Co-channel and Adjacent Channel Interference Mitigation in Cognitive Radio Networks

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***Abstract*—Cognitive radio (CR) is a paradigm of sharing spectrum among licensed (or, primary) and unlicensed (or, CR) users. In CR networks, interference mitigation is crucial not only for primary user protection, but also for the quality of service of CR users. We consider the problem of interference mitigation via channel assignment and power allocation for CR users. We develop a cross-layer optimization framework for minimizing both co-channel and adjacent channel interference; the latter has been shown to have considerable impact in practical systems. Spectrum sensing, opportunistic spectrum access, channel assignment, and power allocation are considered in the problem formulation. We propose a reformulation-linearization technique (RLT) based centralized algorithm that computes near-optimal solutions in polynomial time, and a distributed greedy algorithm that uses local information. Both algorithms are evaluated with simulations and are shown quite effective for mitigating both types of interference and achieving high CR network capacity.**

I. INTRODUCTION

A cognitive radio (CR) is a frequency-agile wireless communication device that can sense the radio environment and dynamically reconfigure its radio parameter and behavior to adapt to changes in the radio environment. CR represents a paradigm change in spectrum regulation and sharing. Its high potential has attracted substantial interest from industry, academia, and policy makers. Considerable CR research has been focused on developing effective spectrum sensing and access techniques (e.g., see [1] and [2]).

Although the basic concept of CR is intuitive, there exist numerous challenging problems to be solved to fully harvest its potential. Due to the use of open space as transmission medium, wireless network capacity is usually constrained by interference. To support many bandwidth-intensive applications in CR networks, it is desirable to achieve high network throughput under the constraint of limited interference to primary users. Interference mitigation is crucial not only for primary user protection, but also for the quality of service of CR users. Effective interference mitigation techniques are indispensable to realize the high potential of CRs.

There are two types of interference that should be considered. The first type, *co-channel interference* (CCI), is due to the coexisting transmitters occupying the same band as the victim receiver. A widely used approach for CCI mitigation is to assign different channels to the interfering transmitters near the victim receiver [3]–[5]. The second type is *adjacent channel interference* (ACI), which is in the form of power leakage from adjacent channels. ACI is mainly due to imperfect design of transmit filters and amplifiers. The harmful impact of ACI on network throughput was demonstrated in a recent work [6]. ACI can also be mitigated by appropriate channel allocation and power control. Both types of interference should be considered in the design of CR networking protocols.

In this paper, we consider a CR network consisting of multiple CR transmitter receiver pairs. The primary network comprises a base station sending data to primary users using a set of licensed channels. The CR nodes collaboratively sense the licensed channels and exploit spectrum white spaces for data transmission. We investigate the problem of maximizing the CR network throughput while bounding the interference to primary users. We incorporate several important components such as cooperative spectrum sensing, spectrum sensing errors, and opportunistic spectrum access into the cross-layer optimization framework. In the problem formulation, we specifically consider mitigating CCI among CR users and ACI for both CR and primary users, through optimized channel assignment and transmit power control for CR users.

The formulated problem is a Mixed Integer Nonlinear Programming (MINLP) problem, due to the use of index variables for channel assignment and logarithmic relationship between link capacity and signal to noise ratio (SNR). Such problems are NP-hard in general. We first propose a reformulation-linearization technique (RLT)-based centralized algorithm that computes near-optimal solutions in polynomial time [7]. We then develop a distributed greedy algorithm that uses only local information and computes near-optimal solutions. Through simulation studies, we find the distributed greedy algorithm outperforms both the RLT-based centralized algorithm and a simple heuristic algorithm with considerable gains.

The remainder of this paper is organized as follows. We describe the system model and preliminaries in Section II. We present the problem formulation and develop the RLT-based centralized algorithm in Section III. The distributed greedy algorithm is presented in Section IV. Our simulation studies are shown in Section V and related work is discussed in Section VI. Section VII concludes the paper.

II. SYSTEM MODEL AND PRELIMINARIES

A. Spectrum and Network Model

We consider a primary network where a base station transmits data to primary users using M licensed channels with non-overlapping spectrum. Without loss of generality, we assume the channels have identical bandwidth. We assume that each primary user is equipped with one transceiver and can

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receive from the primary base station via one of the channels. Let $\mathcal{P}_m$ be the set of primary users that are tuned to channel m. All the $\mathcal{P}_m$'s are generally assumed non-empty.

