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Multiple Antenna Selection for Underlay Cognitive Radio Systems with Interference Constraint

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Abstract The spectrum sharing concept of Cognitive Radio Networks (CRN) improves the efficiency of spectrum utilization by satisfying the current spectrum demands. The combination of Multiple Input Multiple Output (MIMO) and CRN results in achieving high spectrum efficiency and allocation of more spatial dimensions for SUs. But the main drawback is, as the number of antennas increase, the RF chain also increases thereby increasing the computational complexity and hardware costs. Antenna selection (AS) techniques reduce the number of RF chains while guaranteeing the performance of multiple antenna systems. In this paper, we present an AS scheme; in particular we present a joint transmit and receive multiple AS method for underlay CR environment, thus maintaining the multiplexing benefit of MIMO systems. This technique maximizes the capacity as well as minimizes the symbol error probability while satisfying interference constraint at the primary user receiver. The closed form expression for CDF of SNR of the selected Single Input Single output link is derived. The simulation results show that the proposed method achieves improved performance in terms of SNR.

Keywords Antenna selection · Underlay cognitive radio · MIMO cognitive radio · Ergodic rates · Symbol error probability

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1 Introduction

The increasing demand for new wireless services and high data rates increased the need for developing new solutions for efficient spectrum utilization. Cognitive radio technology introduced by Mitola has been considered as a promising technology to improve the efficiency of spectrum usage by allowing the secondary users (SUs)/unlicensed users to opportunistically access the under-used spectrum of primary licensed network on a minimal or non-interfering basis [1, 2]. The existing paradigms of CR implementation are interweave, overlay and underlay modes. In the interweave mode SUs use the Primary Users (PUs) spectrum only when the primary is OFF. While in the overlay and underlay modes, SU transmit even when the PU is ON. In Overlay mode SUs help to maintain and improve the Quality of Service (QoS) of PU while utilizing some spectrum resources for their own communication needs. Whereas, in underlay which is the focus of this paper, SUs share the resources of PUs only if the resultant interference power at the primary receiver (PRX) is below the given threshold. Thus, the main issue in underlay spectrum sharing is to manage the interference at the PRX caused due to SUs. To limit this interference, different Power allocation algorithms for single input single output systems (SISO) are used in literatures. These algorithms manage the system capacity, while satisfying the peak or average interference power constraint of the PU [3–5].

The concept of multiple input multiple output cognitive radio networks (MIMO CRNs) which increases the wireless link performance through capacity and diversity gains [6–8], has received extensive attention in past few years. The main advantage of multi antenna in CR is the spatial multiplexing concept, by which multiple transmit dimensions in the space are allotted to SUs. Thus, the SUs are allocated with more degrees of freedom in space in addition to time and frequency. For a MIMO CRN, it is necessary to solve two conflicting goals i.e. maximizing its own transmit power and minimizing the interference power at the PRX. Various Beamforming techniques and dynamic resource allocation methods for underlay MIMO CRNs are presented in literatures [9, 10]. These techniques avoid the interference at the PRX due to SUs and enhance the capacity of SUs.

A major drawback in the deployment of the MIMO systems is that each antenna requires an expensive analog RF chain. For example, the receiver consists of low noise amplifiers, mixers, analog to digital converters. Increasing the number of antennas will result in significant increase in the cost. Employing Antenna Selection (AS) at the transmitter and/or at the receiver side reduces the hardware complexity. The key idea behind this technology is that the RF chains are multiplexed with the subset of antennas chosen as a function of channel conditions. Thus, it reduces the hardware complexity preserving the diversity benefits of MIMO [11]. These prior works deal with the AS techniques for point to point MIMO systems.

Several AS schemes have also been proposed for MIMO cognitive radio systems to improve the performance of the SUs. Zhou et al. [12, 15], Zhou and Thompson [13] and Wang and Coon [14] deal with transmit AS in MISO system. Zhou et al. [12], Zhou and Thompson [13] considers single and multiple AS for MISO cognitive radio based on minimum interference(MI) rule and maximum signal to leakage interference power ratio(MSLIR) strategy. In MI rule, the transmit antenna with lowest secondary transmitter (STX) to primary receiver (PRX) channel gain is selected. The MSLIR rule selects the transmit antenna having highest ratio of STX to secondary receiver (SRX) and STX to PRX gains. These methods yield sub-optimal results w.r.t SNR. Wang and Coon [14] deals with difference AS technique. By this method, a single transmit antenna which maximizes the weighted difference between STX to SRX and STX to PRX channel gains is selected.

This paper also explains an optimum power allocation under peak secondary transmit power and average interference power constraint. However, this paper has not considered capacity maximization or Symbol Error probability (SEP) minimization. In [15] the authors present an unconstrained rule by which, a subset of transmit antennas are selected according to the maximum norm strategy. An exhaustive search was performed over all possible combinations in the subset to find the optimum set of antennas which maximizes the received Signal-to-noise ratio (SNR). In [16] the authors investigated single transmit AS with incomplete Channel State Information (CSI). They interpreted the Mean Value (MV) based power allocation scheme for MIMO CR systems under average/peak interference power and peak transmit power constraints. However, all the above works are based on single or multiple transmit AS. In [17] the authors proposed two new techniques for joint transmit and receive AS to maximize cognitive radio data rate while satisfying interference constraints at the PRX. The first method is based on convex optimization. Second method is based on maximum norm rule. This method is less complex additionally, the interference from primary transmitter (PTX) to SRX was also considered. But neither method considers the SEP minimization. Another new method which chooses antenna based on minimum SEP and power control is proposed in [18]. In this paper the authors considered only transmit AS and the capacity maximization is not taken into account.

To overcome the above challenges, in this paper we consider multiple AS at both the transmitter and receiver. Our proposed AS algorithm for underlay MIMO CR maximizes the capacity and minimizes the SEP while satisfying the interference constraints at PRX. In order to differentiate the PU and SU channels, we assumed that the strength of the SU to PU interference channel is lower than that of the SU channel. The interference at the SRXs due to PTX is also taken in to account during AS. The partial channel projection method is used for finding the optimum transmit covariance matrix of the SUs in order to maximize the capacity. We assume that perfect CSI is available at all nodes.

