Abstract—Dynamic spectrum access in cognitive radio (CR) networks is emerging concept to utilize the scarce spectrum in an efficient manner. CR systems will operate in heterogeneous networks in which efficient use of resources will require control of both transmission rate and power for active CRs. In this paper we propose an algorithm for resource allocation in dynamic spectrum access ad-hoc networks where active CR links satisfy their own quality-of-service (QoS) requirements as well as the interference constraints to respect the incumbent primary user-transmissions. We formulate the problem of joint transmission rate and power control for active CR links to maximize their surplus (or net utility) functions using distributed interference compensation as a non-cooperative game. We illustrate the proposed approach with numerical results obtained from simulations.

Index Terms—Cognitive radio, resource allocation, dynamic spectrum sharing

I. INTRODUCTION

The key enabling technique of dynamic spectrum access is cognitive radio (CR) approach [1]–[4] which provides the capability to share the licensed spectrum with incumbent licensed primary users in an opportunistic and dynamic manner. Specifically, the CR users are envisioned to be able to provide high bandwidth and efficient utilization of spectrum via dynamic spectrum access in heterogeneous networks. In order to operate in such heterogeneous networks, secondary CR users should be able to support adaptation of different transmission parameters such as data transmission rates, powers, modulation schemes and so on, based on their operating RF environments [1], [2], [4]. In CR systems for dynamic spectrum sharing, there are two basic approaches as mentioned in [5]. One is spectrum overlay where CRs will have to identify the idle spectrum bands for given time and location, and use those idle bands opportunistically. The other is spectrum underlay where CRs can coexist and transmit simultaneously with primary users without identifying any spectrum opportunities but by ensuring not to interfere the primary transmissions. We also note that in order to realize the full potential of CR concept, the mobile CR nodes should be able to switch between spectrum overlay and underlay approach with suitable transmission parameters.

Next generation (XG) wireless networks will operate in heterogeneous systems in which efficient use of resources will require control of both data transmission rate and power of mobile nodes. The power control in wireless system is performed either to achieve specified target signal-to-interference-plus-noise ratio (SINR) with minimum transmit power that is suitable in voice communications or to achieve higher SINR (than the minimum SINR) in data communications to achieve high data rate [7]. The second approach will be more suitable for future generation of heterogeneous (which includes both data and voice) CR wireless systems. The joint power and SINR allocation problem is more difficult than the problem with target SINR matching since in former problem we need to optimize over entire feasible SINR region which leads the optimization problem to non-convex. One of the good candidates to solve this problem is to maximize the throughput $\sum_i \log_2(1 + \text{SINR}_i)$ or the equivalent surplus function using game theory in distributed manner.

In this paper our goal is to perform combined admission, power and rate control for CR links in spectrum underlay by using game theory for spectrum sharing where CR links choose their best strategies in non-cooperative manner so that the surplus of all secondary CR links is maximized. That is, the transmission rate and power control for active CR links is performed to satisfy their imposed QoS constraints and interference power constraints. Furthermore, the CR links choose optimal rates among feasible ones while satisfying other imposed constraints.

The related previous work includes [8]–[15]. We note that the algorithms can be categorized as centralized ones as in [12] or distributed ones as in [9], [11]. In the centralized algorithm proposed in [12] considers game theoretic approach with a single utility function for the system. In [8], distributed power allocation algorithm is investigated using game theory. However, due to the rigid target SINR constraint the proposed power allocation algorithm is not effective in guaranteeing the QoS of CR links in bad channel conditions. The works in [9], [11], [12] consider the game theoretic approach for joint rate

Combined Admission, Power and Rate Control for Cognitive Radios in Dynamic Spectrum Access Ad-hoc Networks

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and power allocation, which can be applied to the systems where only CR links share the same frequency band with the absence of primary users. However, they do not consider the protection of primary users, and thus the approaches can not be extended to the scenario of the co-existence of primary links and multiple CR links in the same frequency bands. While the works in [13], [15] consider the joint rate and power control for a single CR link (so there is no competition for the available spectrum resource among other CR links) which co-exist with primary users.

