Resource Allocation in Wireless Networks

Chapter 7- Cognitive Radio Networks

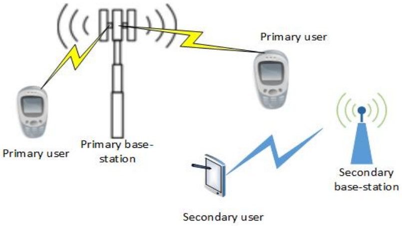
Mehdi Rasti

Department of Computer Engineering and Information Technology
AmirKabir University of Technology

May 27, 2019

Table of contents

Cognitive Radio Networks (CRNs): Short Review



Approaches for Opportunistic Access

- Overlay Spectrum Access: SUs seek idle time-frequency slots (spectrum holes) and try to avoid colliding with PUs.
- Underlay Spectrum Access: SUs try to limit the amount of interference they cause to the PUs and keep it below a specified threshold so that the QoS requirement of all of the PUs are supported.

System Model and Notations

A Cellular Cognitive Network Under Co-Channel Deployment

Consider a multi-cell wireless network consisting of a

- A set of $M = M^p + M^s$ users denoted by $\mathcal{M} = \{1, 2, \cdots, M\}$ including:
  - a set of M^p PUs denoted by $\mathcal{M}^p = \{1, 2, ..., M^p\}$ and
  - a set of M^s SUs denoted by $\mathcal{M}^s = \{M^p + 1, M^p + 2, ..., M^p + M^s\}$.
- and a set of $B = B^p + B^s$ base stations (BSs) denoted by $\mathcal{B} = \{1, 2, \cdots, B\}$ including:
  - a set of B^p primary BSs (PBSs) denoted by $\mathcal{B}^p = \{1, 2, ..., B^p\}$ serving the PUs and
  - a set of B^s cognitive radio (secondary) BSs (SBSs) denoted by $\mathcal{B}^s = \{B^p + 1, B^p + 2, ..., B^p + B^s\}$ serving the SUs.

System Model and Notations

A Cellular Cognitive Network Under Co-Channel Deployment

- The transmit power of user i is denoted by p_i where $p_i \in [0, \bar{p}_i]$
- The base station associated (assigned) to the user i is demoted by b_i, where $b_i \in \mathcal{B}$
- The uplink path-gain from user i toward BS $m \in \mathcal{B}$ is denoted by h_{mi}. Thus $h_{b_i i}$ and $h_{b_j i}$ are uplink path-gain from user i toward BSs associated to user i and j, respectively.
- SINR of User i in Underlay CRNs is:

$$\gamma_i(\mathbf{p}) = \begin{cases} \dfrac{p_i h_{b_i i}}{\sum\limits_{k \in \mathcal{M}^s} p_k h_{b_i k} + \sum\limits_{j \in \mathcal{M}_p, j \neq i} p_j h_{b_i j} + \sigma_{b_i}^2}, & \text{for } i \in \mathcal{M}_p \\ \dfrac{p_i h_{b_i i}}{\sum\limits_{k \in \mathcal{M}^s, k \neq i} p_k h_{b_i k} + \sum\limits_{j \in \mathcal{M}_p} p_j h_{b_i j} + \sigma_{b_i}^2}, & \text{for } i \in \mathcal{M}^s \end{cases} \tag{1}$$

System Model and Notations

Transmit Power Vector Corresponding to a Given SINR Vector

To write a linear equation for relation between the uplink power vector and its corresponding SINR vector, we rewrite (35) as

$$p_i = \sum_{j \neq i} \frac{h_{b_i j}}{h_{b_i i}} \gamma_i p_j + \gamma_i \frac{\sigma_{b_i}^2}{h_{b_i i}}. \tag{2}$$

Rewriting the above linear relation for all $i \in \mathcal{M}$ in Matrix format, we have:

System Model and Notations

Transmit Power Vector Corresponding to a Given SINR Vector

$$\begin{bmatrix} p_1 \\ p_2 \\ \vdots \\ p_m \end{bmatrix} = \begin{bmatrix} 0 & \gamma_1 \frac{h_{b_1 2}}{h_{b_1 1}} & \cdots & \gamma_1 \frac{h_{b_1 M}}{h_{b_1 1}} \\ \gamma_2 \frac{h_{b_2 1}}{h_{b_2 2}} & 0 & \cdots & \gamma_2 \frac{h_{b_2 M}}{h_{b_2 2}} \\ \vdots & \vdots & \ddots & \vdots \\ \gamma_M \frac{h_{b_M 1}}{h_{b_M M}} & \gamma_M \frac{h_{b_M 2}}{h_{b_M M}} & \cdots & 0 \end{bmatrix} \begin{bmatrix} p_1 \\ p_2 \\ \vdots \\ p_m \end{bmatrix} + \begin{bmatrix} \gamma_1 \frac{\sigma_{b_1}^2}{h_{b_1 1}} \\ \gamma_2 \frac{\sigma_{b_2}^2}{h_{b_2 2}} \\ \vdots \\ \gamma_M \frac{\sigma_{b_M}^2}{h_{b_M M}} \end{bmatrix} \quad (3)$$

System Model and Notations

$$\underbrace{\begin{bmatrix} p_1 \\ p_2 \\ \vdots \\ p_m \end{bmatrix}}_{\mathbf{p}} = \underbrace{\begin{bmatrix} \gamma_1 & 0 & \dots & 0 \\ 0 & \gamma_2 & \dots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \dots & \gamma_M \end{bmatrix}}_{\mathbf{D}(\gamma)} \underbrace{\begin{bmatrix} 0 & \frac{h_{b_1 2}}{h_{b_1 1}} & \dots & \frac{h_{b_1 M}}{h_{b_1 1}} \\ \frac{h_{b_2 1}}{h_{b_2 2}} & 0 & \dots & \frac{h_{b_2 M}}{h_{b_2 2}} \\ \vdots & \vdots & \ddots & \vdots \\ \frac{h_{b_M 1}}{h_{b_M M}} & \frac{h_{b_M 2}}{h_{b_M M}} & \dots & 0 \end{bmatrix}}_{\mathbf{G}} \underbrace{\begin{bmatrix} p_1 \\ p_2 \\ \vdots \\ p_m \end{bmatrix}}_{\mathbf{p}} +$$

$$\underbrace{\begin{bmatrix} \gamma_1 & 0 & \dots & 0 \\ 0 & \gamma_2 & \dots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \dots & \gamma_M \end{bmatrix}}_{\mathbf{D}(\gamma)} \underbrace{\begin{bmatrix} \frac{\sigma_{b_1}^2}{h_{b_1 1}} \\ \frac{\sigma_{b_2}^2}{h_{b_2 2}} \\ \vdots \\ \frac{\sigma_{b_M}^2}{h_{b_M M}} \end{bmatrix}} \quad (4)$$

