RESOURCE ALLOCATION FOR ASYNCHRONOUS COGNITIVE RADIO NETWORKS WITH FBMC/OFDM UNDER STATISTICAL CSI

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ABSTRACT

This paper studies resource allocation for a multi-carrier based cognitive radio network under the assumption of statistical channel state information (CSI). To circumvent the inherent high computational complexity investigating the joint power-rate-subcarrier of the outage-constrained sum rate maximization problem, we adopt a sub-optimal strategy by solving independently the subcarrier and power-rate problem. 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. Extensive simulation results are provided to demonstrate the efficiency of our proposed algorithm.

Index Terms— FBMC, resource allocation, cognitive radio, outage probability, multi-carrier modulation

1. INTRODUCTION

Cognitive Radio (CR) is a promising technology that tackles the issue of wireless spectrum scarcity by enabling unlicensed users to opportunistically access and utilize the licensed bands. Two scenarios arise in CR networks: overlay CR where secondary users (SU) can only communicate over unused frequency band and overlay CR where SUs co-exist with primary users (PU) provided they are not degrading the quality of service (QoS) of the PU [1]. Multicarrier modulations such as orthogonal frequency division multiplexing (OFDM) have been proposed as a well suited technology for CR physical layer [2, 3]. Nevertheless, synchronization is hard to maintain in CR networks due to the lack of cooperation between primary and secondary users. Impact of asynchronous interference on asynchronous networks has been studied and filter bank based multi-carrier (FBMC) has been proposed as an alternative to OFDM for asynchronous CR networks.

Mitigating inter-carrier interferences requires judicious resource allocation in asynchronous CR with multi-carrier modulation. This topic was greatly investigated in the literature; [4] studied the downlink network capacity maximization under total power and primary interference constrained, [5] considered the uplink rate maximization under total power constraint, [6] investigated joint downlink subcarrier-power allocation scheme.

All aforementioned works assumed perfect knowledge of channel state information (CSI) at the transmitter side. For practical scenario, obtaining the CSI requires significant signalling overhead. However, less information exchange is needed to feed back channel distribution information (CDI). In this work, we assume that the transmitters only know the statistical distribution of the channels which are assumed to be block-faded. Due to channel fading, the network's performance may suffer from outage. We investigate the problem of secondary sum rate maximization under both primary and secondary outage constraints. We propose a heuristic subcarrier allocation scheme. To solve the power-rate problem, we approximate the outage probability since there exists no closed-form expression for the outage probability. We proposed a sequential algorithm to solve the non-convex power-rate control problem. Simulations analyses demonstrate the efficiency of our proposed schemes.

2. SYSTEM SETUP

We consider an underlay spectrum sharing network with one primary and one secondary system using multi-carrier modulation over L subcarriers. The primary system consists of one base station (BS) that uses non-adaptive uniform power transmission P_p^l within each subcarrier and one mobile terminal (MT). The secondary system is composed of one BS that serves $\mathcal{K}$ MTs. All users are assumed to have a single antenna. Let Ω_k with $\sum_{k=1}^{\mathcal{K}} |\Omega_k| = L,\ \cap_{k=1}^{\mathcal{K}}\Omega_k = \emptyset$, be the set of subcarrier allocated to the kth secondary MT. We consider a frequency selective slow fading channel model and assume single user detection at each MT.

Due to the lack of cooperation between primary and secondary system, there exists a non-zero probability that the clock generator between both BSs is not synchronized. The network may incur intercarrier interferences. The impact of intercarrier interferences was investigated in [7] where the authors provided an interference weight vector for networks using both OFDM and FBMC. The interference weight vector is summarized as [7]

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

In the sequel, the interference weight vector is denoted as $V = [V_0, \cdots, V_S]$ where, $S = 1$ and $S = 8$ in the case of FBMC and OFDM, respectively. For asynchronous CR networks, the achievable primary and secondary signal-to-interference-plus-noise ratio (SINR) on the lth subcarrier is given respectively by

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

where $h_{p,k}^l$ denotes the channel between the primary BS and the kth secondary MT on the lth subcarrier and $h_{s,p}^l$, the channel between the secondary BS and the primary MT on the lth subcarrier. P_s^l represents the power that the secondary BS assigns on the lth subcarrier.

