An SINR Balancing based Beamforming Technique for Cognitive Radio Networks With Mixed Quality of Service Requirements

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Abstract—We consider an underlay cognitive radio network, in which the cognitive users (also referred to as secondary users (SUs)) are allowed to access the licensed spectrum simultaneously with the primary users (PUs). Specifically we solve a beamforming and power allocation problem in the downlink with mixed quality-of-service (QoS) requirements where a set of SUs are required to achieve a specific signal-to-interference and noise ratio (SINR) targets whilst the SINRs for the remaining SUs are balanced. This mixed QoS requirement problem is more complicated in the downlink because of the coupled structure of beamformers and power allocations. Hence, we solve an equivalent uplink problem based on the uplink-downlink duality and subgradient method. An iterative algorithm is proposed to determine the optimal beamformers and power allocation. Simulation results are provided to validate the optimality of the result and the convergence of the proposed algorithm.

Index Terms—Cognitive radio, SINR balancing, beamforming

I. INTRODUCTION

Wireless communication technology has significantly influenced the development of various applications and services resulting in very high demand on high data rates. These have made the radio spectrum a scarce resource. The conventional spectrum management approach based on licensing various frequency spectrums exclusively to different operators is inefficient. For example, recent measurements on spectrum utilization have shown that most of the fixed licensed spectrums are under-utilized [1]. This has motivated the concept of opportunistic spectrum sharing or the so-called cognitive radio technology [2], where a secondary user (SU) may access the spectrum bands allocated to the primary users (PUs) without causing harmful interference to the PUs. This technology has the potential to improve the spectrum utilization [3].

The power allocation and beamforming problems for multiuser networks have been investigated over the past decade [4]–[7]. Within this context, we consider a signal-to-interference and noise ratio (SINR) balancing problem for multiple-input-single-output (MISO) broadcast channels (BC) in a cognitive radio network (CRN). The SINR balancing problem for multiuser networks have been studied recently in [8]–[10]. In [8], the SINR balancing problem for conventional network (i.e., without interference constraint), has been solved using an iterative algorithm, where the worst-case user SINR is maximized with a sum-power constraint. The same problem has been investigated in [9] and [10] for a CRN with interference constraints in addition to the sum-power constraint.

As the need for wireless communications with mixed services such as the real time audio-video and delay tolerant packet radio transmission grows, it is increasingly important for the communication system to support users with mixed quality-of-service (QoS) requirements. Depending on users’ QoS requirements, they can be categorized into two classes: 1) real time users employing interactive voice and video transmissions; and 2) non-real time users adopting delay tolerant packet data services. Data rate in the real time transmission cannot be varied during the communication. Since there is no retransmission concept for the real time communication, signal quality should not be dropped below a certain threshold. At the same time, data rate for non-real time transmission can be varied according to the quality of the channels. Also, if a packet is lost, it can be retransmitted using automatic repeat request. Because of this nature, the real time SUs must achieve their target SINRs at the receiver in order to decode the received signal successfully. For the non-real time SUs, in order to maintain fairness among users, the achievable SINRs can be balanced. In this paper, we propose an algorithm, which optimally design beamformers and transmission powers at the secondary network basestation (SNBS) in order to satisfy real time SUs’ target SINRs all the time whilst balancing the SINRs of the remaining non-real time SUs.

II. SYSTEM MODEL AND PROBLEM STATEMENT

We consider a downlink underlay CRN with $K$ SUs and single PU$^1$. It is assumed that the SNBS consists of $N_t$ transmit antennas. Each user terminal consists of single antenna.

