Game-Theoretic Channel Allocation in Cognitive Radio Networks

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ABSTRACT

Cognitive radio networks provide dynamic spectrum access techniques to support the increase in spectrum demand. In particular, the spectrum sharing among primary and secondary users can improve spectrum utilization in unused spectrum by primary users. In this paper, we propose a novel game theoretic channel allocation framework to maximize channel utilization in cognitive radio networks. We degisn the utility function based on the co-channel interference among primary and secondary users. In addition, we embed the property of the adjacent channel intererence to consider real wireless environment. The results show that the utility function converges quickly to Nash equilibrium and achieves channel gain by up to 25 dB compared to initial assignment.

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1. INTRODUCTION

An allocation policy of existing static frequency resources is able to provide a service that assigns a specific spectrum band during the long time in a wide area to a licensed user. However, this approach not only does not satisfy the needs of the rapidly increasing frequency resources, but also degrades the efficiency of spectrum utilization [1]. In order to dramatically increase the utilization efficiency of the distributed spectrum resources that is not used or rarely occupied, it has been promoted a lot of research of cognitive radio networks based on dynamic spectrum access technology. Cognitive radio is a technique that makes it possible to share the spectrum opportunities between a primary user and a secondary user. A secondary user discovers a white space that is not utilized by a primary user with spectrum sensing, spectrum decision, and spectrum sharing techniques, thereby improving the spectrum effiency [2-5]. In this case, a spectrum allocation method of a secondary user affects a major impact on the overall performance of the cognitive radio network.

Recently, several clever schemes employing a game-theoretic framework were proposed to share efficiently distributed spectrum bands [6-8]. A game-theoretic framework is a tool, which can provide a useful resource allocation algorithm by designing a concrete utility function, so as to optimize a distributed spectrum allocation. M. Felegyhazi [6] has proposed a game-theoretic approach that takes into account the same channel interference from the point of view of a single hop to manage the channel allocation in a typical wireless network. Transmitter and possible transmission data rate (Data rate) is would be determined by defining a couple of recipients as a player participating in the game depending on the number of players sharing the radio channel . Accordingly , each player makes the competition game to maximize the data rate that can he achieved. L. Gao [7] follows the framework of the game theoretic approach of M. Felegyhazi and extends it to multi-hop environment to demonstrate the existence of Nash Equilibrium. L. Gao devised various algorithms to find and satisfy the conditions that can reach Nash Equilibrium. In addition, it proposed a method to allocate a channel considering additionally the concept of a relay node that transmits data in an intermediate structure between the sender and the receiver. In addition, N. Nie [8] defines a utilization function using signal-to-interference and noise ratio due to co-channel interference and suggests a game in which players compete for optimal channel conditions. The author analyzed the characteristics of the distributed adaptive channel allocation scheme of wireless cognitive networks with a game theoretical framework.

In the above-mentioned papers [6-8], they proposed a game theoretical channel allocation method considering only co-channel interference. However, according to the experiment results related to the wireless channel environment, it is mentioned that interference occurring when using different channels also affects wireless communication [9]. Therefore, even if wireless devices use different channels, neighboring channels suffer from diverse interferences when the nodes exist within a transmission range.

In this paper, we propose a novel game-theoretic channel allocation framework which considers both co-channel and adjacent channel interferences. We devise an efficient utilization function of potential game with various behaviours of a primary user and a secondary user. Experimental results show that players are able to reach Nash Equilibrium in a short period of time, and interference of secondary users is reduced.

The rest of this paper proceeds as follows. Section 2 introduces the system model of cognitive radio networks. We then describe the proposed channel allocation framework in Section 3. Section 4 evaluates the proposed scheme. Finally, Section 5 concludes the paper.

2. SYSTEM MODEL

Figure 1 shows the model of cognitive radio networks used in this paper. It is assumed that there are N pairs of secondary sender and receiver and are uniformly distributed in a particular area. It is also assumed that secondary users are fixed and can move slower than the time to reach Nash Equilibrium. In addition, there is one pair of primary user and the channel information for the primary user is known by the secondary user through the primary user information database [3]. In this case, the transmission range of the primary user is large enough for all secondary users to hear, and it is assumed that the available channel set of all secondary users is the same. There are a total of C transmittable channels, and it is assumed that C< N.

