that P_i is interfered by P_j; as the distance between P_i and P_j is nearer, higher will be the interference. The effective BW of a channel depends on the original channel BW and the weight of co-channel interferences among neighbors. For example, if we set the W_{ba} and W_{ca} is 0.4 and 0.5, respectively and assume players P_b and P_c selects channel 1 and channel 2, respectively. Then, Vs_b is (1,0,0,0) and Vs_c is (0,1,0,0). So the utility of player P_a with current strategy is $U_a(s_a, S_{-a}) = Qs_a - Cs_a \cdot Vs_b \times W_{ba} - Cs_a \cdot Vs_c \times W_{ca}$=400–(400,0,0,0)·(1,0,0,0)×0.4–(400,0,0,0)·(0,1,0,0)×0.5. According to this utility function, we can get the current utility for P_a as 240.

In order to obtain a good convergence properties for the allocation algorithm, we have to ensure that the utility function U possess certain mathematical properties. As a result, we will show that the channel allocation game is an ordinal potential game which has NE solution. The ordinal potential function models the information, which associates with the improvement paths of a game instead of the utility of the game. The potential function is able to reflect the global profit in a network. The characteristic for an ordinal potential game is the existence of an ordinal potential function that reflects any unilateral change in the utility function of any player. A potential function $\Phi: S \rightarrow R$ is an ordinal potential function of every player $P_i \in N$ if the condition in equation (3) is satisfied, where player P_i selects strategy s_i, and its opponents select strategies in S_{-i}.

$$U_i(s_i, S_{-i}) - U_i(s_i', S_{-i}) > 0 \Leftrightarrow \Phi(s_i, S_{-i}) - \Phi(s_i', S_{-i}) > 0. \quad (3)$$

We define the ordinal potential function Φ as equation (4) and prove equation (3) is hold in Theorem 1. Assume S $=\{s_1, s_2, \dots s_N\}$

$$\Phi(S) = \sum_{i=1}^{N} \Big(Qs_i - (\sum_{P_j \in N^-(P_i)} Cs_i \cdot Vs_j \times W_{ji}\Big). \quad (4)$$

In quotation (4), the potential function Φ(S) contains the BW of the current channel selections and co-channel interference multiplied by C_i, V_i, and W_{ji} of every player P_i.

Theorem 1 *The channel allocation game is an ordinal potential game with ordinal potential function* Φ.

Proof: We need to prove that Φ is an ordinal potential function in channel allocation game which satisfies equation (3). Assuming, that the player P_i changes its strategy from s_i to s_i'. The difference of utility function is:

$$U_i(s_i, S_{-i}) - U_i(s_i', S_{-i}) = (Qs_i - Qs_i') - \Big(\sum_{P_j \in N^-(P_i)} Cs_i \cdot Vs_j \times W_{ji} + \sum_{P_j \in N^+(P_i)} Vs_i \cdot Cs_j \times W_{ij} - \sum_{P_j \in N^-(P_i)} Cs_i' \cdot Vs_j \times W_{ji} - \sum_{P_j \in N^+(P_i)} Vs_i' \cdot Cs_j \times W_{ij}\Big). \quad (5)$$

Let $\sum_{P_j \in N^-(P_i)} Cs_i \cdot Vs_j \times W_{ji} = A_i$;

$\sum_{P_j \in N^+(P_i)} Vs_i \cdot Cs_j \times W_{ij} = B_i$;

$\sum_{P_j \in N^-(P_i)} Cs_i' \cdot Vs_j \times W_{ji} = A_i'$;

$\sum_{P_j \in N^+(P_i)} Vs_i' \cdot Cs_j \times W_{ij} = B_i'$.

So, $U_i(s_i, S_{-i}) - U_i(s_i', S_{-i}) = (Qs_i - Qs_i') - (A_i + B_i - A_i' - B_i')$

Since only the player P_i changes his strategy from s_i to s_i', the difference between potential functions of $\Phi(s_i, S_{-i})$ and $\Phi(s_i', S_{-i})$ is equal to $(Qs_i - Qs_i')$– $(A + B) + (A' + B')$, where A (A') is the summation of the BW, which is a co-channel interference to player P_i with strategy s_i (s_i') and B (B') represents the summation of BW, which is co-channel interfered by player P_i with strategy s_i (s'_i).

So, $\Phi(s_i, S_{-i}) - \Phi(s_i', S_{-i})$
$= (Qs_i - Qs_i') - (A + B - A' - B')$
$= (Qs_i - Qs_i') - (A_i + B_i - A_i' - B_i')$
$= U_i(s_i, S_{-i}) - U_i(s_i', S_{-i})$.

Thus, our proposed channel allocation game has NE solution.

C. Channel Allocation Algorithm

In this subsection, we will propose our allocation algorithm including the method to choose the strategy and execute it to achieve NE. Since the channel allocation game is an ordinal potential game, any improvement path can lead to an NE. In the game theory approach, we need to array the sequential actions of the players. Each player takes its best to respond the strategy upon its turn.