System Model and Notations

Transmit Power Vector Corresponding to a Given SINR Vector

Using matrix notations, the relation between the uplink transmit power vector and its corresponding uplink SINR vector can be rewritten as

$$\mathbf{p} = \mathbf{D}(\gamma)\mathbf{G}\mathbf{p} + \mathbf{D}(\gamma)\boldsymbol{\eta} \tag{5}$$

where $\mathbf{D}(\gamma)$ denotes a diagonal matrix whose diagonal elements are the corresponding components of the SINR vector $\boldsymbol{\gamma}$, the (i,j) component of $\mathbf{G}_{M\times M}$ is

$$G_{ij} = \begin{cases} \dfrac{h_{b_i j}}{h_{b_i i}} & \text{if } i \neq j \\ 0 & \text{if } i = j \end{cases} \tag{6}$$

and the (i) component of $\boldsymbol{\eta}$ is $\eta_i = \frac{\sigma_{b_i}^2}{h_{b_i i}}$.

System Model and Notations

Transmit Power Vector Corresponding to a Given SINR Vector

From (36) we know that

$$\big(\mathbf{I} - \mathbf{D}(\gamma)\mathbf{G}\big)\mathbf{p} = \mathbf{D}(\gamma)\boldsymbol{\eta}, \tag{7}$$

where $\mathbf{I}$ is a $M \times M$ identity matrix. Given an uplink SINR vectors, its corresponding uplink transmit power vector is thus computed by

$$\mathbf{p} = \big(\mathbf{I} - \mathbf{D}(\gamma)\mathbf{G}\big)^{-1}\mathbf{D}(\gamma)\boldsymbol{\eta}. \tag{8}$$

Existence of A Constrained Transmit Power Vector Corresponding to a Given SINR vector (SINR Feasibility)

Definition

A given SINR vector $\boldsymbol{\gamma} = [\gamma_1, \ldots, \gamma_M]^{\mathrm{T}}$ is feasible if there exists a power vector $\mathbf{0} \leq \mathbf{p} \leq \bar{\mathbf{p}}$ satisfying the SINR vector $\boldsymbol{\Gamma}$.

Existence of A Constrained Transmit Power Vector Corresponding to a Given SINR vector (SINR Feasibility)

Definition

A given SINR vector $\boldsymbol{\gamma} = [\gamma_1, \ldots, \gamma_M]^{\mathrm{T}}$ is feasible if there exists a power vector $\mathbf{0} \leq \mathbf{p} \leq \bar{\mathbf{p}}$ satisfying the SINR vector $\boldsymbol{\Gamma}$.

Centralized Feasibility Cheeking

A given uplink SINR vector $\boldsymbol{\gamma}$ is feasible if

$$\mathbf{0} \leq \left(\mathbf{I} - \mathbf{D}(\boldsymbol{\gamma})\mathbf{G}\right)^{-1}\mathbf{D}(\boldsymbol{\gamma})\boldsymbol{\eta} \leq \bar{\mathbf{p}} \tag{9}$$

Existence of A Constrained Transmit Power Vector Corresponding to a Given SINR vector (SINR Feasibility)

Definition

A given SINR vector $\boldsymbol{\gamma} = [\gamma_1, \ldots, \gamma_M]^{\mathrm{T}}$ is feasible if there exists a power vector $\mathbf{0} \leq \mathbf{p} \leq \bar{\mathbf{p}}$ satisfying the SINR vector $\boldsymbol{\Gamma}$.

Centralized Feasibility Cheeking

A given uplink SINR vector $\boldsymbol{\gamma}$ is feasible if

$$\mathbf{0} \leq \left(\mathbf{I} - \mathbf{D}(\boldsymbol{\gamma})\mathbf{G}\right)^{-1}\mathbf{D}(\boldsymbol{\gamma})\boldsymbol{\eta} \leq \bar{\mathbf{p}} \tag{9}$$

Distributed Feasibility Checking

Target-SINR-Tracking Power control (TPC) Algorithm:

Distributed Target-SINR Tracking Power Control (TPC) Algorithm

The problem: Minimizing Aggregate Transmit Power Subject to the Target-SINR Constraint

$$\begin{aligned} &\min \sum_i p_i \\ &\text{subject to } \gamma_i(\mathbf{p}) \geq \widehat{\gamma}_i, \quad \forall i \in \mathcal{M}, \\ &\mathbf{0} \leq \mathbf{p} \leq \overline{\mathbf{p}}, \\ &\text{variable } \mathbf{p}, \end{aligned} \tag{10}$$

Distributed Target-SINR Tracking Power Control (TPC) Algorithm

The problem: Minimizing Aggregate Transmit Power Subject to the Target-SINR Constraint

$$\begin{aligned} &\min \sum_i p_i \\ &\text{subject to } \gamma_i(\mathbf{p}) \geq \widehat{\gamma}_i, \ \ \forall i \in \mathcal{M}, \\ &\mathbf{0} \leq \mathbf{p} \leq \overline{\mathbf{p}}, \\ &\text{variable } \mathbf{p}, \end{aligned} \tag{10}$$

Centralized Solution

Assuming the feasibility of target-SINR vector, the optimal solution is given by

$$\left(\mathbf{I} - \mathbf{D}(\widehat{\gamma})\mathbf{G}\right)^{-1}\mathbf{D}(\widehat{\gamma})\boldsymbol{\eta} \tag{11}$$

Distributed Target-SINR Tracking Power Control (TPC)

Distributed Solution: TPC Algorithm

$$p_i(t+1) = \frac{\widehat{\gamma}_i}{\gamma_i(\mathbf{p}(t))} p_i(t), \tag{12}$$

where $\gamma_i(\mathbf{p}(t))$ is the actual SINR of user i at iteration t.

Distributed Target-SINR Tracking Power Control (TPC)

Distributed Solution: TPC Algorithm

$$p_i(t+1) = \frac{\widehat{\gamma}_i}{\gamma_i(\mathbf{p}(t))} p_i(t), \tag{12}$$

where $\gamma_i(\mathbf{p}(t))$ is the actual SINR of user i at iteration t.

Theorem

If the target-SINR vector is feasible then the TPC algorithm converges to the optimal solution of the problem of minimizing aggregate transmit power subject to the target-SINR constraint.

Existence of A Constrained Transmit Power Vector Corresponding to a Given SINR vector (SINR Feasibility)

Distributed Feasibility Checking

The TPC algorithm can be employed as a distributed feasibility checking scheme. In fact, when all users employ the TPC, either of following two case may happen at the fixed-point, where the algorithm converge to, depending on the feasibility or infeasibility of the target-SINR vector, respectively:

- If the target-SINR vector is feasible then all users (employing the TPC) reach their target-SINR
- If the target-SINR vector is infeasible then there are some (at least one) users which do not obtain their target-SINRs, while they are transmitting at their maximum power.

