Utility Maximization of Three Phase Spectrum Leasing Scheme Using Stackelberg Game

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***Abstract*—Cognitive Radio (CR) is a promising technology to alleviate spectrum scarcity problem. CR enables a technique called spectrum leasing where the secondary users able to access licensed spectrum bands opportunistically by making monetary payment. A three phase spectrum leasing scheme is considered where primary user allows users in a distributed secondary network to access its licensed band either in underlay or overlay CR transmission manner. A network of multiple users competing for the same idle spectrum ends up causing intolerable interferences to the primary receiver. An improved interference alignment technique is incorporated to reduce the effect of interference at primary receiver while maximizing the SINR at each receiver. Since the idle spectrum of PU is a valuable commodity and many users are competing for the same time, there arises conflict among them in taking decisions. This issue is resolved using game theory. The problem is formulated under Stackelberg game framework and optimal strategies are found out at the equilibrium. Using these optimal strategies, it is found out that the utility of users is improved. Simulations are carried out to study the proposed system and an improvement in performance is observed under various network conditions.**

***Keywords*—Cognitive Radio, Interference Alignment, Spectrum leasing, Stackelberg game.**

I. Introduction

Due to the tremendous increase in wireless data traffic, the availability of usable radio spectrum is quickly depleting. Cognitive radio (CR) is found to be a promising technology for future wireless network, to alleviate scarcity and underutilization of the spectrum. CR users have the ability to detect spatial and temporal spectrum holes, so that it can be used for communication. CR devices perform a kind of operation that is designated as Dynamic Spectrum Access (DSA), where secondary users (SUs) can opportunistically access the white spaces owned by the primary user (PU). A primary network (PN) allows unlicensed or secondary networks (SNs), to temporarily use part of its spectrum in exchange for monetary payments or some type of service provided by the SNs to the spectrum owner, assuring the absence of harmful interference at the primary users (PUs).

Most of the existing spectrum leasing scheme relies on the resource compensation model in which the PUs can obtain performance amelioration aided by SUs in exchange of spectrum bands [1]. In our work, we consider price based spectrum leasing scheme where a primary user allows unlicensed or secondary networks to temporarily use part of its spectrum in exchange for monetary payments. Primary user improves his utility (or revenue or performance), while SUs gain access to spectrum resources, achieving a win-win situation.

Since the idle spectrum of PU is a valuable commodity and many users require it for the same time, there arises a competition among the SUs. The behavior of the competing SUs may be rational and selfish, which give rise to conflict among them. Out of many mathematical tools, Game theory is found to be the most suitable mathematical tool to deal with conflicts among the users. It tries to find an optimal solution, which maximizes every ones need without harming one another. In [2] a cooperative spectrum sharing method is discussed where SU would like to relay PU's traffic for rewards of transmission opportunities. A matching game is used to model the PU-SU interaction, where both PUs and SUs are competing for their own benefits.

In [3] a centralized secondary network is considered where, a spectrum broker continuously monitors its surrounding white spaces and broadcasts the sensed information to all users in its network. Based on the user requirement, spectrum broker would raise a request to PU in order to get access to the idle spectrum. Authors in [4] studied price based spectrum leasing system in a high SNR regime where a distributive SN is considered. Conflict among the users is resolved using Stackelberg game. They try to find out the optimal strategy of PU and SU through numerical derivations.

This work intends to address the issue, when the interference created in the secondary network affects the performance of primary user. Inorder to maintain the quality of service of primary, a significant interference management technique called Interference Alignment (IA) is incorporated while transmission. An improved interference alignment algorithm is used, which makes use of the orthogonality of precoding and post processing filters. Moreover, a network of users attempting for same idle spectrum ends up with a conflict, in taking decisions based on maximizing their utilities. Such conflicts can be well managed through the concepts of game theory. Therefore, we model the spectrum management issue under a non-cooperative game framework. Stackelberg game is used to find out the optimal strategies.

The paper is organized as follows. Section II describes the system model and assumptions. In Section III preliminaries of game theory and problem formulation are detailed. Section IV discusses the results obtained from the simulation study. Section V concludes the paper.

