Resource Allocation for Asynchronous Cognitive Radio Networks with FBMC/OFDM under Statistical CSI

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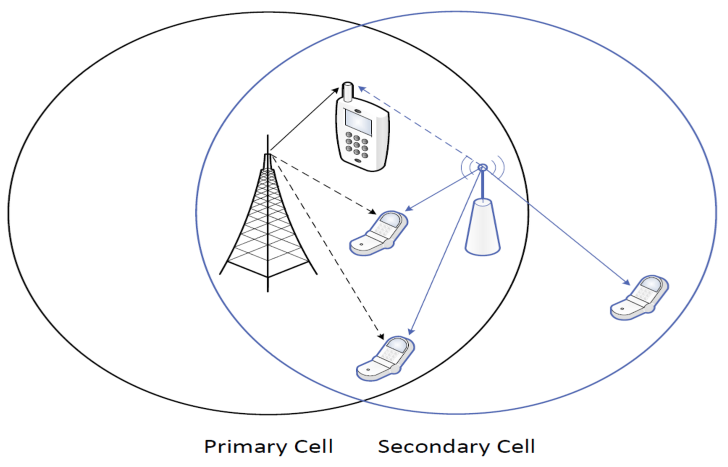
Abstract

We address the problem of resource allocation for a filter banked multi-carrier (FBMC) and orthogonal frequency division multiplexing (OFDM) based cognitive radio network under the assumption of statistical channel state information (CSI). Firstly, we propose a heuristic subcarrier allocation paradigm by utilizing an outage-based metric. Secondly, we conservatively approximate the intractable non-convex power-rate control problem and propose a sequential-based algorithm to efficiently obtain a solution to the problem. The proposed algorithm has been shown to converge to solutions that are stationary points of the original power-rate problem.

System Model and Interference Model

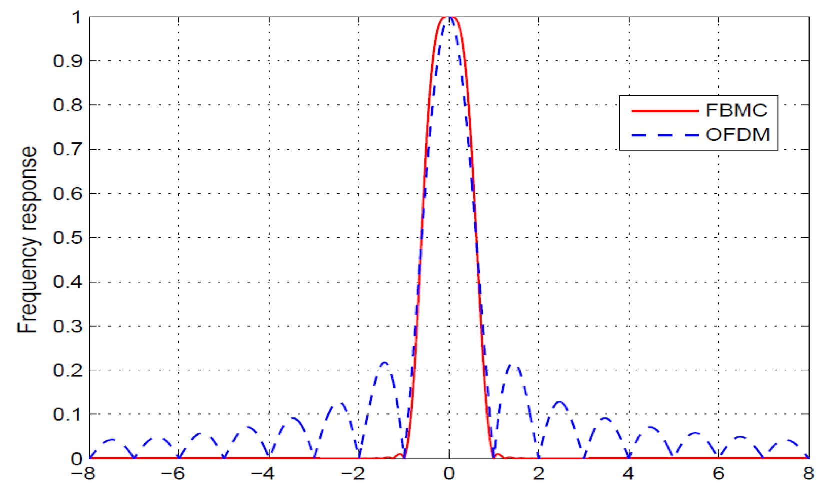


Downlink underlay cognitive network with L subcarriers.

Primary cell: one base station (BS) and one mobile.

Secondary cell: one BS serving $\mathcal{K}$ mobiles.

Single input single output (SISO) system



Asynchronism leads to inter-carrier interferences.

Interference weight vector:

$$V^{\text{OFDM}} = [\{705, 89.4, 22.3, 9.95, 5.6, 3.59, 2.5, 1.84, 1.12\} \times 10^{-3}]$$
$$V^{\text{FBMC}} = [8.23 \times 10^{-1}, 8.81 \times 10^{-2}]$$

Problem Formulation

Goal: maximize the secondary sum rate subject to outage and power constraints.

$$\max_{\substack{\mathbf{P}_s \geq 0, \mathcal{R} \geq 0 \\ \Theta \in \{0,1\}}} \sum_{k=1}^{\mathcal{K}} \mathcal{R}_k$$
$$\text{s.t. } \Pr\left\{\sum_{l=1}^{L} \theta_{s,k}^l \log_2\left(1+\Gamma_{s,k}^l\right) < \mathcal{R}_k\right\} \leq \epsilon_k, \ \forall k$$
$$\Pr\left\{\sum_{l=1}^{L} \log_2\left(1+\Gamma_{p,p}^l\right) < \mathcal{R}_p\right\} \leq \epsilon_p$$
$$\sum_{k=1}^{\mathcal{K}} \theta_{s,k}^l \leq 1 \quad l = 1, \cdots, L, \quad \sum_{l=1}^{L} P_s^l \leq P_{\max}$$