The paper is organized as follows: in Section II, we present system model and problem statement. We formulate a game for the problem in Section III and present an algorithm in Section IV. Simulation results of the proposed algorithm are presented in Section V. Finally, we conclude the paper in Section VI.

II. SYSTEM MODEL AND PROBLEM STATEMENT

We consider a wireless system, which uses code division multiple access technology for the communication, with $M$ primary links and $N$ CR links with transmitters and their corresponding receivers as shown in Figure 1. The licensed spectrum bandwidth is considered as $W$ which will be shared dynamically by CR links.

![System model with a primary link and $N$ secondary CR links](image)

We denote the link gain between CR user-transmitter $j$ and CR user-receiver $i$ as $g_{i,j}^{(s)}$, and the link gain between CR transmitter $j$ and primary receiver $i$ pair as $g_{i,j}^{(p)}$. It is worth to note that these gains are inversely proportional to $d_{i,j}^4$, where $d_{i,j}$ is the distance from $j$th transmitter to $i$th receiver and $4$ is the path loss exponent which depends on propagation circumstances. The SINR corresponding to a given CR link $i$ can be written as [16]

$$
\gamma_i = \frac{W}{R_i} \frac{g_{i,i}^{(s)} p_i}{\sum_{j=1, j \neq i}^N g_{i,j}^{(s)} p_j + N_i}, \quad \forall i = 1, \ldots, N
$$

(1)

where $K_i = W/R_i$ is processing gain, and the interference $N_i$ from active primary links is given as

$$
N_i = \sum_{m=1}^M g_{i,m}^{(p)} p_m + n_i, \quad \forall i = 1, \ldots, N
$$

where $n_i$ is additive white Gaussian noise.

In this scenario, all the CR user-transmitters must control their transmit power in order to protect the licensed primary users from the interference created by them. Therefore, without any modification on the primary system, we being motivated by the interference temperature concept [17], [18], consider that the active primary receivers are capable of tolerating a maximum interference power, $p_{m}^{th}$, $\forall m$. The interference level (caused by CR system to primary receiver $m$) higher than $p_{m}^{th}$ should be avoided not to cause harm to primary receiver $m$, that is

$$
\sum_{i=1}^N g_{i,m}^{(p)} p_i \leq p_{m}^{th}, \quad \forall m = 1, \ldots, M
$$

(2)

We consider that the CR users are aware of the total interference caused to the primary users and the the interference threshold $p_{m}^{th}$, $\forall m$. This is possible either by broadcasting the related interference information by primary users or by using extra sensors (with some ranging capability) at CR users to measure it.

The instantaneous SINR of individual active CR links must be greater than or equal to their corresponding minimum target SINR values to guarantee a reliable transmission, that is

$$
\gamma_i \geq \gamma_i^*, \quad \forall i = 1, \ldots, N
$$

(3)

where $\gamma_i^*$, $\forall i$, is the required minimum SINR that is to be satisfied in order to meet the required QoS of CR links. We note that the allowable bit error rate (BER) and minimum target SINR requirements have one-to-one relationship, and they can be used alternatively.

CR links with bad channel conditions cannot satisfy rigid QoS constraint (3). In such cases, CR links will have two options that is either get rejected from the system using one of the method mentioned in [19] or transmit with different rates $R_i$ (i.e., different processing gain, $K_i$) to satisfy their QoS requirements. In latter case, the adapted rate for CR link is determined as $R_i \in \mathbb{R}$, where $\mathbb{R}$ denotes the set of available transmission rates which can be obtained by implementing different modulation schemes, such that it will comply the QoS requirement in equation (3). We note that, in this case, there might be many transmission rates which satisfy the equation (3), therefore to get transmission rate as high as possible, CR link picks up maximum rate among feasible ones.

