Opportunistic Spatio-Frequency Access in CR-MIMO System Exploiting Primary Transmission Mode Information

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***Abstract*—An opportunistic spatio-frequency access (OSFA) strategy for cognitive radio (CR) multi-input multi-output (MIMO) system is proposed. When spectrum holes exist, cognitive service is implemented employing overlay approach. While there is no idle spectrum available, primary transmission mode information (PTMI) and inter-system interference channel information are utilized. And cognitive service is implemented using spectrum underlay. The method exploits both spatial correlation and eigenmode transmission gain in evaluation the quality of spatial resource. Consequently, selection diversity of both authorized channel and cognitive eigenmode is achieved. Moreover, PTMI based signal processing reduces the power loss of cognitive signal as well as antenna requirements for cognitive system. Simulation results show that the proposed strategy could achieve significant improvement of cognitive throughput on the premise that no interference is imposed on the primary.**

I. Introduction

Recently, significant attention is paid to dynamic spectrum sharing (DSS) due to the facts that (a) there is common belief that we are running out of the radio frequencies available for new wireless applications and (b) actual spectrum usage measurement shows that at any time and location much of the allocated spectrum lies idle. This paradox indicates that spectrum shortage results from the management policy rather than the physical scarcity of usable frequencies [1].

The concept of DSS is to allow new applications to share currently allocated spectrum on the premise that the quality of service of spectrum owner (legacy system) is guaranteed. There are two basic approaches to implement DSS: spectrum underlay and spectrum overlay [2]. The underlay approach allows the secondary to access spectrum continuously, however it imposes severe constraints on the transmission power of secondary users. Differing from spectrum underlay, the overlay approach does not necessarily impose severe restrictions on the transmission power of secondary users. But it has to decide when and where to carry out secondary transmission by accurate spectrum environment sensing. Moreover, in the underlay strategy the secondary must satisfy the interference threshold even though the primary transmitter is idle. Consequently, the potential spectrum opportunities which could have been utilized by properly monitoring the activity of primary network are ignored. The overlay approach does not take the interference tolerability of primary system into account, thus ignores the possibility of system coexistence. Both strategies are not perfect in spectrum resource management.

Cognitive radio that adapts to electromagnetic environment is of important research significance in DSS [3]. As researches go deep and broad, some works introduce MIMO techniques into CR. By exploiting signal processing ability in spatial domain, novel spectrum sensing and sharing schemes are designed [4–7]. Among these works, [4] proposes a multi-antenna based spectrum sensing method. [5] investigates cognitive MIMO communications based on game theory. [6] designs CR-MIMO uplink transmission by expanding frequency spectrum hole to spatial domain opportunity. However, the scheme in [6] works under the condition that primary and secondary service have common destination, i.e. channel matrices of primary and cognitive transmission are identical so that space alignment is achieved. In [7] a combination of spectrum overlay and underlay for CR-MIMO system is proposed. In this method, signal processing algorithms are designed only based on the interference channel. This results in high demands on antenna number of cognitive system. Moreover, cognitive service fixedly adopts the principal eigenmode. All of the above leads to inappropriate resource management.

As a matter of fact, the status of spatial resource available for secondary users in multi-antenna system depends on the specific signal processing of primary system. In this paper, we exploit both inter-system interference channel information and primary transmission mode information to design a new heterogeneous strategy and achieves better resource management.

Notation: Bold-face letters are used to denote matrices and vectors. Let $\boldsymbol{X}^H$ and $\text{rank}(\boldsymbol{X})$ denote the Hermitian and rank of matrix $\boldsymbol{X}$. $|\cdot|$ and $\|\cdot\|$ indicate the scalar norm and the Euclidean norm, respectively. We define $\langle \boldsymbol{a}, \boldsymbol{b} \rangle$ as the inner product of vector $\boldsymbol{a}$ and $\boldsymbol{b}$.

II. System Model

Consider downlink transmission in a single cell system covered by one primary base station (PBS) and one cognitive base station (CBS) cooperatively as shown in Fig. 1. PBS communicates with multiple primary users (PU) through different authorized frequency channels. For simplicity there is only one cognitive user (CU), i.e. competition among CUs is not considered. The number of antennas for PBS and CBS are

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denoted as M_{BS}^p and M_{BS}^c, for PU and CU are M_U^p and M_U^c, respectively.

