QoS-Aware Spectrum Sharing in Cognitive Wireless Networks

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Abstract—We consider QoS-aware spectrum sharing in cognitive wireless networks where secondary users are allowed to access the spectrum owned by a primary network provider. The interference from secondary users to primary users is constrained to be below the tolerable limit. Also, signal to interference plus noise ratio (SINR) of each secondary user is maintained higher than a desired level for QoS insurance. When network load is high, admission control needs to be performed to satisfy both QoS and interference constraints. We propose an admission control algorithm which is performed jointly with power control such that QoS requirements of all admitted secondary users are satisfied while keeping the interference to primary users below the tolerable limit. When all secondary users can be supported at minimum rates, we allow them to increase their transmission rates and share the spectrum in a fair manner. We formulate the joint power/rate allocation with max-min fairness criterion as an optimization problem. We show how to transform it into a convex optimization problem so that its globally optimal solution can be obtained. Numerical results show that the proposed admission control algorithm achieves performance very close to the optimal solution. Also, impacts of different system and QoS parameters on the network performance are investigated for both admission control and rate/power allocation problems.

I. INTRODUCTION

Implementation of emerging high-speed wireless applications requires exponential growth in spectrum demand. However, it has been reported that current utilization of allocated spectrum can be as low as 15% [1]. Thus, there is an increasing interest in developing efficient method for spectrum management and sharing which is encouraged by both industry and FCC authority [2]. This motivates to exploit the spectrum opportunities in space, time, frequency while protecting users of the primary network owner from excessive interference due to opportunistic spectrum access [3]. In fact, it is required that an interference limit corresponding to an interference temperature level be maintained at the receiving points of the primary network.

The key challenge in cognitive radio networks is how to construct spectrum access/sharing schemes such that users of the primary network (will be called primary users in the sequel) are protected from excessive interference due to secondary spectrum access and QoS performance of secondary users are guaranteed. A graph-theoretic model for spectrum sharing/access among secondary users was proposed in [4] where different objective functions were investigated. The formulation of channel allocation problem using game theory was proposed in [5]. In this work, the proposed utility functions capture the interference perceived by one user on each channel and/or the interference this user creates for neighboring ones. However, primary users were not explicitly protected from interference due to spectrum access of secondary users. In [6], heuristic-based channel and power allocation algorithm was proposed where interference constraint for primary users was considered.

In this paper, we present a spectrum sharing framework for cognitive CDMA wireless networks with explicit interference protection for primary users and QoS constraints for secondary users. Secondary users have minimum transmission rates with required QoS performance in terms of SINR (or equivalent bit error rate (BER)) and maximum power constraints. When the network load is high, an admission control algorithm is proposed to guarantee QoS constraints for secondary users and interference constraints for primary users. When all secondary users can be supported, we present a joint rate and power allocation solution with QoS and interference constraints.

The rest of this paper is organized as follows. System models and problem definition are presented in Section II. Admission control algorithm for spectrum access of secondary users is proposed in Section III. The power/rate allocation formulation is presented in Section IV. Numerical results are presented in Section V. Section VI concludes the paper.

II. SYSTEM MODELS AND PROBLEM DEFINITION

We consider the spectrum sharing problem among unlicensed users (secondary users) and licensed users (primary users). The problem considered in this paper applies to both centralized networks (e.g., cellular networks) and distributed networks (e.g., ad hoc and sensor networks). For ease of presentation, we will discuss different problem aspects in the context of centralized setting most of the time. We assume that there are a number of primary and secondary users communicating with their partners simultaneously. Here, the term “user” will be used broadly where it can be a mobile node or base station/access point in centralized networks or simply a mobile node in ad hoc networks. The CDMA technology will be assumed although the model can be extended for other technologies as well.

