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Cooperative Beamforming in Relay Assisted MIMO-OFDMA Cognitive Radio Systems

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Abstract: In this paper, a new algorithm is proposed for cooperative beamforming, power allocation and relay selection in the multiple input multiple output (MIMO) Orthogonal Frequency Division Multiple Access (OFDMA) CR systems where a pair of SU communicates with each other assisted by some single antenna relay nodes. The objective is to maximize signal to interference plus noise ratio (SINR) of SU subject to guarantee the PU's quality of service and power constraints of SU and relay nodes over all subchannels. The transmitter and receiver beamforming vectors of PU and SU are estimated by the proposed two-step iterative algorithm. Simulation results show that the proposed algorithm is able to increase the spectrum usage efficiency and, further, guarantee the required QOS at the PU.

Keywords: Relay assisted MIMO-OFDMA cognitive radio, cooperative beamforming, power allocation, relay selection.

1. Introduction

Spectrum usage efficiency can be improved using cognitive radio (CR) technology in which secondary users (SUs) are allowed to access licensed bands that are originally allocated to primary network without causing any harmful interference to primary users (PUs) [1-4]. There are three kinds of CR networks based on secondary access schemes to licensed bands, called interweave, underlay and overlay. The first approach is based on opportunistic communications in which SUs can access the licensed bands only when PUs are absent. This approach is called “interweave” technique. In the second scheme, SUs are allowed to access the licensed bands simultaneously with PUs. Note that in this scheme the interference induced from SUs to PUs must below a specific threshold which is known as ‘interference temperature’. This scheme is called “underlay” technique. In the overlay CR system, SUs regulate the interference induced to PUs by assisting and relaying PU signals to their destinations [5 -8].

Due to adverse effects of environment such as loss, shadowing and fading, the receive signal at SUs may be too weak, thereby decreasing the quality of service (QoS). To mitigate these destructive effects of channels, SUs can cooperate with each other and some SUs can act as relay nodes. These relay nodes cooperate with SU transmitters to relay SU signals to their desired destinations. Using relay nodes further enhances the spectrum efficiency by increasing spatial diversity.

In recent years, many relay schemes are investigated. In [9], resource allocation in relay OFDM-based CR system is considered based on decode-and-forward (DF) protocol. The dual decomposition technique is adopted to obtain an asymptotically optimal subcarrier pairing, relay selection and power allocation. The optimization problem is based on maximization of sum rate subject to interference limit for PU and power constraints in SU transmitter and relays. In [10], authors investigate power and channel allocation for cooperative relay in a three-node CR network. Three nodes are considered which consists of a source, a relay and a destination. Three end-to-end possible communications are assumed based on three channels consist of direct channel, dual-hop channel and relay channel. The resources are allocated based on maximization of channel capacity under PU’s interference and power constraints in source and relay nodes. In [11], the problem of relay and power allocation for OFDM-based CR systems with single antenna has been considered where the capacity of SU employing relays is maximized subject to total transmission power constraint and interference limit for PU. Due to high computational complexity of the optimization problem, three sub-optimal schemes are presented. The authors in [12] investigate the problem of resource (subcarrier and power) allocation in an OFDMA-based relayed cellular CR network in which a base station services some user equipment via multiple relay stations.

The resource allocation problem must decide for each symbol which subcarrier at which relay stations and at what power level would relay. The objective function is maximization of network capacity. Joint relay selection and power allocation are investigated in [13] to maximize system throughput with limited interference to PUs in CR network. The authors develop an optimal approach based on dual method and then propose a suboptimal algorithm to reduce computational complexity. In [14], the authors present an optimal scheme for power allocation and relay selection in CR networks where a pair of cognitive (secondary) transceiver communicates with each other using some two-way relay nodes. The goal of the proposed power allocation and relay selection algorithm is to maximize the achievable rate subject to interference constraint of PU and power constraints of cognitive transceivers and relay node. In [15], a simplified power

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allocation algorithm is proposed for cognitive multi-node relay networks. The optimization problem is the maximization of secondary system capacity under the interference limit on the PU and the maximum transmission power constraint. A beamforming and power control scheme is proposed for an overlay CR network in [16]. The proposed algorithm minimizes the total power consumed by the network while satisfying each user's SINR requirement. The authors proposed an iterative algorithm based on second-order cone programming and demonstrated that the algorithm greatly improves the overall power saving of the network.

In this paper, we propose a new algorithm for cooperative beamforming, power allocation and relay selection in MIMO-OFDMA CR systems. In this system relay nodes cooperate to deliver SU transmitter's signal to SU receiver in which the relay node that maximizes the criterion of the proposed algorithm, is selected to assist SU transmitter. Relay nodes act based on amplify-and forward (AF) protocol. The proposed algorithm is developed under a criterion with two constraints. In the criterion of the algorithm, sum signal to interference plus noise (sum-SINR) of SU is maximized over all subcannels, subject to 1) maximum allowable transmit power of SU and the selected relay node and 2) a minimum threshold for PU's SINR in order to guarantee the required PU's QoS. A two-step iterative algorithm estimates the transmitter and receiver beamforming vectors of PU and SU by maximizing the sum SINR of SU over all subchannels and also computes allocated powers to the PU, SU and the selected relay node by applying the given two constraints. In the following, a MIMO-OFDMA relay CR system is modeled based on a pair of PU transmitter (PU-Tx) and PU receiver (PU-Rx), a pair of SU transmitter (SU-Tx) and SU receiver (SU-Rx) and also *K* relay nodes in Section II. The proposed algorithm is developed in Section III. Computer simulation results are presented in Section IV and Section V concludes the paper.The notation adopted throughout the paper is defined as follows. Matrices and vectors are denoted by boldface upper and lower letters, respectively. $\mathbf{I}_N$ denotes the identity matrix of order N and $\mathbf{A}^{-1}$ the inverse of a matrix $\mathbf{A}$. Also $(.)^H$ and $E\left[\ .\ \right]$ are used for Hermitian transposition and expectation, respectively. Moreover the notation $\|\ .\ \|$ represents the Euclidean norm of a vector.