Subcarrier allocation vector:
$\Theta = (\theta_{s,1}^1, \cdots \theta_{s,\mathcal{K}}^1, \cdots, \theta_{s,1}^L, \cdots \theta_{s,\mathcal{K}}^L)^\top$

Primary mobile SINR on subcarrier l:

$$\Gamma_{p,p}^l = \frac{P_p^l |h_{p,p}^l|^2}{N_0 + \sum_{l'=1}^{L} P_s^{l'} V_{|l-l'|} |h_{s,p}^{l'}|^2}$$

K-th secondary mobile SINR on subcarrier l:

$$\Gamma_{s,k}^l = \frac{P_s^l |h_{s,k}^l|^2}{N_0 + \sum_{l'=1}^{L} P_p^{l'} V_{|l-l'|} |h_{p,k}^{l'}|^2}, \forall k$$

N_0 : noise variance on each subcarrier .

P_s^l : Secondary power on subcarrier l .

$h_{i,j}^l \sim \mathcal{CN}(0, g_{i,j}^l)$: channel between BS i and user j on subcarrier l.

P_p^l : non-adaptive power of primary BS.

Subcarrier Allocation Scheme

Given a uniform power allocation $P_s^l = \frac{P_{\max}}{L}$ and a transmitted target rate $\bar{r}_l$ per subcarrier, the subcarrier allocation procedure is given by :

$$\theta_{s,k}^l = \arg\max_k e^{-\frac{N_0(2^{\bar{r}_l}-1)}{g_{s,k}^l \frac{P_{\max}}{L}}} \prod_{l' \in \mathcal{L}_l} \left(\frac{g_{s,k}^l}{g_{s,k}^l + g_{p,k}^{l'} V_{|l-l'|}(2^{\bar{r}_l}-1)}\right)$$

where $\mathcal{L}_l$ corresponds to the set of subcarriers that interfere with the lth subcarrier.

Outage Probability Bound

Lemma 1 The primary outage probability can be upper-bounded by :

$$\Pr\left\{\sum_{l=1}^{L}\log_2\left(1+\frac{P_p^l|h_{p,p}^l|^2}{N_0+\sum_{l'\in\mathcal{L}_l}P_s^{l'}|h_{s,p}^{l'}|^2 V_{|l-l'|}}\right) < R_p\right\} \leq 1-\left(\prod_{l=1}^{L} e^{-\frac{N_0\bar{\alpha}}{g_{p,p}^l P_p^l}}\right)\left(\prod_{l'=1}^{L}\left(\frac{1}{1+\bar{\alpha}\sum_{l\in I_{p,l'}}\frac{g_{s,p}^{l'}P_s^{l'}V_{|l-l'|}}{g_{p,p}^l P_p^l}}\right)\right)$$

and the secondary outage probability by :

$$\Pr\left\{\sum_{l\in\Omega_k}\log_2\left(1+\frac{P_s^l|h_{s,k}^l|^2}{N_0+\sum_{l'\in\mathcal{L}_l}P_p^{l'}|h_{p,k}^{l'}|^2 V_{|l-l'|}}\right) < R_k\right\} \leq 1-\left(\prod_{l\in\Omega_k} e^{-\frac{N_0(2^{R_k/|\Omega_k|}-1)}{g_{s,k}^l P_s^l}}\right)\left(\prod_{l'=1}^{L}\left(\frac{1}{1+\sum_{l\in I_{k,l'}}\frac{g_{p,k}^{l'}P_p^{l'}V_{|l-l'|}(2^{R_k/|\Omega_k|}-1)}{g_{s,k}^l P_s^l}}\right)\right)$$

where $I_{j,i}$ denotes the set of subcarriers allocated to user j that suffers interferences generated by the ith subcarrier.

