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Cross-Layer Interference Mitigation for Cognitive Radio MIMO Systems

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***Abstract*—In this paper, we investigate the interference mitigation from a cross-layer perspective for a cognitive radio (CR) multiple-input multiple-output (MIMO) network coexisting with a primary time-division-duplexing (TDD) system. The channel allocation in the media access control (MAC) layer and a subspace-based precoding scheme in the physical layer of the CR network are jointly considered to minimise the interference to the primary user and maximise the CR throughput. Two distributed cross-layer algorithms, namely, joint iterative channel allocation and precoding (JICAP) and non-iterative channel allocation and precoding (NICAP), are proposed for the cases with and without channel information among CR nodes, respectively. Moreover, a channel estimation scheme is also proposed to enable the NICAP. The effectiveness of the proposed algorithms over non-cross-layer counterpart is demonstrated via simulations.**

***Index Terms* – cognitive radio, cross-layer design, interference mitigation.**

I. Introduction

CR technology has become prevailing due to the promising potential to improve spectrum utilization. A CR network is envisioned to have the ability to reuse the unused or underutilized spectra of incumbent systems (also known as primary networks) by sensing its surrounding environment and adapting its operational parameters autonomously [1]– [3]. A CR system may coexist with a primary network on either an interference-free or interference-tolerant basis [4]. For the former case, the CR system only exploits the unused spectra of a primary network, which consequently guarantees no interference to primary users. While, for the latter case, the CR system is allowed to share the spectra assigned to a primary network. A fundamental premise of an interference-tolerant CR network is that it must not impose detrimental interference on the primary network. Therefore, the interference from the CR network to the primary system should be carefully managed and cancelled in order not to disrupt the operation of primary systems.

Various interference mitigation (IM) techniques applicable to CR networks have been reported in [5], including spectrum shaping, predistortion filtering, spread spectrum, etc. As for multiple-antenna CR networks, transmit precoding [6]– [8] is an effective IM approach to proactively mitigate interference from CR transmitters (Txs) to the primary network (CR-primary interference). On one hand, it steers the CR transmission to avoid interfering with the primary network. On the other hand, it exploits either diversity or multiplexing gain of the multiple-antenna CR system to boost the reliability or efficiency of the CR system. The precoding in [6]– [8] assumes that the channel information between CR and primary networks is known. But, this information is not always available to the CR network. This problem was tackled in [9]– [11] by employing subspace technology to estimate the CR-primary channel information before precoding. In [9] and [10], precoding schemes were proposed with the application of the multiple signal classification (MUSIC) technique to estimate the CR-primary channel information. However, the interference from the primary network was simply ignored in these two works during the CR precoding, which leads to CR throughput loss. In [11], an improved precoding scheme was proposed by estimating the interference from the primary to the CR networks and taking it into account for the CR precoding. Therefore, the throughput of the CR network was boosted.

The abovementioned precoding techniques are prominent examples of IM techniques in the physical layer. When multiple CR nodes share the spectrum with the primary network, channel allocation of the CR network opens another door to the CR-primary IM. Channel allocation has been extensively studied especially for cellular networks [12]. For CR networks, two adaptive channel allocation schemes were presented in [13] based on a game theoretic framework. Therefore, it is desirable to jointly consider the channel allocation in the MAC layer and precoding in the physical layer to mitigate interference from CR to primary network. This idea has already been applied to ad hoc networks in [14] and [15], where a joint iterative channel allocation and beamforming algorithm was proposed for interference avoidance. To the best of the authors' knowledge, no research attempt has been made to mitigate interference from CR to primary networks from this perspective.

In this paper, we propose two distributed cross-layer algorithms for CR MIMO systems to minimise the CR-primary interference and maximise the throughput of the CR network.

Channel allocation in the MAC layer and a subspace-based precoding scheme presented in [11] in the physical layer are jointly designed in our work. For the case when channel information among CR nodes is available, we present an iterative algorithm to update the channel allocation and precoding matrices iteratively for all CR Txs to balance between the CR-primary interference and CR throughput. Alternatively, when the channel information among CR nodes is unknown, a non-iterative algorithm together with a channel estimation scheme are proposed to perform the joint channel allocation and precoding.

The remainder of this paper is organized as follows. The system model and problem formulation are given in Section II. The cross-layer interference mitigation algorithms are presented in Section III. The performance of the proposed cross-layer schemes are evaluated via simulations in Section IV. Finally, we conclude the paper in Section V.