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In this work, we assume that the primary links statistical information is available at the secondary BS. This can be done via a band controller [8]. We further assume that the secondary BS can acquire only the statistical distribution of the channel link to its serving MTs. More precisely, the channels are assumed to follow a circularly symmetric complex Gaussian distribution with mean $g_{s,k}^l \geq 0, g_{s,p}^l \geq 0, g_{p,p}^l \geq 0, g_{p,k}^l \geq 0$. Due to channel's fading, the network MTs performance may suffer from outage.

Given an outage probability threshold $\epsilon_k \in (0,1)$ for all secondary MTs k, $\epsilon_p \in (0,1)$ for the primary system and a power constraint $P_{\max}$, we want to optimize the secondary BS resource allocation such that the secondary sum rate is maximized while satisfying the probability of outage of both primary and secondary system. The asynchronous downlink outage constrained sum rate maximization problem is expressed as

$$\begin{aligned}
\max_{\substack{\mathbf{P}_s \geq 0, \mathcal{R} \geq 0 \\ \Theta \in \{0,1\}}} \; & \sum_{k=1}^{\mathcal{K}} \mathcal{R}_k \\
\text{s.t. } & \Pr\left\{ \sum_{l=1}^{L} \theta_{s,k}^l \log_2\left(1+\Gamma_{s,k}^l\right) < \mathcal{R}_k \right\} \leq \epsilon_k, \; \forall k \\
& \Pr\left\{ \sum_{l=1}^{L} \log_2\left(1+\Gamma_{p,p}^l\right) < \mathcal{R}_p \right\} \leq \epsilon_p \\
& \sum_{k=1}^{\mathcal{K}} \theta_{s,k}^l \leq 1 \quad l = 1, \cdots, L, \quad \sum_{l=1}^{L} P_s^l \leq P_{\max}
\end{aligned} \tag{3}$$

where $\mathbf{P}_s = (P_s^1, \cdots, P_s^L)^\top, \mathcal{R} = (\mathcal{R}_1, \cdots, \mathcal{R}_{\mathcal{K}})^\top$ denote the secondar power vector allocation and transmitted rate vector. $\Theta = (\theta_{s,1}^1, \cdots \theta_{s,\mathcal{K}}^1, \cdots, \theta_{s,1}^L, \cdots \theta_{s,\mathcal{K}}^L)^\top$ is the subcarrier vector allocation. The optimization problem (3) is a mixed integer optimization problem therefore of prohibitively high computational complexity. We proposed a suboptimal approach which consists of solving the subcarrier allocation and the power-rate allocation separately.

3. SUBCARRIER AND POWER ALLOCATION

3.1. Subcarrier Allocation Scheme

Given a uniform power allocation $P_s^l = \frac{P_{\max}}{L}$, $\forall l$ and a transmitted target rate $\bar{r}_l$ per subcarrier, the outage probability per subcarrier is written as

$$\begin{aligned}
&\Pr\left\{ \log_2\left(1 + \frac{P_s^l |h_{s,k}^l|^2}{N_0 + \sum_{l'=1}^{L} P_p^{l'} V_{|l-l'|} |h_{p,k}^{l'}|^2}\right) < \bar{r}_l \right\} \\
&= \Pr\left\{ \log_2\left(1 + \frac{\frac{P_{\max}}{L} |h_{s,k}^l|^2}{N_0 + \frac{P_{\max}}{L} \sum_{l'=1}^{L} V_{|l-l'|} |h_{p,k}^l|^2}\right) < \bar{r}_l \right\} \\
&= 1 - e^{-\frac{N_0 (2^{\bar{r}} l - 1)}{g_{s,k}^l \frac{P_{\max}}{L}}} \prod_{l' \in \mathcal{L}_l} \left(\frac{g_{s,k}^l}{g_{s,k}^l + g_{p,k}^{l'} V_{|l-l'|} (2^{\bar{r}_l} - 1)} \right)
\end{aligned} \tag{4}$$

