Spatial Interweave for a MIMO Secondary Interference Channel with Multiple Primary Users

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ABSTRACT

In this paper we consider a Secondary Network, modeled as a K-user Multiple-Input-Multiple-Output (MIMO) interference channel (IFC) that coexists with a set of L multi antenna Primary receivers (PRx). The objective of our investigation is to design Interference Alignment (IA) beamforming matrices at the secondary transmitters such that the interference received at the PRx is confined in a subspace of proper dimension. To solve this optimization problem we propose an iterative algorithm that is based on the algorithm described in [1]. The cognitive radio (CR) communication under investigation can take place exploiting the Spatial Domain of the complete network. For this reason it comes under the purview of Spatial Interweave CR paradigm. In addition we propose a set of feasibility conditions that the CR system should attain in order to admit an IA solution that satisfies the interference constraints on the primary users.

1. INTRODUCTION

Interference is being increasingly accepted as the major bottleneck limiting the throughput in wireless communication networks. A systematic study of the performance of cellular communication systems where each cell communicates multiple streams to its users while enduring/causing interference from/to neighboring cells due to transmission over a common shared resource comes under the purview of MIMO interference channels (MIMO IFC). A K-user MIMO-IFC models a network of K transmit-receive pairs where each transmitter communicates multiple data streams to its respective receiver. In doing so, it generates interference at all other receivers. Recently, it was shown that the concept of interference alignment (IA) [1], maximizes the capacity prelog factor, or degrees of freedom (DoF), in a K-user IFC. The key idea behind interference alignment is to process the transmit signal (data streams) at each transmitter, so as to align all the undesired signals at each receiver in a subspace of suitable dimension. A distributed algorithm that exploits the reciprocity of the MIMO IFC to obtain the transmit and receiver filters in a K-user MIMO IFC was proposed in [1], a similar algorithm has been proposed in [2]. The problem of determining whether an IA solution exists or not for a given antennas and stream distribution among the users for a K-user MIMO IFC it has been studied in [3] and [4].In the former an extensive study of IA feasibility solution for the single stream case has been proposed. In the latter the authors propose a systematic method, and less computational expensive, to check feasibility regardless of the number of transmitted stream per user.

Cognitive Radio (CR) has been recently introduced as a possible solution to enhance the spectral efficiency of modern wireless communication systems. The basic idea behind CR is that an opportunistic system, usually called secondary system, can transmit using the same communication resources of a licensed system, primary system, while keeping the interference to the primary system under control.

From an information theoretic point of view [5], there are three CR paradigms: *Interweave*, *Overlay* and *Underlay*. Interweave exploits the *white spaces* in time, frequency or space [6] of the concurrent transmissions; Overlay is a cooperative technique, in which the secondary transmitted signals are generated to improve the primary communication, requiring thus a shared knowledge of the codebooks and modulation schemes. The Underlay CR allows the coexistence of a Primary (usually licensed) network and a Secondary (cognitive) one, constraining the interference caused by secondary transmitters on primary receivers under a certain threshold. In this work we focus on the *spatial Interweave* paradigm. We consider a secondary network modeled as a MIMO interference channel and where the BF matrices are designed according to IA among secondary users while constraining the interference caused to the primary receiver to be in a subspace of reduced dimensions. A similar setting has been studied in [7] where only one pair of primary and secondary has been considered. In [6] the same scenario of [7] is considered but all the practical aspect of a TDD system are considered. In [8] they extend the setting in [7] to multiple secondary pairs but only one primary. In our work we consider an arbitrary number of secondary users and the solution proposed for the BF filters is different to the one presented in [8]. In addition we study the feasibility of an IA solution of the system under investigation based on the results in [4].

2. SIGNAL MODEL

In this section we describe the cognitive radio scenario that we study in the paper and we give a short introduction of IA.

2.1 Cognitive Radio Scenario

The cognitive radio setting that we consider in this paper is depicted in Fig. 1. The system setting that we study can be used to model the coexistence of a set K of femto-cells with the presence of L macro-users.