II. SYSTEM MODEL

A MIMO CR network with single primary user (primary transmitter and receiver pair) and multiple secondary users is considered. Primary user has a provision to admit secondary users, in its licensed spectrum in exchange for certain revenue paid in price per bit. Thus spectrum sharing concept is extended to spectrum leasing, where primary user also gains something in return of sharing its spectrum to needy users. The secondary network consists of N CR users (ST and SR pair) where, each of them is equipped with M_t transmit antennas and M_r receive antennas as shown in the Fig.1.

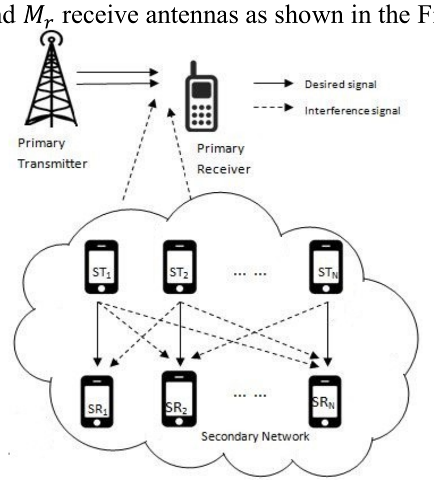

Fig.1. System model for spectrum sharing

It is considered that, PU has some idle spectrum to share for a particular period of time. PU decides on the total time for which the spectrum could be leased. The spectrum leasing scheme is constrained upon the priority of primary transmission and number of secondary users. When there are only a few SUs and PU has got a high rate transmission, then primary user would like to use its entire idle spectrum without sharing it to SUs. If PU has got a low priority transmission, it wishes to maximize its utility by collecting revenue from SUs via leasing. Therefore spectrum leasing comes into picture, only when the primary user concerns more about collecting revenue from SUs than about its own transmissions.

In our study, the entire time of leasing is divided into three phases to incorporate three kinds of transmission viz.

- Primary transmission over time slot T_p defined by a duration αβ
- Underlay transmission over time slot T_u defined by a duration α(1 – β)
- Overlay transmission over time slot T_o defined by a duration (1 – α)

where α and β are the fractional parameters defined for the length of each time slot (i.e. 0 ≤ α ≤ 1 and 0 ≤ β ≤ 1). PU can decide the length of each time slot, based on the utility of both PU and SU.

T_u

Primary Transmission	Underlay CR Transmissio	Overlay CR Transmissions
αβ	α(1 – β)	1 – α

T_p T_o

Fig.2. Three phase spectrum leasing scheme

In phase $\mathrm{T_p}$, primary user transmits its packets at the highest rate possible, using MIMO. In phase$\mathrm{T_u}$, both PU and SU coexist within the available spectrum whereas in phase$\mathrm{T_o}$, PU leases the entire idle spectrum to SUs by ceasing its own transmission. Thus PU increases its utility, by collecting revenue from SUs and SU in turn gets a higher utility, through its own transmission. However, these multiple user transmission results in increased interference in the system. So there lies the importance of having an efficient interference management scheme, to ensure the quality of service of the users.

We consider the scenario where interference signal is comparable to the desired signal. A significant breakthrough technology called Interference Alignment (IA) technique fits well in such cases. Interference Alignment refers to the idea of constructing signals, in such a way that they cast overlapping shadows over one half of the signal space observed by each receiver, where they constitute interference, leaving the other half of the signal space free of interference[5]. It is a linear precoding technique, used to construct transmit signals in such a way that, the interference caused at all the unintended receivers overlaps onto the same subspace, while they still remain separable at the receivers where they are desired.