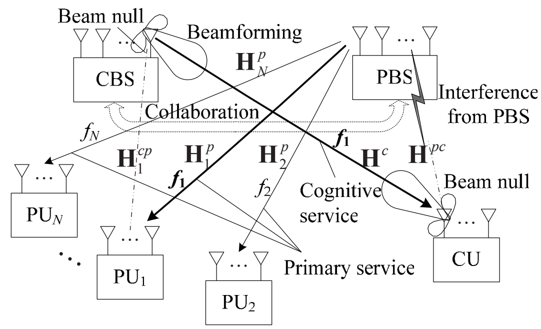


Fig. 1. System model.

The authorized spectrum consists of N channels. The channels are frequency non-selective fading. Assume all channels have identical bandwidth. One channel is designated to only one user at a time. Both PBS and CBS transmit to its subscribers according to a synchronous slot structure. The occupancy of the N channels follows a discrete-time Markov process with 2^N states [8]. The Markov model for an arbitrary channel i is illustrated in Fig. 2. The channel transits from state 0 (idle) to state 1 (busy) with probability α_i^p and stays in state 1 with probability β_i^p. Similarly, the traffic statistics of cognitive service follows another independent discrete-time Markov process whose transition probabilities are α^c and β^c respectively. As is known, $\alpha_i^{p(c)}$ and $\beta_i^{p(c)}$ indicate the heaviness of traffic load.

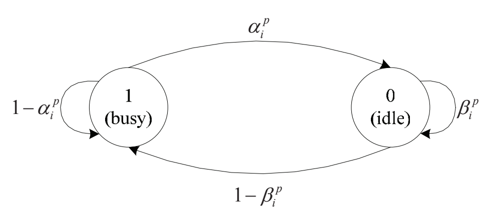


Fig. 2. Markov channel model.

In one slot, channel state information (CSI) between PBS and the PU who is occupying channel i (PU_i) is denoted as $\boldsymbol{H}_i^p$. Similarly, CSI between CBS and CU is $\boldsymbol{H}^c$, CSI between CBS and PU_i is $\boldsymbol{H}_i^{cp}$, and CSI between PBS and CU is $\boldsymbol{H}^{pc}$. Here the time index is omitted for simplicity. Note that our scheme is based on the collaboration between primary and cognitive (secondary) systems [9, 10]. We also assume that the channels are quasi-static, i.e. they remain unchanged during both the periods for obtaining CSI and exchanging information between certain entities. Both primary and cognitive system could obtain their channel information. All the links dedicated to channel information delivery are reliable.

III. Opportunistic Spatio-Frequency Access Exploiting PTMI

In this section an opportunistic spatio-frequency access strategy exploiting primary transmission mode information (OSFA-PTMI) is designed. Here PTMI refers to the information related to specific signal processing procedures of primary transmission such as transmit precoder and receive filter. When spectrum holes exist, cognitive service is implemented employing overlay approach. While there is no idle spectrum available, PTMI and inter-system interference channel information are exploited. And cognitive service is implemented using underlay approach. OSFA-PTMI is a combination of spectrum overlay and spectrum underlay. We focus on the design of underlay part. Assume that the primary service employs transmission mode adaptation of spatial multiplexing (SM) and beamforming (BF). Cognitive service adopts the same adaptation as the primary in spectrum overlay. As for spectrum underlay the cognitive should avoid disturbing PU and eliminate interference from PBS, thus BF is used to guarantee robustness in interference environment.

A. Basic Signal Processing

At first, basic signal processing in primary and secondary system is given. Take authorized channel i for example, the received signal at PU_i after transmit precoding and receive filtering is

$$\begin{aligned}\bar{\boldsymbol{y}}_i^p &= (\widetilde{\boldsymbol{U}}_i^p)^H \boldsymbol{H}_i^p \widetilde{\boldsymbol{V}}_i^p \boldsymbol{x}_i^p + (\widetilde{\boldsymbol{U}}_i^p)^H \boldsymbol{H}_i^{cp} \boldsymbol{P}^c x^c + (\widetilde{\boldsymbol{U}}_i^p)^H \boldsymbol{n} \\ &= \widetilde{\boldsymbol{\Lambda}}_i^p \boldsymbol{x}_i^p + \boldsymbol{M}_i^{e_1} \boldsymbol{P}^c x^c + (\widetilde{\boldsymbol{U}}_i^p)^H \boldsymbol{n}\end{aligned} \tag{1}$$