$^1$For simplicity of description, we first consider the case of only single PU. The result derived, however, can be readily extended to multiple PUs. In the simulation section, we have considered a network with two PUs.
The signal transmitted by the SNBS is given by
\[ x(n) = \hat{U} s(n), \]  
where \( s(n) = [s_1(n) \ldots s_K(n)]^T \), and \( s_k(n), \ k = 1, 2, \ldots, K \) is the symbol transmitted to the \( k \)th SU. The matrix \( \hat{U} = [\sqrt{p_1} u_1 \ldots \sqrt{p_K} u_K] \), and \( \|u_k\| = 1 \). Here, \( u_k \in \mathbb{C}^{N_s \times 1} \) and \( p_k \) are the transmit beamforming weight vector and the power allocated to the \( k \)th SU respectively. The variance of the symbol \( s(n) \) is assumed to be unity. The received signal at the \( k \)th SU can be written as
\[ y_k(n) = h_k^H x(n) + \eta_k(n), \ k = 1, \ldots, K, \]  
where \( h_k \in \mathbb{C}^{N_s \times 1} \) is the channel gain vector between the SNBS and the \( k \)th SU. We assume that \( \eta_k(n) \) is a zero-mean circularly symmetric additive white Gaussian noise (AWGN) with variance \( \sigma^2 \). Let \( g = [\|h_1^H u_1\| \ldots \|h_K^H u_K\|]^T \) and \( p = [p_1 \ldots p_K]^T \), where \( h \in \mathbb{C}^{N_s \times 1} \) is the channel gain vector between the SNBS and the PU. The interference leakage to the PU due to the SU transmission can be written as
\[ \varepsilon = E[\|h^H x(n)x(n)^H h\|] = \sum_{k=1}^K p_k \|h_k^H u_k\|^2 = g^T p. \]  
The SINR of the \( k \)th SU in the downlink can be written as
\[ \text{SINR}^{\text{DL}}_k = \frac{p_k u_k^H \hat{R}_k u_k}{\sum_{i \neq k} p_i u_i^H \hat{R}_k u_i + \sigma^2}, \]  
where \( \hat{R}_k = h_k h_k^H \). \( K \) number of SUs out of the \( K \) SUs are real time users and they should satisfy the target SINRs all the time. The rest of the SUs are non-real-time users and in order to maintain fairness their fairness should be balanced. This problem can be formulated as follows:
\[
\begin{align*}
\max \min_{\mathbf{U}, \mathbf{p}} & \quad \text{SINR}^{\text{DL}}_k(\mathbf{U}, \mathbf{p}), \ k = K + 1, \ldots, K, \\
\text{s.t.} \quad & \text{SINR}^{\text{DL}}_k(\mathbf{U}, \mathbf{p}) \geq 1, \ k = 1, 2, \ldots, K 1, \\
& \mathbf{g}^T \mathbf{p} \leq P_{\text{int}}, \\
& \mathbf{1}^T \mathbf{p} \leq P_{\text{max}},
\end{align*}
\]  
where \( \mathbf{U} = [u_1 \ldots u_K] \), \( \gamma_k \) is the target SINR for the \( k \)th real time SU. \( P_{\text{int}} \) is the interference threshold for the PU, \( P_{\text{max}} \) is the available total transmission power at the SNBS and \( \mathbf{g} \triangleq [1 \ldots 1]^T \). The first set of constraints in (5) ensure that the real time users always achieve their target SINRs, provided the problem is feasible. The constraints in (6) and (7) account for the interference leakage to the PUs and the total transmission power respectively.