As in prior work [1], [8], we assume that the primary network uses a synchronous time slot structure. The occupancy of each channel can be modeled as a discrete-time Markov process. The status of channel m in time slot t is denoted by $S_m(t)$: when the channel is idle, we have $S_m(t) = 0$; when the channel is busy, we have $S_m(t) = 1$. Let P_m^{01} and P_m^{10} be the transition probability from state 0 to 1 and that from state 1 to 0 for channel m, respectively. The utilization of channel m is $\eta_m = \lim_{T\to\infty} \frac{1}{T}\sum_{t=1}^{T} S_m(t) = \frac{P_m^{01}}{P_m^{01}+P_m^{10}}$.

Within the coverage of the primary network, there are K pairs of CR transmitters and receivers that explore the spectrum opportunities in the M channels for data communications. Each CR node is equipped with two transceivers: a control transceiver that operates on a dedicated control channel (which we assume is always available), and a data transceiver incorporating a software defined radio (SDR) that is able to tune to any of the M licensed channels.

CR nodes access the licensed channels following the same time slot structure. For CR nodes, each time slot consists of a sensing phase and a transmission phase. In the sensing phase, a CR node chooses one of the M channels to sense using its data transceiver, and then exchanges the sensed channel information with other CR nodes using its control transceiver over the control channel. During the transmission phase, the CR node chooses one of the M channels to transmit or receive data based on sensing results.

B. Cooperative Spectrum Sensing

We adopt a hypothesis test to detect channel availability. The null hypothesis is $H_0^m : \{\text{channel } m \text{ is idle}\}$ and the alternative hypothesis is $H_1^m : \{\text{channel } m \text{ is busy}\}$. We consider both types of sensing errors, i.e., false alarm with probability ϵ_n^m and miss detection with probability δ_n^m, of the n-th sensing result on channel m, respectively. It has been shown that these sensing errors are inevitable and should be considered in CR networking protocol design [1], [3]. We than have $\epsilon_n^m = \Pr(\Theta_n^m = 1|H_0^m)$ and $\delta_n^m = \Pr(\Theta_n^m = 0|H_1^m)$, where Θ_i^m is the i-th sensing result on channel m. Given N sensing results on channel m, the conditional probability that channel m is available, denoted by $P_m^A(\Theta_1^m, \cdots, \Theta_N^m)$, can be computed iteratively as shown in our prior work [4]

$$\begin{aligned} P_m^A(\Theta_1^m) &= \left[1 + \frac{\eta_m}{1-\eta_m} \times \frac{(\delta_1^m)^{1-\Theta_1^m}(1-\delta_1^m)^{\Theta_1^m}}{(\epsilon_1^m)^{\Theta_1^m}(1-\epsilon_1^m)^{1-\Theta_1^m}}\right]^{-1} \\ P_m^A(\vec{\Theta}_n^m) &= P_m^A(\Theta_1^m, \Theta_2^m, \cdots, \Theta_n^m) \\ &= \left\{1 + \left[\frac{1}{P_m^A(\Theta_1^m, \Theta_2^m, \cdots, \Theta_{n-1}^m)} - 1\right] \times \right. \\ &\qquad \left. \frac{(\delta_n^m)^{1-\Theta_n^m}(1-\delta_n^m)^{\Theta_n^m}}{(\epsilon_n^m)^{\Theta_n^m}(1-\epsilon_n^m)^{1-\Theta_n^m}}\right\}^{-1}, n = 2, \cdots, N. \end{aligned}$$

C. Opportunistic Channel Access

Let $D_m(t)$ be a decision variable indicating whether channel m will be accessed in time slot t. It is defined as

$$D_m(t) = \begin{cases} 0, & \text{if channel } m \text{ is considered idle} \\ 1, & \text{otherwise.} \end{cases} \tag{1}$$

Based on $P_m^A(\vec{\Theta}_N^m)$, channel m will be accessed (i.e., $D_m(t) = 0$) with probability $P_m^D(\vec{\Theta}_N^m)$, and it will not be accessed (i.e., $D_m(t) = 1$) with probability $1 - P_m^D(\vec{\Theta}_N^m)$. We show how to compute $P_m^D(\vec{\Theta}_N^m)$ in the following.