where $\boldsymbol{x}_i^p$ denotes transmit symbol (vector) of PBS and x^c is the transmit symbol of CBS. $\widetilde{\boldsymbol{V}}_i^p \subseteq \boldsymbol{V}_i^p$ and $\widetilde{\boldsymbol{U}}_i^p \subseteq \boldsymbol{U}_i^p$ are obtained from the singular value decomposition (SVD) of $\boldsymbol{H}_i^p$, $\boldsymbol{H}_i^p = \boldsymbol{U}_i^p \boldsymbol{\Lambda}_i^p (\boldsymbol{V}_i^p)^H$. They work as transmit precoder and receive filter. The number of columns in $\widetilde{\boldsymbol{V}}_i^p$ and $\widetilde{\boldsymbol{U}}_i^p$ is determined by the number of eigenmodes employed in primary transmission, which is denoted as m_i^p. when $m_i^p = 1$, primary service adopts BF. When $m_i^p > 1$, SM is employed. $\boldsymbol{n}$ is additive white Gaussian noise (AWGN) vector, whose element has variance σ_n^2. Note that cognitive service employs BF in spectrum underlay, the precoder at CBS is a vector denoted as $\boldsymbol{P}^c$. The second term in the right-hand side (RHS) of (1) indicates the interference from CBS. $\boldsymbol{P}^c$ should be designed such that $(\widetilde{\boldsymbol{U}}_i^p)^H \boldsymbol{H}_i^{pc} \boldsymbol{P}^c = \boldsymbol{0}$. The equivalent matrix $\boldsymbol{M}_i^{e_1}$ is obtained by combining the PTMI ($\boldsymbol{U}_i^p$) and interference channel (from CBS to PU_i) information $\boldsymbol{H}_i^{cp}$.

As for cognitive service who is sharing the ith frequency channel with the primary, the received signal at CU after signal processing is

$$\begin{aligned}\bar{y}^c &= (\boldsymbol{F}^c)^H \boldsymbol{H}^c \boldsymbol{P}^c x^c + (\boldsymbol{F}^c)^H \boldsymbol{H}^{pc} \widetilde{\boldsymbol{V}}_i^p \boldsymbol{x}_i^p + (\boldsymbol{F}^c)^H \boldsymbol{n} \\ &= (\boldsymbol{F}^c)^H \boldsymbol{H}^c \boldsymbol{P}^c x^c + (\boldsymbol{F}^c)^H \boldsymbol{M}_i^{e_2} \boldsymbol{x}_i^p + (\boldsymbol{F}^c)^H \boldsymbol{n}\end{aligned} \tag{2}$$

$\boldsymbol{F}^c$ denotes the filtering vector at CU. The second term in the RHS of (2) indicates the interference from PBS. $\boldsymbol{F}^c$ should be designed such that $(\boldsymbol{F}^c)^H \boldsymbol{H}^{pc} \widetilde{\boldsymbol{V}}_i^p = 0$. $\boldsymbol{M}_i^{e_2}$ is an equivalent matrix incorporating PTMI ($\widetilde{\boldsymbol{V}}_i^p$) and interference channel (from PBS to CU) information $\boldsymbol{H}^{pc}$. Similarly, define the number of eigenmodes employed in cognitive service as m^c.

$$R^c(\hat{i},\hat{j}) = \log_2\left(1+\frac{E^c\left((\boldsymbol{F}^c)^H\boldsymbol{H}^c\boldsymbol{P}^c\right)\left((\boldsymbol{F}^c)^H\boldsymbol{H}^c\boldsymbol{P}^c\right)^H}{E^p\left((\boldsymbol{F}^c)^H\boldsymbol{H}^{pc}\tilde{\boldsymbol{V}}^p_{\hat{i}}\right)\left((\boldsymbol{F}^c)^H\boldsymbol{H}^{pc}\tilde{\boldsymbol{V}}^p_{\hat{i}}\right)^H+\sigma_n^2}\right) = \log_2\left(1+\frac{E^c(\lambda^c_{\hat{j}})^2|\chi_{\hat{i},\hat{j}}|^2}{\sigma_n^2}\right) \tag{9}$$