2. System Model

A MIMO-OFDMA relay CR system with a pair of PU transmitter (PU-Tx) and PU receiver (PU-Rx), a pair of SU transmitter (SU-Tx) and SU receiver (SU-Rx) and also *K* relay nodes is shown in Fig. 1 where the PU-Tx, PU-Rx, SU-Tx and SU-Rx are equipped by antenna arrays with N_p, M_p , N_s and M_s elements, respectively. Each relay node is equipped with single transmit antenna and single receive antenna.

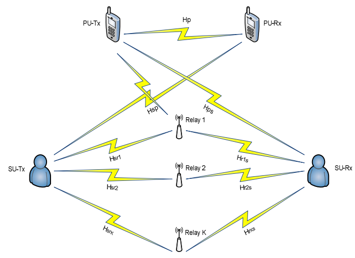

Fig. 1. System model.

A centralized system model is assumed for cooperative communications where all the decisions are made at the SU-Tx as in [11]. All the information, basically channel state information (CSI), is gathered at the SU-Tx and it makes the decision about relay selection procedure and computes transmission power levels and beamforming vectors. The results can then be communicated to relay nodes while transmitting the data. It is assumed that a feedback channel exists between SU-Tx and relay nodes, and between relay nodes and SU-Rx. Hence, the knowledge of CSI of these channels through conventional techniques of estimation and feedback has been assumed at the SU-Tx. Further, it is considered that CR network has a perfect knowledge of CSI between PU and SU [19-20]. PU-Tx transmits beacon signal of fixed power which can be known by SU [21] and then estimation of received signal power can be used to know the channel gain by assuming channel reciprocity [22]. Therefore, channel gains between SU-Tx and PU-Rx and also between relay nodes and PU-Rx are assumed to be known at SU-Tx and relay nodes, respectively. The information about channel gains between relay nodes and PU-Rx, is sent to SU-Tx using the feedback channels.

The structure of each transmitter and receiver are shown in Fig. 2 and Fig. 3, respectively. As seen in Fig. 2 and Fig. 3, beamforming vectors are applied before IFFT blocks in transmitter and after FFT blocks in receiver.

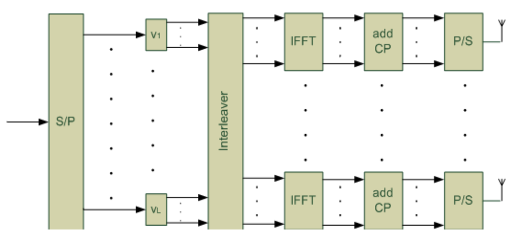

Fig. 2. Transmitter structure of MIMO-OFDMA CR system.

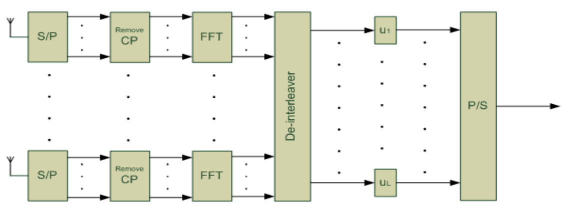

Fig. 3. Receiver structure of MIMO-OFDMA CR system.

The communication between SU-Tx and SU-Rx takes place in two time slots. Note that in each transmission, the relay node which maximizes the sum-SINR of SU over all subchannels is selected to assist in SU link communication. In the first time slot, SU-Tx transmits its signal to relay nodes. When $s_p^{(m)}(j)$ and $s_s^{(m)}(j)$ are transmitted symbols for PU and SU in the *m*th subchannel and *j*th OFDM symbol, respectively, the received signal of *k-th* relay node in the *m*th subchannel and *j*th OFDM symbol $y_{r_k}^{(m)}(j)$, is given as Eq. (1),

where $s_p^{(m)}(j)$ and $s_s^{(m)}(j)$ are normalized energy signals with independent and identically distributions (i.i.d.). The channel from PU-Tx and SU-Tx to *k-th* relay node in the *m*th subchannel are represented with $\mathbf{h}_{pr_k}^{(m)}$ and $\mathbf{h}_{sr_k}^{(m)}$, respectively. Moreover $\mathbf{v}_p^{(m)}$ and $\mathbf{v}_s^{(m)}$ are transmit beamforming vectors of PU and SU in the *m*th subchannel, respectively, such that $p_p^{(m)} = v_p^{(m)^H} v_p^{(m)}$ and $p_s^{(m)} = v_s^{(m)^H} v_s^{(m)}$ are transmitted power of PU and SU in the *m*th subchannel, respectively. $n_{r_k}^{(m)}(j)$ is zero mean additive white Gaussian noise (AWGN) at *k-th* relay node in the *m*th subchannel and *j*th OFDM symbol. Meanwhile, $E\left[n_{r_k}^{(m)}(j) n_{r_k}^{(m)^H}(j)\right] = \sigma_{r_k}^{2^{(m)}}$.