For primary user protection, the probability that a CR transmission collides with primary user transmissions should be smaller with a threshold, denoted by γ_m for channel m. The primary user protection condition can be written as

$$\left[1 - P_m^A(\vec{\Theta}_N^m)\right] P_m^D(\vec{\Theta}_N^m) \le \gamma_m. \tag{2}$$

To maximize the CR network throughput, $P_m^D(\vec{\Theta}_N^m)$ should be set to a probability as large as possible. We have from (2)

$$P_m^D(\vec{\Theta}_N^m) = \min\left\{\gamma_m / \left[1 - P_m^A(\vec{\Theta}_N^m)\right], 1\right\}. \tag{3}$$

Let $\mathcal{A}(t) := \{m | D_m(t) = 0\}$ be the set of idle channels in time slot t. Its complement set $\mathcal{B}(t) = \overline{\mathcal{A}}(t)$ is the set of busy channels in time slot t (i.e., being used by primary users).

D. Channel Interference Model

We consider CCI among CR users and ACI for both CR and primary users in this paper. The CCI and ACI models are presented in the following.

1) Co-channel Interference: CCI is caused by the CR user transmissions using the same channel. Before introducing the model,we define index variables x_k^m as follows:

$$x_k^m = \begin{cases} 1, & \text{if channel } m \text{ is used by CR link } k \\ 0, & \text{otherwise,} \end{cases} \quad m = 1, 2, \cdots, M,\ k = 1, 2, \cdots, K. \tag{4}$$

Let $\mathcal{T}_k$ and $\mathcal{R}_k$ be the transmitter and receiver of CR link k, respectively. The CCI C_k^m at CR receiver k is

$$\begin{aligned} C_k^m &= \sum_{i \in \Phi, i \ne k} G_{\mathcal{T}_i, \mathcal{R}_k}^m P_i^m x_i^m \\ &= \sum_{i \in \Phi} G_{\mathcal{T}_i, \mathcal{R}_k}^m P_i^m x_i^m - G_{\mathcal{T}_k, \mathcal{T}_k}^m P_k^m x_k^m, \end{aligned} \tag{5}$$

where $G_{\mathcal{T}_i, \mathcal{R}_k}^m$ is the channel gain from CR transmitter i to CR receiver k on channel m, P_i^m is the transmit power of CR transmitter i on channel m, and $\Phi := \{1, 2, \cdots, K\}$ is the set of CR transmitter/receiver pairs.

2) Adjacent Channel Interference: A CR receiver may also be interfered by transmissions on an adjacent channel, when the channels are not strictly orthogonal. The interferer could be either a CR transmitter or the primary base station on the adjacent channel. Such ACI is shown to be harmful with testbed experiments in a recent work [6].

For ease of explanation, we only consider the first adjacent channel interference in this paper. Due to the imperfect design of band-pass filters, a portion of the power on the adjacent channel may leak to the channel being used by CR users. Such leakage is also considered as noise. Let β_m^{+1} be the ratio of leakage power from channel $(m+1)$ to m, which is a factor depends on spectral properties, such as inter-channel distance and channel width, and band-pass filter design.

For a channel m, if its adjacent channel $(m+1)$ is idle, then the ACI is due to concurrent CR transmissions. We have

$$\begin{aligned} AC_{m,k}^{+1} &= [1 - D_{m+1}(t)]\beta_m^{+1} \sum_{i \in \Phi, i \neq k} G_{\mathcal{T}_i,\mathcal{R}_k}^{m+1} P_i^{m+1} x_i^{m+1} \\ &= [1 - D_{m+1}(t)]\beta_m^{+1} C_k^{m+1}. \end{aligned} \tag{6}$$

Alternatively, if the adjacent channel $(m+1)$ is busy, then the ACI comes from a primary transmission. We have

$$AP_{m,k}^{+1} = D_{m+1}(t)\beta_m^{+1} G_{0,\mathcal{R}_k}^{m+1} Q_{m+1}, \tag{7}$$

where $G_{0,\mathcal{R}_k}^{m+1}$ is the channel gain from the primary transmitter to CR receiver k on channel $(m+1)$, and Q_{m+1} is the transmit power of the primary transmitter on channel $(m+1)$.