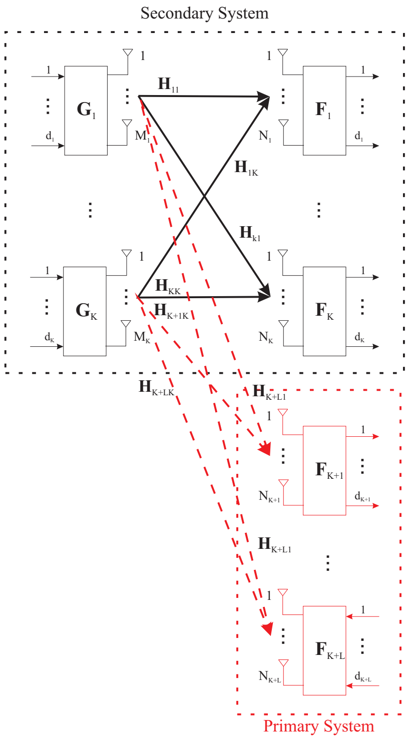

Figure 1: Cognitive Radio System

The secondary network is a K-link MIMO interference channel with K transmitter-receiver pairs. To differentiate the two transmitting and receiving devices we assume that each of the K pairs is composed of a secondary Base station (SBS) and a secondary Mobile user (SMU). This is only for notational purposes. The k-th SBS and its corresponding SMU are equipped with M_k and N_k antennas respectively. The k-th transmitter generates interference at all $l \neq k$ receivers. The received signal $\mathbf{y}_k$ at the k-th SMU, can be represented as

$$\mathbf{y}_k = \mathbf{H}_{kk}\mathbf{x}_k + \sum_{\substack{l=1 \\ l \neq k}}^{K} \mathbf{H}_{kl}\mathbf{x}_l + \mathbf{n}_k \tag{1}$$

where $\mathbf{H}_{kl} \in \mathbb{C}^{N_k \times M_l}$ represents the channel matrix between the l-th SBS and k-th SMU, $\mathbf{x}_k$ is the $\mathbb{C}^{M_k \times 1}$ transmit signal vector of the k-th SBS and the $\mathbb{C}^{N_k \times 1}$ vector $\mathbf{n}_k$ represents (temporally white) AWGN with zero mean and covariance matrix $\mathbf{R}_{n_k n_k}$. The channel is assumed to follow a block-fading model having a coherence time of T symbol intervals without channel variation. Each entry of the channel matrix is a complex random variable drawn from a continuous distribution. It is assumed that each transmitter has complete knowledge of all channel matrices corresponding to its direct link and all the other cross-links in addition to the transmitter power constraints and the receiver noise covariances.

We denote by $\mathbf{G}_k$, the $\mathbb{C}^{M_k \times d_k}$ precoding matrix of the k-th transmitter. Thus $\mathbf{x}_k = \mathbf{G}_k\mathbf{s}_k$, where $\mathbf{s}_k$ is a $d_k \times 1$ vector representing the d_k independent symbol streams for the k-th user pair. We assume $\mathbf{s}_k$ to have a spatio-temporally white Gaussian distribution with zero mean and unit variance, $\mathbf{s}_k \sim \mathcal{N}(0, \mathbf{I}_{d_k})$. The k-th receiver applies $\mathbf{F}_k \in \mathbb{C}^{d_k \times N_k}$ to suppress interference and retrieve its d_k desired streams. The output of such a receive filter is then given by

$$\mathbf{r}_k = \mathbf{F}_k\mathbf{H}_{kk}\mathbf{G}_k\mathbf{s}_k + \sum_{\substack{l=1 \\ l \neq k}}^{K} \mathbf{F}_k\mathbf{H}_{kl}\mathbf{G}_l\mathbf{s}_l + \mathbf{F}_k\mathbf{n}_k$$

The secondary network wants to coexist with a set of L multi antenna primary mobile users (PMU). To simplify the notation we index the L PMU from $K+1$ to $K+L$. With this notation the channel matrix between the SBS_k and the PMU_{K+l} is denoted $\mathbf{H}_{K+lk}$ and has dimensions $N_{K+l} \times M_k$, where N_{K+l} represents the number of antennas at PMU. The receiver filter applied at the PMU_{K+l} is denotes as $\mathbf{F}_{K+l}$, in this paper we do not consider the optimization of the primary transmission so the receiver $\mathbf{F}_{K+l}$ is a general receiver. We only assume that the it involves a fixed number of transmitted stream d_{K+l}. In the following we consider the situation where the primary transmitter (PBS) is located far from the secondary system and hence no interference is caused to the secondary network from the primary communication. We constraint our attention to the scenario where each primary receiver has to suppress only the interference coming from the secondary network. Primary user receiver design is not considered here. In this paper we do not make any assumption on the antenna configuration at the primary and secondary network but we should underline that two possible situations can occur. In particular if the number of antennas in the secondary network is grater that the number of antennas at the primary users then blind channel estimation is possible. On the other hand if the secondary network has less antennas than the primary users then the primary training signal should be explored for the channel estimation process.