The rest of this paper is organized as follows; Sect. 2 describes the system model and basic assumptions. The proposed AS method is discussed in Sect. 3 followed by the performance analysis in Sect. 4. Section 5 presents the simulation results, comparing the performance of the proposed antenna selection method which is followed by conclusion in Sect. 6.

Notation: Matrices and Vectors are denoted by boldface uppercase and boldface lowercase respectively. $\|\mathbf{A}\|$, $\|\mathbf{v}\|_2$ represents frobenius norm of a matrix $\mathbf{A}$ and l^2-norm of a vector $\mathbf{v}$ respectively. $\mathbf{I}_M$ represents $M \times M$ identity matrix. $\mathbb{E}[.]$ represents the statistical expectation operator. $det(.)$, $Tr(.)$ and $(.)^H$ denotes the determinant, trace and conjugate transpose operations. $diag([\mathbf{x}], 0)$ represents diagonal matrix with vector $\mathbf{x}$ along the diagonal. $\mathbf{A}(:, j)$ represents the jth column of matrix $\mathbf{A}(:, j)$ with all the corresponding row elements.

2 System Model

Consider an underlay model of point-to-point MIMO CR channel as shown in Fig. 1. This can be treated as a special case of MIMO CR-MAC (Multiple Access Channel) or MIMO CR-BC (Broadcast Channel) or MIMO CR- IC (Interference Channel) with only one active SU link. The CR_{TX} (Secondary transmitter, STX) transmits data to CR_{RX} (Secondary Receiver, SRX). This causes interference to the PRX. Assume that CR_{TX} has M_{STX} and CR_{RX} has N_{SRX} antennas. Also it has L RF chains at CR_{TX} and R RF chains at CR_{RX}.

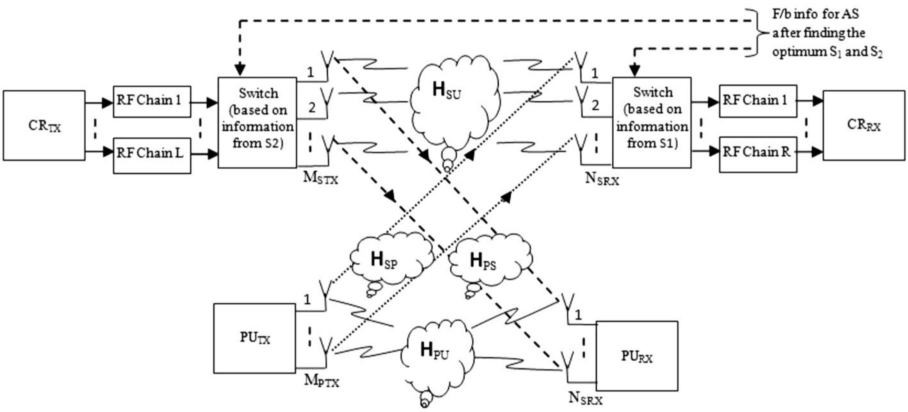

Fig. 1 System model of the proposed AS method

Therefore the AS algorithm has to select L antennas from M_{STX} antennas at CR_{TX} and R antennas from N_{SRX} antennas at CR_{RX}. The received signal $\mathbf{y}_{\text{CR}}$ at the CR_{RX} at time instant n is,

$$\mathbf{y}_{CR}(n) = \mathbf{H}_{SU}(n)\mathbf{x}(n) + \mathbf{H}_{SP}(n)\mathbf{x}_i(n) + \mathbf{z}(n) \tag{1}$$

where $\mathbf{H}_{SU} \in \mathbb{C}^{(N_{SRX} \times M_{SRX})}$ is the channel matrix between CR_{RX} and CR_{TX}. The entries of $\mathbf{H}_{\text{SU}}$ are Zero Mean Circularly Symmetric and Complex Gaussian (ZMCSCG). Also $\mathbb{E}[|(\mathbf{H}_{SU})_{ij}|^2] = 1$. $\mathbf{x}$ is the $M_{STX} \times 1$ transmitted signal vector from CR_{TX}.The transmit covariance matrix of SU is defined as $\mathbf{A} = \mathbb{E}[\mathbf{x}\mathbf{x}^H] \Rightarrow Tr(\mathbf{A}) \le P_{CR}$ where, P_{CR} is the total average power at CR_{TX}. The CR_{RX} may experiences interference from PTX. $\mathbf{H}_{\text{SP}} \in \mathbb{C}^{(N_{SRX} \times M_{PTX})}$ is the interference channel matrix between CR_{RX} and PTX. M_{PTX} is the number of primary transmit antennas Let $\mathbf{x}_i$ be the $M_{PTX} \times 1$ interference signal vector transmitted from PTX to CR_{RX}. It is assumed that $\mathbb{E}[\mathbf{x}_i\mathbf{x}_i^H] = 1$. $\mathbf{z}$ is the $N_{SRX} \times 1$ AWGN at CR_{RX} with zero mean i.e. $\mathbf{z} \in \mathcal{N}(0, \mathbf{I}_{N_{SRX}})$. Thus the total noise at the CR_{RX} is due to both $\mathbf{x}_i$ and $\mathbf{z}$. The covariance matrix of interference-plus-noise is defined as $\mathbf{Q} = \mathbb{E}[\mathbf{H}_{SP}\mathbf{H}_{SP}^H + \mathbf{z}\mathbf{z}^H] = \mathbf{H}_{SP}\mathbf{H}_{SP}^H + \mathbf{I}_{N_{SRX}}$.

$\mathbf{H}_{PS} \in \mathbb{C}^{(N_{PRX} \times M_{STX})}$is the channel matrix between PRX and CR_{TX}. N_{PRX} is the number of primary receive antennas. In order to differentiate this interference channel $\mathbf{H}_{PS}$ w.r.t the data channel $\mathbf{H}_{SU}$, we assumed that $\mathbb{E}[|(\mathbf{H}_{PS})_{ij}|^2] = \frac{1}{\lambda_i}$ where, $j = 1\ldots M_{STX}$ and $\frac{1}{\lambda_i} = \alpha^i$. α represents the strength of the interference channel.