1The maximum permissible interference level should be supplied either by the regulatory body or the licensed primary operator.
A. Admission Control

When network load is high and/or many CR links compete to get access for the same wireless resources, the admission control for CR links can help to limit the number of CR links in the system as well as in order to have smooth communication for already admitted ones. Moreover, the admission control is needed to enhance the network performance. Admission control not only reject the new connection for CR links in the system as well as in order to have smooth communication for already admitted ones. Moreover, the admission control for CR links can help to limit the number of CR links in the system.

In pre-admission control, CR links (who seek access of licensed spectrum) first check their admissibility before they start their transmission to their corresponding intended receivers. In order to apply pre-admission control in distributed manner, we use the channel gain ratio as

$$\lambda_i = \frac{g_{i,s}^{(p)}}{\max_{k=1,...,M} g_{i,k}^{(p)}}$$

A CR user-transmitter will start its transmission to its intended receiver if the channel gain ratio \(\lambda_i\) is greater than threshold \(\lambda_T\).\(^2\) This criteria ensures that if any one of the primary receiver is too nearer than the intended CR receiver, the CR transmitter will not start its transmission since it will create high interference to the primary user-receivers. We consider that the channel gains are available at CR users with the help of some ranging capability.

In post-admission control, the admission control is applied for already admitted CR links by identifying and rejecting the links who do not satisfy the requirements (e.g., minimum interference constraint in equation (2) and SINR requirement in equation (3)). Substituting \(\gamma_i\) from equation (1) into equation (3), the QoS constraint in equation (3) for CR link \(i\) can be expressed as

$$p_i - \sum_{j=1,j\neq i}^{N} \frac{\gamma_j^{s} g_{j,i}^{(s)}}{K_j g_{j,i}^{(s)}} p_j \geq \frac{\gamma_i^{s} N_i}{g_{i,i}^{(s)}}$$

These constraints for all CR links can be written in matrix or vector form as

$$p - F p \geq u \iff (I_N - F)p \geq u$$

where \(N\) dimensional power vector \(p = [p_1, p_2, \ldots, p_N]^{\top}\), \(N \times M\) dimensional matrix \(F\) and \(N\)-dimensional vector \(u\) are, respectively, given by

$$[F]_{i,j} = \begin{cases} \frac{\gamma_j^{s} g_{j,i}^{(s)}}{K_j g_{j,i}^{(s)}}, & i \neq j, \forall i \text{ and } j \\ 0, & i = j \end{cases}$$

and

$$u = \left[ \frac{\gamma_1^{s} N_1}{g_{1,1}^{(s)}}, \frac{\gamma_2^{s} N_2}{g_{2,2}^{(s)}}, \ldots, \frac{\gamma_N^{s} N_N}{g_{N,N}^{(s)}}, \right]^{\top}$$

We can find a power allocation vector in equation (6) for next time instant \(n+1\) from its current time instant \(n\) value as

$$p(n+1) = F p(n) + u$$

and the optimal transmit power for a CR user-transmitter \(i\) to meet SINR requirement can be obtained from equation (9) as

$$p_i(n+1) = \min\{p^i_{\min}, p_i(n) \frac{\gamma_i^{s}}{\gamma_i(n)}\}$$

where \(p^i_{\min}\) is an allowed upper level of transmit power to \(i\)th CR link.

C. Problem Formulation

Combined admission, power and rate control problem can be written as the following constrained optimization problem:

$$\max \sum_{i=1}^{N} \alpha_i \log_2(1 + \gamma_i)$$

subject to

$$p^i_{\min} \leq p_i \leq p^i_{\max}, \forall i = 1, \ldots, N$$

$$\sum_{i=1}^{N} \alpha_i g_{m,i}^{(p)} p_i \leq p^i_{th}, \forall m = 1, \ldots, M$$

$$\gamma_i \geq \gamma_i^{*}, \forall i = 1, \ldots, N$$

where \(p^i_{\min}\) and \(p^i_{\max}\) are, respectively, allowed minimum and maximum transmit power levels for the CR link \(i\), and \(\alpha_i \in \{0, 1\}\) represents \(i\)th CR link status (inactive or active) that is, \(\alpha_i = 0\) represents that a CR link \(i\) is inactive and \(\alpha_i = 1\) represents that the link \(i\) is active in the system.