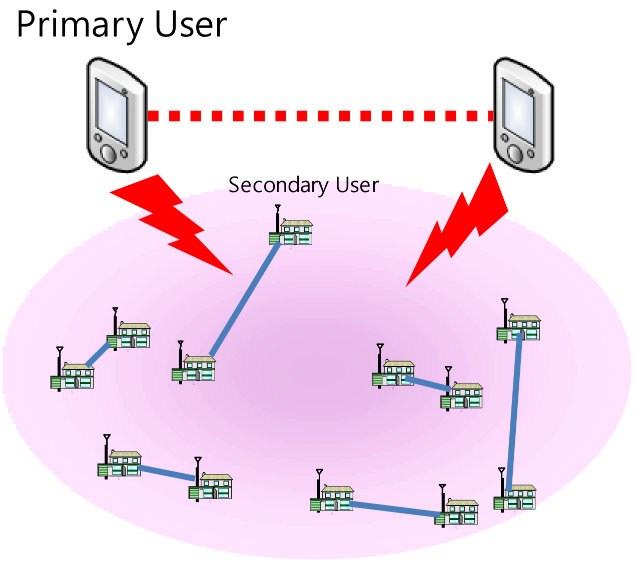


Figure 1. Cognitive Radio Network Moddel

The signal-to-noise and interference ratio of the secondary user player i is given by Equations (1).

$$SINR(i,c_i) = \frac{P_i G(i,i)}{\sum_{j\neq i, j=1}^{N} (\alpha_{|c_i - c_j|} P_j G(j,i)) + n_0} \tag{1}$$

$$where\ \alpha_0 = 1,\ \alpha_{m>M_{aci}} = 0,\ 0 < \alpha_m < 1,\ \alpha_1 > \alpha_2 .... > \alpha_{M_{aci}}$$

SINR (i, c_i) is the signal-to-noise and interference ratio considering co-channel interference and adjacent channel interference when player i uses channel c_i. P_i denotes the transmission power of the player i, and G(i, j) denotes the link gain when the sender of the player i transmits to the receiver of the player j. In addition, □$|C_i - C_j|$ is the interference level (I-factor [9]), which is the distance between the channel of the player i and the channel of the player j. If the distance between the two players' channels is greater than M_{aci}, they will not affect each other. Interference level may vary depending on the type of wireless network. In case of using the same channel, interference may be affected by a ratio of 1, and a smaller ratio of interference may occur as the distance between used channels increases. The case of 802.11b is introduced in [9]. Noises in a normal channel environment is notated as n_0.

The signal and noise-to-interference ratio of the primary user is given by Equations (2).

$$SINR(pu, c_{pu}) = \frac{P_{pu} G(pu, pu)}{\sum_{j=1}^{N} (\alpha_{|c_{pu} - c_j|} P_j G(j, pu)) + n_0} \tag{2}$$

A primary user is not a player and the channel used by a primary user is assumed to be unavailable to secondary users. Therefore, □ is less than 1 for a primary user and all players. When allocating available channels to secondary users, we design to provide minimal adjacent channel interference to the primary user.

3. GAME-THEORETIC FRAMEWORK

Game theory is a mathematical tool used to analyze interactions in decision making [10]. In this paper, we apply this to model the channel assignment problem in a game theoretical way. The player is the sender / receiver pair of the secondary users of the cognitive radio network, and the action or strategy is the choice of channel to use. And their preference is the quality of the channel.

We model the channel assignment problem as a normal form game represented by □ = {N, $\{S_i\}_{i \in N}$, $\{U_i\}_{i \in N}$}. N means a finite number of players making decisions, and S_i means a set of strategies for player i. We also define U_i as a set of utility functions that represent the player's strategy-based payoff. For all players i in the game, U_i is a function of strategy si selected by player i and strategy profile s_{-i} of all other players except player i. To illustrate the strategic interaction of players in this paper, we first introduce Nash Equilibrium. Nash Equilibrium means that no player can modify his strategy unilaterally to increase his gain. Eventually, it is a steady state in a strategic game.

In strategy game □□ = {N, $\{S_i\}_{i \in N}$, $\{U_i\}_{i \in N}$}, the strategy combination S = (s_1, ..., s_n) satisfying the following property is Nash equilibrium. For all players i=1,…,n,

$$U_i(s_i, s_{-i}) = \max_{s_i'} U_i(s_i', s_{-i})$$

3.1. Utility Function

Channel assignment in the cognitive radio network should minimize interference to a primary user when primary and secondary users use different adjacent channels. In addition, when secondary users use the same channel if you use adjacent channels, you should take a strategy that minimizes mutual interference. Therefore, it is the goal of the game to give the least amount of interference to the primary user and to obtain good channel status for secondary users.