B. Cognitive Signal Processing in Spectrum Underlay

According to (1) and (2), take interference elimination, cognitive service improvement and complexity constraints on cognitive terminal into consideration, we place main workload at CBS. Generally speaking, both interference cancellation (including the inter-system as well as intra-cognitive system) and transmit beamforming are implemented at CBS, whereas CU dedicates to the elimination of interference from PBS and receive beamforming.

The underlay strategy for cognitive is as follows.

Step 1) For each authorized frequency channel $i \in \{1,\cdots,N\}$ and cognitive eigenmode $j \in \{1,\cdots,\text{rank}(\boldsymbol{H}^c)\}$, apply SVD to $\boldsymbol{M}_i^{e_1}$ and $\boldsymbol{M}_i^{e_2}$, respectively. We have $\boldsymbol{M}_i^{e_1} = \boldsymbol{U}_i^{e_1}\boldsymbol{\Lambda}_i^{e_1}(\boldsymbol{V}_i^{e_1})^H$ and $\boldsymbol{M}_i^{e_2} = \boldsymbol{U}_i^{e_2}\boldsymbol{\Lambda}_i^{e_2}(\boldsymbol{V}_i^{e_2})^H$. For channel i and eigenmode j, CBS constructs matrix $\boldsymbol{T}_{i,j} = [\boldsymbol{v}^{e_1}_{i,1},\cdots,\boldsymbol{v}^{e_1}_{i,\text{rank}(\boldsymbol{M}_i^{e_1})},\boldsymbol{v}^c_1,\cdots,\boldsymbol{v}^c_{j-1},\boldsymbol{v}^c_{j+1},\cdots,\boldsymbol{v}^c_{\text{rank}(\boldsymbol{H}^c)}]$. Apply Gram-Schmidt orthogonalization to $\boldsymbol{T}_{i,j}$, we obtain $\overline{\boldsymbol{T}}_{i,j} = [\bar{\boldsymbol{t}}^{e_1}_{i,1},\cdots,\bar{\boldsymbol{t}}^{e_1}_{i,\text{rank}(\boldsymbol{M}_i^{e_1})},\bar{\boldsymbol{t}}^c_1,\cdots,\bar{\boldsymbol{t}}^c_{j-1},\bar{\boldsymbol{t}}^c_{j+1},\cdots,\bar{\boldsymbol{t}}^c_{\text{rank}(\boldsymbol{H}^c)}]$. CU constructs matrix $\boldsymbol{R}_{i,j} = \boldsymbol{U}_i^{e_2} = [\boldsymbol{u}^{e_2}_{i,1},\cdots,\boldsymbol{u}^{e_2}_{i,\text{rank}(\boldsymbol{M}_i^{e_2})}]$. Note that the vectors composing $\boldsymbol{R}_{i,j}$ form an orthonormal basis, introduce $\bar{\boldsymbol{R}}_{i,j} = \boldsymbol{R}_{i,j} = [\bar{\boldsymbol{r}}^{e_2}_{i,1},\cdots,\bar{\boldsymbol{r}}^{e_2}_{i,\text{rank}(\boldsymbol{M}_i^{e_2})}]$.

Step 2) Evaluate spatial resource quality according to (3).

$$Q_{i,j} = \lambda_j^c/(CO^{CBS}_{i,j}\cdot CO^{CU}_{i,j}) \tag{3}$$

where λ_j^c is the jth singular value of $\boldsymbol{H}^c$ indicating the transmission gain of the jth cognitive eigenmode. $CO^{CBS}_{i,j}$ and $CO^{CU}_{i,j}$ are the spatial correlation factors computed at CBS and CU, respectively.