Conservative Approximation of the power control problem

Secondary power control sub-problem can be approximated as:

(P1)

$$\max_{\mathbf{P}_s \geq 0, \mathcal{R} \geq 0} \sum_{k=1}^{\mathcal{K}} \mathcal{R}_k$$
$$\text{s.t. } 1-\prod_{l\in\Omega_k} e^{-\frac{N_0(2^{R_k/|\Omega_k|}-1)}{g_{s,k}^l P_s^l}} \prod_{l'=1}^{L}\left(\frac{1}{1+\sum_{l\in I_{k,l'}}\frac{g_{p,k}^{l'}P_p^{l'}V_{|l-l'|}(2^{R_k/|\Omega_k|}-1)}{g_{s,k}^l P_s^l}}\right) \leq \epsilon_k, \forall k$$
$$1-\prod_{l=1}^{L} e^{-\frac{N_0\bar{\alpha}}{g_{p,p}^l P_p^l}} \prod_{l'=1}^{L}\left(\frac{1}{1+\bar{\alpha}\sum_{l\in I_{p,l'}}\frac{g_{s,p}^{l'}P_s^{l'}V_{|l-l'|}}{g_{p,p}^l P_p^l}}\right) \leq \epsilon_p$$
$$\sum_{l=1}^{L} P_s^l \leq P_{\max}$$

(P1) non convex problem. *First*: change of variables

$$e^{z_k} \triangleq 2^{R_k/|\Omega_k|} - 1, k = 1, \cdots, \mathcal{K}$$
$$e^{y_s^l} \triangleq P_s^l, \forall l$$

Equivalent Reformulation of (P 1)

(P1) is equivalent to

(P2)

$$\max_{\mathbf{y},\mathbf{z}\in\mathbb{R}} g(\mathbf{z}) \triangleq \sum_{k=1}^{\mathcal{K}} |\Omega_k| \log_2(1+e^{z_k})$$
$$\text{s.t. } \sum_{l=1}^{|\Omega_k|} N_0 e^{z_k - y_s^l} + \sum_{l'=1}^{L} \log\left(1+\sum_{l\in I_{k,l'}} \frac{g_{p,k}^{l'} P_p^{l'} V_{|l-l'|} e^{z_k - y_s^l}}{g_{s,k}^l}\right) \leq \rho_k, \quad \text{(C1)}$$
$$\sum_{l'=1}^{L} \frac{N_0\bar{\alpha}}{g_{p,p}^{l'} P_p^{l'}} + \sum_{l=1}^{L} \log\left(1+\bar{\alpha}\sum_{l'\in I_{p,l}} \frac{g_{s,p}^l e^{y_s^l} V_{|l-l'|}}{g_{p,p}^{l'} P_p^{l'}}\right) \leq \bar{\rho}_p \quad \text{(C2)}$$
$$\sum_{l=1}^{L} e^{y_1^l} \leq P_{\max} \quad \text{(C3)}$$

where

$$\mathbf{y} \triangleq (y_s^1, \cdots, y_s^L)^\top$$
$$\mathbf{z} \triangleq (z_1, \cdots, z_{\mathcal{K}})^\top$$

Secondly: locally tight lower bound. $\log_2(1+e^{z_k}) \geq \frac{\alpha_k}{\ln 2} z_k + \beta_k$ where $\alpha_k = \frac{e^{\bar{z}_k}}{1+e^{\bar{z}_k}}$, $\beta_k = \log_2(1+e^{\bar{z}_k}) - \frac{\alpha_k}{\ln 2}\bar{z}_k, \forall k$

Convex Reformulation

(P2) can be approximated as

(P3)

$$\max_{\mathbf{y},\mathbf{z}\in\mathbb{R}} f(\mathbf{z},\bar{\mathbf{z}}) \triangleq \sum_{k=1}^{\mathcal{K}} |\Omega_k| \left(\frac{\alpha_k}{\ln 2} z_k + \beta_k\right)$$
$$\text{s.t. } \sum_{l=1}^{|\Omega_k|} N_0 e^{z_k - y_s^l} + \sum_{l'=1}^{L} \log\left(1+\sum_{l\in I_{k,l'}} \frac{g_{p,k}^{l'} P_p^{l'} V_{|l-l'|} e^{z_k - y_s^l}}{g_{s,k}^l}\right) \leq \rho_k,$$
$$\sum_{l'=1}^{L} \frac{N_0\bar{\alpha}}{g_{p,p}^{l'} P_p^{l'}} + \sum_{l=1}^{L} \log\left(1+\bar{\alpha}\sum_{l'\in I_{p,l}} \frac{g_{s,p}^l e^{y_s^l} V_{|l-l'|}}{g_{p,p}^{l'} P_p^{l'}}\right) \leq \bar{\rho}_p$$
$$\sum_{l=1}^{L} e^{y_1^l} \leq P_{\max}$$