III. ALGORITHM SOLUTION

We propose an iterative algorithm to solve the mixed QoS requirement problem by exploiting the uplink-downlink duality and the conventional SINR balancing technique [8]. We start with the problem by assuming that all SUs are non-real time users, where none of the users are required to satisfy the specific SINR targets. Later, we will modify this to account for real time users with specific SINR targets. Hence, the initial problem can be written as an SINR balancing problem for an underlay CRN as follows:
\[
\begin{align*}
\max \min_{\mathbf{U}, \mathbf{p}} & \quad \text{SINR}^{\text{DL}}_k(\mathbf{U}, \mathbf{p}), \ k = 1, \ldots, K \\
\text{s.t.} \quad & \mathbf{g}^T \mathbf{p} \leq P_{\text{int}}, \\
& \mathbf{1}^T \mathbf{p} \leq P_{\text{max}},
\end{align*}
\]  
where \( \gamma_k = 1 \) for \( k = K + 1, \ldots, K \). The solution obtained by solving the above problem might not satisfy the required QoS of the real time SUs. However, we will explain in the subsequent subsections how this SINR balancing problem can be modified to achieve the target SINRs for real time SUs. The SINR balancing problem in (8) can be modified with a single constraint by introducing auxiliary variables as follows [11]:
\[
\begin{align*}
\max \min_{\mathbf{U}, \mathbf{p}} & \quad \text{SINR}^{\text{DL}}_k(\mathbf{U}, \mathbf{p}), \ k = 1, \ldots, K \\
\text{s.t.} \quad & a \mathbf{g}^T \mathbf{p} + b \mathbf{1}^T \mathbf{p} \leq P,
\end{align*}
\]  
where \( a \) and \( b \) are the auxiliary variables for the interference constraint and the sum power constraint respectively and \( P := aP_{\text{int}} + bP_{\text{max}} \). For a given \( a \) and \( b \), the problem in (9) can be solved using the conventional SINR balancing technique [8]. Auxiliary variables \( a \) and \( b \) can be updated using a subgradient method [12]. Since this problem is formulated with two different variables and it is not jointly convex [13] in terms of \( \mathbf{U} \) and \( \mathbf{p} \). Hence, one variable should be fixed while determining the other variable. Determining beamformers \( \mathbf{U} \) in the downlink is more complicated as compared to the uplink beamforming problem because the SINR of each user is a function of the beamforming weight vectors of all other users. In the literature, the uplink-downlink duality method is used to determine the beamformers [8].

A. Beamformer design

From the uplink-downlink duality, the beamformer designed in the virtual uplink can be used in the downlink to achieve the same SINR values by appropriately allocating the downlink power. The virtual uplink SINR of \( k \)th SU can be written as
\[ \text{SINR}^{\text{UL}}_k = \frac{q_k u_k^H \tilde{R}_k u_k}{u_k^H Q_k(q) u_k}, \]  
where
\[ \tilde{R}_k = R_k / \sigma^2, \]  
\[ Q_k(q) = \sum_{i \neq k} q_i \tilde{R}_i + \Omega. \]  
The matrix \( \Omega \) defines the uplink noise covariance at the SNBS which can be written as [11]
\[ \Omega = a \tilde{H}^H \tilde{H} + b I. \]  
The vector \( q = [q_1 \ldots q_K]^T \) and the matrix \( I \) represent the uplink power allocation and the identity matrix respectively. Hence, the beamformer design in the virtual uplink for the \( k \)th SU for a given uplink power allocation \( q_k \) can be stated
as follows:

\[
\hat{u}_i = \arg \max_{u_i} \frac{u_i^H \tilde{R}_k u_i}{u_i^H \tilde{Q}_k(q) u_i}, \text{ s.t. } ||u_i|| = 1, \forall i. \tag{14}
\]

The virtual uplink beamformers can be obtained by finding the dominant generalized eigenvectors of the matrix pairs \((\tilde{R}_k, \tilde{Q}_k(q))\), \(1 \leq k \leq K\).

### B. Power allocation

The conventional SINR balancing problem in the virtual uplink can be written as [8], [11]

\[
\max \min_{U, q} \frac{\text{SINR}_{UL}(U, q)}{\gamma_k}, \quad k = 1, \ldots, K, \quad \text{s.t.} \quad \mathbf{1}^T q \leq P. \tag{15}
\]

The constraints in (9) and (15) are satisfied with equality for optimal downlink and uplink power allocation [8]. As in [8], defining \(\tilde{D} = \text{diag}\{u_1^H \Omega u_1, u_2^H \Omega u_2, \ldots, u_K^H \Omega u_K\}\) and \(\Phi = \left[u_1^H \Omega u_1, u_2^H \Omega u_2, \ldots, u_K^H \Omega u_K\right]^T\), and

\[
[\tilde{\Phi}]_{kk} = \left\{\begin{array}{ll}
u_k^H \tilde{R}_k u_k, & k \neq i, \\
0, & k = i,
\end{array}\right.
\]

the power allocation in the virtual uplink can be obtained by finding the eigenvector corresponding to the largest eigenvalue of a coupling matrix as follows:

