OPPORTUNISTIC INTERFERENCE CANCELATION AND USER SELECTION IN COGNITIVE MULTIPLE ACCESS NETWORK

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ABSTRACT

This paper investigates the problem of spectrally efficient operation of a multi-user uplink cognitive radio system in the presence of a single primary link. The secondary system applies opportunistic interference cancelation (OIC) and decode the primary signal when such an opportunity is created. We derive the achievable rate in the secondary system when OIC is used. This scheme has a practical significance, since it enables rate adaptation without requiring any action from the primary system. The approximated formulas and tight lower and upper bounds for the ergodic sum-rate capacity of the secondary network are found. Next, the power allocation is investigated in the secondary system for maximizing the sum-rate under an interference constraint at the primary system and it is shown that the optimal solution leads to a opportunistic user selection strategy. We propose a simple user selection strategy combined with OIC which achieves the optimal capacity given an interference constraint at the primary system. Finally, the analytical results are confirmed by simulations, indicating the fact that the low-complexity, spectral-efficient, flexible, and high-performing cognitive radio can be designed based on the proposed scheme.

1. INTRODUCTION

Cognitive radio technology offers efficient use of the spectrum, allowing large amounts of spectrum to be used by future high bandwidth applications. Various works have discussed achievable rates in cognitive radio from the viewpoint of information theory (see, e.g., [1, 2]). In [2, 3] the cognitive radio's achievable rate region for Gaussian multiple-access channels (MACs) have been characterized.

Peaceful coexistence of secondary and primary systems requires that the secondary interference at a primary receiver is below a particular threshold. Here, we study the problem of spectrally efficient transmission in a multi-user secondary network under interference from a primary system. On a simultaneous reception of secondary and primary signals, a secondary receiver observes a multiple access channel. The objective of the secondary receiver is to decode the primary signal to help to achieve a better secondary rate. The authors in [4] called this opportunistic interference cancelation (OIC), as the decodability of the primary system signal at the secondary receiver depends on the opportunity created by the selection of the data rate in the primary system and the SNR on the link between the primary transmitter and the secondary receiver. In this paper, we extend [4] from single user secondary system to uplink multiuser secondary network. Hence, the secondary receiver observes a MAC of two group of users: The desired secondary multiuser transmitters and the undesired primary transmitter.

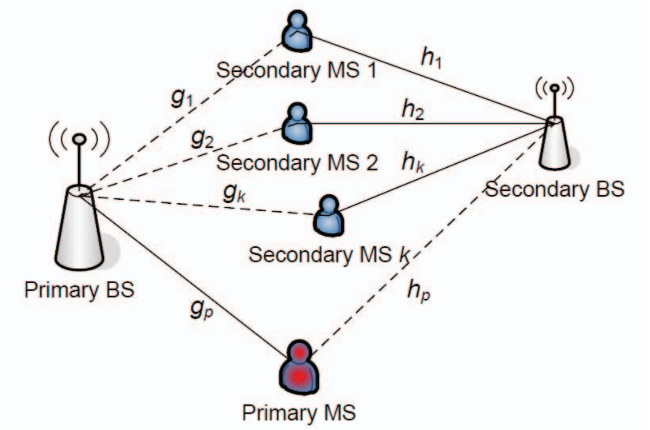

Fig. 1. Wireless network with multiple cognitive users access.

This paper considers a resource allocation scheme for sum–rate maximization of the secondary rates over a Gaussian MAC. We extend the OIC to the case of multiuser secondary network, and depending on decodability of primary signal at the secondary receiver and channel states, appropriate rates are assigned to the secondary users. A set of bounds and approximations for ergodic sum-rate capacity are derived in secondary with OIC rate adaptation scheme. In [5], we proposed

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simple power control schemes to maximize the secondary uplink capacity given the outage probability constraint. Here, we consider the instantaneous SINR as the performance metric for the interference constraint at the primary user. Thus, assuming knowledge of the primary link and local channel amplitude at each secondary user, the sum-rate capacity maximization of OIC is derived when the primary system coexists with the secondary system. It turns out that the optimum strategy is opportunistic user selection.