For an N user secondary network,. The received vector through IA transmission is given by,

$$Y = U_i^H H_{ii} V_i x_i + \sum_{j=1, j\neq i}^{N} U_i^H H_{ij} V_j x_j + U_i^H n_i \qquad (1)$$

where H is the $M_r \times M_t$ channel matrix, x_i is $M_t \times 1$ transmit signal vector and n_i is $M_r \times 1$ noise vector. V_i is $M_t \times d$ precoding vector at the transmitter and U_i is $M_r \times d$ interference suppression filter. Ref. [5] suggests that using IA, every user in a wireless network is able to achieve approximately, one half of the capacity that he could achieve in the absence of all interference. The rate achieved by each user in a high SNR regime is given by,

$$C_i = d_i * log(SNR_i) \qquad (2)$$

where d_i is the capacity pre log factor (degree of freedom), which is defined as the number of interference free Eigen modes (sub channels) available to the i^{th} user[5][6].

III. PROBLEM FORMULATION

The system considers a situation, where the interference generated from the secondary affects PU reception. As the quality of service of primary should not be affected, the interference from the secondary network should be beyond a limit set by PU. Inorder to ensure this condition, Interference Alignment technique is incorporated in transmission. This paper uses an improved version of iterative interference algorithm, which we call as Ortho-IA algorithm for the convenience in referring. Ortho-IA algorithm makes use of duality relationships enabled by the reciprocity of the propagation channel. The algorithm makes use of orthogonality of both precoding and interference suppression matrices; V and U, such that reduction in interference is achieved at the primary receiver whereas maximizing the SINR at each user [8]. The orthogonality ensures the reduction of total leakage interference at the primary receiver, from unintended secondary transmitters.

The Ortho-IA algorithm starts with arbitrary precoding matrix V whose columns are linearly independent unit vectors [5]. The available power at each user is given as

$$\mathbb{E}\left[x_i x_i^H\right] = P_i \tag{3}$$

Then compute the interference covariance matrix:

$$B_k = \sum_{j=1, j\neq k}^{N} \frac{P_i}{d} H_{jk} V_j V_j^H H_{jk}^H \text{ , } k \text{ varies from } 1 \; to \; N. \tag{4}$$

The interference suppression vector at each receiver is given by;

$$u_k = [v_i]\, B_k \tag{5}$$

Orthogonalization of precoding and interference suppression matrices is done through QR decomposition. The orthogonal matrix Q is such that $Q^T Q = 1$. Let r be the rank of upper triangular matrix R. Keeping only r columns of Q that spans the column space of V ensures the desired signal space. This eliminates the chance of interference signal creeping into received signal space. The feasibility of alignment scheme is not affected by the addition of this property. The general feasibility condition is given by [5];

$$U_i^H H_{ii} V_j = 0, \quad \forall\, j \neq i \tag{6}$$

$$\text{rank}(U_i^H H_{ii} V_i) = d_i \;\; \forall\, i \in \{1, \ldots, N\} \tag{7}$$

where, i and j represent the transmitter and receiver of unintended pairs. d_i is the capacity pre-log factor.

A glimpse of Ortho-IA algorithm is given below

1. Starts with an arbitrary precoding vector V_j
2. Compute the interference covariance matrix B_k
3. Calculate interference suppression vector u_k at each receiver.
4. By combining u_k vectors, form interference suppression filter U_i
5. Perform QR decomposition to orthogonalize V_j as well as U_i
6. Find the rank of triangular matrix ,r
7. Keep only r columns of Q that spans the column space of V_j as well as U_i
8. Obtain the modified V_j and U_i
9. Reverse the communication direction and use vector U_i as the precoding matrix of the reciprocal network.
10. Calculate interference covariance matrix in the reciprocal network.
11. Calculate receive combining vector, U_i
12. Do orthogonalization of IA filters
13. Reverse the communication direction and make U_i vector as precoding vector in the original network.
14. Repeat until convergence.

Moreover, in phase T_u and T_o many secondary users compete among themselves to get the idle spectrum form PU. The activities of these competing users may be rational and selfish which drives the primary user to take unfair decisions on the optimal strategies. Since the actions of the secondary users are interdependent, the conflicts arose among them can be well managed under a game theoretic framework.