\[
\lambda_{UL} \mathbf{q}_{\text{ext}} = \begin{bmatrix} \mathbf{MD}\tilde{\Phi}\mathbf{T} & \mathbf{MD}\tilde{\Phi} \end{bmatrix} \begin{bmatrix} \mathbf{q}_{\text{ext}}^T, \mathbf{q}_{\text{ext}}^T \end{bmatrix} = \mathbf{MD}\tilde{\Phi} \mathbf{q}_{\text{ext}}, \tag{16}
\]

where

\[
\mathbf{q}_{\text{ext}} = [q_1^T, q_K^T]^T = [q_1, \ldots, q_K, 1]^T, \tag{17}
\]

which can be obtained by scaling the eigenvector corresponding to the largest eigenvalue of the matrix in (16) such that its last element is equal to one. We introduced a diagonal matrix \(\mathbf{M}\) which is defined as

\[
\mathbf{M} = \text{diag}\{\gamma_1, \gamma_2, \ldots, \gamma_K, 1, 1, \ldots, 1\}. \tag{18}
\]

First \(K\) diagonal elements will be updated during the iterative procedure (will be explained later) in order to ensure the first \(K\) SUs achieve their target SINRs. Similarly, the downlink power allocation is determined by using the following equation [8], [11]:

\[
\lambda_{DL} \mathbf{p}_{\text{ext}} = \begin{bmatrix} \mathbf{MD}\Psi(U) & \mathbf{MD}\sigma \end{bmatrix} \begin{bmatrix} \mathbf{p}_{\text{ext}}^T, \mathbf{p}_{\text{ext}}^T \end{bmatrix} = \mathbf{MD}\Psi(U) \mathbf{p}_{\text{ext}}, \tag{19}
\]

where \(\mathbf{D} = \text{diag}\{\frac{1}{u_1^H \Omega u_1}, \frac{1}{u_2^H \Omega u_2}, \ldots, \frac{1}{u_K^H \Omega u_K}\}\)

\[
[\Psi]_{kk} = \left\{\begin{array}{ll}
u_k^H \tilde{R}_k u_k, & k \neq i, \\
0, & k = i,
\end{array}\right.
\]

\[
\sigma = [\sigma_1^2, \ldots, \sigma_K^2]^T \text{ and }
\]

\[
\mathbf{p}_{\text{ext}} = [\mathbf{p}^T, 1]^T = [p_1, p_2, \ldots, p_K, 1]^T, \tag{20}
\]

which can be obtained similar to (17).

### C. The iterative algorithm

The pseudo code of the algorithm is provided in Table I. Initially, the optimal virtual uplink beamformers are determined by solving (14) for a given initial uplink power allocation \(\mathbf{q}^{(0)}\) and auxiliary variables \(a^{(0)}\) and \(b^{(0)}\) as in step 7. At the \(m\)th iteration, for a given set of beamformers, \(\lambda_{UL}^{(m)}\) and \(\mathbf{q}^{(m)}\) can be obtained by solving (16) as in step 8. In step 9, the first \(K\) diagonal elements of the matrix \(\mathbf{M}\) will be scaled as follows:

\[
\mathbf{M} = \text{diag}\{\lambda_{UL}^{(m)} \gamma_1, \lambda_{UL}^{(m)} \gamma_2, \ldots, \lambda_{UL}^{(m)} \gamma_{K1}, 1, 1, \ldots, 1\}. \tag{21}
\]

The beamforming step 7, power control step 8 and step 9 are repeated until the required accuracy. The beamformers and the power allocation obtained in the virtual uplink will be used in (19) to find the optimal downlink power allocation as in step 11. In step 12, auxiliary variables \(a\) and \(b\) are updated via a subgradient algorithm [12] according to the downlink power allocation as follows:

\[
a^{(n+1)} = a^{(n)} + t(g^T \mathbf{p}^{(n)} - P_{\text{max}}), \tag{22}
\]

\[
b^{(n+1)} = b^{(n)} + t(1^T \mathbf{p}^{(n)} - P_{\text{max}}), \tag{23}
\]

where \(t\) denotes the step size of the subgradient algorithm and superscript \((n)\) denotes the \(n\)th iteration. The iterative process will be repeated until the following stopping criteria are satisfied.