$$CO^{CBS}_{i,j} = \sum_{m=1}^{\text{rank}(\boldsymbol{M}_i^{e_1})} |\langle \boldsymbol{v}^c_j, \bar{\boldsymbol{t}}^{e_1}_{i,m}\rangle| + \sum_{n\neq j}^{\text{rank}(\boldsymbol{H}^c)} |\langle \boldsymbol{v}^c_j, \bar{\boldsymbol{t}}^c_n\rangle| \tag{4}$$

$$CO^{CU}_{i,j} = \sum_{m=1}^{\text{rank}(\boldsymbol{M}_i^{e_2})} |\langle \boldsymbol{u}^c_j, \bar{\boldsymbol{r}}^{e_2}_{i,m}\rangle| \tag{5}$$

In terms of (4), $CO^{CBS}_{i,j}$ includes two parts. The first one is the spatial correlation between cognitive eigenmode j and effective interference from CBS to PU$_i$. The second part is the correlation between eigenmode j and all the other cognitive eigenmodes expect for j. According to (5), $CO^{CU}_{i,j}$ is determined by the spatial correlation between cognitive eigenmode j and effective interference from PBS to CU. Then we can conclude from (3) that $Q_{i,j}$ exploits both cognitive eigenmode gain and spatial correlation between cognitive transmission and inter-system as well as intra-cognitive system interference.

Step 3) Select channel $\hat{i}$ and eigenmode $\hat{j}$ according to (6) to implement cognitive service.

$$(\hat{i},\hat{j}) = \arg\max_{1\le i\le N, 1\le j\le \text{rank}(\boldsymbol{H}^c)}(Q_{i,j}) \tag{6}$$

From (6) it can be seen that selection diversity of both authorized channel and cognitive eigenmode is achieved. Signal processing procedures at CBS and CU are given in Step 4 and Step 5, respectively.

Step 4) Signal processing at CBS. Project $\boldsymbol{v}^c_{\hat{j}}$ onto the orthogonal subspace spanned by $\bar{\boldsymbol{T}}^c_{\hat{i},\hat{j}}$.

$$\tilde{\boldsymbol{v}}^c_{\hat{j}} = \boldsymbol{v}^c_{\hat{j}} - \sum_{m=1}^{\text{rank}(\boldsymbol{M}_{\hat{i}}^{e_1})} (\bar{\boldsymbol{t}}^{e_1}_{\hat{i},m})^H\boldsymbol{v}^c_{\hat{j}}\bar{\boldsymbol{t}}^{e_1}_{\hat{i},m} - \sum_{n\neq\hat{j}}^{\text{rank}(\boldsymbol{H}^c)} (\bar{\boldsymbol{t}}^c_n)^H\boldsymbol{v}^c_{\hat{j}}\bar{\boldsymbol{t}}^c_n \tag{7}$$

Normalize $\tilde{\boldsymbol{v}}^c_{\hat{j}}$, we have the precoding vector $\boldsymbol{P}^c = \tilde{\boldsymbol{v}}^c_{\hat{j}}/\|\tilde{\boldsymbol{v}}^c_{\hat{j}}\|$.

Step 5) Signal processing at CU. Project $u^c_{\hat{j}}$ onto the orthogonal subspace spanned by $\bar{\boldsymbol{R}}^c_{\hat{i},\hat{j}}$.

$$\tilde{\boldsymbol{u}}^c_{\hat{j}} = \boldsymbol{u}^c_{\hat{j}} - \sum_{m=1}^{\text{rank}(\boldsymbol{M}_{\hat{i}}^{e_2})} (\bar{\boldsymbol{r}}^{e_2}_{\hat{i},m})^H\boldsymbol{u}^c_{\hat{j}}\bar{\boldsymbol{r}}^{e_2}_{\hat{i},m} \tag{8}$$

Normalize $\tilde{\boldsymbol{u}}^c_{\hat{j}}$, we have the filtering vector $\boldsymbol{F}^c = \tilde{\boldsymbol{u}}^c_{\hat{j}}/\|\tilde{\boldsymbol{u}}^c_{\hat{j}}\|$.