II. System Model & Problem Formulation

The system model is demonstrated in Fig. 1. Consider K pairs of CR MIMO Tx and receiver (Rx) coexisting with a primary TDD system. Each primary and CR node is equipped with M_p and M_c antennas, respectively. The primary system operates over N sub-channels $\{f_1, f_2, \cdots, f_N\}$. Each CR pair resides in one of the N sub-channels. The channel allocation for all active CR Txs is denoted as $\mathscr{A} = (A_1, A_2, \cdots, A_K)$, where $A_k \in \{f_1, f_2, \cdots, f_N\},\ k = 1, 2, \cdots, K$.

Block fading channels are assumed for the primary and CR systems. In Fig. 1, $\mathbf{H}_{i,j,A_i}$ stands for the channel matrix from the ith CR Tx to the jth CR Rx over sub-channel A_i $(i, j = 1, 2, \cdots, K)$. We assume $\mathbf{H}_{i,j,A_i} \sim \mathcal{CN}(0, \sigma^2_{\mathrm{H},i,j,A_i})$, which means that its elements are independent and identically distributed (i.i.d.) circular symmetric complex Gaussian random variables with zero mean and covariance $\sigma^2_{\mathrm{H},i,j,A_i}$. Here,

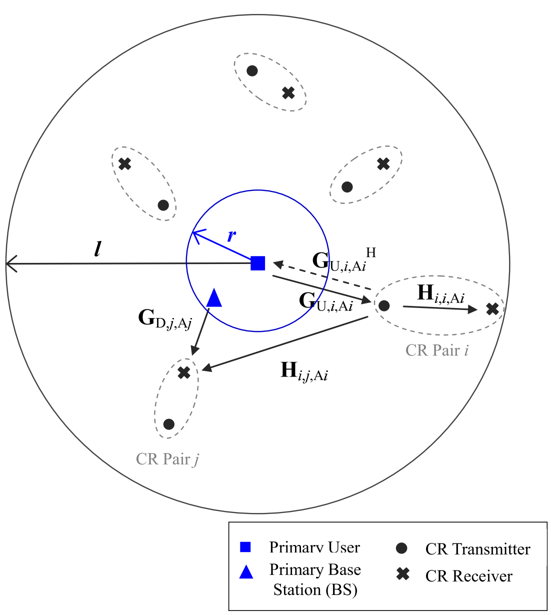

Fig. 1. System model for multiple CR pairs coexisting with a primary system.

$\mathbf{G}_{U,i,A_i} \sim \mathcal{CN}(0, \sigma^2_{\mathrm{U},i,A_i})$ and $\mathbf{G}_{D,j,A_j} \sim \mathcal{CN}(0, \sigma^2_{\mathrm{D},j,A_j})$ $(i, j = 1, 2, \cdots, K)$ represent the interference channel matrices from the primary user to the ith CR Tx during uplink and from the primary base station (BS) to the jth CR Rx during downlink, respectively. Thus, the channel matrix from the ith CR Tx to the primary user is $\mathbf{G}^H_{U,i,A_i}$ due to uplink/downlink reciprocity. These channels are quasi-static over a block of L symbols. The channel between each CR pair $\mathbf{H}_{i,i,A_i}$ $(i = 1, 2, \cdots, K)$ is assumed to be known to CR Txs, but the channels between the primary and CR networks ($\mathbf{G}_{U,i,A_i}$ and $\mathbf{G}_{D,j,A_j}$) are unknown. The source information vector to transmit for the ith CR Tx is denoted as $\mathbf{s}_i$ $(i = 1, 2, \cdots, K)$ and $\mathbb{E}(\mathbf{s}_i\mathbf{s}_i^H) = \mathbf{I}$ is assumed, where $\mathbb{E}(\cdot)$ denotes the expectation operator. The transmitted signal vectors for the primary uplink and downlink are denoted as $\mathbf{x}_u$ and $\mathbf{x}_d$, with their transmit covariance matrices being $\mathbf{Q}_u \triangleq \mathbb{E}(\mathbf{x}_u\mathbf{x}_u^H)$ and $\mathbf{Q}_d \triangleq \mathbb{E}(\mathbf{x}_d\mathbf{x}_d^H)$, respectively.

A. Precoding in the physical layer

A full-projection (FP)-based precoding proposed in [11] is applied to the CR network to proactively mitigate the co-channel CR-primary interference. The system diagram of the FP precoding is shown in Fig. 2. It is capable of estimating the CR-primary interference channel and projecting the CR transmission into the null space of the CR-primary interference channel. Therefore, the resulting CR-primary interference is minimised.