For satisfactory operation of PU in the presence of SU, the secondary terminals has to satisfy two types of power constraints:

– Peak or average power constraint (due to their own transmit power).

$$Tr(\mathbf{A}) \le P_{CR} \tag{2}$$

– Peak or average interference power constraint (due to the interference caused by the SU to the PU; and it should be below the acceptable interference level).

$$Tr(\mathbf{H}_{PS}\mathbf{A}\mathbf{H}_{PS}^H) \le \Omega \tag{3}$$

where $\Omega = diag([\omega_1, \ldots, \omega_{N_{PRX}}], 0).\omega_1, \ldots, \omega_{N_{PRX}}$ is the interference acceptable level at each PRX antenna in the presence of SU. The achievable rate of SU (R_{SU}) using all antennas (before AS) is given by,

$$R_{SU} = \log_2 det(\mathbf{I}_{N_{SRX} \times N_{SRX}} + \mathbf{H}_{SU}\mathbf{A}\mathbf{H}_{SU}^H\mathbf{Q}^{-1}) \tag{4}$$

$$= \log_2 det(\mathbf{I}_{N_{SRX} \times N_{SRX}} + \mathbf{Q}^{-1/2}\mathbf{H}_{SU}\mathbf{A}\mathbf{H}_{SU}^H\mathbf{Q}^{-1/2}) \tag{5}$$

where $\mathbf{Q}$ is the interference plus noise covariance matrix. The aim is to perform joint transmit and receive AS in underlay MIMO CR that maximizes the achievable rate and minimizes the SEP of the SU. Also, it should ensure that the interference caused by the SU to the PU should be within the acceptable level. The general problem statement for AS considering only capacity maximization can be written as,

$$\begin{array}{cc} \underset{\mathbf{A}}{\text{maximize}} & \log_2 det(\mathbf{I}_{R \times R} + \mathbf{H}_{SU}\mathbf{A}\,\mathbf{H}_{SU}^H\mathbf{Q}^{-1})) \\ \text{subjectto} & Tr(\mathbf{A}) \le P_{CR} \\ & Tr(\mathbf{H}_{PS}\mathbf{A}\,\mathbf{H}_{PS}^H) \le \Omega \\ & \mathbf{A} \ge 0 \end{array} \tag{6}$$

where $\mathbf{H}_{SU}, \mathbf{H}_{PS}, \mathbf{A}, \mathbf{Q}$ are the SU channel gain, STX to PRX channel gain, transmit covariance matrix and interference plus noise covariance matrix respectively after performing antenna selection. The objective is not only to maximize the capacity but also to minimize the SEP.

3 Antenna Selection

We now present the proposed method for joint transmit and receive AS. In our proposed method for AS, we follow a heuristic approach. The transmit antennas are selected with an aim to maximize the capacity as well as minimize the SEP while the receive antennas are selected to maximize the capacity. Similar to the method of AS defined in [17], we considered two diagonal selection matrices $\mathbf{S}_1$ and $\mathbf{S}_2$ having dimensions $N_{SRX} \times N_{SRX}$ and $M_{STX} \times M_{STX}$ at the receiver and transmitter sides respectively.

$$(\mathbf{S}_1)_{kk} = \begin{cases} 1, & \text{if } k\text{th receive antenna is selected} \\ 0, & \text{otherwise} \end{cases} \tag{7}$$

Similarly,

$$(\mathbf{S}_2)_{kk} = \begin{cases} 1, & \text{if } k\text{th transmit antenna is selected} \\ 0, & \text{otherwise} \end{cases} \tag{8}$$

where $(\mathbf{S}_1)_{kk}$ is the (k, k)th element of $\mathbf{S}_1$ and similar definition holds for $(\mathbf{S}_2)_{kk}$. Therefore, $Tr(\mathbf{S}_1) = R$ that is, R antennas are selected from N_{SRX} antennas and $Tr(\mathbf{S}_2) = L$ that is, L antennas are selected from M_{STX} antennas. Instead of selecting the antennas especially based on the channel matrix gain, we considered an effective channel matrix which takes into account the interference plus noise effect and power allowable at different transmit antennas. Thus the effective channel matrix is,

$$\tilde{\mathbf{H}}_{SU} = \mathbf{Q}^{\frac{-1}{2}}H_{SU}diag\left(\left[\sqrt{P_1}, \ldots, \sqrt{P_{M_{STX}}}\right], 0\right) \tag{9}$$

where $\sqrt{P_1}, \ldots, \sqrt{P_{M_{STX}}}$ are the allowable powers at different transmit antennas. Therefore, the achievable rate expression of (4) can be rewritten as,

$$R_{SU} = \log_2 det\left(\mathbf{I}_{N_{SRX}\times N_{SRX}} + \mathbf{Q}^{\frac{-1}{2}}\mathbf{S}_1\mathbf{H}_{SU}\mathbf{S}_2\mathbf{A}\mathbf{S}_2^H\mathbf{H}_{SU}^H\mathbf{S}_1^H\mathbf{Q}^{\frac{-1}{2}}\right) \tag{10}$$

And the interference constraint is given by,

$$Tr\left(\mathbf{H}_{PS}\mathbf{S}_2\mathbf{A}\mathbf{S}_2^H\mathbf{H}_{PS}^H\right) \le \Omega, \mathbf{A} \ge 0 \tag{11}$$

3.1 Transmit Antenna Selection

In order to perform transmit AS, we start with temporary allocation of powers for all transmit antennas. The power at jth transmit antenna is $\min_i \frac{\omega_i}{[|(\mathbf{H}_{PS})_{ij}|^2]}, i = 1, 2, \ldots N_{PRX}$ where, $|(\mathbf{H}_{PS})_{ij}|^2$ is the magnitude square of the element $(\mathbf{H}_{PS})_{ij}$ and $\frac{\omega_i}{[|(\mathbf{H}_{PS})_{ij}|^2]}$, represents the power on the ith receiver link. But we should ensure that this should not exceed the maximum power P_{CR} . Therefore the power allocated on different transmit antennas is written as,

$$P_j = \min\left\{P_{CR}, \min_i \frac{\omega_i}{[|(\mathbf{H}_{PS})_{ij}|^2]}\right\}, j = 1, 2, \ldots, M_{STX}, i = 1, 2, \ldots, N_{PRX} \tag{12}$$

It is to be noted that this power allocation is done only to rank the antennas. The actual power allocation is performed through the $\mathbf{A}$ matrix (explained in Sect. 3.3).