where $\mathcal{L}_l$ represents the set of subcarrier that interferes with the lth subcarrier. The secondary BS heuristically allocates the lth subcarrier to the mobile terminal that minimizes the outage probability given in (4). The subcarrier allocation procedure is summarized as

$$\theta_{s,k}^l = \arg\max_k e^{-\frac{N_0 (2^{\bar{r}} l - 1)}{g_{s,k}^l \frac{P_{\max}}{L}}} \prod_{l' \in \mathcal{L}_l} \left(\frac{g_{s,k}^l}{g_{s,k}^l + g_{p,k}^{l'} V_{|l-l'|} (2^{\bar{r}_l} - 1)} \right) \tag{5}$$

Once the subcarrier allocation is known, it remains fixed and we can proceed to address the power-rate control problem. Nevertheless, there is no closed-form expression for the outage probability in the outage constraints. The power-rate control of problem (3) is difficult to handle directly and some careful approximations are needed to tackle this optimization problem.

3.2. Rate and power allocation

Lemma 1 The primary and secondary outage probability can be upper-bounded respectively by

$$\begin{aligned}
&\Pr\left\{ \sum_{l=1}^{L} \log_2\left(1 + \frac{P_p^l |h_{p,p}^l|^2}{N_0 + \sum_{l' \in \mathcal{L}_l} P_s^{l'} |h_{s,p}^{l'}|^2 V_{|l-l'|}}\right) < R_p \right\} \\
&\leq 1 - \prod_{l=1}^{L} e^{-\frac{N_0 \bar{\alpha}}{g_{p,p}^l P_p^l}} \left(\prod_{l'=1}^{L} \left(\frac{1}{1 + \bar{\alpha} \sum_{l \in I_{p,l'}} \frac{g_{s,p}^{l'} P_s^{l'} V_{|l-l'|}}{g_{p,p}^l P_p^l}} \right) \right) \\
&\Pr\left\{ \sum_{l \in \Omega_k} \log_2\left(1 + \frac{P_s^l |h_{s,k}^l|^2}{N_0 + \sum_{l' \in \mathcal{L}_l} P_p^{l'} |h_{p,k}^{l'}|^2 V_{|l-l'|}}\right) < R_k \right\} \\
&\leq 1 - \prod_{l \in \Omega_k} e^{-\frac{N_0 (2^{R_k/|\Omega_k|} - 1)}{g_{s,k}^l P_s^l}} \\
&\times \left(\prod_{l'=1}^{L} \left(\frac{1}{1 + \sum_{l \in I_{k,l'}} \frac{g_{p,k}^{l'} P_p^{l'} V_{|l-l'|} (2^{R_k/|\Omega_k|} - 1)}{g_{s,k}^l P_s^l}} \right) \right)
\end{aligned} \tag{6}$$

where $\bar{\alpha} \triangleq 2^{R_p/L} - 1$ and $I_{j,i}$ denotes the set of subcarriers allocated to j that suffers interferences generated by the ith subcarrier.

Proof: We start by rewriting the primary outage probability

$$\begin{aligned}
&\Pr\left\{ \sum_{l=1}^{L} \log_2\left(1 + \frac{P_p^l |h_{p,p}^l|^2}{N_0 + \sum_{l' \in \mathcal{L}_l} P_s^{l'} |h_{s,p}^{l'}|^2 V_{|l-l'|}}\right) < R_p \right\} \\
&\leq 1 - \Pr\left\{ \bigcap_{l=1}^{L} \left\{ \frac{x_p^l}{N_0 + \sum_{l' \in \mathcal{L}_l} x_s^{l'} V_{|l-l'|}} \geq 2^{R_p/L} - 1 \right\} \right\} \\
&= 1 - \Pr\left\{ \bigcap_{l=1}^{L} \left\{ \frac{x_p^l}{N_0 + \sum_{l' \in \mathcal{L}_l} x_s^{l'} V_{|l-l'|}} \geq \bar{\alpha} \right\} \right\}
\end{aligned} \tag{7}$$