We denote the precoding strategy for all CR Txs during downlink as $\mathscr{F} = (\mathbf{F}_{1,A_1}, \mathbf{F}_{2,A_2}, \cdots, \mathbf{F}_{K,A_K})$. The precoding matrix $\mathbf{F}_{i,A_i}$ for the ith CR Tx at the sub-channel A_i $(i = 1, 2, \cdots, K,\ \forall A_i \in \{f_1, f_2, \cdots, f_N\})$ during the primary downlink can be written as [11]

$$\mathbf{F}_{i,A_i} = \mathbf{U}_i \left[(\mu\mathbf{I} - \mathbf{\Lambda}_i^{-1})^+\right]^{\frac{1}{2}} \tag{1}$$

where $(\cdot)^+ = \mathtt{max}(0, \cdot)$ and μ denotes the water level for the water-filling algorithm. Given the transmission power of each CR Tx P_{cr}, we have $\mathtt{Tr}[(\mu\mathbf{I} - \mathbf{\Lambda}_i^{-1})^+] = P_{cr}$. $\mathbf{U}_i$ and $\mathbf{\Lambda}_i$ are obtained through the following eigenvalue decomposition

$$\begin{aligned}\mathbf{U}_i\mathbf{\Lambda}_i\mathbf{U}_i^H =& (\mathbf{I} - \mathbf{U}_{G,i,A_i}\mathbf{U}^H_{G,i,A_i})^H \mathbf{H}^H_{i,i,A_i}\mathbf{R}^{-1}_{\mathrm{dr},i,A_i} \\ &\times \mathbf{H}_{i,i,A_i}(\mathbf{I} - \mathbf{U}_{G,i,A_i}\mathbf{U}^H_{G,i,A_i})\end{aligned} \tag{2}$$

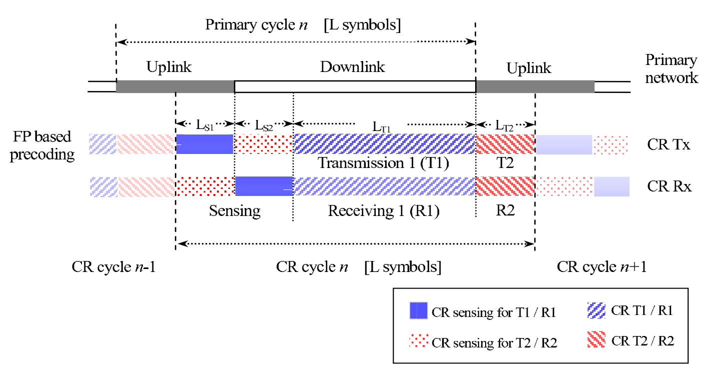

Fig. 2. Diagram for the FP-based precoding [11].

where $\mathbf{U}_{G,i,A_i}$ is the matrix spanning the space of the interference channel from the ith CR Tx to the primary user at sub-channel A_i. It is estimated via sensing at the ith CR Tx during primary uplink. The estimation can be expressed as

$$\mathbf{R}_{\text{ut},i,A_i} = \frac{1}{L_{s1}} \sum_{t=1}^{L_{s1}} \mathbf{r}_{\text{ut},i,A_i}(t)\mathbf{r}^H_{\text{ut},i,A_i}(t) \tag{3}$$

$$= \hat{\mathbf{U}}_i \hat{\mathbf{\Lambda}}_i \hat{\mathbf{U}}_i^H \tag{4}$$

$$= \mathbf{U}_{G,i,A_i}\mathbf{\Lambda}_{G,i,A_i}\mathbf{U}^H_{G,i,A_i} + \mathbf{U}_{n,i,A_i}\mathbf{\Lambda}_{n,i,A_i}\mathbf{U}^H_{n,i,A_i} \tag{5}$$

where $\mathbf{R}_{\text{ut},i,A_i}$ denotes the average covariance matrix of the received symbols at the ith CR Tx over sub-channel A_i during primary uplink, $\mathbf{r}_{\text{ut},i,A_i}(t) = \mathbf{G}_{U,i,A_i}\mathbf{x}_u(t) + \mathbf{n}(t)$ is the tth received symbol at the ith CR Tx with $\mathbf{n}(t) \sim \mathcal{CN}(\mathbf{0}, \sigma_n^2\mathbf{I})$ being the additive white Gaussian noise (AWGN) vector. Eigenvalue decomposition is then performed on $\mathbf{R}_{\text{ut},i,A_i}$ in (4) with $\hat{\mathbf{\Lambda}}_i = \texttt{diag}(\lambda_1, \lambda_2, \cdots, \lambda_{M_c})$. $\mathbf{U}_{G,i,A_i}$ is obtained by further decomposing (4) into interference and noise components as shown in (5) where the diagonal matrix $\mathbf{\Lambda}_{G,i,A_i}$ consists of the M_p largest eigenvalues of $\mathbf{R}_{\text{ut},i,A_i}$ and $\mathbf{U}_{G,i,A_i}$ is the corresponding eigenvectors.