The unconstrained antenna selection just selects the transmit antenna which has the maximum norm [18]. This results in maximizing the capacity. In our proposed method, a subset of transmit antennas (L) are selected by comparing its unconstrained interference Γ_{un} and the average interference Γ_{avg}. The rule for selecting subset of transmit antennas in an unconstrained manner is $\Phi^* = \underset{j=1,2,\ldots,M_{STX}}{\operatorname{argmax}} (\|\tilde{\mathbf{H}}_{SU}(:,j)\|_2)$, where, $\tilde{\mathbf{H}}_{SU}(:,j)$ is a vector with all the channel gains corresponding to the jth transmit antenna from the effective channel matrix $\tilde{\mathbf{H}}_{SU}$ .It is to be noted that Φ^* is a vector which contains the index of the subset of antennas selected. The selected antennas are arranged in the same descending order and the resulting unconstrained interference is, $\Gamma_{un} = Tr(\mathbf{H}_{PS\Phi^*} diag([\sqrt{P_1}, \ldots, \sqrt{P_L}], 0)_{\Phi^*}\mathbf{H}_{PS\Phi^*}^H)$, where, $\mathbf{H}_{PS\Phi^*}$ is the $\mathbf{H}_{PS}$ matrix with columns corresponding to Φ^* and $diag([\sqrt{P_1}, \ldots, \sqrt{P_L}], 0)_{\Phi^*}$ is the diagonal matrix with diagonal elements corresponds to the powers of those selected antennas (Φ^*).

The second rule is for selecting a subset of transmit antennas in a constrained manner based on the minimum SEP and is given as, $\Phi^{**} = \underset{j=1,2,\ldots,M_{STX}}{\operatorname{argmin}} (\mathrm{SEP}(\|\tilde{\mathbf{H}}_{\mathrm{SU}}(:,\mathrm{j})\|_2) + \lambda\|\mathbf{H}_{\mathrm{PS}}(:,\mathrm{j})\|_2)$ where, $\mathbf{H}_{PS}(:,j)$ is a vector with all the channel gains corresponding to the jth transmit antenna from the channel matrix, $\mathbf{H}_{PS}$. The Chernoff upper bound of the SEP(x) for MPSK is given by [18]

$$\mathrm{SEP(x)} \le \mathrm{m}\exp(-\mathrm{x}\mathrm{P_t}\sin^2(\pi/\mathrm{M})/\mathrm{N_0}) \tag{13}$$

where P_t is the transmit power N_0 is the noise variance, M represents constellation number and $m = 1 - \frac{1}{M}$. Note that Φ^{**} is a vector which contains the index of the subset of antennas selected. The selected antennas are arranged in the same ascending order and the resulting interference is the average interference, $\Gamma_{avg} = Tr(\mathbf{H}_{PS\Phi^{**}} diag([\sqrt{P_1}, \ldots, \sqrt{P_L}], 0)_{\Phi^{**}} \mathbf{H}^H_{PS\Phi^{**}})$.

Finally, the actual transmit antenna selection (AS) rule selects the subset of transmit antennas based on,

$$\Phi_t^* = \begin{cases} \underset{j=1,2,\ldots,M_{STX}}{\operatorname{argmax}} \left(\|\tilde{\mathbf{H}}_{SU}(:,j)\|_2\right), & if \, \Gamma_{un} \le \Gamma_{avg} \\ \underset{j=1,2,\ldots,M_{STX}}{\operatorname{argmin}} \left(s_i + \lambda \|\mathbf{H}_{PS}(:,j)\|_2\right), & if \, \Gamma_{un} > \Gamma_{avg} \end{cases} \tag{14}$$

where $s_i = \mathrm{SEP}(\|\tilde{\mathbf{H}}_{\mathrm{SU}}(:,\mathrm{j})\|_2)$. Φ_t^* is a vector which contains the index of the subset of transmit antennas selected (Table 1).

3.2 Receive Antenna Selection

For the case of receive AS the norm based selection rule is used. Maximizing the norm results in maximizing the capacity.We begin the receive AS from the new matrix, $\ddot{\mathbf{H}}_{TX}$. The subset of selected receive antennas is given by,

$$\Phi_r^* = \underset{i=1,2,\ldots,N_{SRX}}{\operatorname{argmax}} \left(\|\ddot{\mathbf{H}}_{TX}(i,:)\|_2\right) \tag{15}$$

where $\ddot{\mathbf{H}}_{TX}(i,:)$ is a vector which contains all the channel gains corresponding to the ith receive antenna from the new channel matrix $\ddot{\mathbf{H}}_{TX}$ and Φ_r^* is a vector which contains the index of selected receive antennas. The selected antennas are arranged in the same descending order (Table 2).

3.3 Partial Channel Projection Method

In this section, the partial channel projection method [10] is studied to solve the problem of finding transmit covariance matrix A to further maximize the capacity and to satisfy the interference constraint at the PRX. This algorithm projects $\mathbf{H}_{SU}$ into the space orthogonal

Table 1 Steps for transmit antenna selection

1.	Allocate transmit power for all transmit antennas based on (12)
2.	Select the subset of the transmit antenna based on (14) and obtain the new $\ddot{\mathbf{H}}_{TX}$ from $\mathbf{H}_{SU}$ by keeping only the columns corresponding to L transmit antennas from Φ_t^*
3.	Update the selection matrix $\mathbf{S}_2$ by assigning 1 in the diagonal element corresponding to the index of the antenna selected

Table 2 Steps for receive antenna selection

1.	Select the subset of receive antennas based on (15) and obtain the new $\ddot{\mathbf{H}}_{TXRX}$ from $\ddot{\mathbf{H}}_{TX}$ by keeping the rows corresponding to R receive antennas
2.	Update the selection matrix $\mathbf{S}_1$ by assigning 1 in the diagonal element corresponding to the index of the antenna selected

to the primary receiver channels. The optimal $\mathbf{A}$ is then found based on the SVD of the projected channel.