Simultaneous communications among users (i.e., both primary and secondary users) will interfere with each other. The entities we will work with are communication links each of which is a pair of users communicating with each other. We will refer to communication links belonging to secondary networks as secondary links. We will also consider the interference constraints at the receiving nodes of primary networks which will be referred to as primary receiving points in the sequel. We assume that each primary receiving point can tolerate a maximum interference level. Also, secondary links have desired QoS performance in terms of BER. Fig. 1 illustrates the transmission setting considered in this paper. One possible example for the
investigated network setting is where primary users communicate with their BS in the uplink direction in a cellular network and secondary users communicate with each other in an ad hoc mode. Here, the total interference that secondary links create at each BS of the primary network should be smaller that the tolerable level.

A. QoS and Interference Constraint Modeling

Assume that there are \( M \) primary receiving points and \( N \) secondary communication links in the considered geographical area. Let us denote the channel gain from the transmitting node of secondary link \( i \) to receiving node of secondary link \( j \) by \( g_{j,i}^{(p)} \) while the channel gain from the transmitting node of secondary link \( i \) to primary receiving point \( j \) as \( g_{j,i}^{(s)} \). If \( N_i \) denotes the total noise and interference at the receiving side of secondary link \( i \), for wireless access based on CDMA, the corresponding effective bit-energy-to-noise spectral density ratio can be written as [9]

\[
\mu_i = \frac{W}{R_i} \sum_{j=1, j \neq i}^{N} g_{j,i}^{(s)} P_{j,i} \quad (1)
\]

where \( W \) is the spectrum bandwidth, \( R_i \) is the transmission rate of secondary link \( i \). Here, \( W/R_i \) is the processing gain which is usually required to be larger than a particular value. The processing gain is simply equal to one for other multiple access technologies such as FDMA and \( \mu_i \) denotes the SINR. In the sequel, we will abuse a bit by referring \( \mu_i \) as SINR in all cases. Now, if a particular modulation scheme is employed, there will be an explicit relation between BER and SINR. Thus, for a specific required BER level of secondary link \( i \), \( \mu_i \) is required to be larger than a corresponding value \( \gamma_i \). Hence, the QoS requirement for secondary link \( i \) can be expressed as

\[
\mu_i \geq \gamma_i, \quad i = 1, 2, \ldots, N. \quad (2)
\]

Now, let \( T_j \) be the maximum interference level tolerable by primary receiving point \( j \). The interference constraint for primary receiving point \( j \) can be written as

\[
\sum_{i=1}^{N} g_{j,i}^{(p)} P_{i} \leq T_j, \quad j = 1, 2, \ldots, M \quad (3)
\]

where total interference at the primary receiving point \( j \) should be smaller the tolerable limit. We will assume that transmission rate of secondary link \( i \) can be adjusted in an allowable range with minimum and maximum values are \( R_i^{\min} \) and \( R_i^{\max} \), respectively. Also, power of secondary link \( i \) is constrained to be smaller than the maximum limit \( P_i^{\max} \).

B. Admission Control Problem

Here, we are interested in the scenario where a number of secondary links wish to access the spectrum with minimum transmission rate (i.e., \( R_i = R_i^{\min} \)) and both the QoS requirements (in (2)) as well as the interference constraints (in (3)) need to be satisfied. The problem is how to choose the subset of requesting links with maximum size such that the constraints in (2) and (3) are both satisfied.

C. Joint Rate and Power Allocation Problem

When the network load is low, all requesting secondary links with minimum transmission rates can be supported while satisfying both QoS and interference constraints in (2), (3). If it is the case, secondary links would increase their transmission rates above the minimum values and share the spectrum in a fair manner. For fairness issue, we adopt the max-min criterion which aims to maximize the transmission rate of the secondary link with a minimum transmission rate.

We will arrange power, rate and other quantities of all secondary links into the corresponding vectors for notational convenience. For example, \( P \) will denote a column vector whose element \( P_i \) is the transmission power of secondary link \( i \). The joint rate and power allocation problem can be stated as

\[
\begin{align*}
\text{maximize} & \quad \{ \min_i R_i \} \\
\text{subject to} & \quad R_i^{\min} \leq R_i \leq R_i^{\max} \\
& \quad P \succeq P_i^{\max} \\
& \quad \text{the constraints in (2), (3)}
\end{align*}
\]

We will show how to solve both admission control problem as well as joint rate and power allocation problem in the following sections.