Another component that needs to be estimated in (2) is the covariance matrix of the received signal at the ith CR Rx during primary downlink over sub-channel A_i $\mathbf{R}_{\text{dr},i,A_i}$ $(i = 1, 2, \cdots, K)$. Given a channel allocation $\mathscr{A}$, it can be written as

$$\mathbf{R}_{\text{dr},i,A_i} = \sum_{\forall k: A_k = A_i, k \neq i} \mathbf{H}_{k,i,A_i}\mathbf{F}_{k,A_i}\mathbf{F}^H_{k,A_i}\mathbf{H}^H_{k,i,A_i} + \mathbf{Z}_{i,A_i} \tag{6}$$

where

$$\mathbf{Z}_{i,A_i} = \mathbf{G}_{D,i,A_i}\mathbf{Q}_d\mathbf{G}^H_{D,i,A_i} + \sigma_n^2\mathbf{I},\ \forall i, \forall A_i \in \{f_1, f_2, \cdots, f_N\}. \tag{7}$$

It can be seen from (6) and (7) that $\mathbf{R}_{\text{dr},i,A_i}$ at the ith CR Rx consists of three components. The first component of the right hand side of (6) is the interference from co-channel CR Txs to the ith CR Rx (co-channel CR-CR interference). While, the interference from the primary BS and the noise constitute the second and third components, respectively. Given $\mathscr{A}$ and $\mathscr{F}$, the co-channel CR-CR interference can be evaluated at each CR Rx. $\mathbf{Z}_{i,A_i}$ is estimated at the ith CR Rx during downlink sensing via a step similar to (3).

B. Channel allocation in the MAC layer

Besides the above mentioned precoding-based interference mitigation scheme, the CR-primary interference can also be managed by carefully selecting the operation channel for each CR node. Therefore, we jointly consider channel allocation in the MAC layer and the FP-based precoding in the physical layer for the CR network to minimise the CR-primary interference and maximise the CR throughput. It can be formulated as the following multiple criteria optimisation (MCO) problem

$$\min_{\mathscr{A},\,\mathscr{F}} \text{Int}_i, \quad i = 1, 2, \cdots, K \tag{8}$$

$$\max_{\mathscr{A},\,\mathscr{F}} \text{I}_i, \quad i = 1, 2, \cdots, K \tag{9}$$

$$\text{subject to} \quad \texttt{Tr}\{\mathbf{F}_{i,A_i}\mathbf{F}^H_{i,A_i}\} \leq P_{cr}, \quad i = 1, 2, \cdots, K \tag{10}$$

$$A_i \in \{f_1, f_2, \cdots, f_N\}, \quad i = 1, 2, \cdots, K \tag{11}$$

where Int_i and I_i are the average interference caused by the ith CR Tx to the primary user and the mutual information of the ith CR link during primary downlink, respectively. They are given by

$$\text{Int}_i = \mathbf{G}^H_{U,i,A_i}\mathbf{F}_{i,A_i}\mathbf{F}^H_{i,A_i}\mathbf{G}_{U,i,A_i} \tag{12}$$

$$\text{I}_i = \log_2 \det\left(\mathbf{I} + \frac{\mathbf{H}_{i,i,A_i}\mathbf{F}_{i,A_i}\mathbf{F}^H_{i,A_i}\mathbf{H}^H_{i,i,A_i}}{\mathbf{R}_{\text{dr},i,A_i}}\right). \tag{13}$$

In this paper, we focus on the joint channel allocation and precoding for CR transmission during the primary downlink. A similar problem for the primary uplink can be formulated by following the similar procedure of the downlink counterpart. However, it is ignored here for brevity.

III. Joint Channel Allocation & Precoding

Scalarisation of multiple objectives is one of the most commonly used approaches for solving MCO problems. The MCO problem (8)–(11) can be scalarised into a single objective optimisation problem as follows

$$\min_{\mathscr{A},\,\mathscr{F}} \sum_{i=1}^{K} \text{obj}_i = \sum_{i=1}^{K} \eta\left(\text{Int}_i\right) - \gamma\left(\text{I}_i\right) \tag{14}$$

$$\text{subject to} \quad \texttt{Tr}\{\mathbf{F}_{i,A_i}\mathbf{F}^H_{i,A_i}\} \leq P_{cr}, \quad i = 1, 2, \cdots, K \tag{15}$$

$$A_i \in \{f_1, f_2, \cdots, f_N\}, \quad i = 1, 2, \cdots, K \tag{16}$$

where $\eta(\cdot)$ and $\gamma(\cdot)$ are continuous and monotonically increasing functions. When $\eta(\cdot)$ is convex and $\gamma(\cdot)$ is concave, the problem (14)–(16) can be transformed into a convex optimisation problem by ignoring the co-channel CR-CR interference when computing the CR throughput I_k in (13) [16]. Then, dual optimisation can be employed to solve the convex optimisation problem as in [17].