Similarly, the ACI may come from the other adjacent channel $(m-1)$. The total ACI on channel m from both its adjacent channels can be written as

$$A_k^m = AC_{m,k}^{+1} + AP_{m,k}^{+1} + AC_{m,k}^{-1} + AP_{m,k}^{-1}. \tag{8}$$

For channels 1 and M, we assume $AC_{1,k}^{-1}$, $AP_{1,k}^{-1}$, $AC_{M,k}^{+1}$ and $AP_{M,k}^{+1}$ are all zero. This is because the adjacent channels 0 and $(M+1)$ are used by neither primary nor CR users.

Primary users may also be interfered by CR users transmitting on an adjacent channel. If channel m is used by primary user j and channel $(m+1)$ is available for CR user access, the ACI received by the primary user is

$$BC_{m,j}^{+1} = [1 - D_{m+1}(t)]\beta_m^{+1} \sum_{i \in \Phi} G_{\mathcal{T}_i,j}^{m+1} P_i^{m+1} x_i^{m+1}. \tag{9}$$

Considering ACI from both sides of channel m, the total ACI at a primary receiver can be written as:

$$B_j^m = BC_{m,j}^{+1} + BC_{m,j}^{-1}. \tag{10}$$

Again, we assume $BC_{1,j}^{-1}$ and $BC_{M,j}^{+1}$ are zero.

III. PROBLEM STATEMENT

A. Channel Selection and Power Allocation Problem

At each CR receiver, both interferences from co-channel and adjacent channels are treated as noise. Let υ_k^m be the SNR at CR receiver k on channel m. Then υ_k^m can be written as

$$\upsilon_k^m = \frac{G_{\mathcal{T}_k,\mathcal{R}_k}^m P_k^m x_k^m}{N_0 + C_k^m + A_k^m}, \tag{11}$$

where N_0 is the channel noise power. The objective is to maximize the capacity of the CR network as approximated by Shannon capacity. Without loss of generality, we assume that each channel has unit bandwidth (e.g., 1 MHz). The objective function becomes

$$\max_{P_k^m, x_k^m} \sum_{k \in \Phi} \sum_{m \in \mathcal{A}(t)} \log_2(1 + \upsilon_k^m). \tag{12}$$

Since each CR user is able to access one channel in each time slot, we have the following channel access constraint.

$$\sum_{m \in \mathcal{A}(t)} x_k^m \leq 1, \quad \text{for all } k \in \Phi. \tag{13}$$

Furthermore, each CR user is limited by a peak power constraint. That is

$$\sum_{m \in \mathcal{A}(t)} P_k^m x_k^m \leq \Gamma, \quad \text{for all } k \in \Phi. \tag{14}$$

As discussed, the interference from CR transmissions to primary users should be bounded. Recall that $\mathcal{B}(t)$ is the set of busy channels and $\mathcal{P}_m$ is the set of primary users using channel m. Letting the bound be Ω, we have

$$B_j^m \leq \Omega, \quad \text{for all } m \in \mathcal{B}(t), j \in \mathcal{P}_m. \tag{15}$$

Problem (12) with constraints (13), (14) and (15) maximizes the CR network capacity while bounding the total interference (i.e., both CCI and ACI) to primary users. Based on spectrum sensing results, it determines channel access (as given by the x_k^m's) as well transmit powers (as given by the P_k^m's) for CR users. This is an MINLP problem, which is NP-hard in general and cannot be solved exactly in polynomial time. For this problem, we first describe below how to derive upper and lower bounds, and then present a distributed algorithm in the next section.

B. Upper and Lower Bounds

We first obtain an upper bound by relaxing the problem with RLT [7]. The lower bound is then computed with a sequential fixing (SF) algorithm.

First, we allow the binary variables x_k^m to take real values in $[0,1]$. Second, the product term $P_k^m x_k^m$ is replaced by a substitution variable $\phi_k^m = P_k^m x_k^m$. Since $0 \leq P_k^m \leq \Gamma$ and $0 \leq x_k^m \leq 1$, the RLT bound-factor product constraints are

$$\left\{ \begin{array}{l} (P_k^m - 0)(x_k^m - 0) \geq 0 \\ (P_k^m - 0)(1 - x_k^m) \geq 0 \\ (\Gamma - P_k^m)(x_k^m - 0) \geq 0 \\ (\Gamma - P_k^m)(1 - x_k^m) \geq 0 \end{array} \right. \Rightarrow \left\{ \begin{array}{l} \phi_k^m \geq 0 \\ P_k^m - \phi_k^m \geq 0 \\ \Gamma x_k^m - \phi_k^m \geq 0 \\ P_k^m + \Gamma x_k^m - \phi_k^m \leq \Gamma. \end{array} \right. \tag{16}$$