According to the above strategy, the achievable rate of cognitive service in spectrum underlay is given in (9). $\chi_{\hat{i},\hat{j}} = (\boldsymbol{F}^c)^H\boldsymbol{u}^c_{\hat{j}}(\boldsymbol{v}^c_{\hat{j}})^H\boldsymbol{P}^c$. E^p and E^c denote the transmit power of PBS and CBS, respectively. For fairness, let $E^p = E^c$. Notice that $|\langle\boldsymbol{v}^c_{\hat{j}},\boldsymbol{P}^c\rangle|^2 < 1$ and $|\langle\boldsymbol{F}^c,\boldsymbol{u}^c_{\hat{j}}\rangle|^2 < 1$, in order to achieve harmless coexistence with the primary, degradation of the expected cognitive signal is resulted from the signal processing at CBS and CU.

C. Antenna Requirements for Cognitive System

According to the strategy in Section B, the implementation of cognitive service employing spectrum underlay is based on the spatial orthogonal projection. Whether non-zero solutions of $\boldsymbol{P}^c$ and $\boldsymbol{F}^c$ exist depends on the number of spatial eigenmodes employed in primary and secondary transmission as well as antenna configuration of cognitive system. In the following, we give a generalized discussion (m^c is not restricted to 1) on the antenna requirements for cognitive system.

Firstly, we discuss the condition on which $\boldsymbol{P}^c$ has non-zero solution. Define the set of eigenmodes employed by cognitive service as $J \in \{j_1,\cdots,j_{m^c}\}$. The design of $\boldsymbol{P}^c$ should meet the following requirements. On one hand, $\boldsymbol{P}^c$ should be orthogonal to $[\bar{\boldsymbol{t}}^{e_1}_{i,1},\cdots,\bar{\boldsymbol{t}}^{e_1}_{i,\text{rank}(\boldsymbol{M}_i^{e_1})}]$, such that CBS avoids disturbing PU$_i$. On the other hand, any column vector of $\boldsymbol{P}^c$, taking $j \in J$ for example, should be orthogonal to all the other eigenmodes $[\bar{\boldsymbol{t}}^c_1,\cdots,\bar{\boldsymbol{t}}^c_{j-1},\bar{\boldsymbol{t}}^c_{j+1},\cdots,\bar{\boldsymbol{t}}^c_{\text{rank}(\boldsymbol{H}^c)}]$ including both the ones used by cognitive service and those unused. Moreover, mutual orthogonality should be guaranteed between any two columns in $\boldsymbol{P}^c$. Based on the discussions above, the following inequality should hold.

$$M_{BS}^c \geq \text{rank}(\boldsymbol{M}_i^{e_1}) + m^c + (\text{rank}(\boldsymbol{H}^c) - m^c) \tag{10}$$

where $\text{rank}(\boldsymbol{M}_i^{e_1}) = \min(m_i^p, M_{BS}^c)$ and $\text{rank}(\boldsymbol{H}^c) = \min(M_{BS}^c, M_U^c)$. In order to have (10), $M_{BS}^c > m_i^p$ and $M_{BS}^c > M_U^c$ should hold. Then inequality (11) is obtained.

$$M_{BS}^c \geq m_i^p + M_U^c \tag{11}$$

Secondly, we discuss the condition on which $\boldsymbol{F}^c$ has non-zero solution. According to Section B, $\boldsymbol{F}^c$ is designed such that receive beamforming is implemented and interference from PBS is eliminated. In other word, $\boldsymbol{F}^c$ should match the transmit precoder and be orthogonal to the first m_i^p columns of $\bar{\boldsymbol{R}}_{i,j}$ (or $\bar{\boldsymbol{U}}_i^{e_2}$). Consequently, inequality (12) should hold.

$$M_U^c \geq m_i^p + m^c \tag{12}$$

Substitute (12) into (11) we obtain

$$M_{BS}^c \geq 2m_i^p + m^c \tag{13}$$

According to (12) and (13), it can be concluded that antenna requirements for cognitive system are determined by the transmission modes of primary and secondary service. Recall that the proposed strategy restrict m^c to 1 in underlay scenario. Substitute $m^c = 1$ into (12) and (13), we have Tab. I. For simplicity, let $m_i^p = \min(\text{rank}(M_{BS}^p, M_U^p), 2)$, i.e. at most two eigenmodes are used in primary transmission.