The co-channel CR-CR interference is not always negligible for the FP-based precoding especially when CR pairs are distributed closely to each other. Moreover, the above optimisation problem requires to be solved in a centralised manner, which is not desirable for CR networks. Next, we propose two distributed cross-layer algorithms for solving the optimisation problem (14)–(16) without ignoring the co-channel CR-CR interference.

A. Known CR-CR interference channels

We first propose a JICAP algorithm when CR-CR interference channels are known to all CR pairs. The proposed JICAP algorithm is depicted in Table I. It works in the following manner. Firstly, all the CR pairs carry out sensing at all sub-channels as depicted in Fig. 2. During the primary uplink, $\mathbf{U}_{G,i,A_i}$ is estimated at each CR Tx from (3)–(5) over all sub-channels. Each CR Rx estimates $\mathbf{Z}_{i,A_i}$ over all sub-channels during the downlink sensing. Secondly, each CR Tx obtains the initial precoding matrices from (1) and (2) for all sub-channels by ignoring the co-channel CR-CR interference. Finally, the channel allocation and precoding are performed iteratively. In each iteration, $\mathscr{A}$ is first updated by selecting a sub-channel minimising the objective function obj_i for each CR Tx. With the updated $\mathscr{A}$, the interference from co-channel

TABLE I
THE JICAP ALGORITHM.

1. Estimate $\mathbf{U}_{G,i,A_i}$ and $\mathbf{Z}_{i,A_i}$ ($\forall i,\ \forall A_i \in \{f_1, f_2, \cdots, f_N\}$) during uplink and downlink sensing at each CR pair.
2. Obtain initial precoding matrices $\mathbf{F}_{i,A_i}$ by ignoring co-channel CR-CR interference for each CR Tx ($\forall i, \forall A_i \in \{f_1, f_2, \cdots, f_N\}$).
3. Start the following iteration
   For $t = 1, 2, \cdots$
      For $i = 1, 2, \cdots, K$
         Select $A_i(t)$ to minimise the obj_i in (14).
      Next i
      Update $\mathscr{A} \leftarrow \{A_1(t), A_2(t), \cdots, A_K(t)\}$.

      For $i = 1, 2, \cdots, K$
         Update $\mathbf{R}_{\mathrm{dr},i,A_i}$ according to $\mathscr{A}$.
         Obtain $\mathbf{F}_{i,A_i}(t)$ from (1)–(7).
      Next i
      Update $\mathscr{F} \leftarrow \{\mathbf{F}_{1,A_1}(t), \mathbf{F}_{2,A_2}(t), \cdots, \mathbf{F}_{K,A_K}(t)\}$.

      Terminate when the channel allocation $\mathscr{A}$ converges.
   Next t

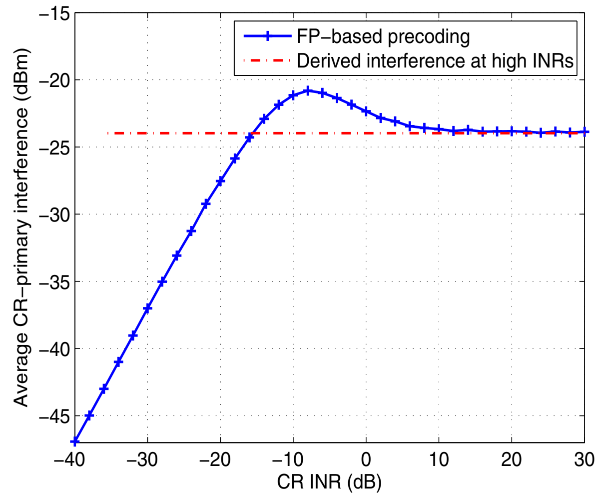

Fig. 3. Relationship between CR INR and the average CR-primary interference ($M_p = 2$, $M_c = 4$, $K = 1$, $L_{S1} = L_{S2} = 50$, $\sigma_H^2 = 1$, $P_{cr} = 1$ unit, and $\sigma_n^2 = 10^{-4}$).

CR Txs is evaluated and the covariance matrix of the received signal $\mathbf{R}_{\mathrm{dr},i,A_i}$ is updated accordingly at each CR Rx. Then, the precoding matrix for each CR Tx is updated from (1) and (2). The iteration terminates when the channel allocation $\mathscr{A}$ converges.