Finally, the logarithm term $\log_2(1 + \upsilon_k^m)$ in the objective function can be decomposed into the difference between two logarithm terms, denoted by y_k^m and z_k^m, respectively.

$$\begin{aligned} \log_2(1 + \upsilon_k^m) = \log_2(N_0 + C_k^m + A_k^m + G_{\mathcal{T}_k,\mathcal{R}_k}^m P_k^m x_k^m) - \\ \log_2(N_0 + C_k^m + A_k^m) \\ := y_k^m - z_k^m. \end{aligned} \tag{17}$$

For a logarithm term $\log(x)$, we can linearize it over some tightly bounded regions as a polyhedral outer approximation. For example, if x is bounded by $x_0 \leq x \leq x_L$, these constraints can be written as follows:

$$\left\{ \begin{array}{l} y \geq \frac{\log_2(x_L) - \log_2(x_0)}{x_L - x_0}(x - x_0) + \log_2(x_0) \\ y \leq \frac{1}{\ln(2) x_l}(x - x_l) + \log_2(x_l), \end{array} \right. \tag{18}$$

TABLE I
SEQUENTIAL FIXING (SF) ALGORITHM

```
1:  Use RLT to linearize the original problem;
2:  Solve the LP relaxation;
3:  Find the minimum value among all $x_k^m$ and $1 - x_k^m$;
4:  IF (the minimum value is in the form of $1 - x_{k'}^{m'}$)
5:      Fix $x_{k'}^{m'}$ to 1;
6:      Fix all $x_{k'}^m$ to 0 for all $m \neq m'$;
7:  ELSE
8:      Fix $x_{k'}^{m'}$ to 0;
9:  END IF
10: IF (all $x_k^m$'s are fixed)
11:     Go to Step 16;
12: ELSE
13:     Reformulate and solve a new LP relaxation based on all
        the $x_k^m$'s that have been fixed;
14:     Go to Step 3;
15: END IF
16: Formulate and solve a new LP for the $P_k^m$'s;
```

where $x_l = x_0 + \frac{l}{L}(x_L - x_0)$ for $l = 0, 1, 2, \cdots, L$. We use a four-pointer ($L = 3$) tangential approximation in this paper. The upper and lower bound of y_k^m and z_k^m can be obtained by letting ϕ_k^m be 0 and Γ, respectively.

We thus obtain a linear programming (LP) relaxation for Problem (12). Solving the LP relaxation with an LP solver, we can obtain a possibly infeasible solution due to the relaxations, which can serve as an upper bound for the original problem.

We next present an SF Algorithm in Table I for deriving a feasible near-optimal solution. In Steps $3 - 9$, the variable $x_{k'}^{m'}$ that is closest to 0 or 1 is chosen and rounded to the nearest binary integer. Once $x_{k'}^{m'}$ is fixed to 1, all the other variables $x_{k'}^m$ with the same subscript k' are fixed to 0, due to constraint (13). Then the problem can be reformulated and solved again iteratively, until all the binary variables x_k^m's are fixed. In Step 16, the transmit powers P_k^m's are derived. Thus a near-optimal feasible solution is found, which can serve as a lower bound for the global optimum.

In our simulations, we find the upper bound quite loose, but the lower bound is reasonably tight. The average-case time complexity of the *simplex method*, a popular LP solving algorithm, is $O(n \log n)$ for a problem with size n. Thus the computational complexity of one iteration in SF is $O(MK \log(MK))$. Since the number of iterations in SF is MK in the worst case, the overall computational complexity of SF is $O(M^2K^2 \log(MK))$.

IV. DISTRIBUTED ALGORITHM

Although SF can compute a near-optimal solution in polynomial time, it is a centralized algorithm that needs to know all channel gains. In this section, we present a distributed greedy algorithm for solving Problem (12). With this algorithm, each CR transmitter estimates channel gains from itself to primary users and all other CR receivers, and each CR receiver estimates channel gains from the primary base station and all other CR transmitters.