In the second slot, the selected relay node retransmits the amplified version of its received signal in the first time slot, $s_{r_k}^{(m)}(j) = \sqrt{p_{r_k}^{(m)}} y_{r_k}^{(m)}(j)$ to SU-Rx, where $p_{r_k}^{(m)}$ is transmit power of selected relay node in the *m*th subchannel. The received signals of PU, $y_p^{(m)}(j)$ and SU, $y_s^{(m)}(j)$, in the *m*th subchannel and *j*th OFDM symbol (after applying $\mathbf{u}_p^{(m)}$, receiver beamforming vector of PU, $\mathbf{u}_s^{(m)}$ and receiver beamforming vector of SU, both in the *m*th subchannel) are given as Eq. (2) and (3),

where $H_p^{(m)}$ is the channel between the PU-Tx and the PU-Rx , $H_{sp}^{(m)}$ is the channel between the SU-Tx and the PU-Rx, $h_{r_k p}^{(m)}$ is the channel between the selected relay node and the PU-Rx, all in the *m*th subchannel. $h_{r_k s}^{(m)}$ denotes the channel between the selected relay node and the SU-Rx and $H_{ps}^{(m)}$ is the channel between the PU-Tx and the SU-Rx, both in the *m*th subchannel. Also $n_p^{(m)}(j)$ and $n_s^{(m)}(j)$ are zero mean AWGN vectors at PU-Rx and SU-Rx, respectively. Meanwhile, $E\left[\mathbf{n}_p^{(m)}(j)\mathbf{n}_p^{(m)^H}(j)\right] = \sigma_p^{2^{(m)}}\mathbf{I}_{M_p}$ and $E\left[\mathbf{n}_s^{(m)}(j)\mathbf{n}_s^{(m)^H}(j)\right] = \sigma_s^{2^{(m)}}\mathbf{I}_{M_s}$. Based on (1)-(3), by substituting (1) into (2) and (3), the SINR of PU, $\text{SINR}_{\text{PU}}^{(m)}$ and the SINR of SU, $\text{SINR}_{\text{SU}}^{(m)}$, are defined as (4) and (5), respectively, where

$$\sigma_p^{2^{(m)}} = E\left[\mathbf{u}_p^{(m)^H} \mathbf{n}_p^{(m)}(j)\mathbf{n}_p^{(m)^H}(j)\mathbf{u}_p^{(m)}\right],$$

$$\sigma_s^{2^{(m)}} = E\left[\mathbf{u}_s^{(m)^H} \mathbf{n}_s^{(m)}(j)\mathbf{n}_s^{(m)^H}(j)\mathbf{u}_s^{(m)}\right].$$

3. Proposed Algorithm

In this section, a new cooperative beamforming, power allocation and relay selection algorithm is proposed to improve spectrum usage efficiency in MIMO-OFDMA relay CR system. In this algorithm, the optimization procedure is based on two phase, beamforming and power allocation phase and relay selection phase. In the former, the beamforming vectors of PU and SU and powers of PU, SU and relay nodes are computed for each of relay nodes. In the latter, the relay node which maximizes the SINR of SU is selected. The algorithm is developed based on a criterion in which sum SINR of SU is maximized over all subchannels under power constraints of SU transmitter and relay nodes while the QoS of PU is guaranteed by means of defining a threshold for SINR_{PU} . The criterion of the proposed algorithm is defined based on maximizing the sum-SINR of SU over all subchannels subject to a maximum transmitted power of SU, $P_s^{\max}$, a maximum transmitted power of relay nodes, $P_r^{\max}$ and the threshold of SINR_{PU}, γ_p. The optimization problem is formulated as follows in the beamforming and power allocation phase.

$$y_{r_k}^{(m)}(j) = \mathbf{h}_{sr_k}^{(m)}\mathbf{v}_s^{(m)}s_s^{(m)}(j) + \mathbf{h}_{pr_k}^{(m)}\mathbf{v}_p^{(m)}s_p^{(m)}(j) + n_{r_k}^{(m)}(j) \tag{1}$$

$$y_p^{(m)}(j) = \mathbf{u}_p^{(m)^H}\mathbf{H}_p^{(m)}\mathbf{v}_p^{(m)}s_p^{(m)}(j) + \mathbf{u}_p^{(m)^H}\mathbf{H}_{sp}^{(m)}\mathbf{v}_s^{(m)}s_s^{(m)}(j) + \mathbf{u}_p^{(m)^H}\mathbf{h}_{r_k p}^{(m)}s_{r_k}^{(m)}(j) + \mathbf{u}_p^{(m)^H}\mathbf{n}_p^{(m)}(j) \tag{2}$$

$$y_s^{(m)}(j) = \mathbf{u}_s^{(m)^H}\mathbf{h}_{r_k s}^{(m)}s_{r_k}^{(m)}(j) + \mathbf{u}_s^{(m)^H}\mathbf{H}_{ps}^{(m)}\mathbf{v}_p^{(m)}s_p^{(m)}(j) + \mathbf{u}_s^{(m)^H}\mathbf{n}_s^{(m)}(j) \tag{3}$$

$$\text{SINR}_{\text{PU}}^{(m)} = \frac{\mathbf{v}_p^{(m)^H}\left(\mathbf{H}_p^{(m)^H} + \sqrt{p_{r_k}^{(m)}}\mathbf{h}_{pr_k}^{(m)^H}\mathbf{h}_{r_k p}^{(m)^H}\right)\mathbf{u}_p^{(m)}\mathbf{u}_p^{(m)^H}\left(\mathbf{H}_p^{(m)} + \sqrt{p_{r_k}^{(m)}}\mathbf{h}_{r_k p}^{(m)}\mathbf{h}_{pr_k}^{(m)}\right)\mathbf{v}_p^{(m)}}{\mathbf{v}_s^{(m)^H}\left[\left(\mathbf{H}_{sp}^{(m)^H} + \sqrt{p_{r_k}^{(m)}}\mathbf{h}_{sr_k}^{(m)^H}\mathbf{h}_{r_k p}^{(m)^H}\right)\mathbf{u}_p^{(m)}\mathbf{u}_p^{(m)^H}\left(\mathbf{H}_{sp}^{(m)} + \sqrt{p_{r_k}^{(m)}}\mathbf{h}_{r_k p}^{(m)}\mathbf{h}_{sr_k}^{(m)}\right) + \left(\frac{\sigma_p^{2^{(m)}} + p_{r_k}^{(m)}\sigma_{r_k}^{2^{(m)}}}{p_s^{(m)}}\right)\mathbf{I}_{N_s}\right]\mathbf{v}_s^{(m)}} \tag{4}$$