From Fig. 1 $\mathbf{H}_{PS}$ is the channel from CR_{TX} to PRX i.e.$\mathbf{H}_{PS} \in \mathbb{C}^{(N_{PRX} \times M_{STX})}$. Let g_j be the jth row of $\mathbf{H}_{PS}$. Define $g_j = \frac{g_j}{\omega_j}, \forall j$. Then $\mathbf{G}$ is defined as, $\mathbf{G} = [g_1^T, \ldots, g_{N_{PRX}}^T]^T$. The SVD of $\mathbf{G}$ is denoted as $\mathbf{G} = \mathbf{U}_G \Delta_G V_G^H$. The singular values of Δ_G are arranged in descending order. The projection of $\mathbf{H}_{PS}$ into the null space of $\mathbf{G}^H$ is $\mathbf{H}_{PS\perp} = \mathbf{H}_{PS}(1 - V_G^l (V_G^l)^H)$,where, V_G^l consist of first l columns of V_G. l represents the number of SU to PU channel dimensions to be null. According to partial channel projection algorithm, the precoding matrix which completely remove the interference at the PRX, is obtained from the SVD of $\mathbf{H}_{PS\perp}$.

Let the SVD of $\mathbf{H}_{PS\perp}$ is $\mathbf{H}_{PS\perp} = \mathbf{U}\Delta\mathbf{V}^H$. Now the transmit covariance matrix $\mathbf{A}$ is in the form of $\mathbf{A} = \mathbf{V}\Sigma\mathbf{V}^H$ where, $\mathbf{V}$ is obtained from the SVD of $\mathbf{H}_{PS\perp}$ and Σ is the power allocation matrix. The optimal power allocation for these subchannels is obtained using water-filling algorithm with $\mathbb{E}[\mathbf{x}\mathbf{x}^H] = P_{CR}$ at time instant n.

4 Performance Analysis

We now derive the CDF of the SNR for single AS based on constrained rule (minimum SEP rule). Let h_{ij} and $\tilde{h}_{ij}$ denote the entries of $\mathbf{H}_{CR}$ and $\mathbf{H}_{PS}$ respectively. $|h_{ij}|^2 \forall_{i,j}$ are exponentially distributed with unit mean and $|\tilde{h}_{ij}|^2 \forall_{i,j}$ are exponentially distributed with mean $1/\lambda_i = \alpha, \forall i = 1, \ldots N_{PRX}$. The SNR for the selected link according to the constrained rule is,

$$Y = \min_{i,j} P_j \left(SEP\left(|h_{ij}|^2 \right) + \lambda |\tilde{h}_{ij}|^2 \right) \tag{16}$$

The CDF of Y is,

$$\begin{aligned} F_Y(y) &= \mathbb{P}(Y \leq y) \\ &= 1 - \mathbb{P}(Y \geq y) \\ &= 1 - \mathbb{E}\left[\mathbb{P}\left(SEP\left(|h_{ij}|^2 \right) + \lambda |\tilde{h}_{ij}|^2 \geq y/P_j \right) \right], \quad \forall_{i,j} \\ &= \mathbb{E}\left[\mathbb{P}\left(SEP\left(|h_{ij}|^2 \right) + \lambda |\tilde{h}_{ij}|^2 \leq y/P_j \right) \right] \end{aligned} \tag{17}$$

Let

$$\begin{aligned} U &= SEP\left(|h_{ij}|^2 \right) + \lambda |\tilde{h}_{ij}|^2 \\ &= \left(1 - \frac{1}{M} \right) exp\left(-|h_{ij}|^2 \frac{P_t}{N_0} sin^2(\pi/M) \right) + \lambda |\tilde{h}_{ij}|^2 \end{aligned}$$

Assume, $a = \frac{P_t}{N_0} sin^2(\pi/M)); X = a * |h_{ij}|^2; Z = \lambda |\tilde{h}_{ij}|^2$. The pdf of X and Z are, $f_X(x) = \frac{1}{a} e^{-\frac{x}{a}}; f_Z(z) = \frac{1}{\alpha\lambda} e^{-\frac{z}{\alpha\lambda}}$.

$|h_{ij}|^2$ and $|\tilde{h}_{ij}|^2$ are independent. Therefore the joint PDF is, $f_{X,Z}(x,z) = \frac{1}{a\alpha\lambda} e^{-\left(\frac{x}{a} + \frac{z}{\alpha\lambda}\right)}$. Let $P = X$, and after performing Jacobian transformation $f_{U,P}(u,p) = 1 * \frac{1}{a\alpha\lambda} e^{-\left(\frac{x}{a} + \frac{z}{\alpha\lambda}\right)} = \frac{1}{a\alpha\lambda} e^{\frac{-p}{a}} e^{\frac{-u}{\alpha\lambda}} e^{\frac{\left(1-\frac{1}{M}\right)}{\alpha\lambda} e^{-p}}$. Therefore $f_U(u)$ is,

$$f_U(u) = \int_0^\infty \frac{1}{a\alpha\lambda} e^{\frac{-p}{a}} e^{\frac{-u}{\alpha\lambda}} e^{\frac{\left(1-\frac{1}{M}\right)}{\alpha\lambda} e^{-p}} dp$$
$$= \frac{e^{-\frac{u}{\alpha\lambda}}}{\alpha\lambda} * B$$