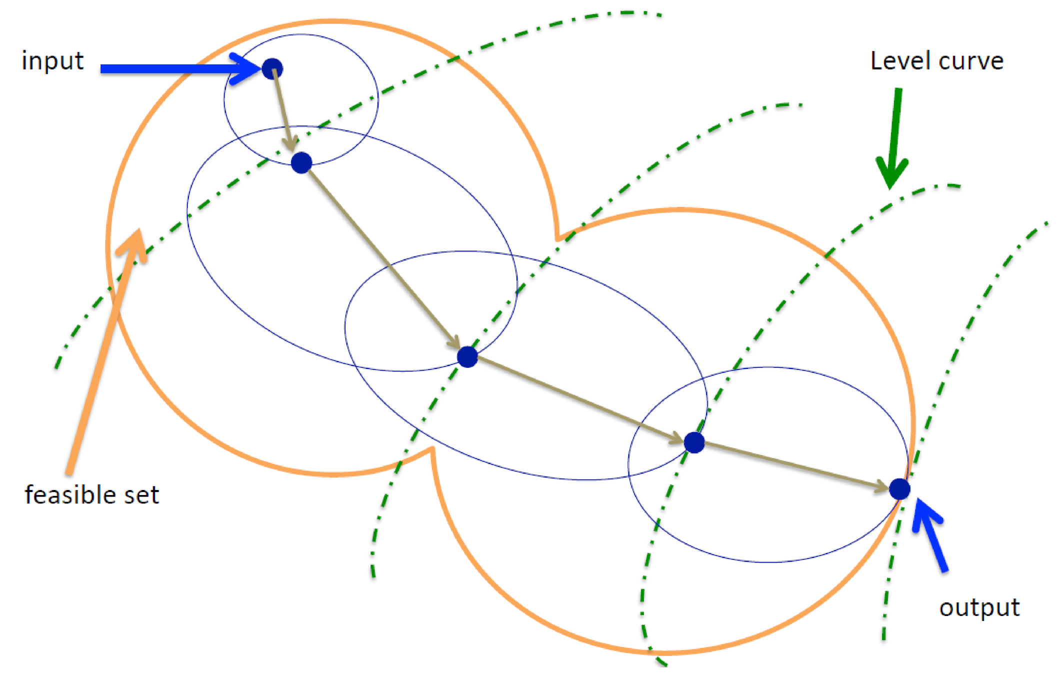
(P3) is a standard convex optimization problem.

Sequential Convex Approximation (SCA) Algorithm

Algorithm 1 Sequential Convex Approximation Algorithm for solving problem (P1)

1: **Input** A solution accuracy $\epsilon > 0$ and a feasible points $\overline{\mathbf{P}}_s, \overline{\mathcal{R}}$ for problem (P1)
2: Set $n = 0$;
3: Compute $\overline{\mathbf{z}}[n]$ using $e^{z_k} \triangleq 2^{R_k/|\Omega_k|}$ and $\alpha_k[n]$, $\beta_k[n]$ by $\alpha_k = \frac{e^{\bar{z}_k}}{1+e^{\bar{z}_k}}$ $\beta_k = \log_2(1+e^{\bar{z}_k}) - \frac{\alpha_k}{\ln 2}\bar{z}_k$;
4: **Repeat**
5: $n = n+1$;
6: Obtain the solutions $\widehat{\mathbf{z}}[n], \widehat{\mathbf{y}}[n]$ by solving problem (P3);
7: Set $\overline{\mathbf{z}}[n] = \widehat{\mathbf{z}}[n]$ and find $\alpha_k[n]$, $\beta_k[n]$ as in Step 3;
8: **Until** $\frac{|f(\widehat{\mathbf{z}}[n], \overline{\mathbf{z}}[n-1]) - f(\widehat{\mathbf{z}}[n-1], \overline{\mathbf{z}}[n-2])|}{f(\widehat{\mathbf{z}}[n-1], \overline{\mathbf{z}}[n-2])} < \epsilon$;
9: **Output** the approximated solutions $\widehat{\mathbf{z}}[n], \widehat{\mathbf{y}}[n]$.