$$\mathrm{SINR}_{\mathrm{SU}}^{(\mathrm{m})} = \frac{p_{r_k}^{(m)} \mathbf{v}_s^{(m)^H} \mathbf{h}_{sr_k}^{(m)^H} \mathbf{h}_{r_k s}^{(m)^H} \mathbf{u}_s^{(m)} \mathbf{u}_s^{(m)^H} \mathbf{h}_{r_k s}^{(m)} \mathbf{h}_{sr_k}^{(m)} \mathbf{v}_s^{(m)}}{\mathbf{v}_p^{(m)^H} \left[\left(p_{r_k}^{(m)} \mathbf{h}_{pr_k}^{(m)^H} \mathbf{h}_{r_k s}^{(m)^H} \mathbf{u}_s^{(m)} \mathbf{u}_s^{(m)^H} \mathbf{h}_{r_k s}^{(m)} \mathbf{h}_{pr_k}^{(m)} + \mathbf{H}_{ps}^{(m)^H} \mathbf{u}_s^{(m)} \mathbf{u}_s^{(m)^H} \mathbf{H}_{ps}^{(m)} \right) + \left(\frac{\sigma_s^{2^{(m)}} + p_{r_k}^{(m)} \sigma_{r_k}^{2^{(m)}}}{p_p^{(m)}} \right) \mathbf{I}_{N_p} \right] \mathbf{v}_p^{(m)}} \tag{5}$$

$$C = \underset{\mathbf{v}_s, \mathbf{u}_s, \mathbf{v}_p, \mathbf{u}_p}{\arg\max} \left\{ \sum_{m=1}^{L} \mathrm{SINR}_{\mathrm{SU}}^{(\mathrm{m})} \right\}, \quad s.t. \begin{cases} \sum_{m=1}^{L} \mathrm{SINR}_{\mathrm{PU}}^{(\mathrm{m})} \ge \gamma_p \\ p_s^{(m)} \le P_s^{\max} \\ p_{r_k}^{(m)} \le P_r^{\max} \quad \text{for } k=1,\cdots,K \end{cases} \tag{6}$$

In this phase, we employ a two-step algorithm in order to maximize the sum-SINR of SU over all subchannels. At the first step, it is assumed that $\mathbf{u}_p^{(m)}$ and $\mathbf{u}_s^{(m)}$ vectors and also the power of *k*th relay node in the *m*th subchannel, $\mathrm{p}_{r_k}^{(m)}$ for $k=1,\cdots,K$, are known. So $\mathbf{v}_p^{(m)}$ and $\mathbf{v}_s^{(m)}$ vectors are estimated by maximizing the criterion of (6). From (5), by using the (7) and (8) eigenvalue decompositions
we can rewrite the objective function as follows

$$C = \underset{\mathbf{v}_s, \mathbf{u}_s, \mathbf{v}_p, \mathbf{u}_p}{\arg\max} \left\{ \frac{\mathbf{v}_s^{(m)^H} \mathbf{Q}_s^{(m)} \mathbf{\Lambda}_s^{(m)} \mathbf{Q}_s^{(m)^H} \mathbf{v}_s^{(m)}}{\mathbf{v}_p^{(m)^H} \mathbf{Q}_p^{(m)} \mathbf{\Lambda}_p^{(m)} \mathbf{Q}_p^{(m)^H} \mathbf{v}_p^{(m)}} \right\} \tag{9}$$

To maximize the criterion of the proposed algorithm, $\mathbf{v}_s^{(m)}$ should be proportional to the eigenvector of $\mathbf{Q}_s^{(m)} \mathbf{\Lambda}_s^{(m)} \mathbf{Q}_s^{(m)^H}$ corresponding to the maximum eigenvalue of $\mathbf{Q}_s^{(m)} \mathbf{\Lambda}_s^{(m)} \mathbf{Q}_s^{(m)^H}$ that we note $\mathbf{q}_s^{\max}$ [17, 18]. Therefore, $\mathbf{v}_s^{(m)}$ becomes

$$\mathbf{v}_s^{(m)} = \sqrt{p_s^{(m)}} \, \mathbf{q}_s^{\max} \tag{10}$$

Also, $\mathbf{v}_p^{(m)}$ should be proportional to the eigenvector of $\mathbf{Q}_p^{(m)} \mathbf{\Lambda}_p^{(m)} \mathbf{Q}_p^{(m)^H}$ corresponding to the minimum eigenvalue of $\mathbf{Q}_p^{(m)} \mathbf{\Lambda}_p^{(m)} \mathbf{Q}_p^{(m)^H}$ which minimizes the criterion that we note it $\mathbf{q}_p^{\min}$. So $\mathbf{v}_p^{(m)}$ becomes

$$\mathbf{v}_p^{(m)} = \sqrt{p_p^{(m)}} \mathbf{q}_p^{\min} \tag{11}$$

By defining $\mathbf{v}_s^{(m)} = \sqrt{p_s^{(m)}} \mathbf{w}_s^{(m)}$ and $\mathbf{v}_p^{(m)} = \sqrt{p_p^{(m)}} \mathbf{w}_p^{(m)}$, only the estimations of $\mathbf{w}_s^{(m)}$ and $\mathbf{w}_p^{(m)}$ can be obtained from (10) to (11). By substituting (10) and (11) in the constraints of (6), $K+2$ unknown parameters $p_p^{(m)}$, $p_s^{(m)}$ and $p_{r_k}^{(m)}$ (for $k=1, \cdots, K$) can be obtained by solving the following equations (12), (13) and (14) in the *m*th subchannel.