where $B = \left[\frac{\left((-1)^a\left(\frac{1-1/M}{\alpha\lambda}\right)\right)^{-1/a}\left(\Gamma(1/a)-\Gamma\left(\frac{1}{a},(-1)^a\left(\frac{1-1/M}{\alpha\lambda}\right)\right)\right)}{a}\right]$; $\Gamma(x)$ is the gamma function and $\Gamma(a,x)$ is the incomplete gamma function. Now, the CDF of U is $F_U^u = \int_0^u F_U^u du = B[1 - e^{-u/\alpha\lambda}]$. Substituting the result in (17),

$$\begin{aligned} F_Y(y) &= \mathbb{E}\left[\prod_{i,j} B\left[1 - e^{-y/\alpha\lambda P_j}\right]\right] \\ &= \prod_{j=1}^{M_{STX}} \mathbb{E}\left[B\left[1 - e^{-y/\alpha\lambda P_j}\right]\right]^{N_{SRX}} \\ &= \left[\mathbb{E}\left[B\left[1 - e^{-y/\alpha\lambda P_j}\right]\right]^{N_{SRX}}\right]^{M_{STX}} \\ &= \left[\sum_{n=0}^{N_{SRX}} \binom{N_{SRX}}{n} (-1)^n \mathbb{E}[e^{-ny/\alpha\lambda P_j}] B^{N_{SRX}}\right]^{M_{STX}} \end{aligned} \tag{18}$$

Let $K = \max_i |\tilde{h}_{ij}|^2$

$$\begin{aligned} F_K(k) = \mathbb{P}(K \le k) &= \mathbb{P}(|\tilde{h}_{ij}|^2 \le k), \forall i \\ &= \prod_{i=1}^{N_{PRX}} (1 - e^{-k/\alpha}) \\ f_K(k) = \frac{d}{dk}\left(1 - e^{-k/\alpha}\right)^{N_{PRX}} &= \frac{N_{PRX}}{\alpha}\left(1 - e^{-k/\alpha}\right)^{N_{PRX}-1} \end{aligned} \tag{19}$$

Therefore,

$$\mathbb{E}[e^{-ny/\alpha\lambda P_j}] = \int e^{-ny/\alpha\lambda P_j} f_K(k) dk \tag{20}$$

According to the power assigned for the TX antennas $P_j = P_{CR}$ when $k < \omega/P_{CR}$ and $P_j = \frac{\omega}{k}$ when $k > \omega/P_{CR}$. Substituting these limits in (20)

$$\begin{aligned}
\mathbb{E}[e^{-ny/\alpha\lambda P_j}] &= \int_0^{\frac{\omega}{P_{CR}}} e^{-ny/\alpha\lambda P_j} f_K(k)dk + \int_{\frac{\omega}{P_{CR}}}^{\infty} e^{-ny/\alpha\lambda P_j} f_K(k)dk \\
&= e^{-ny/\alpha\lambda P_{CR}} F_K\left(\frac{\omega}{P_{CR}}\right) + \int_{\frac{\omega}{P_{CR}}}^{\infty} e^{-nyk/\alpha\lambda\omega} \frac{N_{PRX}}{\alpha}\left(1-e^{-k/\alpha}\right)^{N_{PRX}-1} dk \\
&= e^{-ny/\alpha\lambda P_{CR}} F_K\left(\frac{\omega}{P_{CR}}\right) \\
&\quad + \frac{N_{PRX}}{\alpha}\sum_{r=0}^{N_{PRX}-1}(-1)^r \binom{N_{PRX}-1}{r}\left[\frac{e^{-\left(\frac{ny}{\omega\alpha\lambda}+\frac{r}{\alpha}\right)\frac{\omega}{P_{CR}}}}{\left(\frac{ny}{\omega\alpha\lambda}+\frac{r}{\alpha}\right)}\right]
\end{aligned} \tag{21}$$

Thus the CDF of the SNR expression for the selected SISO link is,

$$\begin{aligned}
F_Y(y) = \Bigg[\sum_{n=0}^{N_{SRX}} \binom{N_{SRX}-1}{n}(-1)^n \Bigg[e^{-ny/\alpha\lambda P_{CR}} F_K\left(\frac{\omega}{P_{CR}}\right) \\
+ \frac{N_{PRX}}{\alpha}\sum_{r=0}^{N_{PRX}-1}(-1)^r \binom{N_{PRX}-1}{r}\left[\frac{e^{-\left(\frac{ny}{\omega\alpha\lambda}+\frac{r}{\alpha}\right)\frac{\omega}{P_{CR}}}}{\left(\frac{ny}{\omega\alpha\lambda}+\frac{r}{\alpha}\right)}\right]\Bigg] B^{N_{SRX}}\Bigg]^{M_{STX}}
\end{aligned} \tag{22}$$

5 Simulation Results

In this section, we present the performance of proposed AS algorithm in terms of the following performance measures such as ergodic rates, SEP and CDF of the achievable rates with respect to SNR. All the results are obtained by averaging over 1000 channel realizations. We have assumed the parameter α as the SNR of PU, β as the noise variance at PRX, N_0 as the noise variance at SRX. Therefore, the interference constraint parameter ω is written as $\omega = \beta \mathrm{SNR}_{\mathrm{PU}}$. QPSK type of modulation is assumed at the transmitter.

Figure 2 shows the plots of ergodic rates Vs SNR for different systems. For this graph we assumed $\alpha = 0.5$, $\beta = 0.1$ and $N_0 = 0.05$. In particular, for all the curves, using the proposed AS method we select the best 2×2 antenna subsystem from $3 \times 3, 4 \times 4$ and 5×5 MIMO channels. The ergodic rates of 2×2 system with-PU and without-PU are also plotted for comparison. The results clearly indicate that the proposed AS method subject to interference constraints yields larger ergodic rates than the CR MIMO system without AS. Also if we reduce α from 0.5 to 0.1, (assume the case of 2×2 AS from 4×4 MIMO) the resultant curve shows substantial increase in ergodic rate.

Figure 3 presents the analysis of partial channel projection method for different values of l (no of SU to PU channel dimensions to be nulled) in terms of achievable ergodic rates. All the curves correspond to 2×2 AS from 4×4 MIMO with $\alpha = 0.5, \beta = 0.1$ and $N_0 = 0.05$. Choosing $l = 1$ yields larger ergodic rates than for all other cases.