Game theory has the ability to model individual, independent decision makers, whose actions potentially affect all other decision makers. The solution to such a conflict scenario, can be obtained through Nash equilibrium. A game in basic form composed of three elements; No. of players, Action strategy, Utility function. Mathematically, games can be written as,

$$G = \{N, S_1, S_{2,\ldots.}S_{N,} u_1, u_2, \ldots . u_N\} \tag{8}$$

where N indicates the number of secondary users in the network.

$\{S_1, S_{2,\ldots.}S_{N,}\}$ is the strategy set of N users. S_i is the strategy space of each user and u_i indicates the utility function of user$i$.

The strategy set of PU and SU are given as;

$$S_p = \{\alpha, \beta, N \mid 0 \leq \alpha \leq 1, 0 \leq \beta \leq 1, 3 \leq N \leq N_T\} \tag{9}$$

$$S_{S_i} = \{P_i \mid 0 \leq P_i \leq P_{max}\}, \forall\, i \tag{10}$$

The utility of primary user is defined as the sum of weighted datarate and revenue collected.

$$U_p = w_p f_p(C_p) + \sum_{n=1}^{N} \lambda P_i \tag{11}$$

where, w_p is the weight factor, C_p is the rate of primary, λ is the price per bit. P_i is the transmission power of the secondary. The utility of secondary user is defined as

$$U_{S_i} = w_s f_s(C_{S_i}) - \lambda P_i \tag{12}$$

where w_s is the weight factor for SU, P_i is the transmit power of i^{th} user.

From secondary users' point of view, staying as long as possible in PhaseT_o is desirable since there is only less number of users than in T_u. If in favor of secondary user's decision, PU has decided to make the total time slot as PhaseT_o, and then utility of PU tends to decrease as it could not conduct its own transmission; which is not desirable. Therefore PU tries to divide the time slot in such a way that it is receiving maximum benefit out of leasing. But such decisions may not be desirable for all SUs, and they tend to leave from the system. This will again decrease the revenue of the PU. So there arises need for an optimal decision where the requirement of every entity is fulfilled.

The issue in spectrum allocation is formulated under Stackelberg game framework. Since PU has been given more priority in terms of accessing the spectrum, it is assigned as the leader and secondary users as followers. The objective of the game is to maximize each user's utility function by taking into account the impact of its decision on the other players. Optimal strategies of PU and SU are obtained at Nash equilibrium point where everyone's utility is maximized [7]. The proposed design flow for implementing the three phase spectrum leasing scheme is as shown in Fig. 3.