\[
|a^{(n+1)}(g^T \mathbf{p}^{(n)} - P_{\text{max}})| \leq \epsilon, \tag{24}
\]

\[
|b^{(n+1)}(1^T \mathbf{p}^{(n)} - P_{\text{max}})| \leq \epsilon. \tag{25}
\]

At the end of the \(m\)th iteration the SINR of the users would appear as

1) Initialization: \(a^{(0)}, b^{(0)}, t, n = 0, m = 0, \)

2) repeat

3) \(n \leftarrow n + 1\)

4) repeat

5) \(m \leftarrow m + 1\)

6) \(\mathbf{q}^{(m)} \leftarrow \mathbf{q}^{(m+1)}\)

7) Solve (14) to obtain \(U\)

8) Solve (16) to obtain \(\lambda_{UL}^{(m)}\) and \(\mathbf{q}^{(m)}\)

9) Update \(M\) by \(\lambda_{UL}^{(m)}\) using (21)

10) until \(\lambda_{UL}^{(m)} - \lambda_{UL}^{(m-1)} \leq \epsilon\)

11) Solve (19) to obtain \(p\)

12) Update \(a\) and \(b\) using (22) and (23)

13) until (24) and (25) are satisfied

<table>
<thead>
<tr>
<th>TABLE I: PSEUDO CODE OF THE ITERATIVE ALGORITHM</th>
</tr>
</thead>
<tbody>
<tr>
<td>SINR(<em>{UL}^{(m)}) = (\frac{\gamma_k \lambda</em>{UL}^{(m-1)}}{\lambda_{UL}^{(m)}}, 1 \leq k \leq K1, \tag{26}|</td>
</tr>
<tr>
<td>SINR(<em>{UL}^{(m)}) = (\frac{1}{\lambda</em>{UL}^{(m)}}, K1 + 1 \leq k \leq K. \tag{27}|</td>
</tr>
</tbody>
</table>

As will be seen in the simulations that at the convergence \(\lambda_{UL}^{(m)} = \lambda_{UL}^{(m-1)}\), hence, the first \(K1\) SUs achieve their target
SINRs at the convergence.

IV. SIMULATION RESULTS

To validate the proposed algorithm and to assess its performance, we consider a CRN with four SUs and two PUs. The first two SUs are considered as real time users and they need to achieve their target SINRs all the time whilst the other two SUs’ SINRs will be balanced. The SNBS consists of five antennas. The interference leakage threshold to PUs and the total available transmission power are set to 0.1 and 2 respectively. The channel coefficients between the SNBS and the SUs as well as those between the SNBS and the PUs are assumed to be known to the SNBS. Channel gains are generated using ZMCS i.i.d. Gaussian random variables. The noise power at each SU receiver is set to 0.05. The stopping criterion $\epsilon$ has been set to 0.001. The auxiliary variables $a$ and $b$ have been initialized with 0.1 and the step size $t$ has been set to 0.01. The target SINRs for the first two SUs have been set to 10dB and 5dB respectively. The power allocations for each SU and the balanced SINR values obtained using the proposed algorithm are depicted for five different random channels in Table II. The table reveals that, the first two SUs achieve their target SINRs whilst the other two users achieve identical SINRs. Note that, the interference and the total power constraints are satisfied with equality.

To validate the optimality of the proposed algorithm, we compared the solution with the SDP approach of [14] by using the same SINRs values obtained in our simulation as targets. For example, according to Table II, the SINR for all four users are chosen as [10.0000 5.0000 4.0399 4.0399]dB, whilst the PUs interference threshold has been set to 0.1. The results using the approach of [14] are shown in Table III. Comparing Table II and Table III, and based on our observation the beamformers of [14] are same as that of the proposed one, and the power allocation obtained using the SDP approach of [14] is the same as that we obtained using the proposed method. We have observed that the interference leakage value for the PUs is equal 0.1 for both schemes. Therefore, the proposed algorithm yields an optimal solution for the mixed QoS problem considered in this paper. Note that the SDP-based method of [14] has been used just to demonstrate the optimality of the proposed scheme. However, it should be stressed that the approach of [14] cannot be directly applied to the considered scenario as the maximum achievable SINR values for the non-real time users are not known a priori.