III. ADMISSION CONTROL ALGORITHM

As has been mentioned in Section II, we will consider the admission control problem when the network load is high and all secondary links transmit with their minimum rate (if admitted). Now, using equation (1), we can rewrite the QoS constraint in (2) as follows:

\[
P_i \geq \sum_{j=1, j \neq i}^{N} \frac{\gamma_i R_i^{\min} g_{j,i}^{(s)}}{W} p_{j,i} + \frac{\gamma_i R_i^{\min} N_i}{g_{i,i}^{(s)}}, \quad i = 1, 2, \ldots, N. \quad (5)
\]

The constraints for all secondary links can be written in the matrix form as follows:

\[
(I - F) P \succeq u \quad (6)
\]

where \( I \) is an identity matrix of order \( N \times N \), \( u \) is a column vector which can be written as

\[
u = \begin{pmatrix}
\frac{\gamma_1 R_1^{\min} N_1}{g_{1,1}^{(s)}} & \frac{\gamma_2 R_2^{\min} N_2}{g_{2,2}^{(s)}} & \cdots & \frac{\gamma_N R_N^{\min} N_N}{g_{N,N}^{(s)}}
\end{pmatrix}^T
\]
where $(\cdot)'$ denotes the matrix/vector transpose. And $F$ is an $N \times N$ matrix whose $(i,j)$-th element is

$$F_{i,j} = \begin{cases} \frac{n_i R_{i,m} g_{i,i}^{(s)}}{W} g_{i,i}' \gamma_i, & \text{if } i \neq j \\ 0, & \text{if } i = j \end{cases}. $$

A. Constrained Power Control

Recall that we are interested in the scenario where not all $N$ secondary links can be admitted into the network while satisfying both QoS and interference constraints stated in (2), (3). We will first focus on the power allocation problem under maximum power constraint (i.e., $P \preceq P_{\text{max}}$) and QoS constraints and ignore the interference constraints for a while. In [8], the authors proposed an efficient iterative power control algorithm which can be implemented distributively. Specifically, let $P_i(t)$ and $P_i(t + \Delta t)$ be the power levels of secondary link $i$ after two consecutive power updates at time instants $t$ and $t + \Delta t$, respectively. The power of secondary link $i$ is updated as follows:

$$P_i(t + \Delta t) = \min \left\{ P_i^{\text{max}}, P_i(t) \frac{\gamma_i}{\mu_i(t)} \right\}. $$

(7)

where $\mu_i(t)$ is the instantaneous SINR at the receiving side of secondary link $i$ at time instant $t$ which can be written as

$$\mu_i(t) = \frac{W g_{i,i}^{(s)} P_i(t)}{R_i \sum_{j=1,j \neq i}^{N} g_{i,j}^{(s)} P_j(t) + N_i}. $$

It was shown in [8] that this power control algorithm converges to the fixed point solution of

$$P = \min \{ P^{\text{max}}, FP + u \} $$

(8)

which will be referred to as stationary power vector. Let $\Omega$ be the set of secondary links and $P^{\Omega}$ be the stationary power vector when the power algorithm with the rule as in (7) is run with secondary link set $\Omega$. From the results of [7], we have the following facts:

Fact 1: If all secondary links in $\Omega$ can be supported (i.e., the power control algorithm in (7) results in a stationary power vector $P^{\Omega}$ satisfying QoS constraints in (2)), the QoS constraints will be satisfied with equality.

Fact 2: If a subset $\Omega_0 \subseteq \Omega$ is the set of secondary links which are not supported with stationary power vector $P^{\Omega}$, then $P_{\Omega}^{\text{max}}$ for $i \in \Omega_0$.