where $x_p^l \triangleq P_p^l |h_{p,p}^l|^2$ and $x_s^{l'} \triangleq P_s^{l'} |h_{s,p}^{l'}|^2$. Hence, x_p^l and $x_s^{l'}$ are exponentially distributed random variables. Denote their respective mean by $\frac{1}{\gamma_p^l}$ and $\frac{1}{\gamma_s^{l'}}$. On the right hand side of (7), we have

$$\begin{aligned}
&\Pr\left\{ \bigcap_{l=1}^{L} \left\{ \frac{x_p^l}{N_0 + \sum_{l' \in \mathcal{L}_l} x_1^{l'} V_{|l-l'|}} \geq \bar{\alpha} \right\} \right\} = \Pr\left\{ \bigcap_{l=1}^{L} \left\{ \mathcal{O}_p^l \right\} \right\} \\
&= \mathbb{E}_{\{x_1^{l'}\}_{l' \in \mathcal{L}_L}} \Big[\cdots \mathbb{E}_{\{x_1^{l'}\}_{l' \in \mathcal{L}_1}} \Big[\mathbb{E}_{x_p^L} \Big[1_{\mathcal{O}_p^L} \cdots \mathbb{E}_{x_p^1} \Big[1_{\mathcal{O}_p^1} | \\
&\qquad \{x_1^{l'}\}_{l' \in \mathcal{L}_1} \Big] \cdots \Big| \{x_1^{l'}\}_{l' \in \mathcal{L}_L} \Big] \Big] \cdots \Big] \\
&= \prod_{l=1}^{L} e^{-\frac{N_0 \bar{\alpha}}{P_p^l g_{p,p}^l}} \left(\prod_{l'=1}^{L} \left(\frac{1}{1 + \bar{\alpha} \sum_{l \in I_{p,l'}} \frac{P_1^{l'} g_{1,p}^{l'} V_{|l-l'|}}{P_p^l g_{p,p}^l}} \right) \right)
\end{aligned} \tag{8}$$

where $\mathcal{O}_p^l$ denotes the non-outage event within the l-th subcarrier and 1_A is the indicator function for event A. The upper bound to the primary outage probability can be found by combining (7) and (8). By a similar reasoning, the upper bound to the secondary user can also by calculated. This concludes our proof. ■

The downlink optimization problem can be conservatively approximated as

$$\begin{aligned}
&\max_{\mathbf{P}_s\geq 0, \mathcal{R}\geq 0} \sum_{k=1}^{\mathcal{K}} \mathcal{R}_k \\
&\text{s.t.} 1-\left(\prod_{l\in\Omega_k} e^{-\frac{N_0(2^{R_k/|\Omega_k|}-1)}{g_{s,k}^l P_s^l}}\right) \\
&\times \prod_{l'=1}^{L}\left(\frac{1}{1+\sum_{l\in I_{k,l'}}\frac{g_{p,k}^{l'}P_p^{l'}V_{|l-l'|}(2^{R_k/|\Omega_k|}-1)}{g_{s,k}^l P_s^l}}\right) \leq \epsilon_k, \forall k \\
&1-\left(\prod_{l=1}^{L} e^{-\frac{N_0\bar{\alpha}}{g_{p,p}^l P_p^l}}\right) \\
&\times \left(\prod_{l'=1}^{L}\left(\frac{1}{1+\bar{\alpha}\sum_{l\in I_{p,l'}}\frac{g_{s,p}^{l'}P_s^{l'}V_{|l-l'|}}{g_{p,p}^l P_p^l}}\right)\right) \leq \epsilon_p \\
&\sum_{l=1}^{L} P_s^l \leq P_{\max}
\end{aligned} \tag{9}$$

Problem (9) is a non-convex optimization problem because of the non-convex primary and secondary outage constraints. In order to transform problem (9) into a convex problem, we use the following change of variables

$$e^{z_k} \triangleq 2^{R_k/|\Omega_k|}-1, k=1,\cdots,\mathcal{K} \quad e^{y_s^l} \triangleq P_s^l, \forall l \tag{10}$$