TABLE I
ANTENNA REQUIREMENTS FOR COGNITIVE SYSTEM

M_{BS}^p	1	1	2	2		4	4		4	
M_U^p	1	2	1	2		1	2		4	
m_i^p	1	1	1	1	2	1	1	2	1	2
M_{BS}^c	3	3	3	3	5	3	3	5	3	5
M_U^c	2	2	2	2	3	2	2	3	2	3

Compared with the results in [7], the antenna demands of cognitive system is significantly reduced and independent of M_{BS}^p and M_U^p.

IV. SIMULATION RESULTS

In this section, we use simulation results to demonstrate the advantages of proposed strategy. According to Tab. I, we adopt $M_{BS}^p = M_U^p = 2$, $M_{BS}^c = 5$ and $M_U^c = 3$. As is mentioned before, $m_i^p \in \{1, 2\}$. For simplicity, let $m^c \in \{1, 2\}$ in spectrum overlay; whereas in spectrum underlay $m^c = 1$. Simulation results under different antenna configurations are not shown, however the same conclusion can be drawn. We investigate four transmission strategies, traditional opportunistic frequency access (OFA), opportunistic spatio-frequency access (OSFA) based on [7] with modified spatial resource evaluation (i.e. both spatial correlation and cognitive eigenmode gain are exploited), the proposed OSFA-PTMI, and an exhaustive searching (ES) method which implements optimal selection of authorized channel and cognitive eigenmode.

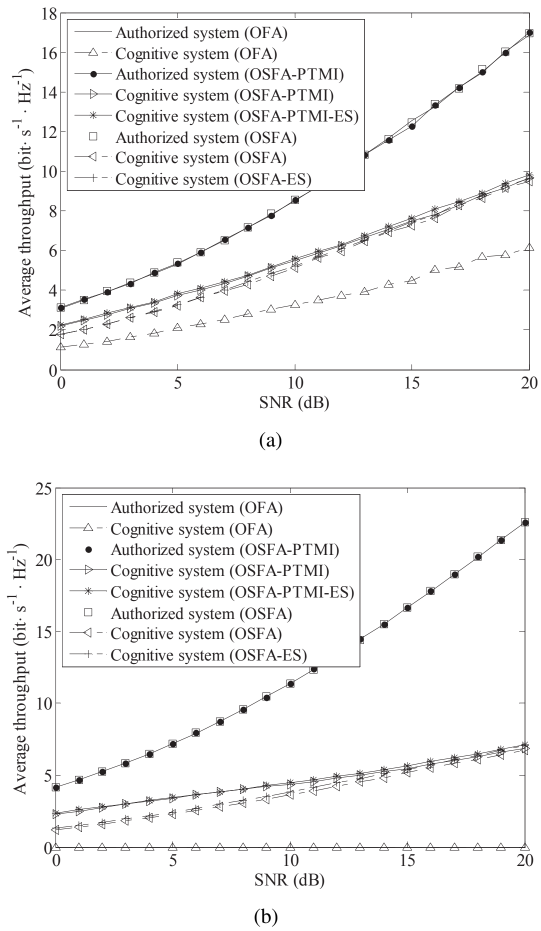
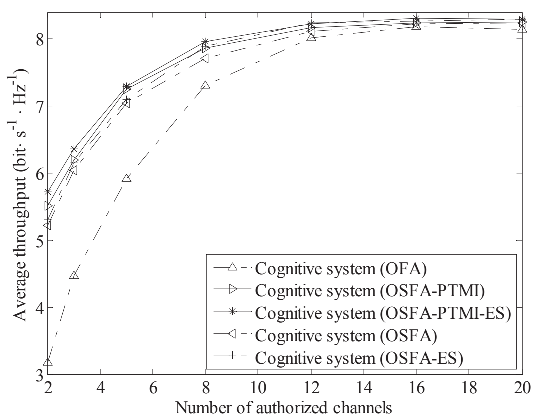
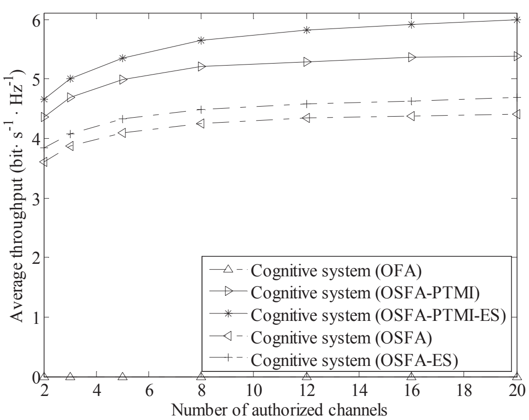


Fig. 3. Average throughput under $N = 2$.