Figure 4 compares the proposed AS algorithms with other AS algorithms such as MIMO-AS using selection matrix in [17], subset selection [15], and simple norm based method. The 2×2 AS from 5×5 MIMO is considered. We performed the subset selection method in the following way. First using norm based selection; we found the best 3×3 subset from 5×5 MIMO. Then an exhaustive search is performed over all 9 possible 2×2 combinations to select the best 2×2. The proposed AS algorithm outperforms the other

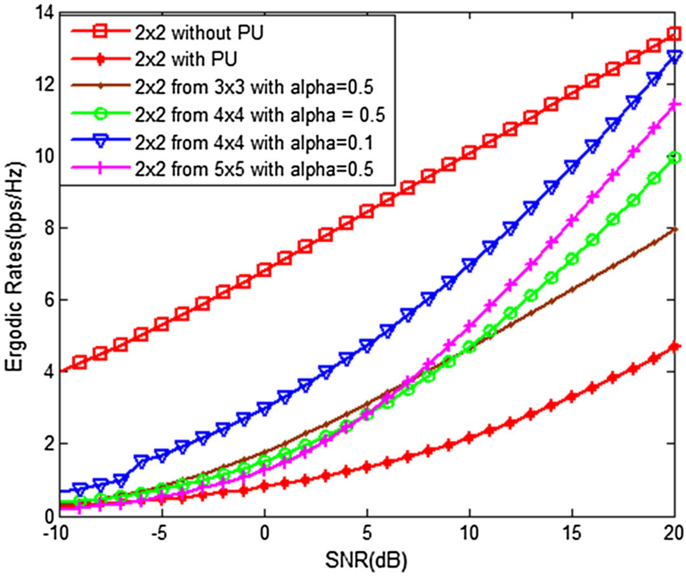

Fig. 2 Ergodic rates versus SNR for different system sizes

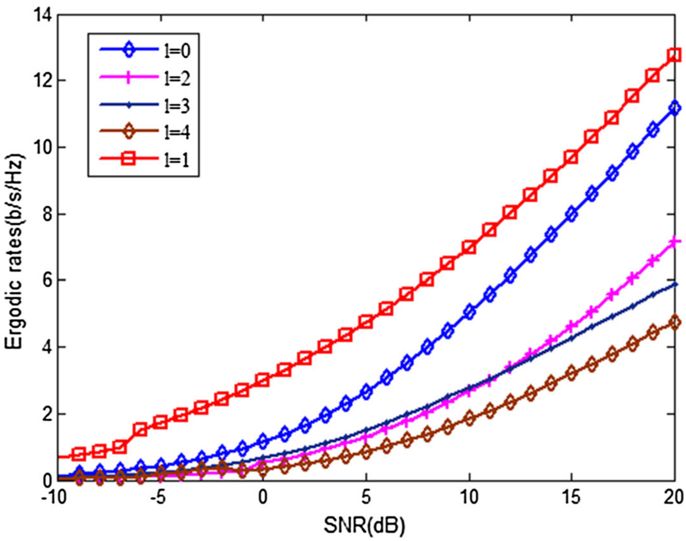

Fig. 3 Ergodic rates versus SNR comparison of different values of l for finding the optimal transmit covariance matrix Via partial channel projection method

methods of AS. Also at low SNR the proposed method gains considerable improvement in ergodic rates. For SNR= 0dB, the ergodic rates obtained by the proposed AS method is around 2 bps/Hz which is further increases drastically with increase in SNR. But for the other methods (Simple norm and subset selection), the ergodic rate is increased only after SNR = 5dB.

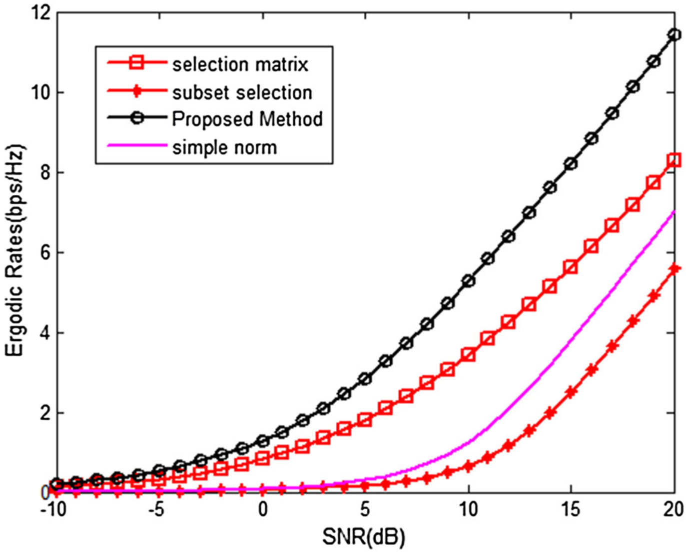

Fig. 4 Ergodic rates versus SNR for different AS methods (2×2 AS from 5×5 MIMO)

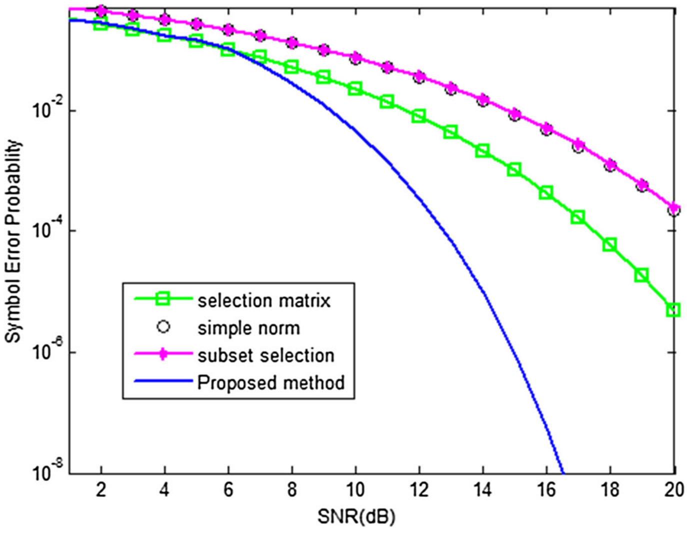

Fig. 5 SEP versus SNR for different AS methods (2×2 AS from 5×5 MIMO, $\lambda = 0.05$)

Figure 5 shows the SEP Vs SNR for different AS methods. The proposed AS method with $\alpha = 0.1, \beta = 0.1$ and $N_0 = 0.05, \lambda = 0.05$ results in very low SEP when compared with other AS methods. For SNR=10dB the SEP obtained by our proposed method is 10^{-3}.