2. SYSTEM MODEL AND PROTOCOL DESCRIPTION

We consider the scenario shown in Fig. 1, consisting of K secondary transmitters, a secondary receiver, a primary transmitter, and one primary receiver. All the nodes are equipped with a single antenna. In this scenario, the primary mobile station (MS) is communicating with the primary base station (BS) and there are multiple secondary MS. The secondary MSs intend to access to the secondary BS using primary frequencies without license. It is assumed that g_p is the channel coefficient from the primary MS to the primary BS, and g_k, $k = 1, 2, \ldots, K$, is the channel coefficient of the interference channel from the secondary MS k to the primary BS. In addition, h_k, $k = 1, 2, \ldots, K$, is the channel coefficient from MS k to the secondary BS and h_p is the interference channel from the primary MS to secondary BS. In this paper, we assume that all links are modeled as independent Rayleigh fading, and the primary and secondary receivers have additive white Gaussian noise with variance $\mathcal{N}_p$ and $\mathcal{N}_s$, respectively. The average power of the primary user is P_0 and the average power of the k-th secondary user is assumed to be P_k, $k = 1, 2, \ldots, K$, respectively.

The primary MS uses fixed transmission rate R_p in the uplink. In absence of interference, the signal received at the primary BS is given by

$$y_p = \sqrt{P_0}\, g_p x_p + v_p, \tag{1}$$

where x_p is the signal sent by the primary user, normalized as $\mathbb{E}\{|x_p|^2\} = 1$, v_p is the complex-valued additive Gaussian noise at the primary BS with variance $\mathcal{N}_p$, and P_0 is the transmit power from the primary MS.

The minimum SNR to support rate R_p is denoted by $\gamma_{\text{th}} = 2^{R_p} - 1$. If the achievable rate is lower than R_p, then outage occurs.

We assume that the signal transmitted from the k-th secondary user is $\sqrt{P_k}\, x_k$, where $\mathbb{E}\{|x_k|^2\} = 1$, for $k = 1, 2, \ldots, K$. The received signal at the secondary BS is given as

$$y_s = \sum_{k=1}^{K} \sqrt{P_k}\, h_k\, x_k + \sqrt{P_0}\, h_p\, x_p + v_s, \tag{2}$$

where v_s is the complex Gaussian noise at the secondary BS with variance $\mathcal{N}_s$.

3. OPPORTUNISTIC INTERFERENCE CANCELATION IN COGNITIVE MAC

The concept of OIC with a *single* secondary user is introduced in [4]. Here, the OIC is generalized to the case of multiuser secondary network, and we explain on how power should be allocated when OIC is used. The interference from the primary transmitter is canceled using OIC by selection of the data rate in the primary system R_p and the link quality between the primary MS and the secondary BS, i.e., h_p. Assuming the co-existence of primary and secondary systems, the cognitive MAC can be considered as a Gaussian MAC with a common interference. Define R_p' and R_s bits/(s Hz) as the achievable rate of the primary signal at the secondary BS and the total normalized transmission rate of the uplink multiuser secondary, respectively. The secondary BS can reliably decode both the primary and secondary messages if the rates R_p' and R_s are within the capacity region of the multiple access channel:

$$\begin{aligned} R_p' &\le C\left(\frac{P_0|h_p|^2}{\mathcal{N}_s}\right) \triangleq R_p^U, \\ R_s &\le C\left(\sum_{k=1}^{K}\frac{P_k|h_k|^2}{\mathcal{N}_s}\right) \triangleq R_s^U, \\ R_p' + R_s &\le C\left(\frac{P_0|h_p|^2}{\mathcal{N}_s} + \sum_{k=1}^{K}\frac{P_k|h_k|^2}{\mathcal{N}_s}\right), \end{aligned} \tag{3}$$

where $C(x) = \log_2(1+x)$.

It is assumed R_p is given as a priori at the secondary receiver. In absence of the primary signal, we have

$$R_s = C\left(\sum_{k=1}^{K}\frac{P_k|h_k|^2}{\mathcal{N}_s}\right).$$

In order to determine the maximum achievable rate using OIC, three regions for $|h_p|^2$ are considered.