Define $\mathbf{z} \triangleq (z_1,\cdots,z_{\mathcal{K}})^\top$ and $\mathbf{y} \triangleq (y_s^1,\cdots,y_s^L)^\top$. Problem (9) is equivalent[1] to

$$\max_{\mathbf{y},\mathbf{z}\in\mathbb{R}} g(\mathbf{z}) \triangleq \sum_{k=1}^{\mathcal{K}} |\Omega_k| \log_2(1+e^{z_k}) \tag{11a}$$

$$\begin{aligned}
\text{s.t.} &\sum_{l\in\Omega_k} N_0 e^{z_k-y_s^l} \\
&+\sum_{l'=1}^{L}\log\left(1+\sum_{l\in I_{k,l'}}\frac{g_{p,k}^{l'}P_p^{l'}V_{|l-l'|}e^{z_k-y_s^l}}{g_{s,k}^l}\right) \leq \rho_k, \forall k
\end{aligned} \tag{11b}$$

$$\sum_{l'=1}^{L}\frac{N_0\bar{\alpha}}{g_{p,p}^{l'}P_p^{l'}}+\sum_{l=1}^{L}\log\left(1+\sum_{l'\in I_{p,l}}\frac{\bar{\alpha}g_{s,p}^l e^{y_s^l}V_{|l-l'|}}{g_{p,p}^{l'}P_p^{l'}}\right) \leq \bar{\rho}_p \tag{11c}$$

$$\sum_{l=1}^{L} e^{y_1^l} \leq P_{\max} \tag{11d}$$

[1] In this work, the equivalence between both problems means that a global solution to problem (9) can be found by a global solution to (11) and vice versa.

where $\bar{\rho}_p = -\log(1-\epsilon_p)$ and $\rho_k = -\log(1-\epsilon_k)$. It can be demonstrated that constraints (11b) - (11d) are convex constraints. However, problem (11) is not a convex optimization problem because of the objective function. We can therefore approximate the objective function by introducing a surrogate function that can provide some flexibility into an algorithm design for the rate and power control. In particular, given a feasible point $\overline{\mathbf{y}}$ and $\overline{\mathbf{z}}$ for problem (11), the objective function is approximated using the following surrogate function [9]

$$\log_2(1+e^{z_k}) \geq \frac{\alpha_k}{\ln 2} z_k + \beta_k \tag{12}$$

where α_k and β_k are given by

$$\alpha_k = \frac{e^{\overline{z}_k}}{1+e^{\overline{z}_k}}, \ \beta_k = \log_2(1+e^{\overline{z}_k}) - \frac{\alpha_k}{\ln 2}\overline{z}_k, \forall k \tag{13}$$

Using (12), problem (11) is conservatively approximated as

$$\begin{aligned}
&\max_{\mathbf{y},\mathbf{z}\in\mathbb{R}} f(\mathbf{z},\overline{\mathbf{z}}) \triangleq \sum_{k=1}^{\mathcal{K}} |\Omega_k| \left(\frac{\alpha_k}{\ln 2} z_k + \beta_k\right) \\
&\quad \text{s.t.} (11\text{b}) - (11\text{d})
\end{aligned} \tag{14}$$

Problem (14) is a convex optimization problem and can therefore be efficiently solved by utilizing interior-point method based solvers such as CVX [10].

4. PROPOSED ALGORITHM: DESCRIPTION AND CONVERGENCE

4.1. Sequential convex approximation (SCA)

The problem formulation (14) is obtained by approximating problem (11) at a feasible point. By following a fixed update pattern for the feasible point, we can successively improve the restrictive approximation. More specifically, we approximate problem (14) by using the optimal solution obtained from previous iteration. The SCA approach to solve problem (9) is summarized in Algorithm 1.

Algorithm 1 Sequential Convex Approximation Algorithm for solving the problem (9)

1: **Input** A solution accuracy $\epsilon > 0$ and a feasible point $\overline{\mathbf{P}}_s, \overline{\mathcal{R}}$ for problem (9).
2: Set $n = 0$;
3: Compute $\overline{\mathbf{z}}[n]$ using (10) and $\alpha_k[n], \beta_k[n], \forall k$ by using (13);
4: **Repeat**
5: $n = n + 1$;
6: Obtain the solutions $\widehat{\mathbf{z}}[n], \widehat{\mathbf{y}}[n]$ by solving problem (14);
7: Set $\overline{\mathbf{z}}[n] = \widehat{\mathbf{z}}[n]$ and find $\alpha_k[n], \beta_k[n], \forall k$ by using (13);
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 $\widehat{\mathbf{z}}[n], \widehat{\mathbf{y}}[n]$.