$$p_s^{(m)} = P_s^{\max} \tag{12}$$

$$p_{r_k}^{(m)} = P_r^{\max} \quad \text{for } k=1, \cdots, K \tag{13}$$

Note that if the minimum value of $p_p^{(m)}$ obtained from the above equations becomes negative value, the algorithm sets $p_p^{(m)} = P_p^{\max}$ and services only the PU where $P_p^{\max}$ is the maximum transmitted power of PU. In other words, despite the maximization of the sum-SINR of SU over all subchannels, it is possible that the SINR of one subchannel is poor. In such situations, the proposed algorithm does not service to SU and allocates power only to PU.

At the second step, we assume that $\mathbf{v}_p^{(m)}$ and $\mathbf{v}_s^{(m)}$ vectors are known and the SINR of SU is maximized by estimating $\mathbf{u}_p^{(m)}$ and $\mathbf{u}_s^{(m)}$ vectors. From (5), by assuming to know $\mathbf{v}_p^{(m)}$ and $\mathbf{v}_s^{(m)}$, the $\mathrm{SINR}_{\mathrm{SU}}$ can be written as follows.

By using the decomposition in (16) and defining $\mathbf{f}_s^{(m)} = \Upsilon_s^{(m)} \mathbf{u}_s^{(m)}$, the objective function appears as Eq. (17)

To maximize the criterion of the proposed algorithm, $\mathbf{u}_s^{(m)}$ should be proportional to the eigenvector of $\mathbf{A} = \Upsilon_s^{(m)^{-H}} p_{r_k}^{(m)} \mathbf{h}_{r_k s}^{(m)} \mathbf{h}_{sr_k}^{(m)} \mathbf{v}_s^{(m)} \mathbf{v}_s^{(m)^H} \mathbf{h}_{sr_k}^{(m)^H} \mathbf{h}_{r_k s}^{(m)^H} \Upsilon_s^{(m)^{-1}}$ corresponding to the maximum eigenvalue of $\mathbf{A}$ that we note it $\mathbf{g}_s^{\max}$. Since the matrix $\mathbf{A}$ is a rank-one, it has only one non-zero eigenvalue. So, $\mathbf{u}_s^{(m)}$ appears as Eq. (18)

$$p_{r_k}^{(m)} \mathbf{h}_{sr_k}^{(m)^H} \mathbf{h}_{r_k s}^{(m)^H} \mathbf{u}_s^{(m)} \mathbf{u}_s^{(m)^H} \mathbf{h}_{r_k s}^{(m)} \mathbf{h}_{sr_k}^{(m)} = \mathbf{Q}_s^{(m)} \mathbf{\Lambda}_s^{(m)} \mathbf{Q}_s^{(m)^H} \tag{7}$$

$$\left(p_{r_k}^{(m)} \mathbf{h}_{pr_k}^{(m)^H} \mathbf{h}_{r_k s}^{(m)^H} \mathbf{u}_s^{(m)} \mathbf{u}_s^{(m)^H} \mathbf{h}_{r_k s}^{(m)} \mathbf{h}_{pr_k}^{(m)} + \mathbf{H}_{ps}^{(m)^H} \mathbf{u}_s^{(m)} \mathbf{u}_s^{(m)^H} \mathbf{H}_{ps}^{(m)} \right) + \left(\frac{\sigma_s^{2^{(m)}} + p_{r_k}^{(m)} \sigma_{r_k}^{2^{(m)}}}{p_p^{(m)}} \right) \mathbf{I}_{N_p} = \mathbf{Q}_p^{(m)} \mathbf{\Lambda}_p^{(m)} \mathbf{Q}_p^{(m)^H} \tag{8}$$

$$p_p^{(m)} \left| \mathbf{w}_p^{(m)^H} \left(\mathbf{H}_p^{(m)^H} + \sqrt{p_{r_k}^{(m)}} \mathbf{h}_{pr_k}^{(m)^H} \mathbf{h}_{r_k p}^{(m)^H} \right) \mathbf{u}_p^{(m)} \right|^2 - p_s^{(m)} \gamma_p \left| \mathbf{w}_s^{(m)^H} \left(\mathbf{H}_{sp}^{(m)^H} + \sqrt{p_{r_k}^{(m)}} \mathbf{h}_{sr_k}^{(m)^H} \mathbf{h}_{r_k p}^{(m)^H} \right) \mathbf{u}_p^{(m)} \right|^2 = \left(\sigma_p^{2^{(m)}} + p_{r_k}^{(m)} \sigma_{r_k}^{2^{(m)}} \right) \gamma_p \tag{14}$$