Let $b_i(s_i)$ denote the utility for player P_i with strategy s_i. In order to let players take actions sequentially, we use the counter T_i, which is randomly generated from 1 to n, where n is the number of players in this network. The purpose of the counter T_i is treated as a waiting time of player P_i sending packet to inform its channel selection. If the sending packets collide due to the same counter value generated by more than one player, our channel algorithm only spends more execution time in order to achieve NE.

At the beginning of the algorithm, each player P_i randomly picks one channel as s_i. Counter T_i is decremented by one in each time slot. When T_i counts to 0, the player P_i will select a new strategy s_i' which has the best utility $U_i(s_i, S_{-i})$. If the new selected strategy is same as the current strategy, value of *cha* is increased by 1. The use of *cha* is to avoid early termination before the channel allocation game converges to an NE. If the new selected strategy is different from the current strategy, we will reset the value of *cha* to 0 and broadcast the new selected strategy s_i' to its neighboring players. The value of *cha* indicates how many times the current strategy has been the best response strategy consecutively. When the value of *cha* reaches n, it means every player will not change their strategies and the algorithm will be terminated. The following is our proposed allocation algorithm.

Algorithm: Channel Allocation Algorithm for each player P_i

Randomly selects one channel as s_i;
Randomly generate a counter T_i from 1 to n, set *cha* = 0;
while true **do**
  if $T_i = 0$ then
    find a strategy s_i' such that $b_i(s_i')$ has the best utility for all strategies;
    if $s_i' = s_i$ **then**
      if $cha = n$ **then break**;
      else $cha = cha + 1$;
    else $\{s_i = s_i'$; $cha = 0$; Broadcast s_i' to its neighboring players; Randomly generate a counter T_i from 1 to $n\}$;
  else $T_i = T_i - 1$;
end

Now, we explain the algorithm procedure with a simple example. We assume that, there are four available channels in a cognitive network and player P_a's original strategy is channel 1. When the value of counter T_a is counted to 0, player P_a has to calculate current best strategy. So player P_a will calculate utility (feedback) for each channel $U_a(1), U_a(2), U_a(3)$, and $U_a(4)$; after calculating the four channel utilities, the player P_a will choose the highest utility strategy as the best one. If player P_a's best response strategy is different from the original strategy. The player P_a, will replace the current strategy with the new selected one and reset the value of *cha* to 0. On the other hand, if player P_a's best response is the same with original strategy, then player P_a will keep original strategy and increase the value of *cha* by 1. When the value of *cha* reaches n, we can notice that the algorithm achieved NE and the algorithm is terminated.

IV. Simulation Results

In simulations, pair of communication links are randomly generated in 200m×200m square. The number of available channels is varied from 4 to 10. The number of communication links is varied from 10 to 30 and the interference range of the communication links are different. A random channel assignment is selected as the initial assignment, and for a fair comparison, all simulations start from the same initial channel allocation. We compare the results of our proposed algorithm with the following algorithms: (1) **Greedy Algorithm**: In this algorithm, each player chooses the current highest BW channel as its strategy. (2) **Interference Algorithm** [11]: By the algorithm, the authors use the concept of the game theory to solve channel allocation problem. But the utility function is calculated only by the number of neighbor's co-channel interference. (3) **RIMCA** [9]: It focuses on decreasing co-channel interference. The algorithm also has a particular function to calculate the effect of co-channel interference, where node's transmission power and distance is an important factor in the function. According to the output value of the utility function, each node will select the smallest value. (4) **Optimal Algorithm**: It calculates all strategies utility value for all players, and chooses the best total available BW.

In Fig. 3, we try to change the interference density from low to high. In the high interference density, a player will interfere with 10 other players. So, the total available BW in the network will decrease as the interference increases. The total available BW of our algorithm is near to the optimal algorithm, and is in an average 20% better than interference algorithm and RIMCA, and outperforms greedy algorithm by 50% in an average.

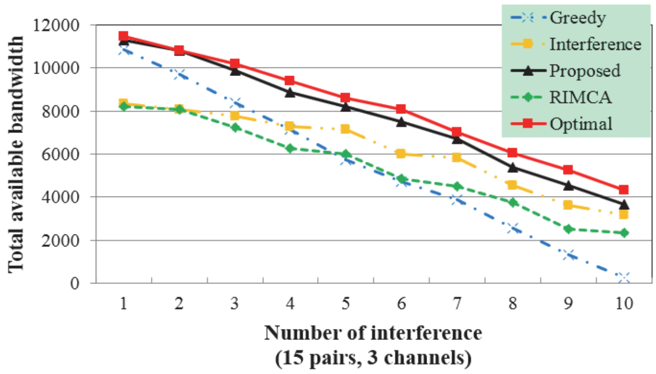


Fig. 3 The total available BW by the number of interferences

In Fig. 4, we evaluate the network throughput by different number of communication links. Though, the available BW in our algorithm decreases as the communication links increase, our proposed algorithm always gets the better performance than other algorithms. The result of the optimal algorithm cannot be calculated once the number of players increases to 15 because its execution time becomes unreasonable long with the exponential time complexity. The total available BW of our algorithm is 15% better than previous algorithms in average, as the number of communication links is smaller than 25; and is 40% better than previous works when the number of the communication links is greater than or equal to 25 in average.