If $|h_p|^2 < \frac{\mathcal{N}_s}{P_0}(2^{R_p} - 1)$, the secondary receiver cannot decode the primary signal and we have

$$R_s = \log_2\left(1 + \frac{\sum_{k=1}^{K} P_k|h_k|^2}{\mathcal{N}_s + P_0|h_p|^2}\right) \triangleq R_s^L. \tag{4}$$

Thus, when the primary signal is not strong - *weak interference* - it is treated as noise at the secondary BS.

In the region $|h_p|^2 \ge \frac{\mathcal{N}_s}{P_0}(2^{R_p} - 1)$, the secondary BS is able to decode the primary signal and R_s is chosen such that (R_s, R_p') belongs to the achievable rate region.

If $R_p^L < R_p$ where

$$R_p^L \triangleq C\left(\frac{P_0|h_p|^2}{\mathcal{N}_s + \sum_{k=1}^{K} P_k|h_k|^2}\right), \tag{5}$$

the *medium interference* case is occurred, and we have

$$\frac{\mathcal{N}_s}{P_0}(2^{R_p}-1) \le |h_p|^2 < \frac{2^{R_p}-1}{P_0}\left(\mathcal{N}_s + \sum_{k=1}^{K} P_k |h_k|^2\right). \tag{6}$$

For this case, the achievable rate for the secondary system can be written as

$$\begin{aligned} R_s &= C\left(2^{-R_p}\left[\frac{P_0|h_p|^2}{\mathcal{N}_s} + \sum_{k=1}^{K}\frac{P_k|h_k|^2}{\mathcal{N}_s} - 2^{R_p} + 1\right]\right) \\ &= -R_p + \log_2\left(1 + \frac{P_0|h_p|^2}{\mathcal{N}_s} + \sum_{k=1}^{K}\frac{P_k|h_k|^2}{\mathcal{N}_s}\right). \end{aligned} \tag{7}$$

Another scenario is when $R_p^L \ge R_p$ where we have a *strong interference* from the primary user. In this case, we have

$$|h_p|^2 \ge \frac{2^{R_p}-1}{P_0}\left(\mathcal{N}_s + \sum_{k=1}^{K} P_k |h_k|^2\right). \tag{8}$$

For this case, the achievable rate for the secondary system can be calculated as

$$R_s = C\left(\sum_{k=1}^{K}\frac{P_k|h_k|^2}{\mathcal{N}_s}\right) = \log_2\left(1 + \frac{\sum_{k=1}^{K} P_k|h_k|^2}{\mathcal{N}_s}\right). \tag{9}$$

For the ergodic sum-rate performance given as $\overline{R}_s = \mathbb{E}\{R_s\}$ where $\mathbb{E}\{\cdot\}$ is the expectation operation, from (9), we have

$$\overline{R}_s = \mathbb{E}\left\{\log_2\left(1 + \frac{\sum_{k=1}^{K} P_k|h_k|^2}{\mathcal{N}_s}\right)\right\}. \tag{10}$$

By the fact that $\log_2(1 + a\,e^{x})$ is a convex function with $a > 0$, and applying Jensen's inequality, a lower-bound for the ergodic capacity in (10) can be calculated

$$\overline{R}_s \ge \log_2\left(1 + \frac{\exp\left(\mathbb{E}\left\{\log\left[\sum_{k=1}^{K} P_k|h_k|^2\right]\right\}\right)}{\mathcal{N}_s}\right). \tag{11}$$

Assuming that $|h_k|^2$ are i.i.d. random variables, a closed-form solution for the expression in (11) is given by

$$\overline{R}_s \ge \log_2\left(1 + \frac{P_s\,\sigma_h^2}{\mathcal{N}_s}\exp\left(\sum_{k=1}^{K-1}\frac{1}{k} - \kappa\right)\right) \tag{12}$$

where $\kappa \approx 0.577$ is Euler's constant, $P_k = P_s$, and $\sigma_{h_k}^2 = \sigma_h^2$, $k = 1, \ldots, K$. The result in (12) is obtained by applying the techniques in [6] and the fact that for no CSI at the transmitters, the ergodic sum capacity of a K users MAC channel, where each user has a single transmit antenna, is equivalent to the ergodic capacity of a single-user system with K transmit antennas [7, Proposition 1].