$$\mathrm{SINR}_{\mathrm{SU}}^{(\mathrm{m})} = \frac{p_{r_k}^{(m)} \mathbf{u}_s^{(m)^H} \mathbf{h}_{r_k s}^{(m)} \mathbf{h}_{sr_k}^{(m)} \mathbf{v}_s^{(m)} \mathbf{v}_s^{(m)^H} \mathbf{h}_{sr_k}^{(m)^H} \mathbf{h}_{r_k s}^{(m)^H} \mathbf{u}_s^{(m)}}{\mathbf{u}_s^{(m)^H} \left(\mathbf{H}_{ps}^{(m)} \mathbf{v}_p^{(m)} \mathbf{v}_p^{(m)^H} \mathbf{H}_{ps}^{(m)^H} + p_{r_k}^{(m)} \mathbf{h}_{r_k s}^{(m)} \mathbf{h}_{pr_k}^{(m)} \mathbf{v}_p^{(m)} \mathbf{v}_p^{(m)^H} \mathbf{h}_{pr_k}^{(m)^H} \mathbf{h}_{r_k s}^{(m)^H} + \left(\sigma_s^{2^{(m)}} + p_{r_k}^{(m)} \sigma_{r_k}^{2^{(m)}} \right) \mathbf{I}_{M_s} \right) \mathbf{u}_s^{(m)}} \tag{15}$$

$$\mathbf{H}_{ps}^{(m)} \mathbf{v}_p^{(m)} \mathbf{v}_p^{(m)^H} \mathbf{H}_{ps}^{(m)^H} + p_{r_k}^{(m)} \mathbf{h}_{r_k s}^{(m)} \mathbf{h}_{pr_k}^{(m)} \mathbf{v}_p^{(m)} \mathbf{v}_p^{(m)^H} \mathbf{h}_{pr_k}^{(m)^H} \mathbf{h}_{r_k s}^{(m)^H} + \left(\sigma_s^{2^{(m)}} + p_{r_k}^{(m)} \sigma_{r_k}^{2^{(m)}} \right) \mathbf{I}_{M_s} = \Upsilon_s^{(m)^H} \Upsilon_s^{(m)} \tag{16}$$

$$C = \underset{\mathbf{v}_s,\mathbf{u}_s,\mathbf{v}_p,\mathbf{u}_p}{\arg\max}\left\{\frac{\mathbf{f}_s^{(m)^H}\Upsilon_s^{(m)^{-H}} p_{r_k}^{(m)}\mathbf{h}_{r_k s}^{(m)}\mathbf{h}_{sr_k}^{(m)}\mathbf{v}_s^{(m)}\mathbf{v}_s^{(m)^H}\mathbf{h}_{sr_k}^{(m)^H}\mathbf{h}_{r_k s}^{(m)^H}\Upsilon_s^{(m)^{-1}}\mathbf{f}_s^{(m)}}{\mathbf{f}_s^{(m)^H}\mathbf{f}_s^{(m)}}\right\} \quad (17)$$

$$\mathbf{u}_s^{(m)} = \frac{1}{\left\|\left(\Upsilon_s^{(m)^H}\Upsilon_s^{(m)}\right)^{-1}\mathbf{h}_{r_k s}^{(m)}\mathbf{h}_{sr_k}^{(m)}\mathbf{v}_s^{(m)}\right\|}\left(\Upsilon_s^{(m)^H}\Upsilon_s^{(m)}\right)^{-1}\mathbf{h}_{r_k s}^{(m)}\mathbf{h}_{sr_k}^{(m)}\mathbf{v}_s^{(m)} \quad (18)$$

To estimate $\mathbf{u}_p^{(m)}$, from (4) and the QoS of PU guarantee constraint in (6), we can rewrite the SINR of PU constraint as Eq. (19)

By using the following decomposition (20)

we can obtain $\mathbf{u}_p^{(m)}$ as

$$\mathbf{u}_p^{(m)} = \mathbf{g}_{\min} \quad (21)$$

where $\mathbf{g}_{\min}$ is the eigenvector of $\mathbf{G}_p^{(m)}\mathbf{\Sigma}_p^{(m)}\mathbf{G}_p^{(m)^H}$ corresponding to the minimum eigenvalue of $\mathbf{G}_p^{(m)}\mathbf{\Sigma}_p^{(m)}\mathbf{G}_p^{(m)^H}$. Note that $p_p^{(m)}$, $p_s^{(m)}$ and $p_{r_k}^{(m)}$ (for $k = 1,\cdots,K$) have been chosen in (12) to (14) such that the left hand side of (19) does not become negative value. In the first phase, transmitter and receiver beamforming vectors of the PU and SU and also the powers of PU, SU and relay nodes are estimated based on the two-step algorithm in an iterative manner.

In the second phase, after power allocation and beamformer estimation phase, the relay is selected based on the maximum sum-SINR of the SU over all subchannels. To do so, the sum-SINR of the SU is computed for each of relay nodes over all subchannels and the relay node with the maximum value of SU's SINR is selected. So the relay selection phase is formulated as follows

$$k^* = \underset{k}{\arg\max}\left\{\sum_{m=1}^{L}\mathrm{SINR}_{\mathrm{SU}}^{(\mathrm{m})}\right\} \quad (22)$$

4. Computer Simulation Results

In this section, simulation results are presented to evaluate the performance of the proposed cooperative beamforming, power allocation and relay selection algorithm. In the simulations, we use flat Rayleigh fading MISO (between PU-Tx or SU-Tx and relay nodes), SIMO (between relay nodes and PU-Rx or SU-Rx) and MIMO (between PU-Tx or SU-Tx and PU-Rx or SU-Rx) channels for PU, SU and relay node such that the elements of the channel matrices are independent and have normal zero mean Gaussian distributions. The modulation is QPSK and results are obtained for 1000000 realizations of channels. In the figures, the number of antennas used in the PU and SU are indicated, respectively, based on PU-Tx, PU-Rx, SU-Tx and SU-Rx array. Meanwhile, the threshold value of $\mathrm{SINR}_{\mathrm{PU}}$ is $\gamma_p = 15\mathrm{dB}$ in simulations. Note that this value for γ_p is appropriate and simulations are done with different number of relay nodes which is indicated in each case.