Fig. 1 and Fig. 2 depict the convergence of the inner loop of the algorithm proposed in Table I. In Fig. 1, SU1 and SU2 achieve their target SINRs of 10dB and 5dB respectively while other SUs achieve equal SINRs at the convergence. In Fig. 2, $\lambda_{UL}$ converges to a feasible positive value. It is worth to note that, at the convergence $\lambda_{UL} = \frac{29}{30}$.

Fig. 3 and Fig. 4 reveal the convergence of the outer loop of the algorithm proposed in Table I. It is clear from the both figures that the transmitted power at the SNBS and the interference leakage to the PUs have reached 2 and 0.1 respectively after the convergence.

V. CONCLUSION

An SINR balancing based beamforming technique for a CRN has been proposed. The proposed technique optimally designs downlink beamformers and the power allocation for a problem with mixed QoS requirements. An iterative algorithm has been proposed to obtain the solution. Simulation results confirmed the optimality and the convergence of the algorithm.

REFERENCES

<table>
<thead>
<tr>
<th>Channels</th>
<th>SU1 (dB)</th>
<th>SU2 (dB)</th>
<th>SU3 (dB)</th>
<th>SU4 (dB)</th>
<th>Power</th>
<th>SU1 (dB)</th>
<th>SU2 (dB)</th>
<th>SU3 (dB)</th>
<th>SU4 (dB)</th>
<th>Inter. Leakage</th>
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<tr>
<td>Channel 1</td>
<td>10.0000</td>
<td>5.0000</td>
<td>4.4039</td>
<td>4.4039</td>
<td>2</td>
<td>1.0286</td>
<td>0.4969</td>
<td>0.2066</td>
<td>0.2678</td>
<td>0.10</td>
</tr>
<tr>
<td>Channel 2</td>
<td>10.0000</td>
<td>5.0000</td>
<td>4.4039</td>
<td>4.4039</td>
<td>2</td>
<td>0.5760</td>
<td>0.2640</td>
<td>0.8025</td>
<td>0.3575</td>
<td>0.10</td>
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<tr>
<td>Channel 3</td>
<td>10.0000</td>
<td>5.0000</td>
<td>9.7150</td>
<td>9.7150</td>
<td>2</td>
<td>0.2372</td>
<td>0.2850</td>
<td>0.7834</td>
<td>0.6944</td>
<td>0.10</td>
</tr>
<tr>
<td>Channel 4</td>
<td>10.0000</td>
<td>5.0000</td>
<td>4.1820</td>
<td>4.1820</td>
<td>2</td>
<td>0.5308</td>
<td>0.4665</td>
<td>0.2612</td>
<td>0.7415</td>
<td>0.10</td>
</tr>
<tr>
<td>Channel 5</td>
<td>10.0000</td>
<td>5.0000</td>
<td>7.6285</td>
<td>9.6285</td>
<td>2</td>
<td>0.7963</td>
<td>0.4745</td>
<td>0.2917</td>
<td>0.4645</td>
<td>0.10</td>
</tr>
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TABLE II: POWER ALLOCATIONS AND ACHIEVED SINRS OF THE PROPOSED METHOD.

<table>
<thead>
<tr>
<th>Channels</th>
<th>SU1 (dB)</th>
<th>SU2 (dB)</th>
<th>SU3 (dB)</th>
<th>SU4 (dB)</th>
<th>Power</th>
<th>SU1 (dB)</th>
<th>SU2 (dB)</th>
<th>SU3 (dB)</th>
<th>SU4 (dB)</th>
<th>Inter. Leakage</th>
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<td>Channel 1</td>
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</tr>
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</table>

TABLE III: TARGET SINRS AND ACHIEVED USER POWERS OF THE SDP-BASED METHOD OF [14].