Problem Statement

General Optimization Problem

In interference management problems for CRN, a given objective function for CRN is optimized subject to the *protection constraints for the PUs*.

$$\begin{array}{ll} \text{Optimize} & f_o(\mathbf{p}) \\ \text{Subject to} & \text{Protection of PUs,} \\ & \text{feasibility of transmit power level,and} \\ & \text{QoS requirements for the admitted SUs.} \\ \text{Variable} & \mathbf{0} \leq \mathbf{p} \leq \overline{\mathbf{p}}. \end{array} \tag{13}$$

Problem Statement

General Optimization Problem

- As implied by the general optimization problem 13, for underlay cognitive radio networks, the same problems discussed in Lec. 3 for conventional cellular networks, can be similarly stated and addressed as long as the protection of PUs is taken into account.
- In other words, from the optimization point of view, the same objective function, constraints and variables considered in traditional wireless networks can be also considered in CRN, but with additional constraint on the protection of PUs.
- Accordingly, the existing solutions may be also extended to be employed in CRNs so that the PUs' protection is guaranteed.

Problem Statement

Primary Users Protection

- The existence of admitted SUs does not cause violation of QoS requirements of any of the PUs,

$$\gamma_i(\mathbf{p}) \geq \widehat{\gamma}_i, \quad \forall i \in \mathcal{M}_p, \tag{14}$$

- The total interference at the primary receiving point j should be smaller than its interference temperature limit,

$$\sum_{j \in \mathcal{A}^s} h_{kj} p_j \leq \mathrm{ITL}_k, \quad \forall k \in \mathcal{B}_p \tag{15}$$

where h_{kj} is the channel gain from SU j to PBS k and $\mathcal{A}^s$ is the admitted SUs set and $\mathcal{B}_p$ is the set of PBSs.

Problem Statement

Formal Definition of Interference Temperature Limit

The maximum value of the total interference caused by the SUs to the primary base station, k, that can be tolerated by all of its PUs is called the Interference Temperature Limit (ITL) and denoted by ITL_k.

Problem Statement

There are two major interference management problems for underlay CRNs which have been considered in the literature.

- In an infeasible system, it is generally desired to devise a joint power and admission control (JPAC) algorithm that may protect all PUs together with maximum number of admitted SUs.
- In a feasible system, it is generally desirable to assign SUs as high SINR values as to maximize aggregate throughput of the SUs subject to the constraint of PUs' protection.

Possible Objective Function

- Minimizing the aggregate transmit power
- Maximizing the number of admitted users,
- Maximizing the aggregate throughput,

Problem Statement

Problem 1: Minimizing the aggregate transmit power subject to target-SINRs constraint

$$
\begin{aligned}
&\text{Minimize} && \sum_{i\in\mathcal{M}_p} p_i + \sum_{j\in\mathcal{M}^s} p_j && && \text{(16a)}\\
&\text{Subject to} && \gamma_i(\mathbf{p}) \geq \widehat{\gamma}_i && \forall i \in \mathcal{M}_p, && \text{(16b)}\\
& && \gamma_j(\mathbf{p}) \geq \widehat{\gamma}_j && \forall j \in \mathcal{M}^s, && \text{(16c)}\\
&\text{Variable} && \mathbf{0} \leq \mathbf{p} \leq \bar{\mathbf{p}}. && && \text{(16d)}
\end{aligned}
$$

where $\mathcal{M}_p$ is the PUs' set and $\mathcal{M}^s$ is the SUs' set.

Problem Statement

Problem 1: Minimizing the aggregate transmit power subject to target-SINRs constraint

$$
\begin{aligned}
&\text{Minimize} && \sum_{i\in\mathcal{M}_p} p_i + \sum_{j\in\mathcal{M}^s} p_j && && \text{(16a)}\\
&\text{Subject to} && \gamma_i(\mathbf{p}) \geq \widehat{\gamma}_i && \forall i \in \mathcal{M}_p, && \text{(16b)}\\
& && \gamma_j(\mathbf{p}) \geq \widehat{\gamma}_j && \forall j \in \mathcal{M}^s, && \text{(16c)}\\
&\text{Variable} && \mathbf{0} \leq \mathbf{p} \leq \bar{\mathbf{p}}. && && \text{(16d)}
\end{aligned}
$$

where $\mathcal{M}_p$ is the PUs' set and $\mathcal{M}^s$ is the SUs' set.

- In a feasible system, where all PUs and SUs can simultaneously be protected, the TPC algorithm is employed to find the optimal solution for (16).
- In an infeasible system, where there exists no power vector for simultaneously protecting all PUs and SUs, the problem is infeasible (it has no solution).

Problem Statement

Problem 2: Maximizing the aggregate throughput of SUs subject to PUs Protection

$$\begin{aligned} &\text{Maximize} && \sum_{j\in\mathcal{M}^s} \log(1+\gamma_j(\mathbf{p})) && \\ &\text{Subject to} && \sum_{j\in\mathcal{M}^s} h_{kj}p_j \le \mathrm{ITL}_k, && \forall k \in \mathcal{B}_p, \\ &\text{Variable} && \mathbf{0} \le \mathbf{p} \le \bar{\mathbf{p}}. && \end{aligned} \tag{17}$$

Problem Statement

Problem 2: Maximizing the aggregate throughput of SUs subject to PUs Protection

$$\begin{aligned} &\text{Maximize} && \sum_{j\in\mathcal{M}^s} \log(1+\gamma_j(\mathbf{p})) && \\ &\text{Subject to} && \sum_{j\in\mathcal{M}^s} h_{kj}p_j \leq \mathrm{ITL}_k, && \forall k \in \mathcal{B}_p, \\ &\text{Variable} && \mathbf{0} \leq \mathbf{p} \leq \overline{\mathbf{p}}. && \end{aligned} \tag{17}$$

Problem 2: Maximizing the aggregate throughput of SUs subject to PUs Protection

$$\begin{aligned} &\text{Maximize} && \sum_{j\in\mathcal{M}^s} \log(1+\gamma_j(\mathbf{p})) && \\ &\text{Subject to} && \gamma_i(\mathbf{p}) \geq \widehat{\gamma}_i && \forall i \in \mathcal{M}_p, \\ &\text{Variable} && \mathbf{0} \leq \mathbf{p} \leq \overline{\mathbf{p}}. && \end{aligned} \tag{18}$$