The criterion to select a sub-channel for the ith CR pair is to minimise the objective function obj_i in (14). Therefore, evaluating the average interference from the ith CR Tx to the primary user Int_i is indispensable for the channel allocation. However, it is impossible to obtain Int_i directly from (12), since the CR-primary channel $\mathbf{G}^H_{U,i,A_i}$ is unknown. The relationship of the average CR-primary interference Int_i with the CR-primary interference channel gain $\sigma^2_{\mathrm{U},i,A_i}$ and noise power σ_n^2 has been given in [11]. As shown in Fig. 3, it is found that Int_i is proportional to $\sigma^2_{\mathrm{U},i,A_i}$ at low CR interference-to-noise ratios (INRs$\triangleq \sigma^2_{\mathrm{U},i,A_i}/\sigma_n^2$). While, in the large INR regime, the average interference can be written as [11]

$$\mathrm{Int}_i = \frac{\sigma_n^2 P_{cr}}{L_{S1}} \mathtt{Tr}\{\mathrm{E}(\mathbf{Q}_u)\} \tag{17}$$

where the noise power σ_n^2 can be estimated from (4) using

$$\sigma_n^2 = \frac{\sum_{i=M_p+1}^{M_c} \lambda_i}{M_c - M_p}. \tag{18}$$

Similarly, the channel gain from the kth CR Tx to the primary user $\sigma^2_{\mathrm{U},i,A_i}$ can be estimated from (4) via

$$\sigma^2_{\mathrm{U},i,A_i} = \frac{\sum_{i=1}^{M_p} \lambda_i}{M_p}. \tag{19}$$

With these two estimations, the average CR-primary interference Int_i can be evaluated by using the results in [11]. Consequently, the channel allocation can be carried out without priori knowledge of $\mathbf{G}^H_{U,i,A_i}$.

It can be seen from the proposed JICAP algorithm that there exist two types of interaction across the MAC and physical layers. On one hand, the channel allocation $\mathscr{A}$ from the MAC layer is passed down to the physical layer to update the precoding matrices. On the other hand, the precoding strategy $\mathscr{F}$ from the physical layer is fed up to the MAC layer to evaluate the objective function obj_i for channel selection.

B. Unknown CR-CR interference channels

To facilitate the proposed JICAP algorithm in Section III.A, it is obvious that the precoding matrices $\mathbf{F}_{i,A_i}$ together with the associated CR-CR interference channel $\mathbf{H}_{i,j,A_i}$ are needed by the jth CR pair ($i, j = 1, 2, \cdots, K,\ \forall i \neq j$) for both channel allocation and precoding. Hereafter, we name them as effective CR-CR interference channels $\mathbf{H}_{i,j,A_i}\mathbf{F}_{i,A_i}$. However, these information is not always available to the CR network. Various estimation techniques can be employed to perform channel estimation [18], but it incurs much communication overhead for the proposed JICAP algorithm due to the iterative nature. In this subsection, we apply a novel channel estimation approach to the cross-layer interference mitigation and propose a NICAP algorithm for the CR MIMO system.

The NICAP works in the same way as the JICAP for the first two steps as shown in Table I. After that, each CR Tx obtains the initial precoding matrices for all sub-channels without taking into account the co-channel CR-CR interference. Each CR pair then selects an initial sub-channel minimising the objective function obj_i by ignoring the co-channel CR-CR interference. Next, the effective CR-CR interference channels $\mathbf{H}_{i,j,A_i}\mathbf{F}_{i,A_i}$ are estimated by each CR pair using the method below. Finally, the ultimate channel allocation and precoding strategy is determined for CR spectrum sharing.

The effective CR-CR interference channels are estimated in the following way. After the initial channel allocation, CR pairs can be divided into N groups according to their operating sub-channels. Each group consists of CR pairs operating at the same sub-channel, i.e., $S_n = \{i\mathrm{th\ CR\ pair} | A_i = f_n,\ i = 1, 2, \cdots, K\}$ ($n = 1, 2, \cdots, N$). For CR pairs within the same group, they work in the time division multiplexing (TDM) manner. All N CR groups are transmitting simultaneously in this phase. During the transmission of a CR Tx, all the rest CR Rxs in the entire CR network are sensing and estimating the average covariance matrix of the received signal. Suppose that each CR pair is allocated a time slot with duration of L_s symbols. The tth ($t = 1, 2, \cdots, L_s$) received signal at the jth CR Rx during the time slot of the ith CR pair ($j = 1, 2, \cdots, K, \forall j \neq i$) is

$$\mathbf{r}_{i,j,A_i}(t) = \mathbf{H}_{i,j,A_i}\mathbf{F}_{i,A_i}\mathbf{s}_i(t) + \mathbf{G}_{D,j,A_i}\mathbf{x}_d(t) + \mathbf{n}(t). \quad (20)$$