2.2 Interference Alignment

The objective in IA, for a traditional K-user MIMO IFC, is to design spatial filters to be applied at the transmitters such that, the interference caused by all transmitters at each non-intended RX lies in a common *interference subspace*. Moreover, the interference subspace and the *desired signal subspace* of each RX should be non-overlapping (linearly independent). If alignment is complete, simple ZF can be applied to suppress the interference and extract the desired signal in the high-SNR regime. Since IA is a condition for joint transmit-receive linear ZF, we need to satisfy the following conditions:

$$\mathbf{F}_k\mathbf{H}_{kl}\mathbf{G}_l = \mathbf{0} \quad \forall l \neq k \tag{2}$$

$$\text{rank}(\mathbf{F}_k\mathbf{H}_{kk}\mathbf{G}_k) = d_k \quad \forall k \in \{1, 2, \ldots, K\} \tag{3}$$

This last rank condition leads to the traditional single user MIMO constraint $d_k \leq \min(M_k, N_k)$ for d_k streams to be able to pass over the k-th link. A closed form expression for the BF and the Rx filters is not known in general, it is derived only for a few simple MIMO interference channel configurations. To determine the IA solution of a general K-User MIMO IFC the only possible alternative is the computation using an iterative algorithm, for example [1].

3. INTERFERENCE ALIGNMENT FOR COGNITIVE RADIO SYSTEM

In this section we specify the IA conditions, presented in section 2.2 for the cognitive radio system that we consider in this paper. As explained before the focus of our work is to design a set of K IA beamformers and receiver filters such that the interference at each primary MU is constrained in the subspace of fixed dimensions. This means that on top of the IA conditions in (2) and (3) we need to impose the following additional constraints:

$$\text{rank}\left[\sum_{k=1}^{K}\mathbf{H}_{K+lk}\mathbf{G}_k\right] \leq N_{K+l} - d_{K+l} \quad \forall l = 1,\dots,L \quad (4)$$

The rank requirements at the primary receiver described above can be interpreted in an alternative way. If we assume that each PMU applies a fictitious interference suppressing filter $\mathbf{F}_{K+l}$ such that it retrieves d_{K+l} interference free streams, condition (4) reads:

$$\mathbf{F}_{K+l}\left[\sum_{k=1}^{K}\mathbf{H}_{K+lk}\mathbf{G}_k\right] = \mathbf{0} \quad \forall l = 1,\dots,L \quad (5)$$

This conditions says that the *Interference Leakage* [1] at each PMU should be equal to zero. The receiver $\mathbf{F}_{K+l}$ is introduced only for the derivation of an iterative algorithm it is not the real receiver applied at the PMUs. With this modification we can interpret the entire network as an asymmetric IFC with K transmitters and $K+L$ receivers. Using the results proposed in [1] we can extend their algorithm to the CR setting that we consider here.

The objective of the algorithm is to find a set of BF and Rx filters such the the leakage interference at each receiver is minimized. If an interference alignment solution exist the residual interference will be completely suppressed.

The interference leakage at receiver k is defined as:

$$IL_k = \text{Tr}\left[\ \mathbf{F}_k\mathbf{R}_{\overline{k}}\mathbf{F}_k^H\ \right] \ \forall k = 1,\dots,K+L \quad (6)$$

where the interference covariance matrix at receiver k is defined as

$$\mathbf{R}_{\overline{k}} = \begin{cases} \sum_{l\neq k}^{K}\frac{P_l}{d_l}\mathbf{H}_{kl}\mathbf{G}_l\mathbf{G}_l^H\mathbf{H}_{kl}^H, & k = 1,\dots,K \\ \sum_{l=1}^{K}\frac{P_l}{d_l}\mathbf{H}_{kl}\mathbf{G}_l\mathbf{G}_l^H\mathbf{H}_{kl}^H, & k = K+1,\dots,K+L \end{cases} \quad (7)$$