Now we consider the case of non-i.i.d. random variables $|h_k|^2$, $k = 1, \ldots, K$. Define the vector $[x_1, \ldots, x_K]$ of multiple variables. Then, $\log_2(1 + \sum_{k=1}^{K} a_k\, e^{x_k})$ is a convex function on $\mathbb{R}^K$ for arbitrary $a_k > 0$ (see e.g. [8, Lemma 3]). Then, by applying Jensen's inequality on (10), we have

$$\overline{R}_s \ge \log_2\left(1 + \sum_{k=1}^{K}\frac{P_k}{\mathcal{N}_s}\exp\left(\mathbb{E}\left\{\log\left[|h_k|^2\right]\right\}\right)\right). \tag{13}$$

Thus, using [9, Eq. (8.360)], a closed-form solution for the expression in (13) is given by

$$\overline{R}_s \ge \log_2\left(1 + \sum_{k=1}^{K}\frac{P_k\sigma_{h_k}^2}{\mathcal{N}_s}\exp(-\kappa)\right). \tag{14}$$

Similarly, for the case of the medium received primary SNR at the secondary receiver, a lower-bound for ergodic capacity of (7) can be written as

$$\overline{R}_s \ge -R_p + \log_2\left(1 + \frac{P_0\sigma_{h_p}^2 e^{-\kappa}}{\mathcal{N}_s} + \frac{\sum_{k=1}^{K} P_k\sigma_{h_k}^2 e^{-\kappa}}{\mathcal{N}_s}\right). \tag{15}$$

Similar to (13), another lower-bound for $\overline{R}_s$ is obtained as

$$\overline{R}_s \ge \log_2\left(1 + \frac{\exp(-\kappa)\sum_{k=1}^{K} P_k\sigma_{h_k}^2}{\mathcal{N}_s + P_0\sigma_{h_p}^2\left(1 - e^{-\frac{c_p}{\sigma_{h_p}^2}}\right) - P_0\,c_p\,e^{-\frac{c_p}{\sigma_{h_p}^2}}}\right). \tag{16}$$

4. PERMISSIBLE POWER ALLOCATION IN MULTIUSER COGNITIVE NETWORK

In this section, permissible power levels in the secondary system are investigated. First, we derive the power allocation for the case that the secondary user experiences strong interference from the primary sender and interference is decoded. Next, we show that for the case of weak interference and treating interference as noise, the same power allocation schemes can be applied.

Here, we assume that the magnitude instantaneous channel gain g_k is available at the kth secondary user, as well as $|h_k|$ and the primary link $|g_p|$. We use the instantaneous SINR as the performance metric for the interference constraint at the primary user. The received SINR at the primary user should be such that $\frac{P_0|g_p|^2}{\mathcal{N}_p+\sum_{k=1}^{K} P_k|g_k|^2} > \gamma_{\text{th}}$, or equivalently, $\sum_{k=1}^{K} P_k|g_k|^2 < \text{CAP}$, where CAP is the maximum allowable interference at the primary user. CAP is determined in a way to make sure that the permissable interference power level limit will not be violated at the primary user's receiver. If the primary user coexist with secondary user, we have CAP $= \frac{P_0|g_p|^2}{\gamma_{\text{th}}} - \mathcal{N}_p$.