The distributed algorithm consists of two tiers: (i) the upper tier is a channel assignment algorithm, and (ii) the low tier is a power allocation algorithm. In the channel assignment algorithm, we assume the transmit powers have been allocated to each available channel and the power allocation, denoted by an $M \times K$ vector $\vec{P}$, can be obtained from the power allocation algorithm. Define $U_k^m = \log_2(1 + \upsilon_k^m)$ as the capacity of CR link k if it uses channel m. Then in each loop, the channel with the lowest $U_k^m(\vec{P})$ is removed from the available channel set $\mathcal{A}_k(t)$ and the corresponding x_k^m is set to 0, until only one available channel is left. The complete channel assignment algorithm is presented in Table II.

TABLE II
CHANNEL ASSIGNMENT ALGORITHM FOR CR LINK k

```
1: Initialize $x_k^m = 1$ for all $m \in \mathcal{A}(t)$ and $\mathcal{A}_k(t) = \mathcal{A}(t)$;
2: WHILE ($|\mathcal{A}_k(t)| > 1$)
3:     Run the power allocation algorithm given in Table III;
4:     Find the channel $m'$ with the minimum $U_k^{m'}$ value:
           $m' = \arg\min_{m \in \mathcal{A}_k(t)} U_k^m(\vec{P})$;
5:     Set $x_k^{m'} = 0$ and remove $m'$ from $\mathcal{A}_k(t)$;
6: END WHILE
7: Run the power allocation algorithm given in Table III;
```

In the power allocation algorithm, the main idea is to iteratively allocate a small amount of power Δ to the CR link that can achieve the largest increase in (12). The algorithm is presented in Table III. Let $\vec{\Delta}_k^m$ be a vector whose $[(k-1) \times M + m]$-th element is Δ and all other elements are 0, indicating that power Δ is allocated to CR link k on channel m. Obviously, if CR link k is allocated with power Δ, the throughput of this link increases, while the throughputs of other CR links decrease. The increase and decrease of throughput are termed *earning* and *cost*, respectively: $EARN_k^m$ is the throughput increase for CR link k on channel m if it gets Δ additional power; $COST_{k',k}^m$ is the throughput decrease for CR link k if another CR link k' on channel m wins the power allocation Δ. In Steps $3 - 7$, we calculate $EARN_k^m$, but set it to 0 if (14) or (15) is not satisfied. In Steps $10 - 11$, the net throughput gains (or, *profit*) of all possible power allocations are calculated and the combination with the largest profit is selected. In Steps $12 - 17$, the CR link with the largest positive profit wins the allocation. Otherwise, the power allocation algorithm is terminated because no further power allocation can improve the total throughput.

V. SIMULATION RESULTS

We evaluate the performance of the proposed algorithms using MATLAB (for solving the LPs). For the results reported in this section, there are $M = 6$ licensed channels (unless otherwise specified) with identical transition probabilities $P_m^{01} = 0.4$ and $P_m^{10} = 0.3$ for all m. The maximum collision probability γ_m is 0.2 for all m. The transmit power of primary base station is 30 dBm and the maximum acceptable interference is $\Omega = 10$ dBm. There are $K = 6$ transmitter and receiver pairs in the CR network. The power of CR transmitter is limited to $\Gamma_m = 27$ dBm for all m. The false alarm probability is $\epsilon_n^m = 0.3$ and the miss detection probability is $\delta_n^m = 0.3$ for all m and n, unless otherwise specified. Rayleigh block fading channels are used in the simulations.

We plot four curves in every figure: (i) the upper bound

TABLE III

POWER ALLOCATION ALGORITHM FOR CR LINK k

```
1:  Initialize $P_k^m = 0$ for all $k \in \Phi$ and $m \in \mathcal{A}_k(t)$;
2:  Calculate $EARN_k^m$ for all $m \in \mathcal{A}_k(t)$;
3:  IF $(\sum_{m \in \mathcal{A}(t)} P_k^m + \Delta \leq \Gamma)$ & $(B_j^m(\vec{P} + \vec{\Delta}_k^m) \leq \Omega$ for $j \in \mathcal{P}_m)$
4:      $EARN_k^m = \sum_{n \in \mathcal{A}(t)} [U_k^n(\vec{P} + \vec{\Delta}_k^m) - U_k^n(\vec{P})]$;
5:  ELSE
6:      $EARN_k^m = 0$;
7:  END IF
8:  Calculate $COST_{k',k}^m$ for all $k' \neq k$ and $m \in \mathcal{A}_{k'}(t)$, where
        $Cost_{k',k}^m = \sum_{n \in \mathcal{A}(t)} [U_k^n(\vec{P} + \vec{\Delta}_{k'}^m) - U_k^n(\vec{P})]$;
9:  Broadcast all $EARN_k^m$ and $COST_{k',k}^m$ to all other CR links;
10: Calculate $PROFIT_k^m$ for all $k \in \Phi$ and $m \in \mathcal{A}_k(t)$, where
        $PROFIT_k^m = EARN_k^m + \sum_{k \neq k'} COST_{k,k'}^m$;
11: Find $\{m', k'\} = \arg\max_{k \in \Phi \& m \in \mathcal{A}_k(t)} PROFIT_k^m$;
12: IF $(PROFIT_{k'}^{m'} > 0)$
13:     $\vec{P} = \vec{P} + \vec{\Delta}_{k'}^{m'}$;
14:     Go to Step 2;
15: ELSE.
16:     The algorithm is terminated;
17: END IF
```