Problem Statement

Problem 3: Maximizing the number of protected SUs (minimizing SUs' outage ratio) in an infeasible system subject to PUs protection

$$
\begin{array}{lll}
\text{Maximize} & \mid \mathcal{A}^s \mid & \\
\text{Subject to} & \gamma_j(\mathbf{p}) \geq \widehat{\gamma}_j & \forall j \in \mathcal{A}^s, \\
& \displaystyle\sum_{j \in \mathcal{A}^s} h_{kj} p_j \leq \mathrm{ITL}_k, & \forall k \in \mathcal{B}_p, \\
\text{Variable} & \mathbf{0} \leq \mathbf{p} \leq \bar{\mathbf{p}} & \\
& \mathcal{A}^s \subseteq \mathcal{M}^s &
\end{array}
\tag{19}
$$

Problem Statement

Problem 3: Maximizing the number of protected SUs (minimizing SUs' outage ratio) in an infeasible system subject to PUs protection

$$\begin{array}{lll} \text{Maximize} & \mid \mathcal{A}^s \mid & \\ \text{Subject to} & \gamma_j(\mathbf{p}) \geq \widehat{\gamma}_j & \forall j \in \mathcal{A}^s, \\ & \gamma_i(\mathbf{p}) \geq \widehat{\gamma}_i & \forall i \in \mathcal{M}_p, \\ \text{Variable} & \mathbf{0} \leq \mathbf{p} \leq \overline{\mathbf{p}} & \\ & \mathcal{A}^s \subseteq \mathcal{M}^s & \end{array} \tag{20}$$

Problem Statement

Problem 3: Maximizing the number of protected SUs (minimizing SUs' outage ratio) in an infeasible system subject to PUs protection

$$\begin{array}{lll} \text{Maximize} & \mid \mathcal{A}^s \mid & \\ \text{Subject to} & \gamma_j(\mathbf{p}) \geq \widehat{\gamma}_j & \forall j \in \mathcal{A}^s, \\ & \gamma_i(\mathbf{p}) \geq \widehat{\gamma}_i & \forall i \in \mathcal{M}_p, \\ \text{Variable} & \mathbf{0} \leq \mathbf{p} \leq \bar{\mathbf{p}} & \\ & \mathcal{A}^s \subseteq \mathcal{M}^s & \end{array} \tag{20}$$

- Generally, this problem is an NP-hard problem.
- There may be many power vectors belonging to the set of optimal solution to (21) and result in minimum outage ratio.
- Those solutions that correspond to the minimum aggregate transmit power of the supported users are of most importance.

Problem Statement

Problem 3: Maximizing the number of protected SUs (minimizing SUs' outage ratio) in an infeasible system subject to PUs protection

$$\begin{array}{lll} \text{Minimize} & O^s(\mathbf{p}) & \\ \text{Subject to} & \gamma_i(\mathbf{p}) \geq \widehat{\gamma}_i & \forall i \in \mathcal{M}_p, \\ \text{Variable} & \mathbf{0} \leq \mathbf{p} \leq \bar{\mathbf{p}}. & \end{array} \tag{21}$$

where $O^s(\mathbf{p}) = \frac{|\mathcal{S}^{s\prime}(\mathbf{p})|}{|\mathcal{M}^s|}$ and $\mathcal{S}^s(\mathbf{p}) = \{j \in \mathcal{M}^s \mid \gamma_j \geq \widehat{\gamma}_j\}$.

Problem Statement

We focus on the problem 3

$$
\begin{array}{lll}
\text{Maximize} & \mid \mathcal{A}^s \mid & \\
\text{Subject to} & \gamma_j(\mathbf{p}) \geq \widehat{\gamma}_j & \forall j \in \mathcal{A}^s, \\
& \sum\limits_{j \in \mathcal{A}^s} h_{kj} p_j \leq \mathrm{ITL}_k, & \forall k \in \mathcal{B}_p, \\
\text{Variable} & \mathbf{0} \leq \mathbf{p} \leq \bar{\mathbf{p}} & \\
& \mathcal{A}^s \subseteq \mathcal{M}^s &
\end{array}
\tag{22}
$$

Existing Heuristic Algorithms

Centralized Algorithms

The centralized JPAC algorithms are categorized according to the procedures of gradually removing SUs.

Existing Heuristic Algorithms

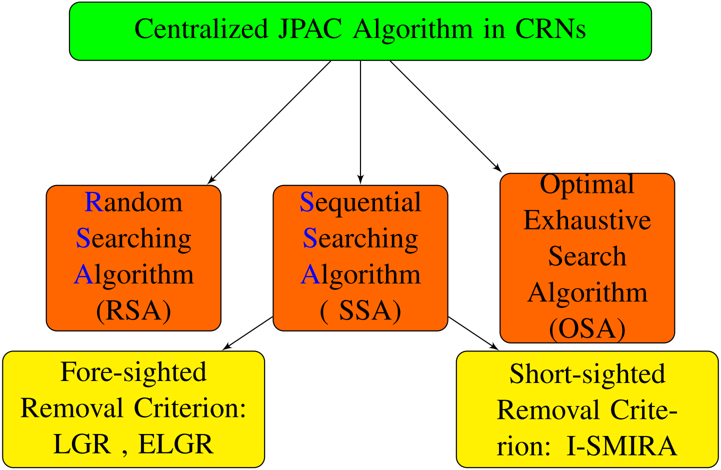
Centralized Algorithms

The centralized JPAC algorithms are categorized according to the procedures of gradually removing SUs.

Distributed Algorithms

Existing distributed power control algorithms in traditional cellular networks with gradual removal capability cannot be directly applied to underlay cognitive radio networks, since it may cause outage of PUs.

Existing Centralized Algorithms



Existing Centralized Algorithms

Optimal Searching Algorithm (OSA)

- They are based on the exhaustive checking of the feasibility of all possible sets of the admitted SUs,
- They obtain the globally optimal solution but may lead to unaffordable computational complexity.

Existing Centralized Algorithms

Optimal Searching Algorithm (OSA)

- They are based on the exhaustive checking of the feasibility of all possible sets of the admitted SUs,
- They obtain the globally optimal solution but may lead to unaffordable computational complexity.

Random Searching Algorithm (RSA)

- They are based on probabilistic mechanisms used for the SUs to access the channel,
- They suffer from low speed of convergence.

Existing Centralized Algorithms

Sequential Searching Algorithm (SSA)

- The opportunity to access the spectrum is quantified by assigning some admission metric to each SU,
  - How to express the admission metric (Removal Criterion),
- The SUs with lower values of the admission metrics are gradually removed until the networks become feasible for remaining SUs along with the PUs.
- The greater value for admission metric, the more opportunity to access the spectrum,

Existing Centralized Algorithms

Psudocode for the SSA

The psuedocode for a general SSA is given in **Algorithm 1**.