Equations (3) represents a utility function applying the signal-to-noise and interference ratio when the player i selects the channel c_i.

$$\begin{aligned} U_i(c_i, c_{-i}) &= P_i G(i,i) \\ &- \left(\sum_{j \neq i, j=1}^{N} \left(\alpha_{|c_i - c_j|} P_j G(j,i) \right) + \sum_{j \neq i, j=1}^{N} \left(\alpha_{|c_j - c_i|} P_i G(i,j) \right) + \beta \left(\alpha_{|c_i - c_{pu}|} P_i G(i, pu) \right) \right) \end{aligned} \tag{3}$$

P_iG(i, i) represents the reward that player i can obtain, and the parts excluding the reward in Equations (3) represent the cost according to the strategy of player i. The cost of player i is such that all other players except player i are interfered with player i by using the same channel or adjacent channel with player i, the interference of player i with other players by selecting channel c_i, and the degree of interference to the user. In addition, □ is the weight for the interference to the primary user.

3.2. Convergence

In this section, it is shown that a general type strategic game with the utility function proposed above has Nash equilibrium state and consequently reaches Nash equilibrium state. To demonstrate the existence of Nash Equilibrium for a utility function defined on the basis of co-channel and adjacent channel interference, we used a Potential Game [11].

If there exists an exact potential function P: S → R that satisfies the following property, then the game is the exact potential game. For all players i=1,…,n,

$$U_i(s_i,s_{-i})-U_i(s_{i'},s_{-i})=P(s_i,s_{-i})-P(s_{i'},s_{-i}).$$

The proposed game has at least one pure Nash equilibrium state, and if each player updates his decision according to the optimal response technique, it eventually converges to Nash equilibrium state [10]. Given the strategy of all the other players in the previous step, if a particular player i takes s_i as a next step strategy that satisfies the following property, then this is the best response technique. For all strategies s_i,

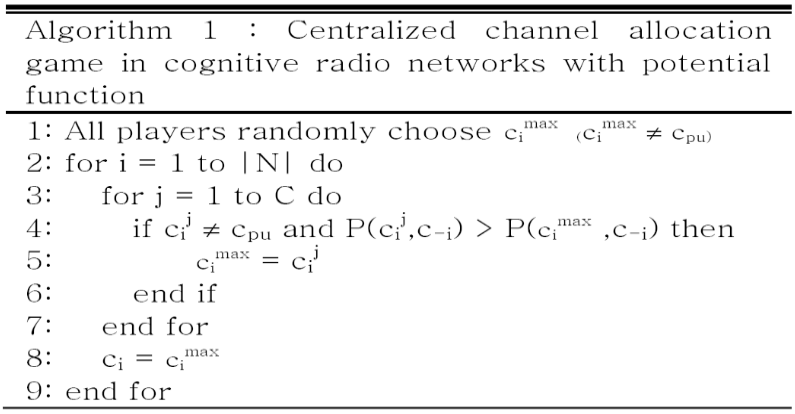
$$s_i^{t+1} = \mathrm{argmax}_{si}\{U_i(s_i,s_{-i}^{t})\}.$$

Equations (4) shows the proposed exact potential function of the utility function. If all the players repeat the process of choosing the appropriate channel by applying the optimal response method according to the potential function, eventually they will reach a situation where they cannot select a higher quality channel when the strategy is changed.

$$P(c_i, c_{-i}) = \sum_{i=1}^{N}\begin{pmatrix} P_iG(i,i) - \frac{1}{2}\sum_{j\neq i, j=1}^{N}\left(\alpha_{|c_i-c_j|}P_jG(j,i)\right) - \frac{1}{2}\sum_{j\neq i, j=1}^{N}\left(\alpha_{|c_j-c_i|}P_iG(i,j)\right) \\ -\beta\left(\alpha_{|c_i-c_{pu}|}P_iG(i,pu)\right) \end{pmatrix} \tag{4}$$

3.3. Channel Allocation Algorithm

This section describes the channel allocation algorithm through the potential game in a coordinated environment. In order to operate a potential game, a central coordinator is required so that each user can participate in the game sequentially. As shown in the Figure 2, each player participates in the game sequentially by the central coordinator. Then, the optimal response scheme is applied to all channels excluding the channel occupied by the primary user, and a channel that can obtain the best channel state in the current state is selected. The algorithm is repeated until the Nash equilibrium state is reached.



Algorithm 1 : Centralized channel allocation game in cognitive radio networks with potential function