P_l represents the Tx power for user l. The algorithm to determine the Tx and Rx filters is based on *Reciprocity of IA* solutions [1]. It iterates between the original and the reciprocal system. The reciprocal network can be the real dual system or a fictitious network used only in the BF design algorithm. In our case the reciprocal, dual network, is described by a dual channel $\overline{\mathbf{H}}_{kl} = \mathbf{H}_{lk}^H$, the reciprocal Tx and Rx filters are $\overline{\mathbf{F}}_k = \mathbf{G}_k^H$, $\overline{\mathbf{G}}_k = \mathbf{F}_k^H$. With those definitions the leakage interference in the reciprocal network is:

$$\overline{IL}_k = \text{Tr}\left[\ \overline{\mathbf{F}}_k\overline{\mathbf{R}}_{\overline{k}}\overline{\mathbf{F}}_k^H\ \right] \ \forall k = 1,\dots,K \quad (8)$$

where the dual interference covariance matrix is defined as:

$$\sum_{l\neq k}^{K+L}\frac{P_l}{d_l}\mathbf{H}_{kl}\overline{\mathbf{G}}_l\overline{\mathbf{G}}_l^H\mathbf{H}_{kl}^H \quad (9)$$

as we can see from the definitions above there is a difference between original and reciprocal network due to the non symmetric structure of our system. As described in [1] to find the Tx and Rx filters we need to minimize the leakage interference in the original and reciprocal system in particular for all $k = 1,\dots,K+L$ we have to solve the following:

$$\min_{\mathbf{F}_k\mathbf{F}_k^H=\mathbf{I}} IL_k \quad (10)$$

The optimal solution of this problem is given by the eigenvectors of $\mathbf{R}_{\overline{k}}$ corresponding to the d_k smallest eigenvalues. In a second step we solve the same problem but for the reciprocal system but now we determine the Rx filter for $k = 1,\dots,K$.

Algorithm 1 Iterative Algorithm for Cognitive IA

Fix the initial set of precoding matrices $\mathbf{G}_k$, $\forall \in k = \{1, 2 \dots K\}$
repeat
  Find $\mathbf{F}_k$ $\ k = 1 : K+L$ as the d_k eigenvector corresponding to the smallest eigenvalue of $\mathbf{R}_{\overline{k}}$
  Reverse the system and solve in the reciprocal system
until convergence

4. INTERFERENCE ALIGNMENT FEASIBILITY

To determine the existence of an IA solution for a given DoF allocation in our CR scenario we the translate the IA equations into a set of conditions that need to be satisfied to admit an IA solution.

$$\mathbf{F}_k\mathbf{H}_{kl}\mathbf{G}_l = \mathbf{0} \quad \forall l \neq k \quad (11)$$

$$\text{rank}(\mathbf{F}_k\mathbf{H}_{kk}\mathbf{G}_k) = d_k \quad \forall k \in \{1, 2, \dots, K\} \quad (12)$$

$$\text{rank}\left[\sum_{k=1}^{K}\mathbf{H}_{K+lk}\mathbf{G}_k\right] \leq N_{K+l} - d_{K+l} \quad \forall l = 1,\dots,L \quad (13)$$

The approach we adopt in this paper is of formulating the given IA problem as finding a solution to a system of equations with limited number of variables dictated by the dimensions of the overall system. The interference aligning beamformer matrix $\mathbf{G}_k$ aligns the transmit signal of the k-th user to the interference subspace at all $l \neq k$ users while ensuring the rank of the equivalent channel matrix $\mathbf{F}_k\mathbf{H}_{kk}\mathbf{G}_k$ is d_k. The only requirement on the $(d_k \times d_k)$ matrix that mixes up the desired streams is that it be of full rank. The beamforming matrix is defined up to an arbitrary $(d_k \times d_k)$ square matrix. Thus, of the total number of $(M_k \times d_k)$ variables available for the design of $\mathbf{G}_k$ matrix reduces to $d_k(M_k - d_k)$.

Considering all the SBS the total number of variable available at the TX side is:

$$\sum_{i=1}^{K} d_i(M_i - d_i) \tag{14}$$

The IA scheme essentially requires that all alignment is done at the TX. Therefore every TX imposes a set of constraints on the entire system whenever it transmits a stream to its RX. An IA solution will be feasible only if the total number of variables available in the system is greater than or equal to the total number of constraints to be satisfied. Moreover, the variables should be distributed appropriately at each of the TX. Here we propose a method of counting the number of variables available for the design of beamformers and comparing them with the number of constraints imposed on the system.