Illustration of the SCA method



Convergence Analysis of SCA Algorithm

Theorem 1 *The sequence* $\{f(\widehat{\mathbf{z}}[n], \overline{\mathbf{z}}[n-1])\}_{n=1}^{\infty}$ *generated by Algorithm 1 converges. Moreover, any limit point of the sequence* $\{\widehat{\mathbf{z}}[n], \widehat{\mathbf{y}}[n]\}_{n=1}^{\infty}$ *generated from Algorithm 1 is a stationary point of Problem (P1).*

Numerical Results

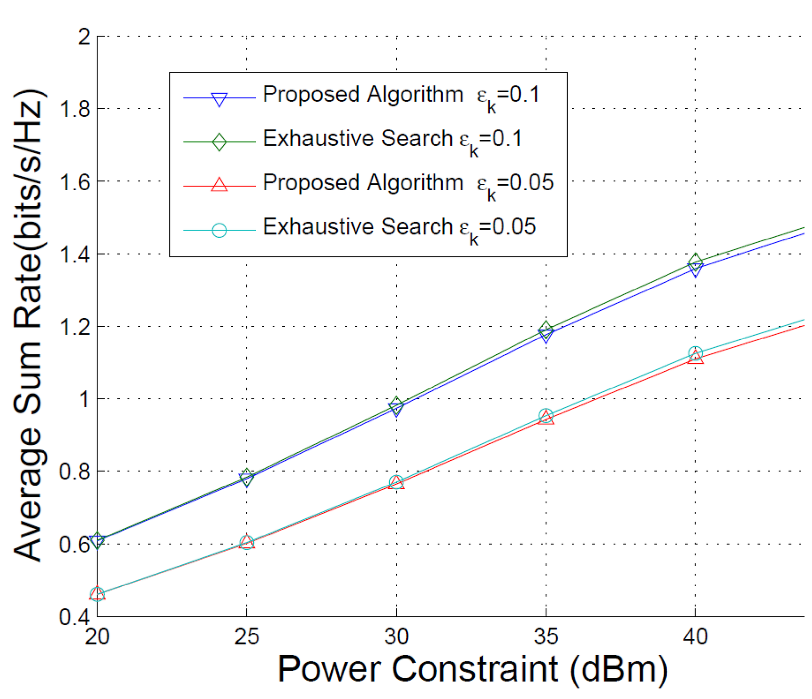


Fig. 1. Performance of proposed scheme

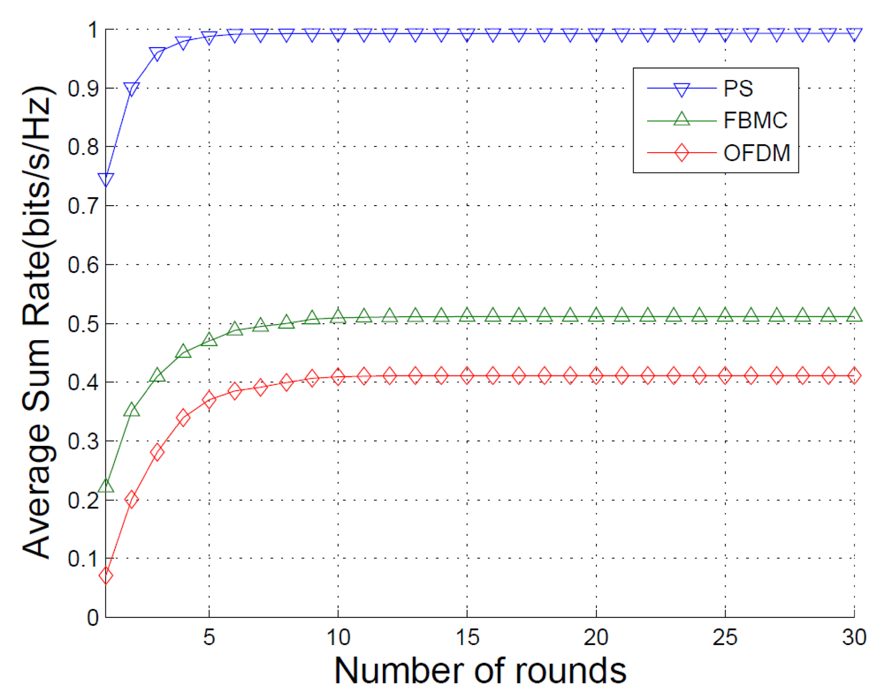


Fig. 2. Convergence behavior of the proposed sequential Algorithm 1