Now, let us define the following “interference measures”:

$$\alpha_i(P^{\Omega}) = \left[ P_i^{\Omega} \sum_{j=1,j \neq i}^{N} g_{i,j}^{(s)} + N_i \right] - \frac{g_{i,i}^{(s)} W}{\gamma_i} \frac{P^{\Omega} i}{R_i}, $$

(9)

$$\beta_i(P^{\Omega}) = \left[ \sum_{j=1,j \neq i}^{N} g_{i,j}^{(s)} P_j^{\Omega} + N_i \right] - \frac{g_{i,i}^{(s)} W}{\gamma_i} \frac{P^{\Omega} i}{R_i}, $$

(10)

$$D^{\Omega}(P^{\Omega}) = \sum_{i \in \Omega} \beta_i(P^{\Omega}). $$

(11)

We can easily see that

$$D^{\Omega}(P^{\Omega}) = \sum_{i \in \Omega} \beta_i(P^{\Omega}) = \sum_{i \in \Omega} \alpha_i(P^{\Omega}). $$

(12)

We can also see that if the QoS constraint for secondary link $i$ is satisfied with equality, then $\beta_i(P^{\Omega}) = 0$. Also, $D^{\Omega}(P^{\Omega}) = 0$ if and only if all secondary links in $\Omega$ are supported. In general, we have $\beta_i(P^{\Omega}) \geq 0$ and the value of $\beta_i(P^{\Omega})$ reflects the degree in which the QoS constraint for secondary link $i$ is violated. Also, it is intuitive that $\alpha_i(P^{\Omega})$ quantifies the aggregate relative interference that secondary link $i$ creates for other links in $\Omega$.

In [7], the authors proposed several removal algorithms which aim at maximizing the number of links which can be admitted into the network while satisfying the QoS requirements. Among these proposed algorithms, SMIRA and SMART(R) are the two most efficient ones. We have observed through simulation that these two algorithms achieve very close performance; therefore, we will only describe the SMIRA algorithm here. Note that the interference measures defined in (9)-(11) are not the same with those in [7]. However, the spirit of the SMIRA algorithm remains the same in this paper. In fact, SMIRA algorithm runs the power control algorithm in (7) and removes links from the network one by one and until the remaining set of links can be supported. The removal criterion of SMIRA is as follows:

$$i^* = \arg\max_{i \in \Omega} \left\{ \max (\alpha_i(P^{\Omega}), \beta_i(P^{\Omega})) \right\}. $$

(13)

Intuitively, SMIRA algorithm removes the link which violates QoS constraints the most and/or creates the largest amount of interference to other links in each step. Thus, it can potentially remove the least number of links from the network.

B. Admission Control with QoS and Interference Constraints

In our spectrum sharing problem, besides QoS constraint, admission and power control should be done such that interference constraints for primary links stated in (3) are also satisfied. We have the following result on the complexity of this admission control problem.

Proposition 1: The admission control problem with QoS and interference constraints is NP-hard.

Proof: It was shown in [7] that the admission control with only QoS constraints is NP-hard. Because the admission control with QoS constraints is a special case of that with both QoS and interference constraints (they become the same when $I_j \rightarrow \infty$ for $j = 1, \ldots, M$). Therefore, our investigated admission control problem is also NP-hard. ■
Case 2: Interference constraints for primary receiving points stated in (3) are violated

Note that this case covers both scenarios where QoS constraints in (2) are violated or not. In this case, we would remove the link which violates both QoS and interference constraints the most in each step. Now, we define the measure which quantifies degree of violation at primary receiving point \( j \) as follows:

\[
\eta_j(\Omega) = T_j - \sum_{i=1}^{N} g^{(p)}_{j,i} p^{\Omega}_i. \tag{14}
\]