The bit error rate (BER) and SINR of PU and SU are shown in Fig. 4 and Fig. 5, respectively for different number of antennas at PU and SU transceiver with one relay node.

As it can be seen, at low signal to noise ratios (SNRs) the BER of the PU is decreased. Because of satisfying the PU's QoS, no power is allocated to the SU. By increasing SNR, the algorithm starts to service to SU. This power allocation to SU leads to induce limited interference to PU.

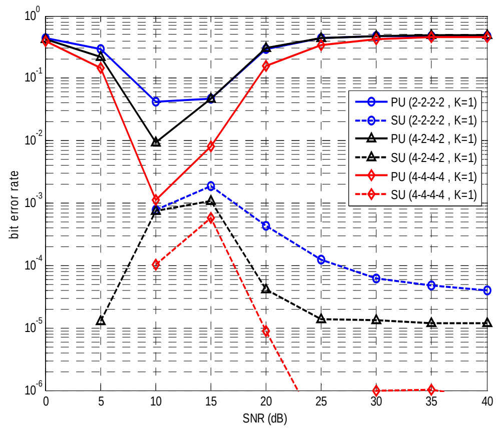

Fig. 4. The BER performances of the PU and SU with different number of antennas and one relay node.

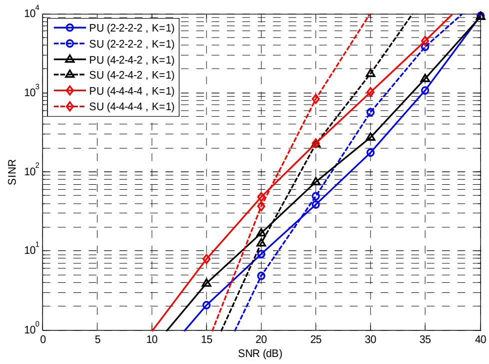

Fig. 5. The SINRs of the PU and SU with different number of antennas and one relay node.

$$\mathbf{u}_p^{(m)^H}\Bigg[\left(\mathbf{H}_p^{(m)} + \sqrt{p_{r_k}^{(m)}}\mathbf{h}_{r_k p}^{(m)}\mathbf{h}_{pr_k}^{(m)}\right)\mathbf{v}_p^{(m)}\mathbf{v}_p^{(m)^H}\left(\mathbf{H}_p^{(m)^H} + \sqrt{p_{r_k}^{(m)}}\mathbf{h}_{pr_k}^{(m)^H}\mathbf{h}_{r_k p}^{(m)^H}\right) - \gamma_p\left(\mathbf{H}_{sp}^{(m)} + \sqrt{p_{r_k}^{(m)}}\mathbf{h}_{r_k p}^{(m)}\mathbf{h}_{sr_k}^{(m)}\right)\mathbf{v}_s^{(m)}\mathbf{v}_s^{(m)^H}\left(\mathbf{H}_{sp}^{(m)^H} + \sqrt{p_{r_k}^{(m)}}\mathbf{h}_{sr_k}^{(m)^H}\mathbf{h}_{r_k p}^{(m)^H}\right) - \gamma_p\left(\sigma_p^{2(m)} + p_{r_k}^{(m)}\sigma_{r_k}^{2(m)}\right)\mathbf{I}_{M_p}\Bigg]\mathbf{u}_p^{(m)} \geq 0 \quad (19)$$

$$\left(\mathbf{H}_{p}^{(m)}+\sqrt{p_{r_k}^{(m)}}\mathbf{h}_{r_k p}^{(m)}\mathbf{h}_{pr_k}^{(m)}\right)\mathbf{v}_{p}^{(m)}\mathbf{v}_{p}^{(m)^H}\left(\mathbf{H}_{p}^{(m)^H}+\sqrt{p_{r_k}^{(m)}}\mathbf{h}_{pr_k}^{(m)^H}\mathbf{h}_{r_k p}^{(m)^H}\right)-\gamma_p\left(\mathbf{H}_{sp}^{(m)}+\sqrt{p_{r_k}^{(m)}}\mathbf{h}_{r_k p}^{(m)}\mathbf{h}_{sr_k}^{(m)}\right)\mathbf{v}_{s}^{(m)}\mathbf{v}_{s}^{(m)^H}\left(\mathbf{H}_{sp}^{(m)^H}+\sqrt{p_{r_k}^{(m)}}\mathbf{h}_{sr_k}^{(m)^H}\mathbf{h}_{r_k p}^{(m)^H}\right)$$
$$-\gamma_p\left(\sigma_p^{2^{(m)}}+p_{r_k}^{(m)}\sigma_{r_k}^{2^{(m)}}\right)\mathbf{I}_{M_p}=\mathbf{G}_p^{(m)}\mathbf{\Sigma}_p^{(m)}\mathbf{G}_p^{(m)^H} \quad (20)$$

For example in 2-2-2-2 situation, the PU's SINR constraint isn't supported until SNR=10dB, thus the algorithm doesn't service to the SU and the PU's BER performance is improved by increasing the SNR. For $SNR \geq 10dB$, although the average SINR of the PU is increased, the BER of the PU is increased . It is because of errors taken place in some realization of channels in which the power is allocated to the SU. Note that in all cases, the PU's SINR constraint is satisfied such that at high SNRs, the BER of PU remains constant, but the SU's BER performance is improved.