Specifically, the optimization problem (11) maximizes the achievable rates of active CR links by allocating feasible powers, and satisfying both QoS and interference constraints.

III. GAME FORMULATION

For distributed scenario, individual user-transmitter simply choose their transmission powers to maximize their corresponding utilities without exchanging any information to others, and we can model the system as a non-cooperative game. Formally, a game consists of three elements as

$$G = \{N, \{P_i\}_{i \in N}, \{u_i(.)\}_{i \in N}\}$$

where

- \(N = \{1, \ldots, N\}\) are players which are active CR links,
strategies of individual players are their transmission powers, and each player picks up its transmit power from the strategy set \( P_i = \{ p_i | p_i \in [p_i^{\min}, p_i^{\max}] \} \), \( i \), if this feasible power does not satisfy SINR requirement of the player \( i \), the player has to transmit with different transmission rate \( R_i \in \mathbb{R} \) to satisfy the requirement, and 

- \( u_i(\cdot) : \mathcal{P}_i \rightarrow (0, \infty) \) is the utility/payoff function\(^3\). That is, the CR user-transmitter maps the strategy space \( \mathcal{P} = \mathcal{P}_1 \times \ldots \times \mathcal{P}_N \), and chooses the feasible power and rate.

We also define complete power profile of all CR links as \( \mathbf{p} \) with the given link \( i \)'s power \( p_i \) and with power profile of its opponents \( \mathbf{p}_{-i} = (p_1, \ldots, p_{i-1}, p_{i+1}, \ldots, P_N) \), so that we can write complete power profile of the system in terms of \( P - i \) and \( \mathbf{p}_{-i} \) as \( \mathbf{p} = \{ p_i, \mathbf{p}_{-i} \} \). Once the power is allocated but the QoS requirement is not satisfied, the CR link has to transmit with different rate among the feasible ones in order to satisfy its SINR requirement.

**A. Utility, Pricing and Surplus Functions**

**Utility Function:**
In this paper, we use the logarithmic utility function which is proportional to its achievable rate (i.e., \( \log_2(1 + \gamma_i) \)), that is 

\[
u_i(\gamma_i) = u_i(\gamma_i(p_i, \mathbf{p}_{-i})) = \theta_i \log_2(1 + \gamma_i), \quad \text{[bits/mission]} \tag{13}\]

where \( \theta_i \) is link \( i \)'s weight with \( \sum_{i=1}^{N} \theta_i = 1 \) to maintain fairness and \( \log_2(1 + \gamma_i) \) is link \( i \)'s achievable rate. Therefore, the process of maximizing the utility function of a link eventually maximizes its rate.

**Pricing Function:**
When the allocated power for CR user-transmitter \( i \) violates the interference limit (2), the pricing function is used to decrease its utility function as a penalty. If link \( i \) does not violate the interference level at primary receivers, it has nothing to pay. Formally, we define a pricing function as

\[
c_i(p_i) = \max \left\{ 0, \frac{\beta}{M} \left( \sum_{m=1}^{M} g_{m,i} p_i - \sum_{m=1}^{M} \omega_m^i p_m \right) \right\} \tag{14}\]

where

\[
\omega_m^i = \frac{g_{m,i} (p)}{\sum_{i=1}^{N} g_{m,i} (p)}
\]

is the weighted coefficient, and \( \beta \) is environmental friendly factor. The price value in equation (14) is the penalty of violating the interference constraints (2).