We propose a removal algorithm with the following removal metric

\[
i^* = \arg\max_{i \in \Omega} \left\{ \sum_{j=1}^{M} \frac{\eta_j(\Omega)}{D^\Omega(P^\Omega)} + \sum_{k=1}^{M} \eta_k(\Omega) \right\}
\]

\[
+ \frac{D^\Omega(P^\Omega)}{D^\Omega(P^\Omega)} \times \max \left\{ \sum_{j \in \Omega, j \neq i} g_{j,i}^{(s)} p^{\Omega}_j, \sum_{j \in \Omega, j \neq i} g_{j,i}^{(s)} p^{\Omega}_j \right\}
\]

In fact, \( \sum_{j \in \Omega, j \neq i} g_{j,i}^{(s)} p^{\Omega}_j \) denotes the total interference that secondary link \( i \) creates to other secondary links while \( \sum_{j \in \Omega, j \neq i} g_{j,i}^{(s)} p^{\Omega}_j \) is the total interference received at the receiving end of link \( i \). In addition, \( g^{(p)}_{j,i} p^{\Omega}_i \) denotes the interference that secondary link \( i \) creates for primary receiving point \( j \). Recall that \( D^\Omega(P^\Omega) \) quantifies the degree of violation for QoS constraints and \( \eta_j(\Omega) \) quantifies the degree of violation for the interference constraint of primary receiving point \( j \). Therefore, the proposed criterion removes in each step the secondary link which creates the largest amount of interference for primary receiving points and other secondary links in the weighted average sense. As a result, it would potentially remove the least number of secondary links from the network. We will refer to this algorithm as interference-aware SMIRA (I-SMIRA) in the sequel. The computation complexity of I-SMIRA is just \( O(N^2) \) which is quite acceptable.

IV. JOINT RATE AND POWER ALLOCATION OPTIMIZATION

When the network load is low, all secondary links can be admitted into the network and they would increase their transmission rates above the minimum values. In essence, we wish to solve the optimization problem stated in (4). The decision variables are transmission rates \( \{R_i\} \) and powers \( \{P_i\} \). We will show how to transform this problem into a convex optimization problem where globally optimal solution can be obtained.

We would like to note that the joint rate and power allocation for cellular CDMA networks has been an active research topics over the last several years. We refer the readers to [9] and references therein for existing literature on the problem. However, the work in [9] is one of the first papers which adapt the problem to the ad hoc network setting. Here, the objective is to minimize the maximum service time on different transmission links. In this paper, we proceed one step further by solving the joint rate and power allocation problem in the spectrum sharing context where interference constraints for primary receiving points are taken into account.

Now, the objective function in (4) is equivalent to minimize \( \{\max_i 1/R_i\} \). By introducing a new variable \( t \) and writing down all the constraints explicitly, the optimization problem (4) is equivalent to

\[
\text{minimize } t \quad \text{subject to} \quad \frac{1}{R_i} \leq t, \quad i = 1, 2, \ldots, N \quad \frac{1}{R_j} \leq \gamma_i, \quad i = 1, 2, \ldots, N, \quad \sum_{i=1}^{N} g^{(p)}_{j,i} P_i \leq T_j, \quad j = 1, 2, \ldots, M \quad R^\min_i \leq R_i \leq R^\max_i, \quad i = 1, 2, \ldots, N \quad P_i \leq P^\max_i, \quad i = 1, 2, \ldots, N. \tag{15}
\]

The optimization problem in (15) is not convex. However, we can transform it into a geometric program which can be solved efficiently (chapter 4, [10]). Now, we show how to transform the optimization problem (15) into a geometric program which can be transformed into a convex optimization problem. Specifically, optimization problem in (15) is equivalent to

\[
\text{minimize } t \quad \text{subject to} \quad t^{-1} R^{-1}_i \leq 1, \quad i = 1, 2, \ldots, N \quad \frac{\gamma_i}{W g^{(s)}_{j,i}} R_i P^{-1}_i \sum_{j=1, j \neq i} g^{(s)}_{j,i} P_j + \frac{\gamma_j}{W g^{(s)}_{j,i}} R_j P^{-1}_i \leq 1, \quad i = 1, 2, \ldots, N \quad \sum_{i=1}^{N} g^{(p)}_{j,i} P_i \leq T_j, \quad j = 1, 2, \ldots, M \quad R^\min_i \leq R_i \leq R^\max_i, \quad i = 1, 2, \ldots, N \quad (P^\max_i)^{-1} R_i \leq 1, \quad i = 1, 2, \ldots, N \quad (P^\max_i)^{-1} P_i \leq 1, \quad i = 1, 2, \ldots, N. \tag{16}
\]