Our proposed Algorithm 1 can be initialized by using a heuristic adaptive power allocation scheme.

4.2. Convergence Analysis

To demonstrate the accuracy of our proposed sequential Algorithm 1, we theoretically investigate its convergence analysis. In fact, our proposed Algorithm 1 has the following properties.

Theorem 1 The sequence $\{f(\widehat{\mathbf{z}}[n], \overline{\mathbf{z}}[n-1])\}_{n=1}^{\infty}$ generated from Algorithm 1 converges. Moreover, any limit point of the sequence $\{\widehat{\mathbf{z}}[n], \widehat{\mathbf{y}}[n]\}_{n=1}^{\infty}$ generated from our proposed Algorithm 1 is a stationary point of problem (11)

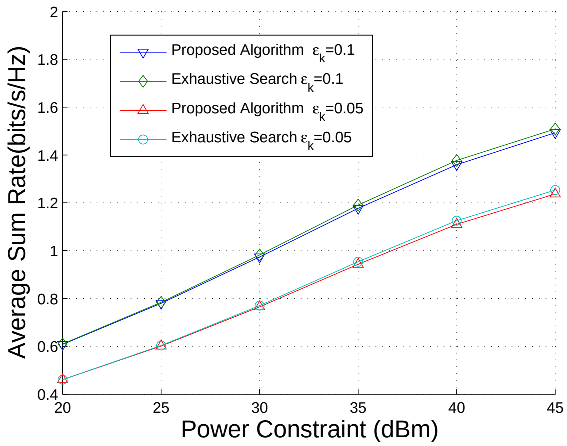

Fig. 1. Performance of proposed scheme

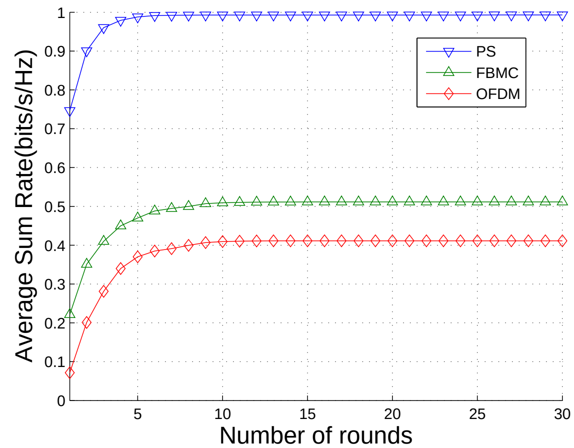

Fig. 2. Convergence behavior of the proposed sequential Algorithm 1

Proof: To prove the theorem, we need to consider the following claim.

Claim 1 *(a)* $f(\mathbf{z}, \overline{\mathbf{z}})$ *is a locally tight lower bound of the function* $g(\mathbf{z})$*, i.e.,*

$$f(\mathbf{z}, \overline{\mathbf{z}}) = \sum_{k=1}^{\mathcal{K}} |\Omega_k| \left(\frac{\alpha_k}{\ln 2} z_k + \beta_k \right) \leq \sum_{k=1}^{\mathcal{K}} |\Omega_k| \log_2(1 + e^{z_k}) = g(\mathbf{z})$$

$$\begin{aligned} f(\overline{\mathbf{z}}, \overline{\mathbf{z}}) &= \sum_{k=1}^{\mathcal{K}} |\Omega_k| \left(\frac{\alpha_k}{\ln 2} \overline{z}_k + \beta_k \right) \\ &= \sum_{k=1}^{\mathcal{K}} |\Omega_k| \left(\frac{\alpha_k}{\ln 2} \overline{z}_k + \log_2(1 + e^{\overline{z}_k}) - \frac{\alpha_k}{\ln 2} \overline{z}_k \right) \\ &= \sum_{k=1}^{\mathcal{K}} |\Omega_k| \log_2(1 + e^{\overline{z}_k}) = g(\overline{\mathbf{z}}) \end{aligned}$$