The main idea behind our method is to convert the alignment requirements at each RX into a rank condition of an associated interference matrix.

Because in our CR system we have a set of additional requirements for the alignment at the primary receiver we have to consider also the interference matrix that the secondary transmissions span at each PMU. For this reason we first study the problem of the alignment at the secondary network and then we consider the primary constraints.

At SMU k, the interference due to all other $(K-1)$ secondary transmitters is grouped into a $(N_k \times \sum_{l=1;l\neq k}^{K} d_l)$ matrix

$$\mathbf{H}_{IS}^{[k]}=[\mathbf{H}_{k1}\mathbf{G}_1, ...\mathbf{H}_{k(k-1)}\mathbf{G}_{(k-1)}, \mathbf{H}_{k(k+1)}\mathbf{G}_{(k+1)}, ...\mathbf{H}_{kk}\mathbf{G}_K],$$

that spans the interference subspace. The total signal-space dimension at SMU k is given by the total number of receive antennas N_k and d_k are to be reserved for the signal from the k-th PBS. This is achieved when the interference from all other transmitters lies in an independent subspace whose dimension can be at most $(N_k - d_k)$. Thus the dimension of the subspace spanned by the matrix $\mathbf{H}_{IS}^{[k]}$ must satisfy

$$\text{rank}(\mathbf{H}_{IS}^{[k]}) = r_{IS}^{[k]} \leq N_k - d_k \tag{15}$$

Imposing a rank $r_{IS}^{[k]}$ on $\mathbf{H}_{IS}^{[k]}$ implies imposing

$$(N_k - r_{IS}^{[k]})(\sum_{\substack{l=1\\ l\neq k}}^{K} d_l - r_{IS}^{[k]})$$

constraints at RX k. In general the rank $r_{IS}^{[k]}$ should satisfy the following upper bound

$$r_{IS}^{[k]} \leq \min(d_{tot}, N_k) - d_k \tag{16}$$

where $d_{tot} = \sum_{k=1}^{K} d_k$.

At PMU $K+l$ the interference coming from the entire secondary network can be identified with an interference matrix of dimensions $(N_{K+l} \times d_{tot})$:

$$\mathbf{H}_{IP}^{[K+l]}=[\mathbf{H}_{K+l1}\mathbf{G}_1, \dots, \mathbf{H}_{K+lK}\mathbf{G}_K].$$

To satisfy the CR constraint the interference matrix $\mathbf{H}_{IP}^{[K+l]}$ should span a subspace of dimensions

$$\text{rank}(\mathbf{H}_{IP}^{[K+l]}) = r_{IP}^{[k]} \leq N_{K+l} - d_{K+l}. \tag{17}$$

According to the rank requirement and the dimensions of the interference matrix $\mathbf{H}_{IP}^{[K+l]}$ satisfies the following upper bound:

$$r_{IP}^{[K+l]} \leq \min(d_{tot}, N_{K+l} - d_{K+l}) \tag{18}$$

Imposing a rank constraint (13) on the interference matrix at the PMU implies imposing

$$(N_{K+l} - r_{IP}^{[K+l]})(d_{tot} - r_{IP}^{[K+l]})$$

constraints. Once we know how to calculate the number of variable available to design the IA precoding matrices and the number of constraints that the IA solution imposes on the system under investigation we can write the final relation in (20).

To evaluate the existence on an IA solution it is not only important that the number of variable is enough to satisfy the constraints that the IA imposes on our system but we should study also how this variables are distributed among all the users. To consider this aspect we propose a recursive procedure based on studying IA feasibility on a subsystem built by successively adding one transmitter at a time [4]. At each step k of the recursion, (20) accumulates the total number of variables available for designing an IA solution in an associated sub-problem comprising of a k-link MIMO IFC in the LHS of (20), where $\underline{d}_k = \sum_{i=1}^{k} d_i$. In the considered subproblem only k transmitters are transmitting non-zero streams and aligning their streams into some interference subspace of all non-intended receivers. The RHS accumulates the total number of constraints at all receivers that arise due to these transmitters.

Consider a network where the secondary system is symmetric hence $M_k = N_k = N_S,\ d_k = d_S\ \forall k = 1, \dots, K$ and a primary system with $N_{K+l} = N_P,\ d_{K+l} = d_P\ \forall l = 1, \dots, L$. In this particular scenario we can specify a condition that the antenna distribution in the secondary network should attain to obtain the desired stream allocation satisfying, at the same time, the rank requirement at the PMU.