Now, defining \( P_i = e^{\xi_i}, R_i = e^{\mu_i} \) and \( t = e^{\phi} \), substituting these new variables into (16), and taking \( \ln \) in both the objective and the constraint functions, we achieve a convex optimization problem which can be solved by the standard interior point algorithm [10]. We have the following property on the solution of joint rate and power allocation problem.

Proposition 2: The optimal solution of the joint rate and power allocation problem satisfies \( R_i = R_j, \forall i, j \).

Proof: This can be proved by contradiction following a procedure similar to the one for proposition 3 in [9].

Hence, the rate and power allocation problem achieves perfectly fair rate for all secondary links in the sense that optimal transmission rates for all links are the same.

V. NUMERICAL RESULTS

We present the numerical results for a simple network setting as shown in Fig. 1. Assume that primary users communicate with its BS in the uplink direction (i.e., a single cell is considered). Transmitting nodes of secondary links are randomly located in a rectangular area and the BS of the primary network is located at the center of the rectangular area. The size of the rectangular area is 2000m \( \times \) 2000m. Also, receiving node of each secondary link is generated randomly in a 1000m \( \times \) 1000m rectangle with its transmitting node being at the center.
The channel gains are modeled as \( g_{i,j}^{(s)} = K_0 - f_{i,j}^{(s)}(d_{i,j}^{(s)})^{-4} \), where \( d_{i,j}^{(s)} \) and \( d_{i,j}^{(p)} \) are the corresponding distances, and \( K_0, \mu_{i,j}^{(s)}, \mu_{i,j}^{(p)} \) are random Gaussian variables with zero mean and standard deviation equal to 6 dB. The maximum transmission power on secondary links is \( P_i^\text{max} = 0.1 \text{ W} \). The spectrum bandwidth is \( W = 5.12 \text{ MHz} \). We will denote the tolerable interference limit at the primary receiving point (i.e., BS) as \( I \).

The minimum transmission rate on secondary links is \( R_i^\text{min} = 64 \text{ Kbps} \) and maximum transmission rate is \( R_i^\text{max} = W/PG \) where \( PG \) is the minimum processing gain. For each simulation run, the locations of secondary links (i.e., transmitting and receiving nodes) are generated randomly. The measure of interest is obtained by averaging over 100 simulation runs.

The average number of accepted link versus the desired SINR for each secondary link (i.e., \( \gamma_i \)) is shown in Fig. 2 for SMIRA, I-SMIRA algorithms and optimal removal. The result for optimal removal is obtained by an exhaustive search with the least number of removed links. As is evident from this figure, the performance of I-SMIRA algorithm is very close to that of optimal removal. Also, I-SMIRA algorithm achieves much higher performance than SMIRA algorithm.

The minimum processing gain is high enough (e.g., close to 40), the throughput is more limited by the maximum transmission rate so the impacts of QoS and interference constraints diminish.

### VI. Conclusions

We have presented a solution approach to the spectrum sharing problem in cognitive wireless networks. In particular, an admission control algorithm has been proposed which aims to remove the least number of secondary links so that both QoS constraints in terms of desired SINR for accepted links and interference constraints for primary links are satisfied. We have also formulated the joint rate and power allocation problem for the secondary links as an optimization problem with both QoS and interference constraints. Numerical results shown the superior performance of the proposed admission control algorithm. Also, several interesting impacts of system, QoS and interference constraint parameters on network performance were investigated and discussed.

### References