Figure 6 shows the plot of SEP Vs SNR for different values of λ (lambda) for the 2×2 AS from 4×4 MIMO. $\lambda = 0$ corresponds to unconstrained rule. As λ increases SEP increases due to tighter average interference constraint. In Fig. 7 we present the CDF of the

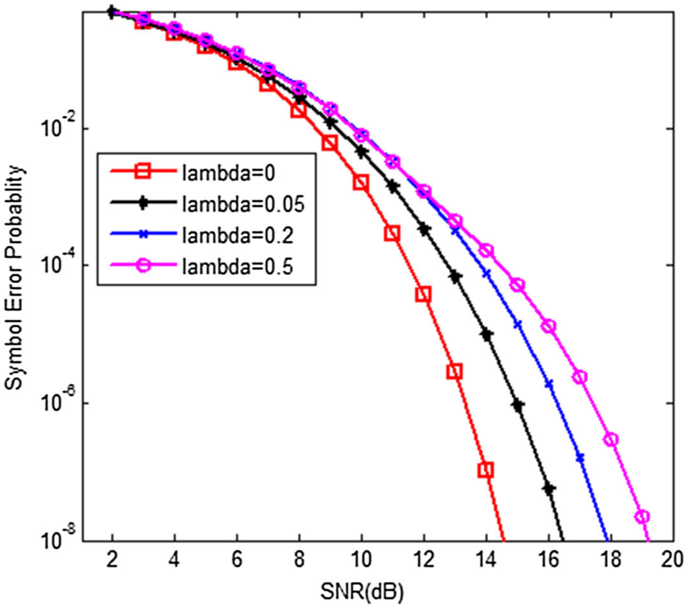

Fig. 6 SEP versus SNR for different values of λ (lambda) (2×2 AS from 4×4 MIMO)

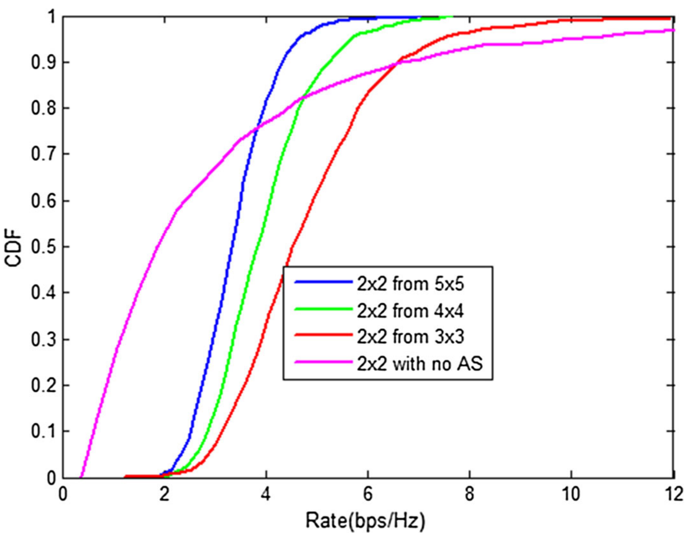

Fig. 7 CDF versus rate for different system sizes. (SNR $=$ 10 dB)

ergodic rate analysis of the proposed AS method. We performed this CDF analysis for SNR of 10dB. Also the CDF of the ergodic rate analysis for SNR of 20dB is presented in Fig. 8.

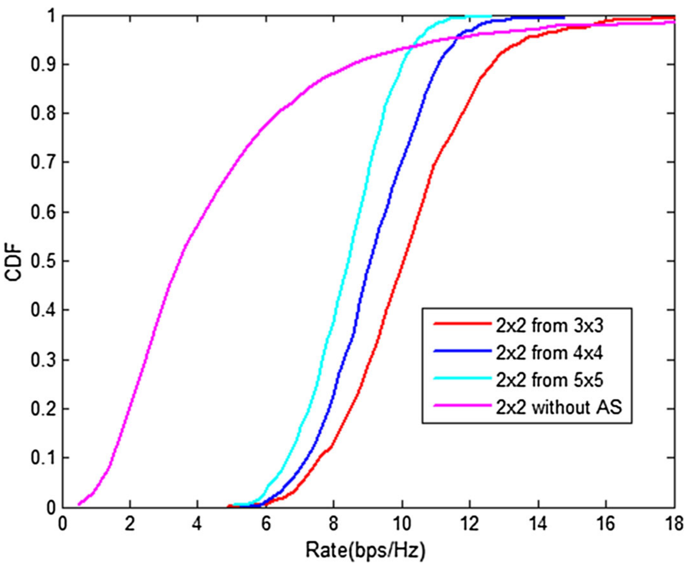

Fig. 8 CDF versus rate for different system sizes. (SNR = 20 dB)

6 Conclusion

In this paper an efficient Antenna selection algorithm which jointly selects multiple antennas at the transmitter and receiver in a constrained manner is proposed. We first present the transmit antenna selection algorithm which compares the unconstrained and average interference, which results in minimum SEP at SRX and maximum capacity. Next, we present the receive antenna selection algorithm based on maximum norm approach. Finally, the optimum transmit covariance matrix to maximize the ergodic rates of the proposed joint transmit and receive antenna selection is found using partial channel projection algorithm. In addition, we derived the CDF of the SNR of the selected SISO link based on the constrained rule. We present the simulation results of the proposed AS method for different antenna configurations. Also we compare our proposed AS method with other AS methods. The results show that there is a considerable improvement in the performance of the proposed AS methods in terms of SNR.

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