Before formulating the problem of maximizing the rate given the interference constraint, we present the following lemma:

Lemma 1 *The optimum point for maximizing the sum-rate capacity of cognitive MAC using OIC over the feasible set of the power coefficients P_k, $k = 1, \ldots, K$, is same as maximizing the rate given in* (9)*, i.e., clean-MAC capacity.*

Proof 1 *By defining $\gamma_k \triangleq \frac{|h_k|^2}{\mathcal{N}_s}$, $\gamma_p \triangleq \frac{P_0|h_p|^2}{\mathcal{N}_s}$, and combining* (4), (7)*, and* (9)*, the sum-rate capacity at the secondary receiver is given by*

$$C_{sum} = \begin{cases} \log_2\left(1 + \frac{\Psi_{\mathcal{P}}}{1+\gamma_p}\right), & \text{if } \gamma_p < \alpha, \\ -R_p + \log_2(1+\gamma_p+\Psi_{\mathcal{P}}), & \text{if } \alpha \le \gamma_p < \alpha(1+\Psi_{\mathcal{P}}), \\ \log_2\left(1 + \Psi_{\mathcal{P}}\right), & \text{if } \gamma_p \ge \alpha\left(1 + \Psi_{\mathcal{P}}\right). \end{cases} \tag{17}$$

where $\alpha = 2^{R_p} - 1$, $\Psi_{\mathcal{P}} = \sum_{k=1}^{K} P_k \gamma_k$, and

$$\mathcal{P} = \left\{ P_k, k = 1, \ldots, K : \sum_{k=1}^{K} s_k \le CAP,\ P_k \ge 0, \forall k \right\}.$$

As it can be seen from (17)*, for a given primary parameters, i.e., R_p, P_0, and $|h_p|^2$, C_{sum} is an increasing function of $\Psi_{\mathcal{P}}$. Moreover, $\Psi_{\mathcal{P}}$ is a weighted sum of the power coefficients $P_k \in \mathcal{P}$ with non-negative weights. Hence, the optimum power coefficients P_k^*, $k = 1, \ldots, K$, for maximizing the strong interference capacity, i.e., $\log_2\left(1 + \Psi_{\mathcal{P}}\right)$ is the same as the optimum power coefficients for maximizing C_{sum}.*

Now, using Lemma 1, we formulate the problem of power allocation in cognitive multiple access channel (or uplink cognitive network). As stated in the previous section, the performance metric for network optimization is the ergodic capacity, or more precisely, its lower bound (14) for the case of strong interference. Note that from Lemma 1, the capacity maximization under different scenarios is equivalent to maximizing the strong interference capacity.

Now, we can formulate the following problem to find the optimum values of P_k:

$$\max_{P_1,\ldots,P_K} \ \log_2\left(1 + \frac{\sum_{k=1}^{K} P_k|h_k|^2}{\mathcal{N}_s}\right),$$
$$\text{s.t.} \ \sum_{k=1}^{K} P_k|g_k|^2 \le \text{CAP}, \quad 0 \le P_k, \ \text{for } k = 1, \ldots, K. \tag{18}$$

By the change of variable to $s_k = P_k|g_k|^2$, the problem above is equivalent to

$$\max_{P_1,\ldots,P_K} \sum_{k=1}^{K} s_k \frac{|h_k|^2}{|g_k|^2}, \ \text{s.t.} \sum_{k=1}^{K} s_k \le \text{CAP}, \ 0 \le s_k, \ k = 1, \ldots, K. \tag{19}$$

Table 1. Maximum rate power allocation of secondary cognitive network with interference constraint at the primary user

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Initialization:
    Set $\mathcal{S} = \{1, 2, \ldots, K\}$.
    Set $P_k = 0$ for $k \in \mathcal{S}$.
Recursion:
    Choose user $k$ where $k = \arg\max_{i \in \mathcal{S}} \frac{|h_i|^2}{|g_i|^2}$.
    Set $P_k = \min\left\{P_{\max}^k, \frac{\text{CAP}}{|g_k|^2}\right\}$.
    If $P_k \neq P_{\max}^k$, end the recursion.
    Set CAP $=$ CAP $- P_{\max}^k|g_k|^2$ and $\mathcal{S} = \mathcal{S} - \{k\}$.
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The optimization problem in (18) is a maximal assignment problem, and it can be shown that the solution to this problem is

$$P_k^* = \begin{cases} \frac{\text{CAP}}{|g_k|^2}, & \text{if } k = \arg \max_{i \in \{1,\ldots,K\}} \frac{|h_i|^2}{|g_i|^2}, \\ 0, & \text{otherwise.} \end{cases} \tag{20}$$