**Surplus Function:**
The net utility/benefit, which is surplus, function for joint rate and power control can be expressed as

\[
s_i(p_i) = u_i(\gamma_i) - c_i(p_i) \tag{15}\]

That is, the surplus \( s_i(p_i) \) of a link \( i \) is the difference between its utility and its price due to the interference it generates in the system to primary user-receivers, and the surplus will be maximized when the reliable communication occurs. We consider that if the instantaneous SINR is greater than or equal to the minimum SINR, there will be reliable communication, and the power allocation is performed according to (10). Once again, it is important to mention that the link’s utility or surplus function is strictly increasing with \( p_i \) for fixed \( \mathbf{p}_{-i} \) (power of other links), and there will be no penalty for high transmission power as long as \( p_i \) is feasible (i.e., \( p_i^{\min} \leq p_i \leq p_i^{\max} \)) and there is no violation of the interference constraint. Furthermore, the interference constraint in equation (2) is compensated by the price function in \( s_i(p_i) \). Therefore, the optimization problem (11) can be written as the following constrained optimization problem:

\[
\max \sum_{i=1}^{N} \alpha_i s_i(p_i) \tag{16}\]

subject to

\[
\begin{align*}
p_i^{\min} & \leq p_i \leq p_i^{\max} \\
\gamma_i & \geq \gamma_i^{\ast} \quad \forall i = 1, \ldots, N
\end{align*}
\]

where the interference constraint is embedded into the surplus function as a pricing factor.

**B. Nash Equilibrium of the Game**

**Definition 1:** Nash Equilibrium (NE) is the steady state in the game, in which no player can increase its utility function unilaterally. Formally, NE satisfies the following relation

\[
u_i(p_i, \mathbf{p}_{-i}) \geq u_i(p_i', \mathbf{p}_{-i}'), \quad p_i \in \mathcal{P}_i \tag{17}\]

That is, the utility function corresponding to action \( p_i \) should be greater than or equal to the utility function corresponding to the previous action \( p_i' \).

In order to see optimality and unique Nash Equilibrium in terms of surplus function for a given rate, we take first order partial derivative of \( s_i(p_i) \) with respect to \( p_i \) as

\[
\frac{\partial s_i(p_i)}{\partial p_i} = \frac{\partial u_i(\gamma_i)}{\partial p_i} - \frac{\beta}{M} \frac{g_{m,i} (p)}{M g_{m,i}(p)} \tag{18}\]

and compute the second order derivative of \( s_i(p_i) \) with respect to \( p_j \), which is less than or equal to zero, that is

\[
\frac{\partial^2 s_i(p_i)}{\partial p_i \partial p_j} \leq 0, \quad \forall i \neq j \tag{19}\]

This result shows that the game is super-modular and there exist unique Nash Equilibrium [21]. At Nash Equilibrium, the power allocation is according to (10).

**IV. COMBINED ADMISSION, POWER AND RATE CONTROL ALGORITHM**

In order to solve the optimization problem (16), we present joint power and rate control algorithm for active CR links by ensuring interference constraint of active primary user-receiver and SINR (QoS) requirements of active CR links. When QoS constraints of some of CR links are not met, their transmission...
rates are adjusted so that the corresponding instantaneous SINRs are no less than their minimum SINRs or simply drop those CR links who do not satisfy their requirements by using one of the approach as mentioned in [19]. Formally, the algorithm is stated as below:

**Algorithm for Combined Admission, Power and Rate Control**

**Initial Data:**
- Randomly generate $M$ primary and $N$ CR links in a network, and assign initial transmit power $p_i$, $\forall i = 1, \ldots, N$, and minimum SINRs $\gamma_i^*$, $\forall i = 1, \ldots, N$, and rate set $R$ for CR links.
- Supply $p_{th}^m$, $\beta$, $\lambda_T$, and the desired tolerance $\epsilon$.

**Pre-admissibility and Feasibility Check:**
- Compute channel gain ratio using (4) and check for pre-admission control.
- For feasibility check of minimum SINRs
  1) Check IF maximum eigenvalue of a matrix $F$ is less than 1. THEN go to “Resource allocation” step. OTHERWISE, Stop, $\gamma_i^*$, $\forall i$, are infeasible.

**Resource allocation.**
- DO Loop for $i = 1$ to $N$
  - Compute instantaneous SINR $\gamma_i$ and surplus $s_i(p_i)$.
  - Check IF QoS requirement in equation (3) is satisfied, THEN Stop.
  - ELSE IF, adopt rate $R_i \in R$ to satisfy (3) or fetch post-admission control mechanism to drop the link which does not satisfy QoS requirement in equation (3).
- Continue the loop until the desired accuracy is met.