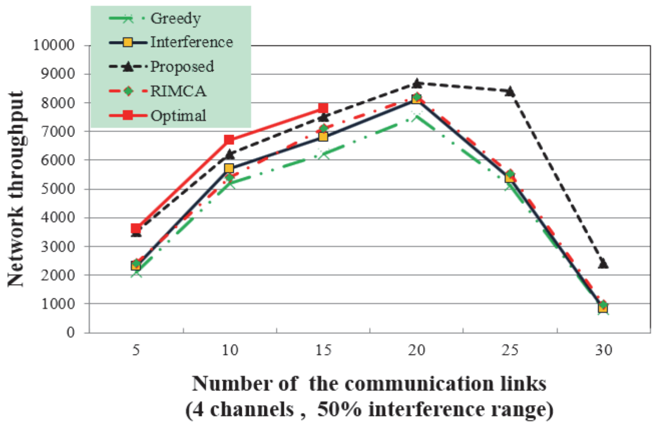


Fig. 4 The total available BW by communication links

In Fig. 5, we assume that the available channel BW has four scenarios: (1) all channels have the same BW=400Mbits/sec,

(2) the channels *BW* varies from 300 Mbits/sec to 500 Mbits/sec, implied by ±100 Mbits/sec in the figure,(3) the channels *BW* varies from 200 Mbits/sec to 600 Mbits/sec, implied by ±200Mbits/sec, and (4) the channels *BW* varies from100 Mbits/sec to 700 Mbits/sec, implied by ±300Mbits/sec. The simulation results show that, our proposed algorithm has better performance than other algorithms in all four scenarios. It can be briefly summarized that our proposed algorithm with game theory concept has good potential to solve the channel allocation problem.

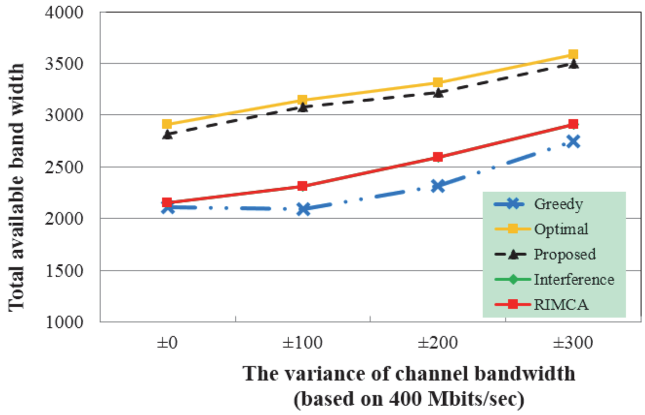


Fig.5 The total available BW by the variance of channel BW

In Fig. 6, we compare our proposed algorithm with other algorithms by the execution time when the number of communication links is varied. It is shown that the execution time for the calculation of our proposed algorithm has no difference with other algorithms, excluding optimal algorithm. Also, we notice that the optimal algorithm cannot achieve an acceptable result in reasonable time period.

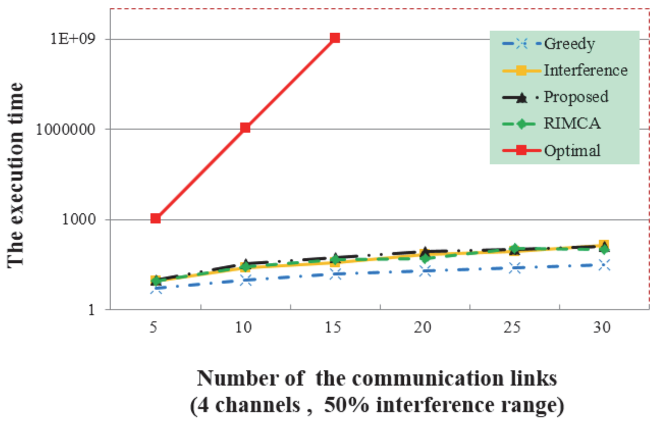


Fig. 6 The execution time versus the number of communication links

V. CONCLUSIONS

In cognitive networks, co-channel interference is an important factor which decreases the total available BW. Moreover, co-channel interferences during the communication affect the transmission of cognitive communication, when there are SUs which share common channels. In this paper, we proposed an interference-aware channel allocation algorithm for cognitive networks. In our algorithm, the effective BW of the communication links is determined by the utility function, which is considered by the BW of the available channels and the heterogeneous interference ranges between communication links. We prove that our proposed allocation algorithm converge to NE. Simulation results show that the average performance in total available BW is 20% better than previous work and close to the optimal algorithm in reasonable time period. Moreover, in the high interference cognitive networks, the total available BW is 40% better than the previous work.

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