Initialization Phase:
Let $\mathcal{M}^p$, and $\mathcal{M}^s$ be sets of the PUs, and SUs, respectively
and let $\mathcal{A}^s = \mathcal{M}^s$ be the admitted SUs
Step 1 (Feasibility Checking Phase):
  Check the feasibility of the target-SINRs vector of the set $\mathcal{A}^s \cup \mathcal{M}^p$
  if the target-SINRs for the set $\mathcal{A}^s \cup \mathcal{M}^p$ is feasible
    Admit all SUs in $\mathcal{A}^s$
    Terminate the Algorithm
  else
    Go to Step 2
Step 2 (Removal Phase):
  $i^* = \text{argmax}_{i \in \mathcal{A}^s} \text{RC}_i$, where RC_i is a removal criterion measured either at this step (short-sighted) or at initialization phase (fore-sighted)
  $\mathcal{A}^s \leftarrow \mathcal{A}^s \backslash i^*$
  Go back Step 1

Algorithm 1: Psuedocode for the SSA

Existing Centralized Algorithms

Psudocode for the SSA

- In SSA, at first (initialization phase), all SUs together with PUs are admitted. Then at the feasibility checking phase, the required target SINRs for all PUs and admitted SUs is checked. If it is feasible, the algorithm terminates, else the SUs are sequentially removed based on a certain removal (or admission) metric, until the target SINRs for all PUs together with remained SUs become feasible.
- As can be seen, a sequential searching algorithm consists of two main phases of feasibility checking and SU removal, which are explained below.

Existing Centralized Algorithms

Feasibility Checking Phase

There are two mechanisms for feasibility checking of a given SINR vector in a conventional cellular wireless network. They are centralized and distributed feasibility checking mechanisms which may be also used in underlay CRNs.

Existing Centralized Algorithms

Centralized feasibility checking

The power vector $\mathbf{p}$ corresponding to a given SINR vector $\boldsymbol{\gamma} = [\gamma_1, \gamma_2, \ldots, \gamma_M]^{\mathrm{T}}$ is obtained as

$$\mathbf{p} = \left(\mathbf{I} - \mathbf{D}(\boldsymbol{\gamma})\mathbf{G}\right)^{-1}\mathbf{D}(\boldsymbol{\gamma})\boldsymbol{\eta}.$$

Therefore, the target-SINRs vector $\widehat{\boldsymbol{\gamma}}$ is feasible, if

$$\mathbf{0} \leq \left(\mathbf{I} - \mathbf{D}(\widehat{\boldsymbol{\gamma}})\mathbf{G}\right)^{-1}\mathbf{D}(\widehat{\boldsymbol{\gamma}})\boldsymbol{\eta} \leq \bar{\mathbf{p}}. \tag{23}$$

This enables us to check the feasibility of a given target SINR vector.

Existing Centralized Algorithms

Centralized feasibility checking

The power vector **p** corresponding to a given SINR vector $\boldsymbol{\gamma} = [\gamma_1, \gamma_2, \ldots, \gamma_M]^{\mathrm{T}}$ is obtained as

$$\mathbf{p} = \left(\mathbf{I} - \mathbf{D}(\boldsymbol{\gamma})\mathbf{G}\right)^{-1}\mathbf{D}(\boldsymbol{\gamma})\boldsymbol{\eta}.$$

Therefore, the target-SINRs vector $\widehat{\boldsymbol{\gamma}}$ is feasible, if

$$\mathbf{0} \leq \left(\mathbf{I} - \mathbf{D}(\widehat{\boldsymbol{\gamma}})\mathbf{G}\right)^{-1}\mathbf{D}(\widehat{\boldsymbol{\gamma}})\boldsymbol{\eta} \leq \bar{\mathbf{p}}. \tag{23}$$

This enables us to check the feasibility of a given target SINR vector.

Distributed feasibility checking

The target-SINR tracking power control algorithm (TPC):

$$p_i(t+1) = \max\{\bar{p}_i, \frac{\widehat{\gamma}_i}{\gamma_i(\mathbf{p}(t))} p_i(t)\}, \quad \forall i \in \mathcal{M} \tag{24}$$

Existing Centralized Algorithms

Removal Critrion (RC)

- Short-sighted RC (Dynamic RC): The admission metric of each SUs is changed as any of SUs is removed from the active SUs at each iteration of removal process,
  - Instantaneous power, interference, effective interference and SINR,
- Fore-sighted RC (Static RC): the admission metric of each SUs is not changed as any of SUs is removed from the active SUs at each iteration of removal process.
  - Path gain, target SINR and maximum transmit power.

Interference constraint-aware Stepwise Maximum Interference Removal Algorithm (I-SMIRA) [1]

Optimization problem: Finding the maximum feasible set

$$
\begin{array}{lll}
\text{Maximize} & \mid \mathcal{A}^s \mid & \\
\text{Subject to} & \gamma_j(\mathbf{p}) \geq \widehat{\gamma}_j & \forall j \in \mathcal{M}^s, \\
& \displaystyle\sum_{j \in \mathcal{A}^s} h_{kj} p_j \leq \mathrm{ITL}_k, & \forall k \in \mathcal{B}_p, \\
\text{Variable} & \mathbf{0} \leq \mathbf{p} \leq \overline{\mathbf{p}} & \\
& \mathcal{A}^s \subseteq \mathcal{M}^s &
\end{array}
\tag{25}
$$

Interference constraint-aware Stepwise Maximum Interference Removal Algorithm (I-SMIRA) [1]

- The short-sighted removal criterion in I-SMIRA depends on the following dynamic parameters:

Interference Measures

Given the transmit power vector $\mathbf{p}$ obtained by the TPC, when all admitted SUs employ the TPC, let define

$$\alpha_j(\mathbf{p}) = \left[p_j \sum_{i \in \mathcal{A}^s, i \neq j} h_{b_i j} + \nu_{b_j} \right] - \frac{h_{b_j j}}{\widehat{\gamma}_j} p_j, \text{ for all } j \in \mathcal{M}^s \tag{26}$$

- ν_{b_j} is the total noise power at receiver b_j,
- α_j quantifies the aggregate relative interference that secondary user j causes to other SUs,

Interference constraint-aware Stepwise Maximum Interference Removal Algorithm (I-SMIRA)[1]

Interference Measures

$$\beta_j(\mathbf{p}) = \left[\sum_{i\in\mathcal{A}^s, i\neq j}^{N} h_{b_j i} p_i + \nu_{b_j}\right] - \frac{h_{b_j j}}{\widehat{\gamma}_j} p_j, \text{ for all } j \in \mathcal{A}^s$$

- β_j reflects the degree by which the QoS constraint for secondary user j is violated,

Interference constraint-aware Stepwise Maximum Interference Removal Algorithm (I-SMIRA) [1]

Interference Measures

$$D = \sum_{j \in \mathcal{A}^s} \beta_j(\mathbf{p})$$

- We can easily see that

$$D = \sum_{j \in \mathcal{A}^s} \beta_j(\mathbf{p}) = \sum_{j \in \mathcal{A}^s} \alpha_j(\mathbf{p})$$

- We can also see that if the QoS constraint for SU i is satisfied with equality, then $\beta_i(\mathbf{p}) = 0$.
- Also $D = 0$ if and only if all admitted SUs in $\mathcal{A}^s$ are supported.