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All players randomly choose $c_i^{max}$ ($c_i^{max} \neq c_{pu}$)
for i = 1 to |N| do
    for j = 1 to C do
        if $c_i^j \neq c_{pu}$ and $P(c_i^j, c_{-i}) > P(c_i^{max}, c_{-i})$ then
            $c_i^{max} = c_i^j$
        end if
    end for
    $c_i = c_i^{max}$
end for
```

Figure 2. Centalized Channel Allocation Algorithm

4. PERFORMANCE EVALUATION

As shown in Figure 3, we set 200m x 200m simulation environment in the MATLAB simulator to measure the performance of the channel allocation algorithm. One receiver of the primary user is placed in the center and 10 pairs of secondary users are randomly arranged. Experiments were conducted in the presence of five channels. The primary user is set to use channel 3, and secondary users arbitrarily assigned channels in the initial state and search for the channel with the highest gain while the algorithm was running.

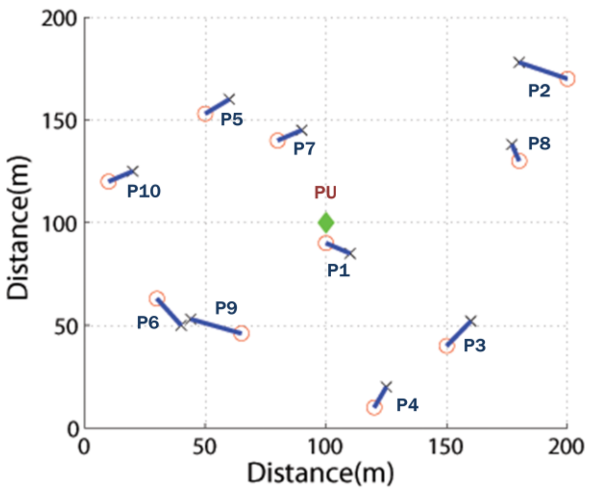

Figure 3. Network Topology

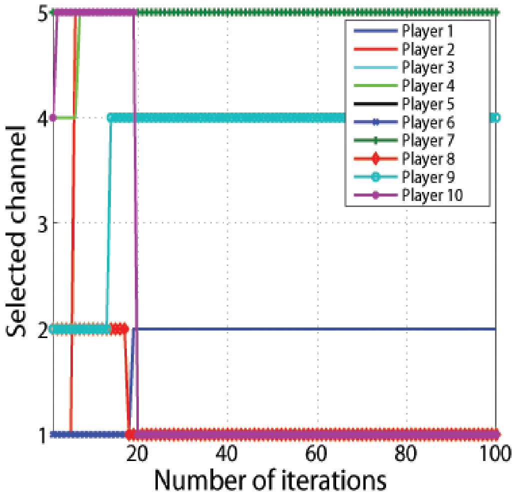

Figure 4. Convergence Result

Figure 4 shows the characteristics of the proposed channel allocation algorithm converging to Nash equilibrium state. It can be seen that the strategy chosen by each player converges to the Nash equilibrium state with fewer than 20 attempts.

Figure 5 shows the signal to interference ratios for each player according to the channel allocation in the initial state and the final channel allocation state when the Nash equilibrium state is reached. This result shows that all players except player 9 and 10 get better channel condition in Nash equilibrium. Particularly, in the case of player 8, the same channel as that of the players existing at a long distance is allocated, and the channel gain of about 25 dB is obtained. In addition, the results of player 9 and 10 are less than 1 dB lower than the initial state. The utility function is designed to reduce the interference to the primary user, so the reduction of the channel gain is partially shown in order to minimize it.

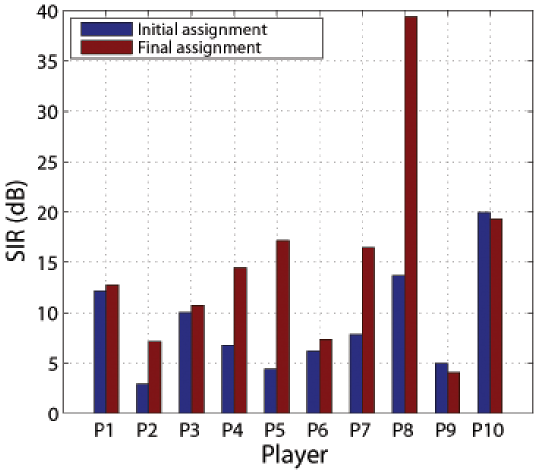

Figure 5. Signal to Interference Ratio Result

5. CONCLUSION

In the traditional wireless network and cognitive radio network, the same channel interference is mainly considered in the channel assignment. However, in this paper, we mainly focus on adjacent channel interference between a primary user and secondary users and propose an efficient channel allocation method considering additional interference. It also proves that potential games can reach Nash equilibrium when unselfish users take a selfish strategy to maximize their own benefits. In the future research, we will propose an algorithm that shows Nash equilibrium and converges to Nash Equilibrium when each node takes a selfish strategy with imperfect information in distributed environment.

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Sangsoon Lim received Ph. D. degree in the School of Computer Science and Engineering from Seoul National University in 2013. Since October 2013, he works as a senior engineer at Software R&D Center, Samsung Electronics. His current research interests are in the area of wireless networks including Wireless LAN, Wireless Sensor Networks, and Wireless Coexistence.