Thus, the optimum solution for the problem stated in (18) is such that the whole power in each channel realization is transmitted by a user with the highest value of $\frac{|h_k|^2}{|g_k|^2}$, which is only a function of the local channel magnitudes $|h_k|$ and $|g_k|$. Intuitively, it can be seen that the user which is closer to secondary BS in relative to primary BS is selected. Hence, the selection with the strategy given in (20) is the capacity achievable transmission for cognitive MAC, when instantaneous channel gains are known at the secondary transmitters. Note that CAP is a function of the magnitude of channel g_p when a primary system coexist with the secondary system. The process of selecting the best user could be done by the secondary BS. This is feasible since the secondary BS should be aware of all channels for coherent decoding. Thus, the same channel state information could be utilized for the purpose of user selection. A distributed user selection algorithm can be also used, in which secondary users independently decide to select the best user among them, such as the method proposed in [10]. Thus, for user selection, only the knowledge of local channel gains $|h_k|$ and $|g_k|$ is required at the kth secondary user. The estimation of $|h_k|$ and $|g_k|$ can be done by transmitting a ready-to-send (RTS) packet and a clear-to-send (CTS) packet in MAC protocols.

If we further have a constraint on the maximum transmit power from each user, i.e., $P_k \le P_{\max}$, for $k = 1, \ldots, K$, the power control problem in (18) can be written as

$$\max_{P_1,\dots,P_K} \sum_{k=1}^{K} P_k|h_k|^2,$$
$$\text{s.t.} \sum_{k=1}^{K} P_k|g_k|^2 \leq \text{CAP}, \quad 0 \leq P_k \leq P_{\max}^k, \text{ for } k=1,\dots,K. \tag{21}$$

The above problem is a Linear Programming (LP) and can be solved numerically for example by Simplex algorithm [11]. However, to give more insight in the problem, we propose an iterative algorithm in Table III based on the result in (20).

5. NUMERICAL ANALYSIS

In this section, numerical results are provided to demonstrate the usefulness of our analytical results, as well as the effectiveness of the proposed resource allocation algorithms. In all the evaluation scenarios we have assumed that the secondary system multiple access links h_k and interference links g_k are independent Rayleigh distributed with variance σ_h^2 and σ_g^2, respectively.

Fig. 2 shows the achievable sum-rate capacity of the secondary system for different number of secondary users. For calculating the achievable capacity, the maximum allowable power is found in (20). We have also assumed that the distance of the secondary users from the primary BS are equal, i.e., $\frac{\sigma_{h_k}^2}{\sigma_{g_k}^2} = 1$. It is shown that the proposed opportunistic user selection scheme outperforms the equal power assignment. It can be seen that when the SNR of the primary system is low, the CR system should be turned off. Furthermore, from Fig. 2 it is observed that in low SNR scenario, a network with a single user achieves slightly higher capacity compared to multiuser CR with equal power allocation.

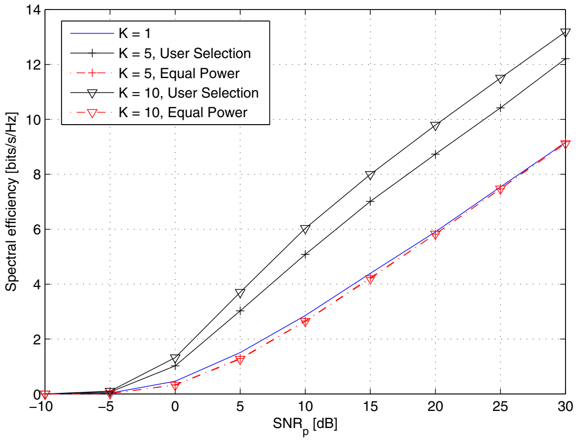

Fig. 2. Ergodic capacity of the secondary users as a function of average SNR of the primary system in a network with $K = 1, 5, 10$ users and the primary rate $R_p = 1$ bits/s/Hz.

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