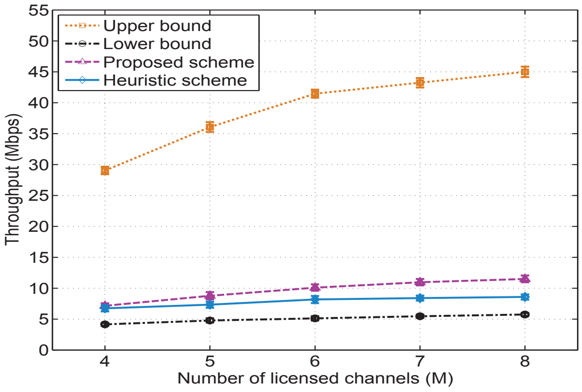

Fig. 1. CR network throughput versus the number of licensed channels.

obtained by solving the RLT relaxation; (ii) the centralized SF algorithm given in Table I (a lower bound); (iii) the distributed greedy algorithm given in Tables II and III; and (iv) a simple centralized heuristic algorithm. In the heuristic algorithm, each CR transmitter chooses the best available channel to access, thus fixing all the x_k^m's. Then it solves the reduced problem (12) with MATLAB Optimization Toolbox to find the power allocation. Each point in the curves is the average of 10 simulations with different random seeds. The 95% confidence intervals are plotted as error bars, which are all negligible.

We first examine the impact of the number of channels M. In Fig. 1, we increase M from 4 to 8, and plot the total throughput of the CR network. As expected, the more licensed channels, the more spectrum opportunities for CR users and the higher the network throughput. The curves of both SF and the heuristic algorithm have lower slop than that of the distributed greedy algorithm. It implies that the greedy algorithm is more efficient in exploiting the addition spectrum opportunities for CR transmissions. We find the upper bound quite loose, while the lower bound is reasonably tight.

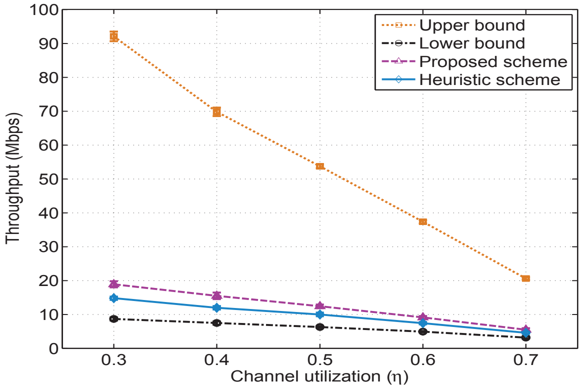

Fig. 2. CR network throughput versus primary user channel utilization.

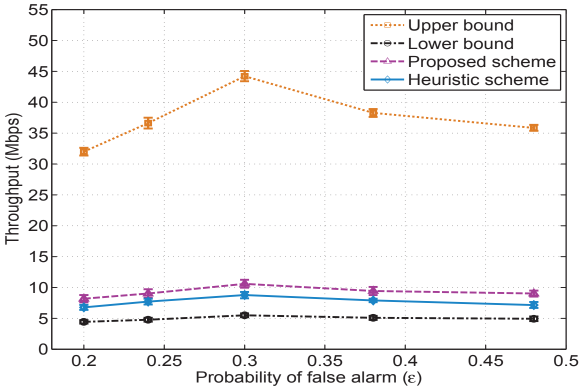

Fig. 3. CR network throughput versus spectrum sensing error probabilities.