Interference constraint-aware Stepwise Maximum Interference Removal Algorithm (I-SMIRA) [1]

Interference Measures

$$\eta_k = \mathrm{ITL}_k - \sum_{j \in \mathcal{A}^s} h_{kj} p_j, \qquad \forall k \in \mathcal{B}_p$$

- η_b measures the feasibility violation at the primary base station k.

Interference constraint-aware Stepwise Maximum Interference Removal Algorithm (I-SMIRA) [1]

Interference Measures

$$\eta_k = \mathrm{ITL}_k - \sum_{j \in \mathcal{A}^s} h_{kj} p_j, \qquad \forall k \in \mathcal{B}_p$$

- η_b measures the feasibility violation at the primary base station k.

Short-sighted Removal Criterion

$$\mathrm{RC}_j = \left\{ \frac{D(\mathbf{p})}{D(\mathbf{p}) + \sum_{k \in \mathcal{B}_p} \eta_b} \times \max \left[\sum_{i \in \mathcal{A}^s, i \neq j}^{N} h_{b_j i} p_i, \sum_{i \in \mathcal{A}^s, i \neq j} h_{b_i j} p_j \right] + \sum_{k \in \mathcal{B}_p} \frac{\eta_k}{D(\mathbf{p}) + \sum_{k' \in \mathcal{B}_p} \eta_k'} h_{kj} p_j \right\}, j \in \mathcal{A}^s \tag{27}$$

Interference constraint-aware Stepwise Maximum Interference Removal Algorithm (I-SMIRA) [1]

I-SMIRA

Initialization:

Let , $\mathcal{A}^s \leftarrow \mathcal{M}^s$;

Step1: Feasibility Checking Phase

Starting from a non-negative power vector, let $\mathbf{p}$ be the stationary solution obtained through the following iterative power update function:

$$p_j^{t+1} = \begin{cases} \min\{\bar{p}_j, \dfrac{\widehat{\gamma}_j}{\gamma_j(\mathbf{p}^t)} p_j^t\}, & \text{if } j \in \mathcal{M}_p \bigcup \mathcal{A}^s, \\ 0, & \text{if } j \in \mathcal{M}^s \backslash \mathcal{A}^s. \end{cases}$$

Check the feasibility of the target-SINRs vector of $\mathcal{A}^s \cup \mathcal{M}_p$ if all PUs are protected and all admitted SUs are supported with target SINR;

if the target SINR vector is feasible

Admit all SUs in $\mathcal{A}^s$;

Terminate the Algorithm;

else

Go to Step2;

Step2: Removal Phase

If the interference limit of the PBSs are not violated but $\exists\, j \in \mathcal{A}^s$ such that $\gamma_j(\mathbf{p}) < \widehat{\gamma}_j$:

$j^* = \max_{j \in \mathcal{A}^s} \{\max(\alpha_j(\mathbf{p}), \beta_j(\mathbf{p}))\}$;

If the interference limits of PBSs are violated: $j^* = \max_{j \in \mathcal{A}^s} \mathrm{RC}_j$:

$\mathcal{A}^s \leftarrow \mathcal{A}^s \backslash j^*$; Go back Step1;

Interference constraint-aware Stepwise Maximum Interference Removal Algorithm (I-SMIRA) [1]

Discussion

- The interference at each SBS due to PUs transmissions is considered as a fixed value.
- The value of the ITL has been assumed constant.
- The overall complexity of the I-SMIRA is at least of $O(|\mathcal{M}^s|^3)$.

Link Gain Ratio (LGR) Algorithm [2]

Optimization problem: Finding the maximum feasible set

$$
\begin{aligned}
&\text{Maximize} && \mid \mathcal{A}^s \mid && && \text{(28a)}\\
&\text{Subject to} && \gamma_j(\mathbf{p}) \geq \widehat{\gamma}_j && \forall j \in \mathcal{M}^s, && \text{(28b)}\\
& && \sum_{j \in \mathcal{A}^s} h_{kj} p_j \leq \mathrm{ITL}_k, && \forall k \in \mathcal{B}_p, && \text{(28c)}\\
&\text{Variable} && \mathbf{0} \leq \mathbf{p} \leq \overline{\mathbf{p}}, && && \text{(28d)}\\
& && \mathcal{A}^s \subseteq \mathcal{M}^s, && && \text{(28e)}
\end{aligned}
$$

where $\mathcal{B}_p$ is the set of PBSs.

Link Gain Ratio (LGR) Algorithm [2]

- The LGR is developed from the constraints on p_j, the transmission power of secondary user $j \in \mathcal{M}^s$.
- Substituting $\gamma_j = \frac{p_j h_{b_j j}}{I_j(\mathbf{p})}$ into the (28b) gives

$$p_j \geq \frac{\widehat{\gamma}_j}{h_{b_j j}}(\nu_{b_j} + \sum_{i \in \mathcal{M}^s, i \neq j} p_i h_{b_j i}). \tag{29}$$

From (28c), we have

$$p_j \leq \frac{\mathrm{ITL}_k}{h_{kj}} - \sum_{i \in \mathcal{M}^s, i \neq j} p_i \frac{h_{ki}}{h_{kj}}, \quad \forall k \in \mathcal{B}_p. \tag{30}$$

- By combining (29) and (30), we obtain

$$\frac{\widehat{\gamma}_j}{h_{b_j j}}(\nu_{b_j} + \sum_{i \in \mathcal{M}^s, i \neq j} p_i h_{b_j i}) \leq p_j \leq \frac{\mathrm{ITL}_k}{h_{kj}} - \sum_{i \in \mathcal{M}^s, i \neq j} p_i \frac{h_{ki}}{h_{kj}}, \quad \forall k \in \mathcal{B}_p \tag{31}$$

- By combining (29) and (30), we obtain

$$f_{kj} \leq \mathrm{ITL}_k \times \frac{h_{b_j j}}{h_{kj}}, \quad \forall k \in \mathcal{B}_p \tag{32}$$

where $f_{kj} = \widehat{\gamma}_j \nu_{b_j} + \sum_{i \in \mathcal{M}^s, i \neq j}(\widehat{\gamma}_j h_{b_j i} + \frac{h_{ki}}{h_{kj}} h_{b_j j}) p_i$, is the interference caused by other secondary users to secondary user j.