It is known from equation (10) that the power allocation is feasible if SINR of each CR link satisfies the condition (3). That is the algorithm will be reached at fixed point if desired accuracy in $p_i(n)$ is met such that $|p_i(n + 1) - p_i(n)| \leq \epsilon$ or $p_i(n + 1) \approx p_i(n)$.

**V. SIMULATIONS AND NUMERICAL EXAMPLES**

In order to corroborate our theoretical findings, we consider an ad-hoc cognitive radio network as shown in Figure 1. We generate $N$ CR links randomly and uniformly distributed over an area of $1000m \times 1000m$ where CR links coexist with $M = 1$ primary link. We chose primary bandwidth $W = 5MHz$, feasible initial power $p_i$s randomly, maximum power $p_{th}^{max} = 1W$, tolerable interference power $p_{th}^m = 0.2W$, noise power $n_i = 0.1W$, threshold $\lambda_T = 0.3$, and the tolerance $\epsilon = 0.0001$. We consider different modulation techniques for CRs as Binary Phase-shift keying (BPSK), Quadrature Phase-shift keying (QPSK), 16-Quadrature Amplitude Modulation (16-QAM), 64-Quadrature Amplitude Modulation (64-QAM), 256-Quadrature Amplitude Modulation (256-QAM) and 1024-Quadrature Amplitude Modulation (1024-QAM), so that the corresponding rates available to CR users will be $R = \{1, 2, 4, 6, 8, 10\}$ bits/symbol respectively.

We consider two different scenarios to illustrate the proposed algorithm. In the first scenario, we ran the algorithm with $N = 10$ admitted CR links (transmitter-receiver pairs) and $M = 1$ primary link with above mentioned simulation configuration. Then, we have plotted the variation of power allocation of individual CR links and their surplus functions as shown in Figure 2 and 3. We noted that some of CR links were communicating to their corresponding receivers with maximum allowed transmit power (1W) as shown in Figure 2 and they were penalized resulting in decrease in their corresponding surplus function as shown in 3. For instance, the CR link 3 was transmitting with maximum allowed power (1W), its surplus function was increasing for first few steps and then after decreased because of the price factor (penalty of high transmit power) in surplus function. Whereas, the CR link 4 was transmitting with power less than 1W and the surplus function was never decreasing since it did not violate the interference constraint. We note that, in general, the surplus function of link $i$ is strictly increasing with $p_i$ for fixed $p_{th}$ since the link has no penalty for high transmission power as long as $p_i$ is feasible and interference constraint is satisfied.

In the next scenario, we ran our algorithm for different number of admitted CR links which coexist with $M = 1$ primary link operating in ad-hoc cognitive networks. In this scenario, we plotted the variation of surplus function vs. the number of active CR links as shown in Figure 4 by taking average of 100 realization. It is worth to point out that the overall surplus value increases with the increased number of admitted CR links. In Figure 4, we observed that the overall surplus is lesser when there were $N > 80$ CR links than that when $N < 80$. This is because some CR user-transmitters...
function. We also noted that the surplus function maximizes the surplus function in which QoS requirements are satisfied. Simulation results have shown that the algorithm converges to an optimal point with feasible power allocation. We also noted that the surplus function decreases through the pricing function when an active CR link violates the interference constraint which results in decrease in overall surplus function. Furthermore, we observed that the overall surplus function increases with the increased number of admitted CR links as long as they transmit with feasible power and satisfy the interference constraints.

VI. CONCLUSION

In this paper we have presented an algorithm for combined admission, power and rate control for CR links. The algorithm maximizes the surplus function in which QoS requirements of CR links and the interference constraints at primary users are satisfied. Simulation results have shown that the algorithm converges to an optimal point with feasible power allocation. We also noted that the surplus function violates interference constraints, and they will be penalized via pricing function which results in decrease in overall surplus function.

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