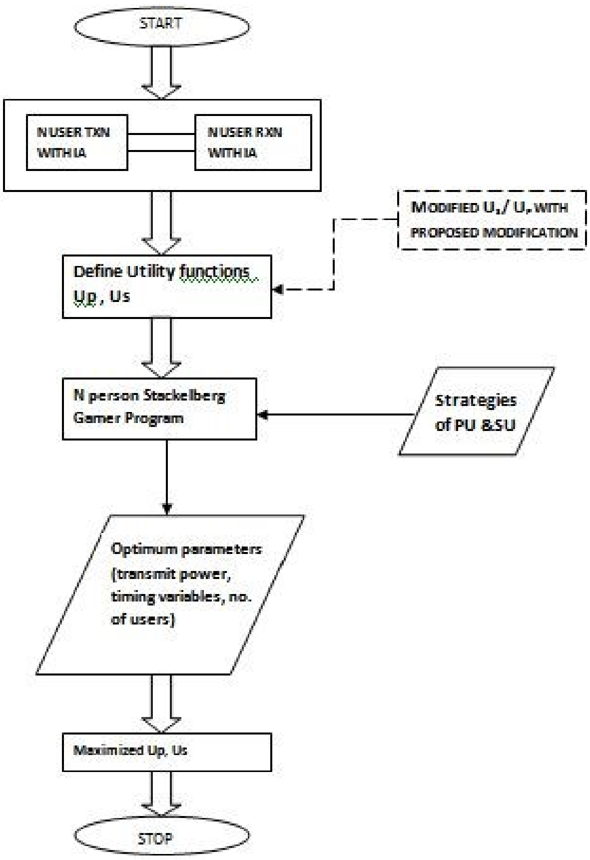

Fig.3. Proposed design flow for the implementation of the system model

IV. SIMULATION RESULTS

Simulation study is carried out in MATLAB R2011a for a CRN with single PU and multiple SUs under different network conditions. We consider an interference limited Gaussian channel where the users are equipped with 4 transmit antennas and 4 receive antennas. The performance of primary user utility is compared for the Ortho-IA algorithm with the min-leakage algorithm given in [4].For simulations, we used noise spectral density, N_0 = 0.1.The unit price per bit power, λ=0.001.The weight factor for secondary, w_s = 0.8. Figure 4 shows the performance of primary utility under Ortho IA algorithm and min.-leakage algorithm for different number of secondary users. The system is simulated with N = 5 and N = 15 no. of secondary users. The convergence rate of Ortho-IA algorithm is around 150 iterations. From the plot it is evident that Ortho-IA algorithm outperforms the algorithm described in [4] even for small number of users. This improvement in utility is because of the fact that, the reduction in interference increases the degree of freedom available to each user. Thus achievable rate (given by (2)) is also increased and henceU_p.

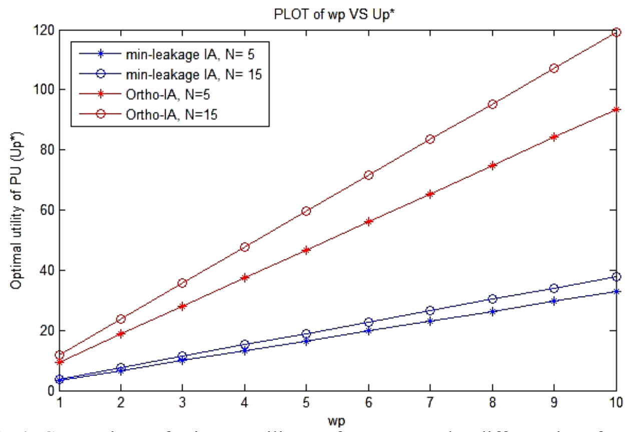

Fig.4. Comparison of primary utility performance under different interference algorithms

Figure 5 shows the performance of primary user utility (U_p^*) against weight factor (w_p) for with and without leasing. The no. of users is selected as 2. The utility of primary user when without leasing in phaseT_p and with leasing in phase T_u is considered. The performance graph shows that even when there is less number of secondary users, leasing out the spectrum is always beneficial.

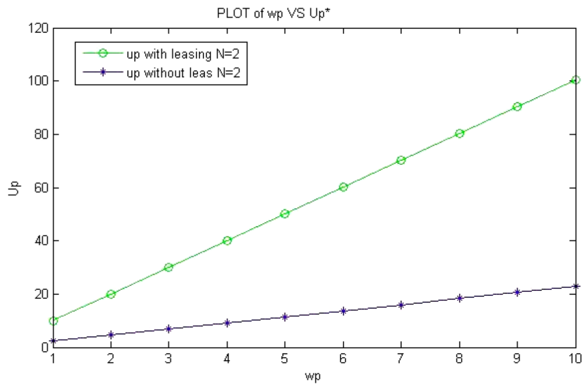

Fig.5. Performance of primary user utility with and without leasing.

V. CONCLUSION

Cognitive Radio is a promising wireless technology to alleviate the spectrum scarcity problem. A price based three phase spectrum leasing scheme is considered where secondary users are allowed to access primary spectrum in exchange of monetary payment. The competition among secondary users results in an increased level of interference at the primary receiver. An improved interference alignment algorithm is incorporated which reduces the total interference at primary receiver by orthogonalizing the IA filters. The issue in spectrum sharing is formulated under Stackelberg game framework. The system model is implemented through a proposed design flow. The equilibrium point gives optimal strategies for both PU and SUs where their utilities are maximized. The proposed system is implemented in Matlab and verified its performance under different network conditions.

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