In Fig. 3 throughputs of different strategies under $N = 2$ and different SNR are plotted. In Fig. 3(a) $\alpha_i^{p(c)} = 0.2$ and $\beta_i^{p(c)} = 0.4$, in Fig. 3(b) $\alpha_i^{p(c)} = 0$ and $\beta_i^{p(c)} = 0$ where $i = 1, \cdots, N$. Because signal processing at CBS guarantees that primary service is not affected by the cognitive, throughputs of authorized system with OSFA and OSFA-PTMI are statistically the same with that employing OFA. Throughputs of all the strategies increase with SNR. As for cognitive service, ES obtains the optimal throughput performance. OSFA and OSFA-PTMI exploit both spatial correlation and eigenmode transmission gain in evaluating spatial resource quality. Consequently, significant cognitive throughput enhancement is achieved compared with OFA. Moreover, OSFA-PTMI exploits PTMI in signal processing design thus outperforms OSFA. And both are close to ES. At low SNR, the advantage of OSFA-PTMI over OSFA is more obvious. This is because authorized service adopts BF with high probability. OSFA-PTMI implements signal processing based on equivalent matrices $\boldsymbol{M}_i^{e_1}$ and $\boldsymbol{M}_i^{e_2}$. The degradation of cognitive signal with OSFA-PTMI is lower than that with OSFA who carries out signal processing in terms of interference channel $\boldsymbol{H}_i^{cp}$ and $\boldsymbol{H}^{pc}$. Along with increasing SNR, the probability that primary service employs SM becomes higher. The cognitive power loss with OSFA-PTMI approximates to that with OSFA, thus throughput performance of both strategies are closing to each other at high SNR. Note that Fig. 3(b) is obtained in the extreme case where both primary and cognitive are busy all the time. As shown in the figure, OFA could not work. It can be concluded that the heavier the traffic load, the more significant improvement of cognitive throughput is achieved by using OSFA and OSFA-PTMI compared with OFA.



(a)



(b)

Fig. 4. Average throughput under SNR $= 10$dB.

Fig. 4 plots the throughputs of different strategies under SNR=10dB and different N. In Fig. 4(a) $\alpha_i^{p(c)} = 0.2$ and $\beta_i^{p(c)} = 0.4$, in Fig. 4(b) $\alpha_i^{p(c)} = 0$ and $\beta_i^{p(c)} = 0$ where $i = 1, \cdots, N$. As all methods guarantee that authorized service is protected from disturbing by the cognitive, only cognitive throughput is under investigation. From Fig. 4(a) it can be seen that smaller N results in higher probability that no idle spectrum is available, OSFA and OSFA-PTMI achieve significant performance enhancement compared with OFA. As N increases, cognitive throughputs of all strategies enlarge and converge to an asymptotic value. This is because the probability that cognitive user could not access to idle frequency channel decreases with increasing N. Consequently, when N is large enough cognitive user could obtain idle frequency channel with probability close to 1. Then overlay approach is employed. And the advantage of OSFA and OSFA-PTMI over OFA diminishes. As shown in Fig. 4(b), OFA could not work without spectrum hole. Due to the fact that the selection diversity gain of frequency channel enlarges with increasing N and goes saturate. Throughputs of OSFA-PTMI and OSFA increase with N and saturate at high N.

V. Conclusion

In this paper an opportunistic spatio-frequency access strategy (OSFA-PTMI) for CR-MIMO system is proposed. When spectrum holes exist, cognitive service is implemented using overlay approach. While there is no idle spectrum available, PTMI and inter-system interference channel information are exploited. And cognitive service is implemented using underlay approach. The method adopts both spatial correlation and eigenmode transmission gain in spatial resource quality evaluation. Consequently, selection diversity of both authorized channel and cognitive eigenmode is achieved. Moreover, PTMI based signal processing reduces antenna requirement for cognitive system as well as the power loss of cognitive signal. The proposed method could achieve significant improvement of cognitive throughput on the premise that no interference is imposed on the primary.

Acknowledgment

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