(b) $\frac{\partial f(\mathbf{z}, \overline{\mathbf{z}})}{\partial \mathbf{z}} |_{\mathbf{z} \to \overline{\mathbf{z}}} = \frac{\partial g(\mathbf{z})}{\partial \mathbf{z}} |_{\mathbf{z} \to \overline{\mathbf{z}}}$

(c) $f(\mathbf{z}, \overline{\mathbf{z}})$ *is a continuous function of* $(\mathbf{z}, \overline{\mathbf{z}})$*.*

In fact, we notice that the proposed Algorithm 1 is essentially the SUM algorithm [11]. Therefore, by Claim 1 and by [11, Theorem1], the sequence generated by the sequential Algorithm 1 is guaranteed to converge and any limit point generated by Algorithm 1 is a stationary point of problem (11). ■

5. SIMULATION RESULTS AND CONCLUSION

In this section, we provide simulation examples to illustrate the performance and the convergence properties of our proposed Algorithm 1. All our simulations are conducted using Monte Carlo simulations by averaging over 300 realizations. Our scenario consists of one BS and 4 MTs within the secondary system. The distance between both BSs is randomly chosen between 0.1 and 0.5 km. Each MT is randomly located within a circle of radius 0.5 km centered at its serving BS. Unless otherwise stated, both primary and secondary BS are communicating over $L = 16$ subcarriers each having a bandwidth of 15 KHz. A total power constraint of $P_{\max} = 33$ dBm is imposed to both systems and the noise power spectral density is $N_0 = -174$ dBm/Hz. The shadowing standard deviation is 9 dB and the path loss is modeled as LdB(d) $= 128.1 + 37.6 \times \log_{10}(d)$. The secondary transmitted target rate per subcarrier is $\bar{r}_l = 15$ kBit/s while the primary system transmitted target rate is $R_p = L \times 15$ kBit/s. The primary maximum tolerable outage probability requirement is fixed to $\epsilon_p = 0.1$ and the solution accuracy $\epsilon = 10^{-4}$.

We start by examining the approximation performance of our proposed sequential Algorithm 1 by comparing it with the exhaustive search. We elaborate the perfect synchronization case denoted as PS. Since the exact outage probability expression in problem (3) has not been derived, the exhaustive search method is therefore done according to the proposed outage probability approximation, i.e., problem (9). Here, we consider a CR network where the users are communicating over $L = 2$ subcarriers. The exhaustive search approach to find the rate is described as follow. A grid of power points (P_s^1, P_s^2) is made. The set of rates corresponding to each point of the power grid is computed after verifying that the 2-tuple power meets the primary outage constraint. The highest rate corresponds to the optimal rate. The performance comparison is given in Figure 1 in terms of average sum rate versus $P_{\max}$ for two different secondary outage requirements $\epsilon_k = (0.05, 0.1)$. Figure 1 demonstrates that our proposed Algorithm 1 achieves almost the same average sum rate as the exhaustive search approach with a relatively small gap. In fact, the gain between the performance of the exhaustive search method and our proposed Algorithm 1 is less than 3%. This clearly indicates that the proposed approach achieves near optimal solution with respect to the conservative approximation.

Figure 2 depicts the sum rate evolution of our proposed Algorithm 1. From Figure 2, it can be observed that the proposed sequential algorithm converges for asynchronous cognitive radio networks irrespective of the multi-carrier modulation utilized. It can also be observed that, there exists a gain of 109% to 147% between the sum rate achieved by PS and FBMC, confirming the degradation of the QoS of the secondary users in the case where the network incurs asynchronous transmission. This is due to the loss of orthogonality between subcarriers and, as demonstrated in [7], to interferences that spread over adjacent subcarriers. We can observe that there is a gain of 21% to 29% between the sum rate achieved using FBMC and the sum rate achieved by utilizing OFDM.

In conclusion, we have presented a heuristic subcarrier allocation scheme and a sequential algorithm for the power-rate control of the outage constrained sum rate maximization problem. Some numerical results were provided in order to demonstrate the effectiveness and fast monotone converge of our proposed schemes.

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