In Fig. 2, we investigate the impact of primary user channel utilization η on the CR network throughput. The throughputs achieved by the algorithms are plotted when η is increased from 0.3 to 0.7. Clearly, a smaller η allows more spectrum opportunities for CR transmissions. It can be seen from the figure that all the four curves decrease as η gets larger. The CR network throughput of the distributed greedy algorithm is better than that of the simple heuristic algorithm and is about twice of that of the centralized SF algorithm.

Next we examine the impact of spectrum sensing errors on the CR network throughput. In Fig. 3, we test five pairs of $\{\epsilon, \delta\}$ values as follows: $\{0.2, 0.48\}$, $\{0.24, 0.38\}$, $\{0.3, 0.3\}$, $\{0.38, 0.24\}$, and $\{0.48, 0.2\}$. The CR network throughputs achieved by the algorithms are plotted in the figure. It is interesting to see that the throughput performance gets worse when the probability of one of the two sensing errors gets large. We can trade-off between false alarm and miss detection probabilities to find the optimal operating point for spectrum sensing. Again, the throughput performance of the greedy algorithm is superior to that of the heuristic algorithm and doubles that of the SF algorithm.

Finally, we investigate the impact of ACI factor β. The simulation results are presented in Fig. 4, where β is increased from 0 to 0.5. As expected, the CR network throughput is reduced by the presence of ACI. The severer the ACI, the lower the CR network throughput. The distributed greedy

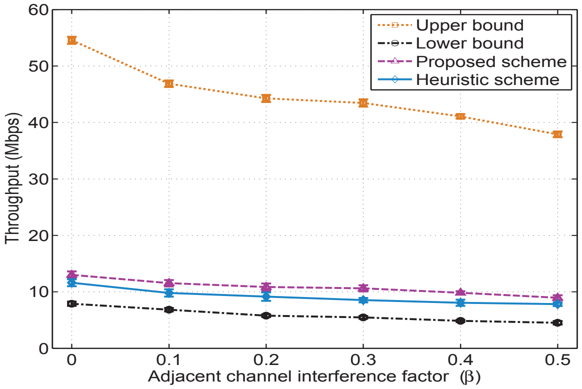

Fig. 4. CR network throughput versus the ACI factor.

algorithm outperforms both the heuristic algorithm and the SF algorithm with considerable gap in CR network throughput.

VI. Related Work

CR has been recognized as a promising technology for efficient spectrum sharing [1], [2]. There is considerable CR research on spectrum sensing and dynamic spectrum access [3], [8]–[10]. The approach of periodically sensing a selected subset of channels has been adopted in the design of CR MAC protocols [3], [8], [10]. Several papers consider sensing errors in the design of spectrum access schemes [3], [11], [12]. The design of opportunistic channel access scheme was considered in [10], [11]. Power allocation for CR users was one of the active research topics in CR networking. In a recent work [13], Zhao and Kwak investigated the power allocation problem for a single secondary user, while considering the mutual interference between primary users and secondary users.

CCI and ACI are the two major factors limiting wireless network capacity. The impact of CCI and ACI on the network throughput performance was investigated in [14], [15]. A commonly used method to reduce CCI is to assign different channels to neighboring transmitters [4], [5]. ACI was described by a simple quantification model that was verified by testbed experiments in [6]. Gidony and Kalet [16] addressed the ACI mitigation problem by exploiting antenna diversity.

In this paper, we consider the challenging problem of channel assignment and power allocation in CR networks in the presence of both CCI and ACI, aiming to maximize the overall CR network capacity without imposing severely harmful impact on the primary users. We propose an RLT-based centralized SF algorithm and a near-optimal distributed greedy algorithm. The proposed algorithm are shown to perform well in achieving the design goals.

VII. Conclusion

In this paper, we investigated the problem of CCI and ACI mitigation via channel assignment and power allocation in CR networks. The objective was to maximize the total CR network throughput while keeping the interference with primary users below a tolerance threshold. We proposed an RLT-based centralized SF algorithm that computes near-optimal solution in polynomial time, and a distributed greedy algorithm that only uses local channel gain information. The proposed algorithms are evaluated with simulations. The distributed greedy algorithm is shown to outperform both the centralized SF algorithm and a centralized heuristic algorithm with considerable gains.

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