It can be seen from (20) that the received signal consists of three components: the co-channel interference from the ith CR Tx, the interference from the primary BS during downlink and the AWGN $\mathbf{n}$. Then the average covariance matrix of the received signal at the jth CR Rx during the ith CR transmission can be expressed as

$$\begin{aligned}\mathbf{R}_{i,j,A_i} &= \sum_{t=1}^{L_s} \mathbf{r}_{i,j,A_i}(t)\mathbf{r}_{i,j,A_i}(t)^H \\ &\overset{(a)}{=} \mathbf{H}_{i,j,A_i}\mathbf{F}_i\mathbf{F}_i^H\mathbf{H}_{i,j,A_i}^H + \mathbf{G}_{D,j,A_i}\mathbf{Q}_d\mathbf{G}_{D,j,A_i}^H + \sigma_n^2\mathbf{I} \\ &\overset{(b)}{=} \mathbf{H}_{i,j,A_i}\mathbf{F}_i\mathbf{F}_i^H\mathbf{H}_{i,j,A_i}^H + \mathbf{Z}_{j,A_i} \quad (21)\end{aligned}$$

where in (21), (a) is due to the fact that $\mathbb{E}(\mathbf{s}_i\mathbf{s}_i^H) = \mathbf{I}$ and $\mathbb{E}(\mathbf{x}_d\mathbf{x}_d^H) = \mathbf{Q}_d$; substituting (7) into (a) yields (b). Therefore, the covariance matrix of the effective CR-CR interference channel from the ith CR Tx to the jth CR Rx at sub-channel A_i can be expressed as

$$\mathbf{H}_{i,j,A_i}\mathbf{F}_{i,A_i}\mathbf{F}_{i,A_i}^H\mathbf{H}_{i,j,A_i}^H = \mathbf{R}_{i,j,A_i} - \mathbf{Z}_{j,A_i}. \quad (22)$$

The above equation suggests that the covariance matrices of the effective CR-CR interference channels needed by the channel allocation and precoding can be obtained via the effective CR-CR channel estimation mentioned above and the primary downlink sensing. It is easy to understand that the average duration for the effective CR-CR interference channel estimation phase is KL_s/N. Moreover, the NICAP algorithm works in a non-iterative manner and the effective CR-CR interference channels are only estimated for one time. Therefore, the cross-layer communication overhead is significantly reduced compared to that of the JICAP.

It is worth noting that compared to non-cross-layer interference mitigation schemes both of the proposed cross-layer approaches are performed at the expense of increased complexity due to the cross-layer consideration. In general, the complexity involved in each proposed approach increases with the increase of CR number. Moreover, the complexity increase of the JICAP algorithm is more obvious than that of the NICAP due to its iterative nature.

IV. Simulation Results

The performance of the proposed JICAP and NICAP algorithms is evaluated via simulations in this section. In our simulations, we consider that $K = 10$ pairs of CR links coexist with a primary system. The primary network operates over $N = 3$ sub-channels. Each primary and CR node is equipped with $M_p = 2$ and $M_c = 4$ antennas, respectively. The primary user locates at the origin of a 2-dimensional plane. As demonstrated in Fig. 1, the primary BS and all the CR pairs are uniformly distributed around the primary user with radii $r = 10$m and $l = 100$m, respectively. Rayleigh fading channels are assumed for the primary and the CR systems. The CR transmission power and the noise power are set as $P_{cr} = 1$ and $\sigma_n^2 = 10^{-4}$. The uplink and downlink sensing for the FP-based precoding both last for 25 symbols. The time slot for each CR pair during the effective CR-CR channel estimation is also set to 25 symbols, i.e., $L_{s1} = L_{s2} = L_s = 25$. The objective function for the JICAP algorithm is designed as $\mathrm{obj}_i = 3 \times 10^5 \mathrm{Int}_i - \mathrm{I}_i$.

With this setup, both the CR sum rate (mutual information) and the overall average resulting interference perceived at the primary user are examined for the two proposed algorithms in Fig. 4. Each point in our simulations is obtained by averaging over 2000 simulation runs. The performance of these two proposed algorithms is compared with that of another two schemes: non-cross-layer and minimum interference approaches. For the former approach, a random channel allocation is performed and then used throughout the whole CR transmission phase. Its channel allocation and precoding are performed separately and no interaction exists between the physical and the MAC layers. Hence, it is termed as the non-cross-layer approach. While, for the latter the channel allocation in each iteration aims at minimising the resulting CR-primary interference, i.e., the second criteria (9) for the MCO problem is ignored.