- $\mathrm{ITL}_k \times \frac{h_{b_j j}}{h_{kj}}$ reflects an interference-resistant capability of the secondary user j.

Link Gain Ratio (LGR) Algorithm [2]

The Fore-sighted Removal Criteion

- The admission metric of secondary use i which is named as LGR is:

$$\min_{k \in \mathcal{B}_p} \mathrm{ITL}_k \times \frac{h_{b_j j}}{h_{kj}} \tag{33}$$

- In general, a secondary user with higher LGR is supported with its target-SINR in presence of stronger interference.

Link Gain Ratio (LGR) Algorithm

[2]

LGRA [2]

Initialization:
    Let, $\mathcal{A}^s \leftarrow \mathcal{M}^s$;
    Let $\mathrm{RC}_j = \min_{k\in\mathcal{B}^p} \mathrm{ITL}_k \times \frac{h_{b_j j}}{h_{kj}}, \quad \forall j \in \mathcal{M}^s$;
Step1: Feasibility Checking Phase
    Employ the second feasibility checking methode and check if the target SINR vector of the set $\mathcal{A}^s \cup \mathcal{M}_p$ is feasible or not;
        if it is feasible
            Admit all SUs in $\mathcal{A}^s$;
            Terminate the Algorithm;
        else
            Go to Step2;
Step2: Removal Phase
    $j^* = \min_{i\in\mathcal{A}^s} \mathrm{RC}_j$;
    $\mathcal{A}^s \leftarrow \mathcal{A}^s \backslash \{j^*\}$;
    Go back Step1;

Link Gain Ratio (LGR) Algorithm

[2]

Discussion

- It is assumed that all SUs have the same QoS (target-SINR).
- The Interference Temperature Limit , ITL_k, is considered fixed $\forall k \in \mathcal{B}_p$.
- When the target-SINRs of the SUs are not the same the performance of the LGRA in terms of outage ratio degrades.
- The complexity of the LGRA is $O(|\ \mathcal{N}\ |^2 \log_2 |\ \mathcal{N}\ |)$

Effective Link Gain Ratio (ELGR) Algorithm [3]

The Fore-sighted Removal Criterion

The network model in [3] is assumed to consists of one primary base station and one secondary base station.

$\frac{\widehat{\gamma}_j}{\widehat{\gamma}_j+1} \times \frac{h_j^{(p)}}{h_j^{(s)}}$ is the effective link gain ratio (ELGR) of SU j, where $h_j^{(p)}$ and $h_j^{(s)}$ are the path gain of user j with primary and secondary BSs, respectively.

A secondary user having the higher ELGR value affects the others more and therefore, should have less opportunity to access the network

Effective Link Gain Ratio (ELGR) Algorithm [3]

ELGRA [3]

Initialization:
    Let, $\mathcal{A}^s \leftarrow \mathcal{M}^s$;
    Let $\mathrm{RC}_j = \frac{\widehat{\gamma}_j}{\widehat{\gamma}_j+1} \times \frac{h_j^{(p)}}{h_j^{(s)}}, \quad \forall j \in \mathcal{M}^s$;
Step1: Feasibility Checking Phase
    Employ the third feasibility checking methode and check if the target SINRs vector of the set $\mathcal{A}^s \cup \mathcal{M}_p$ is feasible or not;
        if it is feasible
            Admit all SUs in $\mathcal{A}^s$;
            Terminate the Algorithm;
        else
            Go to Step2;
Step2: Removal Phase
    $j^* = \max_{j \in \mathcal{A}^s} \mathrm{RC}_j$
    $\mathcal{A}^s \leftarrow \mathcal{A}^s \backslash \{j^*\}$;
    Go back Step1;

Effective Link Gain Ratio (ELGR) Algorithm [3]

Discussion

- The network consists of one primary base station and one secondary base station.
- The ITL at the PBS is

$$\bar{I}^{(p)} = \min_{i \in \mathcal{M}_p} \left(\frac{\bar{p}_i h_i^{(p)}}{\frac{\widehat{\gamma}_j}{\widehat{\gamma}_j + 1}} \right) \times \left(1 - \sum_{j \in \mathcal{M}_p} \frac{\widehat{\gamma}_j}{\widehat{\gamma}_j + 1} \right) - N^{(p)} \qquad (34)$$

- The ELGRA outperforms the LGRA in terms of complexity and performance.
- The complexity of the ELGRA is $O(\mid \mathcal{M}^s \mid \log_2 \mid \mathcal{M}^s \mid)$

Removel Criterion

Short-Sighted Removal Criterion

- I-SMIRA:

$$\mathrm{RC}_j = \left\{ \frac{D(\mathbf{p})}{D(\mathbf{p}) + \sum_{k=1}^{B^p} \eta_b} \times \max\left[\sum_{n=1,n\neq j}^{N} h_{b_j n} p_n , \sum_{n=1,n\neq j}^{N} h_{b_n j} p_j \right] + \sum_{k=1}^{B^p} \frac{\eta_b}{D(\mathbf{p}) + \sum_{k=1}^{B^p} \eta_k} h_{kj} p_j \right\}, j = 1 \ldots N$$

Removel Criterion

Short-Sighted Removal Criterion

- I-SMIRA:

$$\mathrm{RC}_j = \left\{ \frac{D(\mathbf{p})}{D(\mathbf{p}) + \sum_{k=1}^{B^p} \eta_b} \times \max\left[\sum_{n=1,n\neq j}^{N} h_{b_j n} p_n, \sum_{n=1,n\neq j}^{N} h_{b_n j} p_j \right] + \sum_{k=1}^{B^p} \frac{\eta_b}{D(\mathbf{p}) + \sum_{k=1}^{B^p} \eta_k} h_{kj} p_j \right\}, j = 1 \ldots N$$

Fore-Sighted Removal Criterion

- LGRA: $\mathrm{RC}_j = \min_{k\in\mathcal{B}_p} \mathrm{ITL}_k \times \frac{h_{b_j j}}{h_{kj}}, \quad \forall j \in \mathcal{M}^s$
- ELGRA: $\mathrm{RC}_j = \widehat{\theta}_j \times \frac{h_j^{(p)}}{h_j^{(s)}}, \quad \forall j \in \mathcal{M}^s$

Feasibility Checking

Table: Computational Complexity of the Feasibility Checking Mechanisms

Algorithms	Complexity Order
I-SMIRA	$O(\mid \mathcal{M}^s \mid^3)$
LGRA	$O(\mid \mathcal{M}^s \mid^2)$
ELGRA	$O(\mid \mathcal{M}^s \mid)$

Complexity Analysis

Table: Computational Complexity of the Algorithms

Algorithms	Complexity Order
I-SMIRA	$O(\mid \mathcal{M}^s \mid^3)$
LGRA	$O(\mid \mathcal{M}^s \mid^2 \log \mid \mathcal{M}^s \mid)$
ELGRA	$O(\mid \mathcal{M}^s \mid \log \mid \mathcal{M}^s \mid)$

System Model and Notations

Again, consider a multi-cell wireless network.