To show the dependence of algorithm performance on the PU's SINR threshold, the percent of time that the SU is serviced is shown in Fig. 6 for one relay node when $N_p = N_s = M_p = M_s = 2$ with different values of PU's SINR thresholds. As it can be seen in each value of PU's SINR threshold, at low SNRs, the SU is not serviced in order to satisfy the PU’s SINR constraint. However, by increasing the SNR, the percent of time that the SU is serviced is increased. Moreover, as the PU's SINR threshold increases, the algorithm due to guarantee the PU's required QoS, assigns more subchannels to PU. So, increasing PU's SINR threshold leads to decreasing the percent of time that the SU is serviced.

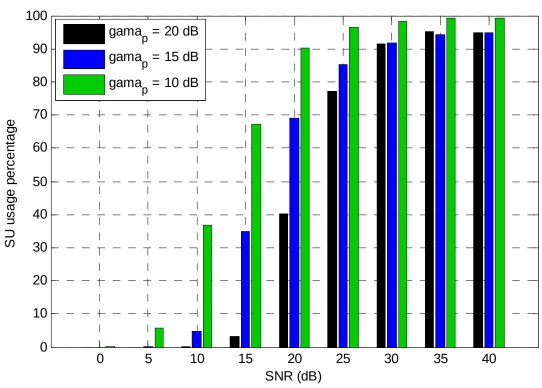

Fig. 6. The percent of time that the SU is serviced in MIMO-OFDMA system with different PU's SINR thresholds ($N_p = N_s = M_p = M_s = 2$).

Fig. 7 and Fig. 8 show the BER and SINR of PU and SU in case of two relay nodes, respectively for different number of antennas. By comparing these results with the ones presented in Fig. 4 and Fig. 5, it can be seen as the number of relay nodes increases, the performance of the proposed algorithm improves. It is because of choosing the best relay node which maximizes the criterion of the algorithm based on (22).

In order to evaluate the performance of the proposed algorithm, the service percentage of SU is plotted in Fig. 9 for both one and two relay nodes. By increasing relay nodes, the chance to have a good link for servicing the SU which is supported the constraints of (6) is increased. So as it is shown, increasing relay nodes can improve service percentage of SU.

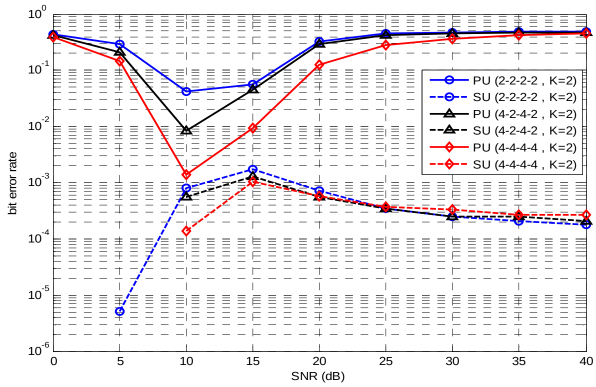

Fig. 7. The BER performances of the PU and SU with different number of antennas and two relay nodes.

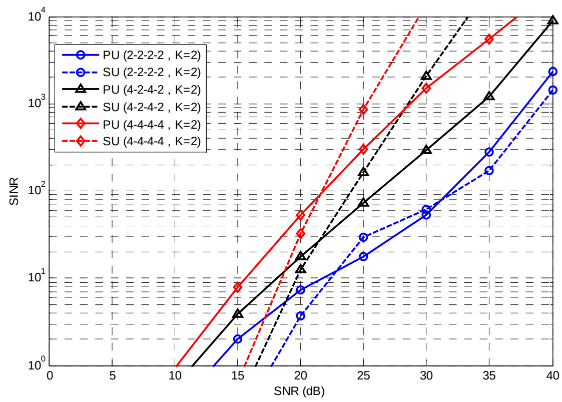

Fig. 8. The SINRs of the PU and SU with different number of antennas and two relay nodes.

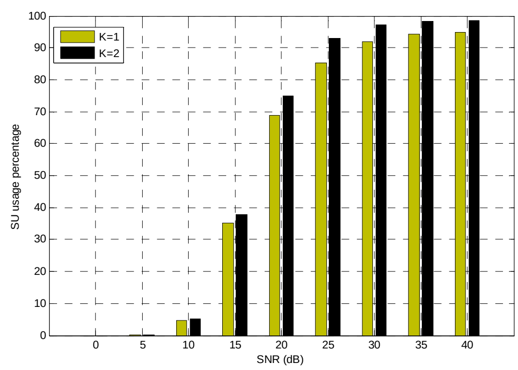

Fig. 9. Comparison of the service percentage of SU in the case of 2-2-2-2 array antenna with one and two relay nodes.

5. Conclusion

A cooperative beamforming, power allocation and relay selection algorithm has been proposed in this paper for MIMO-OFDMA relay cognitive radio systems. The procedure of beamforming, power allocation and relay selection is done in two phase. In the first phase, the proposed algorithm estimates the transmitter and receiver beamforming vectors of primary user (PU) and secondary user (SU) along with allocated powers to PU, SU and relay nodes. In this phase, sum-SINR of SU is maximized over all subchannels under a maximum allowable transmit power of SU and relay nodes and also a threshold SINR of the PU constraints. In the second phase, the relay node that maximizes the sum-SINR of SU over all subchannels is selected. The performance of the algorithm has been evaluated by computer simulations. The results indicated that the proposed algorithm, in addition to guarantee a required performance of the PU, increases spectrum usage efficiency by servicing the SUs. Moreover, by increasing the number of relay nodes, the performance of the algorithm is improved.

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