Neglecting trivial cases as $N_P > Kd_S$ and $N_S > Kd_S$ we can specify condition (20) as follows:

$$N_S \geq \frac{K+1}{2}d_S + \frac{Ld_P}{2Kd_S}(Kd_S - (N_P - d_P)) \tag{19}$$

From the condition above we can see that compare to the simple K-users MIMO IFC introducing a set of primary user interference constraint causes a reduction in terms of performances. In particular to obtain the same DoF of a traditional MIMO IFC additional $\frac{Ld_P}{2Kd_S}(Kd_S - (N_P - d_P))$ antennas are required in order to handle the interference to the primary users. If equation (19) is derived for the case where the PMU does not have any noise subspace $((N_P - d_P))$ our conditions for symmetric systems becomes similar to the equivalent condition given in [8].

5. SIMULATION RESULTS

In this section we present some simulation results for the cognitive radio scenario that we presented. In Fig. 2 we report the sum rate of the primary and secondary system. In particular there is a single primary receiver with $N_P = 2$ antennas. To calculate its rate we assume that it communicates with a primary transmitter according to a single user MIMO communication without receiving interference from

$$\sum_{i=1}^{k} d_i(M_i - d_i) \geq \sum_{i=1}^{k} \Big(N_i - \underbrace{\min(\underline{d}_k - d_i, (N_i - d_i))}_{r_{IS}^{[i]}} \Big)\Big(\underline{d}_k - d_i - \min(\underline{d}_k - d_i, (N_i - d_i)) \Big)$$
$$+ \sum_{i=k+1}^{K} (N_i - \underbrace{\min(\underline{d}_k, (N_i - d_i))}_{\overline{r}_{IS}^{[i]}})(\underline{d}_k - \min(\underline{d}_k, (N_i - d_i))) \tag{20}$$
$$+ \sum_{i=K+1}^{K+L} \Big(N_i - \underbrace{\min(\underline{d}_k, (N_i - d_i))}_{r_{IP}^{[i]}} \Big)\Big(\underline{d}_k - \min(\underline{d}_k, (N_i - d_i)) \Big)$$

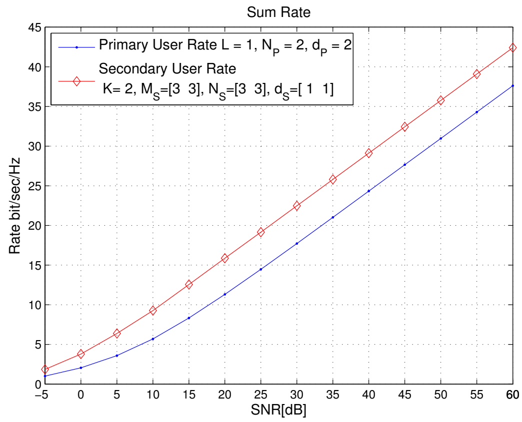

Figure 2: Sum rate performances

the secondary communication. Thus the the primary Tx and Rx are built according to water filling like technique. In high SNR regime this will lead to a maximum of $d_P = 2$ transmitting streams. The secondary network is modeled as a $K = 3$ MIMO IFC where each secondary pairs wants to send $d_k = d_S = 2$ streams. To satisfy its interference free streams requirement and the interference rank constraints to the primary, according to (19), each Tx and Rx pair should be equipped with $M_k = N_k = N_S = 3$ transmitting and receiving antennas.
As we can the two curves are parallel in the high SNR regime. This means that the secondary network is able to achieve the same DoF of the primary network hence the total required number of streams has been sent. The rate curve of the secondary system is characterized by an higher SNR offset, this is due to the higher number of antennas of the cognitive devices compare to the primary users.

6. CONCLUSIONS

In this paper we address the problem of BF design in the CR system where the secondary network is a K-user MIMO IFC. At the same time a set of L multi-antenna primary receivers are affected by the interference generated from the SBS transmitted signals. The objective of our investigation is to design IA BF for the secondary network constraining the interference to the primary receiver to span a subspace of proper dimensions. To accomplish this objective we propose an iterative algorithm. In addition we present a set of IA feasibility conditions that if not satisfied immediately role out the possibility of designing such cognitive IA beamformers.

7. ACKNOWLEDGMENTS

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