New Notations

Let $\mathcal{M}_m^p$ and $\mathcal{M}_n^s$ denote the sub-set of PUs and SUs associated to BSs $m \in \mathcal{B}^p$ and $n \in \mathcal{B}^s$, respectively, i.e., $\mathcal{M}_m^p = \{i \in \mathcal{M}^p | \; b_i = m\}$, and $\mathcal{M}_n^s = \{i \in \mathcal{M}^s | \; b_i = n\}$.

Let us also define the effective SINR of user i by $\theta_i(\mathbf{p}) = \dfrac{\gamma_i(\mathbf{p})}{\gamma_i(\mathbf{p}) + 1}$, which is the ratio of received power of user i to the total received power plus noise, i.e., $\theta_i(\mathbf{p}) = \dfrac{p_i h_{b_i i}}{\varphi_{b_i}(\mathbf{p})}$.

Definitions

Primary Users Protection: Formal Definition

For a given power vector $\mathbf{0} \le \mathbf{p} \le \bar{\mathbf{p}}$, a user $i \in \mathcal{M}$ is said to be protected if $\gamma_i(\mathbf{p}) \ge \widehat{\gamma}_i$, where $\gamma_i(\mathbf{p})$ is obtained from

$$\gamma_i(\mathbf{p}) = \begin{cases} \dfrac{p_i h_{b_i i}}{\sum\limits_{k \in \mathcal{M}^s} p_k h_{b_i k} + \sum\limits_{j \in \mathcal{M}_p, j \neq i} p_j h_{b_i j} + \sigma_{b_i}^2}, & \text{for } i \in \mathcal{M}_p \\ \dfrac{p_i h_{b_i i}}{\sum\limits_{k \in \mathcal{M}^s, k \neq i} p_k h_{b_i k} + \sum\limits_{j \in \mathcal{M}_p} p_j h_{b_i j} + \sigma_{b_i}^2}, & \text{for } i \in \mathcal{M}^s \end{cases} \tag{35}$$

Correspondingly, for a given SINR vector $\boldsymbol{\gamma} \ge \widehat{\boldsymbol{\gamma}}$, a user $i \in \mathcal{M}$ is said to be protected if $0 \le p_i(\boldsymbol{\gamma}) \le \bar{p}_i$ where $p_i(\boldsymbol{\gamma})$ is obtained from

$$\mathbf{p} = \mathbf{D}(\boldsymbol{\gamma})\mathbf{G}\mathbf{p} + \mathbf{D}(\boldsymbol{\gamma})\boldsymbol{\eta} \tag{36}$$

Problem Statement: Characterization of Feasible Interference Region

We wish to state the protection of the PUs' constraints in terms of the constraints on the maximum interference that can be caused to PBSs. For each PBS, this can be defined as:

Interference Feasible Region

- *Total received power* by the corresponding PBS

Corresponding to the above, the *feasible total received-power region* (FTRP) is derived.

Expressing PUs' Protection Constraints Based on FTRP: Total Received-Power-Temperature at the PBS

Given the uplink power vector $\mathbf{p}$ corresponding to an SINR vector $\boldsymbol{\gamma}$, let φ_m^p denote the total received power plus noise at the BS $k \in \mathcal{B}^{\mathrm{p}}$, i.e.,

$$\varphi_k(\mathbf{p}) = \sum_{i \in \mathcal{M}} p_i h_{ki} + N_k. \tag{37}$$

Expressing PUs' Protection Constraints Based on FTRP: Total Received-Power-Temperature at the PBS

Let $\overline{\varphi}_k$ denote the maximum value of the total received power plus noise at the BS $k \in \mathcal{B}^{\mathrm{p}}$ that can be tolerated by all of its associated PUs. We call $\overline{\varphi}_k$ as the *total received-power-temperature* for PBS k, which is formally defined and obtained as follows:

$$\overline{\varphi}_k = \max\left\{\varphi \mid 0 \leq \frac{\widehat{\theta}_i}{h_{k,i}}\varphi \leq \overline{p}_i, \forall i \in \mathcal{M}_k^{\mathrm{p}}\right\} = \min_{i \in \mathcal{M}_k^{\mathrm{p}}} \left\{\frac{\overline{p}_i h_{k,i}}{\widehat{\theta}_i}\right\}. \qquad (38)$$

Lemma

If the transmit power vector $\mathbf{p}$ *satisfies the SINR requirements of all PUs then we have* $\varphi_k(\mathbf{p}) \leq \overline{\varphi}_k$*, for all* $k \in \mathcal{B}^{\mathrm{p}}$*, or equivalently,* $\max_{k \in \mathcal{B}^{\mathrm{p}}} \left\{\frac{\varphi_k(\mathbf{p})}{\overline{\varphi}_k}\right\} \leq 1.$

TPC with PU-protection algorithm (TPC-PP) [4]

$$p_i(t+1)=\begin{cases}\min\left\{\bar{p}_i,\ \dfrac{\widehat{\gamma}_i}{\gamma_i(\mathbf{p}(t))}p_i(t)\right\}, & \text{for all } i\in\mathcal{M}^{\mathrm{p}}\\ \min\left\{\bar{p}_i,\ \beta(t)p_i(t),\ \dfrac{\widehat{\gamma}_i}{\gamma_i(\mathbf{p}(t))}p_i(t)\right\}, & \text{for all } i\in\mathcal{M}^{\mathrm{s}},\end{cases} \tag{39}$$

where $\beta(t) = \min_{k\in\mathcal{B}^{\mathrm{p}}} \left\{\dfrac{\overline{\varphi}_k}{\varphi_k(\mathbf{p}(t))}\right\}$.

References

1 L. B. Le, E. Hossein, "Resource allocation for spectrum underlay in cognitive radio networks," *IEEE Transactions on wireless Communications*, vol. 7, no. 12, Dec. 2008.

2 H. Gu, N. C. Yang, and B. Fong, "Low-complexity centralized joint power and admission control in cognitive radio networks," *IEEE Communication letters,* vol. 13, no. 6, Jun. 2009.

3 M. Monemi, M. Rasti, and E. Hossain, "On joint power and admission control in underlay cognitive radio networks," *IEEE Transactions on wireless Communications,* July 2014.

4 [3] M. Rasti, M. Hasan, L. B. Le, and E. Hossain, ?Distributed uplink power control for multi-cell cognitive radio networks,? *IEEE Transactions on Communications,* vol. 59, no. 3, pp. 628 -642, 2015.