It can be seen from Fig. 4 that compared to the non-cross-layer approach, the proposed JICAP and NICAP algorithms reduce the CR-primary interference and boost the CR throughput at the same time. Therefore, the cross-layer schemes outperform the non-cross-layer counterpart. The minimum interference approach can further reduce the CR-primary interference by compromising the CR throughput. This suggests that the

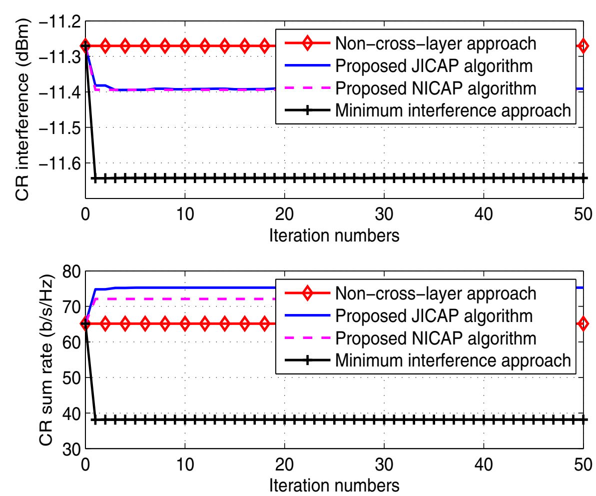

Fig. 4. Performance evaluation of the proposed cross-layer algorithms ($r = 10$m, $l = 100$m, $K = 10$, $N = 3$, $M_p = 2$, $M_c = 4$, $L_{s1} = L_{s2} = L_s = 25$, $P_{cr} = 1$, and $\sigma_n^2 = 10^{-4}$).

proposed cross-layer algorithms can effectively balance the interference minimisation and the CR throughput maximisation. Furthermore, it can also been seen from Fig. 4 that the NICAP algorithm together with the proposed estimation scheme for the effeictive CR-CR interference channels leads to similar performance to that of the JICAP with known CR-CR interference channels.

Finally, the convergence of the proposed JICAP algorithm is evaluated in Fig. 5 for one realisation of the primary and CR systems. We use the same setup as that of Fig. 4. As we can see from Fig. 5, the channel allocation for all 10 CR pairs converges rapidly. Meanwhile, the CR sum rate converges right after the convergence of the channel allocation. This is due to the fact that after the channel allocation is fixed the FP-based precoding does not take long to reach the Nash equilibrium - a stable state where no CR links can improve their throughput by unilaterally changing their own precoding matrices.

V. Conclusions

The IM has been investigated for CR MIMO systems from a cross-layer perspective. A distributed iterative channel allocation and precoding algorithm has been proposed to minimise the CR-primary interference and maximise the CR throughput when interference channels among CR nodes are available. While, for the scenario with unknown CR-CR interference channel information, we have proposed a non-iterative cross-layer algorithm together with an estimation scheme for effective CR-CR interference channels. Simulation results have demonstrated that i) both of the proposed cross-layer algorithms outperform the non-cross-layer approach in terms of the CR-primary interference and the CR throughput, ii) the no-iterative algorithm achieves similar performance to the iterative counterpart without incurring much communication overhead. Future work can be done to incorporate power control of the CR network into the cross-layer design and to evaluate the performance of the proposed algorithms over more realistic channels like [19].

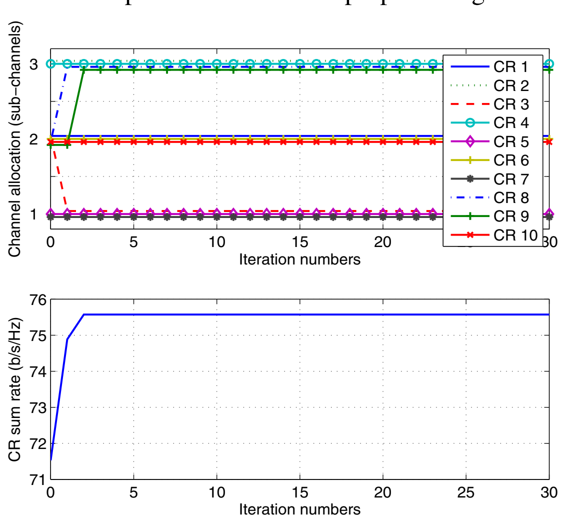

Fig. 5. Convergence of the proposed JICAP algorithm ($r = 10$m, $l = 100$m, $K = 10$, $N = 3$, $M_p = 2$, $M_c = 4$, $L_{s1} = L_{s2} = L_s = 25$, $P_{cr} = 1$, and $\sigma_n^2 = 10^{-4}$).

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